

Supplementary Information

Alkynylation of Aryl Halides with Perfluoro-Tagged Palladium Nanoparticles Immobilized on Silica Gel under Aerobic, Copper-, and Phosphine-Free Conditions in Water

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Experimental Section

General Information

Melting points were determined with a Büchi B-545 apparatus and are uncorrected. 1-ethynyl-4-benzonitrile, 1-ethynyl-4-methoxybenzene and 1-ethynyl-4-acetophenone were prepared from the corresponding aryl iodides and trimethylsilylacetylene according to literature (Mori, A. et al., *J. Org. Chem.*, **2000**, *65*, 1780). The other reagents and solvents are commercially available and were used as purchased, without further purification. Compounds were purified on axially compressed columns, packed with SiO₂ 25-40 µm (Macherey Nagel), connected to a Gilson solvent delivery system and to a Gilson refractive index detector, and eluting with *n*-hexane/AcOEt mixtures. ¹H NMR (400.13 MHz) and ¹³C NMR (100.6 MHz) spectra were recorded with a Bruker Avance 400 spectrometer. Infrared (IR) spectra were recorded on a JASCO FT/IR-430 spectrophotometer. Mass spectra were determined with a Shimadzu QP2010 Gas Chromatograph Mass spectrometer (EI ion source). Determination of Pd at mass 105 was performed by means of a sector field inductively coupled plasma mass spectrometry technique (SF-ICP-MS, Thermo-Fischer, Bremen, Germany) in medium resolution ($m/\Delta m=3000$) to avoid that interferent signals coming from molecular species, *i.e.*, ⁴⁰Ar⁶⁵Cu, could overlap the signal of Pd at the chosen mass and overestimate the actual Pd value. Quantification of Pd was carried out through the external calibration curve. Rhodium (Rh), selected

at mass 103, was used as internal standard to keep under control the instrumental drift. Single element calibrant and internal standard were prepared from 1000 mg/mL stock solutions of Pd in 10% HNO₃ and Rh in 10% HCl (High-Purity Standards, Charleston, USA) by dilution with high purity deionized water. Transmission electron microscopy (TEM) analyses were performed in the “Servei de Microscòpia” of the Universitat Autònoma de Barcelona, in a JEOL JEM-2010 model at 200 kV. The TEM measurements were made by sonication of the nanoparticulate material in perfluorooctyl bromide for several minutes; then, one drop of the finely divided suspension was placed on a specially produced structure less carbon support film having a thickness of 4-6 nm and dried before observation.

Preparation of phosphine-free perfluoro-tagged palladium nanoparticles Pd_{np}-A: A mixture of PdCl₂ (0.060 g, 0.34 mmol), NaCl (0.022 g, 0.38 mmol) and 2 mL of MeOH was stirred at room temperature for 24 h. The mixture was filtered through a glass wool plug. Additional MeOH (28 mL) was added to the filtrate. The solution was heated at 60 °C under stirring and 2,4,6-tris(1H,1H,2H,2H-perfluorodecylthio)-1,3,5-triazine (0.250 g, 0.16 mmol) was added. Then, the mixture was heated under stirring during 24 h. AcONa (0.190 g, 2.32 mmol) was added and stirring was maintained at room temperature for 1 h. The formed black solid was filtered, washed with MeOH, H₂O and Me₂CO; it was then dried to afford 0.270 g of Pd_{np}-A as a black solid. The size of the nanoparticles was 2.3 ± 0.7 nm, as determined by transmission electron microscopy. Pd analysis (ICP): 13.4 %.

Preparation of (Pd_{np}-A)/FSG: 0.020 g of Pd_{np}-A were added to 10 mL of perfluorooctane and the mixture was heated at 100 °C for 14 h. Then, 1 g of FSG (C₈; 35-70 μm) was added and the mixture was stirred at the same temperature for 1 h. After this time, the solvent was evaporated under vacuum to obtain the desired catalyst system.

Preparation of Pd_{np}-B: A 5 mL round-bottom flask was charged with PdCl₂ (17.0 mg, 96 μmol) and NaCl (6.6 mg, 113 μmol). MeOH (1 mL) was added and the mixture was left stirring at room temperature for 24 h; the mixture was then filtered through a plug of glass wool and the filtrate diluted with additional 9 mL of MeOH. Material **B** (199.9 mg) was added to the flask, and the resulting mixture was heated to 60 °C for 24 h. At the end of this period, NaOAc (56.0 mg, 0.68 mmol) was added, the mixture was removed from the oil bath and was allowed to cool for 90 min.

The precipitate was separated by centrifugation, and was washed successively with MeOH, water and acetone, giving the product as a black solid. Yield: 226.3 mg. Palladium content: 3.47 %. Average particle diameter: 3.2 ± 0.4 nm (based on TEM; measurement of 260 particles).

Typical procedure for alkynylation of aryl halides using 0.1 mol% of Pd_{np}-A/FSG or Pd_{np}-B:

3-(trifluoromethyl)iodobenzene (272 mg, 1 mmol), Pd_{np}-A/FSG (40 mg) or Pd_{np}-B (3mg), pyrrolidine (142 mg, 2 mmol) and phenyl acetylene (102 mg, 1 mmol.) in Water (2 mL) were orbitally stirred for 3 h at 100 °C with a Heidolph Synthesis System. Then, after cooling, the reaction mixture was centrifuged. The liquid phase was decanted, diluted with AcOEt, washed with deionized water and dried over Na₂SO₄. The solvent was removed under vacuum and the residue was purified by chromatography (SiO₂, 35 g, *n*-hexane/AcOEt 96/4 v/v) to give 233.7 mg (95% yield) of **3a**: m.p.: 40.1-41.4 °C; IR (KBr) 2925, 1606, 1340, 1168, 1132, 1070 cm⁻¹; ¹H NMR (CDCl₃) δ 7.84 (s, 1H), 7.74–7.72 (d, *J* = 8 Hz, 1H), 7.62-7.59 (t, 3H), 7.52-7.50 (t, 1H), 7.41,7.40 (t, 3H); ¹³CNMR (CDCl₃) δ 134.7, 131.8, 131.2, 130.9, 128.9, 128.8, 128.5, 128.4, 128.4, 125.2, 124.8, 124.8, 124.3, 122.7, 122.5, 90.9, 87.8, 1.1; MS *m/z* (relative intensity) 246 (M⁺,100), 225 (8), 196 (6), 176 (10), 150 (5). Anal Calcd for C₁₅H₉F₃ C, 73.17; H, 3.68; found C, 73.11; H, 3.62. (Known compound, see: Yi, W.-B. et al., *Eur. J. Org. Chem.* **2007**, 3445).

3b: mp: 72.0-73.1 °C; IR (KBr) 1714, 1604, 1263, 1097, 756 cm⁻¹; ¹H NMR (CDCl₃) δ 8.06–8.04 (d, *J* = 8 Hz, 2 H), 7.62-7.56 (m, 3 H), 7.37-7.28 (m, 3 H), 4.43-4.37 (q, 2 H), 1.44-1.38 (t, 3 H); ¹³C NMR (CDCl₃) δ 166.1, 131.8, 131.5, 129.9, 129.5, 128.8, 128.5, 127.9, 122.8, 92.3, 88.8, 61.2, 14.4, MS *m/z* (relative intensity) 250 (M⁺, 96), 222 (6), 204 (100), 176 (24), 151 (31), 88 (30). Anal Calcd for C₁₇H₁₄O₂, C, 81.58; H, 5.64; found C, 81.54; H, 5.60. (Known compound, see: Soler, R. et al., *Synthesis*, **2007**, 19, 3068).

3c: mp: 118.1-119.2 °C; IR (KBr) 2215, 1590, 1509, 1346, 858 cm⁻¹; ¹H NMR (CDCl₃) δ 8.24–8.22 (d, *J* = 8 Hz, 2H), 7.69-7.67 (d, *J* = 8Hz, 2H), 7.60-7.57 (m,2H), 7.42-7.39 (m, 3H); ¹³CNMR (CDCl₃) δ 147.0, 132.3, 131.9, 130.3, 129.3, 128.6, 123.7, 12.2, 94.7, 87.6, MS *m/z* (relative intensity) 223 (M⁺,100), 192 (49), 176(85), 165 (59), 151 (43). Anal Calcd for C₁₄H₉NO₂, C, 75.33; H, 4.06; found C, 75.39; H, 4.09. (Known compound, see: Lee, S. et al., *Org. Lett.*, **2008**, 10, 945).

3d: mp: 57-59 °C; IR (KBr) 2215, 1592, 1508, 1245 cm^{-1} ; ^1H NMR (CDCl_3) δ 7.55–7.49 (m, 4H), 7.39-7.28 (m, 2H), 6.91-6.89 (d, $J = 8\text{Hz}$, 2H), 3.85 (s, 3H); ^{13}C NMR (CDCl_3) δ 159.7, 133.1, 131.5, 128.4, 127.9, 123.6, 114.1, 89.4, 88.1, 55.4, MS m/z (relative intensity) 208 (M^+ , 100), 192 (52), 165 (52), 139 (15), 87 (14). Anal Calcd. for $\text{C}_{15}\text{H}_{12}\text{O}$ C, 86.51; H, 5.81; found C, 86.46; H, 5.75. (Known compound, see: Soler, R. et al., *Synthesis*, **2007**, 19, 3068).

3e: mp: 121.7-122.5 °C; IR (KBr) 2224, 2210, 1595, 1563, 1509, 1291, 1251 cm^{-1} ; ^1H NMR (CDCl_3) δ 7.62–7.56 (q, $J_1 = 8\text{ Hz}$, $J_2 = 8\text{ Hz}$, 4 H), 7.50-7.48 (d, $J = 8\text{ Hz}$, 2 H), 6.92-6.90 (d, $J = 8\text{ Hz}$, 2 H), 3.84 (s, 3 H); ^{13}C NMR (CDCl_3) δ 160.4, 133.4, 132.1, 131.9, 128.7, 118.7, 114.3, 114.2, 111.0, 94.2, 86.8, 55.4, MS m/z (relative intensity) 233 (M^+ , 100), 218 (47), 190 (49), 163 (15). Anal Calcd. for $\text{C}_{16}\text{H}_{11}\text{NO}$ C, 82.38; H, 4.75; found C, 82.32; H, 4.69. (Known compound, see: Mori, A. et al., *J. Org. Chem.*, **2000**, 65, 1780).

3f: mp: 77.6-78.5 °C; IR (KBr) 2931, 1594, 1508, 1245, 1029 cm^{-1} ; ^1H NMR (CDCl_3) δ 7.54-7.52 (d, $J = 8\text{ Hz}$, 2H), 7.28-7.19 (m, 3H), 6.94-6.91 (d, $J = 8\text{ Hz}$, 2H), 3.86 (s, 3H), 2.56 (s, 3H); ^{13}C NMR (CDCl_3) δ 159.7, 140.0, 133.0, 131.7, 129.5, 128.0, 125.6, 123.4, 115.8, 114.1, 93.4, 87.1, 55.4, 20.8; MS m/z (relative intensity) 222 (M^+ , 100), 207 (45), 179 (69), 152 (35), 89 (22). Anal Calcd for $\text{C}_{16}\text{H}_{14}\text{O}$ C, 86.45; H, 6.35; found C, 86.51; H 6.41. (Known compound, see: Meier, H. et al., *Tetrahedron Lett.*, **1976**, 3, 171).

3g: mp: 129.5-130.4 °C; IR (KBr) 2360, 2230, 1605, 1503, 1431, 1339, 1115 cm^{-1} ; ^1H NMR (CDCl_3) δ 7.82 (s, 1H), 7.74–7.72 (d, $J = 8\text{ Hz}$, 1 H), 7.68-7.62 (dd, $J_1 = 8\text{ Hz}$, $J_2 = 8\text{ Hz}$ 5 H), 7.54-7.50 (t, 1 H); ^{13}C NMR (CDCl_3) δ 134.8, 132.2, 132.1, 131.8-130.7 (q, $J_1 = 15\text{ Hz}$, $J_2 = 15\text{ Hz}$), 129.1, 128.7-128.5 (q, $J_1 = 20\text{ Hz}$, $J_2 = 20\text{ Hz}$), 127.7-119.6 (q, $J_1 = 270\text{ Hz}$, $J_2 = 270\text{ Hz}$), 127.5, 125.7- 125.6 (q, $J_1 = 10\text{ Hz}$, $J_2 = 10\text{ Hz}$), 123.3, 118.4, 112.1 MS m/z (relative intensity) 271 (M^+ , 100), 250 (7), 231(3), 69 (76), 50 (33). Anal Calcd. for $\text{C}_{16}\text{H}_8\text{F}_3\text{N}$ C, 70.85; H, 2.97; found C, 70.79; H, 2.91.

3h: mp: 88.1-89.0 °C; IR (KBr) 2361, 2224, 1686, 1602, 1402, 1356, 1263 cm^{-1} ; ^1H NMR (CDCl_3) δ 7.96-7.94 (d, $J = 8\text{ Hz}$, 2H), 7.65-7.60 (m, 6H); ^{13}C NMR (CDCl_3) δ 197, 136.9, 132.3, 132.2, 131.9, 128.4, 127.6, 126.9, 118.4, 112.1, 92.7, 90.6, 26.67 MS m/z (relative intensity) 245 (M^+ , 45),

229 (100), 201 (33), 175 (29), 151 (17). Anal Calcd. for $C_{17}H_{11}NO$ C, 83.25; H, 4.52; found C, 83.19; H, 4.46. (Known compound, see: Mori, A. et al., *J. Org. Chem.*, **2000**, *65*, 1780).

3i: mp: 80.3-81.4 °C; IR (KBr) 3455, 2923, 2235, 1604, 1504, 1033 cm^{-1} ; 1H NMR ($CDCl_3$) δ 7.63–7.61 (d, J = 8 Hz, 2H), 7.54-7.52 (d, J = 8 Hz, 2H), 4.54 (s, 2 H), 1.82 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 132.2, 132.1, 127.5, 118.4, 111.9, 91.7, 84.1, 51.5. Anal Calcd. for $C_{10}H_7NO$ C, 76.42; H, 4.49; found C, 76.44; H, 4.52. (Known compound, see: Santelli, M. et al., *Tetrahedron Lett.*, **2004**, *45*, 1603).

3j: Oil; IR (neat) 3390, 2979, 1606, 1509, 1250, 1169 cm^{-1} ; 1H NMR ($CDCl_3$) δ 7.37–7.35 (d, J = 8 Hz, 2 H), 6.85-6.83 (d, J = 8 Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 159.6, 133.1, 114.8, 113.9, 92.5, 82.0, 65.7, 55.3, 31.6, MS m/z (relative intensity) 190 (M^+ , 4), 172 (32), 157 (66), 128 (18), 51 (100). Anal Calcd for $C_{12}H_{14}O_2$ C, 75.76; H, 7.42; found C, 75.79; H, 7.46. (Known compound, see: Capretta, A. et al., *J. Org. Chem.*, **2004**, *69*, 5082).

3k: Oil; IR (neat) 3425, 2981, 2931, 1606, 1509, 1247 cm^{-1} ; 1H NMR ($CDCl_3$) δ 7.78-7.765 (d, J = 8 Hz, 2 H), 7.48-7.40 (m, 4 H), 7.36-7.32 (m, 1 H), 6.89-6.87 (d, J = 8 Hz, 2 H), 3.84 (s, 3 H), 2.62 (s, 1H), 1.89 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 159.7, 145.9, 133.2, 128.4, 127.7, 125.1, 114.7, 114.0, 91.2, 84.9, 70.5, 55.4, 33.5 MS m/z (relative intensity) 252 (M^+ , 3), 234 (18), 219 (30), 191 (38), 159 (20), 78 (100). Anal Calcd for $C_{17}H_{16}O_2$ C, 80.93; H, 6.39; found C, 80.87; H, 6.33. (Known compound, see: Maleczka jr, R. E. et al., *J. Org. Chem.*, **2003**, *68*, 6775).

3l: mp: 82.2-83.1 °C; IR (KBr) 3379, 2941, 2854, 1664, 1600 cm^{-1} ; 1H NMR ($CDCl_3$) δ 7.86-7.84 (d, J = 8 Hz, 2 H), 7.47-7.45 (d, J = 8 Hz, 2 H), 2.84 (s, 1 H), 2.57 (s, 3 H), 2.02-2.00 (d, J = 8Hz, 2H), 1.75-1.54 (m, 7 H); ^{13}C NMR ($CDCl_3$) δ 197.5, 136.1, 131.8, 128.2, 127.9, 96.6, 83.5, 69.0, 39.9, 26.6, 25.3, 23.4, MS m/z (relative intensity) 242 (M^+ ,), 131 (100), 103 (83), 77 (68). Anal Calcd for $C_{16}H_{18}O_2$ C, 79.31; H, 7.49; found C, 79.33; H, 7.53. (Known compound, see: Srinivasan, K. V. et al., *J. Org. Chem.*, **2005**, *70*, 4869).

3m: mp: 94.7-95.6 °C; IR (KBr) 1679, 1602, 1403, 1359, 1263 cm^{-1} ; 1H NMR ($CDCl_3$) δ 7.96–7.94 (d, J = 8 Hz, 2H) , 7.63–7.61 (d, J = 8Hz, 2H), 7.58-7.56 (m, 2H), 7.39-7.37 (m, 3H);

^{13}C NMR (CDCl_3) δ 197.3, 136.3, 131.8, 131.7, 128.8, 128.5, 128.3, 128.2, 122.7, 92.8, 88.7, 26.6, MS m/z (relative intensity) 220 (M^+ , 6), 205 (10), 176 (74), 150 (40), 126 (20). Anal Calcd for $\text{C}_{16}\text{H}_{12}\text{O}$ C, 87.25; H, 5.49; found C, 87.27; H, 5.53. (Known compound, see: Soler, R. et al., *Synthesis*, **2007**, *19*, 3068).

Recycling procedure: The mixture was cooled at room temperature, centrifuged (3000 rpm \times 20 min.) and the solution was pipetted. Then, the solid supported palladium was washed with methanol (4×3 mL), the resulting suspension was centrifuged and the solvent was decanted each time. The recovered solid material was dried under high vacuum at 60 °C for 2 h and reused.