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# Electrochemical Oxidation Synergizing with Brønsted-Acid Catalysis Leads to [4+2] Annulation for the Synthesis of Pyrazines

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## General information

All glasswares were oven dried at 110 °C for hours and cooled down under vacuum. Unless otherwise noted, materials were obtained from commercial suppliers and used without further purification. The instrument for electrolysis is dual display potentiostat (DJS-292B) (made in China). The anodic electrode was graphite rod (ϕ 6 mm) and cathodic electrode was platinum plate (15 mm×15 mm×0.3 mm). Thin layer chromatography (TLC) employed glass 0.25 mm silica gel plates. Flash chromatography columns were packed with 200-300 mesh silica gel in petroleum (bp. 60-90 °C). $^{1}H$ and $^{13}C$ NMR data were recorded with Bruker Advance III (400 MHz) spectrometers with tetramethylsilane as an internal standard. All chemical shifts (δ) are reported in ppm and coupling constants (*J*) in Hz. All chemical shifts were reported relative to tetramethylsilane (0 ppm for $^{1}H$), $CDCl_3$ (77.0 ppm for $^{13}C$) and DMSO (2.50 ppm for $^{1}H$, 39.50 ppm for $^{13}C$), respectively. High resolution mass spectra (HRMS) were measured with a Waters Micromass GCT instrument and accurate masses were reported for the molecular ion ($M^+$) or molecular hydrogen ion $(M+H)^+$.

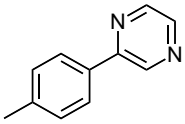
## Experimental procedure

**General procedure for the external oxidant-free electrooxidative [4+2] cyclization for the synthesis of pyrazine:** In an oven-dried undivided three-necked bottle (25 mL) equipped with a stir bar, $TsOH·H_2O$ (0.03 mmol) and KI (64.7 mg, 0.39 mmol) was added. The bottle was equipped with graphite rod (ϕ 6 mm, about 15 mm immersion depth in solution) as the anode and platinum plate (15 mm×15 mm×0.3 mm) as the cathode and charged with nitrogen. Subsequently, ketone (0.3 mmol), ethylenediamine(1.5 mmol) and DMA (9.0 mL) were added. Then the electrolysis system was stirred at a constant current of 13 mA under 100 ˚C for 5.7 h. When the reaction finished, the reaction mixture was washed with water and extracted with diethyl ether (10 mL x 3). The organic layers were combined, dried over $Na_2SO_4$, and concentrated. The pure product was obtained by flash column chromatography on silica gel (petroleum: ethyl acetate = 50:1).

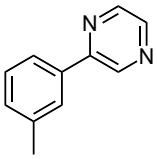
**Procedure for gram scale synthesis of 3aa:** In an oven-dried undivided three-necked bottle (250 mL) equipped with a stir bar, $TsOH·H_2O$ (1.0 mmol) and KI (10 mmol) was added. The bottle was equipped with graphite rod (ϕ 6 mm, about 15 mm immersion depth in solution) as the anode and platinum plate (15 mm×15 mm×0.3 mm) as the cathode and charged with nitrogen. Subsequently,

ketone (10 mmol), ethylenediamine(50 mmol) and DMA (220 mL) were added. Then the electrolysis system was stirred at a constant current of 20 mA under 100 ˚C for 120 h. When the reaction finished, the reaction mixture was washed with water and extracted with diethyl ether (150 mL x 3). The organic layers were combined, dried over $Na_2SO_4$, and concentrated. The pure product was obtained by flash column chromatography on silica gel (petroleum: ethyl acetate = 50:1).

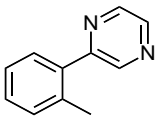
## Detail descriptions for products



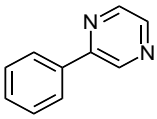
**2-(*p*-Tolyl)pyrazine (3aa)[1]:** white solid was obtained in 83% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.22 (d, $J$ = 1.6 Hz, 1H), 8.68 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.57 (d, $J$ = 2.4 Hz, 1H), 8.11 – 7.99 (m, 2H), 7.48 – 7.27 (m, 2H), 2.37 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 151.48, 144.24, 143.10, 141.78, 139.73, 133.12, 129.68, 126.61, 20.92.



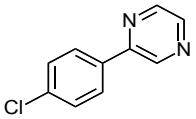
**2-(*m*-Tolyl)pyrazine (3ba)[1]:** colorless liquid was obtained in 81% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.23 (d, $J$ = 1.6 Hz, 1H), 8.71 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.60 (d, $J$ = 2.8 Hz, 1H), 7.99 – 7.95 (m, 1H), 7.94 – 7.90 (m, 1H), 7.42 (t, $J$ = 7.6 Hz, 1H), 7.34 - 7.29 (m, 1H), 2.40 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 151.53, 144.23, 143.33, 142.03, 138.28, 135.81, 130.57, 128.93, 127.25, 123.84, 21.07.



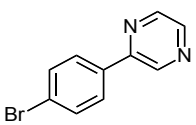
**2-(*o*-Tolyl)pyrazine (3ca)[2]:** colorless liquid was obtained in 65% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.82 (d, $J$ = 1.6 Hz, 1H), 8.74 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.63 (d, $J$ = 2.8 Hz, 1H), 7.46 (dd, $J$ = 7.2, 1.6 Hz, 1H), 7.42 – 7.30 (m, 3H), 2.34 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 154.65, 144.83, 143.93, 142.91, 136.60, 135.97, 130.93, 129.86, 129.11, 126.17, 20.03.



**2-Phenylpyrazine (3da)[3]:** white solid was obtained in 73% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.25 (d, $J$ = 1.6 Hz, 1H), 8.71 (dd, $J$ = 2.4, 1.2 Hz, 1H), 8.61 (d, $J$ = 2.4 Hz, 1H), 8.22 – 8.03 (m, 2H), 7.63 – 7.42 (m, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 151.47, 144.33, 143.46, 142.08, 135.90, 129.98, 129.07, 126.74.

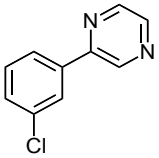


**2-(4-Chlorophenyl)pyrazine (3ea)[3]:** white solid was obtained in 79% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.27 (d, $J$ = 1.6 Hz, 1H), 8.72 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.63 (d, $J$ = 2.8 Hz, 1H), 8.23 – 8.09 (m, 2H), 7.77 – 7.49 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 150.27, 144.34, 143.76, 142.05, 134.91, 134.71, 129.10, 128.49.

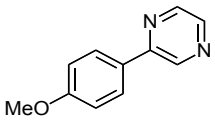


**2-(4-Bromophenyl)pyrazine (3fa)[3]:** white solid was obtained in 73% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.23 (d, $J$ = 1.6 Hz, 1H), 8.69 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.61 (d, $J$ = 2.8 Hz, 1H),

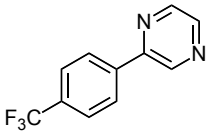
8.11 – 8.00 (m, 2H), 7.75 – 7.60 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 150.27, 144.26, 143.70, 141.91, 134.98, 131.91, 128.63, 123.68.



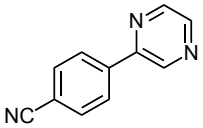
**2-(3-Chlorophenyl)pyrazine (3ga)[3]:** white solid was obtained in 60% isolated yield. $^{1}$H NMR (400 MHz, DMSO-$d_6$) δ 9.29 (d, $J$ = 1.4 Hz, 1H), 8.73 – 8.70 (m, 1H), 8.64 (d, $J$ = 2.4 Hz, 1H), 8.18 – 8.14 (m, 1H), 8.12 – 8.06 (m, 1H), 7.58 – 7.51 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 149.87, 144.35, 144.09, 142.29, 137.95, 133.98, 130.90, 129.72, 126.37, 125.28.



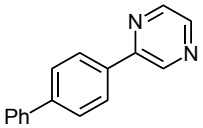
**2-(4-Methoxyphenyl)pyrazine (3ha)[3]:** white solid was obtained in 76% isolated yield. $^{1}$H NMR (400 MHz, DMSO-$d_6$) δ 9.19 (d, $J$ = 1.6 Hz, 1H), 8.64 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.52 (d, $J$ = 2.4 Hz, 1H), 8.20 – 8.01 (m, 2H), 7.20 – 6.93 (m, 2H), 3.82 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 160.82, 151.29, 144.11, 142.50, 141.41, 128.25, 128.18, 114.47, 55.32.



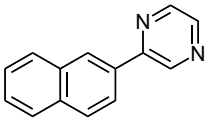
**2-(4-(Trifluoromethyl)phenyl)pyrazine (3ia)[3]:** white solid was obtained in 68% isolated yield. $^{1}$H NMR (400 MHz, DMSO-$d_6$) δ 9.35 (d, $J$ = 1.6 Hz, 1H), 8.78 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.70 (d, $J$ = 2.4 Hz, 1H), 8.40 – 8.31 (m, 2H), 7.96 – 7.77 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 149.92, 144.55, 144.46, 142.61, 139.78 (q, $J_{C\text{-}F}$ = 2.0 Hz), 129.95 (q, $J_{C\text{-}F}$ = 32.0 Hz), 127.53, 125.91 (q, $J_{C\text{-}F}$ = 3.7 Hz), 124.15 (q, $J_{C\text{-}F}$ = 273.7 Hz). $^{19}$F NMR (377 MHz, DMSO-$d_6$) δ -61.24.



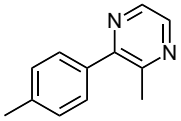
**4-(Pyrazin-2-yl)benzonitrile (3ja)[3]:** white solid was obtained in 51% isolated yield. $^{1}$H NMR (400 MHz, DMSO-$d_6$) δ 9.37 (d, $J$ = 1.6 Hz, 1H), 8.79 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.71 (d, $J$ = 2.4 Hz, 1H), 8.40 – 8.26 (m, 2H), 8.10 – 7.95 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 149.61, 144.67, 144.62, 142.79, 140.18, 133.01, 127.51, 118.64, 112.36.



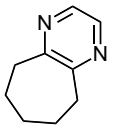
**2-([1,1'-Biphenyl]-4-yl)pyrazine (3ka)[3]:** white solid was obtained in 66% isolated yield. $^{1}$H NMR (400 MHz, DMSO-$d_6$) δ 9.31 (d, $J$ = 1.2 Hz, 1H), 8.73 (dd, $J$ = 2.4, 1.6 Hz, 1H), 8.62 (d, $J$ = 2.4 Hz, 1H), 8.33 – 8.19 (m, 2H), 7.94 – 7.80 (m, 2H), 7.80 – 7.71 (m, 2H), 7.54 – 7.46 (m, 2H), 7.45 – 7.36 (m, 1H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 151.06, 144.40, 143.48, 142.06, 141.54, 139.27, 134.88, 129.10, 127.99, 127.31, 126.78.



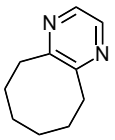
**2-(Naphthalen-2-yl)pyrazine (3la)[3]:** white solid was obtained in 75% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.41 (d, $J$ = 1.6 Hz, 1H), 8.78 – 7.71 (m, 2H), 8.64 (d, $J$ = 2.4 Hz, 1H), 8.27 (dd, $J$ = 8.8, 2.0 Hz, 1H), 8.17 – 8.01 (m, 2H), 8.01 – 7.90 (m, 1H), 7.61 – 7.54 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 151.38, 144.37, 143.46, 142.36, 133.53, 133.25, 132.99, 128.77, 128.68, 127.66, 127.24, 126.74, 126.48, 123.91.



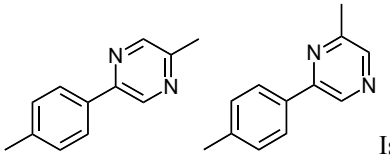
**2-Methyl-3-(p-tolyl)pyrazine (3ma)[3]:** colorless oil was obtained in 72% isolated yield.$^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.56 – 8.52 (m, 1H), 8.49 (d, $J$ = 2.4 Hz, 1H), 7.56 – 7.49 (m, 2H), 7.31 (d, $J$ = 7.6 Hz, 2H), 2.56 (s, 3H), 2.38 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 152.99, 151.12, 142.09, 141.65, 138.16, 135.54, 128.94, 128.83, 23.06, 20.86.



**6,7,8,9-Tetrahydro-5H-cyclohepta[b]pyrazine (3na)[3]:** colorless liquid was obtained in 50% isolated yield.$^1$H NMR (400 MHz, $CDCl_3$) δ 8.24 (s, 2H), 3.60 – 2.68 (m, 4H), 2.10 – 1.82 (m, 2H), 1.78 – 1.68 (m, 4H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 158.58, 140.86, 38.14, 32.19, 26.17.

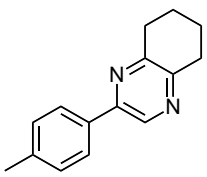


**5,6,7,8,9,10-Hexahydrocycloocta[b]pyrazine (3oa)[3]:** colorless liquid was obtained in 41% isolated yield. $^1$H NMR (400 MHz, $CDCl_3$) δ 8.33 (s, 2H), 3.21 – 2.91 (m, 4H), 1.99 – 1.76 (m, 4H), 1.44 – 1.36 (m, 4H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 156.70, 141.83, 34.30, 30.61, 25.92.

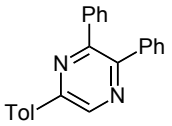


Isomer (1.08:1 based on NMR)

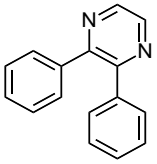
**2-Methyl-5(6)-(*p*-tolyl)pyrazine (3ab)[5]:** white solid was obtained in 82% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.05 (d, $J$ = 1.6 Hz, 0.47H), 8.99 (s, 0.52H), 8.55 (d, $J$ = 1.6 Hz, 0.46H), 8.45 (s, 0.48H), 8.06 – 7.95 (m, 2H), 7.45 – 7.23 (m, 2H), 2.53 (s, 1.55H), 2.50 (s, 1.62H), 2.36 – 2.33 (m, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 152.82, 151.72, 150.27, 148.58, 143.62, 142.56, 140.41, 139.47, 139.14, 138.50, 133.24, 133.21, 129.58, 126.56, 126.25, 21.33, 20.90, 20.88, 20.81. HRMS (ESI) calculated for $C_{20}H_{19}N_2S^+$ $[M+H]^+$: 319.1263; found: 319.1258.



**2-(*p*-Tolyl)-5,6,7,8-tetrahydroquinoxaline (3ac)[6]:** colorless liquid was obtained in 74% isolated yield. $^1$H NMR (400 MHz, $CDCl_3$) δ 8.71 (s, 1H), 7.87 (dt, $J$ = 8.0, 1.6 Hz, 2H), 7.31 – 7.26 (m, 2H), 3.05 – 2.94 (m, 4H), 2.41 (s, 3H), 2.00 – 1.85 (m, 4H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 152.13, 150.69, 149.64, 139.23, 138.56, 134.04, 129.57, 126.55, 32.13, 31.62, 22.67, 21.28.

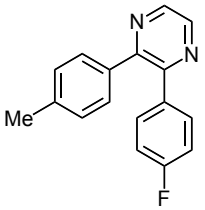



**2,3-Diphenyl-5-(p-tolyl)pyrazine (3ad)[7]**: white solid was obtained in 53% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 9.25 (s, 1H), 8.18 – 8.09 (m, 2H), 7.51 – 7.45 (m, 2H), 7.45 – 7.41 (m, 2H), 7.39 – 7.31 (m, 8H), 2.38 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 150.70, 149.81, 148.58, 139.78, 138.80, 138.62, 138.35, 132.78, 129.69, 129.59, 129.46, 128.65, 128.53, 128.22, 128.18, 126.70, 20.98.

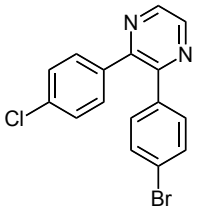



**2-([1,1'-Biphenyl]-4-yl)-3-phenylpyrazine (3pa)[3]:** white solid was obtained in 86% isolated yield.

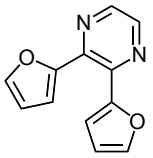
$^1$H NMR (400 MHz, $CDCl_3$) δ 8.60 (s, 2H), 7.51 – 7.42 (m, 4H), 7.35 – 7.27 (m, 6H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 152.74, 142.03, 138.49, 129.56, 128.61, 128.21.



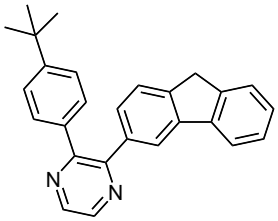

**2-(4-Fluorophenyl)-3-(p-tolyl)pyrazine (3qa):** white solid was obtained in 58% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.67 (dd, $J$ = 8.0, 2.4 Hz, 2H), 7.47 – 7.37 (m, 2H), 7.28 (dt, $J$ = 8.0, 2.0 Hz, 2H), 7.22 – 7.10 (m, 4H), 2.29 (s, 3H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 163.43, 160.99, 151.83, 150.80, 142.31 (d, $J_{C\text{-}F}$ = 35.1 Hz), 138.21, 135.48, 135.10 (d, $J_{C\text{-}F}$ = 3.1 Hz), 131.66 (d, $J_{C\text{-}F}$ = 8.5 Hz), 129.43, 128.89, 115.22 (q, $J_{C\text{-}F}$ = 21.8 Hz), 20.83. $^{19}$F NMR (377 MHz, DMSO-$d_6$) δ -113.02. HRMS (ESI) calculated for $C_{17}H_{14}FN_2^+$ $[M+H]^+$: 265.1136; found: 265.1135.



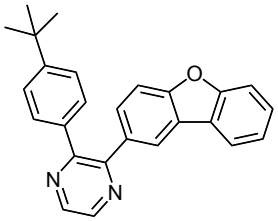

**2-(4-Bromophenyl)-3-(4-chlorophenyl)pyrazine (3ra)**: white solid was obtained in 66% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.75 – 8.70 (m, 2H), 7.64 – 7.48 (m, 2H), 7.44 – 7.39 (m, 4H), 7.37 – 7.29 (m, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 150.82, 150.73, 142.79, 137.44, 137.05, 133.72, 131.63, 131.37, 131.35, 129.51, 128.44, 122.49. HRMS (ESI) calculated for $C_{16}H_{11}BrClN_2^+$ $[M+H]^+$: 344.9789; found: 344.9788.



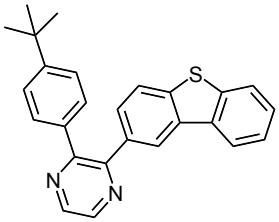

**2,3-Di(furan-2-yl)pyrazine (3sa)[4]:** light yellow solid was obtained in 70% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.62 (s, 2H), 7.82 (dd, $J$ = 2.0, 0.8 Hz, 2H), 6.75 (dd, $J$ = 3.6, 0.8 Hz, 2H), 6.66 (dd, $J$ = 3.2, 2.0 Hz, 2H). $^{13}$C NMR (101 MHz, DMSO-$d_6$) δ 150.37, 144.61, 142.51, 140.87, 112.16, 112.12.



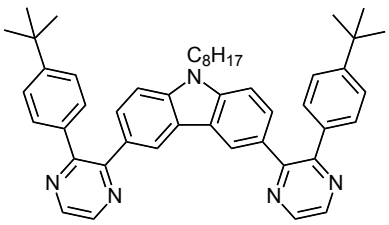
**2-(4-(Tert-butyl)phenyl)-3-(9H-fluoren-3-yl)pyrazine (3ta):** white solid was obtained in 68% isolated yield. $^1$H NMR (400 MHz, $CDCl_3$) δ 8.57 (s, 2H), 7.77 (dt, *J* = 7.6, 1.0 Hz, 1H), 7.71 (q, *J* = 0.8 Hz, 1H), 7.70 – 7.67 (d, *J* = 8.0 Hz, 1H), 7.53 (dt, *J* = 7.2, 1.2 Hz, 1H), 7.48 – 7.40 (m, 3H), 7.37 (td, *J* = 7.6, 1.2 Hz, 1H), 7.34 – 7.27 (m, 3H), 3.85 (s, 2H), 1.29 (s, 9H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 152.86, 152.75, 151.79, 143.69, 143.23, 142.01, 141.80, 141.66, 141.06, 137.16, 135.70, 129.21, 128.60, 127.03, 126.80, 126.13, 125.22, 125.05, 120.16, 119.55, 36.87, 34.60, 31.17. HRMS (ESI) calculated for $C_{27}H_{25}N_2^+$ $[M+H]^+$: 377.2012; found: 377.2013.



**2-(4-(Tert-butyl)phenyl)-3-(dibenzo[b,d]furan-2-yl)pyrazine (3ua):** white solid was obtained in 71% isolated yield. $^1$H NMR (400 MHz, $CDCl_3$) δ 8.60 (s, 2H), 8.18 (dd, *J* = 2.0, 0.4 Hz, 1H), 7.88 – 7.83 (m, 1H), 7.56 (dt, *J* = 8.0, 0.8 Hz, 1H), 7.49 – 7.39 (m, 5H), 7.36 – 7.27 (m, 3H), 1.28 (s, 9H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 156.51, 156.20, 152.82, 152.44, 151.89, 141.91, 141.72, 135.61, 133.53, 129.21, 129.05, 127.31, 125.27, 124.44, 124.00, 122.85, 122.03, 120.70, 111.67, 111.25, 34.59, 31.15. HRMS (ESI) calculated for $C_{26}H_{23}N_2O^+$ $[M+H]^+$: 379.1805; found: 379.1804.



**2-(4-(Tert-butyl)phenyl)-3-(dibenzo[b,d]thiophen-2-yl)pyrazine (3va):** white solid was obtained in 51% isolated yield. $^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.72 (q, *J* = 2.4 Hz, 2H), 8.37 (d, *J* = 1.6 Hz, 1H), 8.08 (d, *J* = 7.6 Hz, 1H), 8.01 (d, *J* = 7.6 Hz, 1H), 7.92 (d, *J* = 8.4 Hz, 1H), 7.53 – 7.41 (m, 3H), 7.40 – 7.28 (m, 4H), 1.20 (s, 9H). $^{13}$C NMR (101 MHz, DMSO) δ 152.03, 151.47, 151.31, 142.43, 142.29, 138.96, 138.92, 135.73, 135.26, 134.96, 134.76, 129.27, 128.23, 127.39, 125.08, 124.89, 123.20, 122.94, 122.69, 121.82, 34.41, 31.00. HRMS (ESI) calculated for $C_{26}H_{23}N_2S^+$ $[M+H]^+$: 395.1576; found: 395.1569.

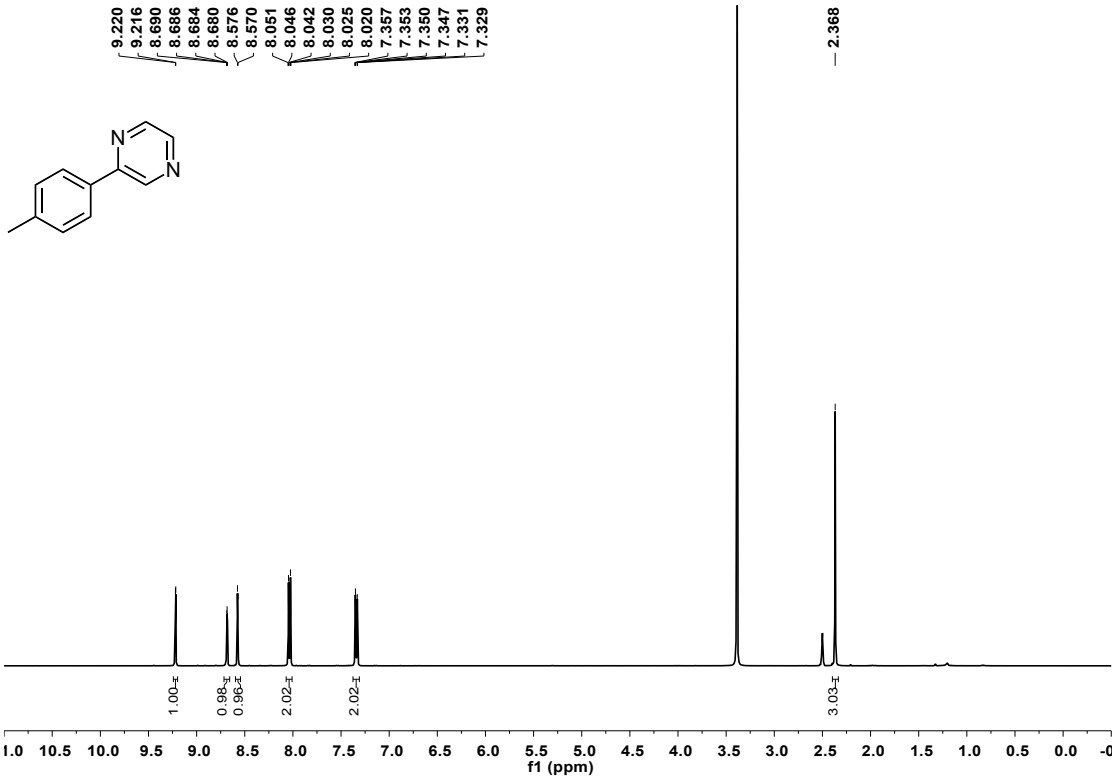


**3,6-Bis(3-(4-(tert-butyl)phenyl)pyrazin-2-yl)-9-octyl-9H-carbazole (3wa):** light yellow oil was obtained in 78% isolated yield. $^{1}$H NMR (400 MHz, $CDCl_3$) δ 8.57 (dd, *J* = 8.8, 2.4 Hz, 4H), 8.18 (d, *J* = 1.6 Hz, 2H), 7.51 (dd, *J* = 8.4, 2.0 Hz, 2H), 7.42 (dt, *J* = 8.4, 2.0 Hz, 4H), 7.30 (dt, *J* = 8.8, 2.0 Hz, 4H), 7.27 (s, 1H), 7.25 (s, 1H), 4.25 (t, *J* = 7.2 Hz, 2H), 1.89 – 1.77 (m, 2H), 1.37 – 1.17 (m, 28H), 0.85 (t, *J* = 6.8 Hz, 3H). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 153.14, 152.58, 151.62, 141.70, 141.24, 140.92, 136.18, 129.63, 129.13, 127.76, 125.25, 123.02, 122.03, 108.43, 43.32, 34.58, 31.71, 31.15, 29.29, 29.10, 28.91, 27.22, 22.53, 14.03. HRMS (ESI) calculated for $C_{48}H_{54}N_5^+$ $[M+H]^+$: 700.4374; found: 700.4374.

## Copies of product NMR Spectra

**3aa**

**$^{1}$H NMR**

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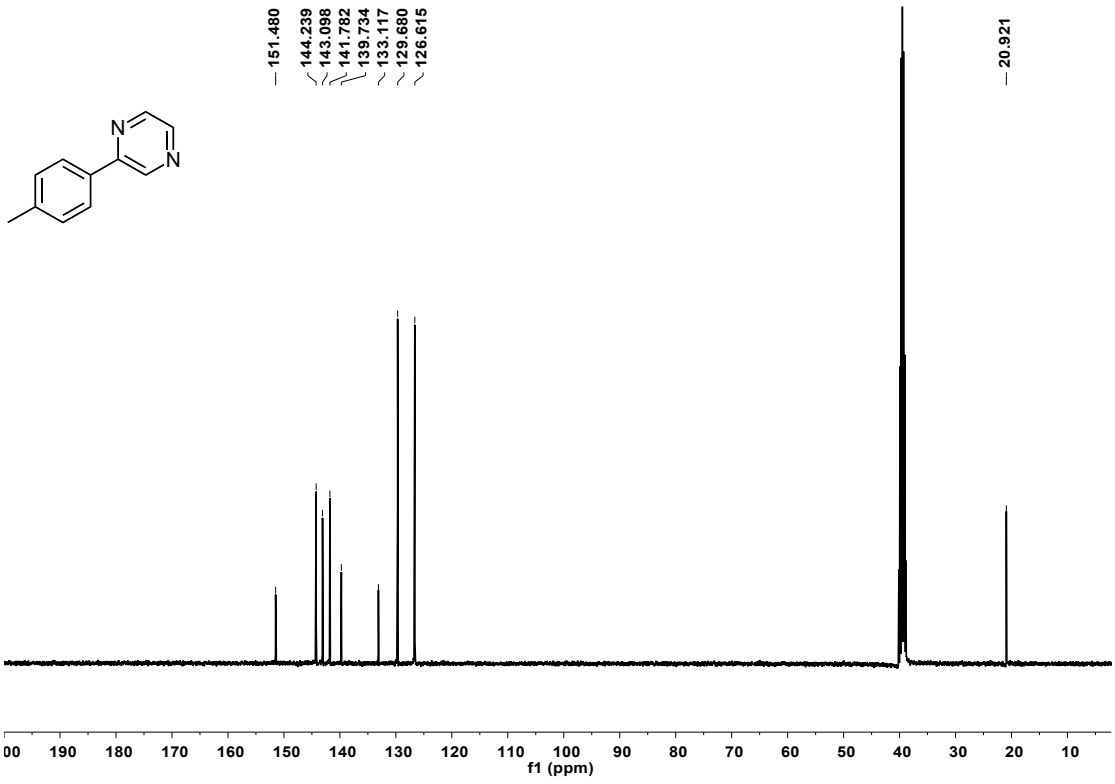
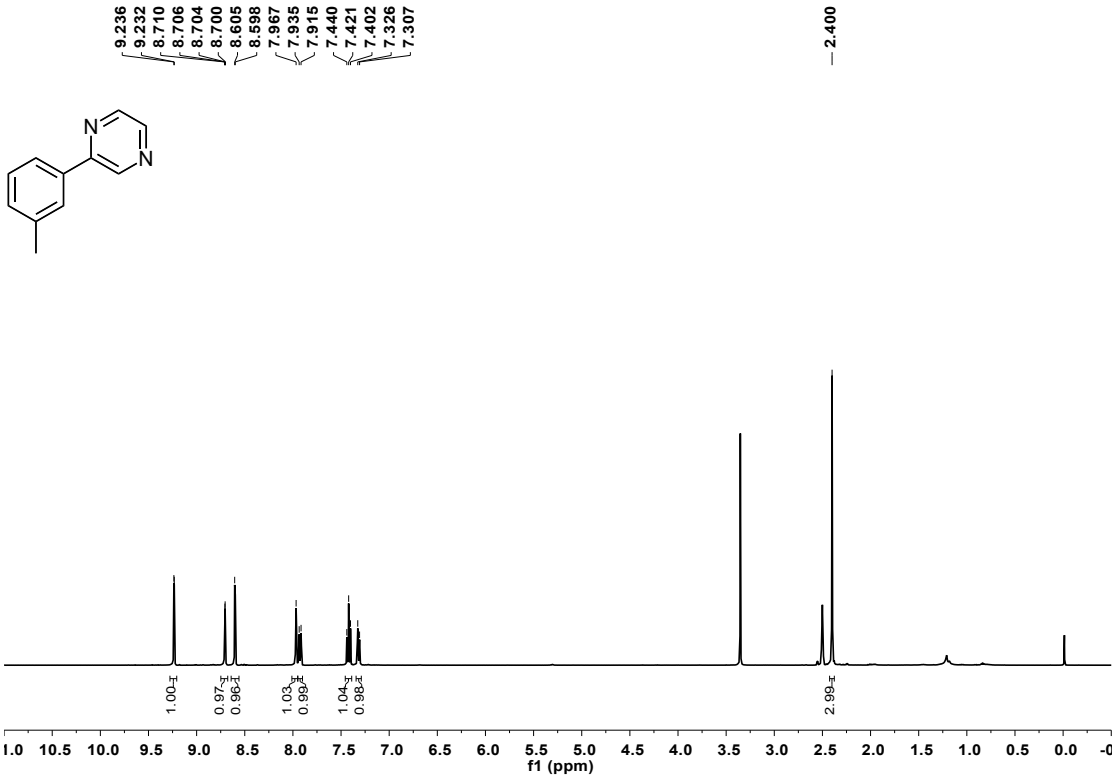


**3ba**

**$^{1}$H NMR**

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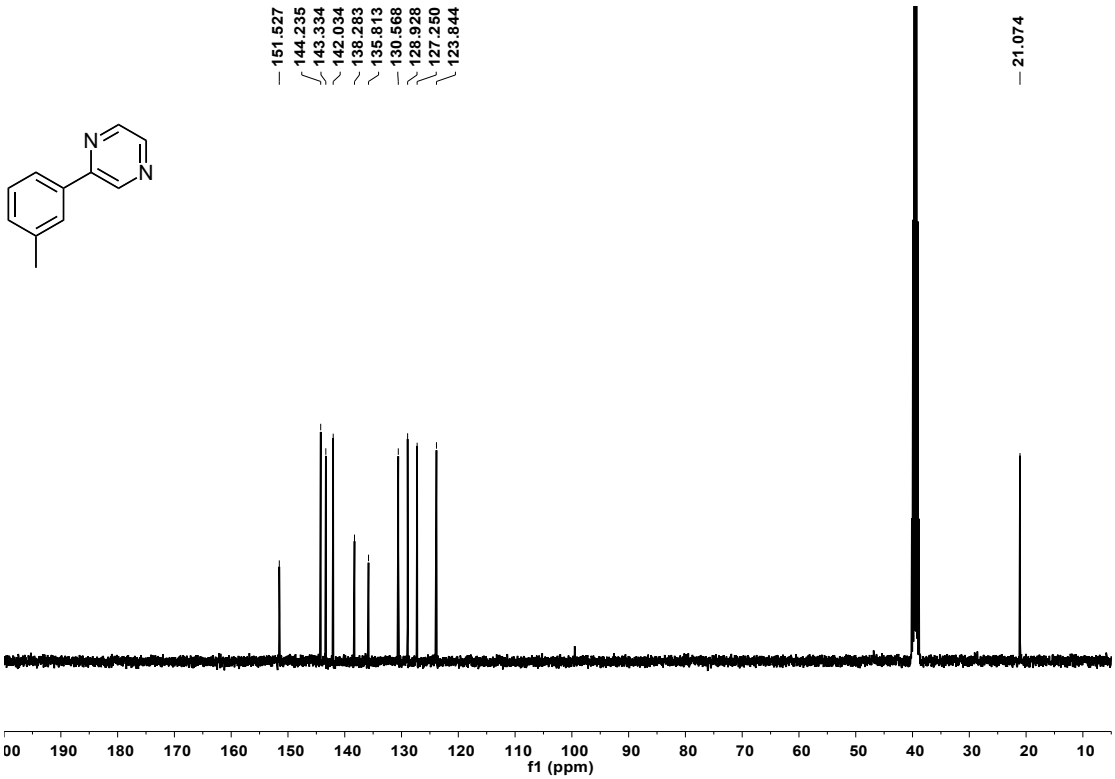

**3ca**

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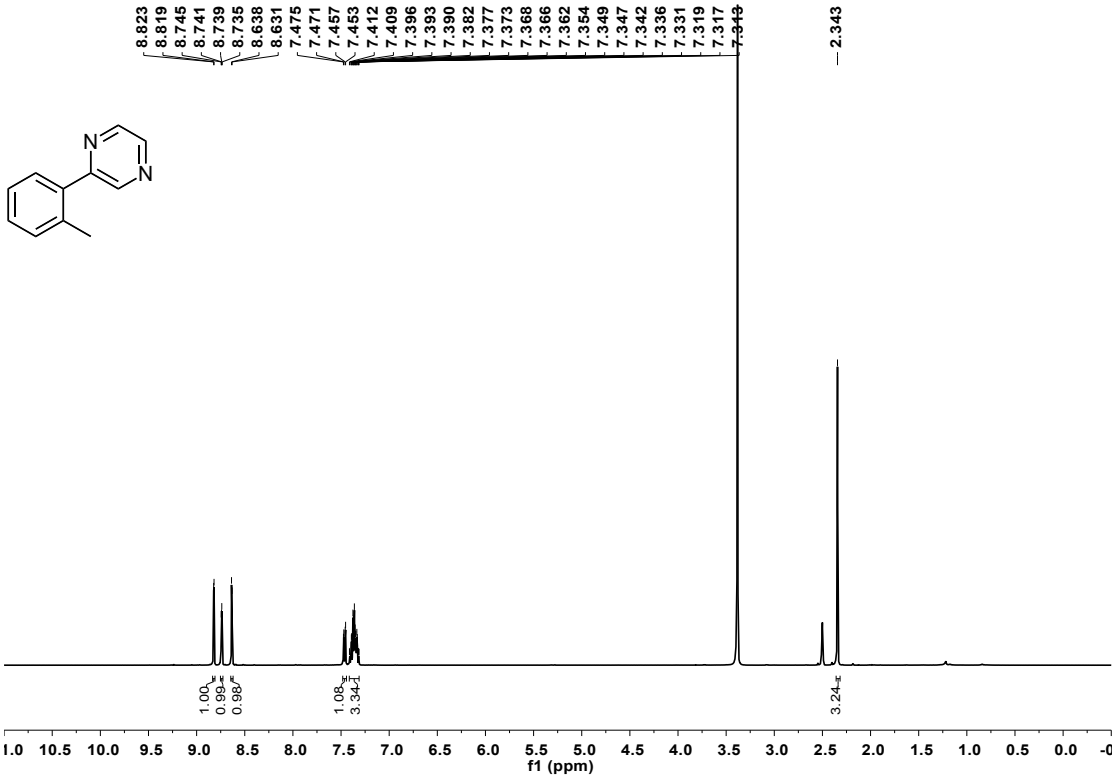


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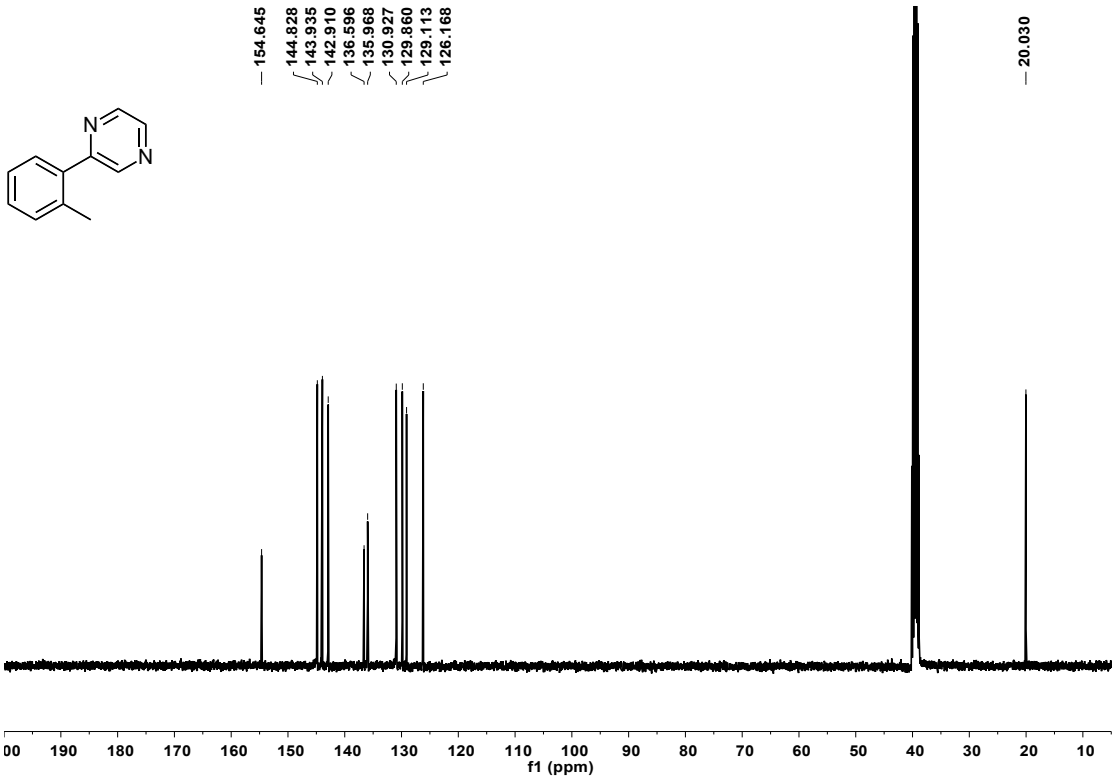

**3da**

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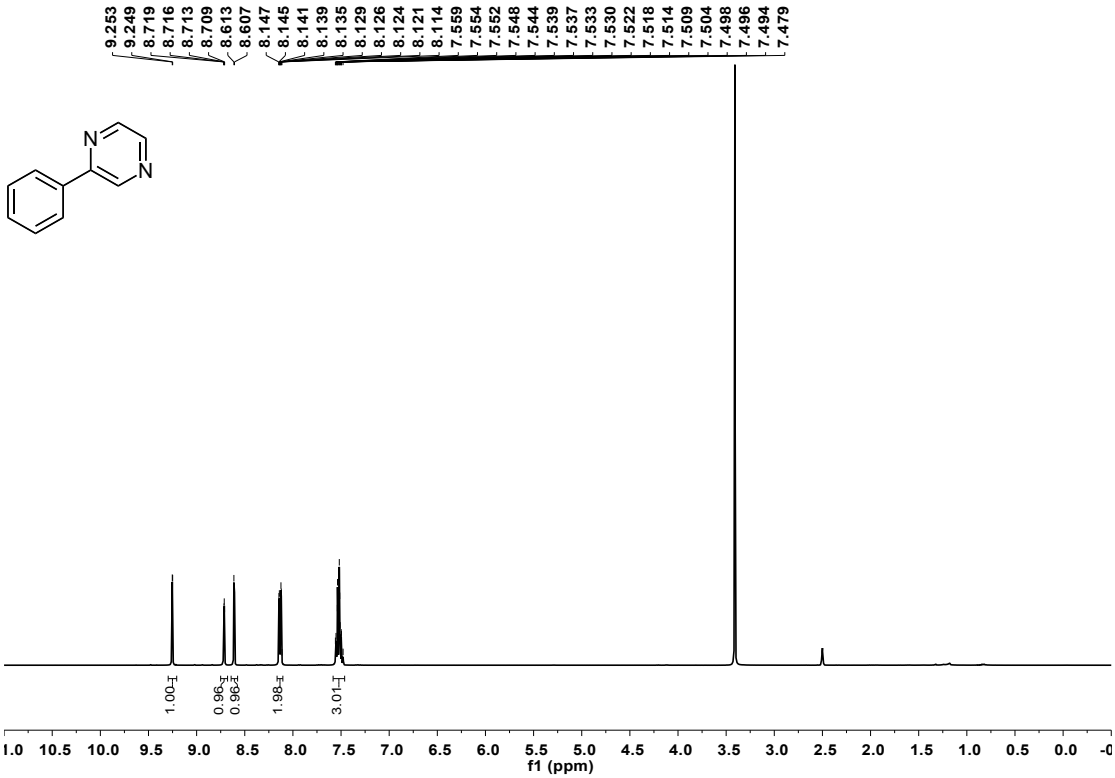


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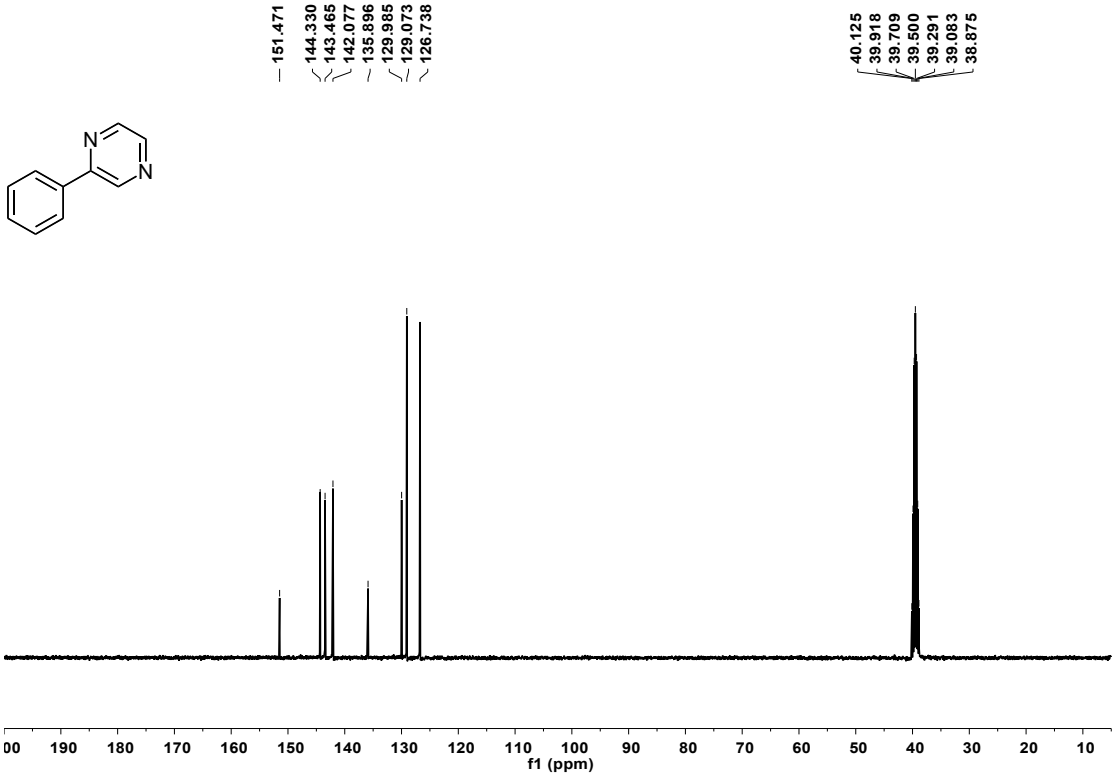

**3ea**

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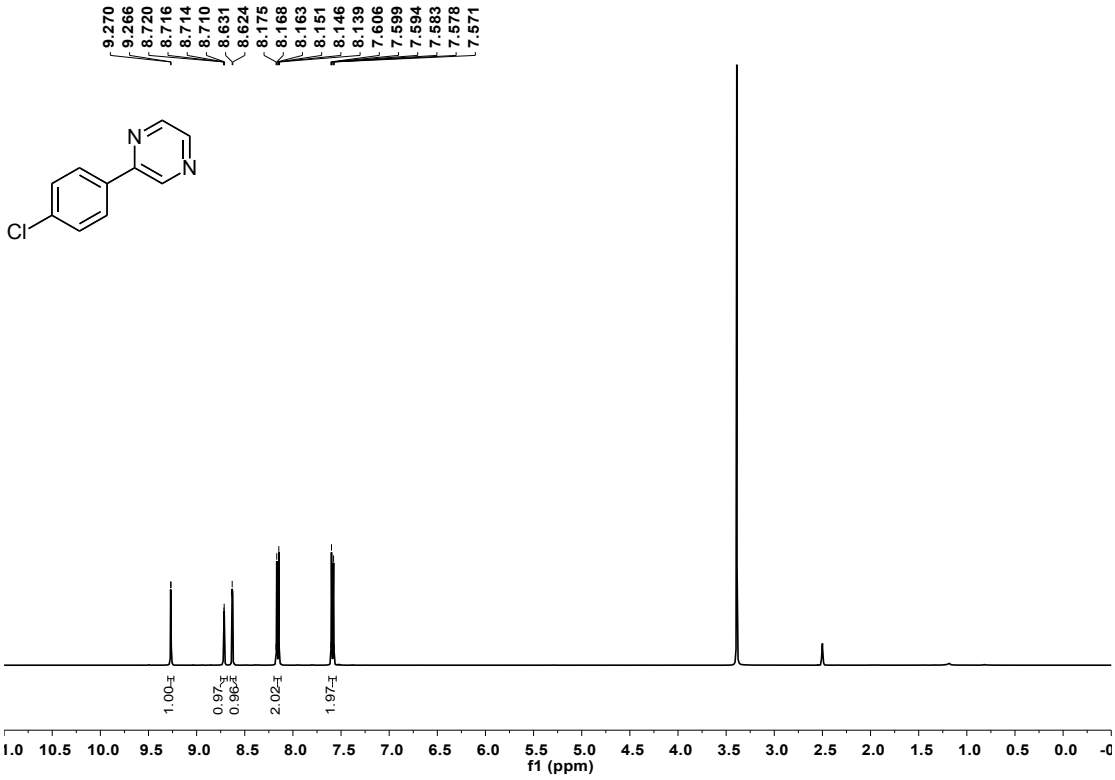


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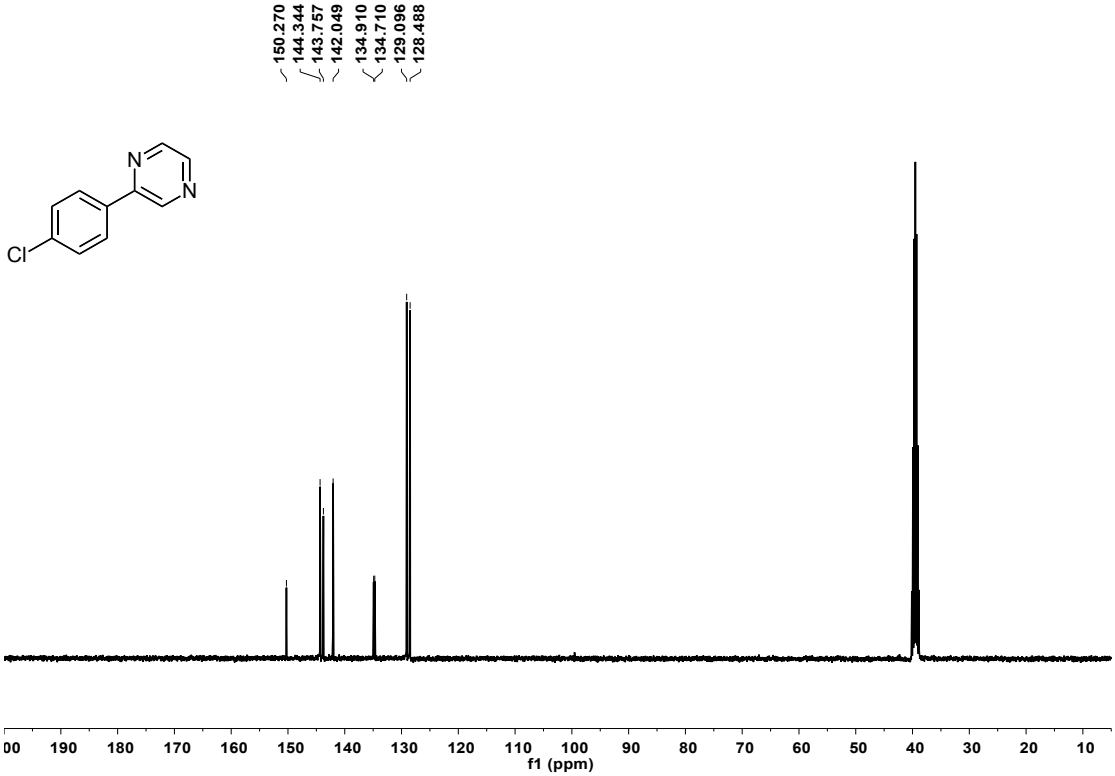
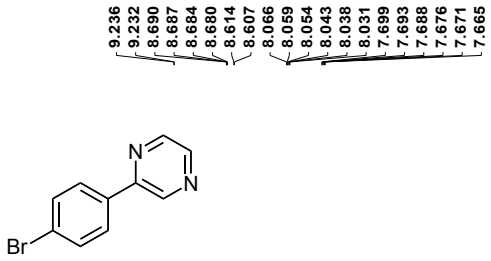
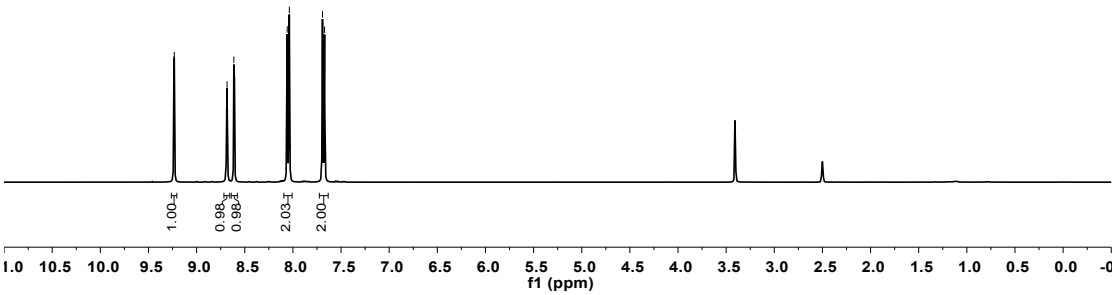


**3fa**

**$^{1}$H NMR**

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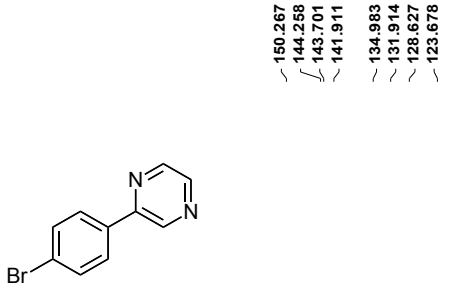


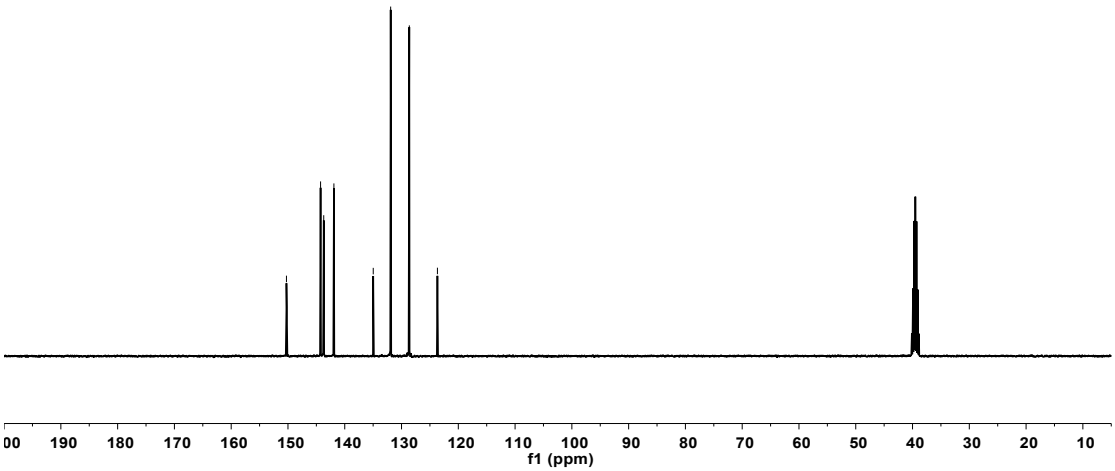

**3ga**

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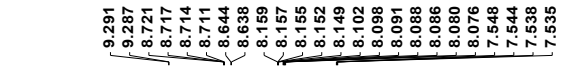


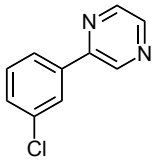


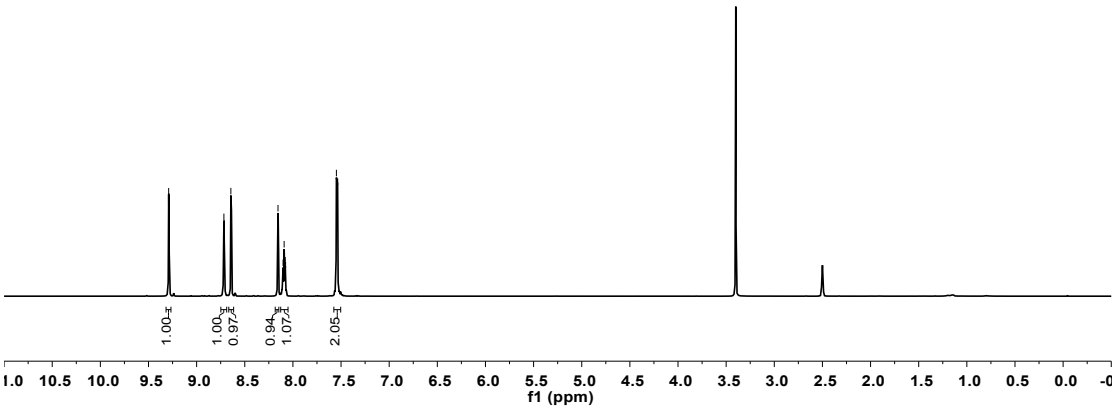


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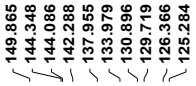


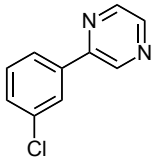


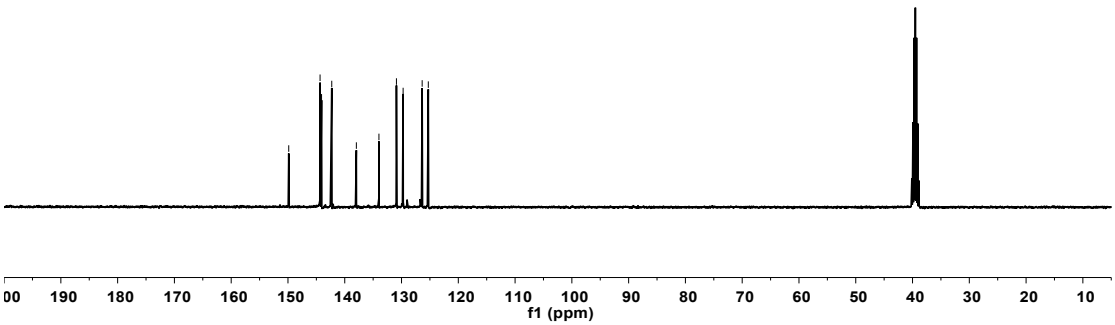

**3ha**

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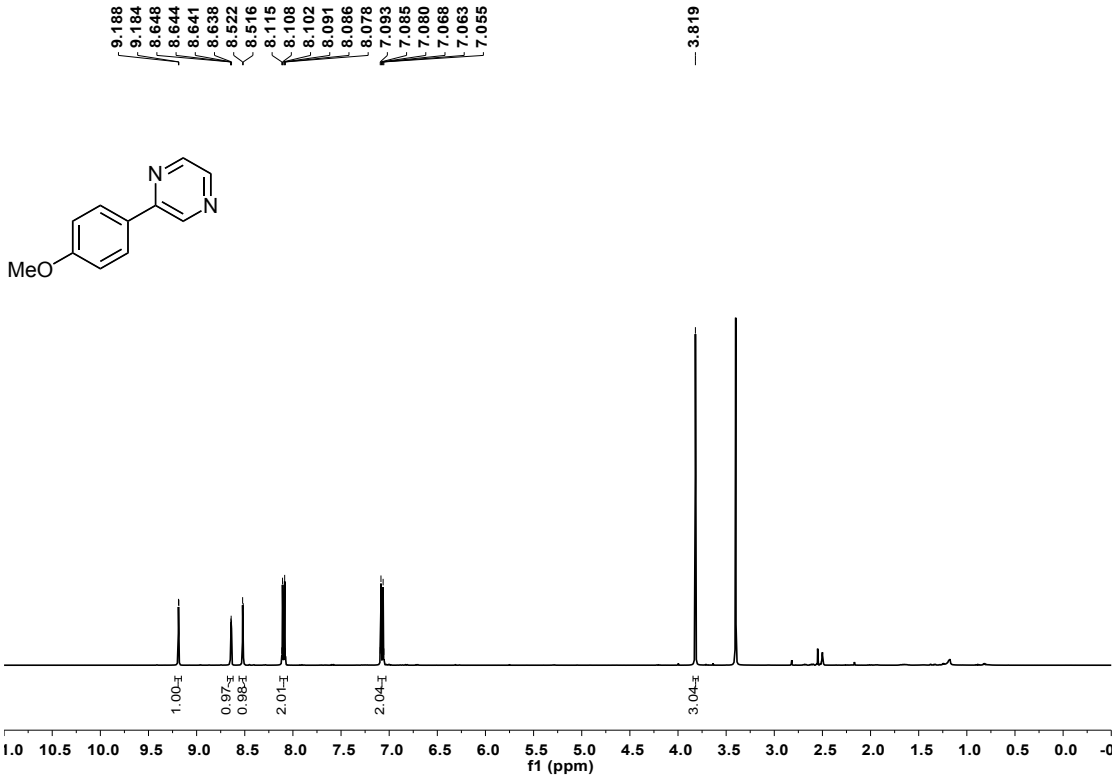


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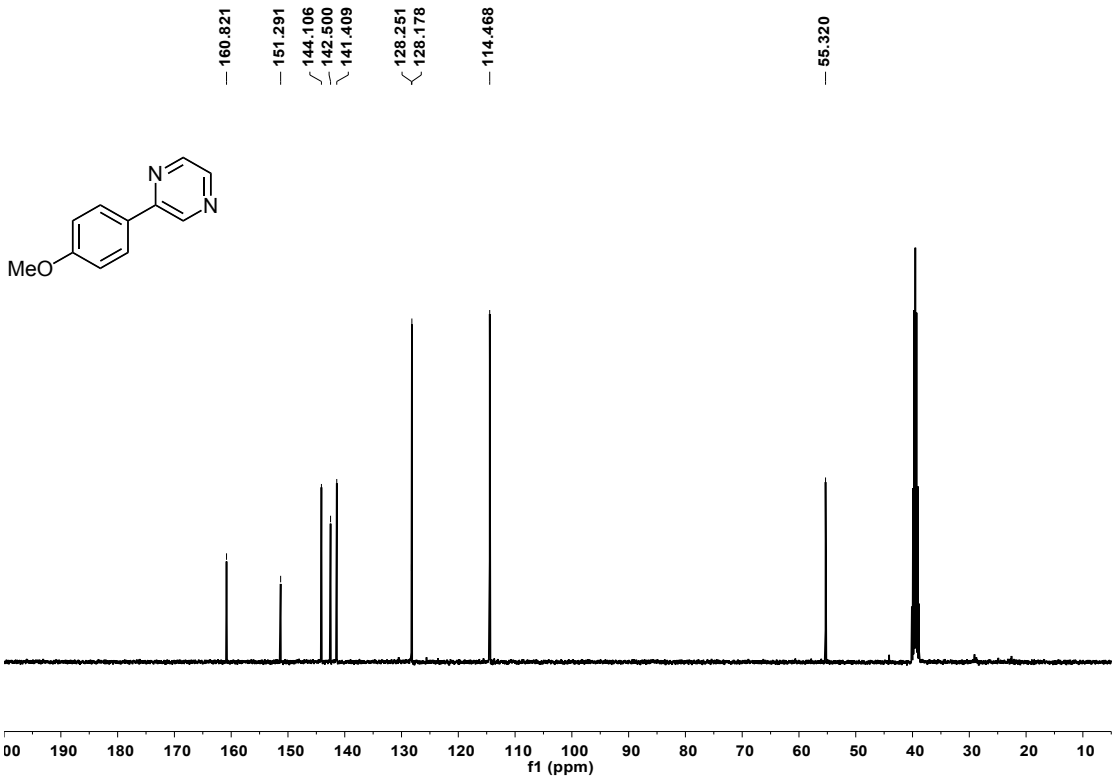
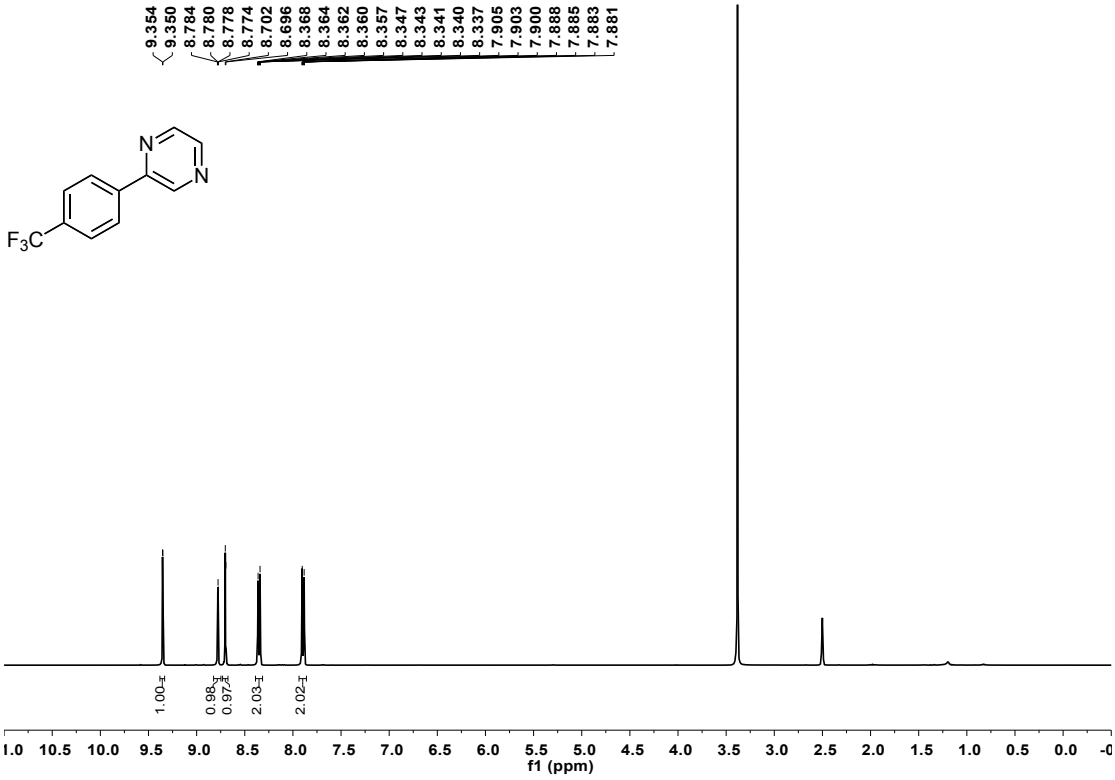


**3ia**

**$^{1}$H NMR**

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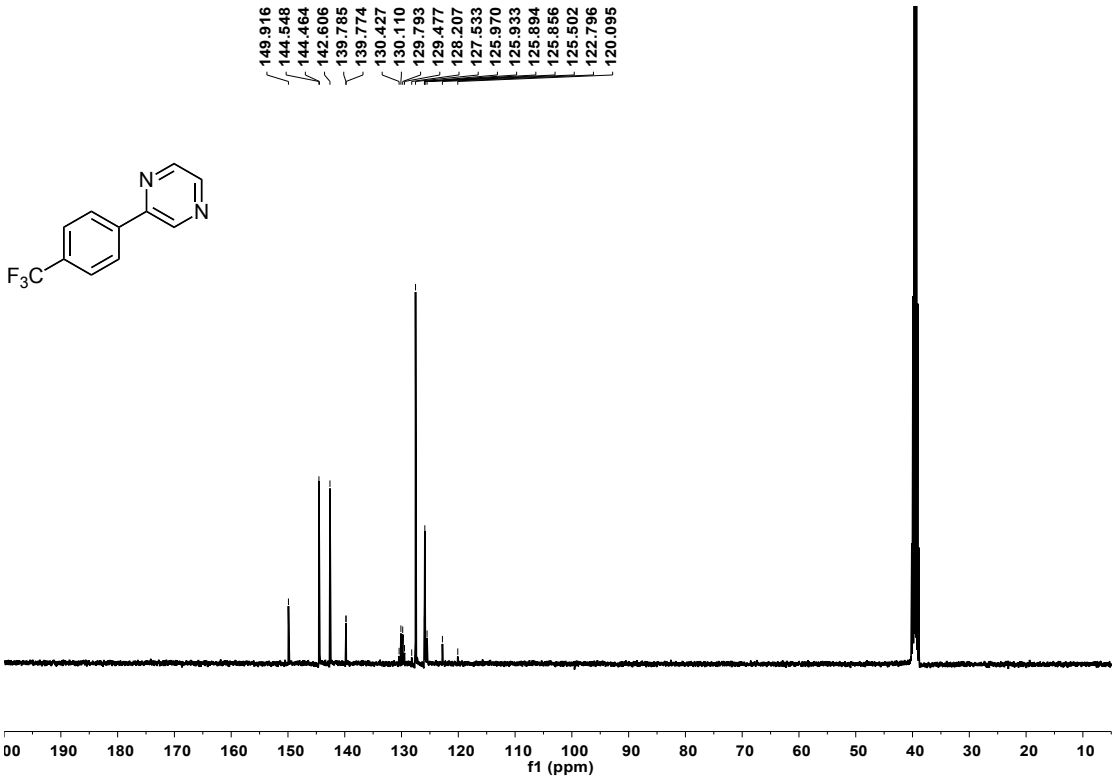

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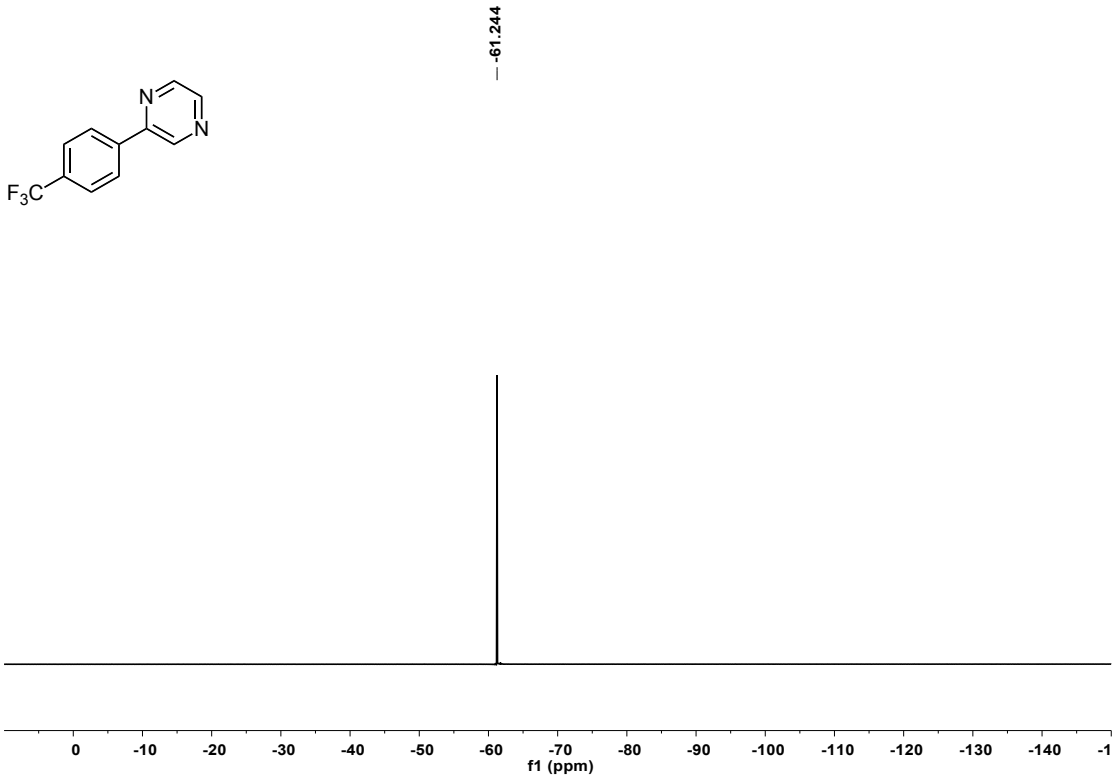
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F3C
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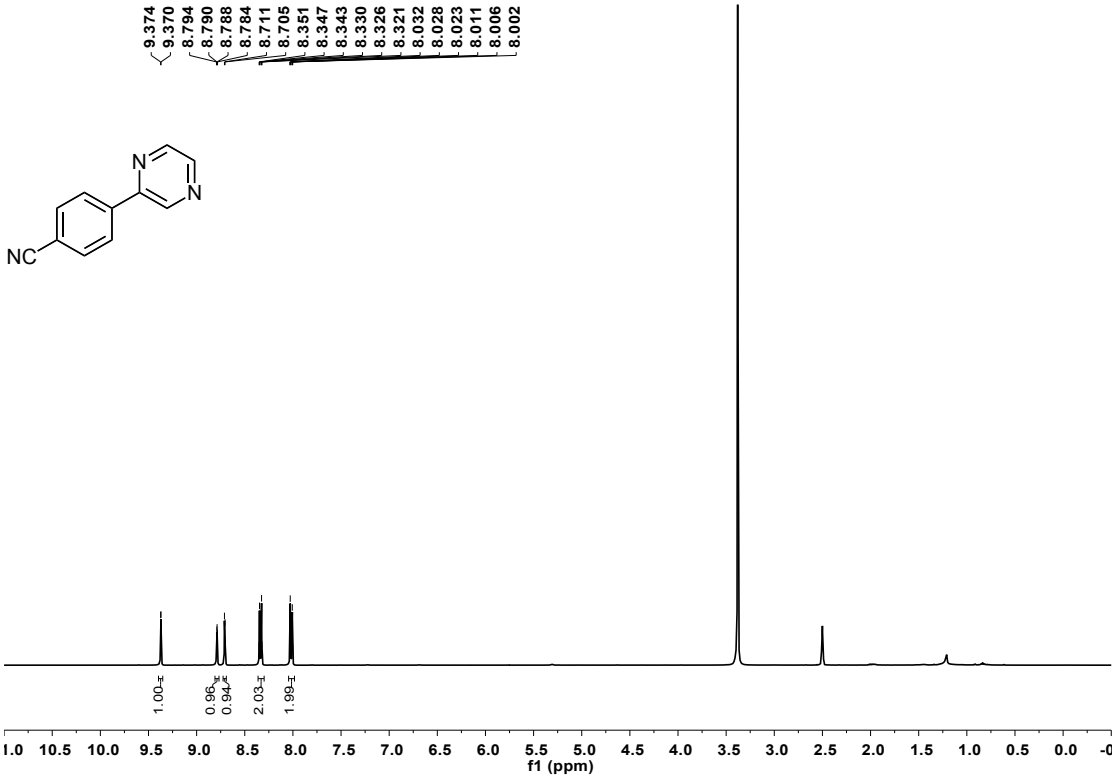
f1 (ppm)

**3ja**

**$^{1}$H NMR**

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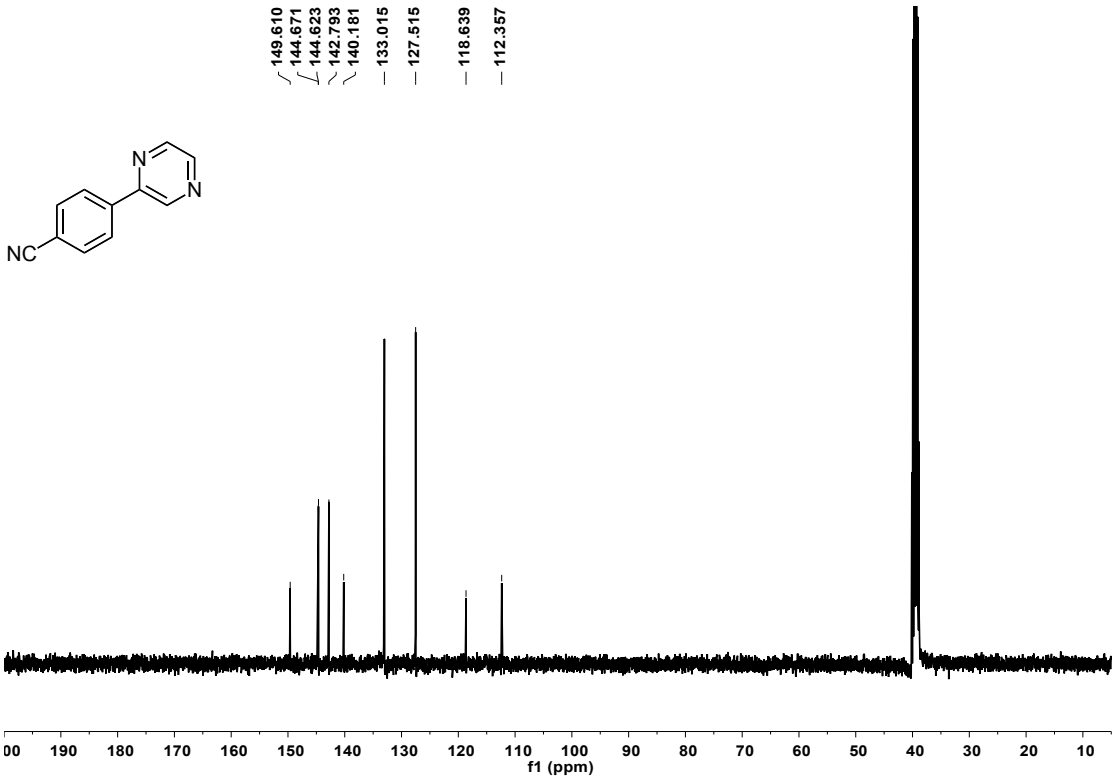

**3ka**

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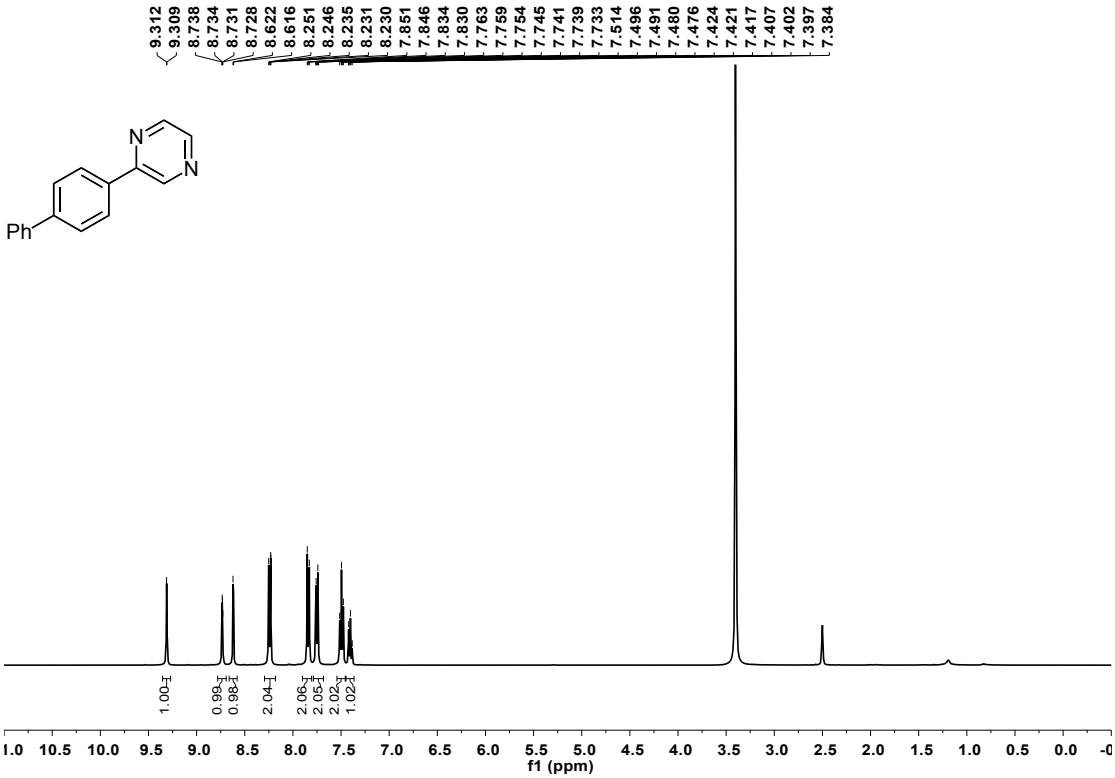


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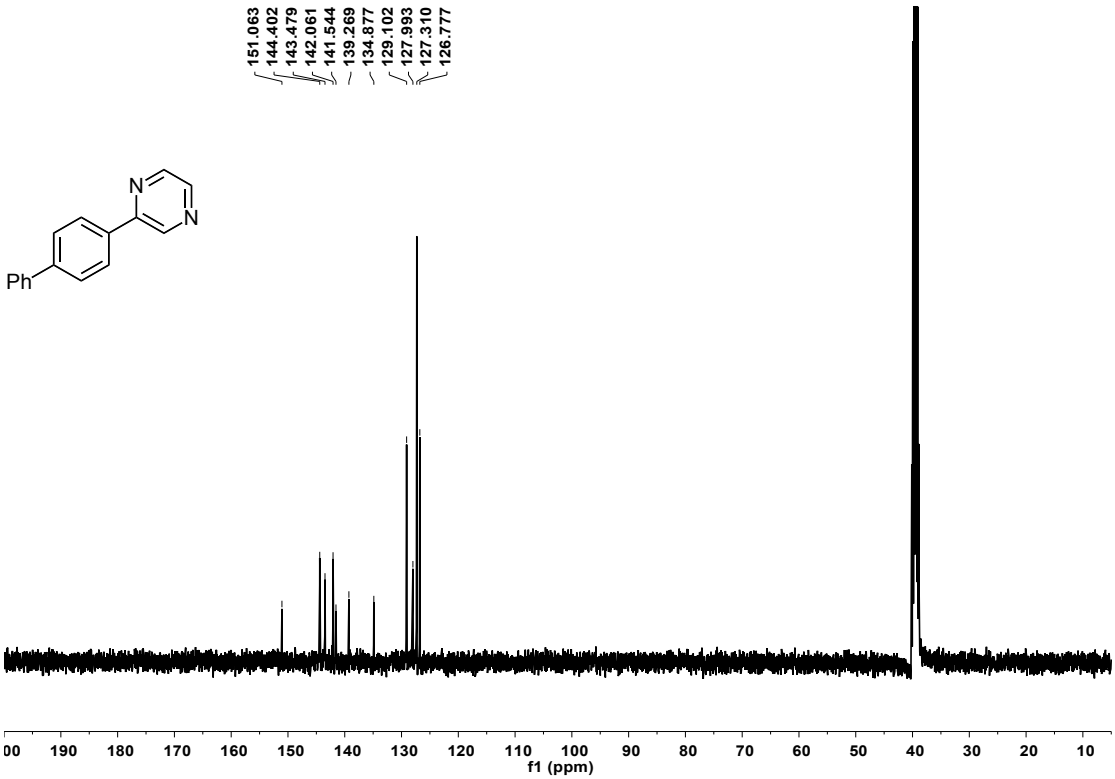

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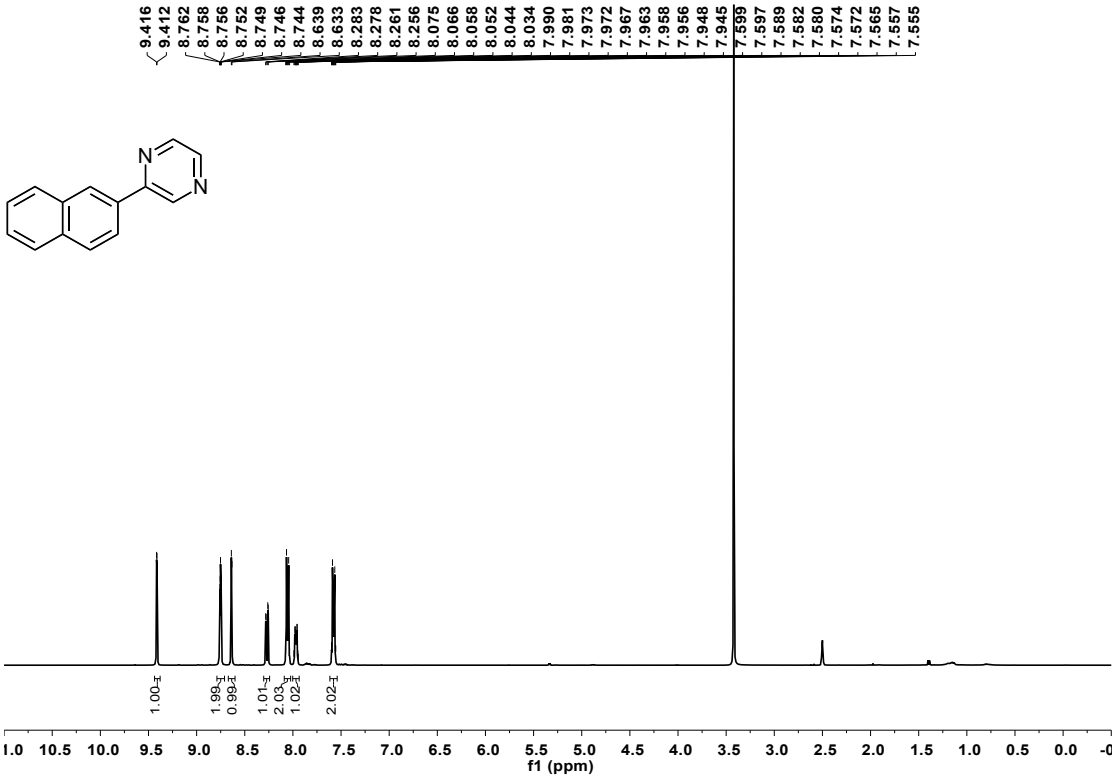


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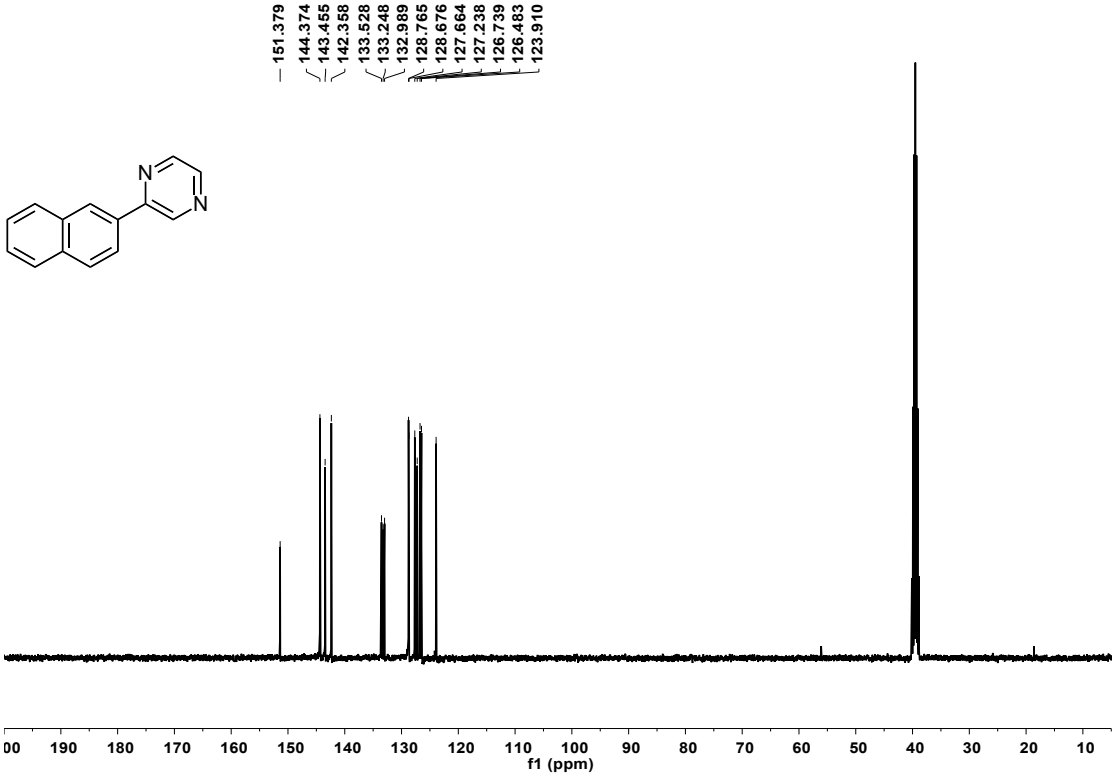
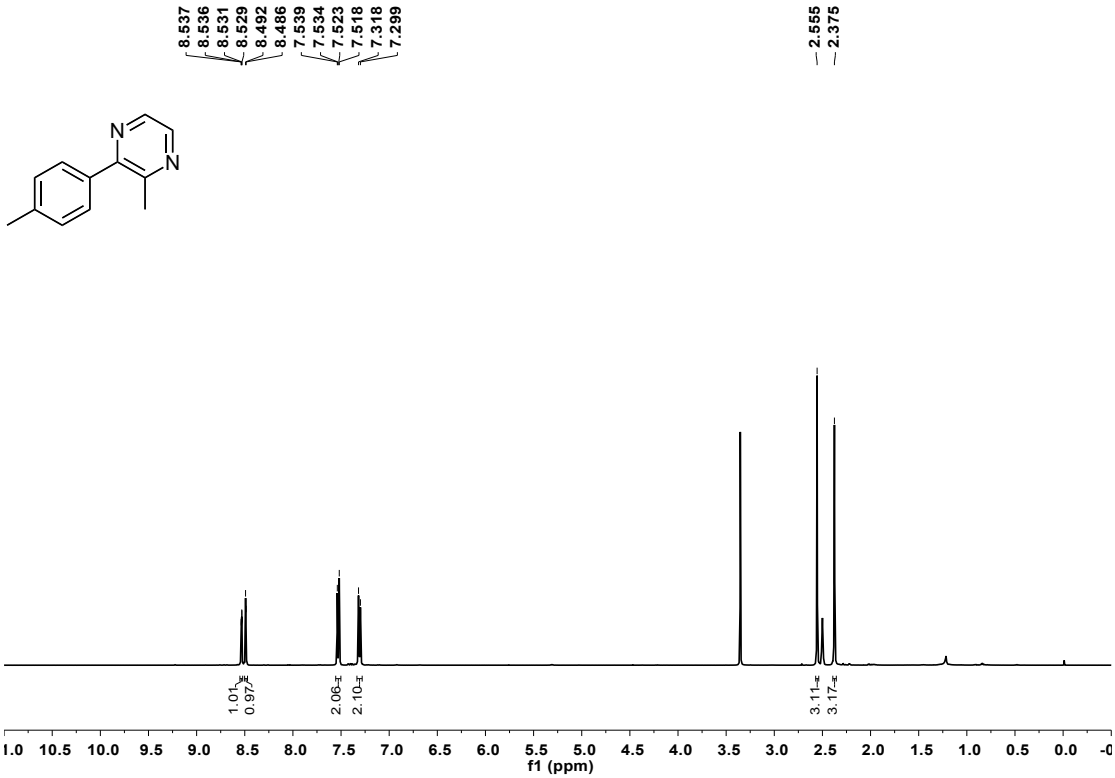


**3ma**

**$^{1}$H NMR**

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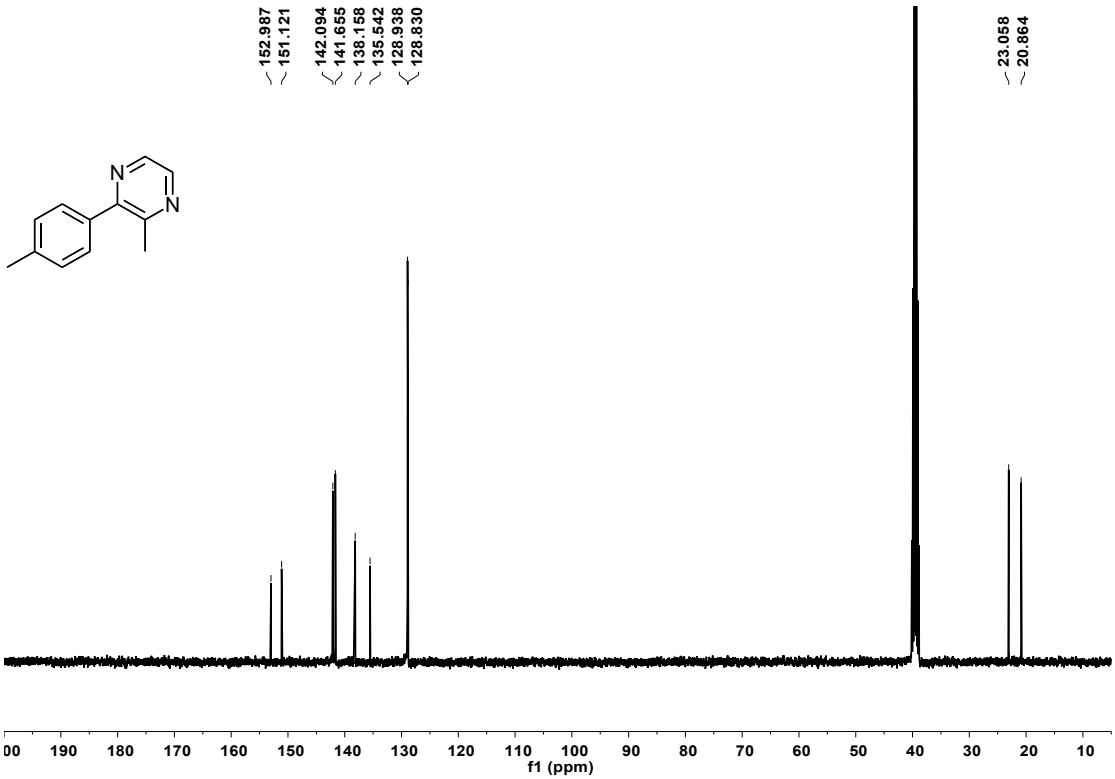

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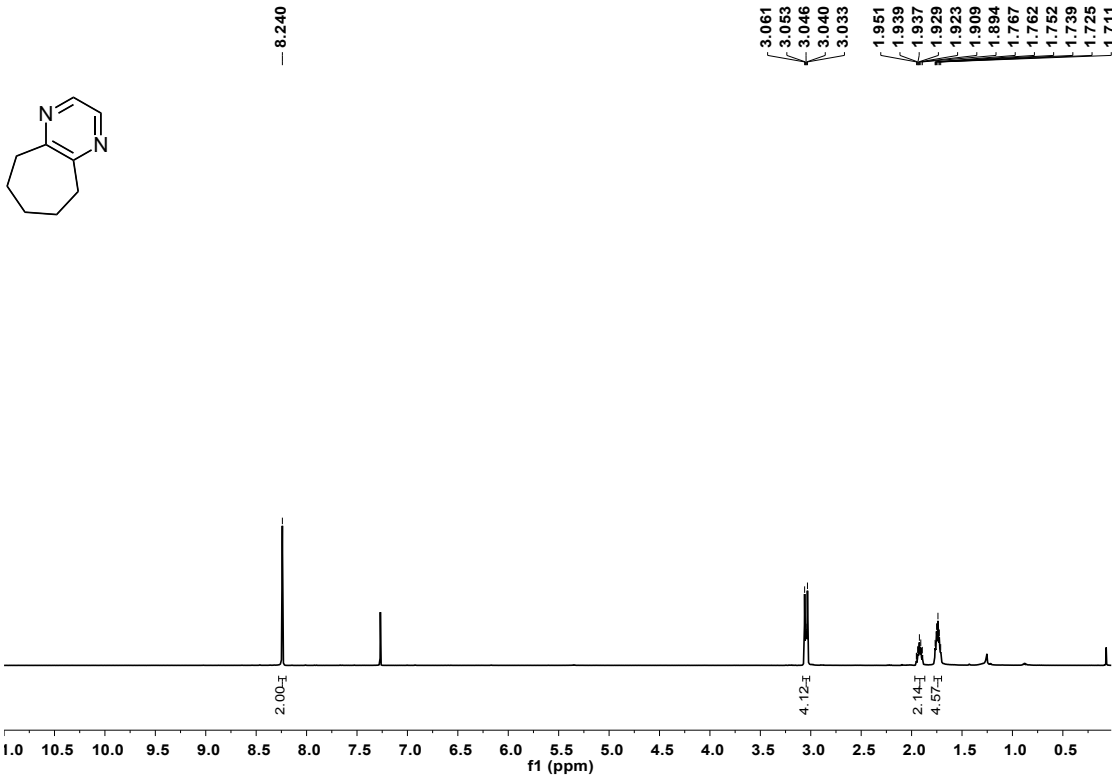


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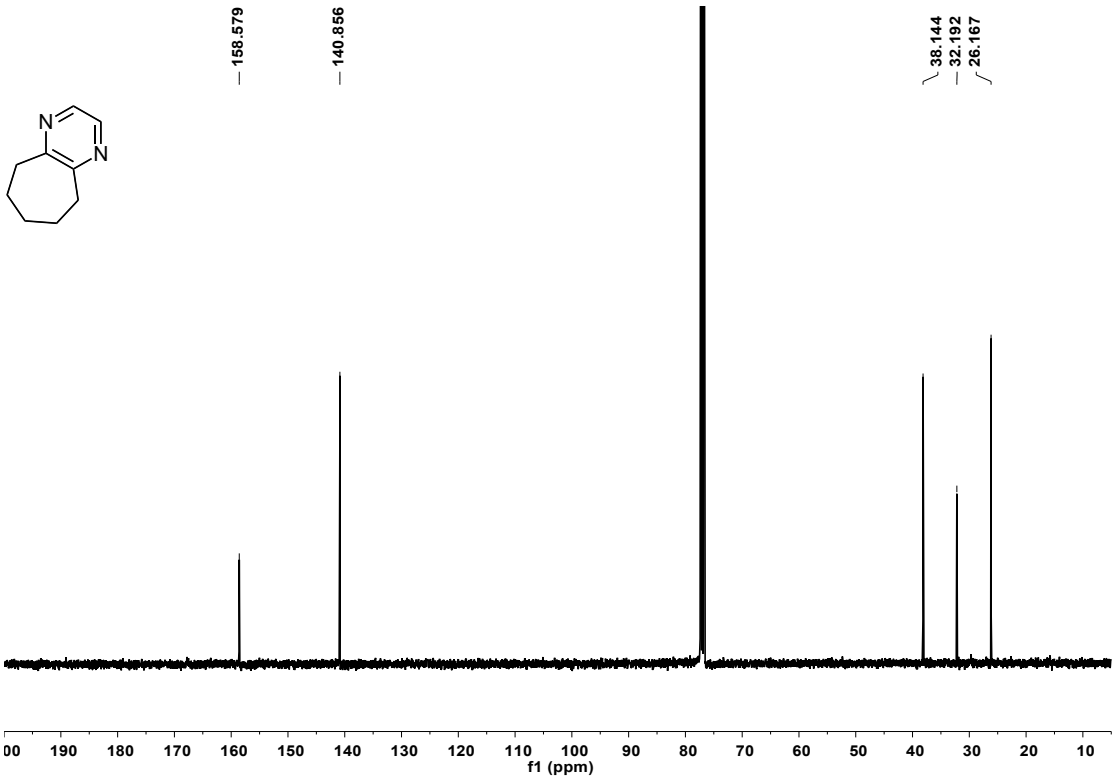

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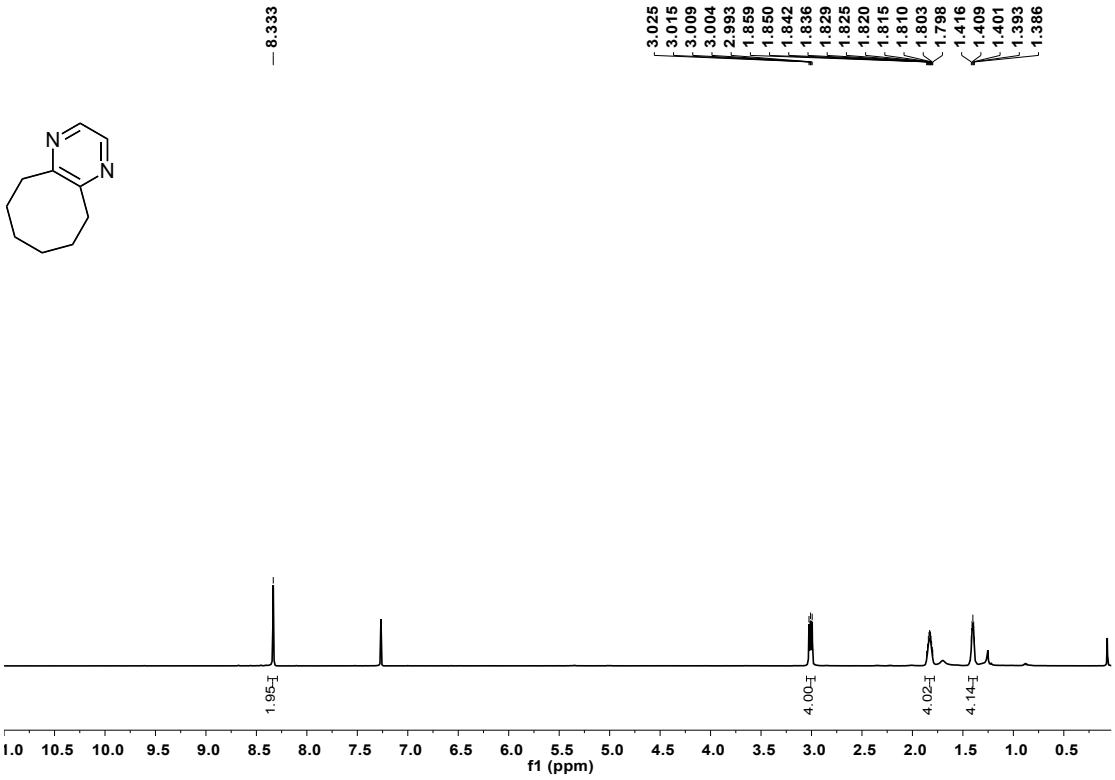


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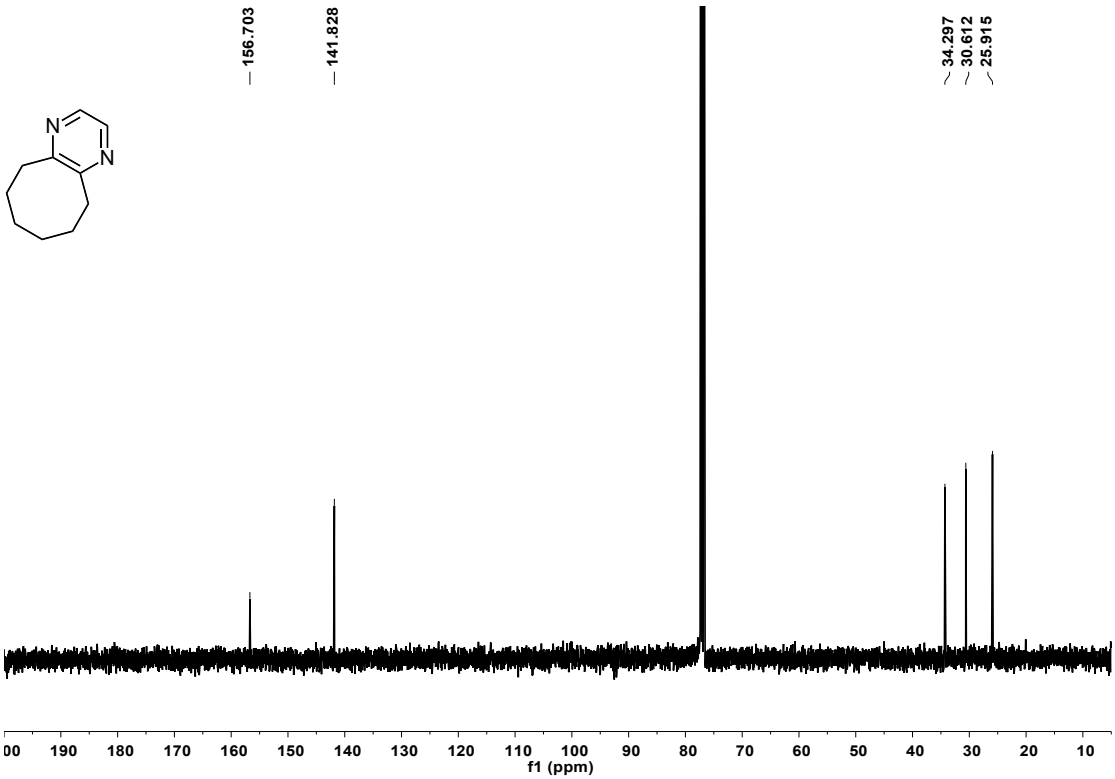

**3ab**

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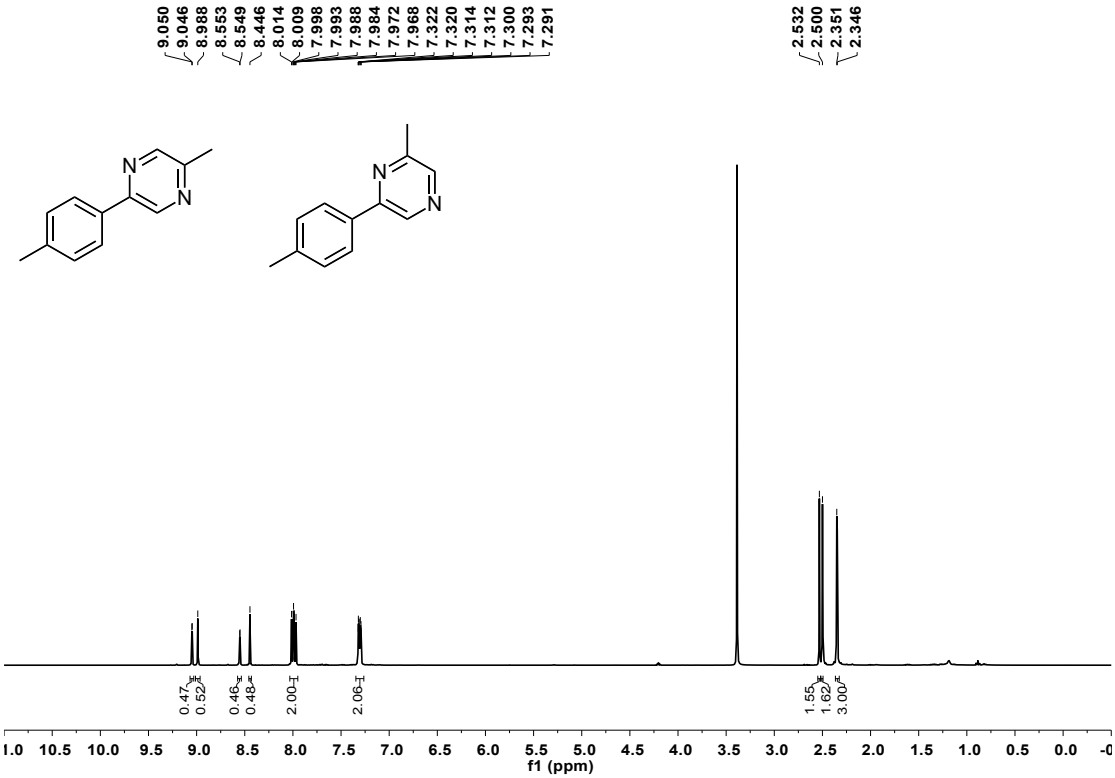
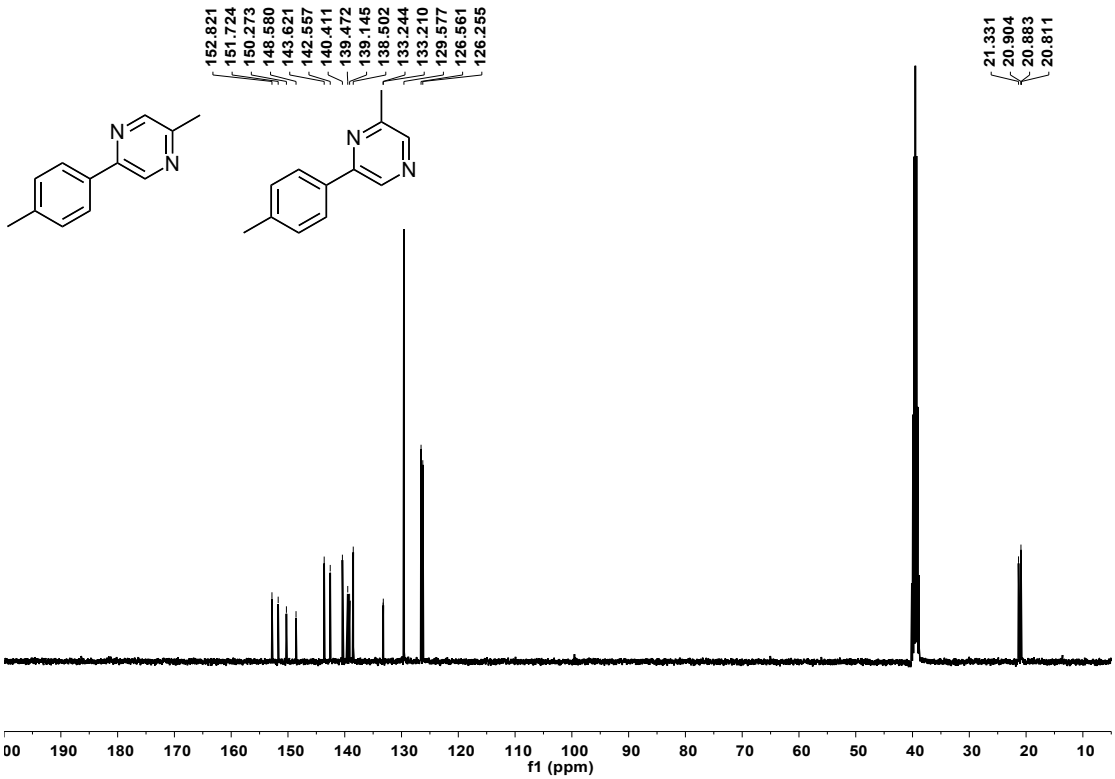
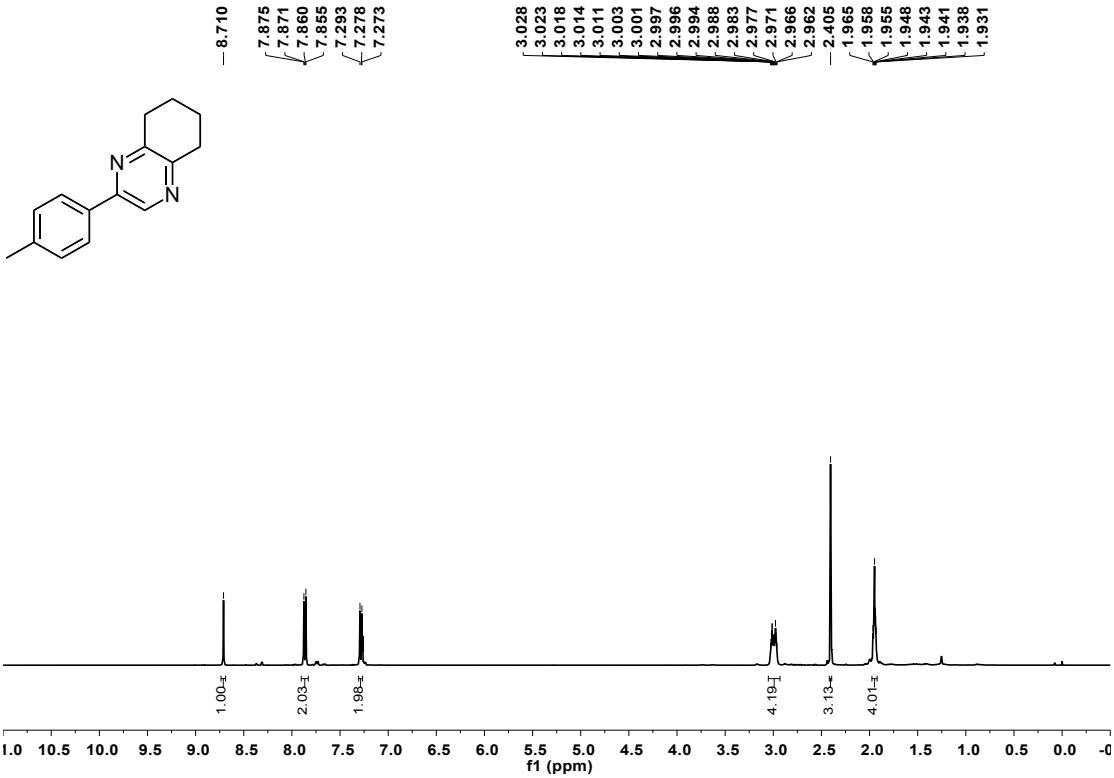



**$^{13}$C NMR**

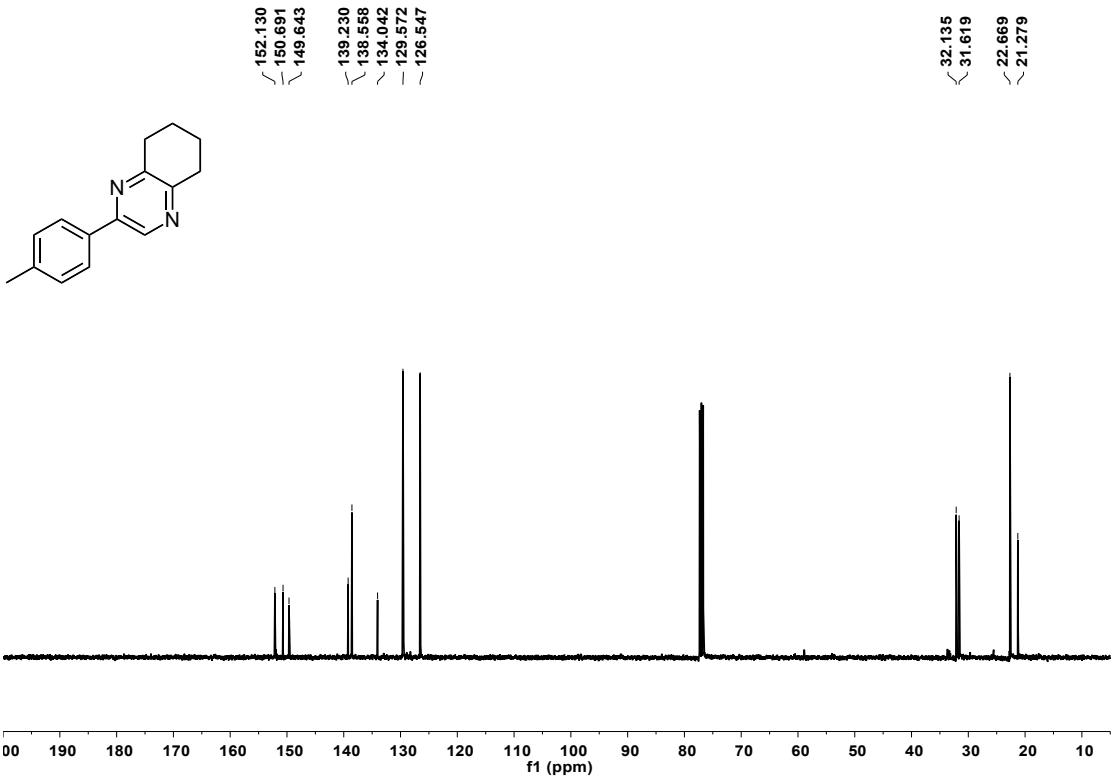


**3ac**

**$^{1}$H NMR**

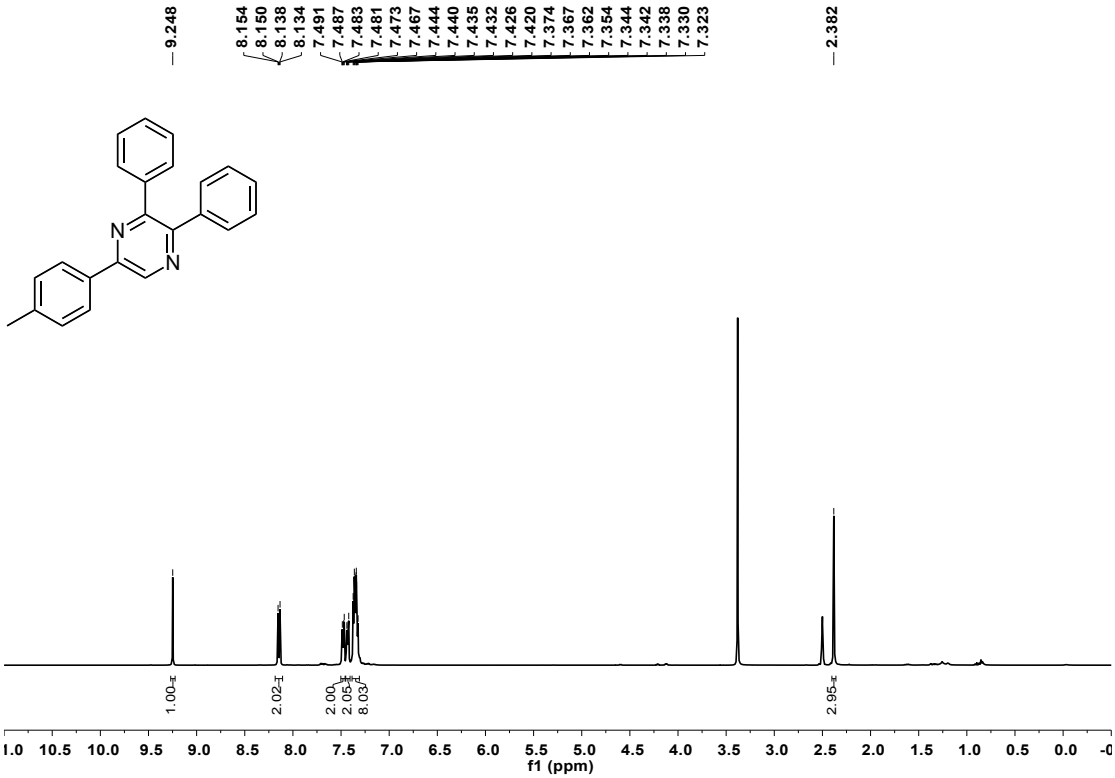



**$^{13}$C NMR**

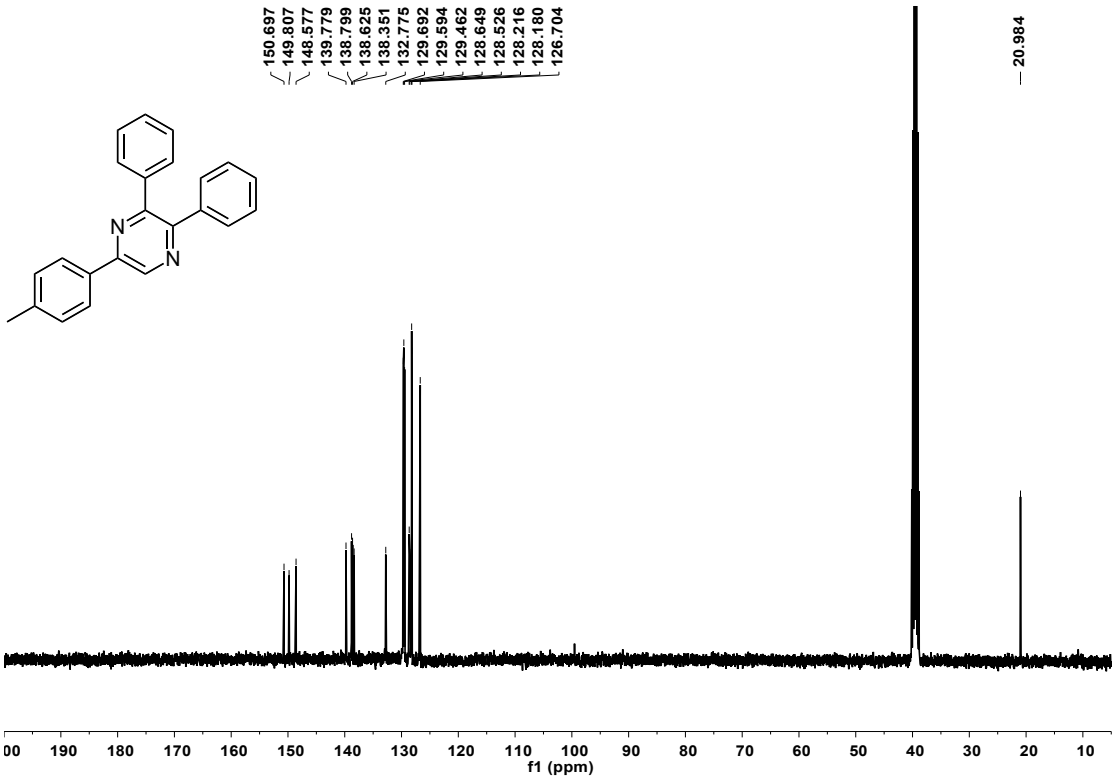


**3ad**

**$^{1}$H NMR**

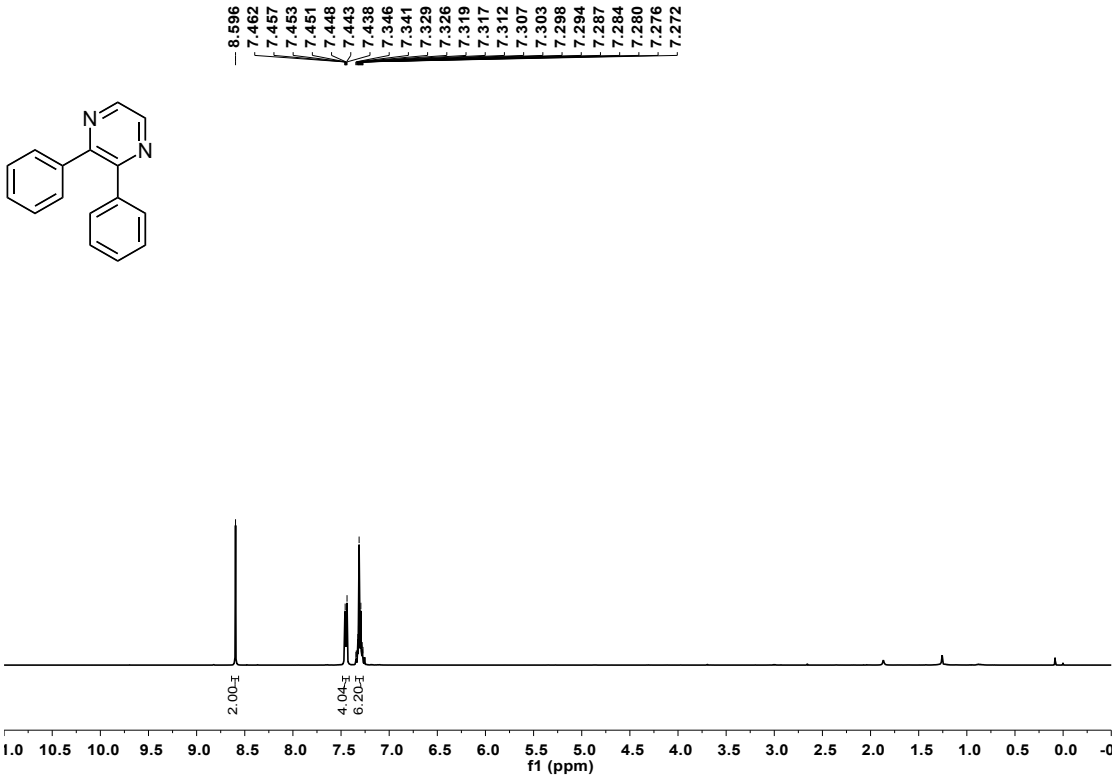



**$^{13}$C NMR**

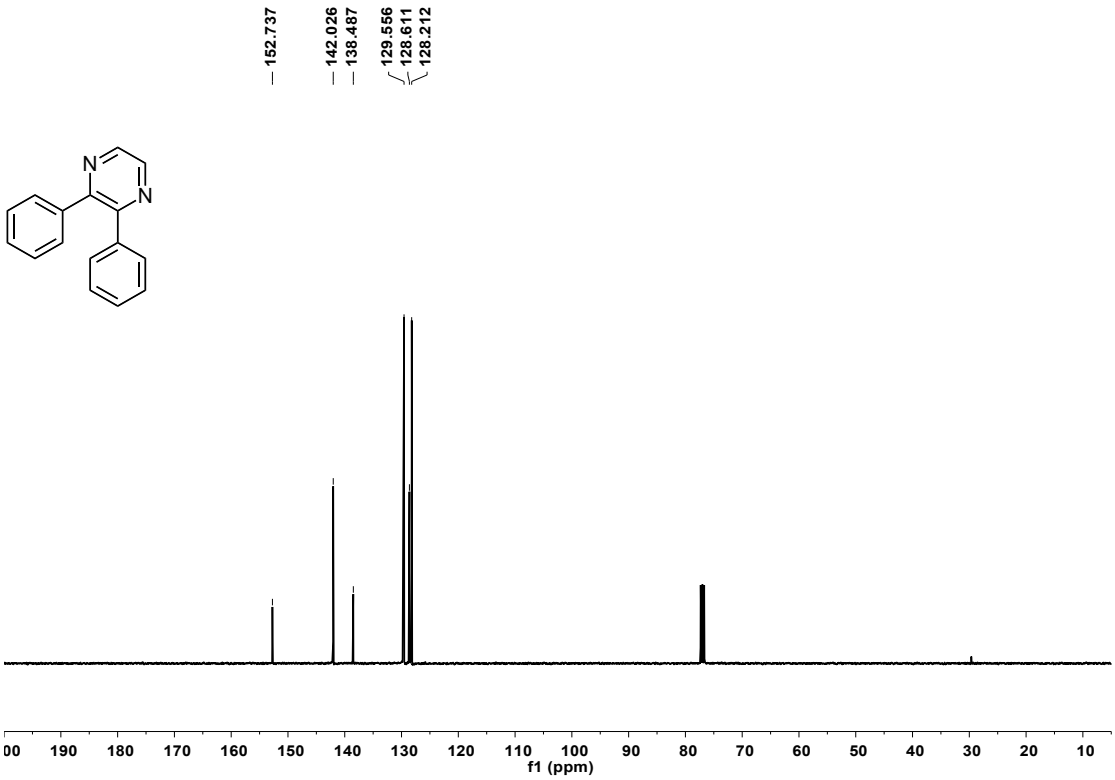


**3pa**

**$^{1}$H NMR**

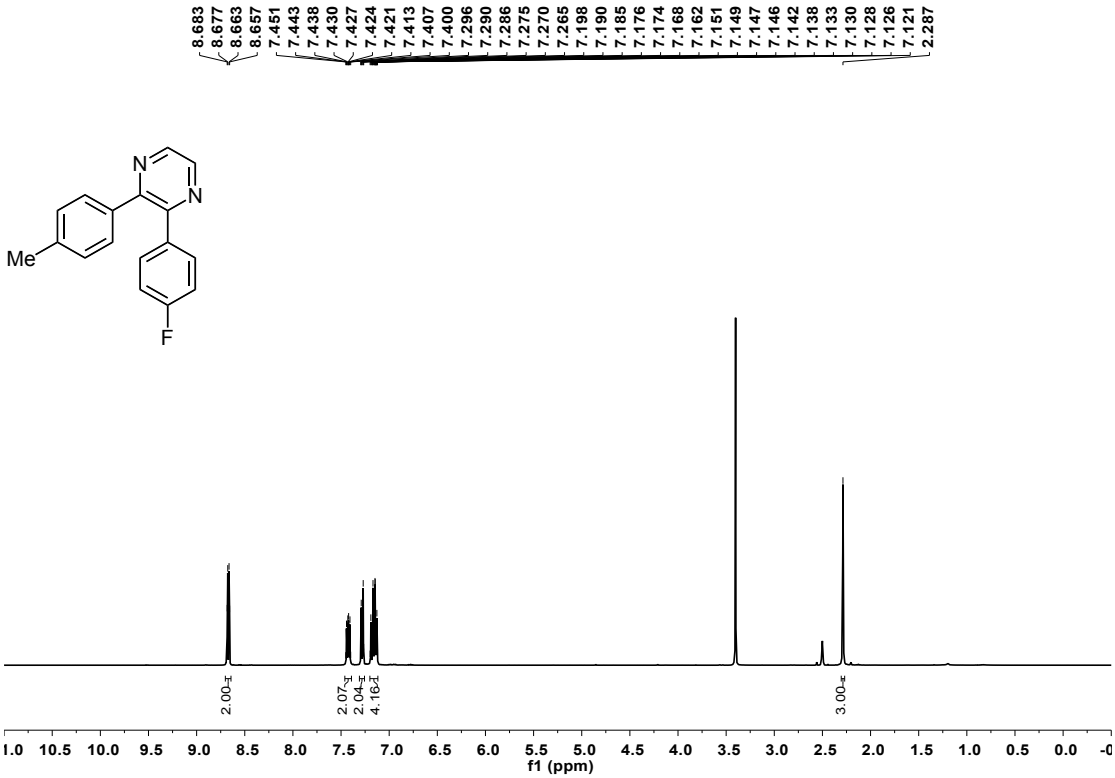



**$^{13}$C NMR**

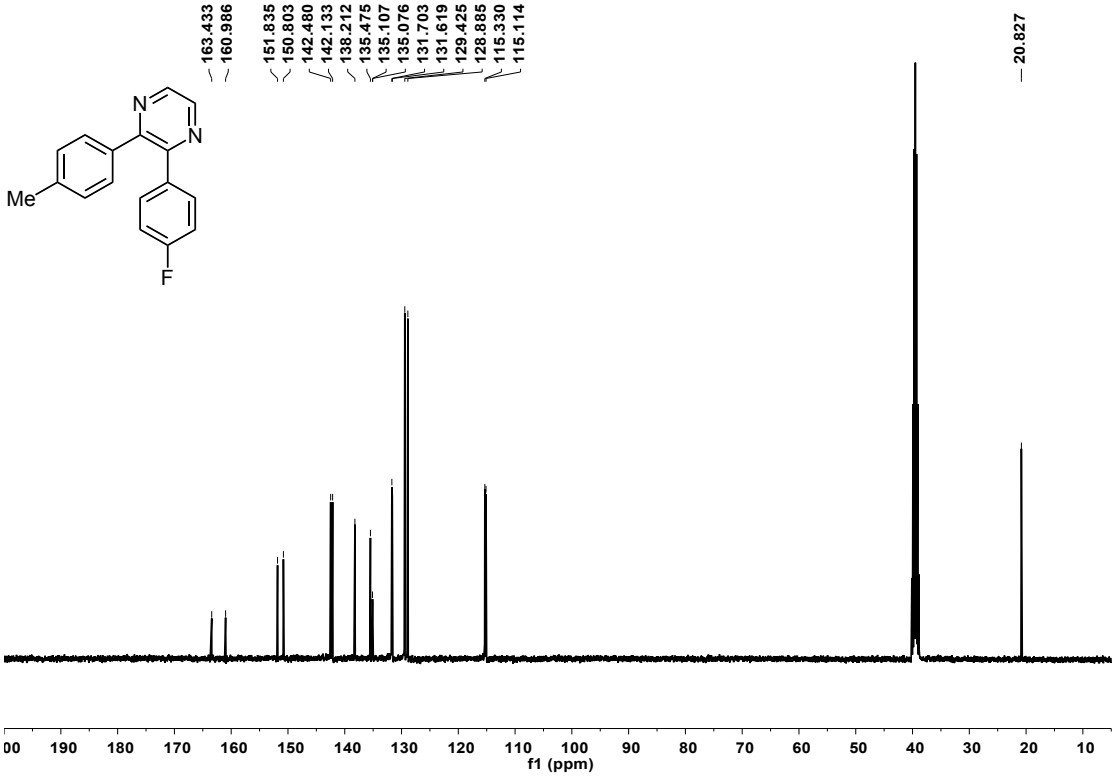


**3qa**

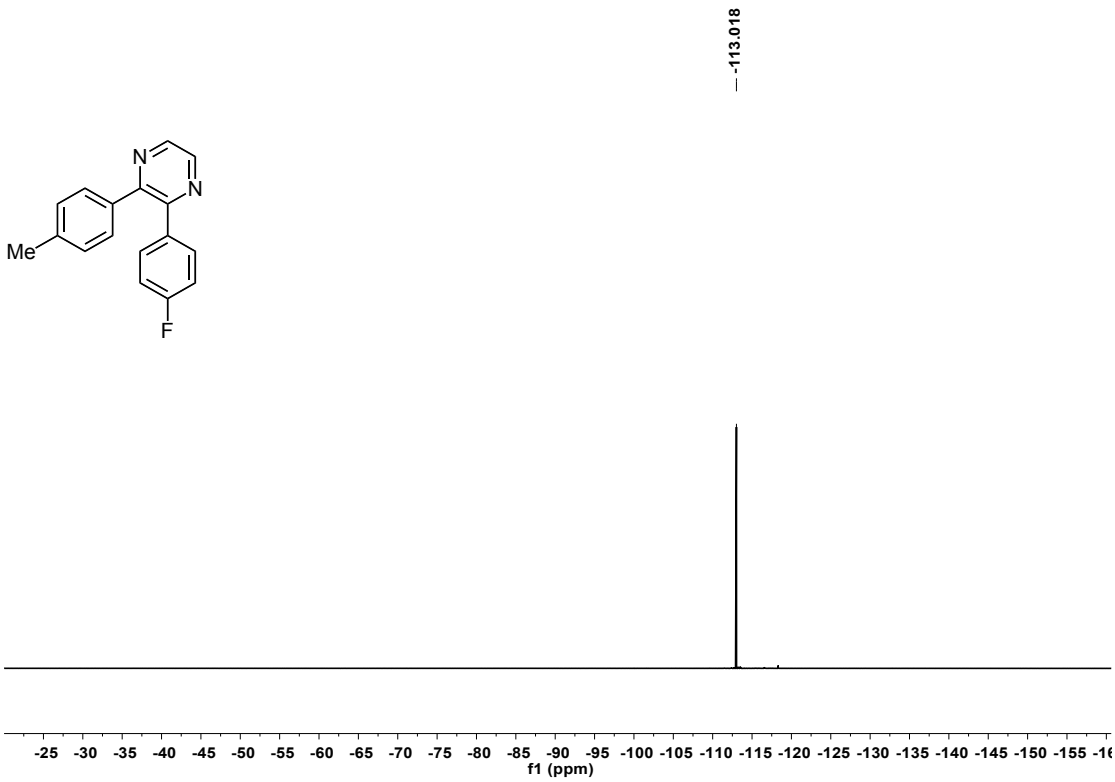
**$^{1}$H NMR**




**$^{13}$C NMR**

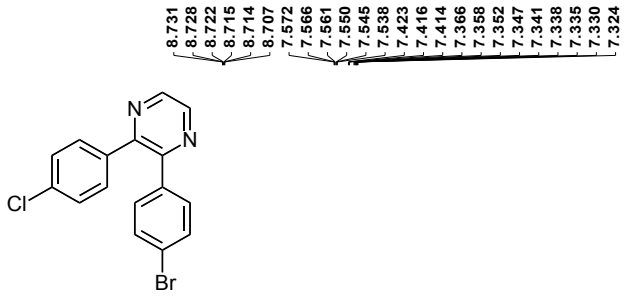


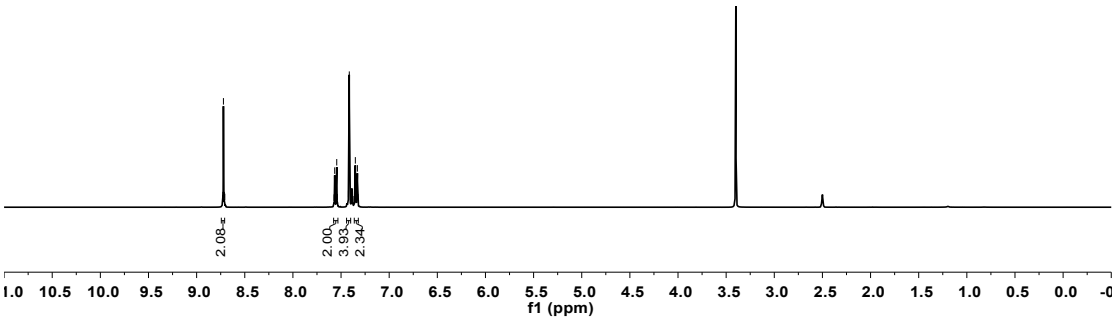
**$^{19}$F NMR**


-113.018
N
N
Me
F
-25 -30 -35 -40 -45 -50 -55 -60 -65 -70 -75 -80 -85 -90 -95 -100 -105 -110 -115 -120 -125 -130 -135 -140 -145 -150 -155
f1 (ppm)

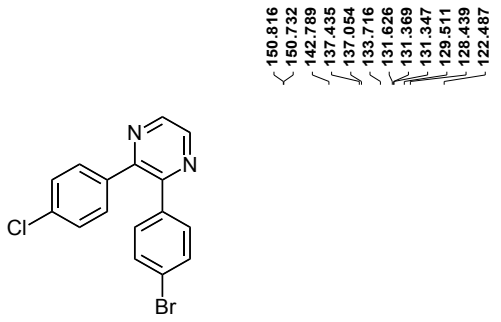
**3ra**

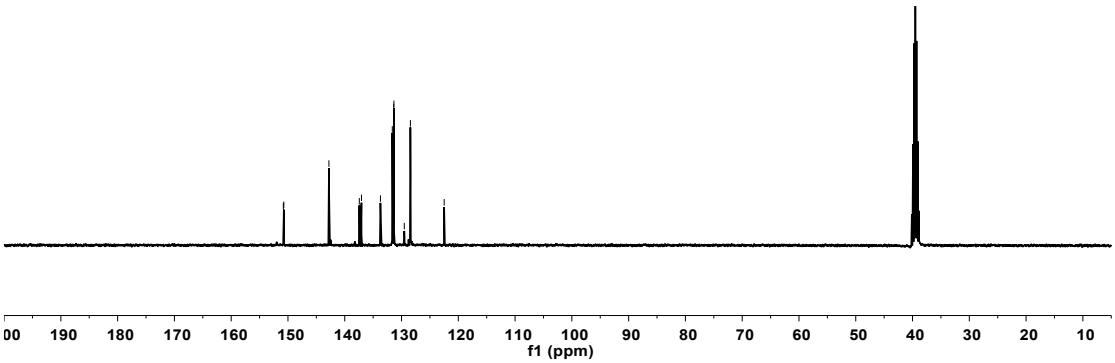
**$^{1}$H NMR**



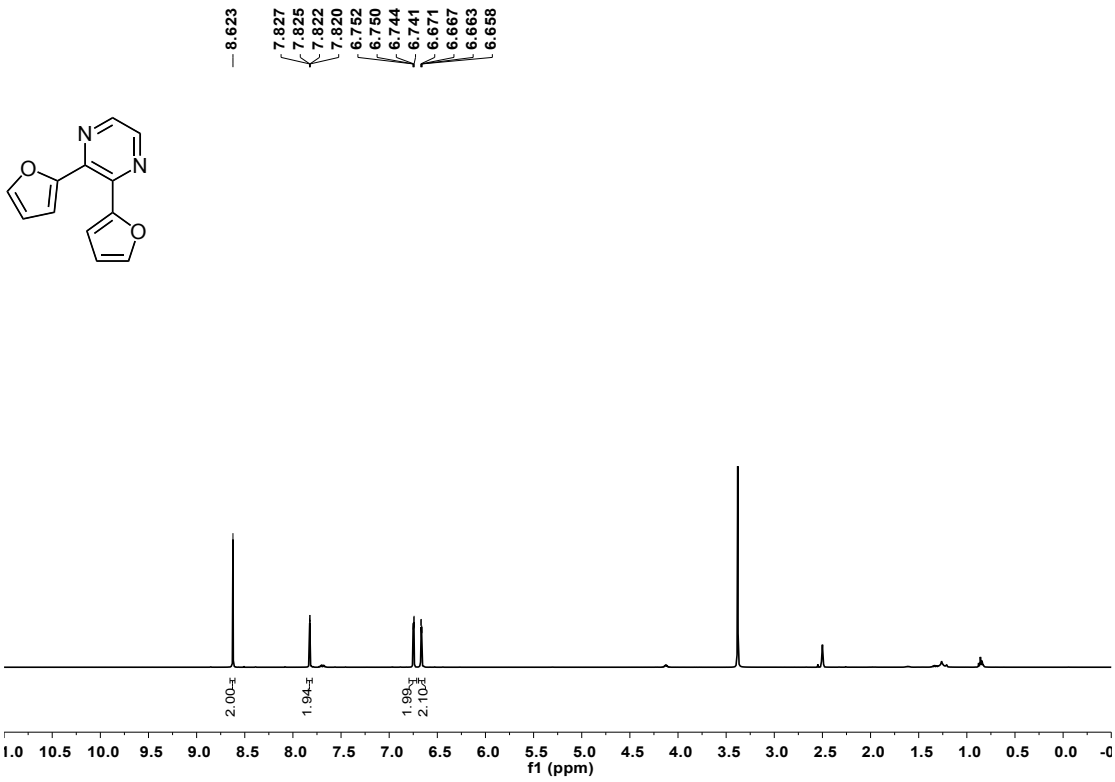

**$^{13}$C NMR**



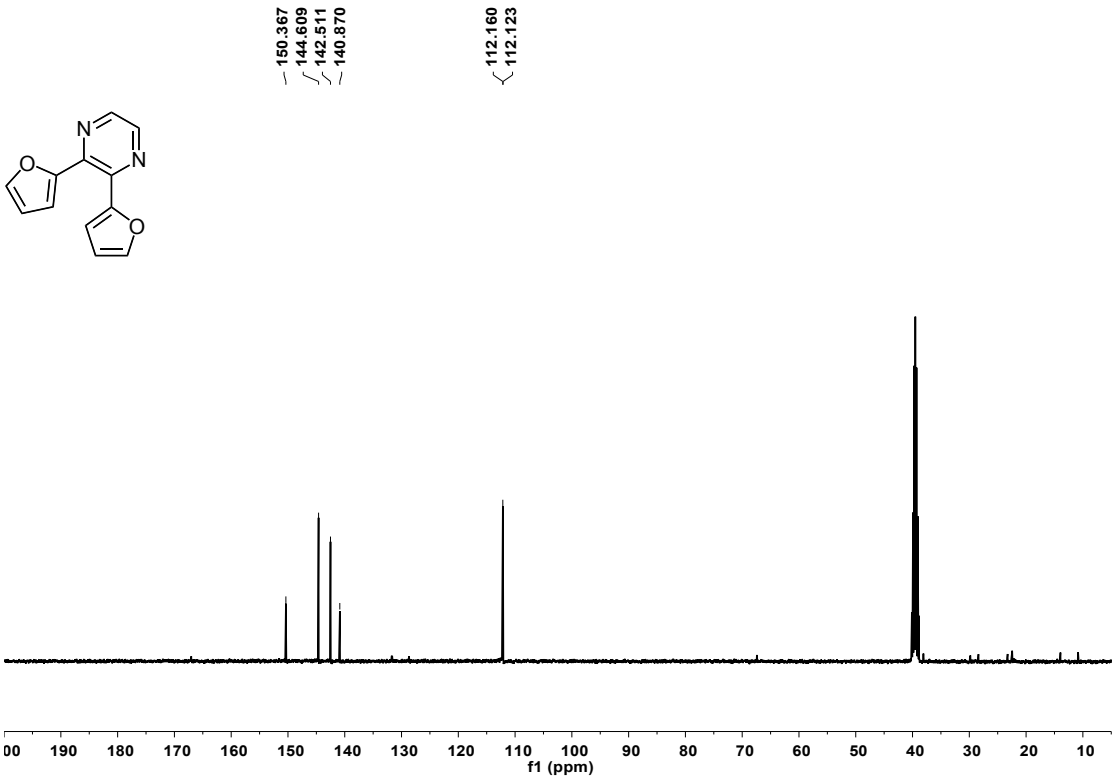



**3sa**

**$^{1}$H NMR**

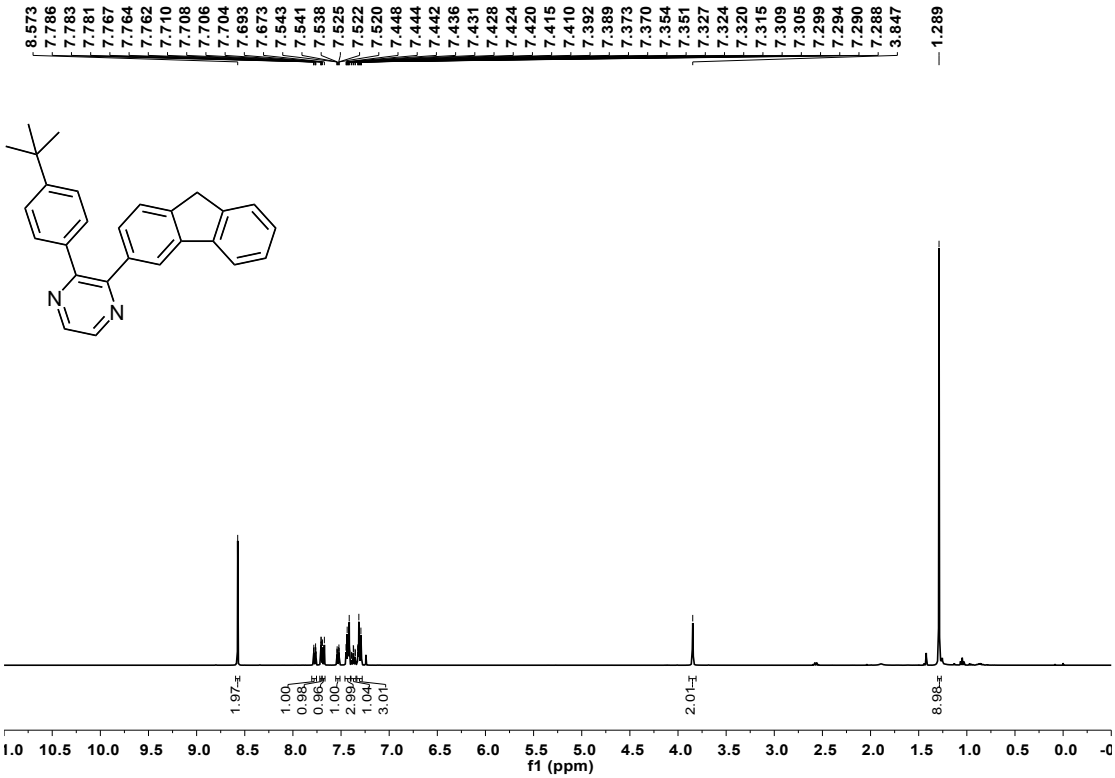



**$^{13}$C NMR**

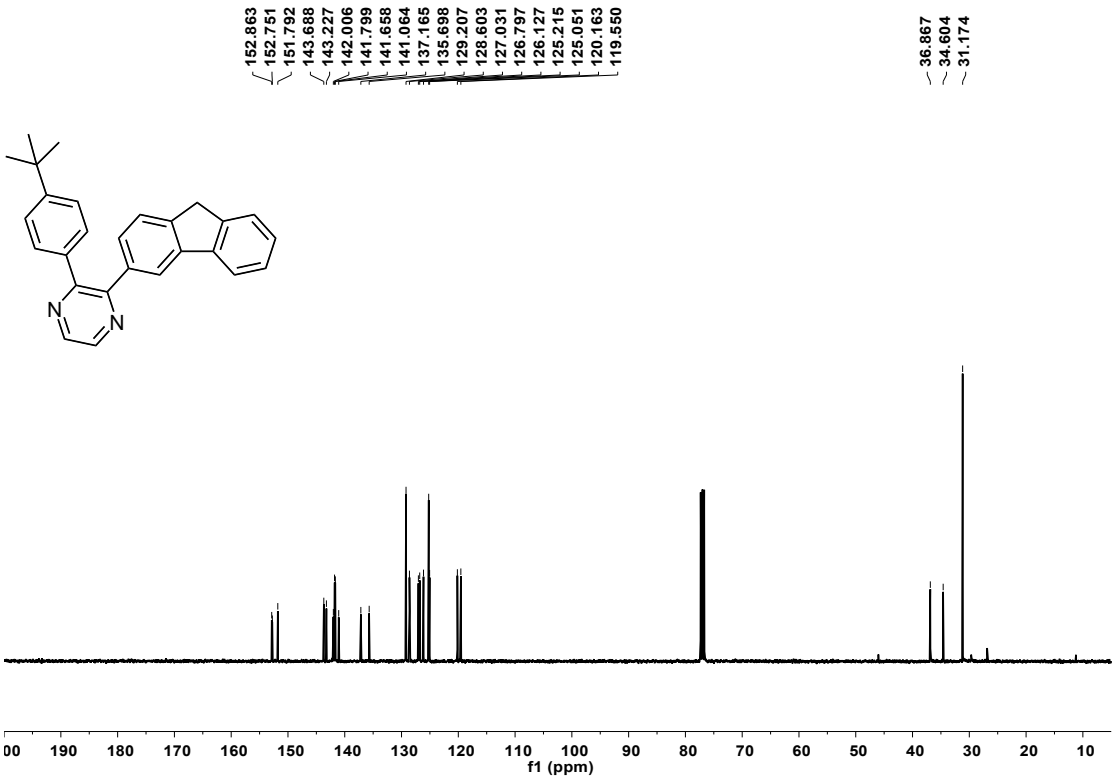


**3ta**

**$^{1}$H NMR**

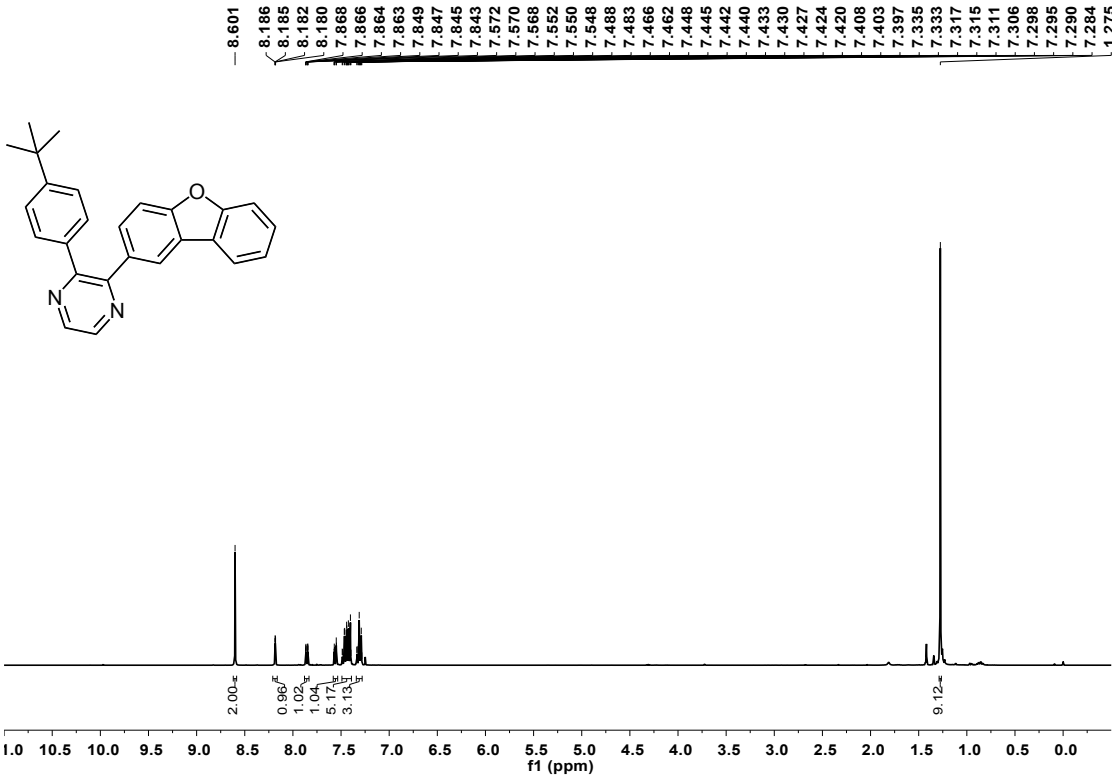



**$^{13}$C NMR**

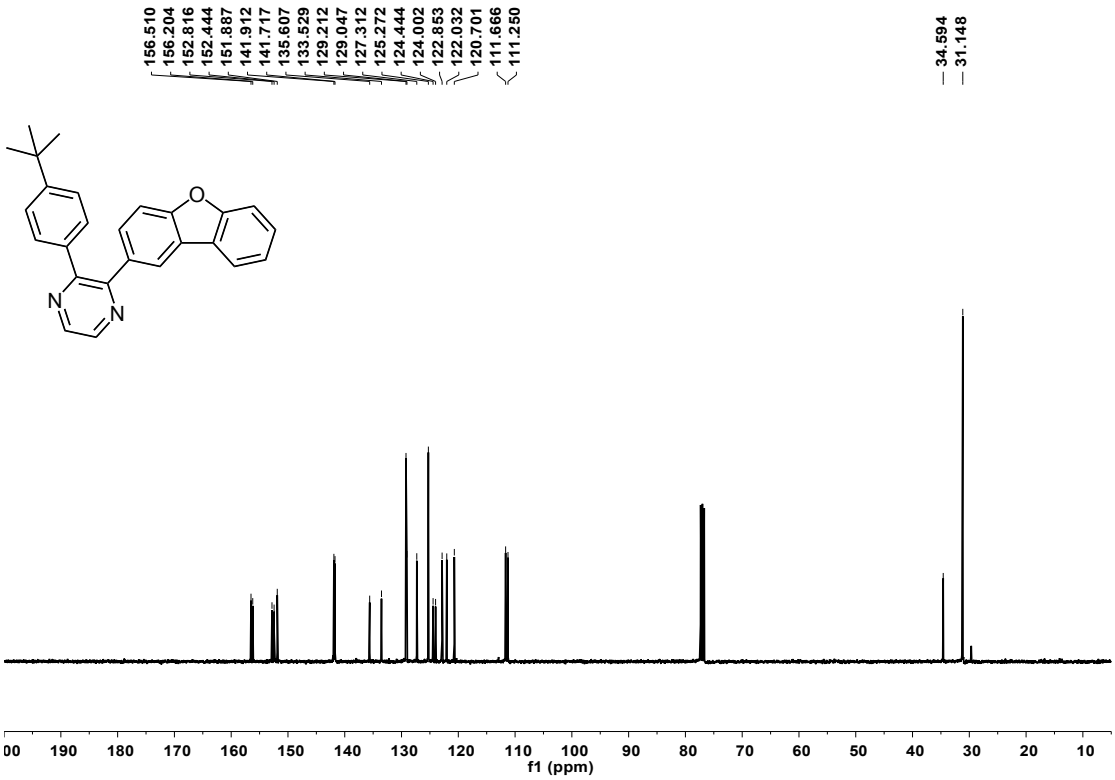


**3ua**

**$^{1}$H NMR**

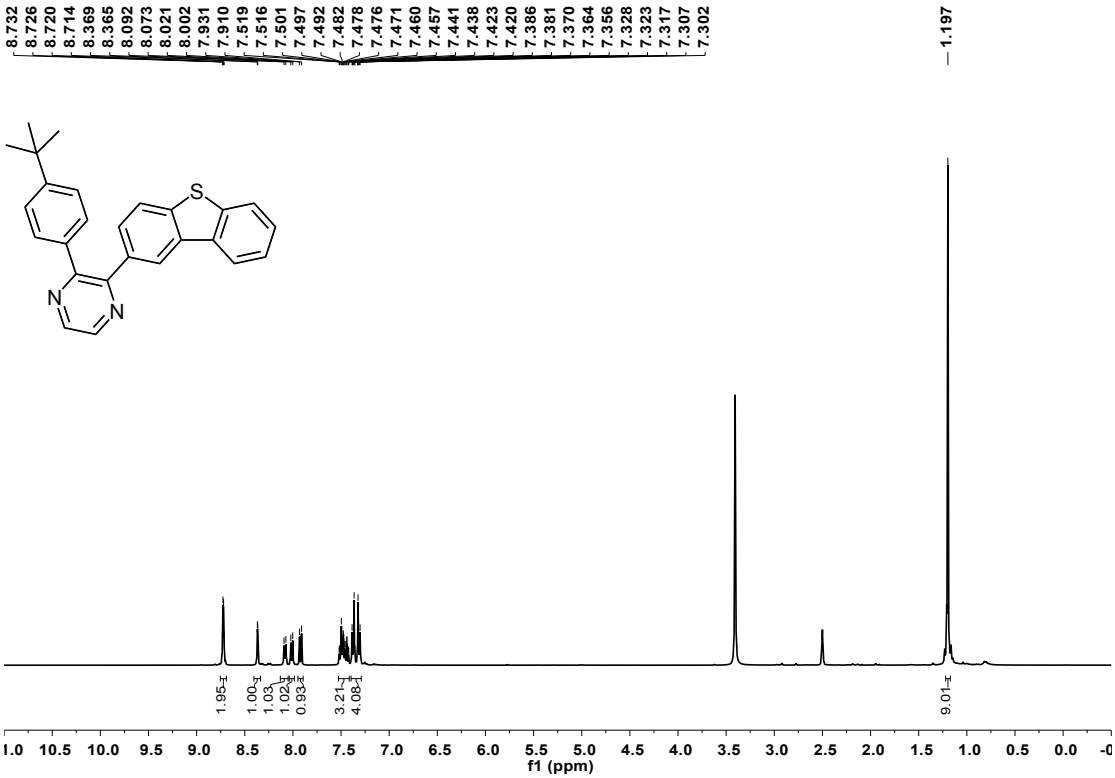



**$^{13}$C NMR**

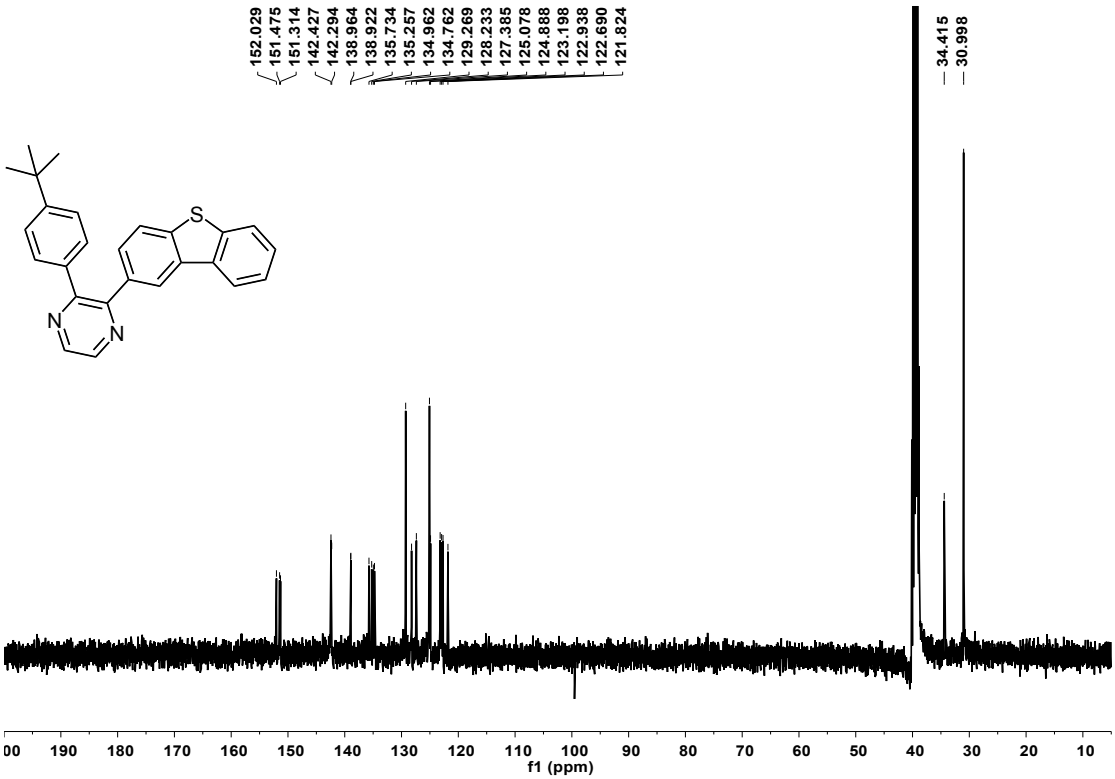


**3va**

**$^{1}$H NMR**

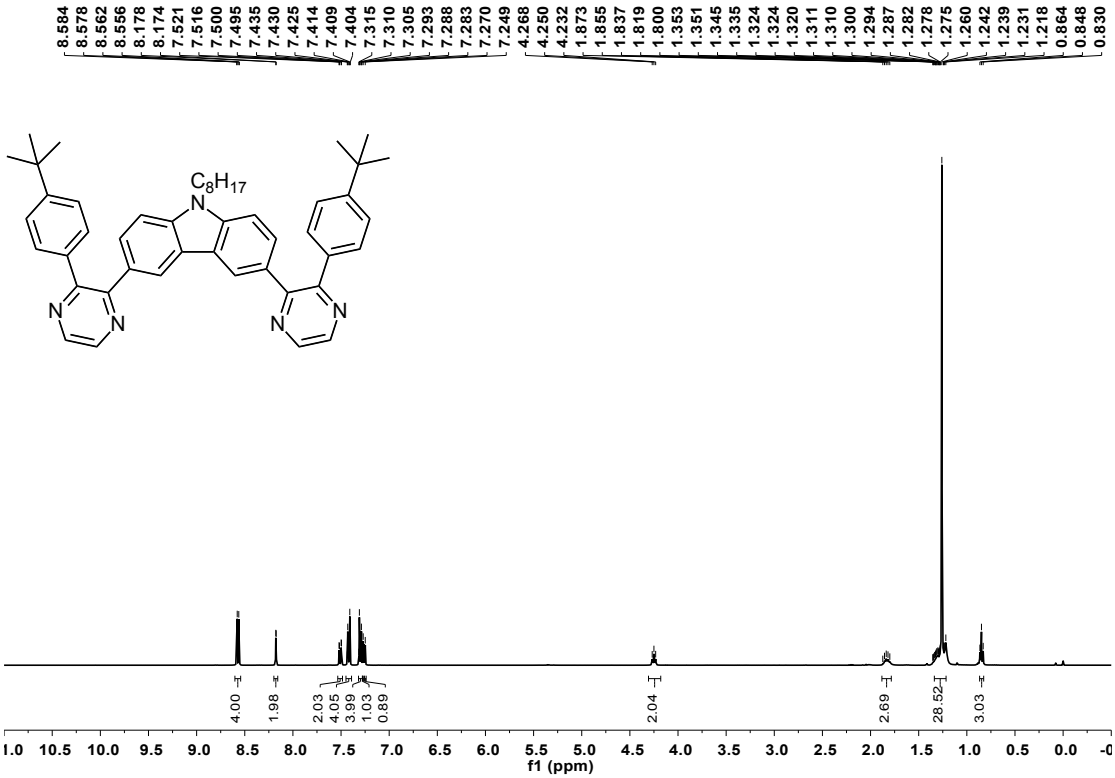



**$^{13}$C NMR**

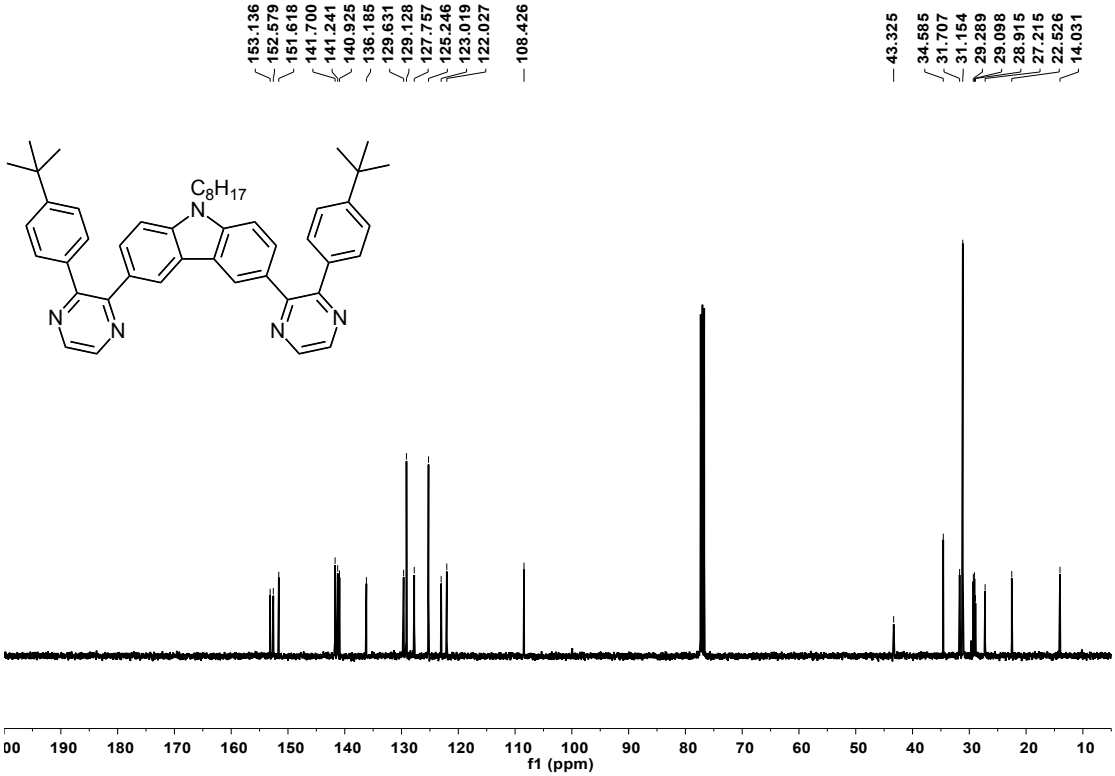


**3wa**

**$^{1}$H NMR**




**$^{13}$C NMR**



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