Introduction

The development of efficient methods for preparing aryl phosphorus compounds is of great importance because of their wide application in medicinal chemistry, materials chemistry, and organic synthesis, and their arylphosphine derivatives play an important role in organometallic catalysis and organocatalysis. Following on from the pioneering work of the Hirao group in this area, after further development and modification, researchers have developed the palladium-, nickel-, and copper-catalyzed processes for the construction of C(sp)2-P bonds (Scheme 1, a). Recently, oxidative phosphorylation of arylibronic acids catalyzed by palladium or nickel has become feasible (Scheme 1, b). Diarylidonium salts, as important and valuable electrophilic arylating reagents, have attracted significant attention in recent years due to their high reactivity and nontoxicity and they have been found to serve as potential arylating agents for phosphorus nucleophiles (Scheme 1, c). The last two decades have witnessed the rapid development of bismuth chemistry. Organobismuth compounds are nontoxic and are easily available building blocks among the heavy nonradioactive main group elements. Recently, Zhao and co-workers described the first examples of reactions of triarylbismuths with P(O)-H compounds under Pd(0) catalysis (Scheme 1, c). Furthermore, microwave-(MW) and visible-light-irradiated P-C coupling reactions have also been developed (Scheme 1, d). To date, very few examples of nickel-catalyzed phosphorylations of aryl mesylates and tosylates have been reported. In 2012, Zhang’s group reported the first Ni-catalyzed P-arylation using aryl mesylates and tosylates as coupling partners in this field, greatly expanding the scope of transition-metal-catalyzed C-P couplings. Yu’s group has reported a novel phosphorylation of alkynyl and aryl C-O bonds via photoredox/nickel dual catalysis. A variety of easily available and inexpensive sulfonates could be transformed into alkynyl phosphonates and aryl phosphate oxides with high selectivity and efficiency under mild reaction conditions. Very recently, Li reported the nickel-catalyzed phosphorylation of aryl tosylates; however, the use of an appropriate phosphine ligand was crucial for this reaction.

Keywords
C-P bond, (het)aromatic tosylates, nickel-catalyzed, phosphorylation, tertiary phosphine oxides

Abstract

A novel and convenient approach to the synthesis of various tertiary phosphine oxides via nickel-catalyzed cross-coupling of (het)aromatic tosylates with secondary phosphine oxides is developed. The reaction employs cheap nickel as the catalyst, 1-{2-(di-tert-butylphosphanyl)phenyl}-4-methoxypiperidine (L3) as the ligand, and pyridine as the base. This reaction produces the corresponding (het)aromatic phosphorus compounds in good to high yields. Moreover, four new tertiary phosphine oxides are reported in this process.

Keywords
C-P bond, (het)aromatic tosylates, nickel-catalyzed, phosphorylation, tertiary phosphine oxides

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

Corresponding author:
Xiao-Yun He, Department of Chemistry and Environmental Engineering, Hebei Chemical and Pharmaceutical College, Shijiazhuang 050026, P.R. China.
Email: 61027391@qq.com

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Results and discussion

Initially, when 1a (0.2 mmol) was added to a mixture of 2a (0.3 mmol), Ni(cod),[L1] (3.0 mol%), and N,N-Diisopropylethylamine (DIPEA) (1.5 equiv.) in Tetrahydrofuran (THF)/toluene (3:1) at 100 °C for 18 h under nitrogen, the desired P-arylation product 3a was obtained in 48% yield (Table 1, entry 1). Encouraged by this result, we further examined the effect of the catalyst, the solvent, the ligand, the temperature, and the base on the reaction yield. Under similar reaction conditions, various Ni salts were examined, with Ni(cod), being the most effective catalyst for the production of 3a (Table 1, entries 1–4). In addition, the catalytic efficiency of various nickel complexes was evaluated (Table 1, entries 5–9). The results showed that among several nickel complexes, Ni(cod),[dcype] was a potential catalyst, affording the desired product 3a in 20% yield (Table 1, entry 1).

We, in Li’s report, have described recently the application of L1 as a catalyst ligand for the cross-coupling of arylosylate and dialkylphosphite, despite the reactivity is modest in our system, L1 was shown to be among the most active ligands in their report. Encouraged by the catalytic abilities of L1, and the needs of our current research, we have designed several new ligands. Next, a subsequent screening of the role of different ligands to gain more insight and to find a more active and robust system was undertaken (Table 1, entries 1 and 10–17). Notably, in the course of these investigations, most of the ligands examined gave fairly poor results, with only bidentate ligand L3 that was giving excellent results in promoting the reaction (Table 1, entry 11). The yield was slightly improved by increasing the molar amount of Ni(cod),[L3] (Table 1, entry 18). Screening of different bases showed that pyridine (Py) was the most suitable base for this procedure, giving 3a in 75% yield (Table 1, entries 18–25). Investigation of different solvents in this transformation was carried out and the results indicated that the solvent plays a crucial role in this reaction system. THF/toluene (3:1) gave the best yield of 85% (Table 1, entries 26–30). Increasing the amount of Py gave a slightly better yield (Table 1, entry 31) and prolonging the reaction time further increased the yield to 93% under otherwise identical conditions (Table 1, entry 32).

Thus, the optimized experimental conditions are as follows: Ni(cod),[L3] (5.0 mol%), Py (2.0 equiv.) as the base in THF/toluene (v/v; 3:1) at 50 °C. The scope of this method was extended to the reaction of a wide range of (het)aryl tosylates with different secondary phosphine oxides. As shown in Table 2, different secondary phosphine oxides were all efficiently coupled under these reaction conditions to provide the corresponding P-(het)arylated derivatives with good to excellent isolated yields, showing that this protocol is a general and practical method for the preparation of various valuable symmetric or nonsymmetric tertiary phosphine oxides. The scope of the substrates was mainly examined by varying the N-heteroaromatic tosylate compounds, which are key to many metal-catalyzed organic transformations.23,24 First, eight (het)aryl tosylates were coupled with Ph,P(O)H to produce the corresponding products in good to high yields. High yields were obtained with both electron-rich and electron-deficient (het)aryl tosylates (Table 2, entries 1–7).

The reaction was inefficient under the current reaction conditions from sesamol derivatives, reaction with 2a gave the desired product 3i in only 35% yield (Table 2, entry 8). In addition to diphenylphosphine oxide, when the aromatic group was substituted with other groups, secondary phosphine oxides with electron-donating groups or electron-withdrawing groups reacted smoothly with hydroxybenzothiazolyl tosylates to provide the desired products in excellent yields (Table 2, entries 11 and 12).

However, secondary phosphine oxides with strong electron-withdrawing groups, such as fluoro, resulted in a lower yield. These results indicate that the yields were dependent primarily on the electronic properties of the secondary phosphine oxides (Table 2, entry 11). Secondary phosphine oxides with sterically demanding o-substituted aromatic rings afforded inferior yields, illustrating that steric hindrance has an influence on this coupling reaction (Table 2, entry 9).

We also tested our cross-coupling procedure for the assembly of a bis(heterocyclic) product. A 2-hydroxybenzothiazolyl tosylate readily underwent coupling with dithiophenylphosphine oxide to provide a bis(heterocyclic) compound (Table 2, entry 12). Other hydrogen phosphoryl compounds were also applicable in this transformation. In addition to diarylphosphine oxides 2a–f, aliphatic α-Bu,P(O)H (Table 2, entry 13), the Cy3,P(O)H (Table 2, entries 15–17), and bulky α-Bu3,P(O)H (Table 2, entries 18–22) coupled with (het)aryl tosylates readily by increasing the equivalent of base, producing the corresponding products in moderate to high yields.

Conclusion

In summary, we have developed a novel nickel-catalyzed carbon-phosphine cross-coupling protocol from a wide range of (het)aromatic tosylates and different secondary...
Table 1. Optimization of the Reaction Conditions.a

| Entry | [Ni]/ligandb | Base | Solvent | Yield (%) | Entry | [Ni]/ligand | Base | Solvent | Yield (%) |
|-------|-------------|------|---------|-----------|-------|-------------|------|---------|-----------|
| 1d    | Ni(cod)₂/L₁ | DIPEA | Toluene | 48        | 17d   | Ni(cod)₂/L₉ | DIPEA | Toluene | 38        |
| 2d    | Ni(OAc)₂·4H₂O/L₁ | DIPEA | Toluene | Trace | 18 | Ni(cod)₂/L₃ | DIPEA | Toluene | 69        |
| 3d    | Ni(acac)₂/L₁ | DIPEA | Toluene | 43 | 19 | Ni(cod)₂/L₃ | TMEDA | Toluene | 45        |
| 4de   | NiCl₂/L₁     | DIPEA | Toluene | n.r. | 20 | Ni(cod)₂/L₃ | t-BuOLi | Toluene | 11        |
| 5de   | NiCl₂(PCy₃)₂ | DIPEA | Toluene | n.r. | 21 | Ni(cod)₂/L₃ | t-BuOK | Toluene | 9         |
| 6d    | NiCl₂(dppe)  | DIPEA | Toluene | Trace | 22 | Ni(cod)₂/L₃ | K₂CO₃ | Toluene | 18        |
| 7de   | NiCl₂(PP₃)₂ | DIPEA | Toluene | n.r. | 23 | Ni(cod)₂/L₃ | K₃PO₄ | Toluene | 15        |
| 8d    | NiCl₂(dcype) | DIPEA | Toluene | 20 | 24 | Ni(cod)₂/L₃ | Py | Toluene | 75        |
| 9d    | NiCl₂(dpdpf) | DIPEA | Toluene | 8 | 25e | Ni(cod)₂/L₃ | – | Toluene | n.r.     |
| 10d   | Ni(cod)₂/L₂  | DIPEA | Toluene | 51 | 26 | Ni(cod)₂/L₃ | Py | Dioxane | 53        |
| 11d   | Ni(cod)₂/L₃  | DIPEA | Toluene | 62 | 27e | Ni(cod)₂/L₃ | Py | Acetonitrile | n.r.     |
| 12d   | Ni(cod)₂/L₄  | DIPEA | Toluene | 45 | 28b | Ni(cod)₂/L₃ | Py | THF | 78        |
| 13d   | Ni(cod)₂/L₅  | DIPEA | Toluene | 5 | 29b | Ni(cod)₂/L₃ | Py | THF | 80        |
| 14d   | Ni(cod)₂/L₆  | DIPEA | Toluene | 31 | 30 | Ni(cod)₂/L₃ | Py | THF/toluene (v/v: 3:1) | 85        |
| 15d   | Ni(cod)₂/L₇  | DIPEA | Toluene | 12 | 31h | Ni(cod)₂/L₃ | Py | THF/toluene (v/v: 3:1) | 89        |
| 16d   | Ni(cod)₂/L₈  | DIPEA | Toluene | 40 | 32i | Ni(cod)₂/L₃ | Py | THF/toluene (v/v: 3:1) | 93        |

aUnless otherwise stated, the reaction conditions are as follows: Heteroaromatic tosylate (1a) (0.2 mmol), diphenyl phosphite (2a) (0.3 mmol), [Ni]/ligand (5.0 mol%), base (1.5 equiv.), solvent (2 mL), reaction time was 12 h, N₂.
bStirred at 80 °C.
cYield of isolated product.
d[Ni]/ligand (3.0%).
eNo reaction.
fNo base was used.
gStirred at 50 °C.
hPy (2.0 equiv.).
iPy (2.0 equiv.), reaction time was 18 h.

Phosphine oxides. Notably, the process is simple and proceeds under mild reaction conditions. Moreover, the process is generally cheaper overall because more accessible (het)aryl phenol derivatives are used to form the C-P bond. These advantages should help this C-P bond-forming method to find broad application in both complex molecule synthesis and for the preparation of P-chiral organophosphorus compounds.

**Experimental**

**General**

Ni(cod)₂ (98%), Ni(acac)₂ (>98%), NiCl₂(PCy₃)₂ (>98%), NiCl₂(dppe) (98%), NiCl₂(dcype) (>98%), NiCl₂(dpdpf) (99%), NiCl₂(PP₃)₂ (>98%), Pd₂dba₃, Pd(OAc)₂, and DiPPF were purchased from Aldrich. Ni(OAc)₂·4H₂O, NiCl₂, racemic-2,2’-Bis(diphenylphosphino)-1,1’,binaphthyl (BINAP), and Tetramethylethlenediamine (TMEDA) (>99%) were purchased from Alfa Aesar. Other reagents were available commercially and were used without further purification, unless otherwise indicated. All aryl tosylates were prepared according to the literature procedures.25–29 Ligands L₁, L₂, L₆, L₇, L₈, and L₉ were prepared according to the literature procedures.22,30–33 Reactions were run under an argon atmosphere with exclusion of moisture from reagents and glassware using standard Schlenk techniques. Solvents were dried from molecular sieves and kept under argon. Spectroscopic data of known compounds matched with the data reported in the corresponding references.34–42 All new compounds were further characterized by high-resolution mass spectrometry (HRMS) (EI), elemental analysis, and 31P, 1H, and 13C NMR spectroscopy. High-resolution mass spectra were obtained using a GCT time of flight (TOF) instrument with the electron ionization (EI) source. Elemental analyses were performed with the German elemental analyzer Vario EL. NMR measured on Bruker 400M spectrometers. 1H NMR and 13C NMR were recorded using tetramethylsilane (TMS) as the internal standard and 85% H₃PO₄ as the external standard for 31P NMR spectra. Chemical shifts are reported in parts per million (δ). The peak patterns are indicated as follows: s,
Table 2. Cross-coupling of various heteroaromatic tosylates with disubstituted phosphine oxide.\(^a\)

| Entry | Substrate 1 | Substrate 2 | Product | Yield\(^b\) (%) | Entry | Substrate 1 | Substrate 2 | Product | Yield\(^b\) (%) |
|-------|-------------|-------------|---------|----------------|-------|-------------|-------------|---------|----------------|
| 1     | 1b          | 2a          | 3b      | 83             | 12    | 1j          | 2e          | 3m      | 87             |
| 2     | 1c          | 2a          | 3c      | 92             | 13    | 1j          | 2f          | 3n      | 72             |
| 3     | 1d          | 2a          | 3d      | 83             | 14    | 1j          | 2g          | 3o\(^c\) | 73             |
| 4     | 1e          | 2a          | 3e      | 86             | 15    | 1j          | 2h          | 3p\(^c\) | 78             |
| 5     | 1f          | 2a          | 3f      | 85             | 16    | 1f          | 2h          | 3q\(^c\) | 75             |
| 6     | 1g          | 2a          | 3g      | 88             | 17    | 1a          | 2h          | 3r\(^c\) | 71             |
| 7     | 1h          | 2a          | 3h      | 89             | 18    | 1a          | 2i          | 3s\(^c\) | 70             |
| 8     | 1i          | 2a          | 3i      | 35             | 19    | 1b          | 2i          | 3t\(^c\) | 75             |
| 9     | 1j          | 2b          | 3j      | 77             | 20    | 1c          | 2i          | 3u\(^c\) | 74             |
| 10    | 1j          | 2c          | 3k      | 88             | 21    | 1d          | 2i          | 3v\(^c\) | 76             |
| 11    | 1j          | 2d          | 3l      | 56             | 22    | 1e          | 2i          | 3w\(^c\) | 73             |

\(^a\)Reaction conditions: heteroaromatic tosylate (1a) (0.2 mmol), diphenyl phosphite (2) (0.3 mmol), Ni(cod)/L2 (5.0 mol%), Py (2.0 equiv.), THF/toluene (v/v: 3/1) (2 mL), N\(_2\), at 50 °C for 18–24 h.

\(^b\)Yield of the isolated product.

\(^c\)Py (3.5 equiv.).
Singlet; d, doublet; t, triplet; dd, doublet of doublets; dt, doublet of triplets; and m, multiplet. The 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 section**

**General procedure A: ligand synthesis and characterization.** A Schlenk tube was charged with reagents: Pd$_2$dba$_3$ (46 mg, 5 mol% Pd), BINAP (93 mg, 7.5 mol%), NaO$t$Bu (231 mg, 1.44 mmol) were added, followed by the aryl halide (1.2 mmol) and a stir bar were added. Then, the mixture was degassed twice. The resulting mixture was heated at 110 $°C$ until complete consumption of the phosphine was achieved. The solution was then cooled and filtered through a plug of silica, which in turn was washed with CH$_2$Cl$_2$. Removal of the solvent from the combined eluent afforded the Ligand L4 in 63% yield that was further purified by recrystallization from the solvent to give the analytically pure product. All products prepared using this synthetic method ($3a$, $3b$, $3c$, $3d$, $3e$, $3f$, $3g$, $3h$, $3i$, $3j$, $3k$, $3l$, $3m$, $3n$, $3o$, $3p$, $3q$, $3r$, $3s$) have been reported earlier, and their spectral data matched with those presented in the literature. Products $3t$, $3u$, $3v$, and $3w$ are novel compounds.

**General procedure B: phosphination of (Het)aromatic tosylates with secondary phosphine oxides**

In an argon-filled glovebox, an oven-dried Schlenk tube equipped with a Teflon stir bar was charged with Ni(cod)/L3 (5 mol%) followed by anhydrous THF (1.0 mL), secondary phosphine oxide (2) (0.3 mmol), and Py (2.0 equiv.). The solution was stirred for 5–10 min. Next, the (het)aromatic tosylate (1) (0.2 mmol) was added at once followed by anhydrous toluene/THF (0.5 mL/0.5 mL). The Schlenk tube was sealed with a Teflon valve and the reaction mixture was stirred at 50 $°C$ for 18–24 h. The reaction mixture was then cooled to room temperature, filtered, and rinsed with dichloromethane to remove any insoluble residues. The filtrate was concentrated in vacuo and the residue was purified by flash column chromatography on silica gel to give the analytically pure product. All products prepared using this synthetic method ($3a$, $3b$, $3c$, $3d$, $3e$, $3f$, $3g$, $3h$, $3i$, $3j$, $3k$, $3l$, $3m$, $3n$, $3o$, $3p$, $3q$, $3r$, $3s$) have been reported earlier, and their spectral data matched with those presented in the literature.

**Scheme 2.** Synthesis of ligands L3, L4, and L5.

(\text{HRMS}) (EI): $m/z$ [M]$^+$ calculated for C$_{20}$H$_{34}$NOP: 335.2378; found: 335.2373. Anal. calcld for C$_{20}$H$_{34}$NOP: C, 71.61; H, 10.22; N, 4.18; found: C, 71.73; H, 10.29; N, 4.31.

1-(2-Dicyclohexylphosphinophenyl)-4-methoxy-piperidine (L4): Colorless oil, yield 63%. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.60–7.53 (m, 1H), 7.30–7.20 (m, 1H), 7.11–7.03 (m, 2H), 3.35 (s, 3H), 3.32–3.26 (m, 1H), 3.24–3.18 (m, 2H), 2.88–2.79 (m, 2H), 2.05–1.97 (m, 2H), 1.94–1.83 (m, 2H), 1.24 (d, $J = 14.8$ Hz, 18H). $^1$C NMR (100 MHz, CDCl$_3$): $\delta$ 159.2 (d, $J_{PC} = 17.2$ Hz), 136.5, 133.7 (d, $J_{PC} = 18.6$ Hz), 130.6, 123.4, 121.2, 75.2, 55.3, 44.7, 44.6, 33.8 (d, $J = 24$ Hz), 30.8 (d, $J = 14.8$ Hz). $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta$ –26.4.

(\text{HRMS}) (EI): $m/z$ [M]$^+$ calculated for C$_{20}$H$_{34}$NOP: 335.2378; found: 387.2687. Anal. calcld for C$_{20}$H$_{34}$NOP: C, 74.38; H, 9.88; N, 3.61; found: C, 74.43; H, 9.93; N, 3.72.

1-(2-(di-tert-butylphosphinophenyl)phenyl)phosphine (L5): Colorless oil, yield 53%. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.61–7.54 (m, 1H), 7.32–7.23 (m, 1H), 7.12–7.00 (m, 2H), 2.75–2.73 (m, 4H), 1.37–1.32 (m, 6H), 1.25 (d, $J = 14.2$ Hz, 18H). $^1$C NMR (100 MHz, CDCl$_3$): $\delta$ 158.9 (d, $J_{PC} = 17.0$ Hz), 136.3, 133.6 (d, $J_{PC} = 18.2$ Hz), 130.4, 123.1, 121.0, 54.3, 33.7 (d, $J = 23.6$ Hz), 30.8 (d, $J = 15.0$ Hz), 26.6, 24.3. $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta$ –22.3.

(\text{HRMS}) (EI): $m/z$ [M]$^+$ calculated for C$_{24}$H$_{38}$NOP: 305.2272; found: 305.2276. Anal. calcld for C$_{24}$H$_{38}$NOP: C, 74.8; H, 7.47; N, 4.60; found: C, 74.75; H, 7.40; N, 4.62.
di-tert-butyl(thiophen-2-yl)phosphine oxide (3u): Colorless oil; yield 76%. \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 7.70–7.65 (m, 1H, H thiophene), 7.51–7.46 (m, 1H, H thiophene), 7.22–7.17 (m, 1H, H thiophene), 1.22 (d, \(J = 13.2\) Hz, 18H). \(^13\)C NMR (100 MHz, CDCl\(_3\)): \(\delta\) 135.7 (d, \(J = 8.1\) Hz), 132.6 (d, \(J = 4.2\) Hz), 132.8 (d, \(J = 102.1\) Hz), 128.8 (d, \(J = 12.0\) Hz), 35.8 (d, \(J = 75.6\) Hz), 35.1 (d, \(J = 75.3\) Hz), 27.2, 26.5. \(^{31}\)P NMR (162 MHz, CDCl\(_3\)): \(\delta\) 46.6.

(HRMS) (EI): m/z [M]+ calecd for C\(_{17}\)H\(_{24}\)NOP: 289.1596; found: 289.1593. Anal. calcd for C\(_{17}\)H\(_{24}\)NOP: C, 70.57; H, 8.36; N, 4.84; found: C, 70.64; H, 8.43; N, 4.88.

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ORCID iD

Xiao-Yun He https://orcid.org/0000-0002-4540-9788

Supplemental material

Supplemental material for this article is available online.

References

1. Yoshino K, Kohno T, Tsukamoto G, et al. J Med Chem 1989; 32: 1528.
2. Hérault D, Nuel D, Buono G, et al. Chem Soc Rev 2015; 44: 2508.
3. McCarthy M and Guiry PJ. Tetrahedron 2001; 57: 3809.
4. Surry DS and Buchwald SL. Chem Sci 2011; 2: 27.
5. Lu X, Zhang C and Xu Z. Acc Chem Res 2001; 34: 355.
6. Wei Y and Shi M. Acc Chem Res 2010; 43: 1005.
7. Hiroa T, Masunaga T, Oshihoro Y, et al. Bull Chem Soc Jpn 1982; 55: 909.
8. Rao HH, Jin Y, Zhao YF, et al. Chem Eur J 2006; 12: 3636.
9. Huang J, Liu Z, Zhang B, et al. Inorg Chem 2019; 58: 4253.
10. Dong JY, Liu L, Han LB, et al. Org Lett 2019; 21: 3198.
11. Fu TT, Qiao HW, Zhao YF, et al. Org Biomol Chem 2014; 18: 2895.
12. Hu GB, Chen WZ, Zhao YF, et al. Org Lett 2013; 15: 5362.
13. Xu J, Zhang PB, Zhao YF, et al. J Org Chem 2013; 78: 8176.
14. Suzuki H and Matano Y. Organo-bismuth chemistry. Amsterdam: Elsevier, 2001.
15. Maeda S and Patai S. In the chemistry of organic arsenic, antimony and bismuth compounds. New York: Wiley, 1994, p. 725.
16. Wang T, Sang S, Zhao YF, et al. J Org Chem 2014; 79: 608.
17. Zeng HY, Dou Q and Li CJ. Org Lett 2019; 21: 1301.
18. Ananthag GS, Mague JT and Balakrishna MS. Dalton Trans 2015; 44: 3785.
19. Zhu DL, Jiang S, Li RX, et al. Org Lett 2021; 23: 160.
20. Shen CR, Yang GQ and Zhang WB. Org Biomol Chem 2012; 10: 3500.
21. Liao LL, Gui YY and Yu DG. Org Lett 2017; 19: 3735.
22. Li CJ. Russ Gen Chem 2020; 90: 725.
23. Minnaard AJ, Feringa BL, Vries JG, et al. Acc Chem Res 2007; 40: 1267.
24. Diederich F and Stang PJ. Metal-catalyzed cross-coupling reactions. Weinheim: Wiley-VCH Verlag GmbH, 1998.
25. Yang JF, Zheng JF, Zhou JR, et al. Eur J Med Chem 2012; 31: 6248.
26. Lei XY, Stafford JM, Cao B, et al. Synthesis 2015; 47: 2578.
27. Kwong FY, Lee HW, So CM, et al. Org Chem Front 2020; 7: 926.
28. Langille NF, Dakin LA, Panek JS, et al. Org Lett 2002; 4: 2485.
29. Kelley M, Douida Z, Mancuso J, et al. Synlett 2005; 2: 247.
30. Cheng K, Zeng MF, Qi CZ, et al. J Med Chem 2013; 37: 99.
31. Harada T, Ueda Y, Sawamura M, et al. Chem Commun 2018; 54: 1718.
32. Bedford RB, Brenner PB, Carter E, et al. Organometallics 2014; 33: 5767.
33. Li PB, Fu CL, Ma SM, et al. Adv Synth Catal 2013; 35: 1255.
34. Yun J, To WP, Che CM, et al. Org Lett 2018; 20: 7816.
35. Zhang HY, Sun M, Yang SD, et al. Org Biomol Chem 2012; 10: 9627.
36. Yang J, Chen TQ and Han LB. J Am Chem Soc 2015; 137: 1782.
37. Ishihiki R, Muto K and Yamaguchi J. Org Lett 2018; 20: 1150.
38. Luo K, Chen YZ, Wu L, et al. Org Lett 2016; 18: 452.
39. Li L, Wang JJ, Wang GW, et al. J Org Chem 2016; 81: 5433.
40. Peng P, Peng L, Lei AW, et al. Org Chem Front 2016; 6: 749.
41. Stankevič M and Wodarczykowski A. Tetrahedron 2013; 69: 73.
42. Gowrisankar S, Neumann H, Beller M, et al. Chem Eur J 2013; 19: 15979.