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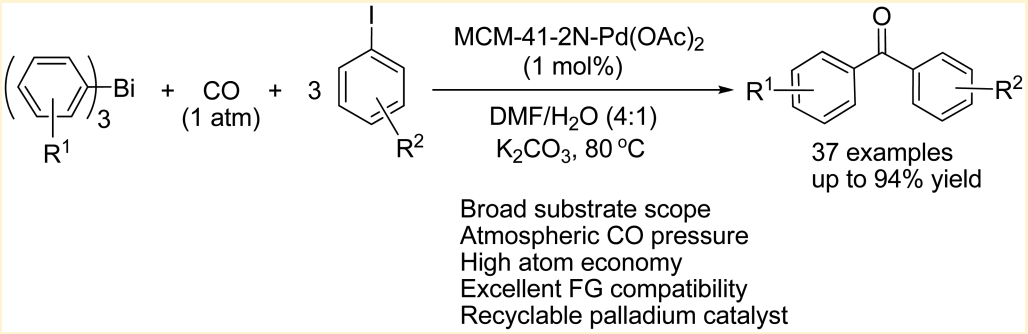
Phosphine-Free, Heterogeneous Palladium-Catalyzed Atom-Efficient Carbonylative Cross-Coupling of Triarylbismuths with Aryl Iodides: Synthesis of Biaryl Ketones

Wenyan Hao, Haiyi Liu, Lin Yin, and Mingzhong Cai*

Key Laboratory of Functional Small Organic Molecule, Ministry of Education and College of Chemistry & Chemical Engineering, Jiangxi Normal University, Nanchang 330022, P. R. China

Supporting Information



ABSTRACT: A novel and highly efficient heterogeneous palladium-catalyzed carbonylative cross-coupling of aryl iodides with triarylbismuths has been developed that proceeds smoothly at atmospheric CO pressure and provides a general and powerful tool for the preparation of various valuable biaryl ketones with high atom economy, good to excellent yield, and recyclability of the catalyst. The reaction is the first example of Pd-catalyzed carbonylative cross-coupling for the construction of biaryl ketones using triarylbismuths as substrates.

INTRODUCTION

Biaryl ketones are important structural units found in a wide variety of molecules, including natural products,[1] compounds of biological and pharmaceutical importance,[2] organic materials,[3] functional molecules,[4] and synthetic intermediates.[5] Development of various approaches to biaryl ketones is of great interest, and many methods for the preparation of them have been reported. One general and straightforward route to biaryl ketones is the Friedel−Crafts acylation of aryl cycles with acid halides or acid anhydrides.[6] However, this methodology suffers from some drawbacks such as the use of more than a stoichiometric amount of aluminum trichloride, which is incompatible with many functional groups, generation of a large amount of highly toxic and corrosive waste, and a narrow scope of substrates. The cross-couplings of a variety of organometallic reagents with electrophilic acid derivatives using the catalysis of transition metals, especially palladium, have also been developed to provide ketones.[7] The transition-metal-catalyzed carbonylative cross-coupling reaction of arylmetal reagents with aryl electrophiles in the presence of carbon monoxide has provided a straightforward and convenient route to unsymmetrical biaryl ketones.[8] Various arylmetal reagents including magnesium,[9] aluminum,[10] silicon,[11] tin,[12] zinc,[13] boron,[14] and indium[15] compounds have been reported to undergo the carbonylative cross-coupling reactions. Although these methods are encouraging, most of them have some drawbacks in one or another respect, such as strict anhydrous conditions, the difficulty in the preparation of arylmetal reagents in some cases, difficult recovery, non-recyclability of homogeneous palladium catalysts, and the formation of side products due to direct coupling. Recently, Zhang et al. described the one-pot synthesis of biaryl ketones through $Pd(OAc)_2/PPh_3$-catalyzed sequential coupling and aerobic oxidation of aryl bromides with acetophenone as a latent carbonyl donor, but only moderate yields were obtained.[16] Therefore, establishing a general, efficient, and practical approach to biaryl ketones is highly desirable.

Organobismuth compounds are less toxic, easily available building blocks and potentially useful candidates for environmentally benign reagents. Because of these attractive features of them, organobismuth compounds have occupied a special place in medicinal chemistry and organic synthesis.[17] For example, triarylbismuths, which could be easily prepared through standard procedures[18] and are stable to air and moisture, have widely been used in palladium-catalyzed carbon−carbon and carbon−heteroatom bond formation reactions.[19] Notably, triarylbismuths can react with 3 equiv of an electrophilic reagent,[19a−g] in line with the Principles of Green Chemistry.[20] In spite of the significant advances made in palladium-catalyzed

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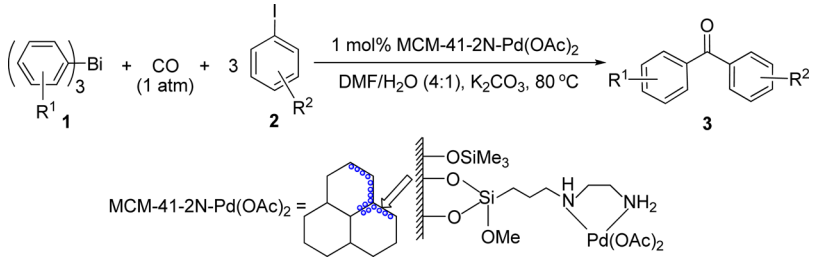
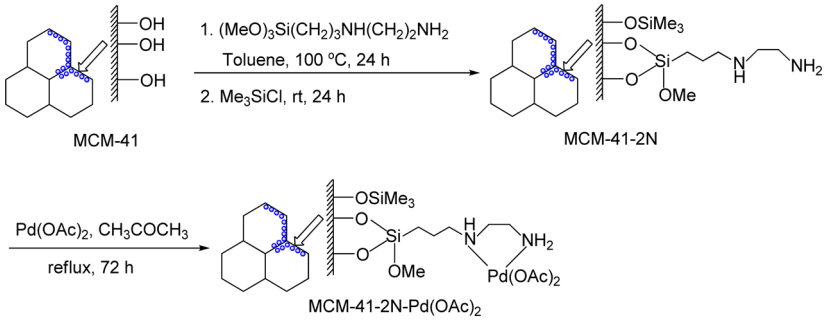
Scheme 1. Phosphine-Free Heterogeneous Palladium-Catalyzed Carbonylative Cross-Coupling of Triarylbismuths with Aryl Iodides



Scheme 2. Preparation of MCM-41-2N-Pd(OAc)$_2$ Complex



cross-coupling of triarylbismuths with electrophiles, there are very few reports on transition-metal-catalyzed carbonylation of triarylbismuths with carbon monoxide.[21] Uemura and co-workers reported rhodium(I)[21a] and palladium(0)[21b]-catalyzed carbonylation of triarylbismuths with carbon monoxide in acetonitrile or methanol, affording symmetrical biaryl ketones and methyl benzoates, respectively. Kang et al.[21c] described palladium-catalyzed carbonylative cross-coupling of pentavalent triarylbismuth(V) derivatives with aryl- or heteroaryltin reagents leading to biaryl ketones. However, there is no report of transition-metal-catalyzed carbonylative cross-coupling reactions of triarylbismuths with aryl electrophiles thus far. In addition, among the successful examples for the construction of carbon−carbon and carbon−heteroatom bonds, homogeneous $Pd(PPh_3)_4$, $Pd(OAc)_2$, $PdCl_2$, or $[RhCl(CO)_2]_2$ are usually used as catalysts for these reactions. These homogeneous catalysts are quite expensive, cannot be recycled, and are difficult to separate from the product mixture, which may have a very serious negative impact on their possible industrial applications, especially the pharmaceutical industry. Inspired by these drawbacks, our ongoing interests[12f,14c,e] in heterogeneous palladium-catalyzed carbonylative cross-coupling reactions have led us to investigate a novel, atom-economical, phosphine-free heterogeneous Pd-catalyzed carbonylative cross-coupling reaction of triarylbismuths with aryl iodides under atmospheric pressure of carbon monoxide (Scheme 1). To the best of our knowledge, this method is the first example of a transition-metal-catalyzed carbonylative cross-coupling reaction of triarylbismuths with aryl halides leading to biaryl ketones.

RESULTS AND DISCUSSION

Although phosphine ligands are usually used to stabilize palladium and influence its activity, the simplest and cheapest palladium catalysts are of course phosphine-free systems. In our previous works, we prepared an MCM-41-immobilized bidentate nitrogen palladium(II) complex [MCM-41-2N-Pd-$(OAc)_2$] via a simple two-step procedure from commercially available and inexpensive 3-(2-aminoethylamino)propyl-trimethoxysilane (Scheme 2). It was found that this phosphine-free heterogeneous palladium complex is a highly efficient and recyclable catalyst for the Suzuki−Miyaura reaction of aryl bromides and the cross-coupling of acyl chlorides with terminal alkynes.[22]

In continuation of our research to employ this heterogeneous palladium system for other organic transformations, we commenced our studies by investigating the carbonylative cross-coupling reaction of $BiPh_3$ with 3-iodotoluene under atmospheric pressure of CO gas to optimize reaction conditions, and the results are summarized in Table 1. At first, the solvent effect was examined by using K_2CO_3 as the base at 80 °C. Among the solvents examined, NMP, DMF, DMSO, and DME afforded good yields (Table 1, entries 1−4), while other solvents such as MeCN and dioxane were substantially less effective (Table 1, entries 5 and 6). To our delight, a mixture of DMF and H_2O was also a suitable solvent for the reaction and DMF/H_2O (4:1) gave the best result (Table 1, entry 7). Our next studies focused on the effect of base on the model reaction. It is evident that good yields were obtained when Na_2CO_3, Cs_2CO_3, K_2CO_3, K_3PO_4, KOAc, and KF were used as the base, and K_2CO_3 was the most effective (Table 1, entries 7 and 10−14), whereas Bu_3N and Et_3N afforded low yields and the reaction was slow in the absence of a base (Table 1, entries 15−17), so K_2CO_3 was finally selected as the base for the reaction. The effect of the temperature on the model reaction was also investigated (Table 1, entries 7 and 18−20). Among the temperatures [60, 80, 100, and 120 °C] tested, 80 °C was found to be the best choice (Table 1 entry 7). Raising the reaction temperature resulted in a decrease in yield due to the decrease in selectivity, and the reaction run at 120 °C gave only a 66% yield of the desired carbonylative coupling product, along with a 26% yield of 3-methyldiphenyl as byproduct owing to the direct coupling (Table 1 entry 20), indicating that reaction temperatures have a significant influence on the selectivity of this reaction. Reducing the

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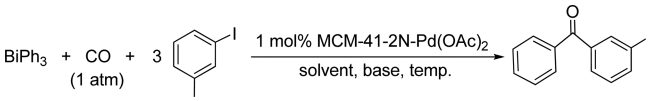
Table 1. Optimization of the Reaction Conditions[a]



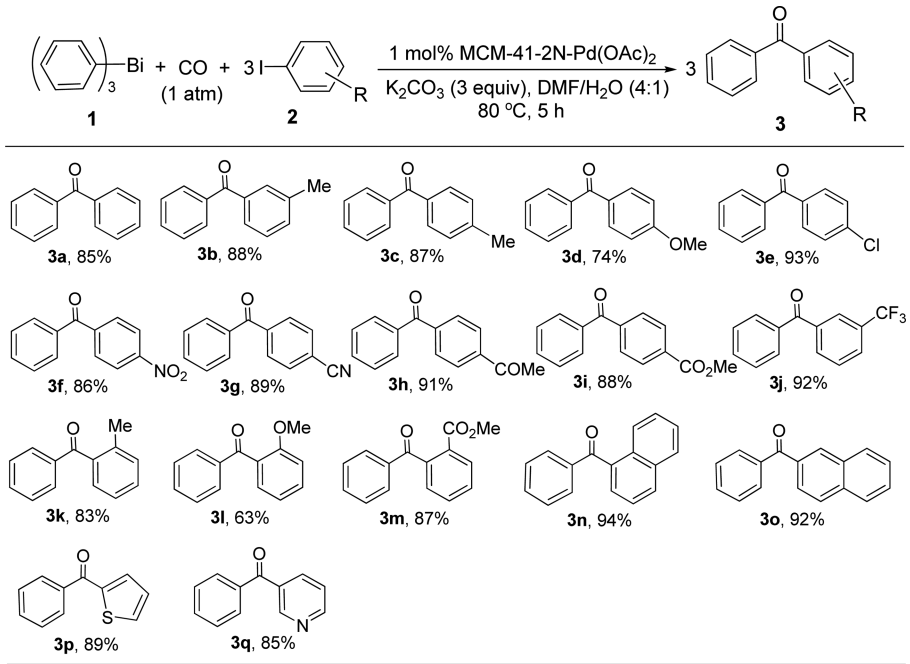
entry	solvent	base	temp (°C)	time (h)	yield (%)[b]
1	NMP	K_2CO_3	80	5	84
2	DMF	K_2CO_3	80	5	83
3	DMSO	K_2CO_3	80	5	78
4	DME	K_2CO_3	80	8	62
5	MeCN	K_2CO_3	80	10	53
6	dioxane	K_2CO_3	80	10	47
7	DMF/H_2O (4:1)	K_2CO_3	80	5	88
8	DMF/H_2O (2:1)	K_2CO_3	80	10	61
9	DMF/H_2O (8:1)	K_2CO_3	80	7	78
10	DMF/H_2O (4:1)	Na_2CO_3	80	6	84
11	DMF/H_2O (4:1)	Cs_2CO_3	80	7	80
12	DMF/H_2O (4:1)	K_3PO_4	80	7	76
13	DMF/H_2O (4:1)	KOAc	80	7	79
14	DMF/H_2O (4:1)	KF	80	7	70
15	DMF/H_2O (4:1)	Bu_3N	80	10	58
16	DMF/H_2O (4:1)	Et_3N	80	10	49
17	DMF/H_2O (4:1)	none	80	24	43
18	DMF/H_2O (4:1)	K_2CO_3	60	24	48
19	DMF/H_2O (4:1)	K_2CO_3	100	5	79
20	DMF/H_2O (4:1)	K_2CO_3	120	3	66
21[c]	DMF/H_2O (4:1)	K_2CO_3	80	12	82
22[d]	DMF/H_2O (4:1)	K_2CO_3	80	3	87

[a]Reaction conditions: $BiPh_3$ (1.0 mmol), 3-iodotoluene (3.2 mmol), MCM-41-2N-Pd(OAc)$_2$ (1 mol %), base (3.0 mmol), solvent (5 mL) under atmospheric pressure of CO. [b]Isolated yield. [c]0.5 mol % catalyst was used. [d]2 mol % catalyst was used.

amount of the catalyst resulted in a decrease in yield (Table 1, entry 21). Increasing the amount of the catalyst could shorten the reaction time, but did not improve the yield of the desired product (Table 1, entry 22). Thus, the optimized conditions for this transformation are the MCM-41-2N-Pd(OAc)$_2$ (1 mol %), K_2CO_3 (3.0 equiv) as base in DMF/H_2O (4/1) as solvent at 80 °C under an atmospheric pressure of CO for 5 h (Table 1, entry 7).

With this promising result in hand, we started to investigate the scope of this heterogeneous palladium-catalyzed carbonylative cross-coupling reaction under the optimized conditions. First, reactions of $BiPh_3$ with various aryl iodides were examined and the results are summarized in Table 2. As shown in Table 2, the carbonylative cross-coupling reaction of $BiPh_3$ with a variety of aryl iodides proceeded smoothly under the optimized reaction conditions, affording the corresponding biaryl ketones **3a**–**o** in good to excellent yields. Various electron-donating and -withdrawing groups such as methyl, methoxy, chloro, nitro, cyano, ketone, ester, and trifluoromethyl on the benzene ring were well tolerated. It is noteworthy that 4-iodoanisole having a strong electron-donating group displayed lower reactivity and gave the desired product **3d** in only 74% yield. The sterically hindered aryl iodides such as 2-iodotoluene and methyl 2-iodobenzoate efficiently underwent the carbonylative cross-coupling reaction with $BiPh_3$ to give the corresponding carbonylative coupling products **3k** and **3m** in high yields. However, 2-iodoanisole also showed lower reactivity due to the strong electron-donating property of the methoxy group and afforded the desired product **3l** in only 63% yield. The reactions of bulky 1-iodonaphthalene and 2-iodonaphthalene with $BiPh_3$ provided the corresponding biaryl ketones **3n** and **3o** in excellent yields under the optimized conditions. In addition, the carbonylative cross-coupling reactions of heteroaryl iodides such as 2-iodothiophene and 3-iodopyridine with $BiPh_3$ also proceeded smoothly to give the corresponding carbonylative coupling products **3p** and **3q** in high yields.

Table 2. Heterogeneous Palladium-Catalyzed Carbonylative Coupling of $BiPh_3$ with Various Aryl Iodides[a,b]



[a]Reaction conditions: $BiPh_3$ (1.0 mmol), aryl iodide (3.2 mmol), MCM-41-2N-Pd(OAc)$_2$ (1 mol %), K_2CO_3 (3.0 mmol), DMF/H_2O (4:1) (5 mL) at 80 °C under atmospheric pressure of CO for 5 h. [b]Isolated yield.

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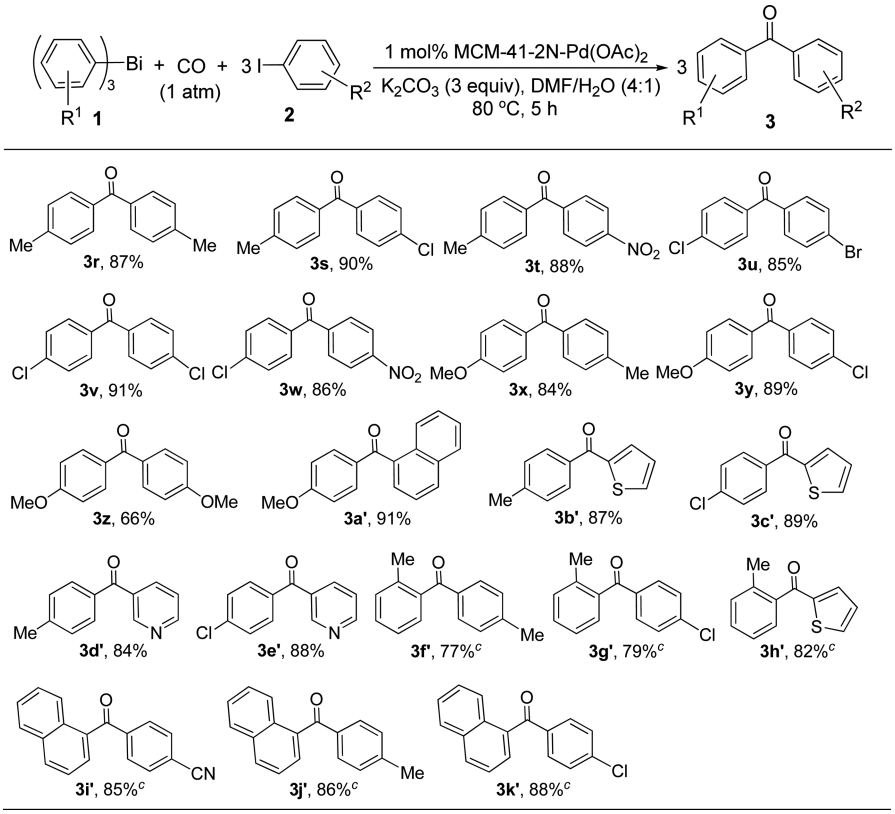
Table 3. Heterogeneous Palladium-Catalyzed Carbonylative Coupling of Triarylbismuths with Various Aryl Iodides[a,b]



[a]Reaction conditions: $BiAr_3$ (1.0 mmol), aryl iodide (3.2 mmol), MCM-41-2N-Pd$(OAc)_2$ (1 mol %), K_2CO_3 (3.0 mmol), and DMF/H_2O (4:1) (5 mL) at 80 °C under atmospheric pressure of CO for 5 h. [b]Isolated yield. [c]For 8 h.

Encouraged by the above-mentioned results, the carbonylative cross-coupling reactions of substituted triphenylbismuths such as tri(4-tolyl)bismuth, tri(4-chlorophenyl)bismuth, tri(4-methoxyphenyl)bismuth, tri(2-tolyl)bismuth, and tri(1-naphthyl)bismuth with a variety of aryl and heteroaryl iodides were then examined under optimized reaction conditions, and the results are listed in Table 3. As shown in Table 3, the carbonylative cross-coupling reactions of triarylbismuths bearing both electron-donating and -withdrawing groups with various aryl iodides proceeded smoothly under the optimized conditions to afford the corresponding carbonylative products **3r**−**z** in good to excellent yields within 5 h. The results indicated that the electronic natures of the substituents on the triarylbismuths have limited influence on this heterogeneous palladium-catalyzed carbonylative cross-coupling reaction. A variety of electron-donating and -withdrawing groups such as methyl, methoxy, chloro, bromo, and nitro on both triarylbismuths and aryl iodides were well tolerated. In addition, the reactions of substituted triphenylbismuths with bulky 1-iodonaphthalene or heteroaryl iodides also proceeded quite well, and the desired products **3a′**−**e′** were obtained in high yields. Interestingly, both sterically hindered tri(2-tolyl)bismuth and bulky tri(naphthalen-1-yl)bismuth were also found to be suitable reaction partners and afforded the corresponding carbonylative coupling products **3f′**−**k′** in good to high yields on slightly longer reaction times, clearly indicating that steric hindrance was not evident in this reaction. The present method provides a quite general route for the synthesis of unsymmetrical biaryl ketones having various functionalities. The results mentioned above prompted us to investigate the carbonylative cross-coupling reaction of aryl bromides with triarylbismuths; unfortunately, aryl bromides were not reactive under the conditions optimized for aryl iodides even at higher temperatures. This lowers the synthetic value of this protocol to some extent. In order to ascertain whether anchoring of the catalyst to the support limits its activity, we also performed the carbonylative coupling reaction of bromobenzene (3.2 equiv) with triphenylbismuth in DMF/H_2O (4/1) at 80 °C by using Pd$(OAc)_2$/$H_2N(CH_2)_2NH_2$ (1 mol %) as catalyst and K_2CO_3 (3.0 equiv) as base under CO (1 atm) for 5 h. It was found that only a trace of the desired **3a** was detected and diphenyl was formed as a direct coupling product in 17% yield.

To verify whether the observed catalysis was due to the heterogeneous catalyst MCM-41-2N-Pd$(OAc)_2$ or to a leached palladium species in solution, we performed the hot filtration test.[23] We focused on the carbonylative cross-coupling reaction of 3-iodotoluene with $BiPh_3$. We removed the catalyst from the reaction mixture by filtration after 2 h of reaction time, and the filtrate was allowed to react further. The catalyst filtration was performed at the reaction temperature (80 °C) in order to avoid possible recoordination or precipitation of soluble palladium upon cooling. In this case, no significant increase in conversion was observed, indicating that leached palladium species from the catalyst (if any) are not responsible for the observed activity. It was also confirmed by ICP-AES analysis that no palladium species could be detected in the filtrate. These results suggest that the palladium catalyst remains on the support at elevated temperatures during the reaction and the observed catalysis was intrinsically heterogeneous.

A plausible mechanism for heterogeneous palladium-catalyzed carbonylative cross-coupling reaction of triarylbismuths **1** with aryl iodides **2** is illustrated in Scheme 3. First, the

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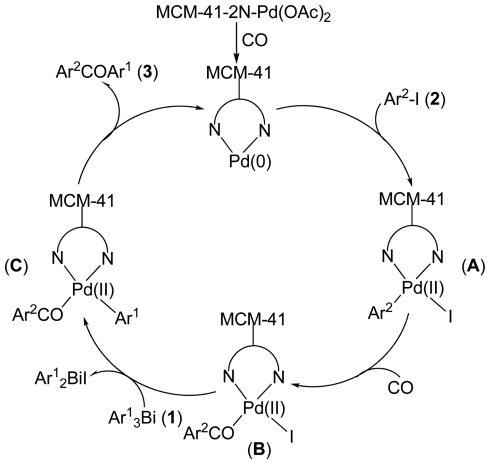
Scheme 3. Proposed Catalytic Cycle



$MCM\text{-}41\text{-}2N\text{-}Pd(OAc)_2$ can be easily reduced to the MCM-41-2N-Pd(0) in the presence of carbon monoxide. Oxidative addition of Ar^2I (**2**) to the MCM-41-2N-Pd(0) provides an MCM-41-bound arylpalladium(II) complex intermediate (**A**), which is followed by migratory insertion of carbon monoxide giving an MCM-41-bound acylpalladium(II) complex intermediate (**B**). Subsequent transmetalation between intermediate **B** and $Ar^1{}_3Bi$ (**1**) and reductive elimination of unsymmetrical biaryl ketone (**3**) from intermediate **C** regenerate the MCM-41-2N-Pd(0) complex to complete the catalytic cycle.

For the practical application of a heterogeneous transition-metal catalyst system, its ease of separation, recoverability, and reusability are important factors. The $MCM\text{-}41\text{-}2N\text{-}Pd(OAc)_2$ can be easily separated and recovered by a simple filtration of the reaction solution. We next investigated the recycle of the catalyst by using the carbonylative cross-coupling reaction of 4-chloroiodobenzene with $BiPh_3$. After carrying out the reaction, the catalyst was recovered by simple filtration and washed with distilled water, DMF, and diethyl ether. After being air-dried, it can be reused directly without further purification. The recovered palladium catalyst was used in the next run, and almost consistent activity was observed for eight consecutive cycles (Figure 1). In addition, the Pd leaching in the supported catalyst was also determined by ICP analysis. The palladium content of the catalyst was found to be 0.27 mmol/g after eight consecutive runs, indicating that only 3.6% of palladium had been lost from the MCM-41 support.

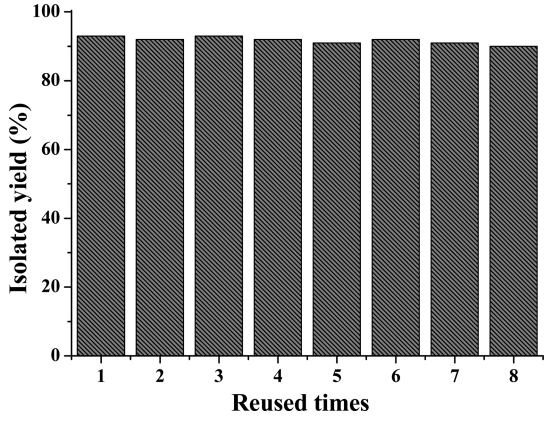


Figure 1. Recycle of the $MCM\text{-}41\text{-}2N\text{-}Pd(OAc)_2$ catalyst.

CONCLUSIONS

In conclusion, we first developed the carbonylative cross-coupling reaction of readily available, stable, and environmentally benign triarylbismuth compounds with various aryl iodides leading to a variety of unsymmetrical biaryl ketones in good to excellent yields. This carbonylative cross-coupling has many attractive features: (1) triarylbismuths act as less toxic and atom-efficient coupling reagents; (2) 1 equiv of triarylbismuths gives 3 equiv of carbonylative coupling products; (3) the reaction is tolerant of water and a wide range of functional groups; (4) this phosphine-free heterogeneous palladium catalyst can easily be prepared via a two-step procedure from commercially available and inexpensive reagents, recovered by a simple filtration of the reaction solution, and recycled for at least eight times without significant loss of activity.

EXPERIMENTAL SECTION

General Methods. All chemicals were reagent grade and used as purchased. All triarylbismuth reagents were obtained from commercial sources and used as received. The products were purified by flash chromatography on silica gel. A mixture of EtOAc and light petroleum ether was generally used as eluent. All products were characterized by comparison of their spectra and physical data with authentic samples. IR spectra were recorded on an FT-IR spectrometer. ^1H and ^{13}C NMR spectra were recorded at 400 or 100 MHz with $CDCl_3$ as the solvent and TMS as an internal standard. Chemical shifts are reported in δ (ppm) relative to TMS. HRMS spectra were recorded on a Q-Tof spectrometer with micromass MS software using electrospray ionization (ESI). Melting points are uncorrected. The $MCM\text{-}41\text{-}2N\text{-}Pd(OAc)_2$ complex was prepared according to our previous procedure,[22b] the palladium content was determined to be 0.28 mmol/g by ICP-AES.

General Procedure for the Heterogeneous Palladium-Catalyzed Carbonylative Cross-Coupling of Triarylbismuths with Aryl Iodides. A 50 mL round-bottomed flask equipped with a gas inlet tube, a reflux condenser, and a magnetic stirring bar was charged with $MCM\text{-}41\text{-}2N\text{-}Pd(OAc)_2$ (36 mg, 0.01 mmol Pd), K_2CO_3 (3.0 mmol), aryl iodide (3.2 mmol), and triarylbismuth (1.0 mmol). The flask was flushed with carbon monoxide, and then DMF (4 mL) and H_2O (1 mL) were added. The reaction mixture was stirred at 80 °C under CO (1 atm) for 5−8 h until complete consumption of starting material as judged by TLC. After being cooled to room temperature, the mixture was diluted with diethyl ether (20 mL) and filtered. The catalyst was washed with water (2 × 5 mL), DMF (2 × 5 mL), and diethyl ether (2 × 5 mL) and reused in the next run. The filtrate was washed with water (3 × 10 mL) and dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. The residue was purified by flash column chromatography on silica gel (light petroleum−ethyl acetate = 10:1 to 15:1) to afford the desired products **3**.

*Benzophenone (**3a**).*[16] White solid (465 mg, 85%). Mp 47−48 °C. IR (KBr): 3061, 1659, 1599, 1578, 941, 764, 701 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.81 (d, J = 7.2 Hz, 4H), 7.59 (t, J = 7.6 Hz, 2H), 7.49 (t, J = 7.6 Hz, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.8, 137.6, 132.4, 130.1, 128.3.

*3-Methylbenzophenone (**3b**).*[14f] Colorless oil (518 mg, 88%). IR (neat): 3060, 2923, 1660, 1598, 1585, 1448, 1280, 720, 704 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.80 (d, J = 7.6 Hz, 2H), 7.63 (s, 1H), 7.58 (t, J = 7.2 Hz, 2H), 7.50−7.44 (m, 2H), 7.41−7.33 (m, 2H), 2.42 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.0, 138.2, 137.8, 137.7, 133.2, 132.4, 130.5, 130.1, 128.3, 128.1, 127.4, 21.4.

*4-Methylbenzophenone (**3c**).*[19g] White solid (512 mg, 87%). Mp 56−57 °C. IR (KBr): 3059, 2922, 1658, 1606, 1578, 1446, 1277, 730, 700 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.78 (d, J = 7.2 Hz, 2H), 7.72 (d, J = 6.8 Hz, 2H), 7.56 (t, J = 7.2 Hz, 1H), 7.47 (t, J = 7.2 Hz, 2H), 7.28 (d, J = 7.2 Hz, 2H), 2.44 (s, 3H). ^{13}C NMR (100 MHz,

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$CDCl_3$): δ 196.5, 143.3, 138.0, 134.9, 132.2, 130.3, 130.0, 129.0, 128.2, 21.7.

*4-Methoxybenzophenone (**3d**).*[19g] White solid (471 mg, 74%). Mp 59−60 °C. IR (KBr): 3061, 2934, 1651, 1599, 1508, 1446, 1258, 1172, 844, 742, 701 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.85−7.82 (m, 2H), 7.77−7.74 (m, 2H), 7.58−7.54 (m, 1H), 7.47 (t, *J* = 7.6 Hz, 2H), 6.96 (dd, *J* = 8.8, 2.0 Hz, 2H), 3.88 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.6, 163.2, 138.3, 132.6, 131.9, 130.1, 129.8, 128.2, 113.6, 55.5.

*4-Chlorobenzophenone (**3e**).*[14f] White solid (604 mg, 93%). Mp 75−76 °C. IR (KBr): 1651, 1597, 1585, 1285, 1137, 1070, 955, 729, 696 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.79−7.74 (m, 4H), 7.60 (t, *J* = 7.4 Hz, 1H), 7.52−7.44 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.5, 138.9, 137.2, 135.9, 132.7, 131.5, 130.0, 128.7, 128.4.

*4-Nitrobenzophenone (**3f**).*[14f] Yellow solid (586 mg, 86%). Mp 136−137 °C. IR (KBr): 3101, 1652, 1595, 1578, 1515, 1358, 1318, 1278, 852, 706, 693 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.35 (d, *J* = 8.8 Hz, 2H), 7.95 (d, *J* = 8.4 Hz, 2H), 7.81 (d, *J* = 8.4 Hz, 2H), 7.66 (t, *J* = 7.2 Hz, 1H), 7.53 (t, *J* = 7.8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.8, 149.8, 142.9, 136.3, 133.5, 130.7, 130.1, 128.7, 123.6.

*4-Cyanobenzophenone (**3g**).*[14h] White solid (553 mg, 89%). Mp 110−112 °C. IR (KBr): 2229, 1651, 1592, 1579, 1404, 1312, 1282, 1067, 857, 736, 696 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.88 (d, *J* = 8.8 Hz, 2H), 7.81−7.77 (m, 4H), 7.65 (t, *J* = 7.6 Hz, 1H), 7.52 (t, *J* = 7.6 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.5, 140.7, 135.9, 132.8, 131.7, 129.7, 129.5, 128.1, 117.5, 115.2.

*4-Acetylbenzophenone (**3h**).*[24] White solid (612 mg, 91%). Mp 83−84 °C. IR (KBr): 1689, 1656, 1595, 1446, 1357, 1278, 931, 698 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.06 (dd, *J* = 6.6, 1.8 Hz, 2H), 7.87 (dd, *J* = 6.6, 1.8 Hz, 2H), 7.81 (d, *J* = 7.6 Hz, 2H), 7.65−7.61 (m, 1H), 7.51 (t, *J* = 7.6 Hz, 2H), 2.68 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.5, 196.0, 141.4, 139.6, 136.9, 133.0, 130.1, 130.0, 128.5, 128.2, 26.9.

*Methyl 4-Benzoylbenzoate (**3i**).*[24] White solid (634 mg, 88%). Mp 108−109 °C. IR (KBr): 1716, 1647, 1616, 1595, 1147, 1076, 826, 712 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.15 (dd, *J* = 6.6, 1.8 Hz, 2H), 7.84 (dd, *J* = 6.8, 2.0 Hz, 2H), 7.81 (d, *J* = 8.0 Hz, 2H), 7.65−7.60 (m, 1H), 7.50 (t, *J* = 7.6 Hz, 2H), 3.97 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.0, 166.3, 141.3, 137.0, 133.2, 133.0, 130.1, 129.8, 129.5, 128.5, 52.5.

*3-(Trifluoromethyl)benzophenone (**3j**).*[25] White solid (690 mg, 92%). Mp 50−51 °C. IR (KBr): 3068, 1667, 1611, 1598, 1337, 1268, 1171, 1128, 715 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.07 (s, 1H), 7.98 (d, *J* = 7.6 Hz, 1H), 7.85 (d, *J* = 7.6 Hz, 1H), 7.81−7.77 (m, 2H), 7.69−7.60 (m, 2H), 7.52 (t, *J* = 7.6 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.1, 138.3, 136.8, 133.1, 133.0, 131.0 (q, $^2J_{C-F}$ = 36.4 Hz), 130.0, 128.9, 128.8 (q, $^3J_{C-F}$ = 3.6 Hz), 128.6, 126.7 (q, $^3J_{C-F}$ = 3.8 Hz), 123.5 (q, $^1J_{C-F}$ = 272.0 Hz).

*2-Methylbenzophenone (**3k**).*[14f] Colorless oil (488 mg, 83%). IR (neat): 3062, 2927, 1664, 1598, 1579, 1449, 1268, 924, 732, 709 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.80 (d, *J* = 7.6 Hz, 2H), 7.57 (t, *J* = 7.6 Hz, 1H), 7.45 (t, *J* = 7.6 Hz, 2H), 7.39 (t, *J* = 7.6 Hz, 1H), 7.33−7.24 (m, 3H), 2.33 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.1, 138.2, 137.3, 136.2, 132.6, 130.5, 129.7, 129.6, 128.0, 127.9, 124.7, 19.5.

*2-Methoxybenzophenone (**3l**).*[14d] Colorless oil (401 mg, 63%). IR (neat): 3061, 2945, 1667, 1599, 1581, 1487, 1294, 1245, 1023, 926, 756, 703 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.81 (d, *J* = 7.6 Hz, 2H), 7.55 (t, *J* = 7.4 Hz, 1H), 7.49−7.34 (m, 4H), 7.04 (t, *J* = 7.4 Hz, 1H), 6.99 (d, *J* = 8.4 Hz, 1H), 3.72 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.5, 157.4, 137.8, 133.0, 131.9, 129.8, 129.6, 128.9, 128.2, 120.5, 111.5, 55.6.

*Methyl 2-Benzoylbenzoate (**3m**).*[26] White solid (627 mg, 87%). Mp 50−52 °C. IR (KBr): 3064, 2952, 1728, 1653, 1597, 1280, 1084, 717 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.04 (dd, *J* = 7.8, 1.0 Hz, 1H), 7.74 (d, *J* = 8.0 Hz, 2H), 7.64 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.62−7.52 (m, 2H), 7.45−7.39 (m, 3H), 3.60 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.0, 166.4, 141.7, 137.2, 133.1, 132.4, 130.1, 129.6, 129.5, 129.3, 128.5, 127.8, 52.1.

*1-Benzoylnaphthalene (**3n**).*[19g] Colorless oil (654 mg, 94%). IR (neat): 3058, 2926, 1659, 1597, 1578, 1507, 1448, 1315, 1282, 1249, 1206, 912, 775, 712 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.09 (d, *J* = 7.6 Hz, 1H), 7.95 (d, *J* = 8.4 Hz, 1H), 7.89−7.83 (m, 3H), 7.56−7.37 (m, 7H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.0, 138.4, 136.5, 133.8, 133.3, 131.3, 131.1, 130.5, 128.5, 128.4, 127.8, 127.3, 126.5, 125.8, 124.4.

*2-Benzoylnaphthalene (**3o**).*[19g] White solid (641 mg, 92%). Mp 77−78 °C. IR (KBr): 3056, 1657, 1594, 1497, 1446, 1272, 1116, 819, 754, 698 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.24 (s, 1H), 7.95−7.82 (m, 6H), 7.61−7.45 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.7, 138.0, 135.3, 134.9, 132.4, 132.3, 131.9, 130.1, 129.5, 128.4, 128.3, 127.9, 126.8, 125.8.

*2-Benzoylthiophene (**3p**).*[19g] White solid (502 mg, 89%). Mp 54−55 °C. IR (KBr): 1634, 1599, 1577, 1447, 1413, 1290, 910, 843, 729 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.88−7.85 (m, 2H), 7.74−7.71 (m, 1H), 7.66−7.64 (m, 1H), 7.60 (t, *J* = 7.4 Hz, 1H), 7.50 (t, *J* = 7.6 Hz, 2H), 7.18−7.15 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 188.2, 143.7, 138.2, 134.8, 134.2, 132.3, 129.2, 128.4, 128.0.

*3-Benzoylpyridine (**3q**).*[27] White solid (467 mg, 85%). Mp 39−41 °C. IR (KBr): 3058, 2923, 1660, 1415, 1282, 923, 713 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 9.02 (s, 1H), 8.83 (s, 1H), 8.13 (d, *J* = 8.0 Hz, 1H), 7.81 (d, *J* = 7.6 Hz, 2H), 7.64 (t, *J* = 7.4 Hz, 1H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.48−7.44 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.7, 152.5, 150.7, 137.3, 136.7, 133.2, 130.0, 128.6, 127.6, 123.5.

*4,4′-Dimethylbenzophenone (**3r**).*[14g] White solid (548 mg, 87%). Mp 94−95 °C. IR (KBr): 1646, 1606, 1569, 1277, 1176, 926, 844, 752 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.70 (d, *J* = 8.0 Hz, 4H), 7.27 (d, *J* = 8.4 Hz, 4H), 2.44 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.3, 142.9, 135.3, 130.2, 128.9, 21.6.

*4-Chloro-4′-methylbenzophenone (**3s**).*[14g] White solid (623 mg, 90%). Mp 128−129 °C. IR (KBr): 1645, 1607, 1585, 1287, 1147, 1087, 929, 854, 749 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, *J* = 8.4 Hz, 2H), 7.69 (d, *J* = 8.0 Hz, 2H), 7.45 (d, *J* = 8.8 Hz, 2H), 7.29 (d, *J* = 8.0 Hz, 2H), 2.45 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.3, 143.5, 138.6, 136.2, 134.5, 131.4, 130.2, 129.1, 128.6, 21.7.

*4-Methyl-4′-nitrobenzophenone (**3t**).*[14e] Yellow solid (636 mg, 88%). Mp 120−122 °C. IR (KBr): 1653, 1600, 1563, 1521, 1353, 1315, 1145, 1078, 933, 853, 732 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.34 (d, *J* = 8.8 Hz, 2H), 7.92 (d, *J* = 8.8 Hz, 2H), 7.72 (d, *J* = 8.0 Hz, 2H), 7.33 (d, *J* = 8.0 Hz, 2H), 2.47 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.5, 149.7, 144.6, 143.4, 133.7, 130.5, 130.3, 129.4, 123.5, 21.7.

*4-Bromo-4′-chlorobenzophenone (**3u**).*[14e] White solid (753 mg, 85%). Mp 146−148 °C. IR (KBr): 3056, 1646, 1586, 1289, 855, 753 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.72 (d, *J* = 8.4 Hz, 2H), 7.64 (s, 4H), 7.47 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.4, 139.2, 136.0, 135.5, 131.8, 131.4, 131.3, 128.8, 127.8.

*4,4′-Dichlorobenzophenone (**3v**).*[14e] White solid (685 mg, 91%). Mp 146−147 °C. IR (KBr): 1655, 1589, 1565, 1287, 1147, 1089, 852, 755 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.73−7.71 (m, 4H), 7.48−7.45 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.2, 139.2, 135.5, 131.4, 128.8.

*4-Chloro-4′-nitrobenzophenone (**3w**).*[14e] Yellow solid (675 mg, 86%). Mp 100−101 °C. IR (KBr): 1669, 1584, 1520, 1349, 1272, 1170, 1088, 929, 851, 738 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 8.37−8.35 (m, 2H), 7.93−7.91 (m, 2H), 7.77−7.75 (m, 2H), 7.52−7.50 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 193.6, 149.9, 142.5, 140.1, 134.5, 131.5, 130.6, 129.1, 123.7.

*4-Methoxy-4′-methylbenzophenone (**3x**).*[14g] White solid (570 mg, 84%). Mp 88−89 °C. IR (KBr): 1645, 1598, 1505, 1316, 1261, 1169, 1147, 1023, 929, 849, 761 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.81 (d, *J* = 8.8 Hz, 2H), 7.68 (d, *J* = 8.0 Hz, 2H), 7.27 (d, *J* = 8.4 Hz, 2H), 6.96 (d, *J* = 8.8 Hz, 2H), 3.89 (s, 3H), 2.44 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 195.4, 163.1, 142.6, 135.5, 132.4, 130.5, 130.0, 128.9, 113.5, 55.5, 21.6.

*4-Chloro-4′-methoxybenzophenone (**3y**).*[14g] White solid (658 mg, 89%). Mp 116−117 °C. IR (KBr): 1646, 1607, 1586, 1287, 1146, 1088, 930, 854, 749 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, *J* = 8.8 Hz, 2H), 7.70 (d, *J* = 8.4 Hz, 2H), 7.44 (d, *J* = 8.0 Hz, 2H), 6.96

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(d, J = 8.8 Hz, 2H), 3.88 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.3, 163.4, 138.3, 136.6, 132.5, 131.2, 129.8, 128.5, 113.7, 55.5.

*4,4′-Dimethoxybenzophenone (**3z**).*[19g] White solid (479 mg, 66%). Mp 136−137 °C. IR (KBr): 3065, 2926, 1653, 1597, 1506, 1447, 1259, 1175, 846, 743, 702 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, J = 8.8 Hz, 4H), 6.96 (d, J = 8.8 Hz, 4H), 3.88 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.5, 162.9, 132.2, 130.8, 113.5, 55.5.

*1-(4-Methoxybenzoyl)naphthalene (**3a′**).*[19g] Colorless oil (716 mg, 91%). IR (neat): 3056, 2923, 1652, 1587, 1574, 1501, 1446, 916, 773, 732 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.99 (d, J = 8.0 Hz, 1H), 7.92 (d, J = 8.0 Hz, 1H), 7.85 (d, J = 8.4 Hz, 1H), 7.81 (d, J = 8.8 Hz, 2H), 7.51−7.40 (m, 4H), 6.86 (d, J = 8.8 Hz, 2H), 3.78 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.7, 163.9, 137.1, 133.7, 132.8, 131.1, 130.9, 130.7, 128.4, 127.0, 126.8, 126.4, 125.8, 124.5, 113.8, 55.5.

*2-(4-Methylbenzoyl)thiophene (**3b′**).*[14b] White solid (527 mg, 87%). Mp 67−68 °C. IR (KBr): 2915, 1623, 1604, 1568, 1513, 1414, 1291, 1053, 844, 728 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, J = 8.0 Hz, 2H), 7.71−7.70 (m, 1H), 7.66−7.64 (m, 1H), 7.30 (d, J = 8.0 Hz, 2H), 7.17−7.15 (m, 1H), 2.45 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 187.9, 143.8, 143.0, 135.4, 134.5, 133.8, 129.4, 129.1, 127.9, 21.6.

*2-(4-Chlorobenzoyl)thiophene (**3c′**).*[14e] White solid (594 mg, 89%). Mp 94−95 °C. IR (KBr): 1632, 1588, 1566, 1414, 1161, 1068, 951, 854, 722 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.81 (d, J = 8.4 Hz, 2H), 7.75−7.73 (m, 1H), 7.63−7.61 (m, 1H), 7.47 (d, J = 8.4 Hz, 2H), 7.18−7.15 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 186.9, 143.2, 138.7, 136.4, 134.8, 134.6, 130.6, 128.8, 128.1.

*3-(4-Methylbenzoyl)pyridine (**3d′**).*[27] White solid (497 mg, 84%). Mp 76−77 °C. IR (KBr): 1651, 1419, 1288, 1024, 929, 740 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.99 (s, 1H), 8.81 (s, 1H), 8.11 (d, J = 7.6 Hz, 1H), 7.74 (d, J = 8.0 Hz, 2H), 7.47−7.43 (m, 1H), 7.32 (d, J = 8.0 Hz, 2H), 2.46 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.6, 152.6, 150.8, 144.2, 137.2, 134.1, 133.5, 130.3, 129.3, 123.4, 21.8.

*3-(4-Chlorobenzoyl)pyridine (**3e′**).*[28] White solid (574 mg, 88%). Mp 87−89 °C. IR (KBr): 1645, 1585, 1402, 1301, 1285, 746, 712 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.97 (d, J = 1.6 Hz, 1H), 8.83 (dd, J = 4.8, 1.6 Hz, 1H), 8.12−8.09 (m, 1H), 7.78 (d, J = 8.4 Hz, 2H), 7.53−7.45 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 193.6, 153.1, 150.8, 139.8, 137.1, 134.9, 132.8, 131.4, 129.0, 123.5.

*2,4′-Dimethylbenzophenone (**3f′**).*[19g] Colorless oil (485 mg, 77%). IR (neat): 2924, 1661, 1606, 1573, 1295, 1269, 1152, 926, 838, 743 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70 (d, J = 8.0 Hz, 2H), 7.38−7.35 (m, 1H), 7.31−7.22 (m, 5H), 2.42 (s, 3H), 2.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.4, 144.1, 139.0, 136.5, 135.2, 130.9, 130.3, 130.0, 129.2, 128.2, 125.2, 21.7, 19.9.

*4-Chloro-2′-methylbenzophenone (**3g′**).* Colorless oil (546 mg, 79%). IR (neat): 3062, 1668, 1587, 1493, 1265, 1091, 925, 721 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (dd, J = 6.8, 2.0 Hz, 2H), 7.42 (dd, J = 6.8, 2.0 Hz, 2H), 7.39−7.37 (m, 1H), 7.30−7.24 (m, 3H), 2.32 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.3, 139.7, 138.2, 136.8, 136.2, 131.5, 131.1, 130.5, 128.8, 128.4, 125.3, 19.9. HRMS calcd for $C_{14}H_{11}ClO^+$ [M^+]: 230.0498, found 230.0493.

*2-(2-Methylbenzoyl)thiophene (**3h′**).*[29] Colorless oil (497 mg, 82%). IR (neat): 2925, 1645, 1514, 1407, 1298, 1047, 848, 739 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.71−7.69 (m, 1H), 7.45−7.36 (m, 3H), 7.29−7.22 (m, 2H), 7.11−7.09 (m, 1H), 2.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 190.4, 145.0, 138.6, 136.5, 135.4, 134.8, 131.1, 130.3, 128.1, 128.0, 125.2, 19.7.

*1-(4-Cyanobenzoyl)naphthalene (**3i′**).* White solid (656 mg, 85%). Mp 80−81 °C. IR (KBr): 2231, 1674, 1506, 1280, 1246, 912, 781 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.15−8.12 (m, 1H), 8.06 (d, J = 8.0 Hz, 1H), 7.96−7.92 (m, 3H), 7.76 (d, J = 8.4 Hz, 2H), 7.60−7.52 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.4, 141.8, 134.7, 133.8, 132.5, 132.3, 130.8, 130.6, 128.8, 128.6, 127.9, 126.8, 125.4, 124.3, 118.0, 116.3. HRMS calcd for $C_{18}H_{11}NO^+$ [M^+]: 257.0841, found 257.0833.

*1-(4-Methylbenzoyl)naphthalene (**3j′**).*[19g] White solid (635 mg, 86%). Mp 83−84 °C. IR (KBr): 1646, 1603, 1507, 1282, 1247, 914, 780 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05 (d, J = 8.0 Hz, 1H), 7.99 (d, J = 8.0 Hz, 1H), 7.93−7.90 (m, 1H), 7.77 (d, J = 8.0 Hz, 2H), 7.57−7.46 (m, 4H), 7.25 (d, J = 8.4 Hz, 2H), 2.42 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.8, 144.3, 136.7, 135.7, 133.7, 131.0, 130.9, 130.6, 129.2, 128.4, 127.4, 127.2, 126.4, 125.7, 124.4, 21.8.

*1-(4-Chlorobenzoyl)naphthalene (**3k′**).*[12f] White solid (704 mg, 88%). Mp 126−128 °C. IR (KBr): 1648, 1585, 1508, 1402, 1283, 1251, 1091, 779 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.06 (d, J = 8.4 Hz, 1H), 8.02 (d, J = 8.0 Hz, 1H), 7.93 (d, J = 7.2 Hz, 1H), 7.81 (d, J = 8.4 Hz, 2H), 7.58−7.48 (m, 4H), 7.43 (d, J = 8.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.8, 139.8, 136.6, 135.8, 133.7, 131.8, 131.6, 130.8, 128.9, 128.5, 127.8, 127.5, 126.6, 125.6, 124.4.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00570.

Copies of ^{1}H and ^{13}C NMR spectra for the products (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mzcai@jxnu.edu.cn.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Cueto, M.; Jensen, P. R.; Kauffman, C.; Fenical, W.; Lobkovsky, E.; Clardy, J. *J. Nat. Prod.* **2001**, *64*, 1444.

(2) (a) Ghinet, A.; Tourteau, A.; Rigo, B.; Stocker, V.; Leman, M.; Farce, A.; Dubois, J.; Gautret, P. *Bioorg. Med. Chem.* **2013**, *21*, 2932. (b) Luque-Ortega, J. R.; Reuther, P.; Rivas, L.; Dardonville, C. *J. Med. Chem.* **2010**, *53*, 1788. (c) Guay, D. R. *Pharmacother.* **1999**, *19*, 6. (d) Pettit, G. R.; Toki, B.; Herald, D. L.; Verdier-Pinard, P.; Boyd, M. R.; Hamel, E.; Pettit, R. K. *J. Med. Chem.* **1998**, *41*, 1688.

(3) (a) Tanaka, D.; Nakagawa, K.; Higuchi, M.; Horike, S.; Kubota, Y.; Kobayashi, T. C.; Takata, M.; Kitagawa, S. *Angew. Chem., Int. Ed.* **2008**, *47*, 3914. (b) Peng, H. *J. Am. Chem. Soc.* **2008**, *130*, 42.

(4) (a) Cisar, J. S.; Cravatt, B. F. *J. Am. Chem. Soc.* **2012**, *134*, 10385. (b) Qin, Q.; Mague, J. T.; Pascal, R. A., Jr *Org. Lett.* **2010**, *12*, 928. (c) Kim, H.; So, S. M.; Yen, C. P.-H.; Vinhato, E.; Lough, A. J.; Hong, J.-L.; Kim, H.-J.; Chin, J. *Angew. Chem., Int. Ed.* **2008**, *47*, 8657.

(5) (a) Wei, Y.; Deb, I.; Yoshikai, N. *J. Am. Chem. Soc.* **2012**, *134*, 9098. (b) Seo, J. W.; Kim, H. J.; Lee, B. S.; Katzenellenbogen, J. A.; Chi, D. Y. *J. Org. Chem.* **2008**, *73*, 715.

(6) (a) Song, C. E.; Shim, W. H.; Roh, E. J.; Choi, J. H. *Chem. Commun.* **2000**, 1695. (b) Furstner, A.; Voigtlander, D.; Schrader, W.; Giebel, D.; Reetz, M. T. *Org. Lett.* **2001**, *3*, 417. (c) Gmouh, S.; Yang, H.; Vaultier, M. *Org. Lett.* **2003**, *5*, 2219. (d) Sarvari, M. H.; Sharghi, H. *J. Org. Chem.* **2004**, *69*, 6953. (e) Fillion, E.; Fishlock, D.; Wilsily, A.; Goll, J. M. *J. Org. Chem.* **2005**, *70*, 1316.

(7) (a) Chen, H.; Deng, M.-Z. *Org. Lett.* **2000**, *2*, 1649. (b) Goossen, L. J.; Ghosh, K. *Angew. Chem., Int. Ed.* **2001**, *40*, 3458. (c) Perez, I.; Sestelo, J. P.; Sarandeses, L. A. *J. Am. Chem. Soc.* **2001**, *123*, 4155. (d) Duplais, C.; Bures, F.; Sapountzis, I.; Korn, T. J.; Cahiez, G.; Knochel, P. *Angew. Chem., Int. Ed.* **2004**, *43*, 2968. (e) Zhang, Y.; Rovis, T. *J. Am. Chem. Soc.* **2004**, *126*, 15964. (f) Lerebours, R.; Camacho-Soto, A.; Wolf, C. *J. Org. Chem.* **2005**, *70*, 8601. (g) Xin, B.; Zhang, Y.; Cheng, K. *J. Org. Chem.* **2006**, *71*, 5725. (h) Villalobos, J. M.; Srogl, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2007**, *129*, 15734.

DOI: 10.1021/acs.joc.6b00570
J. Org. Chem. 2016, 81, 4244−4251

(8) (a) Brunet, J. J.; Chauvin, R. *Chem. Soc. Rev.* **1995**, *24*, 89. (b) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. Soc. Rev.* **2011**, *40*, 4986. (c) Cheng, L.; Zhong, Y.; Ni, Z.; Du, H.; Jin, F.; Rong, Q.; Han, W. *RSC Adv.* **2014**, *4*, 44312. (d) Long, Y.; Liang, K.; Niu, J.; Tong, X.; Yuan, B.; Ma, J. *New J. Chem.* **2015**, *39*, 2988.
(9) Yamamoto, T.; Kohara, T.; Yamamoto, A. *Chem. Lett.* **1976**, 1217.
(10) Bumagin, N. A.; Ponomaryov, A. B.; Beletskaya, I. P. *Tetrahedron Lett.* **1985**, *26*, 4819.
(11) (a) Hatanaka, Y.; Fukushima, S.; Hiyama, T. *Tetrahedron* **1992**, *48*, 2113. (b) Hatanaka, Y.; Hiyama, T. *Synlett* **1991**, *1991*, 845. (c) Hatanaka, Y.; Hiyama, T. *Chem. Lett.* **1989**, 2049.
(12) (a) Kang, S. K.; Yamaguchi, T.; Kim, T.-H.; Ho, P.-S. *J. Org. Chem.* **1996**, *61*, 9082. (b) Davies, S. G.; Pyatt, D.; Thomson, C. *J. Organomet. Chem.* **1990**, *387*, 381. (c) Echavarren, A. M.; Stille, J. K. *J. Am. Chem. Soc.* **1988**, *110*, 1557. (d) Ceccarelli, S.; Piarulli, U.; Gennari, C. *J. Org. Chem.* **2000**, *65*, 6254. (e) Dubbaka, S. R.; Vogel, P. *J. Am. Chem. Soc.* **2003**, *125*, 15292. (f) Cai, M.; Zheng, G.; Ding, G. *Green Chem.* **2009**, *11*, 1687. (g) Lindh, J.; Fardost, A.; Almeida, M.; Nilsson, P. *Tetrahedron Lett.* **2010**, *51*, 2470.
(13) Wang, Q.; Chen, C. *Tetrahedron Lett.* **2008**, *49*, 2916.
(14) (a) Ishiyama, T.; Kizaki, H.; Hayashi, T.; Suzuki, A.; Miyaura, N. *J. Org. Chem.* **1998**, *63*, 4726. (b) Tambade, P. J.; Patil, Y. P.; Panda, A. G.; Bhanage, B. M. *Eur. J. Org. Chem.* **2009**, *2009*, 3022. (c) Cai, M.; Zheng, G.; Zha, L.; Peng, J. *Eur. J. Org. Chem.* **2009**, *2009*, 1585. (d) Khedkar, M. V.; Tambade, P. J.; Qureshi, Z. S.; Bhanage, B. M. *Eur. J. Org. Chem.* **2010**, *2010*, 6981. (e) Cai, M.; Peng, J.; Hao, W.; Ding, G. *Green Chem.* **2011**, *13*, 190. (f) Zhou, Q.; Wei, S.; Han, W. *J. Org. Chem.* **2014**, *79*, 1454. (g) Niu, J.; Liu, M.; Wang, P.; Long, Y.; Xie, M.; Li, R.; Ma, J. *New J. Chem.* **2014**, *38*, 1471. (h) Gautam, P.; Bhanage, B. M. *J. Org. Chem.* **2015**, *80*, 7810.
(15) (a) Lee, P. H.; Lee, S. W.; Lee, K. *Org. Lett.* **2003**, *5*, 1103. (b) Lee, S. W.; Lee, K.; Seomoon, D.; Kim, S.; Kim, H.; Shim, E.; Lee, M.; Lee, S.; Kim, M.; Lee, P. H. *J. Org. Chem.* **2004**, *69*, 4852.
(16) Wang, X.; Liu, F.-D.; Tu, H.-Y.; Zhang, A.-D. *J. Org. Chem.* **2014**, *79*, 6554.
(17) (a) Gaspard-Iloughmane, H.; Le Roux, C. *Eur. J. Org. Chem.* **2004**, *2004*, 2517. (b) Kricheldorf, H. R. *Chem. Rev.* **2009**, *109*, 5579. (c) Bothwell, J. M.; Krabbe, S. W.; Mohan, R. S. *Chem. Soc. Rev.* **2011**, *40*, 4649.
(18) (a) *Organobismuth Chemistry*; Suzuki, H., Matano, Y., Eds.; Elsevier: Amsterdam, 2001. (b) Ohe, T.; Tanaka, T.; Kuroda, M.; Cho, C. S.; Ohe, K.; Uemura, S. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 1851. (c) Urano, M.; Wada, S.; Suzuki, H. *Chem. Commun.* **2003**, 1202.
(19) (a) Barton, D. H. R.; Ozbalik, N.; Ramesh, M. *Tetrahedron* **1988**, *44*, 5661. (b) Rao, M. L. N.; Yamazaki, O.; Shimada, S.; Tanaka, T.; Suzuki, Y.; Tanaka, M. *Org. Lett.* **2001**, *3*, 4103. (c) Rao, M. L. N.; Banerjee, D.; Dhanorkar, R. J. *Synlett* **2011**, *2011*, 1324. (d) Monguchi, Y.; Hattori, T.; Miyamoto, Y.; Yanase, T.; Sawama, Y.; Sajiki, H. *Adv. Synth. Catal.* **2012**, *354*, 2561. (e) Wang, T.; Sang, S.; Liu, L.; Qiao, H.; Gao, Y.; Zhao, Y. *J. Org. Chem.* **2014**, *79*, 608. (f) Rao, M. L. N.; Banerjee, D.; Jadhav, D. N. *Tetrahedron Lett.* **2007**, *48*, 6644. (g) Rao, M. L. N.; Venkatesh, V.; Banerjee, D. *Tetrahedron* **2007**, *63*, 12917. (h) Sorenson, R. J. *J. Org. Chem.* **2000**, *65*, 7747.
(20) (a) Trost, B. M. *Science* **1991**, *254*, 1471. (b) Anastas, P.; Eghbali, N. *Chem. Soc. Rev.* **2010**, *39*, 301. (c) Sheldon, R. A. *Chem. Soc. Rev.* **2012**, *41*, 1437. (d) Dunn, P. J. *Chem. Soc. Rev.* **2012**, *41*, 1452.
(21) (a) Cho, C. S.; Ohe, T.; Itoh, O.; Uemura, S. *J. Chem. Soc., Chem. Commun.* **1992**, 453. (b) Cho, C. S.; Yoshimori, Y.; Uemura, S. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 950. (c) Kang, S.-K.; Ryu, H.-C.; Lee, S.-W. *Synth. Commun.* **2001**, *31*, 1027.
(22) (a) Zhao, H.; Peng, J.; Xiao, R.; Cai, M. *J. Mol. Catal. A: Chem.* **2011**, *337*, 56. (b) Huang, B.; Yin, L.; Cai, M. *New J. Chem.* **2013**, *37*, 3137.
(23) Lempers, H. E. B.; Sheldon, R. A. *J. Catal.* **1998**, *175*, 62.
(24) Wong, Y.-C.; Parthasarathy, K.; Cheng, C.-H. *Org. Lett.* **2010**, *12*, 1736.
(25) Yasuda, S.; Yorimitsu, H.; Oshima, K. *Organometallics* **2009**, *28*, 4872.
(26) Okimoto, M.; Yoshida, T.; Hoshi, M.; Chiba, T.; Maeo, K. *Synth. Commun.* **2011**, *41*, 3134.
(27) Maerten, E.; Sauthier, M.; Mortreux, A.; Castanet, Y. *Tetrahedron* **2007**, *63*, 682.
(28) Baeckvall, J. E.; Nordberg, R. E.; Nystroem, J. E.; Hoegberg, T.; Ulff, B. *J. Org. Chem.* **1981**, *46*, 3479.
(29) Keumi, T.; Yoshimura, K.; Shimada, M.; Kitajima, H. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 455.

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J. Org. Chem. 2016, 81, 4244−4251