Check for updates

Article

Journal of Chemical Research

Journal of Chemical Research
1–7
© The Author(s) 2021
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/17475198211026479
journals.sagepub.com/home/chl
SAGE

Organozinc-mediated direct cross-coupling under microwave irradiation

Chun-Jing Li

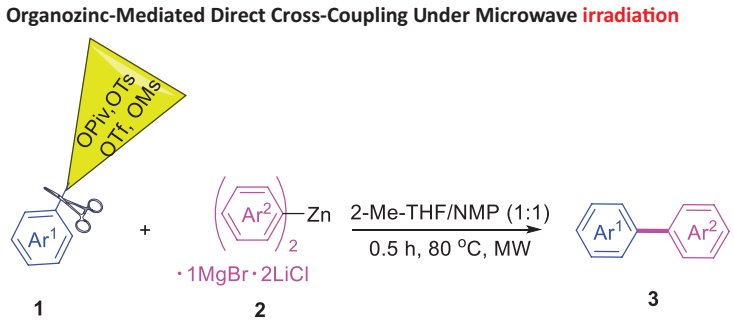
Abstract

We report a direct cross-coupling reaction between (het)aryl pivalates/tosylates and di(het)arylzinc species in 2-methyltetrahydrofuran/*N*-methyl pyrrolidone (1:1), which occurs via C–O bond cleavage under microwave irradiation. The reaction takes place smoothly in short reaction times without the addition of any catalyst or ligand. The reaction is suitable for a broad scope of substrates and exhibits good functional group compatibility, utilizes a simple work-up procedure, and gives the desired products in high purity.

Keywords

aryl pivalates, arylzinc reagents, C–C bond, microwave, organozinc-mediated

Date received: 17 March 2021; accepted: 2 June 2021



Introduction

Biaryls have been widely applied in the syntheses of natural products, polyaromatic molecules, and pharmaceuticals.[1–3] Transition-metal (TM) catalyzed cross-coupling reactions are very powerful tools for constructing such structural units. However, various issues remain, including high costs and the poor stability of many TM catalysts and ligands, and the necessity of disposal of heavy-metal residues. Transition-metal-free (TM-free) cross-coupling methods have attracted significant attention in recent years.[4–12] Examples include the reactions of organohalides (R-Hal, including R-I, R-Br, and unreactive R-Cl) with aryl Grignard,[13,14] arylzinc,[15,16] organoaluminum[17] reagents, and among others.[5,18] Different from classical cross-coupling reactions, most TM-free couplings occur as single-electron transfer (SET) processes, and can be regarded as one-electron-catalyzed cross-coupling reactions.[19] The key process in the SET catalytic cycle is the formation of the radical anion R-Hal$^{\bullet-}$, which undergoes further propagation (with R-M) and electron exchange (with another R-Hal) to form the product and to regenerate itself.[20] The SET mechanisms have been clarified by means of both experimental[21] and theoretical[22] methods.

Department of Chemistry and Environmental Engineering, Hebei Chemical and Pharmaceutical College, Shijiazhuang, China

Corresponding author:
Chun-Jing Li, Department of Chemistry and Environmental Engineering, Hebei Chemical and Pharmaceutical College, Shijiazhuang 050026, China.
Email: wyclichunjing@126.com

Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).

Phenol derivatives have some advantages: (1) phenol derivatives are easily available and are less expensive than the corresponding halides; (2) the use of halides, which pollute the environment is avoided; and (3) phenol derivatives can exhibit orthogonal reactivity to organohalides.[23] There are many known methods for cross-coupling phenols derivatives.[24] However, no examples utilize simple phenol derivatives (e.g. pivalate esters, sulfonates, carbamates, and sulfamates) for cross-coupling by SET processes. Organozinc reagents have emerged as attractive candidates due to their easy preparation and high functional group tolerance in cross-coupling reactions for the construction of biaryl and aryl–vinyl structural scaffolds.[25,26] To the best of our knowledge, phenol derivatives have never been used in couplings with organozinc reagents by SET-catalyzed cross-coupling. Herein, we report the first cross-coupling reactions of phenol derivatives with arylzinc reagents to construct C–C bonds under SET-catalyzed cross-coupling reaction conditions.

Results and discussion

We started our investigation by utilizing phenyl pivalate ester **1a** as a model substrate. The desired biaryl **3a** was not obtained using 1 equiv. of the 4-methoxyphenylzinc reagent prepared from the corresponding arylmagnesium bromide and zinc bromide (Table 1, entry 1). The method utilized to prepare the arylzinc reagent is crucial for smooth conversion.

No matter if 1 or 2 equiv. of the arylmagnesium bromide is mixed with 1 equiv. of zinc bromide (Table 1, entries 2 and 3), the response was very poor. The reaction yield was improved slightly by adding 1 equiv. of lithium chloride (Table 1, entries 4 and 5); however, the reaction proceeded sparingly or not at all when lithium bromide or magnesium bromide were added (Table 1, entries 6 and 7). The yield reached 46% using 2 equiv. of lithium chloride (Table 1, entry 8), but the yield did not increase significantly when 3 equiv. of lithium chloride were added (Table 1, entry 9).

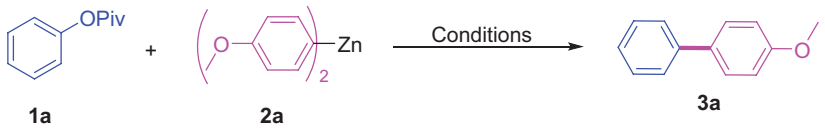
Under the same conditions as those in entry 9, microwave (MW) heating led to a yield of 68% (Table 1, entry 10). Actually, the arylzinc iodide/lithium chloride complex reported by Knochel[27] gave lower yields of the product, even in the presence of an external magnesium salt (Table 1, entries 11 and 12). The use of N,N-dimethylacetamide (DMA), $^{i}Pr_2O$, and 1,4-dioxane as solvents were demonstrated to be of no effect (Table 1, entries 13, 15, and 16). When N,N-dimethylformamide (DMF) was used, a yield of 5% was obtained (Table 1, entry 17). The use of 1-methylpyrrolidin-2-one (NMP), 2-Me-Tetrahydrofuran (THF), diglyme, and toluene led to the desired product, and 2-Me-THF gave the highest yield (Table 1, entries 14 and 18–20). Mixtures (1:1) of 2-Me-THF/toluene, 2-Me-THF/NMP, or 2-Me-THF/diglyme behaved better than a single solvent, with 2-Me-THF/NMP (1:1) leading to the highest yield (Table 1, entries 21–23). The reaction yield did not increase on extending the reaction time, with only 0.5 h being required to obtain the highest yield (Table 1, entries 24–26). When the reaction was run at 80 °C, a 93% yield was achieved. A reaction temperature higher than 80 °C did not further improve the yield, while a temperature lower than 80 °C led to a decrease in the yield (Table 1, entries 25, 27, and 28). However, conventional heating led, under the same conditions, to a yield of only 25% (Table 1, entry 29).

With promising results in hand, we next tested the analogous cross-coupling of several other electrophilic partners (Table 2). In addition to the aryl pivalate ester (Table 2, entry 1), the corresponding carbamate and sulfamate were deemed competent substrates (Table 2, entries 2 and 3). Furthermore, sulfonate derivatives of phenol also gave high yields of the coupled product (Table 2, entries 4–6), and aryl sulfonates (in particular, tosylates) were relatively unreactive compared to triflates; however, tosylates were more easily handled, stable and considerably less expensive than aryl triflates. Moreover, the use of a phenyl methyl ether did not lead to the desired product under our optimized conditions (Table 2, entry 7).

Having identified optimized reaction conditions (Table 1, entry 25), we next investigated the scope of the substrates (Table 3). Aryl pivalates/tosylates containing electron-donating groups were efficiently coupled to provide the corresponding biaryl products in good to excellent yields (Table 3, entries **3b**, **3c**, **3d**, and **3e**), with the *ortho* methyl-substituted aryl pivalates/tosylates giving lower yields compared to their *meta*- and *para*-substituted analogues. More sterically hindered 2,6-xylyl pivalate underwent the reaction with **2a** to afford **3g** in 49% yield (Table 3, entry **3g**); however, 2,6-xylyl triflate gave a more satisfactory yield under the same conditions. Aryl pivalates/tosylates containing electron-withdrawing groups (Table 3, entries **3i**, **3j**, and **3k**) and naphthyl pivalates/tosylates (Table 3, entry **3f**) were efficiently coupled to provide the corresponding biaryl products in excellent isolated yields. It is worth mentioning that an aryl triflate containing chloride reacted with **2a** occurred efficiently, with the potentially reactive C−Cl bond untouched (Table 3, entry **3k**), p-Bromophenyl pivalate reacted with **2a** to give product **3l** in 35% yield (Table 3, entry **3l**) along with 1,4-bis(4-methoxyphenyl)benzene (16%) as a by-product. Various sensitive functional groups, including unprotected phenol (Table 3, entry **3h**), ester (Table 3, entries **3n** and **3o**), and amide (Table 3, entry **3m**) groups were well tolerated. *N*-Methylindolyl and pyridyl pivalates/tosylates also gave good yields of the expected products (Table 3, entries **3p** and **3q**).

We further inspected the reactivity of different zinc reagents (Table 4). Both electron-rich and electron-deficient (het)aryl zinc reagents (Table 4, entries **3r, 3s, 3t, 3u, 3v, 3w, 3ae**, and **3ag**) were smoothly participated in the cross-coupling. Compared with **3w**, the reaction of **3v** was not sensitive to the steric hindrance of (het)aryl zinc reagents. Heteroaryl zinc reagents were efficiently coupled with aryl pivalates/tosylates in excellent yields (Table 4, entries **3w, 3x, 3y, 3z, 3af, 3ah, 3aj**, and **3ak**). A variety of functional groups was also compatible under these reaction conditions, including nitrile, ketone, amide, and ester (Table 4, entries **3aa, 3ab, 3ac, 3ad**, and **3ai**). It is worth noting that an easily enolizable ketone (Table 4, entry **3ah**) was well tolerated, and no notable byproducts resulting from the addition of Grignard reagents to these groups were found.

Table 1. Optimization of the reaction conditions.[a]



1a **2a** **3a**

Entry	Organic zinc reagent	Solvent	Time (h)	Temperature (°C)	Mode of heating[b]	Yield[c]
1	1 ArMgBr + 1 $ZnCl_2$	THF	8	80	Δ	–
2	1 ArMgBr + 1 $ZnBr_2$	THF	8	80	Δ	<5%
3	2 ArMgBr + 1 $ZnBr_2$	THF	8	80	Δ	10%
4	1 ArMgBr + 1 $ZnBr_2$ + 1 LiCl	THF	8	80	Δ	18%
5	2 ArMgBr + 1 $ZnBr_2$ + 1 LiCl	THF	8	80	Δ	39%
6	2 ArMgBr + 1 $ZnBr_2$ + 1 LiBr	THF	8	80	Δ	<5%
7	2 ArMgBr + 1 $ZnBr_2$ + 1 $MgBr_2$	THF	8	80	Δ	–
8	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	THF	8	80	Δ	46%
9	2 ArMgBr + 1 $ZnBr_2$ + 3 LiCl	THF	8	80	Δ	47%
10	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	THF	8	80	MW	68%
11[d]	2 ArZnI LiCl	THF	8	80	MW	23%
12[d]	2 ArZnI LiCl + 2 $MgBr_2$	THF	8	80	MW	24%
13	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	DMA	8	80	MW	–
14	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	NMP	8	80	MW	35%
15	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	$^{i}Pr_2O$	8	80	MW	–
16	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	1,4-dioxane	8	80	MW	–
17	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	DMF	8	80	MW	5%
18	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF	8	80	MW	75%
19	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	Diglyme	8	80	MW	32%
20	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	Toluene	8	80	MW	37%
21	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/toluene (1:1)	8	80	MW	56%
22	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	8	80	MW	87%
23	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/diglyme (1:1)	8	80	MW	61%
24	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	1	80	MW	92%
25	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	0.5	80	MW	93% (91%)
26	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	10 min	80	MW	88%
27	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	0.5	50	MW	45%
28	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	0.5	100	MW	92%
29	2 ArMgBr + 1 $ZnBr_2$ + 2 LiCl	2-Me-THF/NMP (1:1)	0.5	80	Δ	25%

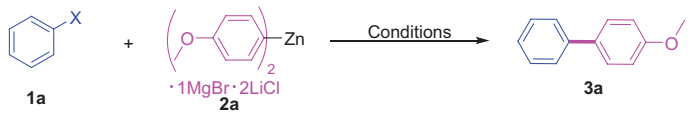
MW: microwave.
[a]Conditions: **1a** (0.2 mmol) was treated with **2a** (0.3 mmol, 1.5 equiv.) in solvent (3 mL) by heating under argon.
[b]Δ conventional heating.
[c]GC yield using tridecane as an internal standard; isolated yield is given in parentheses.
[d]See Chen et al.[13]

The SET-catalyzed cross-coupling reactions are more sensitive to steric hindrance. However, the promising results obtained for *para*- and *meta*-substituted aryl pivalates/tosylates render this system a new and useful tool in SET-catalyzed cross-coupling reactions. For instance, under these conditions, the selective one-pot synthesis of disubstituted phenol sulfonates gave unsymmetrically substituted terphenyl compounds in satisfactory yields (Scheme 1).

In Hayashi's report,[28] the occurrence of SET initiation in the coupling of aryl Grignard reagents with aryl halides was confirmed by the observation that the addition of lithium 4,4-di-*tert*-butylbiphenylide (LDBB) drastically accelerated the coupling. This result may be rationally understood by inferring that LDBB works as a much more efficient single-electron donor than Grignard reagents in the slow initiation step, and thus, the overall reaction rate is increased. We conducted similar experiments on the arylzinc coupling using LDBB as a single-electron donor. The reactivity of PhOPiv (**1a**) toward $(4\text{-MeOC}_6H_4)_2Zn$ **2a** was quite low at 50 °C over 30 min, when giving only a 45% yield of the coupling product **3a** (Scheme 2). By contrast, treatment of **1a** with LDBB (0.2 equiv.)[29] gave **3a** in 54% yield. The observed acceleration is compatible with SET initiation, and it is likely that [PhOPiv]•−, generated by SET, has a lifetime long enough to react with **1a** before undergoing decomposition to Ph•.[30,31]

Considering the above result in conjunction with similarities in the intrinsic character between arylzinc and arylmagnesium reagents, the present coupling reaction likely follows a Grignard cross-coupling mechanism[2,4,32–34] as shown in Scheme 3, and exemplified by the reaction of PhOPiv **1a** with $(4\text{-MeOC}_6H_4)_2Zn$ **2a**. The reaction is initiated by SET from $(4\text{-MeOC}_6H_4)_2Zn$ to PhOPiv to give the anion radical [PhOPiv]•−, which reacts with $(4\text{-MeOC}_6H_4)_2Zn$. SET from

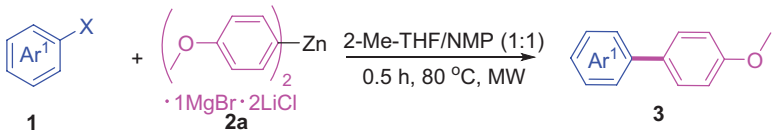
Table 2. Survey of cross-coupling partners.[a]



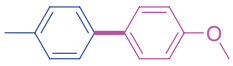
Entry	X	Yield (%)[b]
1	OPiv	93
2	OSO_2NMe_2	75
3	$OCONEt_2$	56
4	OTs	88
5	OMs	85
6	OTf	96
7	OMe	–

[a]Conditions: **1a** (0.2 mmol), **2a** (0.3 mmol, 1.5 equiv.), in 2-Me-THF/NMP (1:1) (3 mL), MW irradiation, 80 °C, 0.5 h.
[b]GC yield using tridecane as an internal standard.

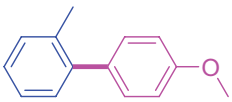
Table 3. Cross-couplings of aryl pivalate esters and sulfonates with the 4-methoxyphenylzinc reagent.[a,b]



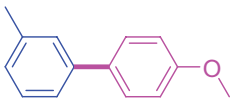
X = OPiv,OTs, OTf, OMs



3b
87% (X = OPiv)
89% (X = OTs)

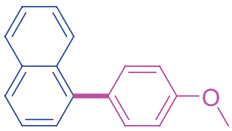


3c
69% (X = OPiv)
72% (X = OTs)

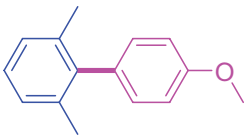


3d
81% (X = OPiv)
83% (X = OTs)

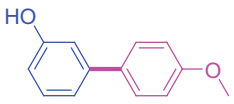
3e
69% (X = OPiv)
77% (X = OTs)



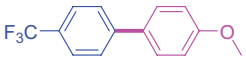
3f
93% (X = OPiv)
91% (X = OTs)



3g
49% (X = OPiv)
85% (X = OTf)

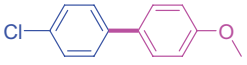


3h
65% (X = OPiv)
80% (X = OTs)

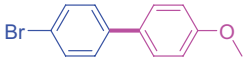


3i
89% (X = OPiv)
87% (X = OTs)
86% (X = OMs)

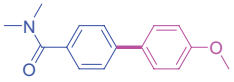
3j
91% (X = OPiv)
93% (X = OTs)



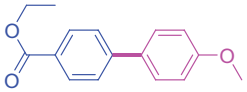
3k
81% (X = OTf)



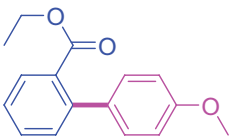
3l
35% (X = OTf)



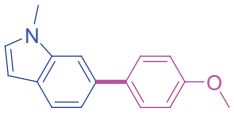
3m
81% (X = OTs)



3n
84% (X = OTs)
83% (X = OMs)



3o
65% (X = OTs)
82% (X = OTf)

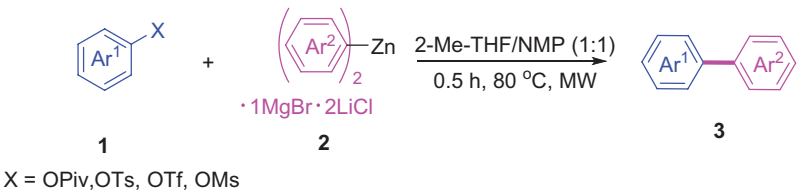


3p
84% (X = OPiv)
82% (X = OTs)

3q
77% (X = OPiv)
83% (X = OTs)

[a]Conditions: 1 (0.2 mmol), 2 (0.3 mmol, 1.5 equiv.), 2-Me-THF/NMP (1:1) (3 mL), MW irradiation, 80 °C, 0.5 h.
[b]Isolated yields.

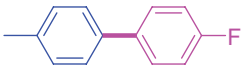
Table 4. Cross-coupling of aryl pivalate esters and sulfonates with different zinc reagents.[a,b]



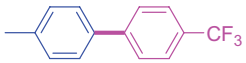
1
X = OPiv,OTs, OTf, OMs

2

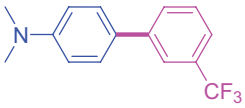
3



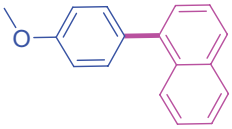
3r
65% (X = OPiv)
78% (X = OTs)
76% (X = OMs)



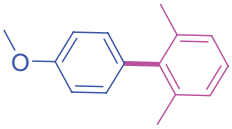
3s
86% (X = OPiv)
87% (X = OTs)
83% (X = OMs)



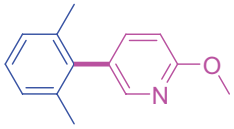
3t
81% (X = OPiv)
83% (X = OTs)



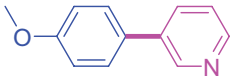
3u
85% (X = OPiv)
86% (X = OTs)



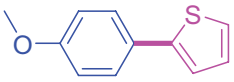
3v
78% (X = OPiv)
81% (X = OTs)



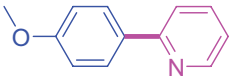
3w
45% (X = OPiv)
81% (X = OTf)



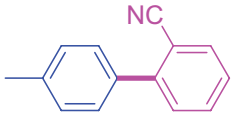
3x
77% (X = OPiv)
78% (X = OTs)
76% (X = OMs)



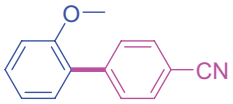
3y
78% (X = OPiv)
79% (X = OTs)
75% (X = OMs)



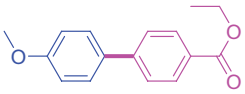
3z
75% (X = OPiv)
78% (X = OTs)



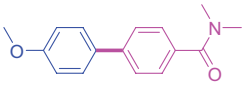
3aa
78% (X = OPiv)
79% (X = OTs)



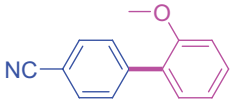
3ab
65% (X = OPiv)
68% (X = OTs)



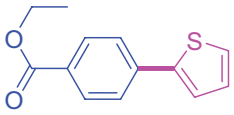
3ac
76% (X = OPiv)
79% (X = OTs)



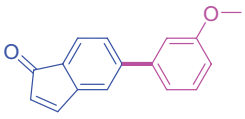
3ad
75% (X = OPiv)
77% (X = OTs)



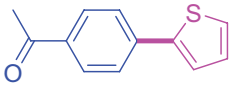
3ae
81% (X = OPiv)
80% (X = OTs)



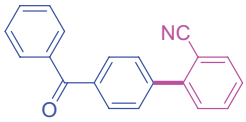
3af
83% (X = OPiv)
85% (X = OTs)



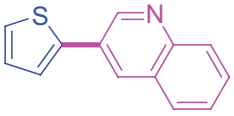
3ag
81% (X = OPiv)
84% (X = OTs)



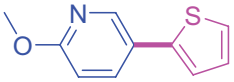
3ah
78% (X = OPiv)
82% (X = OTs)



3ai
81% (X = OPiv)
83% (X = OTs)



3aj
82% (X = OPiv)
83% (X = OTs)



3ak
83% (X = OPiv)
85% (X = OTs)

[a]Conditions: 1 (0.2 mmol), 2 (0.3 mmol, 1.5 equiv.), 2-Me-THF/NMP (1:1) (3 mL), MW irradiation, 80 °C, 0.5 h.
[b]Isolated yields.

the resulting anion radical, [4-MeOC$_6$H$_4$-Ph]•−, to PhOPiv gives the coupling product 4-MeOC$_6$H$_4$-Ph and regenerates [PhOPiv]•−, thereby beginning another propagation cycle.

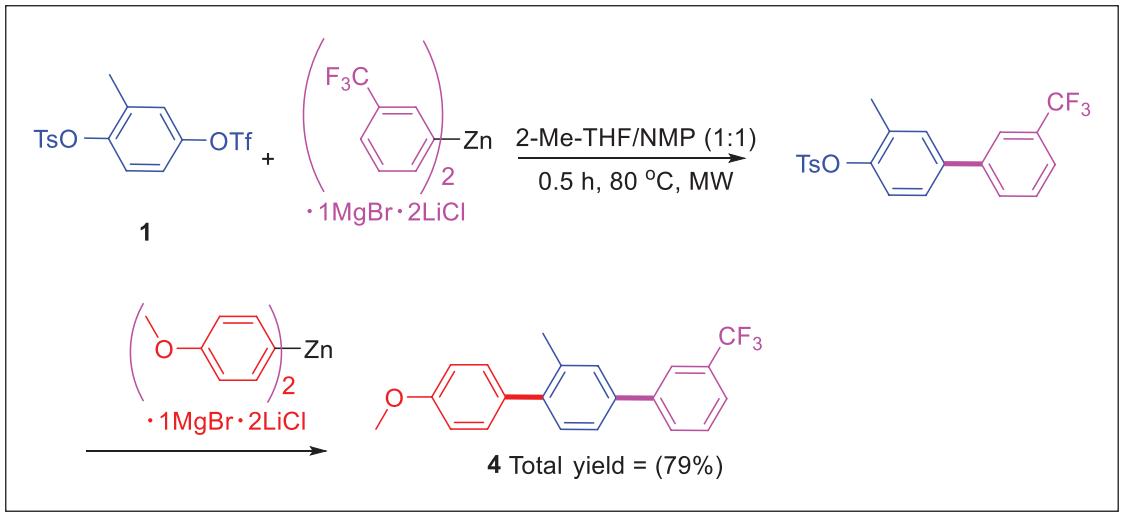
Conclusion

The reactions of (het)aryl pivalates/tosylates with di(het) arylzincs gave biaryl compounds in short reaction times under microwave irradiation. The reaction is suitable for a broad scope of substrates and exhibits good functional group compatibility. This reaction is applicable to simple hydroxybenzenes that are widely distributed in nature. No catalyst or ligand is required, and a simple work-up procedure is employed. The reaction is believed to occur via a SET mechanism for activation of the aryl pivalates.

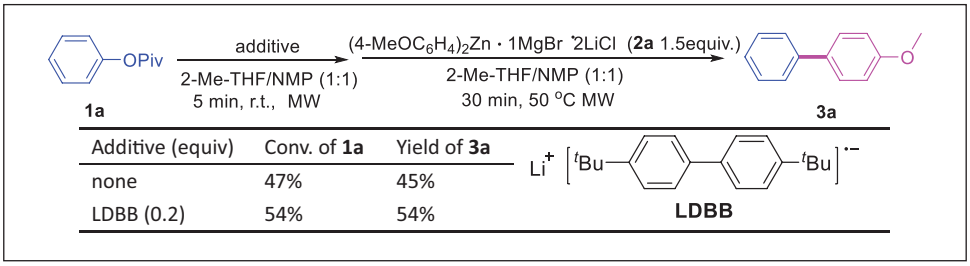
Experimental

General information

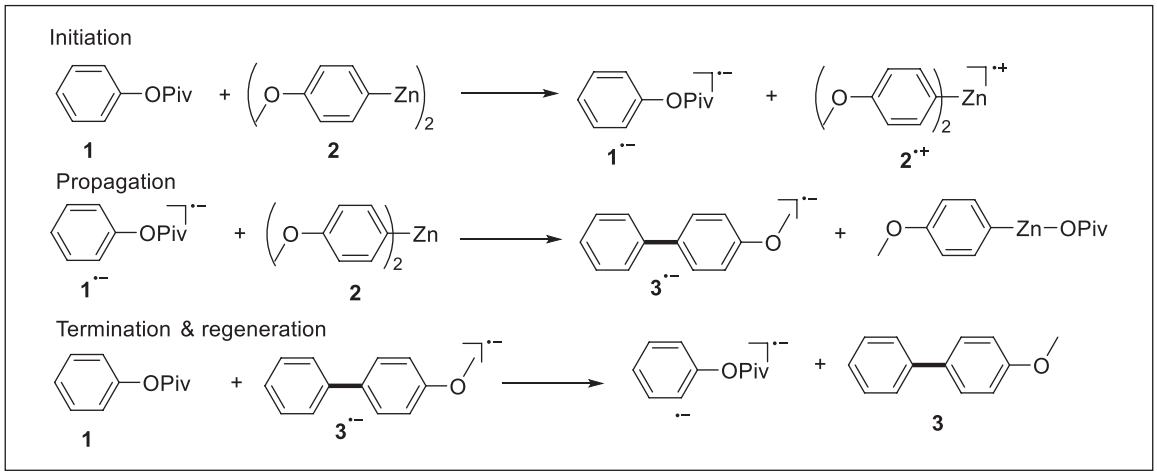
The reactions were carried out at 50–80 W in a CEM Discover (0–600 W, 2450M) focused microwave reactor equipped with a pressure controller under isothermal conditions. Standard 5 mL glass reaction vessels were used as supplied with the CEM reactor. The reaction mixtures were stirred magnetically. LiCl, $ZnBr_2$, $ZnCl_2$, and LiBr were purchased from Aldrich. $MgBr_2$ was purchased from Alfa



Scheme 1. One-pot synthesis of an unsymmetric terphenyl compound.



Scheme 2. Effect of the addition of single-electron donors.



Scheme 3. A plausible mechanism.

Aesar. Other reagents are available commercially and were used without further purification, unless otherwise indicated. All reactions were carried out under an argon atmosphere with dry solvents under anhydrous conditions, unless otherwise noted. THF was dried over alumina under N_2 using a Grubbs-type solvent purification system. All arylzinc reagents were prepared from the corresponding arylmagnesium bromides, LiCl and $ZnBr_2$. All aromatic phenols were purchased from Alfa Aesar. Spectroscopic data for known compounds match with the data reported in the corresponding references. Reactions were monitored with Agilent GC Series 6890N and instruments GCMS 7890A. All compounds were characterized by ^{1}H NMR spectroscopy using a Bruker 400 M spectrometer (Bruker Avance III 400 MHz NMR). New compounds are characterized by HRMS (TripleTOF™ 5600+). ^{1}H NMR was recorded in $CDCl_3$ using tetramethylsilane (TMS) and deuterium oxide as the internal standard. Chemical shifts were reported in parts per million. The signal patterns are indicated as follows: s, singlet; d, doublet; t, triplet; dd, doublet of doublets; dt, doublet of triplets; and m, multiplet. Coupling constants, *J*, are reported in Hertz (Hz). The products were purified by column chromatography on Aladdin silica gel 300–400 mesh under an argon atmosphere.

Experimental procedures

General procedure for the reaction between (het)aryl pivalates **1** and diarylzinc reagents **2**. In a glovebox, (het)aryl pivalate **1** (0.2 mmol) and NMP (1.5 mL) were added to the diarylzinc **2** (0.3 mmol, prepared by mixing zinc bromide, lithium chloride, and the corresponding aryl magnesium bromide in 1.5 mL of THF) in a reaction tube. The reaction mixture was then heated at 80 °C for 0.5 h under MW irradiation. After completion of the reaction, the mixture was concentrated under vacuum, and saturated NH_4Cl added. The mixture was extracted with CH_2Cl_2 several times. The combined organic layers were dried over anhydrous $MgSO_4$, concentrated in vacuo, and the residue was purified by column chromatography on silica gel to give the coupling product **3**.

*(2,6-Dimethylphenyl)-5-methoxypyridine (**3w**).* Product **3w** was obtained following the general procedure. Purification via silica gel column chromatography (petroleum ether/EtOAc = 10:1, v/v) afforded the desired product. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.99 (dd, J = 2.4, 0.8 Hz, 1H), 7.39 (dd, J = 8.4, 2.4 Hz, 1H), 7.21-7.12 (m, 3H), 6.84 (dd, J = 8.4, 0.7 Hz, 1H), 4.01 (s, 3H), 2.07 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 163.1, 146.6, 139.7, 137.9, 136.9, 129.4, 127.5, 110.7, 53.4, 21.0. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{14}H_{15}NO$: 214.1154; found: 214.1229.

*4'-Benzoyl-[1,1'-biphenyl]-2-carbonitrile (**3ai**).* Product **3ai** was obtained following the general procedure. Purification via silica gel column chromatography (petroleum ether/EtOAc = 10/1, v/v) afforded the desired product. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (dt, J = 8.2, 1.7 Hz, 2H), 7.87~7.85 (m, 2H), 7.82~7.81 (m, 1H), 7.70~7.67 (m, 3H), 7.62~7.56 (m, 2H), 7.54~7.49 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 196.2, 144.4, 142.1, 137.7, 137.4, 134.0, 133.1, 132.8, 130.6, 130.2, 128.9, 128.5, 128.4, 118.5, 111.4. HRMS (ESI): m/z $[M + H]^+$ calcd for $C_{20}H_{13}NO$: 284.0997; found: 284.1075.

Acknowledgements

The author is thankful to Hebei University of Science & Technology for ^{1}H NMR, ^{13}C NMR, and HRMS (ESI) facilities.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The author gratefully acknowledges the financial support from Hebei Chemical & Pharmaceutical College.

ORCID iD

Chun-Jing Li https://orcid.org/0000-0002-3874-9936

Supplemental material

Supplemental material for this article is available online.

References

1. Diederich F and Stang PJ (eds). *Metal-catalyzed cross-coupling reactions*. New York: Wiley, 1998.
2. Miyaura N (ed.) *Cross-coupling reactions: a practical guide*. Berlin: Springer, 2002.
3. Kertesz M, Choi CH and Yang S. *Chem Rev* 2005; 105: 3448.
4. Sun CL and Shi ZJ. *Chem Rev* 2014; 114: 9219.
5. Zhang N, Samanta SR, Rosen BM, et al. *Chem Rev* 2014; 114: 5848.
6. De Carolis M, Protti S, Fagnoni M, et al. *Angew Chem Int Ed* 2005; 44: 1232.
7. Protti S, Fagnoni M and Albini A. *Angew Chem Int Ed* 2005; 44: 5675.
8. Dichiarante V, Fagnoni M and Albini A. *Angew Chem Int Ed* 2007; 46: 6495.
9. Studer A and Curran DP. *Angew Chem* 2016; 55: 58.
10. Holmberg-Douglas N and Nicewicz DA. *Org Lett* 2019; 21: 7114.
11. Liu W, Li J and Li CJ. *J Am Chem Soc* 2019; 141: 6755.
12. Liu W, Li J, Huang CY, et al. *Angew Chem Int Ed* 2020; 59: 1786.
13. Chen Q, Lejn T and Knochel P. *Angew Chem Int Ed* 2014; 53: 8746.
14. Murarka S and Studer A. *Angew Chem Int Ed* 2012; 51: 12362.
15. Dunsford JJ, Clark ER and Ingleson MJ. *Angew Chem Int Ed* 2015; 54: 5688.
16. Shirakawa E, Tamakuni F, Kusano E, et al. *Angew Chem Int Ed* 2014; 53: 521.
17. Minami H, Saito T, Wang C, et al. *Angew Chem Int Ed* 2015; 54: 4665.
18. He Q, Wang L, Liang Y, et al. *J Org Chem* 2016; 81: 9422.
19. Shirakawa E. *J Synth Org Chem Jpn* 2013; 71: 526.
20. Wang DY, Morimoto KK, Yang ZK, et al. *Chem Asian J* 2017; 12: 2554.
21. Shirakawa E, Hayashi Y, Itoh KI, et al. *Angew Chem Int Ed* 2012; 51: 218.
22. Haines BE and Wiest O. *J Org Chem* 2014; 79: 2771.
23. Li BJ, Xu L, Wu ZH, et al. *J Am Chem Soc* 2009; 131: 14656.
24. Molander GA and Beaumard F. *Org Lett* 2010; 12: 4022.
25. Knochel P and Jones P. *Organozinc reagents: a practical approach*. New York: Oxford, 1999.
26. Erdik E. *Organozinc Reagents in Organic Synthesis*. Boston, MA: CRC Press, 1996.
27. Krasovskiy A, Malakhov V, Gavryushin A, et al. *Angew Chem Int Ed* 2006; 45: 6040.
28. Shirakawa E, Hayashi Y, Itoh K, et al. *Angew Chem Int Ed* 2012; 51: 218.
29. Russell GA, Norris RK and Panek EJ. J Am Chem Soc 1971; 93: 5839.
30. Costentin C, Robert M and Savéant JM. *J Am Chem Soc* 2004; 126: 16051.
31. Takeda N, Poliakov PV, Cook ARM, et al. *J Am Chem Soc* 2004; 126: 4301.
32. Uchiyama N, Shirakawa E and Hayashi T. *Chem Commun* 2013; 49: 364.
33. Shirakawa E, Watabe R, Murakami T, et al. *Chem Commun* 2013; 49: 5219.
34. Chan TL, Wu Y, Choy PY, et al. *Chem* Eur J 2013; 19: 15802.