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$PdCl_2(Ph_3P)_2$/Salicylaldimine Catalyzed Diarylation of Anilines with Unactivated Aryl Chlorides

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Triphenylphosphine and salicylaldimine could be used as a mixed ligand system to obtain a high catalytic activity for palladium catalyzed diarylation of primary anilines with unactivated aryl chlorides by the synergistic effect of ligands. The activity and selectivity of the catalytic system could be improved by modifying the structure of salicylaldimine. In refluxing *o*-xylene, $PdCl_2(Ph_3P)_2$ with 2,5-ditrifluoromethyl *N*-phenylsalicylaldimine as a coligand shows high efficiency for the diarylation of various anilines. The catalytic system shows good toleration for the steric hindrance of the substrates. The facile catalytic system works as well on the multiple arylation of 1,1'-biphenyl-4,4'-diamine with aryl chlorides to afford *N*,*N*,*N*′,*N*′-tetraaryl-1,1'-biphenyl-4,4'-diamines which are important intermediates of organic light emitting diode (OLED) hole transport materials.

Keywords palladium, diarylation, aryl chloride, triphenylphosphine, salicyaldimine

Introduction

The palladium-catalyzed cross-coupling of aryl halides and amines is a well $C(sp^2)-N$ bond-forming methodology and has been found widespread using in many areas, such as the synthesis of important intermediates for fine chemicals, photographic materials, conducting polymers and pharmaceuticals.[1] In recent years, a considerable effort in ligand designing has been devoted to improving the efficiency and the substrate scope of the cross-coupling reactions. Most ligands were designed and synthesized which bear the electron-rich and steric bulk character to promote the oxidative addition of the organic electrophile and the reductive elimination of the desired coupling product to regenerate the catalytically active species, such as bulky and electron-rich phosphine[2] and *N*-heterocyclic carbene ligands.[3] However, the syntheses of these ligands always suffer from tedious steps or expensive materials. Recent researches show that ancillary ligands surrounding the catalytic metal center also play a very crucial role in their catalytic performance.[4] Therefore, using a mixed ligand system may be an alternative strategy to obtain a high catalytic activity by the synergistic effect of ligands, which is a synthetically convenient method to adjust the electronic and steric environments surrounding the catalytic center.

Triphenylphosphine (Ph_3P), a simple and cost-efficient phosphine, has been used as a ligand in most of Pd-catalyzed coupling reactions.[5] However, it is generally less effective for the intermolecular coupling reaction of amines and aryl halides, possibly due to its relatively less electron richness and smaller steric hindrance.[6] Therefore, seeking an accessible ancillary ligand to improve the activity of $PdCl_2(Ph_3P)_2$ for the formation of C—N bonds is attractive, because the industrial process appeals to the inexpensive and readily accessible catalytic systems.[1c] Salicylaldimine ligands are a type of simple and versatile bidentate ligands which can be readily prepared by the condensation of amines with salicylaldehyde. Moreover, the electronic and steric properties of these ligands can be easily tuned using appropriate substituents. These ligands have been utilized extensively in the metal catalyzed reactions.[7] Jin *et al*. utilized salicylaldimines as ancillary ligands in the Pd/*N*-heterocyclic carbene catalytic system to develop an effective catalytic system for the coupling of aryl chlorides and amines under aerobic conditions.[4a] Our preliminary research found that $PdCl_2(Ph_3P)_2$/salicylaldimine catalytic system showed good catalytic activity for the palladium catalyzed amination of unactivated aryl chlorides with anilines to prepare diarylamines.[8] However, the catalytic system did not work effectively for the synthesis of triarylamines which are commonly encountered in photographic materials and

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conducting polymers.[9] The problems for diarylation of anilines with unactivated arylchlorides are that the monoarylation intermedium, secondary aryl amine, shows less nucleophilicity and bulkier hindrance for coupling. Herein, we reported that palladium and simple mixed ligand (triphenylphosphine and salicylaldimine) catalyzed effectively the diarylation of anilines with unactivated aryl chlorides, and the effect of steric and electronic nature of ancillary ligands (salicylaldimines) on the catalytic activity for the diarylation.

Experimental

Materials and methods

All reagents and solvents were obtained from commercial sources. Anhydrous toluene was pre-dried over sodium wire prior to continuous distillation over sodium-benzophenone. Xylene and mesitylene were pre-dried over sodium wire and freshly distilled. Reactions were routinely carried out under an atmosphere of nitrogen with magnetic stirring. The crude products were purified by flash column chromatography on silica gel. ^{1}H NMR and ^{13}C NMR spectra were recorded on 500 or 400 MHz spectrometer. High resolution mass spectra (HRMS) were obtained on an ESI-TOF mass spectrometer.

Experimental procedure and characterization data of salicylaldimine (L1—L11)

To a solution of aniline (1.0 equiv., 10.0 mmol) and salicylaldehyde (1.1 equiv, 11.0 mmol) in anhydrous ethanol (20 mL) was added a drop of formic acid at room temperature (25 ℃). The mixture was heated to reflux and stirred for 6 h. The reaction completion was detected by TLC. After cooling to room temperature, an amount of crystalline solid was precipitated. The mixture was filtrated and the solid was washed with ethanol (5 mL×2). The salicylaldimine was obtained after drying *in vacuo*.

2-((Phenylimino)methyl)phenol (L1)[10] Yellow acicular crystal (yield: 85%); m.p. 51—52 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 13.26 (br, 1H), 8.60 (s, 1H), 7.35—7.43 (m, 4H) 7.26—7.29 (m, 3H), 7.02 (d, J=7.5 Hz, 1H), 6.93 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 117.20, 118.99, 119.17, 121.11, 126.83, 129.34, 132.23, 133.08, 148.44, 161.12, 162.60.

(*E*)-2-((*p*-Tolylimino)methyl)phenol (L2)[11] Yellow acicular crystal (yield: 89%); m.p. 90—91 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 13.36 (br, 1H), 8.62 (s, 1H), 7.37—7.41 (m, 2H), 7.19—7.25 (m, 4H), 7.01 (d, J=7.5 Hz, 1H), 6.91 (t, J=7.5 Hz, 1H), 2.38 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 21.01, 117.48, 119.10, 121.01, 129.97, 132.01, 132.74, 136.90, 145.85, 161.59.

(*E*)-2-(((4-Methoxyphenyl)imino)methyl)phenol (L3)[12] Yellow acicular crystal (yield: 93%); m.p. 84—85 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 13.41 (br, 1H), 8.60 (s, 1H), 7.34—7.38 (m, 2H), 7.25—7.28 (m, 2H), 7.02 (d, J=7.5 Hz, 1H), 6.91—6.95 (m, 3H), 3.83 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 55.50, 114.61, 117.14, 118.94, 119.38, 122.26, 131.93, 132.65, 141.37, 158.85, 160.41, 161.01.

(*E*)-2-(((4-Fluorophenyl)imino)methyl)phenol (L4)[13] Yellow acicular crystal (yield: 89%); m.p. 80—81 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 13.09 (br, 1H), 8.57 (s, 1H), 7.36—7.39 (m, 2H), 7.24—7.26 (m, 2H), 7.10 (t, J=7.5 Hz, 2H), 7.02 (d, J=7.5 Hz, 1H), 6.94 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 116.05, 116.23, 117.22, 119.08, 122.51, 122.58, 132.24, 133.16, 144.60, 160.63, 161.02, 162.37, 162.59; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –115.51.

(*E*)-2-(((2-Fluorophenyl)imino)methyl)phenol (L5)[13] Yellow acicular crystal (yield: 90%); m.p. 69—70 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 13.04 (br, 1H), 8.71 (s, 1H), 7.39 (t, J=7.5 Hz, 2H), 7.17—7.28 (m, 4H), 7.04 (d, J=7.5 Hz, 1H), 6.95 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 116.48, 116.63, 117.42, 119.06, 121.45, 124.61, 124.66, 127.79, 127.85, 132.45, 133.53, 136.33, 154.70, 156.69, 161.34, 164.58; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –125.58.

(*E*)-2-(((2,4-Difluorophenyl)imino)methyl)phenol (L6)[8] Yellow acicular crystal (yield: 90%); m.p. 51—53 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.94 (br, 1H), 8.65 (s, 1H), 7.36—7.40 (m, 2H), 7.22—7.27 (m, 1H), 7.02 (d, J=7.5 Hz, 1H), 6.90—6.95 (m, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 104.71, 104.91, 105.11, 111.49, 111.67, 117.38, 119.03, 119.11, 121.81, 121.88, 132.43, 133.57, 154.76, 156.78, 160.16, 161.19, 162.15, 164.24; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –111.64, –111.66, –120.68, –120.70.

(*E*)-2-(((3,4-Difluorophenyl)imino)methyl)phenol (L7) Yellow acicular crystal (yield: 94%); m.p. 88—89 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.79 (br, 1H), 8.55 (s, 1H), 7.38—7.41 (m, 2H), 7.17—7.23 (m, 1H), 7.10—7.14 (m, 1H), 7.02—7.03 (m, 2H), 6.95 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 110.06, 110.21, 117.32, 117.67, 117.81, 118.83, 119.26, 132.50, 133.62, 145.15, 148.22, 149.70, 150.29, 151.58, 161.05, 163.36; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –135.55, –135.61, –139.69, –139.74; HRMS (m/z): calcd for $C_{13}H_9F_2NO$ (M^++H): 234.0730, found: 234.0734.

(*E*)-2-(((2-(Trifluoromethyl)phenyl)imino)methyl)-phenol (L8)[14] Yellow acicular crystal (yield: 91%); m.p. 51—53 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.55 (br, 1H), 8.58 (s, 1H), 7.72 (d, J=7.5 Hz, 1H) 7.60 (t, J=7.5 Hz, 1H), 7.41—7.43 (m, 2H), 7.36 (t, J=7.5 Hz, 1H), 7.24 (d, J=7.5 Hz, 1H), 7.05 (d, J=7.5 Hz, 1H), 6.95 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 117.52, 119.01, 119.19, 119.38, 122.71, 124.89, 126.31, 126.55, 126.59, 132.72, 133.15, 133.98, 147.05, 161.22, 164.10; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –60.49.

(*E*)-2-(((3-(Trifluoromethyl)phenyl)imino)methyl)-phenol (L9)[15] Yellow acicular crystal (yield: 95%); m.p. 85—86 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.81 (br, 1H), 8.63 (s, 1H), 7.51—7.55 (m, 3H) 7.40—7.44 (m, 3H), 7.04 (d, J=7.5 Hz, 1H), 6.97 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 117.39, 118.01,

118.03, 118.90, 119.29, 123.31, 123.34, 124.58, 139.98, 132.63, 133.78, 149.19, 161.18, 164.19; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –62.64.

(*E*)-2-(((2,4-Bis(trifluoromethyl)phenyl)imino)-methyl)phenol (L10) Yellow acicular crystal (yield: 95%); m.p. 142－143 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.19 (br, 1H), 8.59 (s, 1H), 7.97 (s, 1H) 7.87 (d, J= 7.5 Hz, 1H), 7.43－7.47 (m, 2H), 7.33 (d, J=7.5 Hz, 1H), 7.05 (d, J=7.5 Hz, 1H), 6.97 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 117.70, 118.71, 119.49, 120.35, 121.93, 124.10, 124.81, 128.37, 128.64, 130.29, 133.14, 134.80, 150.19, 161.38, 165.66; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –61.05, –62.43; HRMS (*m*/*z*): calcd for $C_{15}H_9F_6NO$ (M^++H): 334.0667, found: 334.0659.

(*E*)-2-(((2,5-Bis(trifluoromethyl)phenyl)imino)-methyl)phenol (L11) Yellow acicular crystal (yield: 96%); m.p. 90－91 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 12.25 (br, 1H), 8.62 (s, 1H), 7.85 (d, J=7.5 Hz, 1H), 7.62 (d, J=7.5 Hz, 1H), 7.43－7.47 (m, 3H), 7.05 (d, J=7.5 Hz, 1H), 6.98 (t, J=7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 116.62, 116.64, 117.62, 118.72, 119.44, 121.98, 122.82, 122.84, 124.15, 127.45, 127.49, 133.14, 134.67, 147.89, 161.33, 165.48; ^{19}F NMR (376 MHz, $CDCl_3$) δ: –61.14, –63.15; HRMS (*m*/*z*): calcd for $C_{15}H_9F_6NO$ (M^++H): 334.0667, found: 334.0658.

Experimental procedure for the diarylation of anilines catalyzed by $PdCl_2(Ph_3P)_2$/L11

In a Schlenk tube with a magnetic bar, *t*-BuONa (3.0 mmol) was suspended in *o*-xylene (8.0 mL), and then aryl chloride (2.5 mmol), aryl amine (1.0 mmol), $PdCl_2(Ph_3P)_2$ (21.0 mg, 3.0 mol%) and **L11** (20.0 mg, 6.0 mol%) were added in sequence under nitrogen. The resulting mixture was stirred at reflux (145 ℃) for 12 h under nitrogen. After the solvent was evaporated *in vacuo*, the residue was purified by flash column chromatography (petroleum ether and ethyl acetate) to give the product. The purified products were characterized by comparing their ^{1}H and ^{13}C NMR spectra with those found in literatures.

Procedure for the tetraarylation of 4,4'-diaminobiphenyl catalyzed by $PdCl_2(Ph_3P)_2$/L11

In a Schlenk tube with a magnetic bar, 4,4'-diaminobiphenyl hydrochloride (128.5 mg, 0.5 mmol) was suspended in *o*-xylene (8.0 mL), and then NaH (40.0 mg, 1 mmol, 60%) was added. The mixture was stirred for 30 min at room temperature. Then *t*-BuONa (6.0 mmol), aryl chloride (6.0 mmol), $PdCl_2(Ph_3P)_2$ (21.0 mg, 3.0 mol%) and **L11** (20.0 mg, 6.0 mol%) were added in sequence under nitrogen. The resulting mixture was stirred at reflux (145 ℃) for 24 h under nitrogen. After the solvent was evaporated *in vacuo*, the residue was purified by flash column chromatography (petroleum ether and ethyl acetate) to give the product.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetraphenyl-[1,1'-biphenyl]-4,4'-diamine (6a)**[16] White solid (yield: 93%); m.p.: 222－224 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.36 (d, J=8.5 Hz, 4H), 7.16－7.19 (m, 8H), 7.04－7.05 (m, 12H), 6.94 (t, J=7.5 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 122.81, 124.08, 124.30, 127.28, 129.23, 134.76, 146.75, 147.74.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetra-*p*-tolyl-[1,1'-biphenyl]-4,4'-diamine (6b)**[17] White solid (yield: 92%); m.p.: 213－215 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.38 (d, J=8.5 Hz, 4H), 7.04－7.06 (m, 12H), 7.01 (d, J=8.5 Hz, 8H), 2.30 (s, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 20.83, 122.98, 124.55, 127.09, 129.88, 132.41, 134.03, 145.37, 147.05.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetra-(*p*-methoxyphenyl)-[1,1'-biphenyl]-4,4'-diamine (6c)**[18] White solid (yield: 72%); m.p.: 177－180 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.38 (d, J=8.0 Hz, 4H), 7.01 (d, J=8.0 Hz, 8H), 6.89 (d, J=8.0 Hz, 8H), 6.80 (d, J=8.0 Hz, 4H), 3.73 (s, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 55.70, 115.40, 120.48, 126.92, 127.06, 132.27, 140.68, 147.59, 156.10.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetra-*m*-tolyl-[1,1'-biphenyl]-4,4'-diamine (6d)**[19] White solid (yield: 90%); m.p.: 166－169 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.44 (d, J=8.0 Hz, 4H), 7.14 (t, J=8.0 Hz, 4H), 7.07 (d, J=8.0 Hz, 4H) , 6.94 (s, 4H), 6.91 (d, J=8.0 Hz, 4H), 6.83 (d, J= 8.0 Hz, 4H), 2.30 (s, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 21.41, 121.58, 123.65, 123.97, 125.02, 127.15, 129.99, 134.46, 139.04, 146.91,147.76.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetra-*o*-tolyl-[1,1'-biphenyl]-4,4'-diamine (6e)** White solid (yield: 88%); m.p.: 195－196 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.23 (d, J=8.0 Hz, 4H), 7.20 (d, J=8.0 Hz, 4H), 7.14 (t, J=8.0 Hz, 4H), 6.96－6.98 (m, 4H), 6.95 (t, J=8.0 Hz, 4H), 6.88 －6.92 (m, 4H), 2.26 (s, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 18.23, 117.75, 119.21, 120.77, 122.36, 127.10, 128.70, 129.64, 131.28, 141.54, 144.34; HRMS (*m*/*z*): calcd for $C_{40}H_{36}N_2$ (M^+ + H): 545.2957, found: 545.2912.

***N*^{4},*N*^{4},*N*$^{4'}$,*N*$^{4'}$-Tetrakis(3-methoxyphenyl)-[1,1'-biphenyl]-4,4'-diamine (6f)**[19] White solid (yield: 79%); m.p.: 146－148 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.45 (d, J=8.3 Hz, 4H), 7.13－7.17 (m, 8H), 6.67－6.72 (m, 8H), 6.58 (d, J=8.0 Hz, 4H), 3.73 (s, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ: 55.25, 108.36, 110.17, 116.85, 124.56, 127.29, 129.79, 135.02, 146.51, 148.85, 160.49.

***N*^{1},*N*$^{1'}$-([1,1'-Biphenyl]-4,4'-diyl)bis(*N*^{1}-(4-(diphenylamino)phenyl)-*N*^{4},*N*^{4}-diphenylbenzene-1,4-diamine) (6g)**[19] Yellow solid (yield: 60%); m.p.: 213－215 ℃; ^{1}H NMR (500 MHz, C_6D_6) δ: 7.37 (d, J=8.0 Hz, 4H), 7.19 (d, J=8.0 Hz, 4H), 7.11－7.14 (m, 16H), 7.02－7.05 (m, 24H), 6.97 (d, J=8.0 Hz, 8H), 6.81 (t, J=8.3 Hz, 8H); ^{13}C NMR (125 MHz, C_6D_6) δ: 122.49, 123.58, 123.94, 125.35, 125.59, 127.97, 129.26, 134.65, 142.96, 143.11, 146.93, 148.11.

Results and Discussion

Because aryl chlorides, which are low-cost and wide available as electrophiles in the coupling reactions, are

more attractive for industrial applications,[2,20] the diarylation of aniline (**1a**) with 4-chlorotoluene (**2a**) was chosen as the model reaction to explore the catalytic activity of $PdCl_2(Ph_3P)_2$/salicylaldimines. The coupling of aniline (**1a**) with excess 4-chlorotoluene (**2a**) in refluxing *o*-xylene catalyzed only by $PdCl_2(Ph_3P)_2$ gave no diarylated product (**3aa**), and only 10% of the aniline was converted to the monoarylated product (**4aa**) as shown in Figure 1. When 6 mol% of *N*-phenylsalicylaldimine (**L1**) was added to the $PdCl_2(Ph_3P)_2$ catalytic system, the conversion of aniline was increased to 68%, though the monoarylated product (**4aa**) was the main product. Introducing an electron-donating group to *N*-phenyl group of salicylaldimine (**L2** and **L3**) did not improve the activity of the catalyst system, while the conversion decreased a little as *N*-phenyl salicylaldimine with the methoxy group (**L3**) was used as the coligand. When fluorine was introduced to the *N*-phenyl group of salicylaldimine either at *para* or *ortho* position (**L4** and **L5**), the conversion of aniline increased obviously, and the target diarylated product (**3aa**) was observed. When the di-fluoro substituted coligand (**L6**) was used which showed good activity for the monoarylation of aniline with aryl chloride,[8] the conversion of aniline reached 93% and the selectivity ratio for the diarylation was 22∶78. Replacing the substituents with trifluoromethyl groups increased the yield of diarylated product significantly. The coligand (**L10** or **L11**) with the substituents of 2,4- or 2,5-ditrifluoromethyl groups gave almost the absolute selectivity for the diarylation, and 97% conversion of aniline was observed as *N*-phenylsalicylaldimine with 2,5-ditrifluoromethyl groups (**L11**) was used. The result was consistent with Jin's research on the Pd/*N*-heterocyclic carbenes catalytic system. Their studies demonstrated the introduction of electron-withdrawing (bis)trifluoromethyl groups into the *N*-aryl ring of the salicylaldimine ligand weakens the strength of the Pd—N bond. This decreased strength of the Pd—N bond may result in that the palladium(II) complexes were prone to be activated into Pd(0) species.[4a] Moreover, the catalytic activity increased with the increase of steric hindrance of *N*-aryl ring of the salicylaldimine, therefore the salicylaldimine ligand may benefit the step of the reductive elimination in the catalytic cycle. When **L11** was used as ligand, $Pd(OAc)_2$ or $PdCl_2$ as palladium source and no PPh_3 was added, the coupling reaction did not occur. Therefore, PPh_3 was necessary for the catalyst system. Consequently, the mixed ligand strategy was a convenient method to adjust the electronic and steric environments surrounding the Pd center.[8]

Using **L11** and $PdCl_2(Ph_3P)_2$ as the catalyst system, the effect of solvents and bases on the diarylation of aniline (**1a**) with 4-chlorotoluene (**2a**) was explored (Table 1). Replacing *o*-xylene with toluene as the solvent resulted in no conversion (Table 1, entry 2). When *p*-xylene or mesitylene was used as the solvent at the same reaction temperature (145 ℃), both the activity

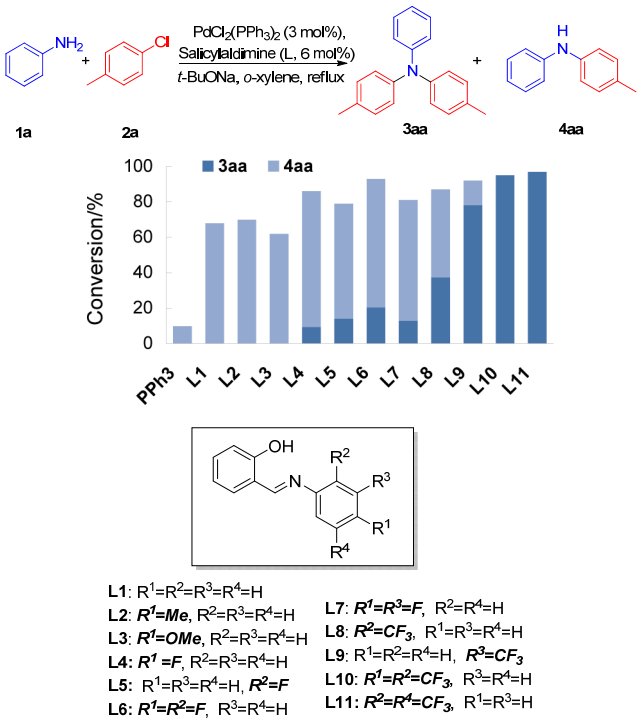


Figure 1 The structure effect of salicylaldimine on $PdCl_2(PPh_3)_2$ catalyzed the diarylation of aniline with aryl chloride. Reaction conditions: aniline (**1a**, 1.0 mmol), 4-chlorotoluene (**2a**, 2.5 mmol), [Pd] (0.03 mmol), ligand (0.06 mmol), and *t*-BuONa (3.0 mmol), *o*-xylene (8 mL), 145 ℃, 12 h.

Table 1 Effect of the reaction conditions on the diarylation of aniline with 4-chlorotoluene in the catalyst system of $PdCl_2(Ph_3P)_2$ and **L11**[a]

Entry	Base	Solvent	Conv.[b]/%	Selectivity[b] **3aa**∶**4aa**
1	*t*-BuONa	*o*-xylene	97	>99∶1
2[c]	*t*-BuONa	toluene	0	—
3	*t*-BuONa	*p*-xylene	53	80∶20
4	*t*-BuONa	mesitylene	58	62∶38
5	K_3PO_4	*o*-xylene	57	58∶42
6	Cs_2CO_3	*o*-xylene	62	11∶89
7	*t*-BuOK	*o*-xylene	61	33∶67
8	NaOH	*o*-xylene	36	31∶69
9	KOH	*o*-xylene	50	45∶55
10	NaH	*o*-xylene	82	85∶15
11[d]	*t*-BuONa	*o*-xylene	71	67∶33
12[e]	*t*-BuONa	*o*-xylene	98	>99∶1

[a] Reaction conditions: aniline (**1a**, 1.0 mmol), 4-chlorotoluene (**2a**, 2.5 mmol), base (3.0 mmol), $PdCl_2(Ph_3P)_2$ (0.03 mmol, 3 mol%), **L11** (0.06 mmol, 6 mol%) and solvent (8.0 mL), 145 ℃ for 12 h under nitrogen; [b] conversion based on aniline and selectivity measured by GC; [c] reaction temperature: 110 ℃; [d] *t*-BuONa (1.5 mmol) was used; [e] *t*-BuONa (4.5 mmol) was used.

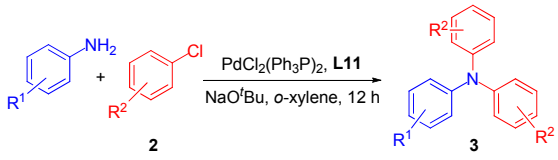
and selectivity of the catalyst system decreased (Table 1, entries 3 and 4). These results indicated that the structure of solvent affects significantly activity of the catalytic system. These were also observed in the Pd/Ph_3P catalyzed coupling reaction of aryl bromides and ani-

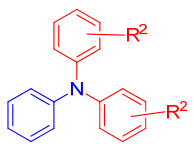
CHINESE JOURNAL OF CHEMISTRY

lines.[19] The activity and selectivity of the catalyst system dropped with the decreasing alkalinity of the base. When K_3PO_4 was used as the base, 57% conversion of aniline was observed, and the selectivity for the diarylation was reduced to the ratio of 58 : 42 (Table 1, entry 5). It's notable that the selectivity tends to the monoarylation as Cs_2CO_3 was used as base (Table 1, entry 6). NaOH and KOH were inferior for the catalytic system. Reducing the amount of base led to the incomplete conversion. Therefore, the optimized conditions for diarylation of anilines were identified as: $PdCl_2(Ph_3P)_2$/**L11** as catalyst, *t*-BuONa as base and *o*-xylene as solvent at 145 ℃.

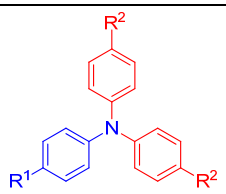
Under the optimized conditions, the scope and limitations of the catalytic system ($PdCl_2(Ph_3P)_2$/salicylaldimine) for the diarylation were investigated. The alkyl groups of aryl chlorides and anilines had no obvious impact on the diarylation. The reaction of *m*- and *p*-methyl chlorobenzene with aniline or *p*-toluidine cleanly provided triaryl products (**3aa**, **3ad**, **3ba** and **3bb**, Table 2) in excellent yields. While the electron-rich *p*-chloroanisole reacted with aniline to afford triaryl products in reduced yields (**3ac**, Table 2). The catalyst system tolerated the chloride on the aryl anilines. The diarylation of 4-chloroaniline gave the triaryl amine (**3cb**) with the intact chloride in 71% yield. The reduced yield may result from the decreased nucleophilicity of aryl amine with chloride as an electron-withdrawing group. In addition, the catalytic system showed good toleration for the steric hindrance of both substrates. Bulky anilines, such as 2,4,6-trimethylaniline, were diarylated in high yields (**3fa** and **3fg**, Table 2).

Table 2 Diarylation of anilines with aryl chorides catalyzed by $PdCl_2(Ph_3P)_2$/**L11**[a]

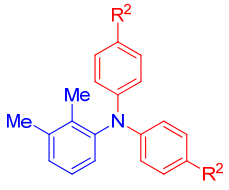




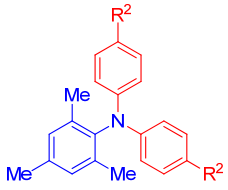
R^2= *p*-Me: **3aa**, 94%
H: **3ab**, 95%
p-OMe: **3ac**, 77%
m-Me: **3ad**, 92%



R^1=Me, R^2= Me: **3ba**, 96%
H: **3bb**, 94%
R^1=Cl, R^2=H: **3cb**, 71%
R^1=OMe, R^2=H: **3db**, 85%



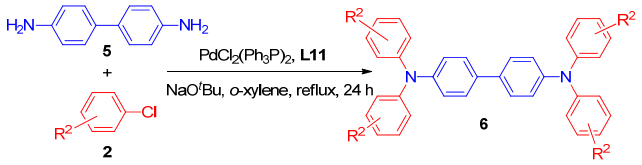
R^2= *p*-Me: **3ea**, 89%
p-Cl: **3ef**, 92%



R^2= *p*-Me: **3fa**, 88%
m-OMe: **3fg**, 90%

[a] Reaction conditions: aryl amine (1.0 mmol), aryl chloride (2.5 mmol), *t*-BuONa (3.0 mmol), $PdCl_2(Ph_3P)_2$ (0.03 mmol, 3 mol%), **L11** (0.06 mmol, 6 mol%) and *o*-xylene (8.0 mL), 145 ℃, 12 h, under nitrogen; the isolated yields were obtained.

Scheme 1 Tetraarylation of 4,4'-diaminobiphenyl with aryl chlorides catalyzed by $PdCl_2(Ph_3P)_2$/**L11**



R^2= H, **6a**, 93%; R^2= *o*-Me, **6e**, 88%
p-CH_3, **6b**, 92%; *m*-OMe, **6f**, 79%
p-OMe, **6c**, 72%; *p*-NPh_2, **6g**, 60%
m-CH_3, **6d**, 90%

N,N,N′,N′-Tetraaryl-1,1'-biphenyl-4,4'-diamines (**6**) are receiving increasing attention because they are important intermediates of the hole transport materials of organic light emitting diode (OLED) and dye-sensitized solar cells (DSSCs).[21] Inspired by the above results, we explored the synthesis of these compounds by the coupling reaction of 4,4'-diaminobiphenyl and aryl chlorides with the mixed-ligand catalytic system. The coupling reaction of 4,4'-diaminobiphenyl and 4-chlorotoluene gave the tetraaryl product (**6b**) in a 92% yield under the optimized conditions. We then examined the scope of the tetraarylation of 4,4'-diaminobiphenyl with unactivated aryl chlorides (Scheme 1). The catalyst system, $PdCl_2(Ph_3P)_2$/**L11**, allowed for the synthesis of *N,N,N′,N′*-tetraaryl-1,1'-biphenyl-4,4'-diamines in moderate to excellent yields. The electron-neutral aryl chlorides worked well to provide the corresponding products in slightly diminished yields of 72% (**6c**) and 79% (**6f**), respectively. In addition, when 4-chloro-*N,N*-diphenylaniline (**3cb**) was used as the substrate, the corresponding product (**6g**) with six triarylamine blocks was successfully obtained in 60% yield.

Conclusions

In summary, the results described herein that $PdCl_2(Ph_3P)_2$ with salicylaldimine as a coligand can exhibit high activity for the diaylation of aryl amines with unactivated aryl chlorides. The structure of salicylaldimine affected observably the activity and selectivity of the catalyst system. *N*-Phenylsalicylaldimine with 2,5-ditrifluoromethyl groups (**L11**) as the coligand shows high activity and selectivity for the diaylation. The catalytic system tolerates sterically hindered anilines and aryl chlorides. While the reaction is influenced by the electronic nature of the substrates: the diarylation with the electron-rich aryl chlorides performs in moderate yields.

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