Room Temperature Ni(0)-Catalyzed Cross Coupling Reactions of Aryl Arenesulfonates with Arylboronic Acids

Zhen-Yu Tang and Qiao-Sheng Hu*

Department of Chemistry
College of Staten Island and the Graduate Center of the City University of New York,
Staten Island, New York 10314

Supporting Information

General:

NMR spectra were recorded on Varian 200 MHz or 600 MHz spectrometers. Elemental analyses were performed by AtlanticMicro Analysis, Inc., Norcross, GA. IR spectra were recorded on a Nicolet Magna-IR spectrometer. All yields reported refer to isolated yields (average of two runs) unless otherwise indicated, and the product purity was estimated to be greater than 95% as determined by ^{1}H NMR. Compounds described in the literature were characterized by comparison of their melting points, ^{1}H NMR and ^{13}C NMR spectra to reported data. New compounds were also characterized by elemental analysis.

THF were dried with sodium/benzophenone. $Pd(OAc)_2$, $Ni(COD)_2$, $NiCl_2$, phenylboronic acid, PPh_3, PCy_3, *n*-Bu_3P, *i*-Bu_3P, *t*-Bu_3P, DPPF, DPPE, and potassium fluoride were purchase from Strem and used directly. $Ni(PCy_3)_2Cl_2$ was prepared according to the reported procedure.[1] Other chemical reagents were purchase from Aldrich and used directly.

General procedure for the preparation of aryl arenesulfonates:[2]

To a solution of phenol (20 mmol) in dichloromethane (80 ml), 15 ml of triethylamine and 0.4 mmol of trimethylamine hydrochloride was added *p*-toluenesulfonyl chloride or benzenesulfonyl chloride (24 mmol) portionwise at room temperature. After stirring overnight, 25 ml of water was added to the mixture and the mixture was stirred for 3 h. The mixture was extracted with ethyl acetate (200 ml) and the organic layer was washed with water (150 ml), 10% aqueous HCl (150 ml) three times, water (150 ml) twice, saturated aqueous $NaHCO_3$ (twice) and brine (100 ml, twice), and dry over Na_2SO_4. The solvent was evaporated under vacuum. Flash chromatography on silica gel (hexane: ethyl acetate = 95: 5 to 80: 20) yielded the aryl arenesulfonates.

4-Methylphenyl tosylate. 4.12 g (79%), white solid, m. p.: 58-60 $^{\circ}$C. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.700 (d, J=8.2 Hz, 2H), 7.303 (d, J=8 Hz, 2H), 7.065 (d, J=8.8 Hz, 2H), 6.848 (d, J=4.2 Hz, 2H), 2.447 (s, 3H), 2.304 (s, 3H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 147.476, 145.185, 136.911, 132.516, 130.054, 129.677, 128.517, 122.046, 21.687, 20.855.

2-Naphthyl tosylate. 4.77 g (80%), white solid: m. p.: 122-124 $^{\circ}$C. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.797 (d, J=9.6 Hz, 1H), 7.745~7.713 (m, 4H), 7.478~7.467 (m, 3H),

---

[1] Barnett, K. W. *J. Chem. Educ.* **1974**, *51*, 422-423.

[2] (a) Zim, D.; Lando, V. R.; Dupont, J.; Monteiro, A. L. *Org. Lett.* **2001**, *3*, 3049-3051. (b) Huang, X.; Anderson, K. W.; Zim, D.; Jiang, L.; Klapars, A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2003**, *125*, 6653-6655.

7.280 (d, J=8.4 Hz, 2H), 7.091 (d, J=9.6 Hz, 1H), 2.424 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 147.210, 145.387, 133.441, 132.470, 131.882, 129.777, 129.473, 128.549, 127.868, 127.746, 126.848, 126.375,121.164, 119.939, 21.695.

4-Methoxyphenyl tosylate. 5.3 g (96%), white solid: m. p.: 69-71 °C. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.681 (d, J=8.4 Hz, 2H), 7.297 (d, J=7.8 Hz, 2H), 6.873 (d, J=8.4 Hz, 2H), 6.763 (d, J=8.4 Hz, 2H), 3.756 (s, 3H), 2.440 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 158.183, 145.240, 143.066, 132.342, 129.692, 128.546, 123.331, 114.453, 55.534, 21.682.

2-Methylphenyl tosylate. 5.0 g (91 %), white solid: m. p.: 48-49 °C.^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.736 (d, J=8.4 Hz, 2H), 7.315 (d, J=8.4 Hz, 2H), 7.147~7.108 (m, 3H), 6.989 (d, J=7.2Hz, 1H), 2.449 (s, 3H), 2.074(s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 148.334, 145.283, 133.021, 131.579, 131.541, 129.760, 128.365, 126.932, 126.862, 122.270, 21.674, 16.254.

2-Trifluoromethyphenyl tosylate. 5.7 g (90%), white solid. m. p.: 62-64 °C. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.707 (d, J=8.4, 2H), 7.543~7.396 (m, 2H), 7.335 (d, J=9.4 Hz, 2H), 7.244~7.185 (m, 2H), 2.458(s, 3H). ^{13}C NMR ($CDCl_3$, 50.31MHz) δ 149.848, 146.139, 132.390(q, J = 33.0 Hz), 132.148, 130.517, 130.123, 128.735, 126.210, 124.071 (d, J=3.8 Hz), 119.938 (d, J=3.8 Hz), 21.876. Anal. calcd for $C_{14}H_{11}SO_3F_3$: C, 53.20%; H, 3.48%. Found: C, 53.46%; H, 3.76%.

4-Acetylphenyl tosylate. 5.9 g (95%), white solid. m. p.: 67-69 °C. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.897 (d, J=8.4 Hz, 2H), 7.711 (d, J=8.4 Hz, 2H), 7.326 (d, J=8.4 Hz, 2H), 7.087 (d, J=8.4 Hz, 2H), 2.573 (s, 3H), 2.454 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 196.624, 152.957, 145.784, 135.678, 132.094, 130.028, 129.917, 128.442, 122.472, 26.583, 21.709.

Phenyl tosylate. 3.45 g (70%), white solid. m. p.: 90-92 °C. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.693 (d, J=8.4 Hz, 2H), 7.304 ~ 7.219 (m, 5H), 6.974 (d, J=9.6 Hz, 2H), 2.437(s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 149.624, 145.344, 132.344, 129.726, 129.589, 128.483, 127.075, 122.364, 21.691.

4-Methoxyphenyl benzenesulfonate. 4.36 g (82%), white solid. m. p.: 42-44 °C.^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.812 (d, J=9.6 Hz, 2H), 7.661~7.624 (m, 1H), 7.550 ~ 7.476 (m, 2H), 6.866 (d, J=9.4 Hz, 2H), 6.765 (d, J=9.4 Hz, 2H), 3.754(s, 3H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 158.516, 143.258, 135.651, 134.339, 129.304, 128.758, 123.518, 114.744, 55.774.

4-Methylphenyl benzenesulfonate. 4.47 g (90%), white solid: m. p.: 36-38 °C. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.817 (d, J=4.2 Hz, 2H), 7.691~7.607 (m, 1H), 7.542~7.460 (m, 2H), 7.065 (d, J=8.8 Hz, 2H), 6.837 (d, J=8.6, 2H), 2.289 (s, 3H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 147.686, 137.274, 135.780, 134.339, 130.335, 129.311, 128.712, 122.228, 114.744, 21.064. Anal. calcd. for $C_{13}H_{12}SO_3$: C, 62.90%; H, 4.84%. Found: C, 63.19%; H, 4.97%.

General procedure for the Suzuki-Miraura couplings of aryl arenesulfonates:

In a glove box with N_2-atmosphere, to a mixture of phenylboronic acid (0.75 mmol), potassium phosphate (1.5 mmol) and 2 ml THF (in a vial) were added bis(1,5-cyclopentadiene) nickel(0)(4.2 mg, 0.015 mmol) and tricyclohexylphosphine (16.8 mg, 0.06 mmol). After stirred for 5-10 minutes, aryl tosylate or aryl benzenesulfonate

(0.5 mmol) was added. The mixture was allowed to stir for 8 hours. After quchening with water, the reaction mixture was extracted with ethyl acetate. The organic layer was washed with brine and the solvent was evaporated under vacuum. Flash chromatography on silica gel (hexane: ethyl acetate = 100 : 0 to 85: 15) yielded the cross-coupling products:[3]

4-Methylbiphenyl. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.566 (d, J=8.4 Hz, 2H), 7.484 (d, J=6.6 Hz, 2H), 7.409 (t, J=14.4 Hz, 2H), 7.320~7.296 (m, 1H), 7.236 (d, J=7.2 Hz, 2H), 2.381 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 141.174, 138.369, 137.035, 129.501, 128.736, 127.015, 126.994, 21.125.

4-Methoxylbiphenyl. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.550~7.507 (m, 4H), 7.402 (t, J=7.8 Hz,2H), 7.291 (t, J=7.2 Hz, 1H), 6.966 (d, J=8.4 Hz, 2H), 3.829 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 159.144, 140.822, 133.766, 128.736, 128.163, 126.745, 126.668, 114.205, 55.336.

4-Acetylbiphenyl. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 8.023 (d, J=8.4 Hz, 2H), 7.675 (d, J=7.8 Hz, 2H), 7.619 (d, J=9 Hz, 2H), 7.463 (t, J=8.4 Hz, 2H), 7.394 (t, J=7.2 Hz, 1H), 2.626 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 197.771, 145.755, 139.836, 135.816, 128.953, 128.911, 128.234, 127.258, 127.205, 26.662.

2-Phenylnaphthalene. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 8.033 (s, 1H), 7.891 (t, J=9 Hz, 2H), 7.851 (d, J=7.8 Hz, 1H), 7.738 (dd, J=8.4, 1.8 Hz, 1H), 7.714 (d, J=8.4 Hz, 2H), 7.502 ~ 7.456 (m, 4H), 7.368 (t, J=7.8 Hz, 1H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 166.369, 141.138, 138.565, 133.685, 132.625, 128.876, 128.434, 128.216, 127.661, 127.451, 127.366, 126.303, 125.948, 125.818, 125.615.

2-Methylbiphenyl. ^{1}H NMR ($CDCl_3$, 600 MHz) δ 7.421 ~ 7.395 (m, 2H), 7.347 ~7.316 (m, 3H), 7.275 ~ 7.255 (m, 2H), 7.241 ~ 7.229 (m, 2H), 2.273 (s, 3H). ^{13}C NMR ($CDCl_3$, 150.868 MHz) δ 141.942, 141.914, 135.335, 130.291, 129.785, 129.181, 128.051, 127.233, 126.745, 125.745, 20.465.

Biphenyl ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.612 ~ 7.556 (m, 4H), 7.471 ~ 7.327 (m, 6H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 141.513, 128.993, 127.491, 127.416.

4-Methoxy-4'-methyl-biphenyl. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.494(d, J = 9.0 Hz, 2H), 7.436 (d, J = 8.2 Hz, 2H), 7.206 (d, J=8.0 Hz, 2H), 6.946 (d, J=8.8, 2H), 3.814 (s, 3H), 2.366 (s, 3H).). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 159.221, 138.237, 136.569, 134.021, 129.683, 128.189, 126.824, 114.433, 55.554, 21.277.

4,4'-dimethylbiphenyl. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.466 (d, J=7.6 Hz, 4H), 7.215 (d, J=7.8 Hz, 4H), 2.372 (s, 6H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 138.579, 136.925, 129.698, 127.067, 21.315.

4-Methoxy-2'-methylbiphenyl. ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.273 ~7.208 (m, 6H), 6.948 (d, J=8.8, 2H), 3.850 (s, 3H), 2.276 (s, 3H). ^{13}C NMR ($CDCl_3$, 50.31 MHz) δ 158.834, 141.855, 135.727, 134.688, 130.555, 130.510, 130.168, 127.234, 126.013, 113.796, 55.509, 20.776.

---

[3] (a) Wolfe, J. P; Singer, R. A.; Yang, B. H.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121,* 9550 - 9561. (b) Littke, A. F.; Dai, C.; Fu, G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020-4028.

2, 4'-Dimethylbiphenyl. ^{1}H NMR (CDCl$_3$, 200 MHz) δ 7.228~ 7.211 (m, 8H), 2.393 (s, 3H), 2.269 (s, 3H). ^{13}C NMR (CDCl$_3$, 50.31 MHz) δ 142.166, 139.329, 136.599, 135.636, 130.525, 130.108, 129.327, 129.023, 127.317, 125.990, 21.406, 20.738.

2-(4-Methoxyphenyl)naphthalene. ^{1}H NMR (CDCl$_3$, 200 MHz) δ 7.979 (s, 1H), 7.894 ~ 7.812 (m, 3H), 7.724 ~ 7.623 (m, 3H), 7.486 ~ 7.429 (m, 2H), 7.003 (d, J=8.8 Hz, 2H), 3.848 (s, 3H). ^{13}C NMR (CDCl$_3$, 50.31 MHz) δ 159.524, 138.412, 134.028, 133.892, 132.588, 128.659, 128.583, 128.295, 127.863, 126.460, 125.876, 125.679, 125.269, 114.584, 55.607.

3-Trifluoromethybiphenyl. ^{1}H NMR (CDCl$_3$, 200 MHz) δ 7.828 (s, 1H), 7.743 (d, J=7 Hz, 1H), 7.605 ~ 7.556 (m, 4H), 7.523~7.373 (m, 3H). ^{13}C NMR (CDCl$_3$, 50.31 MHz) δ 142.317, 140.035, 132.633, 131.469(q, J=32.2 Hz), 130.669, 129.463, 128.243, 128.280, 127.438, 124.182(q, J=3.8 Hz), 121.796.

Oxidative addition intermediate of 4-methoxyphenyl tosylate with Ni(0): **Preparative synthesis:**

In a glove-box with N$_2$ atmosphere, to a solution of bis(1,5-cyclopentadiene)nickel(0) (275 mg, 1.0 mmol), tricyclohexylphosphine (1.08 g, 4 mmol, 4 equiv.) in THF (5 ml) was added 4-methoxyphenyl tosylate (278 mg, 1.0 mmol) while stirring. The resulting solution turned into red immediately and was allowed to stir for overnight. After filtration, the solvent was evaporated. The residue was mixed with hexanes (N$_2$ degassed) for 5- 10 min and hexanes was pippetted out. This process was repeated for 5 more times. After drying under vacuum, the oxidative addition product was obtained as a yellow solid, 500 mg (56% yield). ^{1}H NMR (benzene-*d$_6$*, 200 MHz) δ 8.045 (d, J=7.8 Hz, 2H), 7.499 (d, J=8.0 Hz, 2H), 6.896 (d, J=8.2 Hz, 2H), 6.627 (d, J=8.2 Hz, 2H), 3.405 (s, 3H), 2.203 (br.s, 12 H), 1.975 (s, 3H), 1.712 ~ 1.221 (m, 54 H). ^{13}C NMR (benzene-*d$_6$*, 150.9 MHz) δ 157.171, 143.736, 139.710, 139.004, 128.690, 127.314, 121.184 (t, J=35.5 Hz), 112.675, 55.150, 34.294, 30.369, 27.943, 26.876, 21.066. ^{31}P NMR (benzene-*d$_6$*, 90 MHz, H$_3$PO$_4$ as standard, δ_{PCy3} = 11.046) δ 11.641(br.s). IR (KBr, cm^{-1}): 2924.8 (s), 2850.2(s), 1600.0(w), 1477.1(m), 1446.2(m), 1261.3(m), 1228.5(m), 1162.4(s), 1110.8(m), 1029.1(m), 1005.6(s), 915.1(w), 890.5(w), 849.6(w), 813.6(m), 675.0(m), 567.9(m). Anal. calcd for $C_{50}H_{80}P_2SO_4Ni$: C, 66.91; H, 8.92; O, 7.13. Found: C, 66.92; H, 9.18; O, 6.97.

NMR study:

Oxidative addition of 4-methoxyphenyl tosylate with Ni(0): In a glove-box with N$_2$ atmosphere, to a solution of bis(1,5-cyclopentadiene)nickel(0) (33 mg, 0.12 mmol), tricyclohexylphosphine (134 mg, 0.48 mmol) in THF-*d$_8$* (0.75 ml) was added 4-methoxyphenyl tosylate (33 mg, 0.12 mmol) while stirring. 50 or 100 μL of the resulting solution was taken every 5 or 10 minutes for ^{1}H NMR analysis (benzene-*d$_6$* as NMR solvent). ^{1}H NMR showed that 67% conversion was observed in 15 minutes and 94% conversion after 4 h.

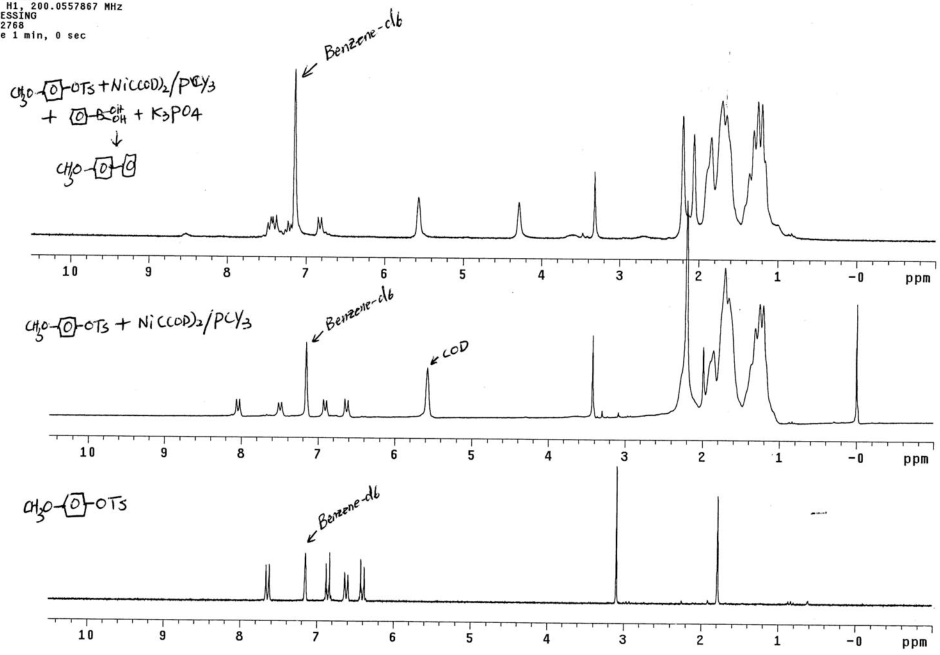
Transmetallation/reductive elimination steps: After 4 hours, when the oxidative addition was completed, phenylboronic acid (8.8 mg, 0.048 mmol, 1.5 eq.) and potassium phosphate (44 mg, 0.096 mmol, 3 eq.) were added to the remaining solution. 50 ~ 100 μL was taken every 5 or 10 minutes for ^{1}H NMR analysis (benzene-*d$_6$* as NMR solvent). The intermediate was completely converted to the coupling product in 60 mins.

$Ni(COD)_2/PCy_3$-catalyzed cross-coupling of 4-methoxyphenyl tosylate with phenylboronic acid in the presence of K_3PO_4: In a glove-box with N_2 atmosphere, to a mixture of bis(1,5-cyclopentadiene)nickel(0) (33 mg, 0.12 mmol), tricyclohexylphosphine (134 mg, 0.48 mmol), phenylboronic acid(22mg, 0.18 mmol), and potassium phosphate (77 mg, 0.36 mmol, 3 eq.) in THF-d_8 (0.75 ml) was added 4-methoxyphenyl tosylate (33 mg, 0.12 mmol) while stirring. 50 or 100 μL of the resulting solution was taken every 5 minutes for ^{1}H NMR analysis (benzene-*d6* as NMR solvent). Complete conversion was observed for 4-methoxyphenyl tosylate in 10 minutes with oxidative addition product as the intermediate. After 30 minutes, all the intermediates have been converted to the coupling product.

```
STANDARD 1H OBSERVE

Pulse Sequence: s2pul
 Solvent: Benzene
 Ambient temperature
UNITY-200  "u200"

 Pulse 31.5 degrees
 Acq. time 3.744 sec
 Width 3000.1 Hz
 16 repetitions
OBSERVE   H1, 200.0557867 MHz
DATA PROCESSING
FT size 32768
Total time 1 min, 0 sec
```



```
STANDARD 1H OBSERVE

Pulse Sequence: s2pul
 Solvent: Benzene
 Ambient temperature
UNITY-200  "u200"

 Pulse 31.5 degrees
 Acq. time 3.744 sec
 Width 3000.1 Hz
 16 repetitions
OBSERVE   H1, 200.0557867 MHz
DATA PROCESSING
FT size 32768
Total time 1 min, 0 sec
```