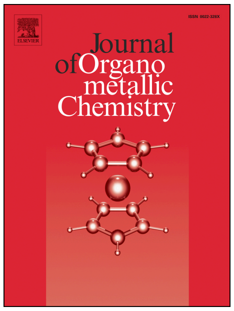

Catalytic application of zwitterionic palladium complexes in Mizoroki–Heck reactions using ionic liquid as solvent

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PII: S0022-328X(15)00302-2

DOI: 10.1016/j.jorganchem.2015.05.020

Reference: JOM 19058

To appear in: *Journal of Organometallic Chemistry*

Received Date: 23 January 2015

Revised Date: 5 May 2015

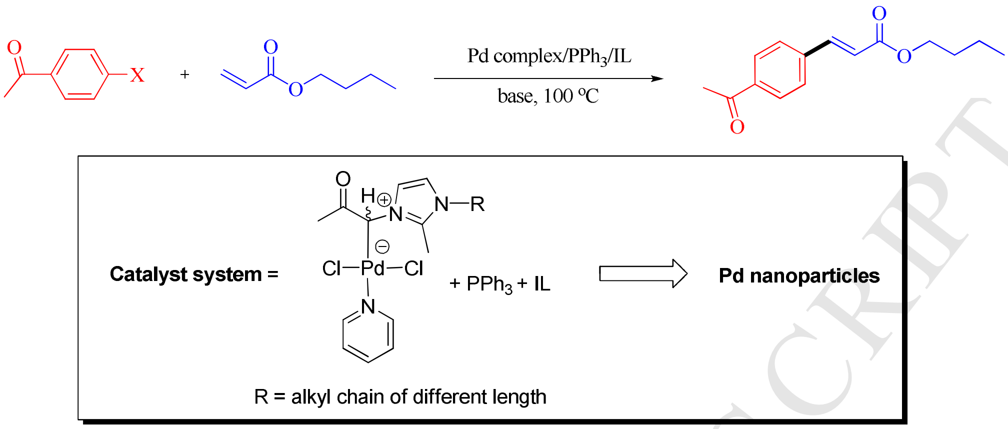
Accepted Date: 7 May 2015

Please cite this article as: Y.-P. Wang, H.M. Lee, Catalytic application of zwitterionic palladium complexes in Mizoroki–Heck reactions using ionic liquid as solvent, *Journal of Organometallic Chemistry* (2015), doi: 10.1016/j.jorganchem.2015.05.020.

Graphical abstract (synopsis)

By reacting 1-alkyl-2-methyl-1*H*-imidazoles with chloroacetone, we developed new ligand precursors with different pendent alky chain length. Novel zwitterionic complexes were synthesized by reacting $PdCl_2$ with these derivatives. The complexes formed effective recyclable catalyst systems for Mizoroki–Heck reactions in ILs. TEM revealed the formation of palladium nanoparticles during the catalytic process.

Graphical abstract (pictogram)



Catalytic application of zwitterionic palladium complexes in Mizoroki—Heck reactions using ionic liquid as solvent

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Abstract

New ligand precursors with different pendent alky chain length were obtained in a single step by reacting appropriate 1-alkyl-2-methyl-1*H*-imidazoles with chloroacetone in THF at 80 °C overnight. Zwitterionic palladium complexes were prepared by reacting $PdCl_2$ with these new imidazole derivatives in DMF with the presence of pyridine and Cs_2CO_3 as base at room temperature for 5 h. These new compounds were characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, elemental analysis, and electrospray ionization mass spectrometry. They were effectively applied as recyclable catalysts for mediating Mizoroki–Heck reactions in ionic liquids. Transmission emission microscopy revealed that palladium nanoparticles were formed during the catalytic process.

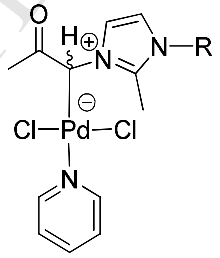
Keywords

Mizoroki-Heck reaction; Zwitterionic complexes; Palladium nanoparticles; Ionic liquids

Introduction

Ionic liquids (ILs) are salts with melting points below the boiling point of water and in their molten state they are composed of solely ions. Their properties such as the vapor pressure, thermal stability, solubility, solvating power can be tuned by varying the structures of cations/anions. The need for the development of sustainable processes leads to ILs being used as green solvents in a wide range of chemical processes.[1] In this context, ILs in particular those derived from imidazolium salts have been shown to be excellent stabilizing agents for monodispersed metal nanoparticles (NPs), preventing them from agglomeration to form bulk metal.[2,3] Examples of ILs which are commonly used for the stabilization of NPs are [bmim][BF_4] and [bmim][PF_6] (bmim = 1-butyl-3-methylimidazolium cation). Thus transition metal NPs in ILs have emerged as highly promising recyclable catalysts in a wide variety of organic processes, in particular, carbon–carbon bond-forming reactions.[2,4] Controlled thermal decomposition of $Pd(dba)_2$,[5] $Pd(OAc)_2$ or palladium carbene complexes[6] represented one of the convenient routes for the preparation of Pd NPs in ILs. Other common methods to produce metal NPs in IL are the reduction of metal precursors such as $PdCl_2$, Na_2PdCl_4 in the presence of hydrides or molecular hydrogen gas and from the reactions of palladacycles with dienes.[7] Thus the choice of metal precursor and reducing agent play key roles in influencing the reactivity and stability of metal NPs in IL. Lately, our group has been devoting efforts in developing zwitterionic palladium complexes based on imidazole derivatives[8] and we have established that these complexes were effective in catalyzing room temperature Suzuki cross-coupling of sterically hindered substrates in an aqueous medium.[8b] We envisioned that such zwitterionic complexes that exhibit formal charge separation within an overall neutral molecular framework[9] should exhibit good solubility in ILs (Chart 1). Also, the solubility of the complex could be further tuned by varying the alkyl chain length on the ligand scaffold. In the presence of a suitable reducing agent, IL stabilized Pd NPs should be formed. Herein, we detail the synthesis and characterization of the new ligand precursors and their transformation into zwitterionic palladium complexes. The ligand precursors were designed taking into the consideration of the cost and simplicity of the procedure. Their new zwitterionic complexes with good miscibility in IL were excellent precursors for the formation of Pd NPs in the presence of excess PPh_3. Pleasingly; these Pd NPs could be applied as recyclable catalysts in Mizoroki–Heck reactions. Catalyst recyclability up to 9 catalytic runs in the reaction between 4-iodoacetophenone and *n*-butyl acrylate could be achieved.

Chart 1.Target zwitterionic Pd(II) complexes for Mizoroki–Heck reactions in ionic liquid

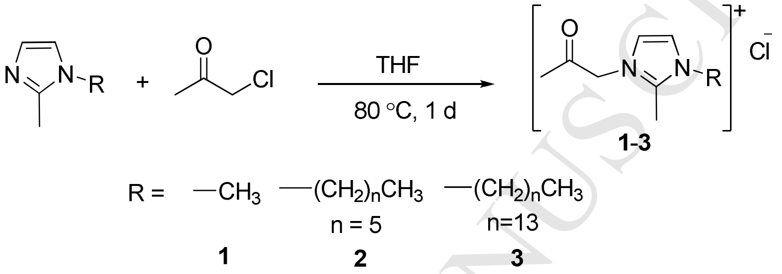


R = alkyl chain of different length

Results and discussion

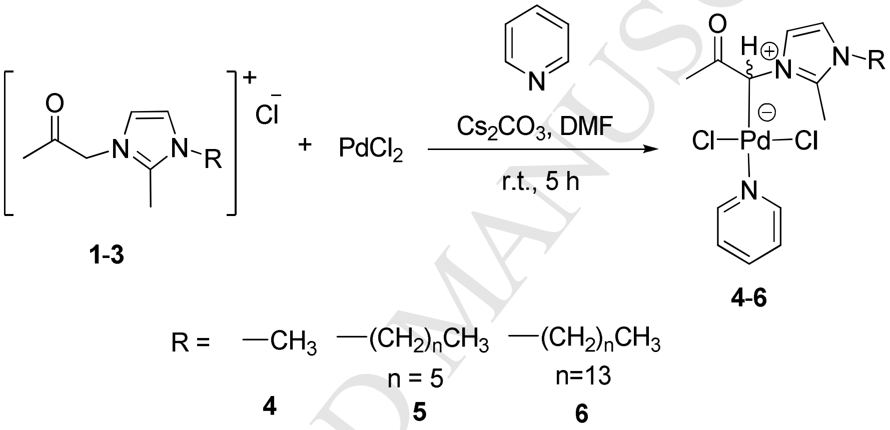
Syntheses of ligand precursors. Our target compounds were imidazole derivatives with **1** featuring a *N*-methyl group, whereas **2** and **3** possess long alkyl chains of 6 and 14 carbon atoms, respectively (Scheme 1). Each ligand precursor could be obtained in a single step by reacting appropriate

1-alkyl-2-methyl-1*H*-imidazole with chloroacetone in THF at 80 °C overnight (Scheme 1). Excellent product yields in the range of 89–95 % were obtained and in each case, viscous liquid was formed. In the ^{1}H NMR spectra, the characteristic methylene singlets for **1**–**3** were observed at 5.89, 5.97, and 5.70 ppm, respectively. The downfield chemical shifts for these signals reflected the acidic nature of the methylene protons. In the HRMS spectra of **1**–**3**, positive ions due to $[M – Cl]^{+}$ were observed.



Scheme 1. Synthesis of ligand precursors **1**-**3**.

Syntheses of zwitterionic palladium complexes. Zwitterionic palladium complexes **4**–**6** were prepared following our previous established procedures for similar compounds.[8b] The ligand precursors **1**–**3** were allowed to react with $PdCl_2$ in DMF with the presence of pyridine and Cs_2CO_3 as base at room temperature for 5 h. Amorphous solids were obtained for **1** and **2**, whereas **3** featuring a 14-carbon chain formed a viscous liquid. Decent yields of 70 and 78% were obtained for **5** and **6**, respectively. In contrast, only a poor yield of 11 % was obtained for **4**, despite attempts in tuning reaction parameters such as base, reaction time, and temperature. The successful coordination of the ligands to the Pd(II) ion was confirmed by the presence of a singlet corresponding to a single proton at 6.16, 6.19, and 6.19 ppm for **4**–**6**, respectively. Upon deprotonation and coordination to the metal ions, the C*H* proton were downfield shifted *ca*. 0.2–0.5 ppm with respect to the methylene signals of the ligand precursors (*vide supra*). The ^{13}C NMR signals for the coordinated carbons were observed at 41.1, 40.6, and 40.5 ppm, respectively. Although based on the NMR data, it is ambiguous with respect to the *cis* or *trans* conformation of these complexes, they were mostly likely in *trans* forms with reference to a vast amount of *trans*-$PdCl_2$ complex with pyridine reported in the literature.[8b,10] Attempts to obtain crystalline materials of **4–6** suitable for X-ray diffraction studies were, nevertheless, unsuccessful.



Scheme 2. Synthesis of palladium(II) NHC complexes **4–6**.

Catalytic reactions. Initially, to understand if our new complexes were effective precatalyst in mediating Mizorok–Heck reaction, we followed our previous published procedure using **5** as a representative example in the reaction of aryl halide with styrene.[11] The catalyst system utilized 0.5 mol% of **5** as precatalyst, sodium acetate as base, the molten salt of *n*-tetrabutylammonium bromide (TBAB) as solvent, a reaction temperature of 140 °C, and a reaction duration of 2 h, leading to the formation of coupled products in 88 and 47 % yields with 4-bromo and 4-chloroacetophenone, respectively (Table 1). Noteworthy, TBAB is an ionic salt but not a room temperature ionic liquid.

After confirming that the new complex was catalytically active, we started to screen the reaction parameters in the benchmark reaction between 4-bromoacetophenone and *n*-butyl acrylate (Table 2). The base of choice was triethylamine which gave a much superior yield of 95 % compared with 18, 38, 4, and 3 % delivered by NaOAc, $NaHCO_3$, and K_2CO_3, and Cs_2CO_3, respectively (entries 4 vs. 9–12). Next, we optimized the reaction time and as shown in entries 1–4, a reaction period of 12 h gave an optimum yield. The catalyst loading was evaluated in entries 4 and 6–8, revealing that a medium catalyst loading of 2.0 mol% delivered the best yield in 12 h. The choice of ILs was then screened and both [bmim]BF_4] and [bmim][PF_6] were found to give the same level of yields (entry 4 and 14). But taking into an account of the cost of the IL, [bmim][BF_4] was chosen for the subsequent investigations. The IL with a coordinating bromide ion, [bmim][Br], gave a poor product yield of 30 % only (entry 13). Importantly, Pd NPs were generated in situ by the reduction of the zwitterionic complexes with 4 mol% of PPh_3 during the catalytic process (*vide infra*). Without the addition of PPh_3, the product yield dropped significantly (entries 4 vs 5). Thus the optimized conditions of 2.0 mol% of catalyst precursor, 4.0 mol% of PPh_3, triethylamine as base, [bmim][BF_4] as solvent, a reaction temperature of 100 °C, and a heating duration of 12 h was established. With this optimized condition in our hands, the catalytic performance of **4**–**6** were investigated (Table 3). Entries 1 and 3 revealed that the precatalysts **4** and **6** featuring the *N*Me group and an alkyl chain of 14 carbons, respectively, gave the same level of product yields (>95 %), whereas the catalyst **5** with alky chain of 6 carbons gave a slightly lower yield of 89 % (entry 2).

The substrate scope of the new zwitterionic palladium precatalysts were thoroughly investigated in Table 4, using **5** as a representative example (Table 4). In general, employing *n*-butyl acrylate as coupling partner, the catalyst system was efficient towards a range of aryl iodide substrates affording yields in the range of 73–93 % (entries 1–5). Pleasingly, sterically hindered 2,4,6-trimethylphenyliodide and 2-iodoanisole were tolerated affording excellent yields of 90 % (entries 4 and 5). The catalyst system was less efficient towards aryl bromides, particularly, in case of substrates with electron-releasing and electron-neutral groups (entries 6 and 7). Mediocre yields of 48 and 44 % could be achieved with substrates bearing electron-withdrawing groups of cyano and acyl groups (entries 8 and 9). The catalyst system was also capable of utilizing styrene as coupling partner. As shown in entry 10, 4-iodoanisole coupled with styrene giving a good yield of 90 % and a high *trans* selectivity. Sterically hindered aryl iodides could also be used affording decent yields of 66 and 99 % (entries 11 and 12). However, low product yields were obtained with aryl bromide substrates (entries 13 and 14).

Finally, we investigated the reusability of the catalyst systems in the Mizoroki–Heck reaction of 4-iodoacetophenone and *n*-butyl acrylate under our optimized conditions. As shown in Table 5, among the three new complexes, Pd NPs derived from **4** featuring a simple *N*Me group offered the best reusability and it could be used for up to 9 catalytic runs without significant loss in activity. Notably, ligand-less $PdCl_2$ did show reasonable activity and reusability under the same catalytic conditions. However, as shown in Figure 1, the ligand did provide enhancement in product yields and recyclability of catalysts (blue vs. yellow curves). In the case of 4-bromoacetophenone as substrate, Pd NPs derived from **5** bearing a six-carbon chain provided the best reusability instead (Table 6). In the second catalytic run, still 89% yield of product could be achieved, whereas those derived from **4** and **6** afforded only 65 and 80% yield, respectively. The yields decreased drastically in the third run. Figure 2 clearly illustrated that NPs derived from **4–6** bearing ligands did provide significant enhancement in catalytic activity in comparison with that derived from ligandless $PdCl_2$ (see the yellow curve of $PdCl_2$ at the bottom).

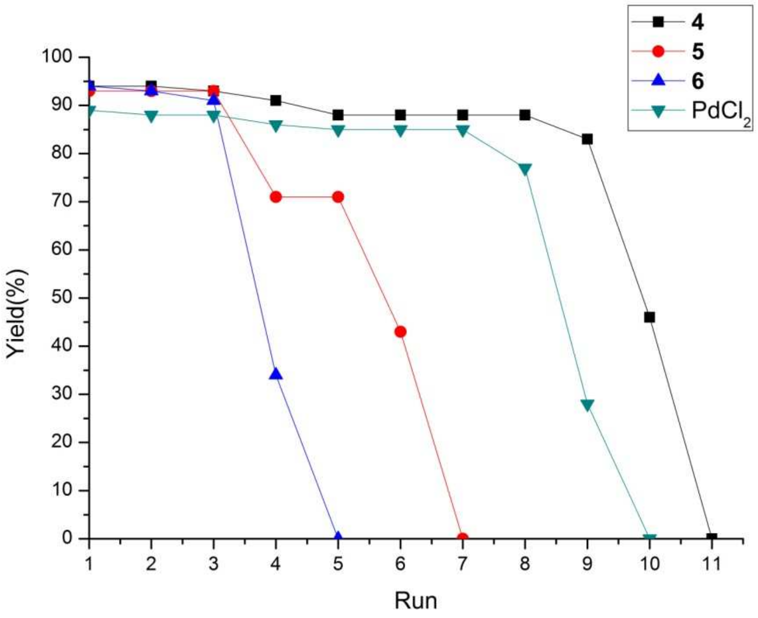


Figure 1. Recycle experiment of the Mizoroki–Heck Reaction of 4-iodoacetophenone with butyl acrylate Using Pd(II) Complexes **4–6** as Precatalysts.

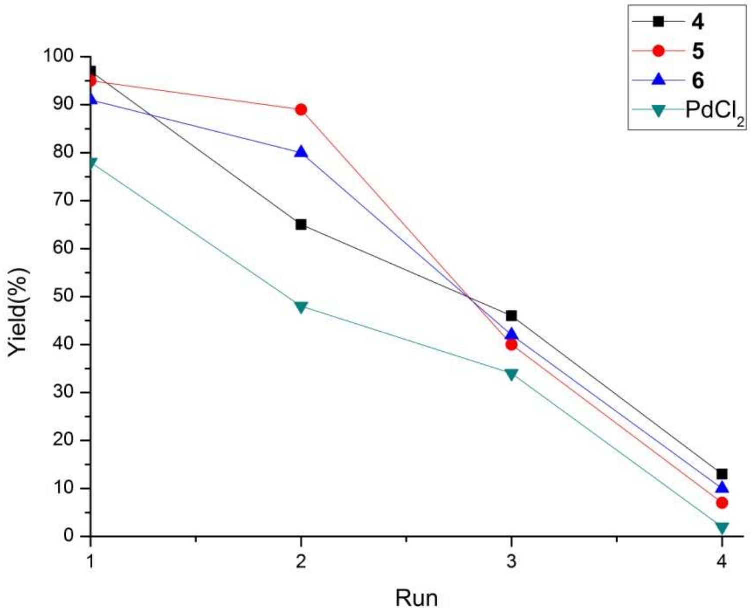


Figure 2. Recycle experiment of the Mizoroki–Heck Reaction of 4-bromoacetophenone with butyl acrylate catalyzed using Pd(II) complexes **4**–**6** as precatalysts.

Mechanistic aspects.

After the completion of the first catalytic run, the reaction mixture catalyzed by **4** appeared as a transparent reddish solution. This solution containing Pd NPs was revealed by the observation of Tyndall effect using a laser pointer (Figure 1S). Solid evidence came from the acquisition of a TEM image (Figure 1), revealing the average size of Pd NPs in **4**, **5**, and **6** to be ca. 5.5, 4.6, and 2.7 nm, respectively. The formation of Pd NPs was due to the reduction of the Pd(II) complexes by the excess PPh_3. For C–C coupling reactions involving NPs, soluble metal species and insoluble metal particles may present in the reaction vessel and contribute to the product formation.[12] For Pd NPs stabilized in IL, it is a generally accepted hypothesis that the particles acted as a reservoir for the real catalytic active molecular Pd species.[7a] In our cases, for the second and subsequent catalytic runs, the addition of PPh_3 was still required to maintain good yields in the recycle runs. This is consistent with the argument that molecular Pd species was formed after oxidative addition of aryl halides on the surface of NPs. These molecular Pd species were then stabilized by PPh_3.[13] It should be noted that the addition of excess PPh_3 is a poisoning test to verify the heterogeneous nature of a catalyst system.[14] The opposite effect observed in our case precluded the involvement of Pd NPs as the real catalytic species. Furthermore, the Hg test[15] showed a partial reduction in the product yield from 94 to 60 % for the reaction between 4-iodoacetophenone and *n*-butyl acrylate catalyzed by **4** (Table 7), reflecting the presence of both homogeneous and heterogeneous species in the reaction vessel. Pd NPs prepared from metal precursors of long alkyl chains was shown to have a higher catalytic activity in Suzuki coupling relative to those of shorter chains. The surface of NPs was shown to have higher carbon content, leading to the better dispersion of NPs in ILs. Consequently, a higher catalytic activity was observed.[16] In our case, **5** and **6** prepared from precursors with long alky chains exhibited poorer recyclability relative to that of **4** bearing a Me group in the reaction of 4-iodoacetophenone and *n*-butyl acrylate. This can be accounted by the higher carbon content on the surfaces of the NPs derived from **5** and **6** leading to the better stability of these NPs in IL. However, the higher carbon content might limit the free access of the reactants to the Pd NP surface and so the formation of soluble Pd species from the oxidative addition of aryl halides was retarded, leading to the presence of low level of active catalysis in **5** and **6**. A supportive evidence for this claim came from the ICP-OES analysis on the Pd content leaching into the organic solvent in the fourth catalytic run from the reaction between 4-iodoacetopenone and *n*-butyl acrylate, revealing the Pd content to be 11.9, 6.1, 5.4, ppm for **4–6**, respectively. Notably, for the reaction with 4-bromoacetophenone, the yields of product was best from **5**, followed by **6**, **4**, and free $PdCl_2$ in the second catalytic run. This difference from the case with reactive 4-iodoacetophenone reflected that other factors come into display when the oxidative addition of aryl bromide on the Pd NPs became slow.

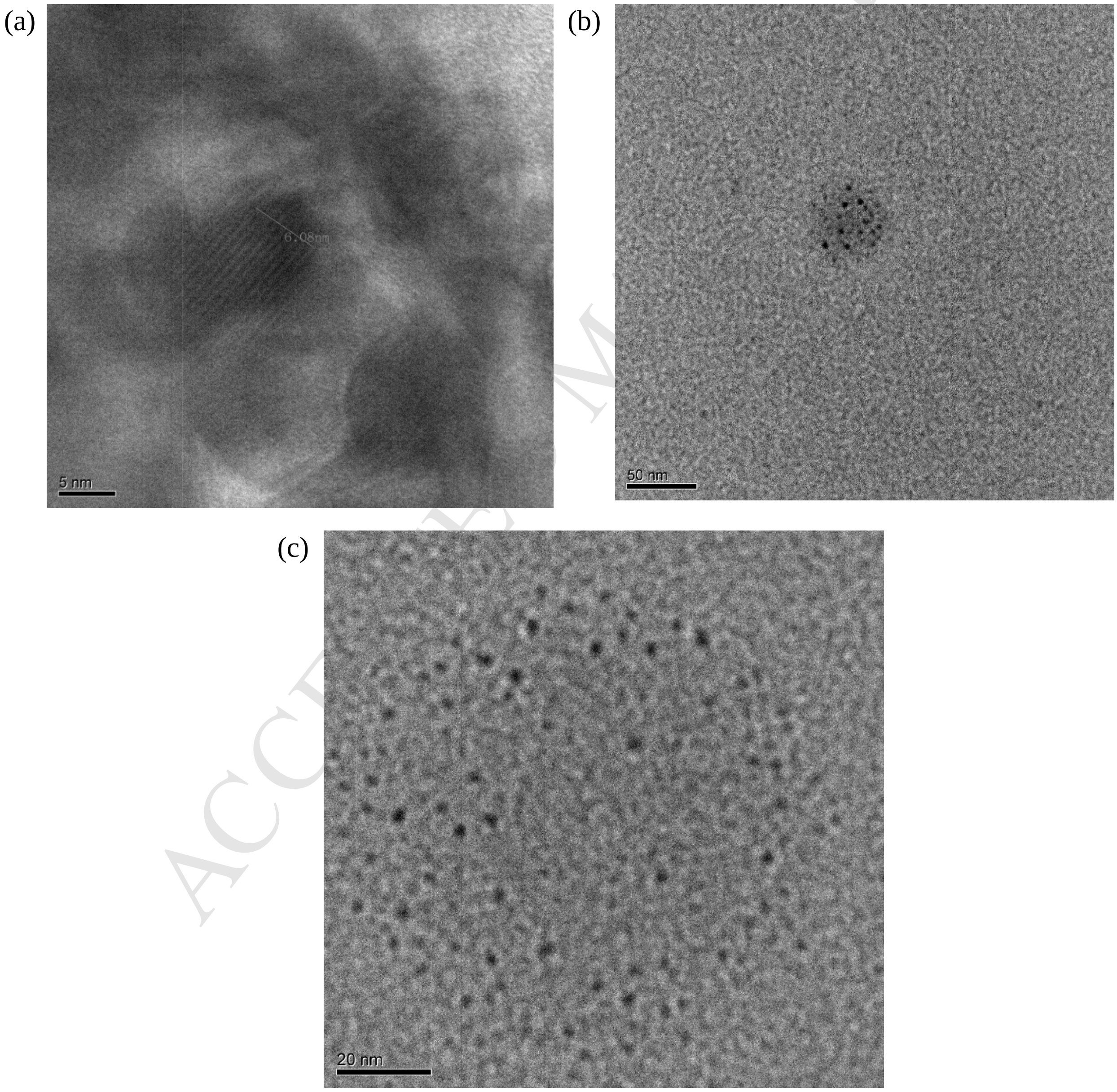


Figure 3. TEM image of *in situ* generated Pd NPs from (a) **4,** (b) **5**, and (c) **6.**

Conclusion

We showed that simple zwitterionic complexes **4–6** derived easily from simple starting materials were successfully applied as metal precursors to generate Pd NPs. These IL stabilized NPs formed effective recyclable catalyst systems for Mizoroki–Heck reactions. For the reaction between 4-iodoacetophenone and *n*-butyl acrylate, a high yield of the coupled product could be obtained and reusability with up to nine consecutive catalytic runs was achieved employing **4** as precatalyst. The activity and reusability were, however, lower when bromide substrate was applied. The use of long alkyl chain on the ligand framework did not provide significant enhancement on activity and recyclability. Efforts on modifying the structure of ligands of zwitterionic palladium complexes to obtain more effective Pd NP catalyst systems for C–C coupling reactions are ongoing.

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 source and used as received. The ^{1}H and ^{13}C{^{1}H}NMR spectra were recorded at 300.13 and 75.48 MHz, respectively, on a Bruker AV-300 spectrometer. Elemental analyses were performed on a Thermo Flash 2000 CHN-O elemental analyzer. Electrospray Ionization mass spectrometry (ESI-MS) was carried out on a Finnigan/Thermo Quest MAT 95XL mass spectrometer. Transmission electronic microscopy (TEM) was performed on a Jeol JEM-2010 at 200 kV. Inductively coupled plasma optical emission spectrometer (ICP-OES) was carried out using an Agilent 725.

Synthesis of 1. A mixture of 1,2-dimethyl imidazole (1.85 mL, 20.81 mmol) and chloroacetone (1.66 mL, 20.81 mmol) in THF (25 mL) was placed in a 50 mL Schlenk flask. The mixture was heated under reflux for 24 h. After cooling, then washed with THF, the viscous liquid was collected, and dried under vacuum. Yield: 3.53 g (90 %). ^{1}H NMR ($CDCl_3$): δ 2.35 (s, 3H, $CH_3C{=}O$), 2.59 (s, 3H, CH_3), 3.85 (s, 3H, NCH_3), 5.89 (s, 2H, $CH_2C{=}O$), 7.40 (s, 1H, imi *H*), 7.80 (s, 1H, imi *H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 9.9, 27.8 ($CH_3{=}O$), 35.5, 57.4 ($CH_2C{=}O$), 122.6 (imi *C*), 122.87 (imi *C*), 146.16 (N*C*N), 201.02 (*C*=O). HRMS (ESI) *m*/*z* calcd for $C_8H_{13}N_2O$ $[M - Cl]^+$ 153.1022, found 153.1020.

Synthesis of 2. A mixture of 1-hexyl-2-methyl-1*H*-imidazole (2.74 g, 16.50 mmol) and chloroacetone (1.36 mL, 16.50 mmol) in THF (25 mL) was placed in a 50 mL Schlenk flask. The mixture was heated under reflux for 24 h. After cooling, then washed with THF, the viscous liquid was collected, and dried under vacuum. Yield: 3.80 g (89 %). ^{1}H NMR ($CDCl_3$): δ 0.82 (t, 3H, J = 6.0 Hz, CH_3), 1.26 (br s, 6H, CH_2), 1.77 (t, 2H, J = 6.0 Hz, CH_2), 2.37 (s, 3H, $CH_3C{=}O$), 2.61 (s, 3H, CH_3), 4.10 (t, 2H, J = 6.0 Hz, NCH_2), 5.97 (s, 2H, $CH_2C{=}O$), 7.38 (s, 1H, imi *H*), 7.87 (s, 1H, imi *H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 10.2, 13.6, 22.0, 25.6, 27.5 ($CH_3C{=}O$), 29.4, 30.8, 48.5, 57.7 ($CH_2C{=}O$), 120.25 (imi *C*), 123.12 (imi *C*), 144.53 (N*C*N), 199.68 (*C*=O). HRMS (ESI) *m*/*z* calcd for $C_{13}H_{23}N_2O$ $[M - Cl]^+$ 223.1805, found 223.1799.

Synthesis of 3. A mixture of 2-methyl-1-tetradecyl-1*H*-imidazole (5.94 g, 21.35 mmol) and chloroacetone (1.70 mL, 21.35 mmol) in THF (25 mL) was placed in a 50 mL Schlenk flask. The mixture was heated under reflux for 24 h. After cooling, then washed with THF, the viscous liquid was collected, and dried under vacuum. Yield: 7.48 g (95 %). ^{1}H NMR ($CDCl_3$): δ 0.82 (t, 3H, *J* = 6.0 Hz, C*H*$_3$), 1.20–1.26 (m, 22H, C*H*$_2$), 1.75 (s, 2H, C*H*$_2$), 2.34 (s, 3H, C*H*$_3$C=O), 2.52 (s, 3H, C*H*$_3$), 4.06 (t, 2H, *J* = 6.0 Hz, NC*H*$_2$), 5.70 (s, 2H, C*H*$_2$C=O), 7.30 (s, 1H, imi *H*), 7.62 (s, 1H, imi *H*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 10.3, 14.1, 22.7, 26.4, 27.6 (C*H*$_3$C=O), 29.2, 29.4–29.7, 31.9, 48.7, 57.8 (C*H*$_2$C=O), 120.52 (imi *C*), 123.20 (imi *C*), 144.85 (N*C*N), 200.67 (*C*=O). HRMS (ESI) *m*/*z* calcd for $C_{21}H_{39}N_2O$ [M – Cl]$^+$ 335.3053, found 335.3057.

Synthesis of 4. To a 20 mL Schlenk flask, $PdCl_2$ (0.19 g, 1.06 mmol), **1** (0.20 g, 1.06 mmol), pyridine (85.6 μmL, 1.06 mmol), and Cs_2CO_3 (1.38 g, 4.24 mmol) were dissolved in dry DMF (10 mL) under nitrogen. The solution was allowed to heat at 25 ºC for 5 h. After cooling, the solvent was removed completely under vacuum. The residual was washed with water and extract with DCM twice. The extract was dried over anhydrous $MgSO_4$ and evaporated to dryness under vacuum to give a solid. Diethyl ether was added and the yellow solid formed was collected on frit and dried under vacuum. Yield: 0.0462 g (11 %). Mp =165.8–166.5 °C. Anal. Calc. For $C_{13}H_{17}Cl_2N_3Opd$: C, 38.21; H, 4.20; N, 10.28. Found: C, 38.17; H, 4.11; N, 10.03 %. ^{1}H NMR ($CDCl_3$): δ 2.48 (s, 3H, C*H*$_3$C=O), 2.65 (s, 3H, C*H*$_3$), 3.68 (s, 3H, C*H*$_3$), 6.16 (s, 1H, PdC*H*), 6.95 (d, 1H, *J* = 2.1 Hz, imi *H*), 7.21–7.26 (m, 2H, py *H*), 7.65 (t, 1H, *J* = 6.0 Hz, py *H*), 8.12 (d, 1H, *J* = 3.0 Hz, imi *H*), 8.85 (d, 2H, *J* = 6.0 Hz, py *H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 10.8, 28.8 (*C*H_3C=O), 34.9, 41.1 (Pd*C*), 119.2 (py *C*), 124.2, 126.1, 137.4 (py *C*), 140.90 (N*C*N), 151.6 (py *C*), 205.0 (*C*=O).

Synthesis of 5. To a 20 mL Schlenk flask, $PdCl_2$ (0.14 g, 0.77 mmol), **2** (0.20 g, 0.77 mmol), pyridine (62.5 μmL, 0.77 mmol), and Cs_2CO_3 (1.00 g, 3.09 mmol) were dissolved in dry DMF (10 mL) under nitrogen. The solution was allowed to heat at 25 ºC for 5 h. After cooling, the solvent was removed completely under vacuum. The residual was washed with water and extract with DCM twice. The extract was dried over anhydrous $MgSO_4$ and evaporated to dryness under vacuum to give a solid. Diethyl ether was added and the orange solid formed was collected on frit and dried under vacuum. Yield: 0.26 g (70 %). Mp = 112.8–113.5 °C. Anal. Calc. For $C_{18}H_{27}Cl_2N_3Opd$: C, 45.16; H, 5.68; N, 8.78. Found: C, 44.92; H, 6.15; N, 8.72 %. ^1H NMR ($CDCl_3$): δ 0.88 (t, 3H, *J* = 6.0 Hz, C*H*$_3$), 1.32 (br s, 6H, C*H*$_2$), 1.78 (t, 2H, *J* = 9.0 Hz, C*H*$_2$), 2.51 (s, 3H, C*H*$_3$C=O), 2.65 (s, 1H, C*H*$_3$), 3.90 (t, 2H, *J* = 6.0 Hz, NC*H*$_2$), 6.19 (s, 1H, PdC*H*), 6.93 (d, 1H, *J* = 3.0 Hz, imi *H*), 7.21–7.26 (m, 2H, py *H*), 7.62–7.68 (m, 1H, py *H*), 8.19 (d, 1H, *J* = 3.0 Hz, imi *H*), 8.86–8.89 (m, 2H, py *H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 10.5, 13.7, 22.1, 25.9, 28.6 (*C*H_3C=O), 29.6, 30.9, 40.6 (Pd*C*), 48.1, 117.7, 123.9 (py *C*), 125.9, 137.1 (py *C*), 139.9 (N*C*N), 151.4 (py *C*), 204.7 (*C*=O).

Synthesis of 6. To a 20 mL Schlenk flask, $PdCl_2$ (0.096 g, 0.54 mmol), **3** (0.20 g, 0.54 mmol), pyridine (43.6 μmL, 0.54 mmol), and Cs_2CO_3 (0.70 g, 2.16 mmol) were dissolved in dry DMF (10 mL) under nitrogen. The solution was allowed to heat at 25 ºC for 5 h. After cooling, the solvent was removed completely under vacuum. The residual was washed with water and extract with DCM twice. The extract was dried over anhydrous $MgSO_4$ and evaporated to dryness under vacuum to give a viscous liquid. Diethyl ether was added and the viscous liquid formed was collected on frit and dried under vacuum. Yield: 0.25 g (78 %). ^{1}H NMR ($CDCl_3$): δ 0.85 (t, 3H, *J* = 6.0 Hz, C*H*$_3$), 1.23 (br s, 22H, C*H*$_2$), 1.75 (t, 2H, *J* = 15.0 Hz, C*H*$_2$), 2.51 (s, 3H, C*H*$_3$C=O), 2.65 (s, 3H, C*H*$_3$), 3.90 (t, 2H, *J* = 9.0 Hz, NC*H*$_2$), 6.19 (s, 1H, PdC*H*), 6.93 (d, 1H, *J* = 3.0 Hz, imi *H*), 7.21–7.26 (m, 2H, py *H*), 7.65 (t, 1H, *J* = 9.0 Hz py *H*), 8.19 (d, 1H, *J* = 3.0 Hz, imi *H*), 8.86–8.89 (m, 2H, imi *H*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 10.5, 13.9, 22.4, 26.2, 28.8 (*C*H$_3$C=O), 28.6–30.1 (m, *C*H$_2$), 31.6, 40.5 (Pd*C*), 48.1, 117.8, 124.0 (py *C*), 125.8, 137.2 (py *C*), 139.9 (N*C*N), 151.4 (py *C*), 204.66 (*C*=O). HRMS (ESI) *m*/*z* calcd for $C_{30}H_{51}N_3O_2Cl_2Pd$ [M–Cl]$^+$ 661.2388, found 661.4387.

Catalytic Mizoroki–Heck reaction. In a typical run, a Schlenk tube was charged with aryl halide (1.0 mmol), alkene (1.4 mmol), anhydrous sodium acetate or triethylamine (1.1 mmol), triphenylphosphine (4.0 mol% in the ionic liquid case) and an appropriate amount of palladium precatalyst **4–6** (0.5–2.0 mol%). The flask was thoroughly degassed, added with TBAB (2 g) or ionic liquid (3 mL), and then placed in a preheated oil bath at the appropriate temperature listed in Table 1–4. After the mixture was cooled, in the case of using TBAB, the mixture was diluted with water (10 mL) and extracted with ether (3 x 10 mL). The combined organic portions were dried over anhydrous $MgSO_4$. After filtration, the solvent was removed completely under vacuum. In case of using ionic liquid, after the mixture was cooled, the mixture was then extracting with toluene (40 mL) for 5 times. And the solvent was removed completely under vacuum. Products were identified by comparison of NMR data with those in the literature; yields and regioselectivity were determined by integration ratio using 1,3,5-trimethoxylbenzene as internal standard.

Recycle experiments. In a first run, a Schlenk tube was charged with aryl halide (1.0 mmol), *n*-butyl acrylate (1.4 mmol), triethylamine (1.1 mmol), triphenylphosphine (4.0 mol%) and an appropriate amount of palladium precatalyst **4–6** (2.0 mol%). The flask was thoroughly degassed, added with ionic liquid (3 mL), and then placed in a preheated oil bath at 100 ^{o}C. After the mixture was cooled, the mixture was then extracting with toluene (40 mL) for 5 times. And the solvent was removed completely under vacuum. Yields were determined by integration ratio using 1,3,5-trimethoxylbenzene as internal standard. After the first run, a Schlenk tube was charged with aryl halide (1.0 mmol), *n*-butyl acrylate (1.4 mmol), triethylamine (1.1 mmol), triphenylphosphine (4.0 mol%). And it was then placed in a preheated oil bath at 100 ^{o}C. After the mixture was cooled, the mixture was then extracting with toluene (40 mL) for 5 times. And the solvent was removed completely under vacuum. Yields were determined by integration ratio using 1,3,5-trimethoxylbenzene as internal standard.

Procedure for TEM measurement. A 0.15 mL of the catalytic solution (theoretically containing 0.001 mmol of Pd) was diluted to 0.40 mL by the addition of CH_2Cl_2. A drop of this ionic liquid solution was then placed in a carbon grid, pumped under vacuum for a week, and analyzed by TEM.

Procedure for ICP-OES measurement. The extracting organic phase containing leached Pd was evaporated under reduced pressure and diluted with $CH_2Cl_{2.}$ (10 mL). A portion of this solution (5 mL) was dissolved in nitric acid hydrochloride/H_2O (1:6). The solution was then analyzed by ICP-OES.

Acknowledgements

We are grateful to the Ministry of Science and Technology of Taiwan for financial support of this work (MOST 101-2113-M-018-003-MY3).

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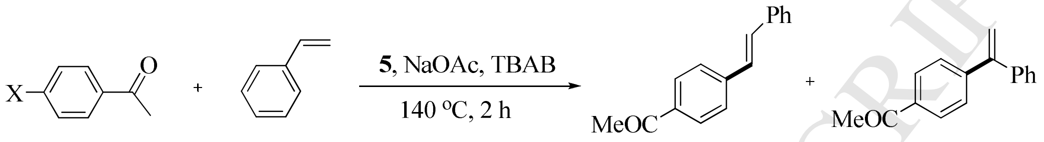
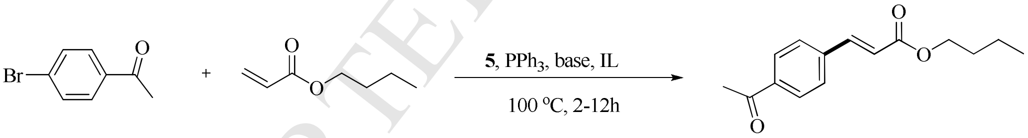
Table 1. Mizoroki–Heck reaction of aryl halide with styrene using **5** as precatalyst.[a]



Entry[a]	X	Yield (%)
1	Br	88 (98:2)
2	Cl	47 (95:5)

[a] Reaction conditions: 1.0 mmol of aryl halide, 1.4 mmol of styrene, 1.1 mmol of NaOAc, 2 g of TBAB, 0.5 mol% of **5**, 140 °C, 2 h. Yield and regioselectivity determined by using 1,3,5-trimethoxybenzene as internal standard.

Table 2. Optimizing of reaction conditions of the Mizoroki–Heck reaction of 4-bromoacetophenone with *n*-butyl acrylate Using **5** as precatalyst.[a]

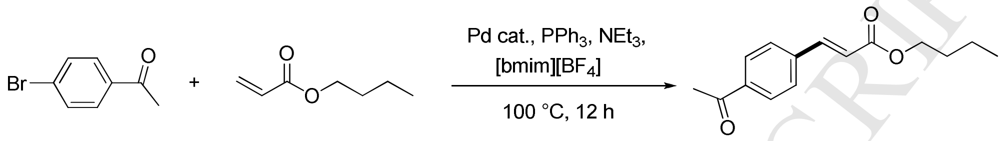


Entry	Time (h)	Base	IL	Catalyst loading (mol%)	Yield (%)
1	2	NEt_3	[bmim][BF_4]	2.0	63
2	4	NEt_3	[bmim][BF_4]	2.0	69
3	8	NEt_3	[bmim][BF_4]	2.0	72
4	12	NEt_3	[bmim][BF_4]	2.0	**95**
5	12	NEt_3	[bmim][BF_4]	2.0	26[b]
6	12	NEt_3	[bmim][BF_4]	1.5	80
7	12	NEt_3	[bmim][BF_4]	1.0	44
8	12	NEt_3	[bmim][BF_4]	0.5	34
9	12	NaOAc	[bmim][BF_4]	2.0	18
10	12	$NaHCO_3$	[bmim][BF_4]	2.0	38
11	12	K_2CO_3	[bmim][BF_4]	2.0	4
12	12	Cs_2CO_3	[bmim][BF_4]	2.0	3
13	12	NEt_3	[bmim][Br]	2.0	30

14	12	NEt_3	[bmim][PF_6]	2.0	90

[a] Reaction conditions: 1.0 mmol of 4-bromoacetophenone, 1.4 mmol of *n*-butyl acrylate, 1.0–4.0 mol% PPh_3, 1.1 mmol of base, 3 mL of IL, 0.5–2.0 mol% of **5**, 100 °C, 2–12 h. Yield determined by using 1,3,5-trimethoxybenzene as internal standard. [b] without the addition of PPh_3.

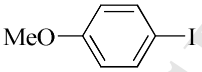
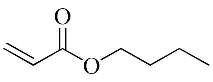
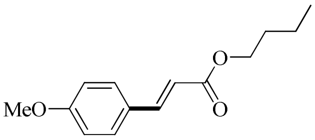
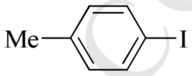
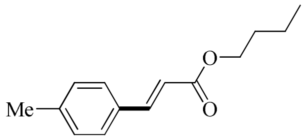
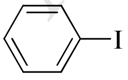
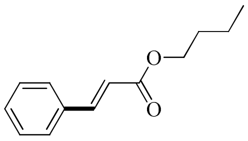
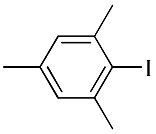
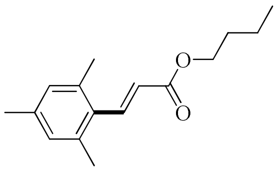
Table 3. Effect of different zwitterionic Pd(II) precatalysts on the Mizoroki–Heck reaction of 4-bromoacetophenone with *n*-butyl acrylate.[a]

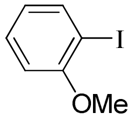
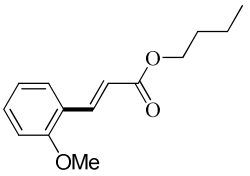
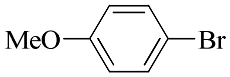
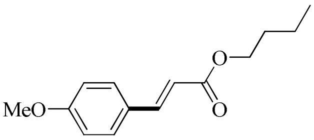
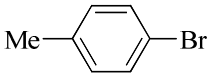
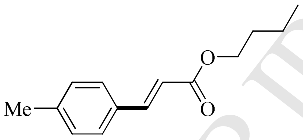
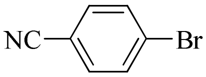
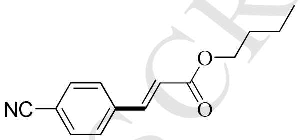
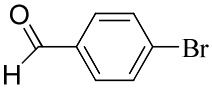
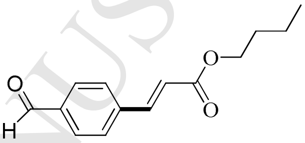
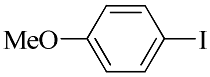
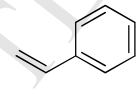
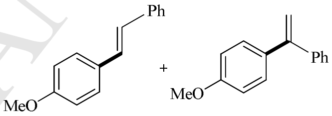
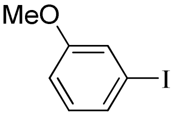
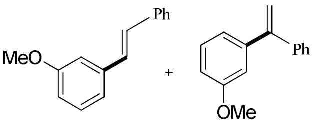
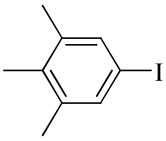
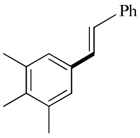
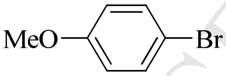
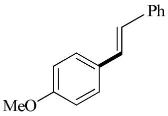
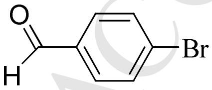
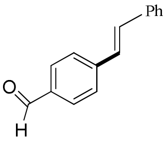


Entry	Catalyst	Yield (%)
1	**4**	97
2	**5**	89
3	**6**	95

[a] Reaction conditions: 1.0 mmol of 4-bromoacetophenone, 1.4 mmol of *n*-butyl acrylate, 4.0 mol% of PPh_3, 1.1 mmol of NEt_3, 3 mL of [bmim][BF_4], 2.0 mol% of Pd cat., 100 °C, 12 h. Yield determined by using 1,3,5-trimethoxybenzene as internal standard.

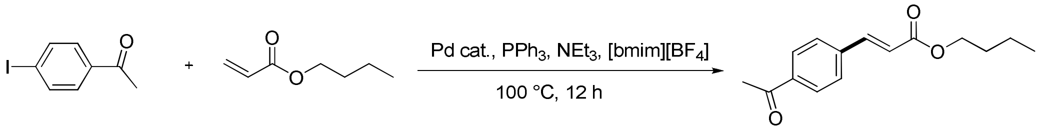
Table 4. Functional group tolerance of the Mizoroki–Heck reaction of aryl halide with alkene using **5** as precatalyst.[a]

Entry	Aryl halide	Alkene	Product	Yield (%)
1				73
2				93
3				93
4				90

5				90
6				28
7				10
8				48
9				44
10				90 (98:2)
11				66 (99:1)
12				72
13				19
14				31

[a]Reaction conditions: 1.0 mmol of 4-bromoacetophenone, 1.4 mmol of *n*-butyl acrylate, 4.0 mol% of PPh_3, 1.1 mmol of NEt_3, 3 mL of [bmim][BF_4], 2.0 mol% of **5**, 100 °C, 12 h. Yields and product ratios determined by using 1,3,5-trimethoxybenzene as internal standard.

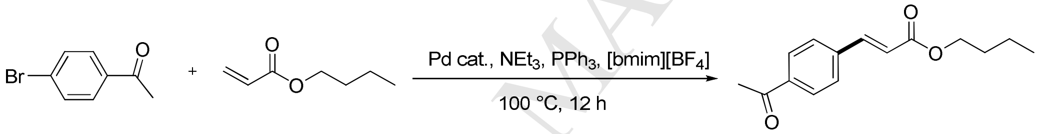
Table 5. Recyclability of Pd NP in the Mizoroki–Heck reaction of 4-iodoacetophenone with *n*-butyl acrylate.[a]



Run	1	2	3	4	5	6	7	8	9	10	11
Yield (%) from **4**:	94	94	93	91	88	88	88	88	83	46	0
Yield (%) from **5**	93	93	93	71	71	43	0	--	--	--	--
Yield (%) from **5**[b]	98	97	95	41	0	--	--	--	--	--	--
Yield (%) from **6**	94	93	91	34	0	--	--	--	--	--	--
Yield (%) from $PdCl_2$	89	88	88	86	85	85	85	77	28	0	--

[a] Reaction conditions: 1.0 mmol of 4-iodoacetophenone, 1.4 mmol of *n*-butyl acrylate, 4.0 mol% PPh_3, 1.1 mmol of NEt_3, 3 mL of [bmim][BF_4], 2.0 mol% of Pd cat., 100 °C, 12 h. Yield determined by using 1,3,5-trimethoxybenzene as internal standard. [b] without the addition of PPh_3.

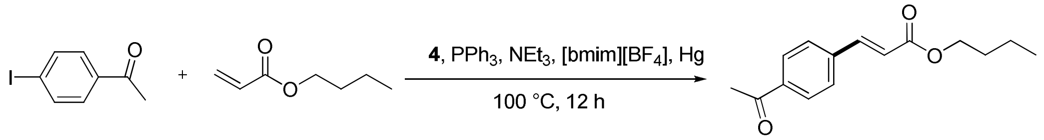
Table 6. Recyclability of Pd NPs in the Mizoroki–Heck reaction of 4-bromoacetophenone with *n*-butyl acrylate.[a]



Run	1	2	3	4
Yield (%) from **4**	97	65	46	13
Yield (%) from **5**	95	89	40	7
Yield (%) from **5**[b]	90	73	67	20
Yield (%) from **5**[c]	26	20	--	--
Yield (%) from **6**	91	80	42	10
Yield (%) from $PdCl_2$	78	48	34	2

[a] Reaction conditions: 1.0 mmol of 4-bromoacetophenone, 1.4 mmol of *n*-butyl acrylate, 4.0 mol% of PPh_3, 1.1 mmol of NEt_3, 3 mL of [bmim][BF_4], 2.0 mol% of Pd cat., 100 °C, 12 h. Yield determined by using 1,3,5-trimethoxybenzene as internal standard. [b] without the addition of PPh_3. [b] [bmim][PF_6] was used instead. [c] without the addition of PPh_3.

Table 7. Effect of Hg additive on the Mizoroki–Heck reaction of 4-iodoacetophenone with *n*-butyl acrylate.[a]



Entry[a]	Additive	Cat.	Yield (%)
1	--	**4**	94
2	Hg	**4**	60

[a]Reaction conditions: 1.0 mmol of 4-iodoacetophenone, 1.4 mmol of *n*-butyl acrylate, 4.0 mol% of PPh_3, 1.1 mmol of NEt_3, 3 mL of [bmim][BF_4], 2.0 mol% of **4**, 2.1 mmol of Hg, 100 °C, 12 h. Yield determined by using 1,3,5-trimethoxybenzene as internal standard.

Highlights

- Three new ligand precursors with different dangling alkyl chain length were prepared.
- Three new zwitterionic palladium complexes based on the new ligand precursors were synthesized.
- The new palladium complexes were effectively applied as catalysts for Mizoroki–Heck reactions in ionic liquid.
- TEM analysis revealed the formation of palladium nanoparticles in the catalytic reactions.