Copper-Catalyzed Direct Oxidative Annulation of N-Iminopyridinium Ylides with Terminal Alkynes Using O₂ as Oxidant

(Supporting Information)

Shengtao Ding,† Yuepeng Yan,† and Ning Jiao*,‡

† State Key Laboratory of Natural and Biomimetic Drugs, School of Pharmaceutical Sciences, Peking University, Xue Yuan Rd. 38, Beijing 100191, China,
‡ State Key Laboratory of Organometallic Chemistry, Chinese Academy of Sciences, Shanghai 200032, China.
E-mail: jiaoning@bjmu.edu.cn
Fax: (+86)10-82805297

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General Information

All manipulations were conducted with a standard Schlenk technique under oxygen atmosphere (1 atm). $^1$H-NMR spectra were recorded with a Bruker AVIII-400 spectrometer. Chemical shifts (in ppm) were referenced to tetramethylsilane ($\delta = 0$ ppm) in CDCl$_3$ as an internal standard. $^{13}$C-NMR spectra were obtained by the same NMR spectrometer and were calibrated with CDCl$_3$ ($\delta = 77.00$ ppm). Mass spectra were recorded by PE SCLEX QSTAR spectrometer. Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Compounds 1a,$^1$ 1b – 1f$^2$ were synthesized according to related literatures.
**Table S1.** Optimization of the reaction conditions.\(^a\)

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\(^a\) General condition: 1a (0.2 mmol), 2a (0.6 mmol), additives, solvent (2 mL) under O\(_2\) (1 atm) for 48 h. \(^b\) Isolated yields. \(^c\) The reaction was carried out under 100 °C. \(^d\) The reaction was carried out under air.

**Scheme S1.** Kinetic isotope effect experiment.
Experimental procedures and characterization of products

1. 2-Phenylpyrazolo[1,5-\(a\)]pyridine (3a) \(^3\)

Typical procedure: Substrate 1a (39.6 mg, 0.20 mmol), CuI (3.8 mg, 10 mol %), Ag\(_2\)CO\(_3\) (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv) were added to a 20 mL Schlenk tube under O\(_2\), followed by addition of 2a (66 \(\mu\)l, 0.60 mmol) and PhCl (2.0 mL). The formed mixture was stirred at 125 °C under O\(_2\) (1 atm.) for 48 h as monitored by TLC. The solution was then cooled to rt., diluted with ethyl acetate (15 mL), and evaporated under vaccum. The crude product was purified by column chromatography on silica gel (hexane : ethyl acetate = 10:1) to afford 29.3 mg (74%) of product 3a: light yellow solid; m.p. 95-97 °C (\(n\)-hexane/ethyl acetate); IR: (KBr) \(\nu\)\(_{max}\) 1944, 1889, 1632, 1512, 1470, 1332, 762 cm\(^{-1}\); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \(\delta\) 8.46 (d, \(J = 7.2\) Hz, 1 H), 7.96 (d, \(J = 8.0\) Hz, 2 H), 7.51-7.42 (m, 3 H), 7.36 (t, \(J = 7.2\) Hz, 1 H), 7.06 (t, \(J = 8.0\) Hz, 1 H), 6.78 (s, 1 H), 6.71 (dt, \(J = 1.2, 7.2\) Hz, 1 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \(\delta\) 153.5, 141.6, 133.2, 128.7, 128.5, 128.4, 126.4, 123.4, 117.9, 111.6, 93.7; MS (EI) \(m/z\) (relative intensity) 194.1 (100) \([M]^{+}\).

2. 2-o-Tolylpyrazolo[1,5-\(a\)]pyridine (3b) \(^3\)

The reaction of 1a (39.6 mg, 0.20 mmol), 1-ethynyl-2-methylbenzene (78 \(\mu\)l, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag\(_2\)CO\(_3\) (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 34.2 mg (82%) of 3b: light beige solid; m.p. 70-73 °C (\(n\)-hexane/ethyl acetate); IR: (KBr) \(\nu\)\(_{max}\) 1752, 1633, 1520, 1508, 1461, 1329, 1251, 762 cm\(^{-1}\); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \(\delta\) 8.47 (d, \(J = 7.2\) Hz, 1 H), 7.67 (t, \(J = 3.6\) Hz, 1 H), 7.50 (d, \(J = 9.2\) Hz, 1 H), 7.30-7.23 (m, 3 H), 7.08 (t, \(J = 8.0\) Hz, 1 H), 6.72 (t, \(J = 7.2\) Hz, 1 H), 6.62 (s, 1 H), 2.53 (s, 3 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \(\delta\) 154.0, 140.7, 136.4, 133.1, 130.8, 129.9, 128.4, 128.1, 125.8, 123.2, 117.8, 111.4, 96.9, 21.1; MS (EI) \(m/z\) (relative intensity) 208.2 (82), 207.2 (100) \([M]^{+}\).
3. **2-m-Tolylpyrazolo[1,5-a]pyridine (3c)**

The reaction of 1a (39.6 mg, 0.20 mmol), 1-ethynyl-3-methylbenzene (81 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 33.9 mg (81%) of 3c: light yellow solid; m.p. 87-88 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1755, 1634, 1520, 1467, 1419, 1331, 1256, 772, 733 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.46 (d, J = 6.8 Hz, 1 H), 7.81 (s, 1H), 7.74 (d, J = 8.0 Hz, 1 H), 7.48 (d, J = 9.2 Hz, 1 H), 7.34 (t, J = 7.6 Hz, 1 H), 7.18 (d, J = 7.2 Hz, 1 H), 7.06 (t, J = 7.6 Hz, 1 H), 6.77 (s, 1 H), 6.70 (t, J = 6.8 Hz, 1 H), 2.42 (s, 3 H); ¹³C NMR: (100 MHz, CDCl₃) δ 153.7, 141.6, 138.3, 133.1, 129.2, 128.6, 128.4, 127.0, 123.6, 123.3, 117.8, 111.6, 93.7, 21.4; MS (EI) m/z (relative intensity) 208.2 (100) [M]+. HRMS m/z (ESI) calcd. for C₁₄H₁₃N₂ (M + H)+ 209.1073, found 209.1077.

4. **2-p-Tolylpyrazolo[1,5-a]pyridine (3d)**

The reaction of 1a (39.6 mg, 0.20 mmol), 1-ethynyl-4-methylbenzene (78 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 31.6 mg (76%) of 3d: light yellow solid; m.p. 106-108 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1909, 1633, 1514, 1474, 1331, 1255, 825, 778, 763 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.45 (d, J = 6.8 Hz, 1 H), 7.85 (d, J = 8.0 Hz, 2 H), 7.48 (d, J = 8.8 Hz, 1 H), 7.25 (d, J = 7.2 Hz, 2 H), 7.06 (t, J = 8.0 Hz, 1 H), 6.75 (s, 1 H), 6.70 (t, J = 6.4 Hz, 1 H), 2.39 (s, 3 H); ¹³C NMR: (100 MHz, CDCl₃) δ 153.6, 141.6, 138.3, 130.4, 129.4, 128.5, 126.3, 123.3, 117.8, 111.5, 93.4, 21.3; MS (EI) m/z (relative intensity) 208.2 (100) [M]+.

5. **2-(4-tert-Butylphenyl)pyrazolo[1,5-a]pyridine (3e)**

The reaction of 1a (39.6 mg, 0.20 mmol), 1-tert-butyl-4-ethynylbenzene (84 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 36.5 mg (73%) of 3e:
white solid; m.p. 108-110 °C (n-hexane/ethyl acetate); IR: (KBr) ν max 1918, 1751, 1632, 1513, 1473, 1328, 841, 776 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.46 (d, J = 6.8 Hz, 1 H), 7.89 (d, J = 8.4 Hz, 2 H), 7.49-7.45 (m, 3 H), 7.08-7.02 (m, 1 H), 6.76 (s, 1 H), 6.69 (t, J = 6.8 Hz, 1 H), 1.36 (s, 9 H); 13C NMR: (100 MHz, CDCl₃) δ 153.6, 151.4, 141.6, 130.4, 128.5, 126.2, 125.6, 123.3, 117.8, 111.4, 93.5, 34.6, 31.3; MS (EI) m/z (relative intensity) 250.2 (36), 235.2 (100) [M⁺]; HRMS m/z (ESI) calcd. for C₁₇H₁₉N₂ (M + H)⁺ 251.1543, found 251.1548.

6. 2-(4-Methoxyphenyl)pyrazolo[1,5-a]pyridine (3f)³,⁴

The reaction of 1a (39.6 mg, 0.20 mmol), 1-ethynyl-4-methoxybenzene (82 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 31.3 mg (70%) of 3f: white solid; m.p. 111-114 °C (n-hexane/ethyl acetate); IR: (KBr) ν max 2363, 1858, 1631, 1613, 1514, 1463, 1246, 1029, 772 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.44 (d, J = 6.4 Hz, 1 H), 7.89 (d, J = 8.8 Hz, 2 H), 7.46 (d, J = 9.2 Hz, 1 H), 7.05 (t, J = 7.6 Hz, 1 H), 6.98 (d, J = 9.2 Hz, 2 H), 6.80-6.66 (m, 2 H), 3.84 (s, 3 H); 13C NMR: (100 MHz, CDCl₃) δ 159.9, 153.4, 141.6, 128.4, 127.7, 125.9, 123.3, 117.7, 114.1, 111.3, 93.0, 55.3; MS (EI) m/z (relative intensity) 224.2 (100), 209.1 (56) [M⁺].

7. 2-(4-Bromophenyl)pyrazolo[1,5-a]pyridine (3g)

The reaction of 1a (39.6 mg, 0.20 mmol), 1-bromo-4-ethynylbenzene (108.6 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 44.9 mg (82%) of 3g: white solid; m.p. 174-177 °C (n-hexane/ethyl acetate); IR: (KBr) ν max 2851, 1727, 1634, 1506, 1467, 1427, 1069, 1010, 775 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.44 (d, J = 6.4 Hz, 1 H), 7.82 (d, J = 8.4 Hz, 2 H), 7.56 (d, J = 8.0 Hz, 2 H), 7.49 (d, J = 8.8 Hz, 1 H), 7.11-7.05 (m, 1 H), 6.76-6.71 (m, 2 H); ¹³C NMR: (100 MHz, CDCl₃) δ 152.4, 141.7, 132.2, 131.8, 128.5, 128.0, 123.6, 122.4, 117.9, 111.9, 93.7; MS (EI)
m/z (relative intensity) 272.1 (7), 192.0 (12), 117.0 (20), 62.6 (100) [M]+; HRMS m/z (ESI) calcd. for C_{13}H_{10}N_{2}Br (M + H)^+ 273.0022, found 273.0029.

8. 2-(4-Chlorophenyl)pyrazolo[1,5-a]pyridine (3h)

The reaction of 1a (39.6 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag_2CO_3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 40.5 mg (89%) of 3h: light yellow solid; m.p. 158-160 °C (n-hexane/ethyl acetate); IR: (KBr) \( \nu \) max 1899, 1634, 1508, 1469, 1090, 1012, 774 cm\(^{-1}\); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \( \delta \) 8.45 (d, \( J = 7.2 \) Hz, 1 H), 7.89 (d, \( J = 8.4 \) Hz, 2 H), 7.50 (d, \( J = 9.2 \) Hz, 1 H), 7.41 (d, \( J = 8.0 \) Hz, 2 H), 7.09 (t, \( J = 8.0 \) Hz, 1 H), 6.76-6.72 (m, 2 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \( \delta \) 152.3, 141.7, 134.2, 131.8, 128.9, 128.4, 127.7, 123.5, 117.9, 111.9, 93.6; MS (EI) m/z (relative intensity) 228.2 (100), 192.1 (31), 62.7 (94) [M]+; HRMS m/z (ESI) calcd. for C\(_{13}\)H\(_{10}\)N\(_{2}\)Cl (M + H)^+ 229.0527, found 229.0532.

9. 2-(2,4-Difluorophenyl)pyrazolo[1,5-a]pyridine (3i)

The reaction of 1a (39.6 mg, 0.20 mmol), 1-ethynyl-2,4-difluorobenzene (85.4 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag_2CO_3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 35.2 mg (77%) of 3i: white solid; m.p. 96-98 °C (n-hexane/ethyl acetate); IR: (KBr) \( \nu \) max 1919, 1896, 1765, 1624, 1601, 1515, 1477, 1265, 1140, 973, 844, 767 cm\(^{-1}\); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \( \delta \) 8.46 (d, \( J = 6.4 \) Hz, 1 H), 8.14 (dd, \( J = 8.4, 15.2 \) Hz, 1 H), 7.52 (d, \( J = 8.8 \) Hz, 1 H), 7.09 (t, \( J = 8.0 \) Hz, 1 H), 7.01-6.85 (m, 3 H), 6.75 (d, \( J = 6.4 \) Hz, 1 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \( \delta \) 162.9 (dd, \( J = 11.8, 213.4 \) Hz), 160.4 (dd, \( J = 12.3, 216.9 \) Hz), 147.2, 141.4, 130.0 (dd, \( J = 4.4, 10.0 \) Hz), 128.3, 123.4, 118.1, 117.6 (dd, \( J = 3.2, 11.3 \) Hz), 112.1, 111.7 (dd, \( J = 3.5, 20.5 \) Hz), 104.4 (t, \( J = 26.1 \) Hz), 97.0 (d, \( J = 10.8 \) Hz); MS (EI) m/z (relative intensity) 230.2 (100) [M]+; HRMS m/z (ESI) calcd. for C\(_{13}\)H\(_{9}\)N\(_{2}\)F\(_{2}\) (M + H)^+ 231.0728, found 231.0733.

10. 2-(3,5-difluorophenyl)pyrazolo[1,5-a]pyridine (3j)
The reaction of 1a (39.6 mg, 0.20 mmol), 3-ethynylthiophene (74 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag2CO3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 29.1 mg (63%) of 3j: white solid; m.p. 99-102 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1919, 1896, 1633, 1602, 1512, 1419, 1115, 989, 763 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.44 (d, J = 7.2 Hz, 1 H), 7.54-7.45 (m, 3 H), 7.14-7.08 (m, 1 H), 6.83-6.73 (m, 3 H); ¹³C NMR: (100 MHz, CDCl₃) δ 163.3 (dd, J = 12.4, 246.6 Hz), 151.3, 141.7, 136.6 (t, J = 9.6 Hz), 128.5, 123.7, 118.1, 112.4, 109.2 (dd, J = 7.8, 19.0 Hz), 103.5 (t, J = 25.3 Hz), 94.1; MS (EI) m/z (relative intensity) 230.2 (100) [M⁺]; HRMS m/z (ESI) calcd. for C₁₃H₉N₂F₂ (M + H)⁺ 231.0728, found 231.0733.

11. 2-(Thiophen-3-yl)pyrazolo[1,5-a]pyridine (3l)

The reaction of 1a (39.6 mg, 0.20 mmol), 3-ethynylthiophene (59 μl, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag2CO3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 25.8 mg (67%) of 3l: white solid; m.p. 115-118 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1630, 1513, 1345, 1326, 1252, 858, 775 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.44 (d, J = 6.8 Hz, 1 H), 7.76 (d, J = 0.4 Hz, 1 H), 7.62 (s, 1 H), 7.59 (d, J = 4.4 Hz, 1 H), 7.48 (d, J = 8.8 Hz, 1 H), 7.39 (s, 1 H), 7.11-7.04 (m, 1 H), 6.72 (t, J = 6.8 Hz, 1 H), 6.67 (s, 1 H); ¹³C NMR: (100 MHz, CDCl₃) δ 149.7, 141.4, 135.0, 128.4, 126.3, 126.0, 123.4, 121.9, 117.7, 111.6, 93.9; MS (EI) m/z (relative intensity) 200.2 (80), 62.7 (100) [M⁺]; HRMS m/z (ESI) calcd. for C₁₁H₉N₂S (M + H)⁺ 201.0481, found 201.0486.

12. 2-(4-Chlorophenyl)-5-benzoylpyrazolo[1,5-a]pyridine (3m)

The reaction of 1b (57.7 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 28.2 mg (42%) of 3m: light yellow solid; m.p. 161-164 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1787, 1733, 1657, 1525, 1320, 1260, 831, 705 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.53 (d, J = 7.0 Hz, 1 H), 7.95 (s,
13. 2-(4-Chlorophenyl)-5-acetylpyrazolo[1,5-a]pyridine (3n)

The reaction of 1c (48.1 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag2CO3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 17.8 mg (33%) of 3n: light yellow solid; m.p. 170-174 °C (n-hexane/ethyl acetate); IR: (KBr) \( \nu \) max 1909, 1866, 1683, 1498, 1476, 1357, 1096, 833, 774 cm \(^{-1} \); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \( \delta \) 8.46 (d, \( J = 7.2 \) Hz, 1 H), 8.14 (s, 1 H), 7.90 (d, \( J = 8.0 \) Hz, 2 H), 7.43 (d, \( J = 8.0 \) Hz, 2 H), 7.32 (d, \( J = 6.0 \) Hz, 1 H), 6.99 (s, 1 H), 2.65 (s, 3 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \( \delta \) 195.6, 153.6, 140.4, 136.8, 136.2, 134.3, 133.9, 133.7, 131.4, 129.9, 128.9, 128.7, 128.6, 127.8, 127.7, 119.9, 109.7, 97.3, 26.2; MS (EI) \( m/z \) (relative intensity) 270.1 (8), 200.2 (16), 49.9 (100) [M]\(^+\); HRMS \( m/z \) (ESI) calcd. for C\(_{13}\)H\(_{12}\)N\(_2\)ClO (M + H\(^+\)) 271.0633, found 271.0631.

14. 2-(4-Chlorophenyl)-7-benzoylpyrazolo[1,5-a]pyridine (3o)

The reaction of 1d (60.2 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag2CO3 (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 26.3 mg (40%) of 3o: light yellow solid; m.p. 140-143 °C (n-hexane/ethyl acetate); IR: (KBr) \( \nu \) max 2225, 1729, 1599, 1524, 1474, 1437, 1334, 1092, 1013, 822, 770 cm \(^{-1} \); \(^1\)H NMR: (400 MHz, CDCl\(_3\)) \( \delta \) 7.86 (d, \( J = 7.2 \) Hz, 2 H), 7.72 (d, \( J = 8.0 \) Hz, 2 H), 7.69-7.58 (m, 2 H), 7.46 (t, \( J = 7.2 \) Hz, 2 H), 7.31 (d, \( J = 8.0 \) Hz, 2 H), 7.18 (t, \( J = 7.6 \) Hz, 1 H), 6.95 (d, \( J = 6.4 \) Hz, 1 H), 6.85 (s, 1 H); \(^{13}\)C NMR: (100 MHz, CDCl\(_3\)) \( \delta \) 189.5, 152.6, 142.3, 136.8, 136.2, 134.3, 133.9, 133.7, 131.4, 129.9, 128.9, 128.7, 128.6, 127.8, 127.7, 120.1, 113.8, 94.2; MS (EI) \( m/z \) (relative
15. 4-Chloro-2-(4-chlorophenyl)pyrazolo[1,5-a]pyridine (3p)

The reaction of 1e (46.6 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 28.4 mg (54%) of 3p & 3q (2.4:1).

3p: light yellow solid; m.p. 157-160 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1899, 1771, 1629, 1510, 1463, 1094, 830, 755 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.37 (d, J = 6.8 Hz, 1 H), 7.90 (d, J = 8.0 Hz, 2 H), 7.14 (d, J = 7.2 Hz, 1 H), 6.90 (s, 1 H), 6.68 (t, J = 7.2 Hz, 1 H); ¹³C NMR: (100 MHz, CDCl₃) δ 152.7, 140.8, 134.6, 131.2, 129.0, 127.8, 123.8, 122.7, 111.3, 94.1; MS (EI) m/z (relative intensity) 262.1 (73), 111.0 (70), 75.1 (100) [M]⁺; HRMS m/z (ESI) calcd. for C₁₃H₉N₂Cl₂ (M + H)⁺ 263.0137, found 263.0143.

3q: light yellow; m.p. 125-128 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1765, 1463, 1245, 800 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.50 (s, 1 H), 7.86 (d, J = 8.0 Hz, 2 H), 7.72 (d, J = 7.6 Hz, 1 H), 7.66 (t, J = 7.2 Hz, 1 H), 7.44-7.37 (m, 5 H), 6.82 (s, 1 H); ¹³C NMR: (100 MHz, CDCl₃) δ 153.0, 140.1, 134.5, 131.3, 129.0, 127.7, 126.6, 125.2, 120.0, 118.1, 94.4; MS (EI) m/z (relative intensity) 262.1 (75), 110.9 (83), 75.1 (100) [M]⁺; HRMS m/z (ESI) calcd. for C₁₃H₉N₂Cl₂ (M + H)⁺ 263.0137, found 263.0142.

16. 2-(4-Chlorophenyl)pyrazolo[1,5-a]quinoline (3r)

The reaction of 1f (49.7 mg, 0.20 mmol), 2b (82.0 mg, 0.60 mmol), CuI (3.8 mg, 10 mol %), Ag₂CO₃ (5.5 mg, 10 mol %), DABCO (44.8 mg, 2.0 equiv), in PhCl (2.0 mL) under oxygen for 48 h afforded 45.5 mg (82%) of 3r: white solid; m.p. 155-158 °C (n-hexane/ethyl acetate); IR: (KBr) νmax 1913, 1614, 1462, 1422, 1090, 812, 753 cm⁻¹; ¹H NMR: (400 MHz, CDCl₃) δ 8.63 (d, J = 8.0 Hz, 1 H), 7.96 (d, J = 7.6 Hz, 2 H), 7.72 (d, J = 7.6 Hz, 1 H), 7.66 (t, J = 7.2 Hz, 1 H), 7.44-7.37 (m, 5 H), 6.82 (s, 1 H);
$^{13}$C NMR: (100 MHz, CDCl$_3$) $\delta$ 151.7, 139.4, 134.8, 134.0, 133.7, 132.0, 129.4, 128.9, 128.3, 127.6, 124.8, 124.6, 123.3, 116.5, 115.6, 96.6; MS (EI) $m/z$ (relative intensity) 278.2 (50), 139.9 (90), 74.7 (100) [M]$^+$; HRMS $m/z$ (ESI) calcd. for C$_{17}$H$_{12}$N$_2$Cl (M + H)$^+$ 279.0684, found 279.0690.
Kinetic Isotopic Experiment Study

Compound [D₅]-1a was synthesized according to the reported procedure. Substrates 1a (39.6 mg, 0.20 mmol), [D₅]-1a (40.6 mg, 0.20 mmol), Cul (7.6 mg, 10 mol %), Ag₂CO₃ (11.0 mg, 10 mol %), DABCO (89.6 mg, 2.0 equiv) were added to a 20 mL Schlenk tube and the tube was purged with O₂ for three times, followed by addition of 2a (132 μl, 0.60 mmol) and PhCl (4.0 mL). The formed mixture was stirred at 125 ºC under O₂ (1 atm.) for 4 h. The solution was then cooled to rt., diluted with ethyl acetate (15 mL), and evaporated under vacum. The crude product was purified by column chromatography on silica gel (hexane : ethyl acetate = 10:1) to afford 4.6 mg (6%) of the product. Compared with the standard ¹H NMR spectrum of 3a, the integration of the peak at 7.97 ppm was 2.84 instead of 2.00, at 7.48-7.43 ppm was 2.94 instead of 2.00, at 7.40-7.34 ppm was 1.47 instead of 1.00, in 6.80 was 1.20 instead of 1.00.

\[
k_H/k_D = \frac{2/0.84 + 2/0.94 + 1/0.47}{3} = (2.38 + 2.13 + 2.13)/3 = 2.21
\]

Meanwhile, the percentage of the deuterium incorporation at C-3 position could be calculated as follow:

\[
[(1 + 1/2.21) - 1.20]/(1 + 1/2.21) = 17%
\]

This result indicated the protonation process in this transformation.
$^1$H NMR spectrum of the product

Standard $^1$H NMR spectrum of 3a


References

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![Chemical structure diagram]

3j
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![Chemical Structure](image)

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![Chemical Structure 3r](image)

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