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***t*Bu₃P-Coordinated 2-Phenylaniline-Based Palladacycle Complex As Precatalyst for Pd-Catalyzed Coupling Reactions of Aryl Halides with Polyfluoroarenes via C-H Activation Strategy**

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Abstract

*t*Bu₃P-Coordinated 2-phenylaniline-based palladacycle complex was demonstrated to be an efficient precatalyst for Pd-catalyzed coupling reactions of aryl halides with polyfluoroarenes via C-H activation strategy. The readily accessibility and easy handling nature of *t*Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex and the high yields of the reaction makes *t*Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex an attractive precatalyst for the cross-coupling reaction of aryl halides with polyfluoroarenes.

Keywords

Coupling Reaction; Aryl halides; Fluoroarenes; Palladacycle Complex; C-H Activation

Palladium-catalyzed Suzuki coupling reaction of aryl halides with arylboronic acids has become a powerful tool for the synthesis of biaryl compounds.¹ Recently, the use of arenes to substitute for arylboronic acids as the coupling partners represents a significant step forward in the coupling reaction field.² Due to the importance of electron-deficient fluorobiaryls in medicinal and materials chemistry,^{3,4} the coupling reaction of aryl halides with fluoroarenes has attracted much attention in recent years. Different transition metal catalysts, e.g., Pd(OAc)₂/*t*Bu₂PMe,^{5a} Pd(OAc)₂/S-Phos,^{5b} Pd(OAc)₂/MePhos,^{5c} (*N*-heterocyclic carbene)₂PdBr₂,^{5d,5e} Pd(OAc)₂/PPh₃,^{5f} and Pd(OAc)₂,^{5g} and CuI/phenanthroline,⁶ have been developed for this transformation.^{5–7} While some of the catalyst systems are operationally convenient, they required either high temperature, typically 100 °C or higher,^{5a, 5d, 5e, 5g, 6} or the use of aryl iodide as substrates^{5c} and/or the use of silver salts such as Ag₂O or Ag₂CO₃ as base or additive.^{5c, 5f, 5g} It is thus still synthetically desirable to search for operationally convenient palladium catalysts that can catalyze the reaction under mild conditions with inexpensive inorganic bases.

In our laboratory, we have become interested in employing *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex as precatalyst for cross-coupling reactions

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Copies of NMR spectra of Pd-catalyzed coupling reactions of aryl halides and fluoroarenes.

because *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex is air/moisture stable⁸ and could generate highly reactive 12-electron (*t*Bu₃P)Pd(0) species with a base, rather than an organometallic reagent, under mild conditions.^{9,10} In this context, we have recently reported *t*-Bu₃P-coordinated 2-phenylaniline-based palladacycle complex as a highly efficient precatalyst for the polymerization of aryl dibromides with aryldiboronic acids.¹¹ The easy handling nature of *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex and its high efficiency for the Suzuki cross-coupling polymerization prompted us to examine its use for other bond forming reactions. Because the coupling reactions of aryl halides with fluoroarenes via C-H activation strategy was believed to involve the deprotonation of fluoroarenes with ArPd(II)(L)X¹² and ArPd(II)(L)X could be obtained from the oxidative addition of ArX with 12-electron (*t*Bu₃P)Pd(0) species, which could be readily generated from *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex, we envisioned that *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex could be an efficient precatalyst for the coupling reactions of aryl halides with fluoroarenes via C-H activation strategy. In this article, we report our study on using *t*Bu₃P-coordinated 2-phenylaniline-based palladacycle complex (**1a**), as well as other monophosphine-coordinated 2-phenylaniline-based palladacycle complexes **1b–1g** (Scheme 1),^{9b, 11, 13} as a general, efficient precatalyst for coupling reactions of aryl halides with fluoroarenes via C-H activation strategy.^{14,15}

Results and Discussion

We began our study by examining the coupling reaction of bromobenzene (**2a**) and pentafluorobenzene (**3a**) at 80 °C by using 2-phenylaniline-based palladacycle complexes **1** (Chart 1) as the precatalysts. We found that with KOAc as the base and DMA as the solvent, precatalysts with bulkier ligands were more efficient than that with less bulkier ligands (Table 1, entries 1–7), with **1a** being the most efficient one (Table 1, entry 1). For comparison purpose, palladium catalysts derived from Pd(OAc)₂/*t*Bu₂PMe^{5a} (1:1, 1:1.5 and 1:2) and Pd(OAc)₂/*t*Bu₃P (1:1, 1:1.5 and 1:2) were also employed for the coupling reaction under the same reaction condition. Moderate conversions were observed (Table 1, entries 8–13), suggesting the unique efficiency of **1a** for this reaction. Changing the solvent to DMF or *i*PrOAc led to lower reaction conversions (Table 1, entries 14,15). The combination of K₂CO₃ as base and *i*PrOAc as solvent, which was used in reported Pd(OAc)₂/S-Phos catalyst system,^{5b} was also tested and moderate conversions were observed (Table 1, entries 16,17). A higher conversion was achieved by lengthening the reaction time (Table 1, entry 18). With DMA as solvent, we then briefly examined other bases (Table 1, entries 19–23) and found that Cs₂CO₃ (2 equiv.)/(CH₃)₃CCO₂H (PivOH) (0.5 equiv.) and K₃PO₄ (2 equiv.)/PivOH (0.5 equiv.) were the base combinations (Table 1, entries 22 and 23). With K₃PO₄/PivOH as the base system, we examined the coupling reaction again with precatalysts **1b–1g**, Pd(OAc)₂/*t*Bu₃P, Pd(OAc)₂/*t*Bu₂PMe, Pd(OAc)₂/*t*Bu₃P.HBF₄, and Pd(OAc)₂/*t*Bu₂PMe.HBF₄. These Pd catalysts exhibited lower catalytic efficiency than **1a**, as evidenced by the lower conversions (Table 1, entries 24–33). We further found that the reaction could be carried out at lower temperatures, *e.g.* 60 °C or 50 °C (Table 1, entries 34–35). Complete conversion at 60 °C was achieved by lengthening the reaction time (Table 1, entry 34).

With *t*Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex **1a** as the precatalyst, the coupling reaction of a number of aryl bromides with fluoroarenes were examined at 60–80 °C and our results are listed in Table 2. As shown in Table 2, fluoroarenes bearing 3 or more fluoro groups were found to be suitable coupling partners for the reaction (Table 2, entries 1–8). Different phenyl bromides, including *ortho*-, *meta*- and *para*-substituted ones, were all found to be suitable substrates for this reaction (Table 2, entries 1, 9–16). *Ortho*-substituted phenyl bromides were found to be less reactive than *meta*- and *para*-substituted ones as a higher temperature (100 °C) was needed for the reaction (Table 2, entries 12 and 14). Bromothiophenes were also found to be suitable substrates for this reaction (Table 2, entries 17 and 18). Aryl iodides were also examined for the reaction and exhibited lower reactivities than aryl bromides as evidenced by their incomplete conversions (Table 2, entries 19 and 20).^{5a} We also tested aryl chlorides as the substrates for the reaction and found by using 10 mol% of precatalyst, complete conversions and high yields could be achieved (Table 2, entries 21–24).

We have also carried out the reaction of 2,7-dibromo-9,9-dioctylfluorene with 1,2,4,5-tetrafluorobenzene with **1a** as the precatalyst, leading a polymeric product with a Mn of 14 100 (Scheme 2).¹⁶

Conclusions

In summary, we demonstrated that *t*-Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex **1a** was an efficient precatalyst for the coupling reaction of aryl halides with polyfluoroarenes. Good to excellent yields were obtained for different aryl bromides, including a dibromide, iodides and chlorides for the reaction. The easy handling nature of **1a** and the high yields of the reaction make *t*-Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex **1a** a practically attractive precatalyst for the coupling reactions of aryl halides via C-H activation strategy. Our study might pave the road for us to investigate other coupling reactions via C-H activation strategy with this *t*-Bu₃P-coordinated 2-aminobiphenyl-based palladacycle complex as precatalyst.

Experimental Section

General

¹H, ¹⁹F, ¹³C NMR spectra were recorded on Varian 600 MHz NMR spectrometer. Chemical shifts were determined relative to internal (CH₃)₄Si (TMS). All yields reported refer to isolated yields unless otherwise indicated. GC-MS experiments were carried out using an Agilent GC/MS instrument consisting of a 6890N series GC and a 5973 Mass Selective Detector System.

All the solvents were degassed with N₂ for 2 h before use. All the reagents were purchased from commercial sources and used as received. Precatalysts **1a**,¹¹ **1d**,^{13a} **1e**,¹¹ **1f**,^{13c} **1g**^{9b} were prepared by following reported procedures. Precatalysts **1b** and **1c** were prepared by the following procedure.

Preparation of Precatalysts **1b** and **1c**

In a glove-box, a mixture of Pd(OAc)₂ (336 mg, 1.5 mmol) and 2-aminobiphenyl (264 mg, 1.5 mmol) in anhydrous toluene (10 mL) was heated at 60 °C under N₂ atmosphere for 30 min. After the reaction was cooled to room temperature, toluene was removed. The remaining solid was washed with anhydrous toluene (2 × 2 mL) and then suspended in anhydrous acetone (10 mL). Lithium chloride (191 mg, 4.5 mmol) was added to the suspension and the mixture was stirred at room temperature under N₂ atmosphere for 1 h. *t*Bu₂MeP or *t*Bu₂CyP (1.4 mmol) was then added to the solution. The mixture was stirred at room temperature for 2.5 h. Removal of about 90% of the solvent under vacuum afforded a yellow slurry, which was treated with methyl *t*-butyl ether (5 mL) and pentane (10 mL). The mixture was then placed in refrigerator for 1 h. Then, the mixture was filtered, washed with water and pentane and dried under vacuum to afford complex **1b** or **1c**.

1b: 52% yield. Gray solid. Mp: 158.0–158.8 °C. ¹H NMR (600 MHz, CDCl₃): δ 7.41 (dd, *J* = 2.4 Hz, *J* = 9.6 Hz, 1 H), 7.26 ~ 7.27 (m, 1 H), 7.15 ~ 7.24 (m, 4 H), 7.06 ~ 7.09 (m, 2 H), 4.73 (s, 1 H), 4.61 (s, 1 H), 1.42 (d, *J* = 15.6 Hz, 9 H), 1.05 (d, *J* = 15.6 Hz, 9 H), 0.85 (d, *J* = 9.0 Hz, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 140.1, 139.2, 138.3, 138.2, 135.6, 128.1, 127.5, 127.2, 125.6, 125.0, 119.8, 34.8 (q, *J* = 14.8 Hz), 29.2 (q, *J* = 7.0 Hz) ppm. ³¹P NMR (121 MHz, CDCl₃): δ 49.02 ppm. HRMS (ESI) Calcd for: C₂₄H₃₇NPPd ([M+H-HCl]⁺) 434.1229. Found: 434.1232.

1c: 43% yield. Gray solid. Mp: 160.8–161.4 °C. ¹H NMR (600 MHz, CDCl₃): δ 7.46 (d, *J* = 6.6 Hz, 1 H), 7.36 (d, *J* = 6.6 Hz, 1 H), 7.15 ~ 7.19 (m, 4 H), 7.05 ~ 7.06 (m, 2 H), 4.88 (s, 1 H), 4.59 (s, 1 H), 0.99 ~ 1.64 (m, 28 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 140.4, 140.1, 136.9, 135.6, 128.1, 127.5, 126.7, 125.3, 125.0, 124.9, 119.4, 38.1, 38.0, 37.3, 37.2, 31.4, 31.1, 30.9, 27.9, 27.8, 27.3, 27.2, 26.3 ppm. ³¹P NMR (121 MHz, CDCl₃): δ 67.59 ppm. Elemental analysis: Anal. Calcd. for C₂₆H₃₉ClNPPd: C, 58.00; H, 7.30. Found: C, 58.18; H, 7.26.

General Procedure for Pd-Catalyzed Coupling Reactions of Aryl Halides with Fluoroarenes with **1a** as Precatalyst

In a glovebox, to 5-mL vial containing bromobenzene (62 mg, 0.4 mmol), precatalyst **1a** (10.0 mg, 0.02 mmol), pivalic acid (20 mg, 0.2 mmol), K₃PO₄ (168 mg, 0.8 mmol) and DMA (1 mL) was added pentafluorobenzene (98 mg, 0.6 mmol). After stirring at 80 °C for 2 h-4 h, the reaction was quenched with saturated NH₄Cl solution. The product was extracted with ethyl acetate (3 × 15 mL). The combined organic layer was washed with brine and dried over Na₂SO₄. After removal of solvents under vacuum, the crude product was purified via column chromatography (silica gel, hexanes eluent) to yield colorless oil.

2,3,4,5,6-Pentafluorobiphenyl (4a):^{7a}—99% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.37 (d, *J* = 9.0 Hz, 2 H), 7.02 (d, *J* = 8.4 Hz, 2 H), 3.87 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.1 (dm, *J_F* = 205.5 Hz), 140.3 (dm, *J_F* = 210.0 Hz), 137.8 (dm, *J_F* = 207.9 Hz), 130.1, 129.3, 128.7, 126.4, 115.9 (td, *J_{FI}* = 14.4 Hz, *J_{F2}* = 3.2 Hz) ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -143.2 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -155.6 (t, *J_F* = 23.1 Hz, 1 F), -162.6 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,5,6-Tetrafluoro-4-methylbiphenyl (4b):^{7b}—82% yield with phenyl bromide as coupling partner and 80% yield with phenyl chloride as coupling partner. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.44 ~ 7.50 (m, 5 H), 2.32 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 146.0 ~ 146.2 (m), 144.3 ~ 144.5 (m), 142.6 ~ 142.8 (m), 130.1, 128.8, 128.5, 127.7, 117.9 (t, *J_F* = 11.0 Hz), 115.0 (t, *J_F* = 13.0 Hz), 7.6 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -144.2 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -145.6 (dd, *J_{FI}* = 13.2 Hz, *J_{F2}* = 24.3 Hz, 2 F) ppm.

2,3,5,6-Tetrafluoro-4-methoxybiphenyl (4c):^{7b}—84% yield with phenyl bromide as coupling partner and 81% yield with phenyl chloride as coupling partner. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.43 ~ 7.49 (m, 5 H), 4.12 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.3 (dm, *J_F* = 204.6 Hz), 141.1 (dm, *J_F* = 205.0 Hz), 137.4 (m), 130.2, 128.9, 128.5, 127.3, 114.2 (t, *J_F* = 13.06 Hz), 62.2 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -150.0 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -161.4 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 23.4 Hz, 2 F) ppm.

2,3,5,6-Tetrafluorobiphenyl (4d):^{7b}—78% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.46 ~ 7.53 (m, 5 H), 7.05 ~ 7.09 (m, 1 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 146.2 (dm, *J_F* = 205.5 Hz), 142.8 (dm, *J_F* = 210.0 Hz), 130.1, 129.1, 128.5, 127.4, 121.5 (t, *J_F* = 14.4 Hz) ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -139.1 (m, 2 F), -143.9 (m, 2 F) ppm. 2,3,5,6-Tetrafluoroterphenyl was also isolated as a minor product in 12% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.52 (d, *J* = 4.2 Hz, 8 H), 7.46 ~ 7.49 (m, 2 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 130.1, 129.1, 128.6, 127.5 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -144.3 (s, 4 F) ppm.

2,4,6-Trifluorobiphenyl (4e):¹⁷—85% yield. White solid. ¹H NMR (600 MHz, CDCl₃): δ 7.44 ~ 7.48 (m, 5 H), 6.78 (t, *J* = 7.8 Hz, 2 H) ppm. ¹³C NMR (125 MHz, CDCl₃): δ 161.7 (dt, *J_F* = 206.0 Hz, *J_F* = 13.0 Hz), 160.3 (dm, *J_F* = 207.5 Hz), 130.2, 128.4, 115.0 (td, *J_{FI}* = 15.9 Hz, *J_{F2}* = 3.7 Hz), 100.4 ppm. 3-Phenyl-2,4,6-trifluorobiphenyl was also isolated as a minor product in 8% yield as a colorless liquid. ¹H NMR (600 MHz, CDCl₃): δ 7.39 ~ 7.47 (m, 10 H), 6.86 ~ 6.90 (m, 1H) ppm. ¹³C NMR (125 MHz, CDCl₃): δ 159.6 ~ 159.7 (m), 157.9 ~ 158.1 (m), 130.3, 128.6, 128.3, 115.0 ~ 115.3 (m), 100.3 ~ 110.7 (m) ppm.

2,6-Difluorobiphenyl (4f):¹⁷—30 % yield. White solid. ¹H NMR (600 MHz, CDCl₃): δ 7.39 ~ 7.48 (m, 5 H), 7.26 ~ 7.30 (m, 1 H), 6.98 ~ 7.00 (m, 2 H) ppm. ¹³C NMR (125 MHz, CDCl₃): δ 160.3 (dd, *J_F* = 206.0 Hz, *J_F* = 5.6 Hz), 130.3, 129.1, 128.8 (t, *J_F* = 8.7 Hz), 128.5, 128.2, 118.5 (t, *J_F* = 13.8 Hz), 111.5 ~ 111.7 (m) ppm.

2,3,4,5,6-Pentafluoro-4'-methylbiphenyl (4g):^{7a}—90% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.31 (s, 4H), 2.42 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.2 (dm, *J_F* = 204.5 Hz), 139.7 (dm, *J_F* = 209.6 Hz), 139.4, 137.8 (dm, *J_F* = 207.2 Hz), 129.9, 129.4, 123.3, 115.9 (td, *J_{FI}* = 14.4 Hz, *J_{F2}* = 3.2 Hz), 21.2 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -143.4 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -156.1 (t, *J_F* = 23.1 Hz, 1 F), -162.4 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-4'-methoxybiphenyl (4h):^{5c}—98% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.47 ~ 7.53 (m, 3 H), 7.45 (d, *J* = 6.6 Hz, 2 H), 3.87 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 160.2, 144.1 (dm, *J_F* = 204.5 Hz), 140.0 (dm, *J_F* = 209.6 Hz), 137.8 (dm, *J_F* = 207.2 Hz), 131.4, 118.3, 115.7 (td, *J_{FI}* = 14.4 Hz, *J_{F2}* = 3.2 Hz), 114.2, 55.2 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -143.6 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -156.5 (t, *J_F* = 23.1 Hz, 1 F), -162.5 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-3'-methylbiphenyl (4i):^{7a}—99% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.39 (t, *J* = 7.2 Hz, 1 H), 7.28 ~ 7.29 (m, 1 H), 7.21 ~ 7.23 (m, 2 H), 2.43 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.1 (dm, *J_F* = 205.0 Hz), 140.3 (dm, *J_F* = 210.1 Hz), 138.5, 137.8 (dm, *J_F* = 207.4 Hz), 130.7, 130.0, 128.6, 127.2, 126.2, 116.1 (td, *J_{FI}* = 14.4 Hz, *J_{F2}* = 3.2 Hz), 21.4 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -143.1 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -155.8 (t, *J_F* = 23.1 Hz, 1 F), -162.3 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-2'-methylbiphenyl (4j):^{7a}—99% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.39 ~ 7.41 (m, 2 H), 7.31 (t, *J* = 7.2 Hz, 1 H), 7.20 (d, *J* = 7.8 Hz, 1 H), 2.20 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.1 (dm, *J_F* = 205.5 Hz), 140.3 (dm, *J_F* = 210.4 Hz), 137.7 (dm, *J_F* = 207.4 Hz), 137.4, 130.6, 130.5, 129.6, 126.0, 125.9, 115.4 (td, *J_{FI}* = 16.2 Hz, *J_{F2}* = 3.2 Hz), 19.6 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -140.5 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 25.5 Hz, 2 F), -155.4 (t, *J_F* = 21.9 Hz, 1 F), -162.2 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 23.4 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-3'-methoxybiphenyl (4k):^{7a}—98% yeild. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.41 (t, *J* = 8.4 Hz, 1 H), 7.00 (m, 2 H), 6.94 (s, 1 H), 3.84 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 159.7, 144.1 (dm, *J_F* = 208.2 Hz), 140.4 (dm, *J_F* = 210.6 Hz), 137.8 (dm, *J_F* = 207.8 Hz), 129.7, 122.4, 115.8, 114.8, 55.3 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -140.2 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -156.1 (t, *J_F* = 23.1 Hz, 1 F), -163.1 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-2'-methoxybiphenyl (4l):^{5c}—96% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.44 ~ 7.47 (m, 1 H), 7.22 (t, *J* = 6.0 Hz, 1 H), 7.01 ~ 7.07 (m, 2 H), 3.81 (s, 3 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 157.1, 144.1 (dm, *J_F* = 208.2 Hz), 140.4 (dm, *J_F* = 210.6 Hz), 137.8 (dm, *J_F* = 207.8 Hz), 131.7, 131.1, 120.5, 115.2, 111.2, 55.6 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -140.2 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.3 Hz, 2 F), -156.1 (t, *J_F* = 23.1 Hz, 1 F), -163.1 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-4'-trifluoromethylbiphenyl (4m):^{5b}—80% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.76 (d, *J* = 8.4 Hz, 2 H), 7.56 (d, *J* = 7.8 Hz, 2 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 163.9, 162.3, 144.2 (dm, *J_F* = 205.2 Hz), 140.5 (dm, *J_F* = 209.1 Hz), 137.8 (dm, *J_F* = 207.9 Hz), 132.0 (dm, *J_F* = 5.5 Hz), 122.2, 116.0, 115.9, 114.9 (td, *J_{FI}* = 13.9 Hz, *J_{F2}* = 3.2 Hz) ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -62.9 (s, 3F), -142.9 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 25.5 Hz, 2 F), -155.7 (t, *J_F* = 21.9 Hz, 1 F), -162.3 (ddd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 21.0 Hz, *J_{F3}* = 24.0 Hz, 2 F) ppm.

2,3,4,4',5,6-hexafluorobiphenyl (4n):^{7a}—98% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.41 ~ 7.43 (m, 2 H), 7.18 ~ 7.21 (m, 2 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.1 (dm, *J_F* = 205.0 Hz), 140.3 (dm, *J_F* = 210.1 Hz), 138.5, 137.8 (dm, *J_F* = 207.4 Hz), 130.7, 130.0, 128.6, 127.2, 126.2, 116.1 (td, *J_{FI}* = 14.4 Hz, *J_{F2}* = 3.2 Hz), 21.4 ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -111.3 (s, 1F), -143.3 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 25.5 Hz, 2 F), -155.2 (t, *J_F* = 21.9 Hz, 1 F), -162.0 (ddd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 21.0 Hz, *J_{F3}* = 24.0 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-1-(2-thiophenyl)benzene (4o):¹⁸—85% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.65 (d, *J* = 1.2 Hz, 1 H), 7.45 ~ 7.47 (m, 1 H), 7.35 ~ 7.36 (m, 1 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.2 (dm, *J_F* = 206.0 Hz), 140.0 (dm, *J_F* = 210.1 Hz), 138.0 (t, *J* = 2.7 Hz), 128.1, 127.0, 125.6, 111.1 (td, *J_{FI}* = 13.5 Hz, *J_{F2}* = 3.2 Hz) ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -142.0 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 25.5 Hz, 2 F), -156.2 (t, *J_F* = 21.9 Hz, 1 F), -162.3 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 23.4 Hz, 2 F) ppm.

2,3,4,5,6-Pentafluoro-1-(3-thiophenyl)benzene (4p):¹⁸—90% yield. white solid. ¹H NMR (600 MHz, CDCl₃): δ 7.65 (dd, *J₁* = 1.2 Hz, *J₂* = 3.0 Hz, 1 H), 7.46 (dd, *J₁* = 3.0 Hz, *J₂* = 4.8 Hz, 1 H), 7.35 ~ 7.36 (m, 1 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 144.2 (dm, *J_F* = 206.0 Hz), 140.3 (dm, *J_F* = 210.1 Hz), 128.2 (t, *J* = 2.7 Hz), 127.1, 125.8, 125.6, 111.1 (td, *J_{FI}* = 13.5 Hz, *J_{F2}* = 3.2 Hz) ppm. ¹⁹F NMR (282 MHz, CDCl₃): δ -142.0 (dd, *J_{FI}* = 8.4 Hz, *J_{F2}* = 25.5 Hz, 2 F), -156.2 (t, *J_F* = 21.9 Hz, 1 F), -162.3 (dt, *J_{FI}* = 8.4 Hz, *J_{F2}* = 23.4 Hz, 2 F) ppm.

Polymerization of 2,7-dibromo-9,9-dioctyl-9H-fluorene with 1,2,4,5-tetrafluorobenzene

Under N₂ atmosphere, to a solution of 2,7-dibromo-9,9-dioctyl-9H-fluorene (110 mg, 0.2 mmol), KOAc (10 mg, 0.1 mmol), K₃PO₄ (84 mg, 0.4 mmol) and precatalyst **1a** (5.1 mg, 0.01 mmol) in DMA (0.4 mL) 2,3,5,6-tetrafluorobenzene (30 mg, 0.2 mmol) was added. After stirring at 100 °C for 12 h, the mixture was poured into HCl solution (5 M, 10 mL) with stirring. The product was extracted with CH₂Cl₂ (3 × 15 mL), the combined organic layer was washed with brine and dried over Na₂SO₄. After removal of solvents under vacuum, the residue was dissolved in a small amount of THF and the solution was added slowly to methanol with stirring. The precipitate was collected by filtration. After washing with methanol, the solid was dried under vacuum for 4 h. Yield: 80%. ¹H NMR (600 MHz, CDCl₃): δ 7.92 (d, *J* = 7.8 Hz, 2 H), 7.57 (s, 4 H), 2.06 (br, 4 H), 1.12 ~ 1.26 (m, 20 H), 0.81 ~ 0.84 (m, 10 H) ppm. ¹³C NMR (150.8 MHz, CDCl₃): δ 151.4, 145.0, 143.4, 141.2, 129.1, 126.5, 125.0, 120.2, 55.5, 40.1, 31.7, 29.9, 29.2, 23.8, 22.6, 14.0 ppm. GPC (THF, polystyrene as standard): *M_n* = 14 100 (PDI = 2.44).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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1a: L = *t*Bu₃P

1b: L = *t*Bu₂PMe

1c: L = *t*Bu₂PCy

1d: L = PPh₃

1e: L = Cy₃P

Scheme 1.

Monophosphine-Coordinated 2-Phenylaniline-Based Palladacycle Complexes

Scheme 2.

1a-Catalyzed Coupling Polymerization of Aryl Dibromide with 1,2,4,5-Tetrafluorobenzene via C-H Activation Strategy

Table 1

Pd-Catalyzed Cross-Coupling Reaction of Bromobenzene with Pentafluorobenzene via C-H Activation^a

Entry	Catalyst	Base	Solvent	Yield ^b
1	1a	KOAc	DMA	80%
2	1b	KOAc	DMA	33%
3	1c	KOAc	DMA	65%
4	1d	KOAc	DMA	25%
5	1e	KOAc	DMA	13%
6	1f	KOAc	DMA	48%
7	1g	KOAc	DMA	40%
8	Pd(OAc) ₂ + <i>t</i> Bu ₃ P (1:1)	KOAc	DMA	10% ^c
9	Pd(OAc) ₂ + <i>t</i> Bu ₃ P (1:1.5)	KOAc	DMA	10% ^c
10	Pd(OAc) ₂ + <i>t</i> Bu ₃ P (1:2)	KOAc	DMA	43%
11	Pd(OAc) ₂ + <i>t</i> Bu ₂ PMe(1:1)	KOAc	DMA	15% ^c
12	Pd(OAc) ₂ + <i>t</i> Bu ₂ PMe(1:1.5)	KOAc	DMA	17% ^c
13	Pd(OAc) ₂ + <i>t</i> Bu ₂ PMe(1:2)	KOAc	DMA	43%
14	1a	KOAc	DMF	69%
15	1a	KOAc	<i>i</i> -PrOAc	23% ^c
16	1a	K ₂ CO ₃	<i>i</i> -PrOAc	38% ^c
17	1f	K ₂ CO ₃	<i>i</i> -PrOAc	35% ^c
18	1a	KOAc	DMA	97% ^d
19	1a	K ₂ CO ₃	DMA	24% ^d
20	1a	K ₂ CO ₃ + KOAc+ LiCl	DMA	82% ^d
21	1a	K ₂ CO ₃ + PivOH	DMA	94%
22	1a	CS ₂ CO ₃ + PivOH	DMA	99%
23	1a	K ₃ PO ₄ + PivOH	DMA	99%
24	1b	K ₃ PO ₄ + PivOH	DMA	31%
25	1c	K ₃ PO ₄ + PivOH	DMA	66%
26	1d	K ₃ PO ₄ + PivOH	DMA	30%
27	1e	K ₃ PO ₄ + PivOH	DMA	17%
28	1f	K ₃ PO ₄ + PivOH	DMA	60% ^c
29	1g	K ₃ PO ₄ + PivOH	DMA	48% ^c
30	Pd(OAc) ₂ + <i>t</i> Bu ₃ P (1:2)	K ₃ PO ₄ + PivOH	DMA	35%
31	Pd(OAc) ₂ + <i>t</i> Bu ₂ PMe (1:2)	K ₃ PO ₄ + PivOH	DMA	10%
32	Pd(OAc) ₂ + <i>t</i> Bu ₃ P, HBF ₄ (1:2)	K ₃ PO ₄ + PivOH	DMA	35%

Entry	Catalyst	Base	Solvent	Yield ^b
33	Pd(OAc) ₂ + <i>t</i> Bu ₂ PMe. HBF ₄ (1:2)	K ₃ PO ₄ + PivOH	DMA	31%
34	1a	K ₃ PO ₄ + PivOH	DMA	99% ^e
35	1a	K ₃ PO ₄ + PivOH	DMA	68% ^f

^a Reaction condition: bromobenzene (0.4 mmol), pentafluorobenzene (1.5 equiv.), Pd catalyst (5 mol%), base (2 equiv.), PivOH (0.5 equiv. for entries 21–35), solvent, 80 °C, 2 h.

^b Based on GC-MS analysis.

^c Based on ¹H NMR analysis.

^d Reaction time: 4 h.

^e Reaction condition: 60 °C, 14 h.

^f Reaction condition: 50 °C, 14 h.

Table 2**1a**-Catalyzed Cross-Coupling Reaction of Aryl Halides with Polyfluorobenzenes via C-H Activation^a

Entry	ArX	3	Product	Yield (%) ^b
1		3a (R ₁ = R ₂ = R ₃ = F)	4a	86% ^c
2	2a	3b (R ₁ = R ₃ = F, R ₂ = CH ₃)	4b	82%
3	2a	3c (R ₁ = R ₃ = F, R ₂ = OCH ₃)	4c	84%
4	2a	3d (R ₁ = R ₃ = F, R ₂ = H)	4d	78% ^d
5	2a	3e (R ₁ = R ₃ = H, R ₂ = F)	4e	85% ^e
6	2a	3f (R ₁ = R ₂ = R ₃ = H)	4f	30%
7	2a	3g (1,2-difluorobenzene)	-	0
8	2a	3h (fluorobenzene)	-	0
9		3a	4g	94% ^c
10		3a	4h	95% ^c
11		3a	4i	98%
12		3a	4j	97% ^f
13		3a	4k	99%
14		3a	4l	96% ^f
15		3a	4m	80%
16		3a	4n	98%
17		3a	4o	85%
18		3a	4p	90%
19		3a	4a	82% ^g
20		3a	4g	52% ^h

Entry	ArX	3	Product	Yield (%) ^b
21	Cl (2n)	3a	4a	95% ⁱ
22	Cl (2o)	3a	4g	90% ⁱ
23	2n	3b	4b	80% ⁱ
24	2n	3c	4c	81% ⁱ

^a Reaction condition: aryl halide (0.4 mmol), fluorobenzene (1.5 equiv.), **1a** (5 mol%), K_3PO_4 (2 equiv.), PivOH (50 mol%), DMA, 80 °C, 2–4 h.

^b Isolated yields.

^c Reaction condition: 60 °C, 14 h.

^d 12% double cross-coupling product was obtained.

^e 8% double cross-coupling product was obtained.

^f Reaction temperature: 100 °C.

^g Conversion: 86%.

^h Conversion: 56%.

ⁱ Catalyst loading of **1a**: 10 mol%.