

## Research paper

# Catalytic cross-coupling reaction of aryl iodides with triarylbi-muths by an N-heterocyclic carbene-PdCl<sub>2</sub> based on benzo-9-crown-3 catalyst at room temperature



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## ARTICLE INFO

## Article history:

Received 12 July 2017

Received in revised form

30 September 2017

Accepted 3 October 2017

Available online 6 November 2017

## Keywords:

N-Heterocyclic carbene

Triarylbi-muths

Cross-coupling

Catalyst

Palladium

## ABSTRACT

We have developed the N-heterocyclic carbene ligand/PdCl<sub>2</sub> catalyst for C–C coupling reaction of aryl iodides and organobismuths at room temperature. The established catalytic system exhibited high cross-coupling reactivity between a variety of organobismuths and aryl iodides in the presence of K<sub>2</sub>CO<sub>3</sub> as base in NMP or DMSO at room temperature. The simple and efficient transformation can tolerate either electron-withdrawing or electron-donating functional groups. It was notably found that both aryl bromide and aryl chloride generated moderate to good yields of the corresponding biphenyl products using 5 mol% of PPh<sub>3</sub>/ligand 5 (1:1) as catalyst.

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## 1. Introduction

The palladium catalyzed cross-coupling reactions is one of the most important reaction for C–C bonds forming in synthetic organic chemistry [1]. Aryl-aryl bond formation is one of the most studied processes in cross-coupling chemistry such as the Suzuki-Miyaura [2], Stille [3], and Hiyama coupling reactions [4]. Recently, the use of bismuth-derived compounds as alternative reagents for the cross-coupling has attracted increasing attention [5–8]. Organobismuth compounds are emerging as prospective organometallic green reagents for coupling reaction in organic synthesis due to low-level toxic, stable to air, and environmentally benign nature.

The known palladium catalyzed cross-coupling reaction of organobismuth compounds were performed under 80–130 °C conditions with aryl halides [9,10]. Several protocols with a variety of ligands and palladium based on phosphines and amines are reported with promising reactivity in coupling reactions. For example, Yasunari Monguchi reported that a ligand-free 10% Pd/C-

catalyzed cross-coupling reaction between the aryl iodides and triarylbi-muths by the addition of 2,2'-biquinoline in 120 °C [11]. In 2010, Maddali L. N. Rao established a catalytic protocol using Pd(OAc)<sub>2</sub>(Cy<sub>2</sub>NH)<sub>2</sub> system for the coupling reaction with a variety of triarylbi-muth and aryl iodides under mild condition (35 °C) [12]. Then, he unravelled an unprecedented cross-coupling of triarylbi-muth reagents with aryl iodides under task specific Pd-Cu dual catalytic conditions in 2016 (Pd(OAc)<sub>2</sub>/CuI, dppf, DMF, 90 °C, 4 h) [13].

Although organobismuth compounds have been successfully utilized for the cross-coupling reaction, the studies are scarce in the literature for the palladium catalyzed cross-coupling of organobismuth compounds with aryl halides. Thus, it is still desirable to develop inexpensive and efficient catalytic methods for the cross-coupling reaction using organobismuth reagents at the room temperature. As far as we know, N-heterocyclic carbenes (NHCs) have been extensively studied in the field of organometallics as ligands comparable to the conventional phosphine ligands capable of coordination with a wide range of transition metals [14]. N-heterocyclic carbenes (NHCs) are now regarded as an efficient catalyst as possible alternatives to Pd-phosphine systems in the cross-coupling reaction [15]. Some highly active palladium systems with N-heterocyclic carbene ligands for the activation of aryl

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halides have been developed [16]. In 2016, C. Pichon reported the first cross-coupling reaction of  $\text{Ar}_3\text{Bi}$  with  $\text{Ar}'\text{X}$  mediated by  $\text{Pd-NHC-PPh}_3$  (ratio PEPPSI IPr/ $\text{PPh}_3$ : 1/1) in  $90^\circ\text{C}$ . Efforts were focussed on the rule of each additive such as  $\text{PPh}_3$  and the base. It was notably found that the presence of  $\text{PPh}_3$  was essential to keep the process efficient [17]. In this paper, we report the modular synthesis of an imidazolium salts based on benzo-9-crown-3 and a practical and efficient method for the cross-coupling reaction of aryl iodides with organobismuth catalyzed by N-heterocyclic carbene- $\text{PdCl}_2$  at the room temperature.

## 2. Experimental section

### 2.1. General procedures

The compounds  $\text{PdCl}_2(\text{CH}_3\text{CN})_2$  and  $\text{Ar}_3\text{Bi}$  were prepared according to literature methods. All manipulations were performed using Schlenk techniques, and solvents were thoroughly dried and deoxygenated by standard methods. All reagents were obtained from commercial sources and used without further purification. NMR spectra were obtained on a Bruker Avance III HD 600 MHz spectrometer. The chemical shifts are expressed in ppm and are internally referenced. Positive-ion mass spectra were recorded by Bruker Impact II. All products were characterized by their  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR that were identical to those in the literature.

### 2.2. Synthesis of imidazolium salt ligand (5)

#### 2.2.1. Preparation of 4-aldehyde-benzo-9-crown-3 (2)

Aldehyde **1** (18.0 g, 74 mmol) was added to a suspension of powdered  $\text{K}_2\text{CO}_3$  (20 g, 147 mmol) in DMF (500 mL). After stirring under Ar at  $90^\circ\text{C}$  for 24 h, the mixture was filtered and the solvent was evaporated in vacuo. The residues were poured into water, the aqueous phase was extracted with  $\text{CH}_2\text{Cl}_2$ , washed with brine and dried with  $\text{MgSO}_4$ . The combined organic phase was concentrated under vacuum. The crude product was purified by column chromatography ( $\text{SiO}_2$ ; hexanes: EtOAc 2:1) to afford the pure product **2** (7.0 g, 45%) as a white solid.  $^1\text{H}$  NMR (600 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ): 9.81 (s, 1H) 7.52 (d, 1H,  $J=1.93$  Hz), 7.47–7.49 (dd, 1H,  $J=1.93$ , 8.28 Hz), 7.04 (d, 1H,  $J=8.28$  Hz), 4.61 (t, 2H,  $J=4.26$  Hz), 4.26 (t, 2H,  $J=4.36$  Hz), 3.86–3.91 (m, 4H) ppm;  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ):  $\delta=189.41$ , 155.86, 150.17, 130.88, 125.75, 123.88, 121.32, 74.19, 71.67, 70.95, 70.65 ppm. Anal. Calcd for  $\text{C}_{11}\text{H}_{12}\text{O}_4$ : C, 63.45; H, 5.81. Found: C, 63.50; H, 5.75%.

#### 2.2.2. Preparation of 4-methanol-benzo-9-crown-3 (3)

Aldehyde **2** (5.0 g, 24 mmol) was dissolved in MeOH (80 mL), the resulting solution was cooled to  $0^\circ\text{C}$  and  $\text{NaBH}_4$  (1.8 g, 48 mmol) was added in batches. The resulting colourless solution was stirred at room temperature for 2 h, when it was poured into water (100 mL). The mixture was extracted with  $\text{CH}_2\text{Cl}_2$  (200 mL). The combined organic layers were dried ( $\text{MgSO}_4$ ), filtered, and concentrated in vacuo to afford the title compound **3** (4.8 g, 95%) as a white solid.  $^1\text{H}$  NMR (600 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ): 6.97 (s, 1H), 6.90 (d, 2H,  $J=1.59$  Hz), 4.61 (s, 2H), 4.18–4.20 (m, 4H), 3.90–3.92 (m, 4H) ppm.  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ):  $\delta=151.33$ , 150.75, 137.04, 122.93, 122.59, 121.53; 74.13, 74.00, 72.49, 72.46, 64.57 ppm. Anal. Calcd for  $\text{C}_{11}\text{H}_{14}\text{O}_4$ : C, 62.85; H, 6.71. Found: C, 62.84; H, 6.73%.

#### 2.2.3. Preparation of 4-bromomethyl-benzo-9-crown-3 (4)

Crude alcohol **3** (4.8 g, 23 mmol),  $\text{CBr}_4$  (11.5 g, 35 mmol) were dissolved in  $\text{CH}_2\text{Cl}_2$  (200 mL),  $\text{PPh}_3$  (9.1 g, 35 mmol) was added in one portion. The reaction mixture turned to a dark orange solution, which was stirred at room temperature for 5 h. The mixture was concentrated under reduced pressure to afford a dark orange oil, which was purified by FC ( $\text{SiO}_2$ : hexane/EtOAc 3:1)

to give the pure title compound **4**.  $^1\text{H}$  NMR (600 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ): 7.04 (d, 1H,  $J=2.16$  Hz), 7.00 (dd, 1H,  $J=2.16$ , 8.23 Hz), 6.98 (d, 1H,  $J=8.23$  Hz), 4.42 (s, 2H), 4.34–4.37 (m, 4H), 3.90–3.92 (t, 4H,  $J=4.33$  Hz) ppm.  $^{13}\text{C}$  NMR (125 MHz,  $\text{CDCl}_3$ ,  $25^\circ\text{C}$ ):  $\delta=150.41$ , 150.09, 132.30, 123.68, 122.72, 122.07, 73.12, 72.82, 71.29, 71.23, 32.13 ppm. Anal. Calcd for  $\text{C}_{11}\text{H}_{13}\text{O}_3\text{Br}$ : C, 48.37; H, 4.80. Found: C, 48.39; H, 4.78%.

#### 2.2.4. Preparation of imidazolium salt ligand (5)

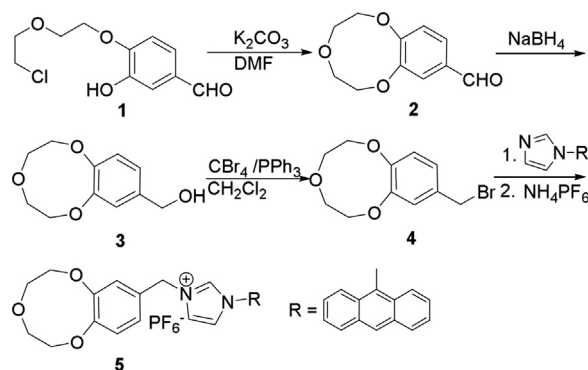
A solution of **4** (4.1 g, 15.1 mmol) and 1-(9-anthracenylmethyl)imidazole (3.89 g, 15.1 mmol) in THF (60 mL) was stirred and refluxed for three days, a yellow precipitate was formed. The raw imidazolium salt was purified by recrystallization with DMF and water.  $\text{NH}_4\text{PF}_6$  (2.46 g, 15.1 mmol) was added to a DMF (15 mL) solution of the obtained imidazolium salt, then water (30 mL) was added the DMF solution, and a yellow precipitate formed immediately. The pure imidazolium salt was obtained by recrystallization with  $\text{CH}_2\text{Cl}_2$  and ethyl ether. Yield: 8.1 g (90%).  $^1\text{H}$  NMR (600 MHz,  $\text{DMSO}-d_6$ ,  $25^\circ\text{C}$ ): 9.08 (s, 1H), 8.85 (s, 1H), 8.46 (d, 2H,  $J=8.85$  Hz), 8.24 (d, 2H,  $J=8.32$  Hz), 7.74 (s, 1H), 7.61–7.69 (m, 5H), 6.94–6.97 (m, 2H), 6.90 (dd, 1H,  $J=2.12$ , 8.22 Hz), 6.49 (s, 2H), 5.18 (s, 2H), 4.26 (t, 2H,  $J=4.36$  Hz), 4.24 (t, 2H,  $J=4.36$  Hz), 3.79 (m, 4H) ppm;  $^{13}\text{C}$  NMR (125 MHz,  $\text{DMSO}-d_6$ ,  $25^\circ\text{C}$ ):  $\delta=44.94$ , 51.07, 71.65, 72.87, 122.34, 122.47, 122.85, 122.86, 123.20, 123.23, 125.51, 127.68, 127.73, 129.33, 129.88, 130.06, 130.54, 131.00, 135.56, 150.98, 151.21 ppm; HRMS (QTOF)  $m/z$ :  $[\text{M}]^+$  Calcd for  $\text{C}_{29}\text{H}_{27}\text{N}_2\text{O}_3^+$  451.2016; found 451.2021.

### 2.3. Typical procedure for the cross-coupling between triaryl bismuths and aryl iodides

In a typical run, a mixture of  $\text{PdCl}_2(\text{CH}_3\text{CN})_2$  (3 mol%), triaryl-bismuths (0.195 mmol), aryl iodides (0.45 mmol), base (1.8 mmol), ligand (5 mol%), solvent (2 mL) was stirred at room temperature for 24 h under nitrogen. After the reaction time, the contents were quenched with 15 mL water and extracted with dichloromethane. The combined organic extract was washed with brine (15 mL) and dried over anhydrous  $\text{MgSO}_4$ , filtered, and concentrated under vacuum. The crude product was purified by column chromatography to afford biaryl compounds.

## 3. Results and discussion

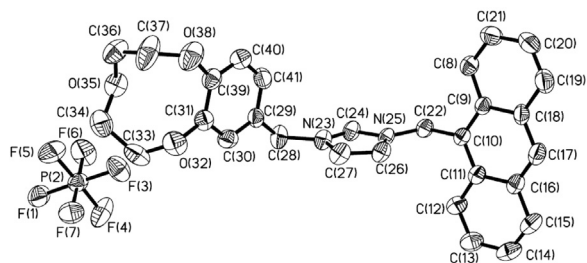
The synthetic routes of the NHC-benzo-crown ether ligand (**5**) were demonstrated in Scheme 1. Compound **1** was readily obtained by the alkylation of 3,4-dihydroxybenzaldehyde and an excess of bis(2-chloroethyl) ether as described in previous literature [18]. We investigated synthetic strategy for preparing a mono-imidazolium salt based on benzo-9-crown-3. Cyclization of **1**, carried out by base  $\text{K}_2\text{CO}_3$  in DMF, yielded 4-aldehyde-benzo-9-



Scheme 1. Synthesis of NHC ligand 5.

**Table 1**Optimization of reaction conditions for the cross-coupling of 4-iodonitrobenzene with BiPh<sub>3</sub>.

| Entry | Solvent | Base                            | Loading of ligand 5 (mol%) | Loading of PdCl <sub>2</sub> (CH <sub>3</sub> CN) <sub>2</sub> (mol%) | Temp(°C) | Time (h) | Yield (%) <sup>a</sup> |
|-------|---------|---------------------------------|----------------------------|-----------------------------------------------------------------------|----------|----------|------------------------|
| 1     | DMF     | KOH                             | 5                          | 3                                                                     | 90       | 5        | 30                     |
| 2     | DMF     | KOAc                            | 5                          | 3                                                                     | 90       | 5        | 40                     |
| 3     | DMF     | K <sub>3</sub> PO <sub>4</sub>  | 5                          | 3                                                                     | 90       | 5        | 44                     |
| 4     | DMF     | Na <sub>3</sub> PO <sub>4</sub> | 5                          | 3                                                                     | 90       | 5        | 41                     |
| 5     | DMF     | Na <sub>2</sub> CO <sub>3</sub> | 5                          | 3                                                                     | 90       | 5        | 50                     |
| 6     | DMF     | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 90       | 5        | 60                     |
| 7     | DMF     | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 70                     |
| 8     | Acetone | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 21                     |
| 9     | THF     | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 29                     |
| 10    | Dioxane | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 25                     |
| 11    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 95                     |
| 12    | NMP     | K <sub>2</sub> CO <sub>3</sub>  | 5                          | 3                                                                     | 25       | 24       | 85                     |
| 13    | NMP     | KO <sup>t</sup> Bu              | 5                          | 3                                                                     | 25       | 24       | 15                     |
| 14    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 1                          | 1                                                                     | 25       | 24       | 65                     |
| 15    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 2                          | 2                                                                     | 25       | 24       | 71                     |
| 16    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 3                          | 3                                                                     | 25       | 24       | 85                     |
| 17    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 4                          | 3                                                                     | 25       | 24       | 90                     |
| 18    | DMSO    | K <sub>2</sub> CO <sub>3</sub>  | 8                          | 3                                                                     | 25       | 24       | 95                     |

<sup>a</sup> Isolated yield based on an aryl iodide.**Fig. 1.** X-Ray crystal structure of imidazolium salt 5. Atomic displacement parameters obtained at 293 K are drawn at the 30% probability level.

crown-3 (**2**), TLC monitoring shows that an appropriate reaction time for 48 h. Purification of the crude product from the reaction mixture using silica-gel chromatography afforded the product in 45% yield [19–21]. The aldehyde **2** was reduced following by NaBH<sub>4</sub> in methanol to give 4-methanol-benzo-9-crown-3 (**3**), which brominated to mono-bromide **4**, and subsequently transformed into mono-imidazolium salt **5**.

The structure of ligand **5** was established by <sup>1</sup>H NMR, <sup>13</sup>C NMR, and X-ray. <sup>1</sup>H NMR spectra of **5** in DMSO-*d*<sub>6</sub>, the proton peak from the imidazolium (NCHN) was observed at 9.08 ppm, which is consistent with the chemical shifts of known imidazolium salts [22]. The signals of salt **5** displays three resonances at 4.26, 4.24, 3.79 ppm for the CH<sub>2</sub>O-ether groups, which reveal the molecular asymmetry. Yellow single crystals of salt **5** were obtained by a solution of diethyl ether and acetonitrile at room temperature (Fig. 1). The crystals belong to the monoclinic space group P2<sub>1</sub>/c, and the X-ray structure was determined at 293 K. The benzene and anthracene ring are respectively positioned on both sides of the imidazole ring, the dihedral angle of the two rings with imidazole ring are 87.9° and 83.5°, respectively.

The initial reaction conditions were optimized using 4-iodonitrobenzene and triphenylbismuth as the model substrates under different bases, solvent, and temperature conditions (Table 1, entries 1–18). As shown in Table 1, when 4-iodonitrobenzene (1 equiv) was stirred with BiPh<sub>3</sub> (0.43 equiv) in presence of PdCl<sub>2</sub>(CH<sub>3</sub>CN)<sub>2</sub>, ligand **5** and different bases in heated DMF (90 °C), the corresponding 4-nitrobiphenyl was obtained in 30–60% yields (Table 1, entries 1–6). The catalytic activity of **5** is highly dependent on bases. Among the several bases examined, the use of KOH, KOAc, K<sub>3</sub>PO<sub>4</sub>, Na<sub>3</sub>PO<sub>4</sub> and Na<sub>2</sub>CO<sub>3</sub> as the bases in DMF at 90 °C gave 4-nitrobiphenyl in about 30–50% yields after 5 h (Table 1, entries 1–5).

**Table 2**

The cross-coupling reaction of triarylbi-muths and aryl iodides with electron-withdrawing group.

| Entry | Products  | R <sub>1</sub>     | R <sub>2</sub>     | Yield (%) <sup>a</sup> |
|-------|-----------|--------------------|--------------------|------------------------|
| 1     | <b>6a</b> | 4-NO <sub>2</sub>  | H                  | 95 (75 <sup>b</sup> )  |
| 2     | <b>6b</b> | 4-NO <sub>2</sub>  | 4-CH <sub>3</sub>  | 94 (72 <sup>b</sup> )  |
| 3     | <b>6c</b> | 4-NO <sub>2</sub>  | 4-OCH <sub>3</sub> | 90 (69 <sup>b</sup> )  |
| 4     | <b>6d</b> | 4-CN               | H                  | 89 (73 <sup>b</sup> )  |
| 5     | <b>6e</b> | 4-CN               | 4-CH <sub>3</sub>  | 85 (73 <sup>b</sup> )  |
| 6     | <b>6f</b> | 4-CN               | 4-OCH <sub>3</sub> | 80 (70 <sup>b</sup> )  |
| 7     | <b>6g</b> | 4-Ac               | H                  | 93 (70 <sup>b</sup> )  |
| 8     | <b>6h</b> | 4-Ac               | 4-CH <sub>3</sub>  | 90 (69 <sup>b</sup> )  |
| 9     | <b>6i</b> | 4-Ac               | 4-OCH <sub>3</sub> | 86 (65 <sup>b</sup> )  |
| 10    | <b>6j</b> | 2-CN               | 4-OCH <sub>3</sub> | 85                     |
| 11    | <b>6k</b> | 2-CN               | 2-CN               | 86                     |
| 12    | <b>7a</b> | 4-OCH <sub>3</sub> | H                  | 72                     |

<sup>a</sup> Isolated yield base on an aryl iodides, using 5 mol% ligand **5**.<sup>b</sup> Isolated yield base on an aryl iodides, using 5 mol% ligand **6**.

It is noteworthy that the desired product was obtained in 60% yield using the base K<sub>2</sub>CO<sub>3</sub> in DMF at 90 °C (Table 1, entry 6). Encouragingly, this cross-coupling reaction was founded to be effective even at room temperature in 70% yield (Table 1, entry 7). Lower reaction temperature led to higher yield. This might be attributed to the reduction of by-products of biphenyl from BiPh<sub>3</sub> and homo-coupled product from aryl iodide at room temperature. Therefore, the base K<sub>2</sub>CO<sub>3</sub> was proven to be effective in DMF at room temperature. Among the solvents tested, the cross-coupling product was poor in THF, acetone and 1,4-dioxane (Table 1, entries 8–10). However, excellent yields were obtained when the solvent was changed to DMSO or NMP (Table 1, entries 11–12). Under the best conditions described in Table 1, the reaction afforded a 95% isolated yield of 4-nitrobiphenyl by employing 5 mol% of ligand **5**, 3 mol% of PdCl<sub>2</sub>(CH<sub>3</sub>CN)<sub>2</sub>, 4 equiv K<sub>2</sub>CO<sub>3</sub> in DMSO at room temperature for 24 h (Table 1, entry 11).

Using optimized conditions, the cross-coupling scope and generality of a variety of aryl iodides with different triarylbi-muths was investigated in DMSO at room temperature (Table 2). The presence of an electron-withdrawing group of aryl iodide is tolerated. As shown in Table 2 (entries 1–11), electron-withdrawing substituents on the aryl iodide gave higher yields of isolated pure compound at room temperature. Besides, electron-donating substituents on the triarylbi-muths result in slightly lower yields. It has been suggested that the presence of an electron-donating group of triarylbi-muths is favourable to increase side products of biaryl from triarylbi-muths. Unfortunately, a substrate with an

**Table 3**

The cross-coupling reaction of triarylbiomuths and 4-iodoanisole.

| Entry | Solvent | Base                           | Temp (°C) | Time (h) | Yield (%) <sup>a</sup> |
|-------|---------|--------------------------------|-----------|----------|------------------------|
| 1     | DMSO    | K <sub>2</sub> CO <sub>3</sub> | 90        | 5        | 56                     |
| 2     | DMF     | K <sub>2</sub> CO <sub>3</sub> | 90        | 5        | 61                     |
| 3     | NMP     | K <sub>2</sub> CO <sub>3</sub> | 90        | 5        | 70                     |
| 4     | DMA     | K <sub>2</sub> CO <sub>3</sub> | 90        | 5        | 51                     |
| 5     | DMSO    | K <sub>3</sub> CO <sub>3</sub> | 50        | 5        | 65                     |
| 7     | DMF     | K <sub>2</sub> CO <sub>3</sub> | 50        | 12       | 61                     |
| 8     | NMP     | K <sub>2</sub> CO <sub>3</sub> | 50        | 12       | 76                     |
| 9     | NMP     | K <sub>2</sub> CO <sub>3</sub> | 25        | 24       | 91                     |
| 10    | DMSO    | K <sub>2</sub> CO <sub>3</sub> | 25        | 24       | 72                     |
| 11    | THF     | K <sub>2</sub> CO <sub>3</sub> | 25        | 24       | 29                     |

<sup>a</sup> Isolated yield base on an aryl iodides.

electron-donating group at the para-position of aryl iodide did not afford the corresponding biaryl in high yield because of the competitive and intercurrent homo-coupling of 4-iodoanisole (Table 2, entry 12, 72% yield). So, we commenced our studies by examining the effects of various reactions parameters on the yield of this cross-coupling using 4-iodoanisole and triphenylbismuth. After the Pd-NHC was shown to be an effective catalyst for the cross-coupling of aryl iodides and triarylbiomuths, the ligand 6 was also prepared for comparison. This imidazolium salt 6 was then compared with NHC-benzo-crown ether ligand 5 in standard cross-coupling forming biaryls (Table 2, entries 1–9). It was worth noting that both precursors gave comparable reaction yields under optimized reaction conditions of cross-coupling aryl iodides and triarylbiomuth. It is surprising that ligand 5 seems to have a large impact on the coupling (Table 2, entries 1–9). Palladium complexes with the supermolecular NHC ligands have been studied previously and shown to be efficient in Suzuki-Mayarua cross coupling reaction [23–25]. For example, Luo M. group reported palladium (II)-NHC Metallacrown Ether Complexes in 2009 [24]. We have prepared the NHC ligand based porphyrins and metallacrown ether scaffold, and discussed the catalytic activity of Suzuki coupling [25]. The crownether-based imidazolium salt is promising for the constructions of highly active supramolecular catalytic systems.

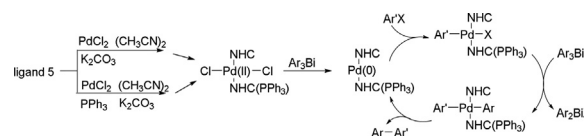
The model reaction was also tested under the reaction conditions used in the synthesis of 4-methoxybiphenyl (5 mol%) of ligand 5, 3 mol% of PdCl<sub>2</sub>(CH<sub>3</sub>CN)<sub>2</sub>, 4 equiv K<sub>2</sub>CO<sub>3</sub> and the results are summarized in Table 3. In the current studies, we usually investigated the effect of solvent and reaction temperature on the model reaction. Among the solvents examined, DMSO was afforded moderate yield (72%), regardless of the reaction temperature (Table 3, entries 1, 5 and 10). NMP was found to be the best solvent, and the yields increase with the decrease of reaction temperature (Table 3, entries 3, 8 and 9). The nature of the initial precatalyst, solvent and base is crucial for the success of the cross-coupling reaction, especially. Electron-withdrawing substituents on the aryl iodide gave higher yields of isolated pure compound in DMSO at room temperature. Besides, electron-donating substituents on the triarylbiomuths result in slightly lower yields. It has been suggested that the presence of an electron-donating group of aryl iodides is favourable to increase side products of biaryl from aryl iodides in DMSO. We found that the substrate with an electron-donating group underwent the reaction smoothly to furnish the corresponding biaryl in higher yield and minimized side products in NMP at room temperature. Using NMP as solvent led to higher yield. This might be attributed to the reduction of by-products from homo-coupling of aryl iodide at room temperature. Therefore, the optimal catalytic system involved the use of ligand 5 (5 mol%), PdCl<sub>2</sub>(CH<sub>3</sub>CN)<sub>2</sub> (3 mol%), K<sub>2</sub>CO<sub>3</sub> (4 equiv) in NMP at room temperature for 24 h.

The scope of this cross-coupling reaction of triarylbiomuths and aryl iodides with electron-donating group was also established by

**Table 4**

The cross-coupling reaction of triarylbiomuths and aryl iodides with electron-donating group.

| Entry | Products  | R <sub>1</sub>     | R <sub>2</sub>     | Yield (%) <sup>a</sup> |
|-------|-----------|--------------------|--------------------|------------------------|
| 1     | <b>7a</b> | 4-OCH <sub>3</sub> | H                  | 91                     |
| 2     | <b>7b</b> | 4-CH <sub>3</sub>  | H                  | 93                     |
| 3     | <b>7c</b> | 3-NH <sub>2</sub>  | H                  | 90                     |
| 4     | <b>7d</b> | 4-NH <sub>2</sub>  | H                  | 89                     |
| 5     | <b>7e</b> | 4-CH <sub>3</sub>  | CH <sub>3</sub>    | 90                     |
| 6     | <b>7f</b> | 4-OCH <sub>3</sub> | CH <sub>3</sub>    | 85                     |
| 7     | <b>7g</b> | 3-NH <sub>2</sub>  | CH <sub>3</sub>    | 80                     |
| 8     | <b>7f</b> | 4-CH <sub>3</sub>  | OCH <sub>3</sub>   | 86                     |
| 9     | <b>7h</b> | 4-OCH <sub>3</sub> | OCH <sub>3</sub>   | 84                     |
| 10    | <b>7i</b> | 3-NH <sub>2</sub>  | OCH <sub>3</sub>   | 83                     |
| 11    | <b>7j</b> | 4-NH <sub>2</sub>  | OCH <sub>3</sub>   | 83                     |
| 12    | <b>7k</b> | 4-OCH <sub>3</sub> | H                  | 84                     |
| 13    | <b>7l</b> | 2-OCH <sub>3</sub> | 2-CH <sub>3</sub>  | 82                     |
| 14    | <b>7l</b> | 2-CH <sub>3</sub>  | 4-OCH <sub>3</sub> | 80                     |
| 15    | <b>6j</b> | 4-OCH <sub>3</sub> | 2-CN               | 87                     |

<sup>a</sup> Isolated yield base on an aryl iodides.**Scheme 2.** Proposed mechanism cycle for the cross-coupling reaction.

different triarylbiomuths and various aryl iodides (Table 4). Using the NHC-benzo-9-crown-3 ligand 5, PdCl<sub>2</sub>(CH<sub>3</sub>CN)<sub>2</sub> as the catalyst and K<sub>2</sub>CO<sub>3</sub> as the base, the cross-coupling reactions of aryl iodides and triarylbiomuths were carried out in NMP at room temperature. The cross-coupling reactivity with aryl iodides with electron donating was found to be efficient even with a lower palladium catalyst (3 mol%) loading (Table 4, entries 1–15) at room temperature. The reactions of electron-rich *p*-methyl, *p*-methoxy and *p*-amino substituted iodophenyl gave high yields of the cross-coupling products. In general, strong electron-donating substituents on the aryl iodide or triarylbiomuths result in lower slightly yields.

The Pd-NHC was shown to be an effective catalyst for the cross-coupling of triarylbiomuths and aryl iodides. Despite the lower reactivity of aryl chlorides and bromides compared with the corresponding aryl iodides. Aryl chlorides and bromides are the most desirable substrates because of their lower cost and ready availability. Here, we have performed the reaction of triarylbiomuths with aryl bromides and chlorides in order to extend scope and define limitation of our strategy (Table 5). Unfortunately, in our system, the ligand 5 only demonstrated a low level of catalytic activity compared with aryl iodides at room temperature (entries 1 and 5), but showed higher activities in 90 °C (entries 4 and 8). When 5 mol% of PPh<sub>3</sub>/ligand 5 (1:1) were employed in cross-coupling reaction at room temperature, both aryl bromide and aryl chloride generated moderate to good yields of the corresponding biphenyl products (Table 5, entries 3 and 7). It was notably found that the presence of PPh<sub>3</sub> was essential to keep the process efficient. The hypothesis of the reaction mechanism has been described in reference (Scheme 2) [17].

#### 4. Conclusions

In summary, we have developed an efficient reaction of aryl iodides and triarylbiomuths catalyzed by N-heterocyclic carbene-PdCl<sub>2</sub> based on benzo-9-crown-3 at room temperature. Aryl iodides bearing an electron-withdrawing or electron-donating group underwent the reaction smoothly to furnish the corresponding biaryl in high yields in NMP or DMSO by combined use of imidazolium salt 5 with K<sub>2</sub>CO<sub>3</sub> as ligand and base, respectively. The

**Table 5**

The cross-coupling reaction of triarylbiomethanes and aryl chloride and bromide.

| Entry | X  | R               | Solvent | Loading of ligand (X mol%) | Loading of PPh <sub>3</sub> (X mol%) | Temp (°C) | Yield (%) <sup>a</sup> |
|-------|----|-----------------|---------|----------------------------|--------------------------------------|-----------|------------------------|
| 1     | Br | NO <sub>2</sub> | DMSO    | 5                          | 0                                    | 25        | 15                     |
| 2     | Br | NO <sub>2</sub> | DMSO    | 0                          | 5                                    | 25        | 20                     |
| 3     | Br | NO <sub>2</sub> | DMSO    | 5                          | 5                                    | 25        | 90                     |
| 4     | Br | NO <sub>2</sub> | DMSO    | 5                          | 0                                    | 90        | 76                     |
| 5     | Cl | CH <sub>3</sub> | NMP     | 5                          | 0                                    | 25        | 40                     |
| 6     | Cl | CH <sub>3</sub> | NMP     | 0                          | 5                                    | 25        | 10                     |
| 7     | Cl | CH <sub>3</sub> | NMP     | 5                          | 5                                    | 25        | 85                     |
| 8     | Cl | CH <sub>3</sub> | NMP     | 5                          | 0                                    | 90        | 66                     |

<sup>a</sup> Isolated yield base on an aryl iodides.

transformation can tolerate either electron-donating or electron-withdrawing functional groups. When 5 mol% of PPh<sub>3</sub>/ligand **5** (1:1) were employed in cross-coupling reaction at room temperature, both aryl bromide and aryl chloride generated moderate to good yields of the corresponding biphenyl products. This exploration is expected to have great applications in organic synthesis.

#### 4.1. X-ray structure crystallography

Crystals of **5** suitable for X-ray diffraction analysis were grown from layering a saturated CH<sub>3</sub>CN and chlorobenzene solution with diethyl ether. Suitable crystals of **5** were mounted on a glass fiber in a random orientation. The structures were solved by direct methods and all nonhydrogen atoms were subjected to anisotropic refinement by full-matrix least squares on F<sup>2</sup> using the SHELXTL package. Data collection was performed at room temperature on a Bruker SMART 1000 CCD diffractometer operating at 50 kV and 20 mA using Mo-Kα radiation (0.71073 Å). An empirical absorption correction was applied using the SADABS program. All hydrogen atoms were generated geometrically (C–H bond lengths fixed at 0.96 Å), assigned appropriate isotropic thermal parameters and included in structure factor calculations.

#### Acknowledgements

This work is supported by the Research Fund for the Education Department of Shanxi Province (No. 2010111), and the Shanxi Natural Science Foundation of China for the project (No. 2011011006-4).

#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.mcat.2017.10.004>.

Crystallographic data for the structure reported in this paper has been deposited with the Cambridge Crystallographic Data Center: CCDC-714292 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre, [www.ccdc.cam.ac.uk/datarequest/cif](http://www.ccdc.cam.ac.uk/datarequest/cif).

<sup>1</sup>H and <sup>13</sup>C NMR Spectra of Products

X-ray crystallographic data for compound **5** (CIF)

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