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Supporting Information

N-monomethylation of amines using paraformaldehyde and H_2

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I. General Information and Experimental Section

General Information:

XRD measurements were conducted by using a STADIP automated transmission diffractometer (STOE) equipped with an incident beam curved germanium monochromator with CuKa1 radiation and current of 40 kV and 150 mA, respectively. The XRD patterns were scanned in the 2 Theta range of 10-85°. XPS were obtained using a VG ES-CALAB 210 instrument equipped with a dual Mg/Al anode X-ray source, a hemispherical capacitor analyzer, and a 5 keV Ar^+ iron gun. The electron binding energy was referenced to the C1s peak at 284.8 eV. The background pressure in the chamber was less than 10-7 Pa. The peaks were fitted by Gaussian–Lorentzian curves after a Shirley background subtraction. For quantitative analysis, the peak area was divided by the element-specific Scofield factor and the transmission function of the analyzer. The BET surface area measurements were performed on a Quantachrome IQ_2 at the temperature of 77 K. The pore size distribution was calculated from the desorption isotherm by using the Barrett, Joyner, and Halenda (BJH) method. Prior to measurements, the samples were degassed at 200 °C for 10 h, at a rate of 10 °C/min. TEM was carried out by using a Tecnai G2 F30 S-Twin transmission electron microscope operating at 300 kV. Single-particle EDX analysis was performed by using a Tecnai G2 F30 S-Twin Field Emission TEM in STEM mode. For TEM investigations, the catalysts were dispersed in ethanol by ultrasonication and deposited on carbon-coated copper grids. Extended X-ray absorption fine structure (EXAFS) experiments were performed at the Beijing Synchrotron Radiation Facility (BSRF) in Beijing Institute of High Energy Physics, Chinese Academy of Sciences with storage ring energy of 2.5 GeV and a beam current between 150 and 250 mA. The Cu K edge absorbance of powder catalysts was measured in transmission geometry at room temperature. The energy was scanned from -200 eV below to 800 eV above the Cu K edge (8979 eV). EXAFS data analysis was carried out using iffeffit analysis programs (http://cars9.uchicago.edu/ifeffit/). NMR spectra were measured by using a Bruker ARX 400 or ARX 100 spectrometer at 400 MHz (^1H) and 100 MHz (^{13}C). Chemical shifts were reported in parts per

million (ppm) down field from TMS with the solvent resonance as the internal standard. Coupling constants (*J*) were reported in Hz and refered to apparent peak multiplications.

Experimental Section:

All solvents and chemicals were obtained commercially and were used as received.

Typical procedure for catalyst preparation:

$Cu(NO_3)_2 \cdot 3H_2O$ (4.356g, 18 mmol) and $Al(NO_3)_3 \cdot 9H_2O$ (6.750 g, 18 mmol) were added to deionized water (60 mL) at rt and agitated until complete dissolution. Then, aqueous Na_2CO_3 (75 mL, 0.9 M) was added dropwise and the mixture was stirred for a further 5 h at 80 ^oC. The reaction mixture was centrifuged and washed with water to remove the base until the pH value of the aqueous solution was ≈ 7. Subsequently, the solid was dried at 100 ºC in air for 5 h, calcined at 400 °C for 4 h, and then reduced under a hydrogen flow at 450 ºC for 2.0 h. The resulting catalyst samples were denoted as CuAlOx(5 : 5).

Typical procedure for N-monomethylation of amines with $(HCHO)_n$ and H_2

A mixture of aniline **1a** (97 mg, 1.0 mmol), paraformaldehyde (36 mg, 1.2 mmol), $CuAlO_x$(5:5) (20 mg) and THF (3 mL) were added a glass tube which was placed in an 100 mL autoclave. Then the autoclave was purged and charged with H_2 (0.5 MPa) three times. The reaction mixture was stirred at 120 ^oC for 9 h. After the reaction finished, the autoclave was cooled to room temperature and the pressure was carefully released. Subsequently, the reaction mixture was diluted with 5 mL of methanol for quantitative analysis by GC-FID (Agilent 7890A). The crude reaction mixture was concentrated by rotary evaporator and purified by column chromatography on a silica gel column. The isolated product was treated with HCl to give the desired produts **3a**.

Typical procedure for N-monomethylation of benzylamine with formaldehyde and H_2

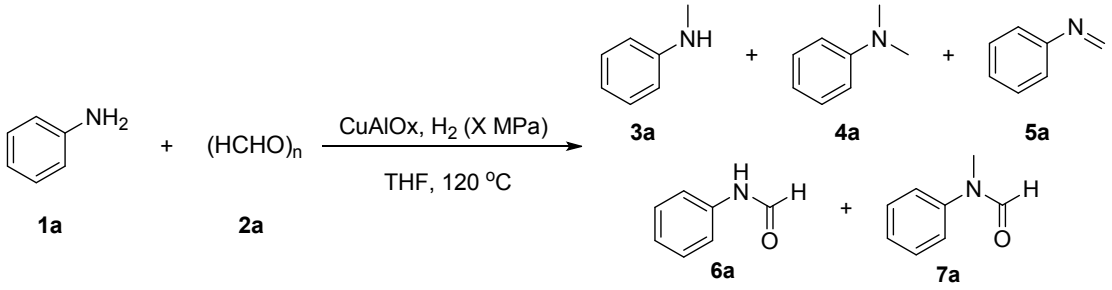
A mixture of benzylamine **1m** (128 mg, 1.2 mmol), 37% formaldehyde (81 mg, 1.0 mmol), and THF (3 mL) were added a glass tube which was placed in an 100 mL autoclave. The reaction mixture was stirred at 120 ^oC for 9 h. Then, the autoclave was cooled to room temperature and purged and charged with H_2 (0.5 MPa) three times. The reaction mixture was stirred at 140 ^oC for 9 h. After the reaction finished, the autoclave was cooled to room temperature and the pressure was carefully released. Subsequently, biphenyl was added to the reaction mixture which was diluted with 7 mL of methanol for quantitative analysis by GC-FID (Agilent 7890A).

Typical procedure for N-monomethylation of cyclohexylamine with formaldehyde and H_2

A mixture of cyclohexylamine **1n** (120 mg, 1.2 mmol), 37% formaldehyde (81 mg, 1.0 mmol), and THF (3 mL) were added a glass tube which was placed in an 100 mL autoclave. The reaction mixture was stirred at 120 ^oC for 9 h. Then, the autoclave was cooled to room temperature and purged and charged with H_2 (0.5 MPa) three times. The reaction mixture was stirred at 140 ^oC for 9 h. After the reaction finished, the autoclave was cooled to room temperature and the pressure was carefully released. The crude reaction mixture was filtered and filtrate was concentrated by rotary evaporator. $MeNO_2$ was added to mixture for quantitative analysis by ^1H NMR.

II. Characterization results of catalysts

1. Table S1. Reaction conditions optimization for N-methylation of aniline[a]



Entry	$CuAlO_X$	H_2 (x MPa)	solvent	Conv.[b] (%)	Sel.[c] (%)				
					3a	4a	5a	6a	7a
1	(2 : 8) 50 mg	1.0	THF	80	76	10	13	--	--
2	(3 : 7) 50 mg	1.0	THF	78	87	1	10	2	--
3	(5 : 5) 50 mg	1.0	THF	94	97	3	--	--	--
4	(7 : 3) 50 mg	1.0	THF	90	91	9	--	--	--
5	(8 : 2) 50 mg	1.0	THF	90	91	8	--	1	--
6	(5 : 5) 50 mg	1.0	toluene	75	44	48	--	2	1
7	(5 : 5) 50 mg	1.0	1,4-dioxane	90	98	2	--	--	--
8	(5 : 5) 50 mg	1.0	cyclohexane	86	94	6	--	--	--
9	(5 : 5) 30 mg	1.0	THF	91	98	2	--	--	--
10	(5 : 5) 20 mg	1.0	THF	96	96	4	--	--	--
11	(5 : 5) 10 mg	1.0	THF	94	89	3	3	3	2
12	(5 : 5) 5 mg	1.0	THF	93	77	2	13	6	2
13	(5 : 5) 20 mg	0.5	THF	89	94	1	2	2	2
14	(5 : 5) 20 mg	0.2	THF	83	95	--	3	1	--
15[d]	(5 : 5) 20 mg	0.5	THF	80	96	1	--	3	--
16[e]	(5 : 5) 20 mg	0.5	THF	56	3	--	97	--	--
17[f]	**(5 : 5) 20 mg**	**0.5**	**THF**	**97(98[g])**	**93(91[g])**	**7(9[g])**	**--**	**--**	**--**

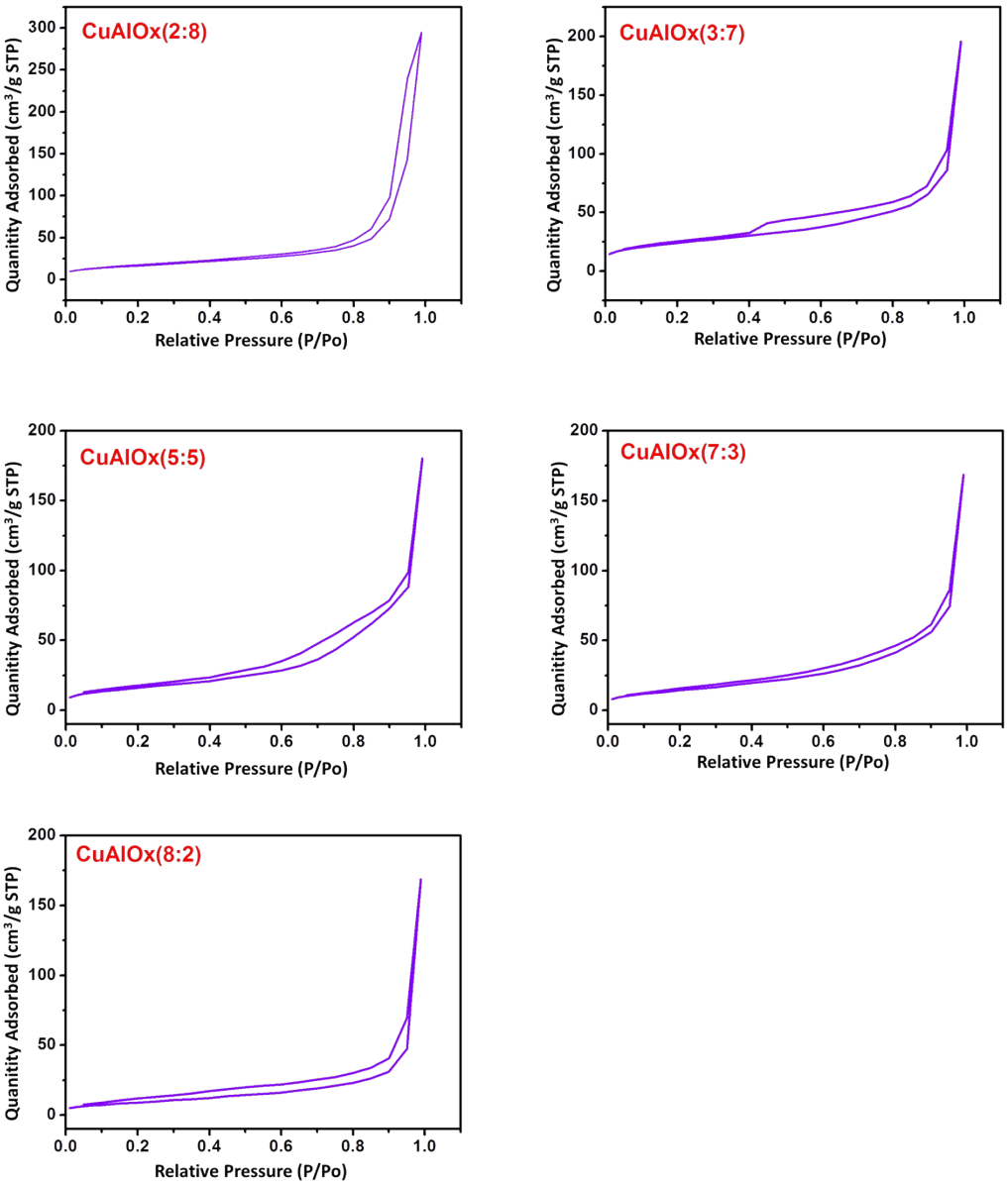
[a]1a (1.0 mmol), paraformaldehyde (1.2 mmol), CuAlOx (5 : 5) (20 mg), H_2 (1.0 Mpa), THF (3.0 mL), 120 °C, 5 h; [b]Conversion of aniline was determined by GC-MC; [c]Selectivity by GC-MS analysis based on the aniline consumed; [d]100 °C; [e]80 °C; [f]9 h. [g]The catalyst was recovered and reused at the 3rd run.

2. Table S2. The physical properties of catalysts

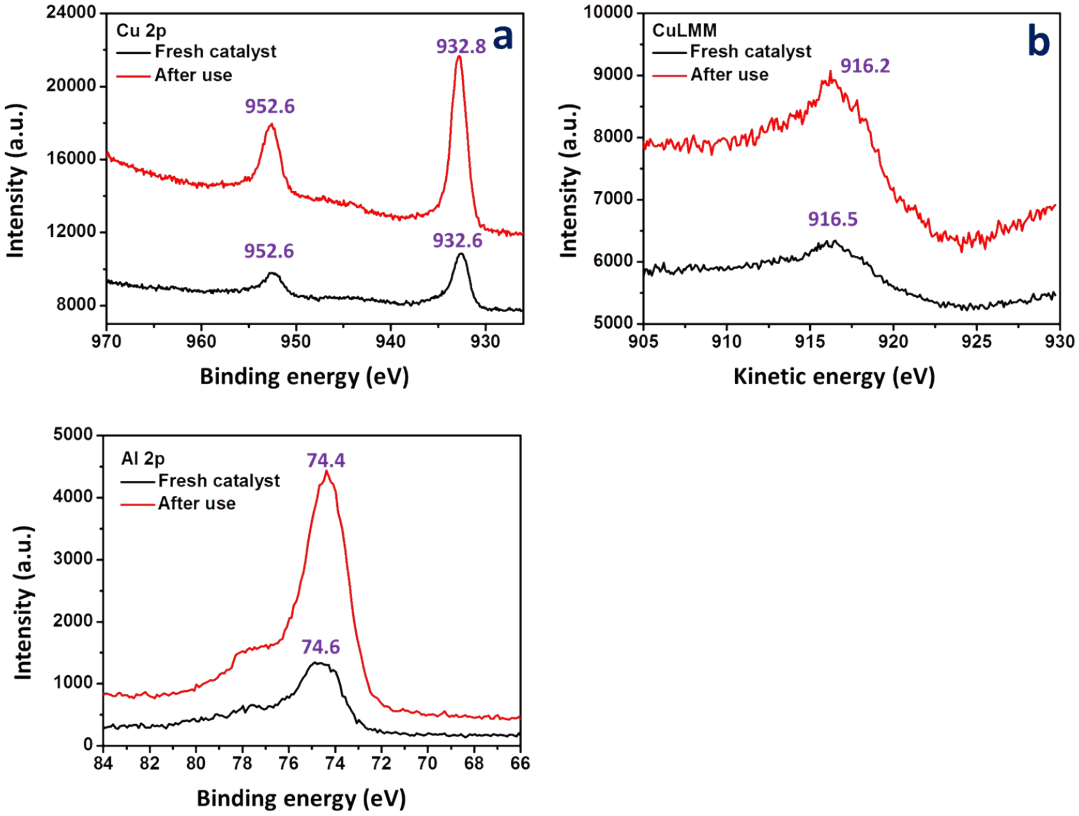
Entry	Catalysts	Cu[a] wt%	SA[b] (m^2/g)	PV[b] (cm^3/g)	APS[b] (nm)
1	CuAlOx (2:8)	17	59.2	0.46	15.4
2	CuAlOx (3:7)	27	85.9	0.30	7.0
3	CuAlOx (5:5)	57	58.7	0.28	9.5
4	CuAlOx (7:3)	82	52.4	0.27	10.0
5	CuAlOx (8:2)	83	36.3	0.26	15.5

[a] Determined by ICP-AES. [b]Determined by an IQ_2 automated gas sorption analyser. SA:Surface area; PV: Pore volume; APS: Average pore size

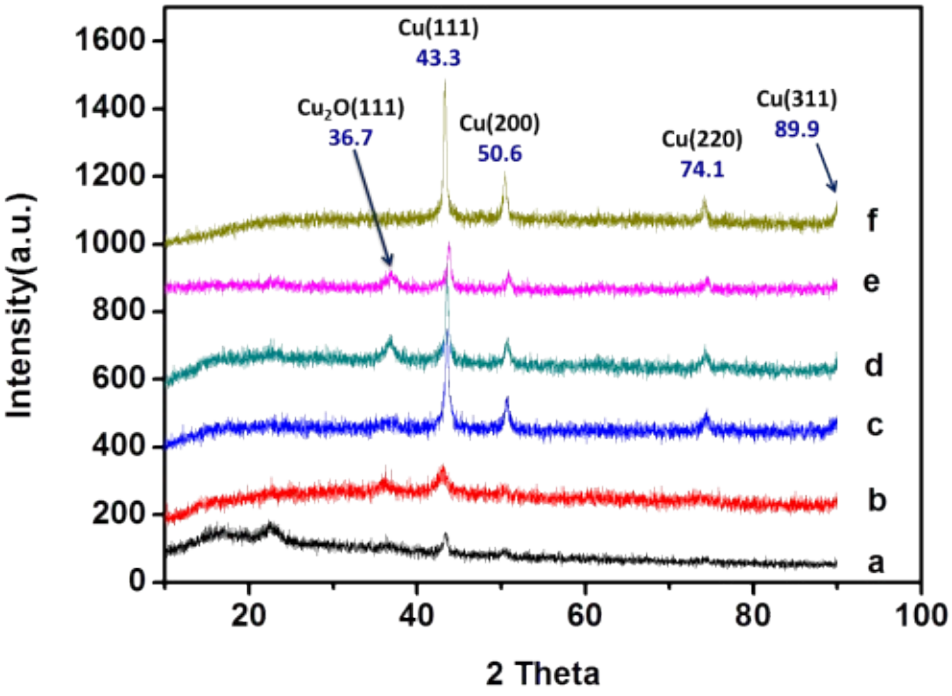
3. Fig. S1 BJH Desorption patterns of prepared CuAlOx catalysts



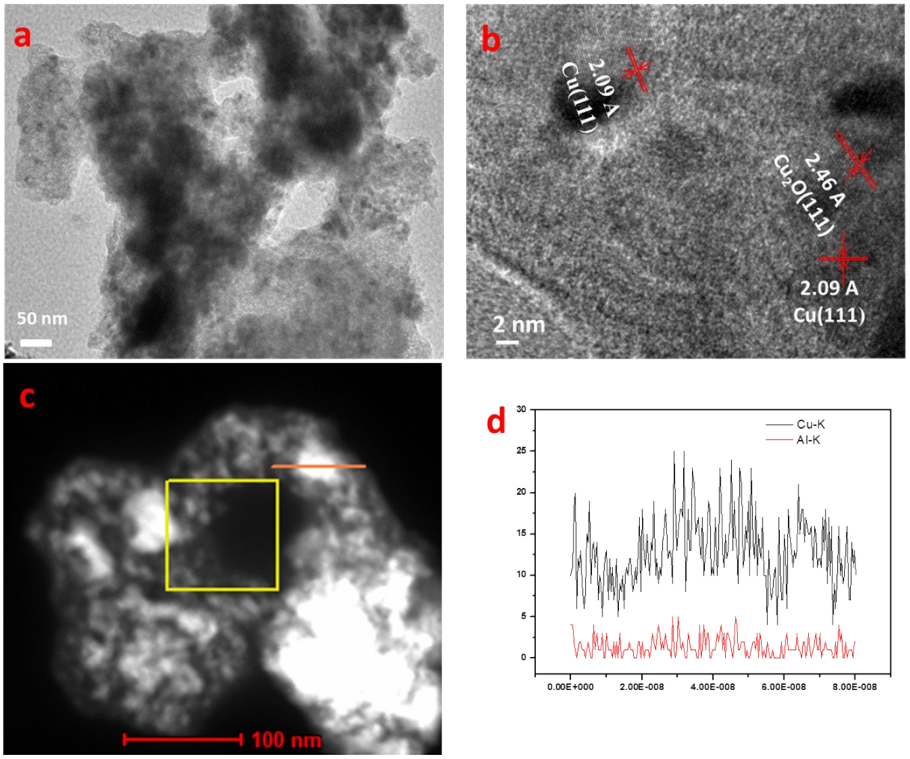
4. **Fig. S2 XPS diffraction patterns of prepared CuAlOx(5:5)**



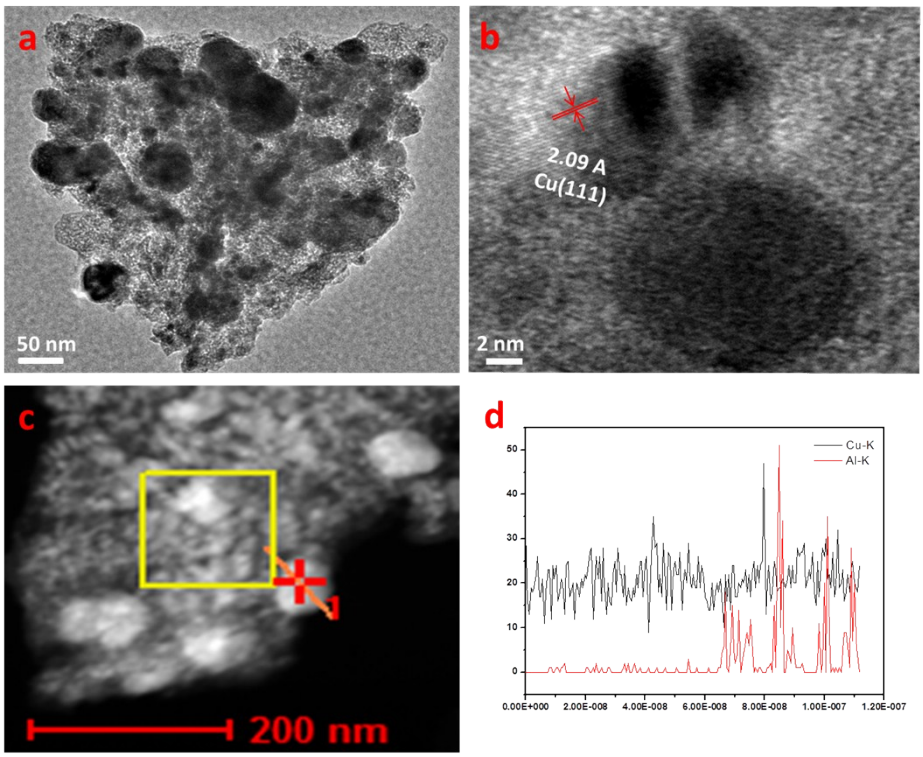
5. **Fig. S3 XRD diffraction patterns for (a) CuAlOx (2:8), (b) CuAlOx (3:7), (c) CuAlOx (5:5), (d) CuAlOx (7:3), (e) CuAlOx (8:2), (f) CuAlOx (5:5) used three times.**



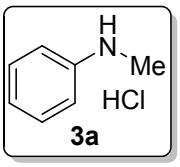
6. **Fig. S4 TEM (a), HR-TEM (b), HAADF (c) and the line-scan EDS analysis (d) images of the fresh catalyst CuAlOx(5:5)**



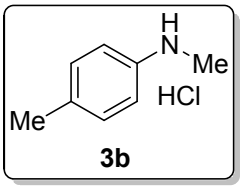
7. **Fig. S5 TEM (a), HR-TEM (b), HAADF (c) and the line-scan EDS analysis (d) images of the used three times catalyst CuAlOx(5:5)**



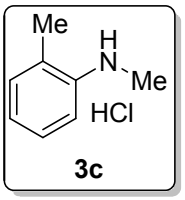
Ⅲ. Characterization data for products



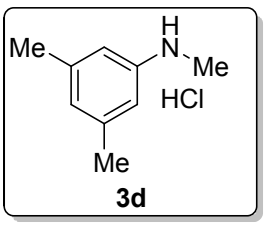
N-methylaniline hydrochloride (3a)[1]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (30 : 1 to 10 : 1) to give the desired product which was treated with HCl to give a brown solid. 127 mg, 89% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.03 (s, 3H), 7.40-7.48 (m, 3H), 7.64-7.66 (m, 2H), 11.55 (brs, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 37.9, 122.6, 129.5, 130.2, 137.0.



N,4-dimethylaniline hydrochloride (3b)[2]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (40 : 1 to 10 : 1) to give the desired product which was treated with HCl to give a red-brown solid. 134 mg, 85% yield. **^{1}H NMR** (400 MHz, D_2O) δ 2.33 (s, 3H), 3.02 (s, 3H), 7.31-7.36 (m, 4H); **^{13}C NMR** (100 MHz, D_2O) δ 20.1, 36.8, 121.5, 130.7, 133.5, 140.4.

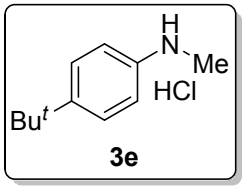


N, 2-dimethylaniline hydrochloride (3c)[3]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (50 : 1 to 30 : 1)to give the desired product which was treated with HCl to give a red-brown solid. 132 mg, 84% yield. **^{1}H NMR** (400 MHz, D_2O) δ 2.39 (s, 3H), 3.04 (s, 3H), 7.37-7.39 (m, 4H); **^{13}C NMR** (100 MHz, D_2O) δ 16.0, 35.8, 121.8, 127.8, 129.8, 131.0, 132.3, 134.6.



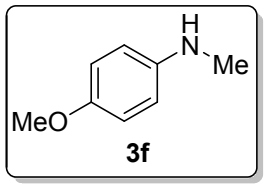
N, 3, 5-trimethylaniline hydrochloride (3d)[4]: The title compound was prepared according to the general procedure and purified by column chromatography using

petroleum ether /diethyl ether (30 : 1 to 10 : 1) to give the desired product which was treated with HCl to give a red-brown solid. 142 mg, 83% yield. **^{1}H NMR** (400 MHz, D_2O) δ 2.30 (s, 6H), 3.00 (s, 3H), 7.07 (s, 2H), 7.16 (s, 1H); **^{13}C NMR** (100 MHz, D_2O) δ 20.2, 36.8, 119.1, 131.1, 136.1, 140.9.



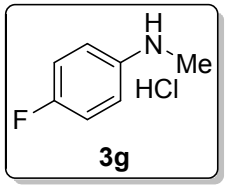
3e

4-(tert-butyl)-N-methylaniline hydrochloride (3e)[5]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (30 : 1 to 10 : 1) to give the desired product which was treated with HCl to give red-brown solid. 160 mg, 80% yield. The product was treated with HCl to give a red-brown solid. **^{1}H NMR** (400 MHz, D_2O) δ 1.29 (s, 9H), 3.06 (s, 3H), 7.42 (d, J = 8.0 Hz, 2H), 7.63 (d, J = 8.0 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 30.4 34.2, 37.0, 121.5, 127.4, 133.6, 153.6.



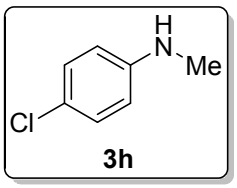
3f

4-methoxy-N-methylaniline (3f)[6]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (10 : 1 to 6 : 1) to give a brown solid. 104 mg, 76% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.81 (s, 3H), 3.25 (brs, 1H), 3.76 (s, 3H), 6.58-6.62 (m, 2H), 6.79-6.83 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 31.6, 55.8, 113.6, 114.9, 143.6, 152.1.



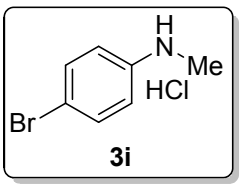
3g

4-fluoro-N-methylaniline hydrochloride (3g)[7]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (30 : 1 to 10 : 1) to give the desired product which was treated with HCl to give a purple solid. 113 mg, 70% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.98 (s, 3H), 7.08-7.13 (m, 2H), 6.63-7.66 (m, 2H), 11.50 (brs, 2H); **^{19}F NMR** (376 MHz, $CDCl_3$) δ -110.34; **^{13}C NMR** (100 MHz, $CDCl_3$) δ 38.2, 117.2 (J = 23.1 Hz), 124.6 (J = 8.7 Hz), 132.91 (J = 3.1 Hz), 162.6 (J = 249.1 Hz).



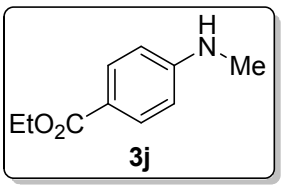
3h

4-chloro-N-methylaniline (3h)[6]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (40 : 1 to 10 : 1) to give yellow oil. 105 mg, 74% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.82 (s, 3H), 3.72 (brs, 1H), 6.53 (d, *J* = 8.8 Hz, 2H), 7.13 (d, *J* = 8.8 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 30.8, 113.4, 121.8, 129.0, 147.8.



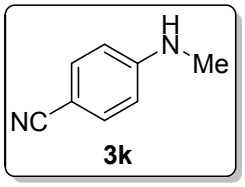
3i

4-bromo-N-methylaniline hydrochloride (3i)[8]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (10 : 1 to 6 : 1) to give the desired product which was treated with HCl to give a red-brown solid. 154 mg, 69% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.98 (s, 3H), 7.51-7.57 (m, 4H), 11.55 (brs, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 37.9, 123.7, 124.4, 133.4, 136.0.



3j

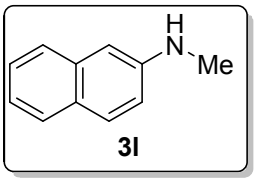
Ethyl 4-(methylamino)benzoate (3j)[7]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (8 : 1 to 4 : 1) to give a white solid. 141 mg, 79% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 1.36 (t, *J* = 7.0 Hz, 3H), 2.88 (s, 3H), 4.29 (brs, 1H), 4.32 (t, *J* = 7.0 Hz, 2H), 6.55 (d, J = 8.4 Hz, 2H), 7.88 (d, J = 8.8 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 14.4, 30.1, 60.1, 111.1, 118.6, 131.4, 152.8, 166.9.



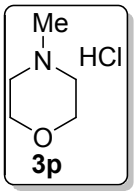
3k

4-(methylamino)benzonitrile (3k)[6]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (3 : 1) to give white solid. 81 mg, 61% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.87 (s,

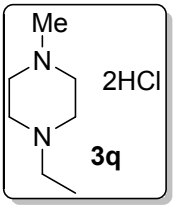
3H), 4.33 (brs, 1H), 6.55 (d, J = 8.8 Hz, 2H), 7.42 (d, J = 8.4 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 29.9, 98.4, 111.8, 120.5, 133.6, 152.2.



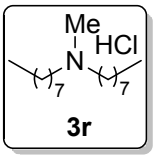
N-methylnaphthalen-2-amine (3l)[6]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (50 : 1 to 10 : 1) to give yellow oil. 127 mg, 81% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.01 (s, 3H), 4.54 (brs, 1H), 6.61 (d, J = 7.6 Hz, 1H), 7.25 (d, J = 8.0 Hz, 1H), 7.37 (t, J = 8.0 Hz, 1H), 7.41-7.47 (m, 2H), 7.76-7.80 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 31.1, 103.9, 117.4, 119.8, 123.4, 124.7, 125.7, 126.6, 128.6, 134.2, 144.4.



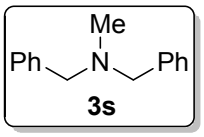
4-methylmorpholine hydrochloride (3p)[9]: The title compound was prepared according to the general procedure and purified by column chromatography using DCM / MeOH (30 : 1 to 10 : 1) to give the desired product which was treated with HCl to give a white solid. 109 mg, 79% yield. **^{1}H NMR** (400 MHz, D_2O) 2.92 (s, 3H), 3.20 (td, J_1 = 12.4 Hz, J_2 = 3.6 Hz, 2H), 3.47-3.50 (m, 2H), 3.80 (td, J_1 = 12.6 Hz, J_2 = 2.0 Hz, 2H), 4.2 (dd, J_1 = 13.2 Hz, J_2 = 3.2 Hz, 2H); **^{13}C NMR** (100 MHz, D_2O) δ 43.3, 53.2, 63.9.



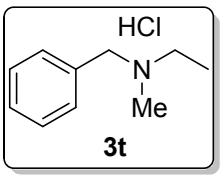
1-ethyl-4-methylpiperazine hydrochloride (3q)[9]: The title compound was prepared according to the general procedure and purified by column chromatography using DCM / MeOH (10 : 1 to 6 : 1) to give the desired product which was treated with HCl to give white solid. 199 mg, 99% yield. **^{1}H NMR** (400 MHz, D_2O) 1.33 (t, J = 7.4 Hz, 3H), 3.01 (s, 3H), 3.34 (q, J = 7.2 Hz, 2H), 3.43 (brs, 2H), 3.89 (brs, 2H); **^{13}C NMR** (100 MHz, D_2O) δ 8.6, 42.9, 48.1, 50.3, 52.4.



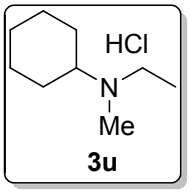
N-methyl-N-octyloctan-1-amine hydrochloride (3r)[9]: The title compound was prepared according to the general procedure and purified by column chromatography petroleum ether / ethyl acetate (6 : 1 to 4 : 1) to give the desired product which was treated with HCl to give a white solid. 256.5 mg, 88% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) 0.85 (t, J = 6.8 Hz, 6H), 1.22-1.29 (m, 20 H), 1.79 (brs, 4H), 2.70 (s, 3H), 2.91 (brs, 4H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 14.0, 22.5, 23.6, 26.7, 28.9, 31.6, 39.76, 55.66.



N-benzyl-N-methyl-1-phenylmethanamine (3s)[9]: The title compound was prepared according to the general procedure and purified by column chromatography using petroleum ether /diethyl ether (30 : 1 to 10 : 1) to give yellow oil. 158 mg, 75% yield. **^{1}H NMR** (400 MHz, $CDCl_3$) 2.18-2.19 (m, 3H), 3.52 (s, 4H), 7.23-7.26 (m, 2H), 7.30-7.38 (m, 8H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 42.2, 61.9, 126.9, 128.2, 128.9, 139.3.

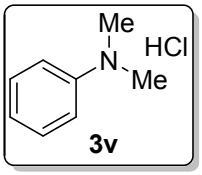


N-benzyl-N-methylethanamine hydrochloride (3t)[10]: The title compound was prepared according to the general procedure and purified by column chromatography petroleum ether / ethyl acetate (4 : 1 to 2 : 1) to give the desired product which was treated with HCl to give a white solid. 183 mg, 99% yield. **^{1}H NMR** (400 MHz, D_2O) 1.28 (t, J = 7.4 Hz, 3H), 2.71 (s, 3H), 3.04-3.13 (m, 1H), 3.22-3.31 (m, 1H), 4.16(d, J = 13.2 Hz, 1H), 4.36(d, J = 13.2 Hz, 1H), 7.42-7.48 (m, 5H); **^{13}C NMR** (100 MHz, D_2O) δ 8.7, 38.5, 50.9, 59.2, 129.2, 129.3, 130.1, 130.9.



N-ethyl-N-methylcyclohexanamine hydrochloride (3u)[11]: The title compound was prepared according to the general procedure and purified by column chromatography using DCM / MeOH (10 : 1 to 8 : 1) to give the desired product which was treated with HCl to give a

white solid. 175 mg, 99% yield. **^{1}H NMR** (400 MHz, D_2O) 1.02-1.12 (m, 1H), 1.20-1.47 (m, 7H), 1.58 (d, *J* = 6.2 Hz, 1H), 1.80 (d, *J* = 6.2 Hz, 2H), 1.90 (brs, 2H), 2.68 (s, 3H), 2.99-3.08 (m, 1H), 3.15-3.25 (m, 2H); **^{13}C NMR** (100 MHz, D_2O) δ 9.2, 24.3, 24.5, 24.5, 25.3, 27.2, 35.2, 48.9, 64.2.

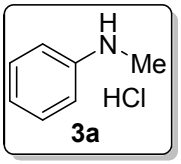


N,N-dimethylaniline hydrochloride (3v)[12]: The title compound was prepared according to the general procedure and purified by column chromatography petroleum ether /diethyl ether (50 : 1 to 30 : 1) to give the desired product which was treated with HCl to give a white solid. 106 mg, 67% yield. **^{1}H NMR** (400 MHz, D_2O) 3.26-3.27 (m, 6H), 7.57-7.58 (m, 5H); **^{13}C NMR** (100 MHz, D_2O) δ 46.3, 120.2, 130.4, 130.6, 141.9.

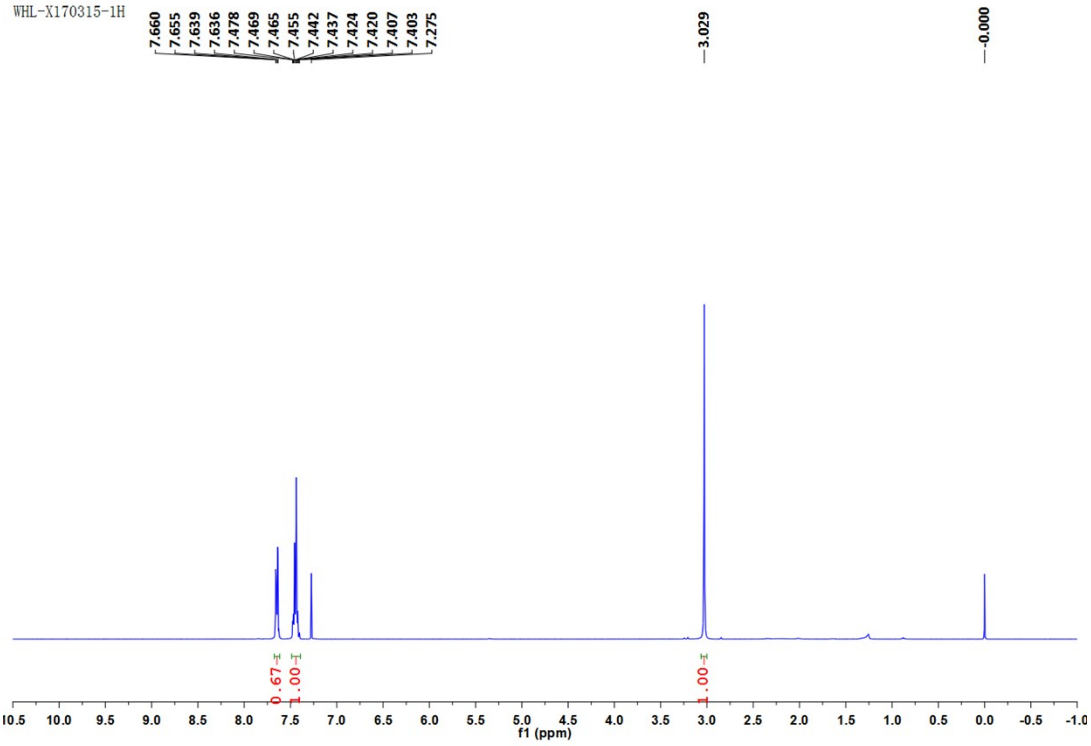
References:

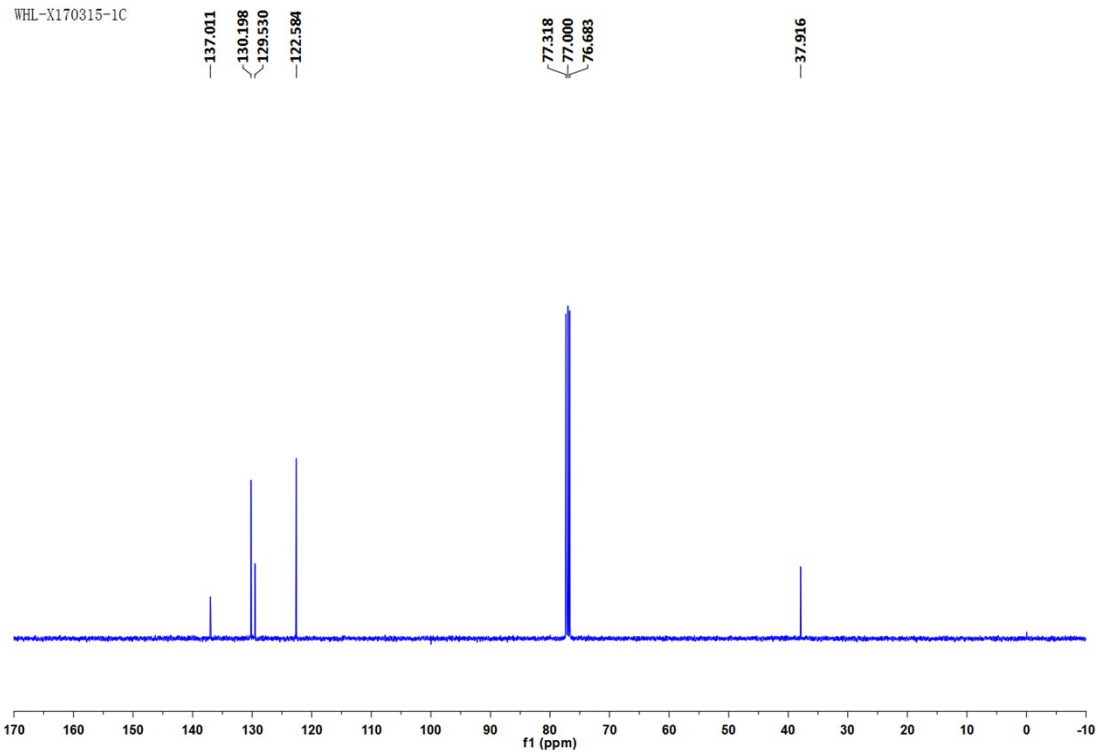
1. A. Bugarin , K. D. Jones and B. T. Connell, *Chem. Commun.*, 2010, **46**, 1715−1717.
2. M. Kitamura , T. Suga , S. Chiba , and K. Narasaka, *Org. Lett.*, 2004, **6**, 4619–4621.
3. H. Shen, L. Hu, Q. Liu, M. I. Hussain, J. Pan, M. Huang and Y. Xiong, *Chem. Commun.*, 2016, **52**, 2776−2779.
4. S. B. Herzon and J. F. Hartwig, *J. Am. Chem. Soc.*, 2007, **129**, 6690−6691.
5. M. Rueping, C. Vila, A. Szadkowska, R. M. Koenigs and J. Fronert, *ACS Catal.*, 2012, **2**, 2810−2815.
6. J. Jiao, X.-R. Zhang, N.-H. Chang, J. Wang, J.-F. Wei, X.-Y. Shi and Z.-G. Chen, *J. Org. Chem.*, 2011, **76**, 1180–1183.
7. N. Sun, S. Wang, W. Mo, B. Hu, Z. Shen and X. Hu, *Tetrahedron* 2010, **66**, 7142−7148.
8. N. L. Lampland, M. Hovey, D. Mukherjee and A. D. Sadow, *ACS Catal.*, 2015, **5**, 4219−4226.
9. Z. Ke, X.Cui. and F. Shi, *ACS Sustainable Chem. Eng*., 2016, **4**, 3921−3926.
10. J. Jaźwiński, *Tetrahedron Asym.,* 2006, **17**, 2358-2365.
11. M. Kurosu, S. S. Dey and D. C. Crick, *Tetrahedron Lett.*, 2006, **47**, 4871−4875.
12. N. Bavarian and M. C. Baird, *Organometallics*, 2005, **24**, 2889−2897.

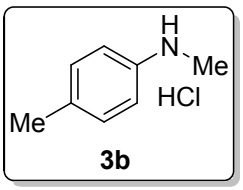
Ⅳ.NMR spectra of all products



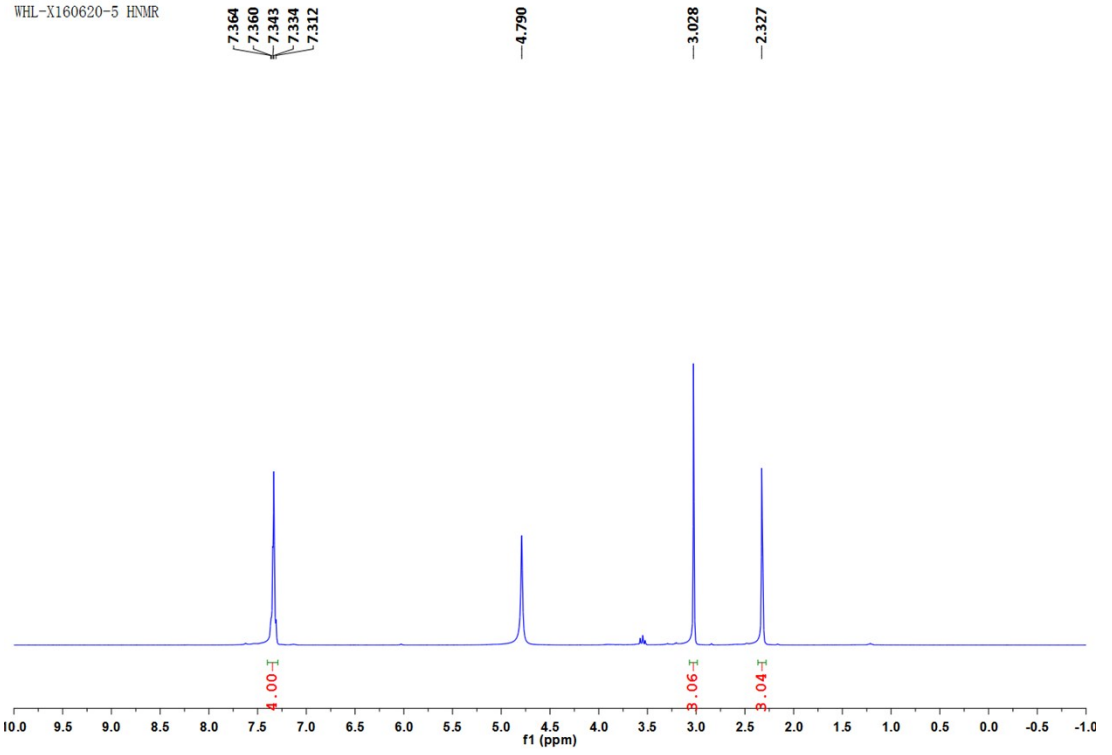
3a






H
N
Me
HCl
Me

3b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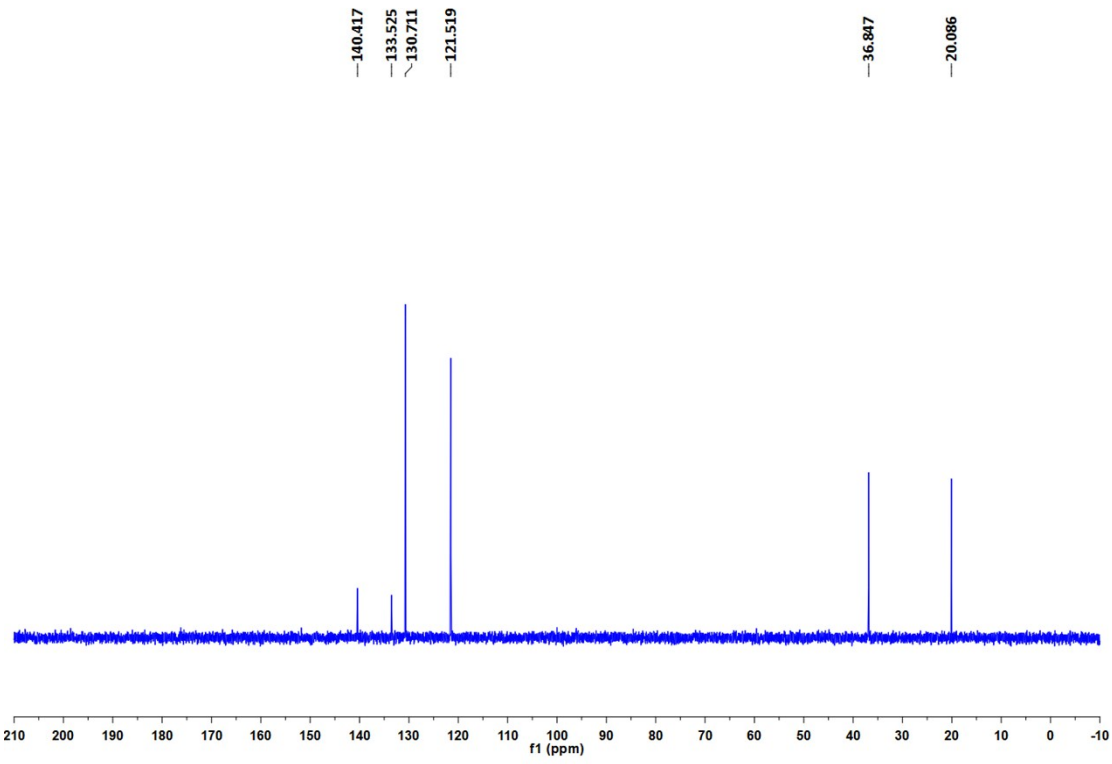
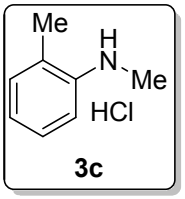
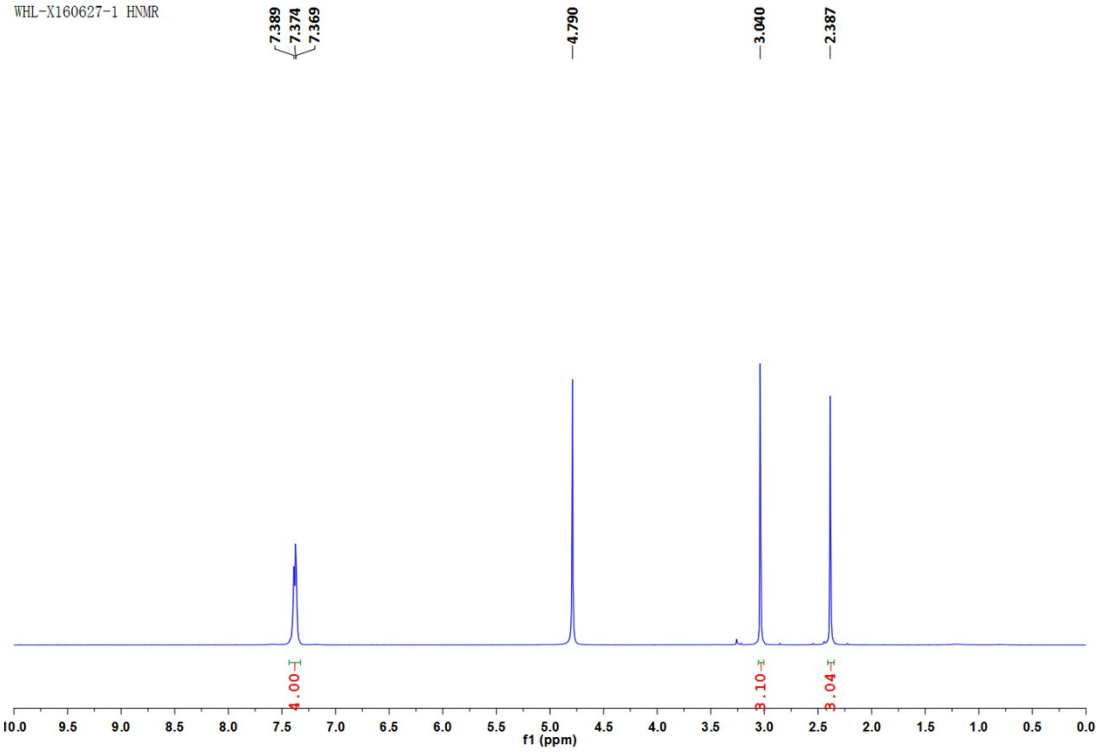
7.364
7.360
7.343
7.334
7.312
4.790
3.028
2.327
4.00
3.06
3.04
f1 (ppm)


140.417
133.525
130.711
121.519
36.847
20.086
f1 (ppm)



3c

WHL-X160627-1 HNMR



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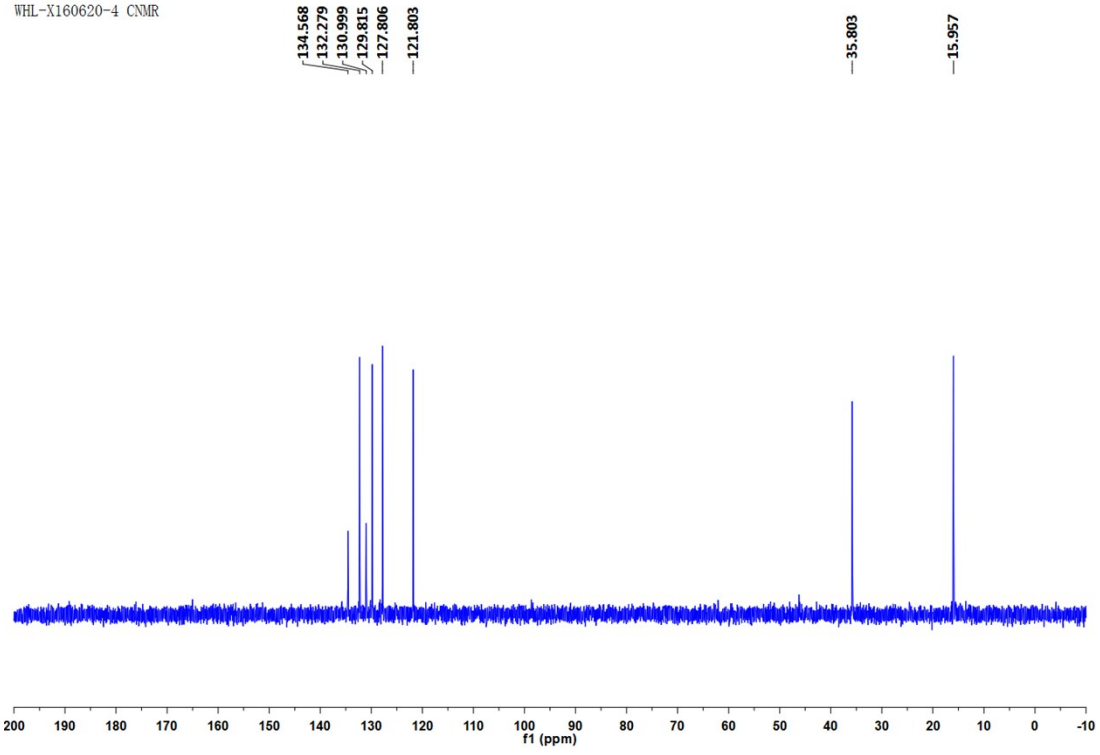
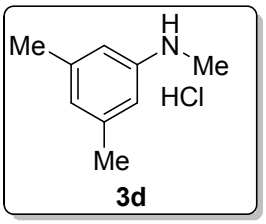
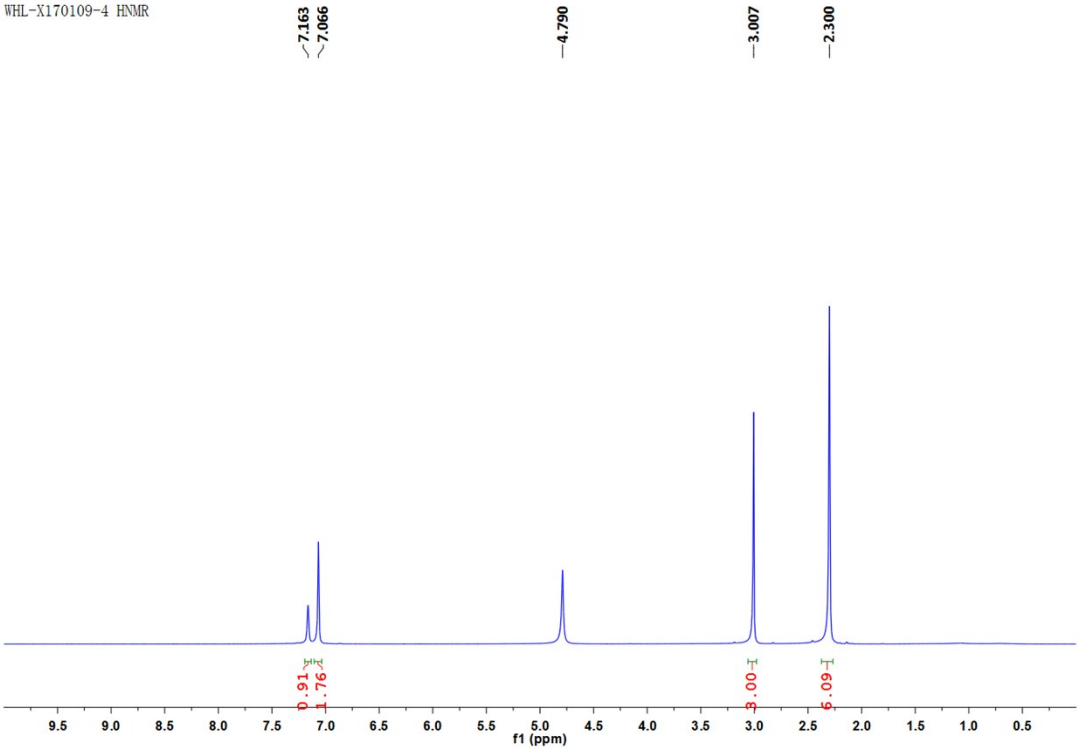




3d

WHL-X170109-4 HNMR



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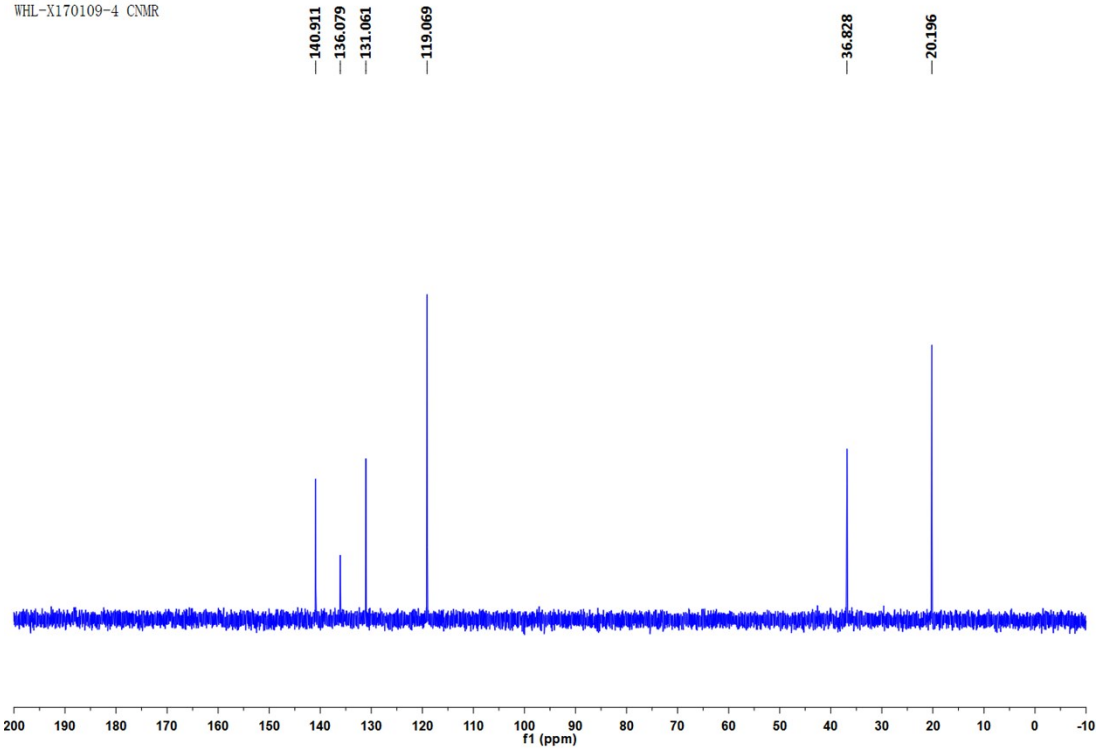
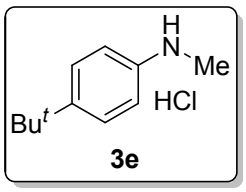
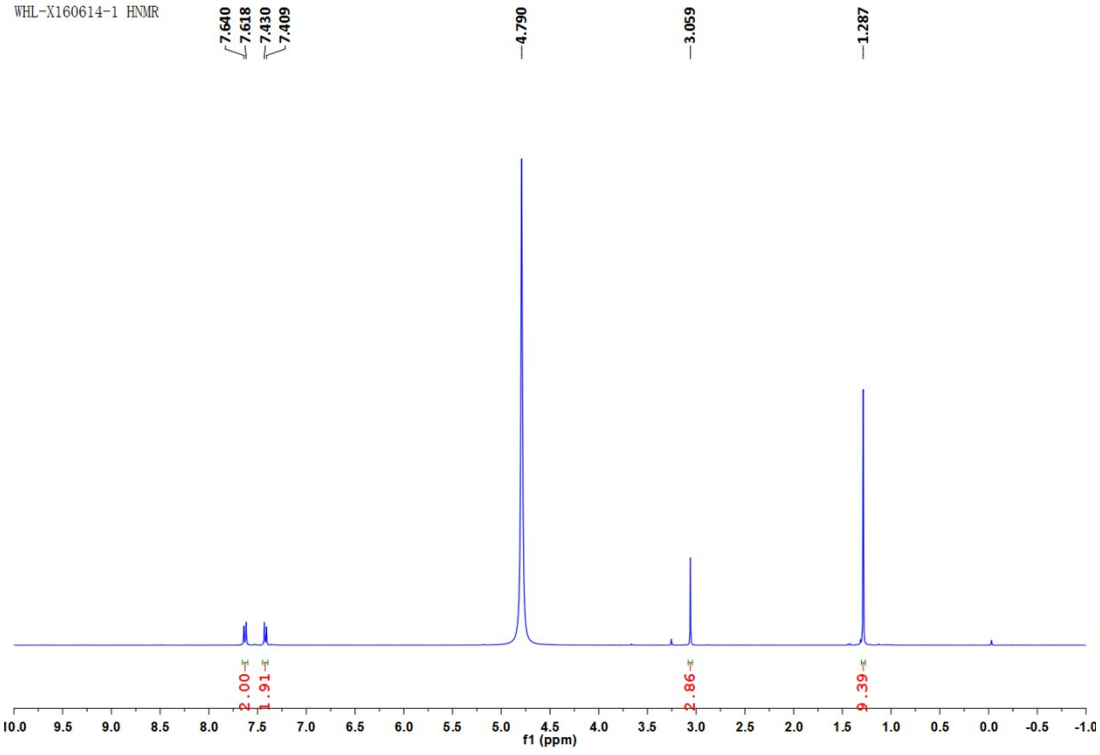



H
N
Me
HCl
Bu^t

3e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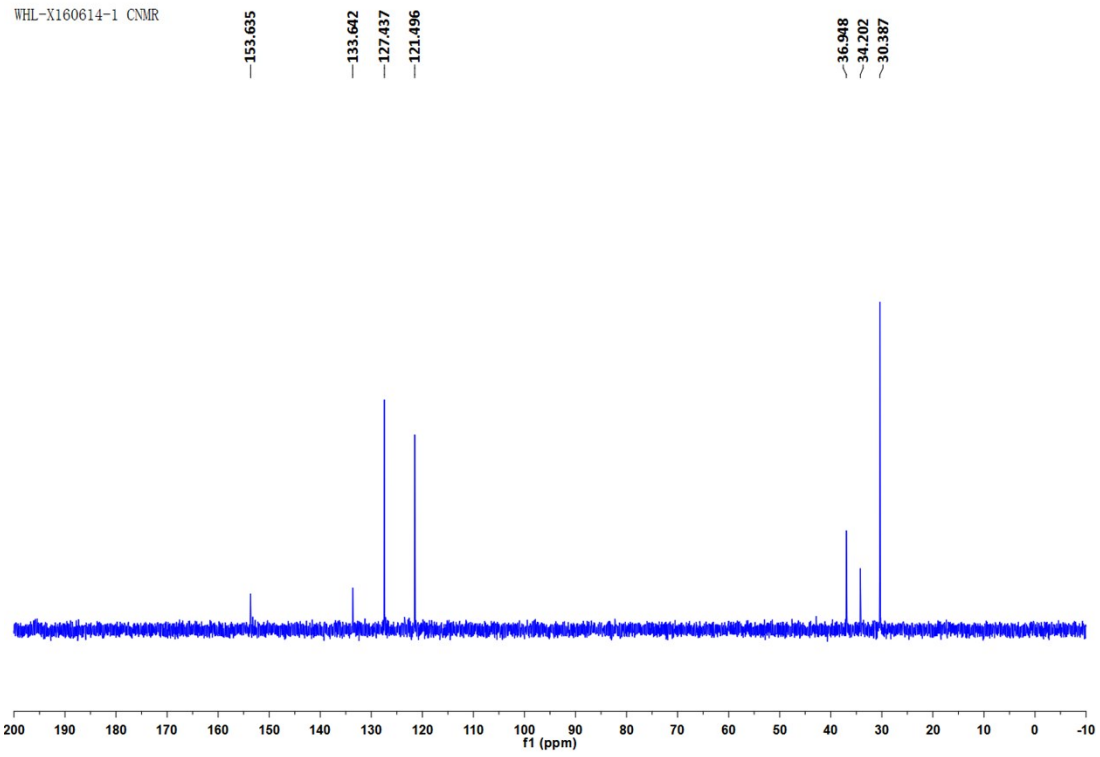
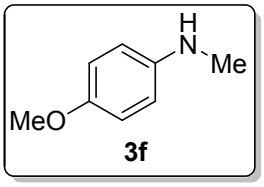
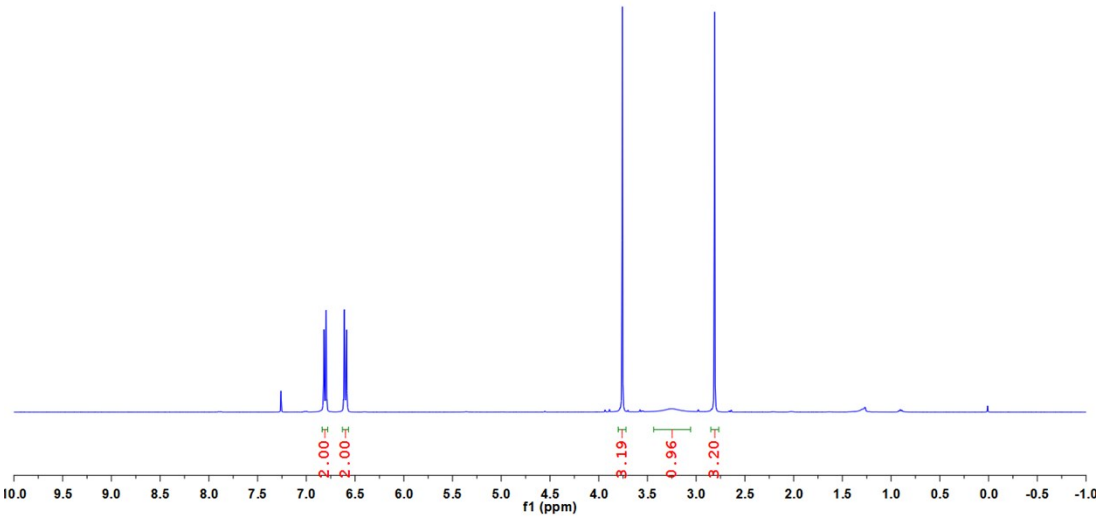
7.640
7.618
7.430
7.409
4.790
3.059
1.287
2.00
1.91
2.86
9.39
f1 (ppm)


WHL-X160614-1 CNMR
153.635
133.642
127.437
121.496
36.948
34.202
30.387
f1 (ppm)

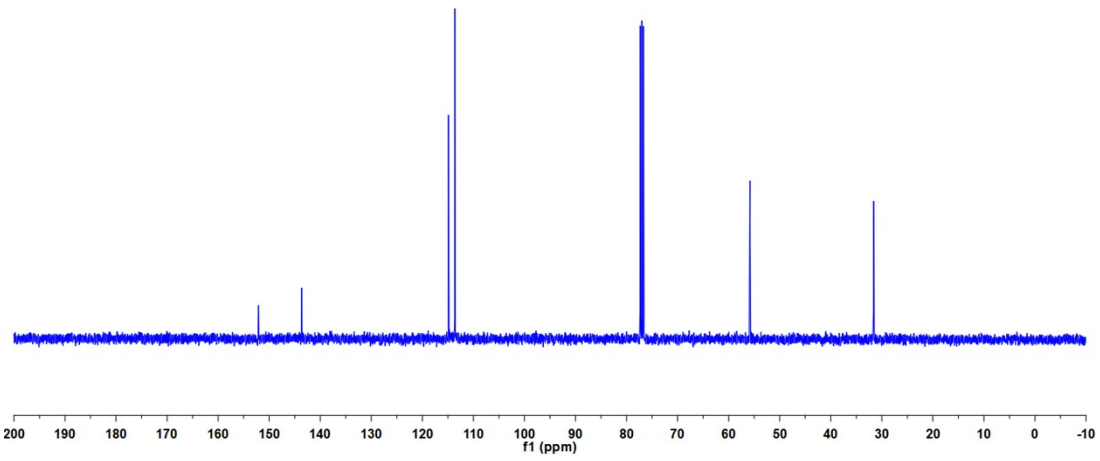


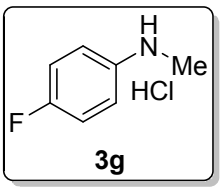
3f

WHL-X160602-3 HNMR

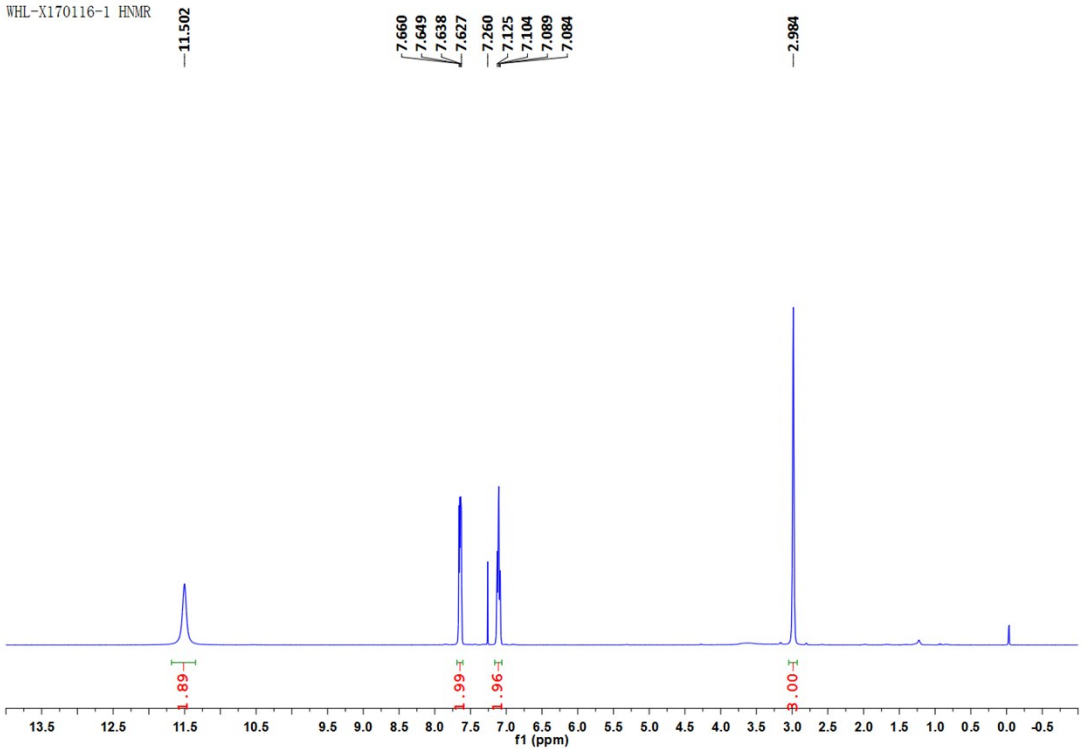


WHL-X160602-3 CNMR

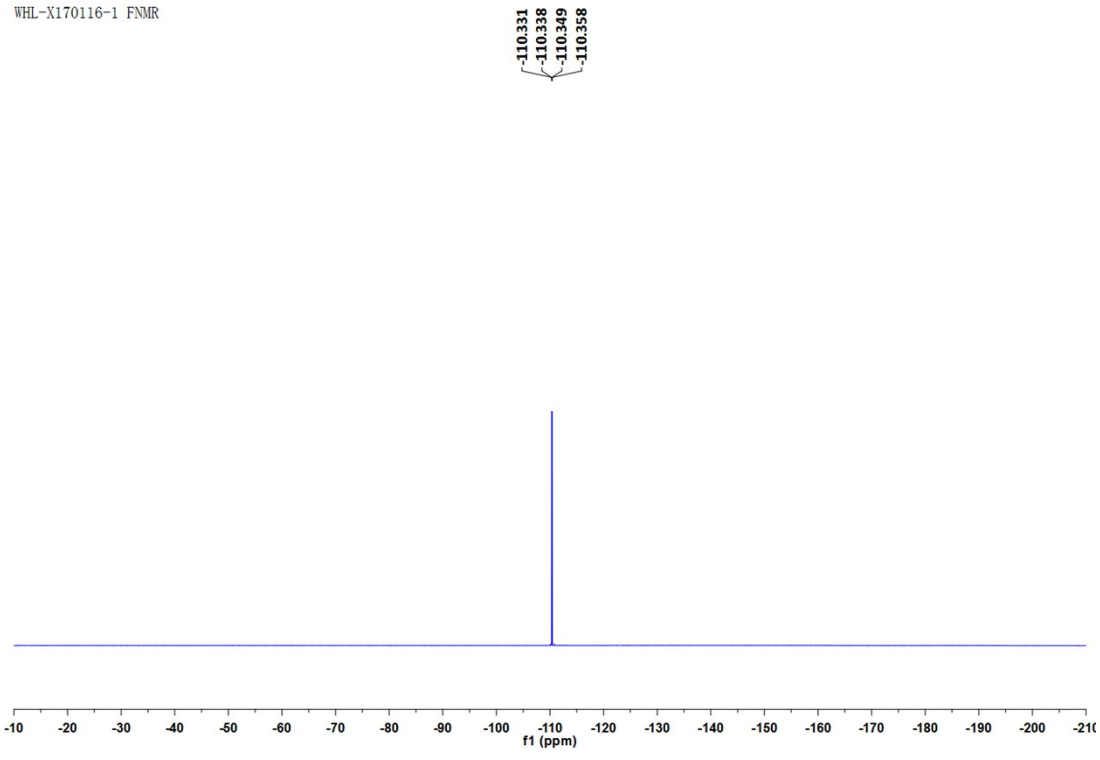


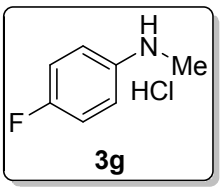


WHL-X170116-1 HNMR

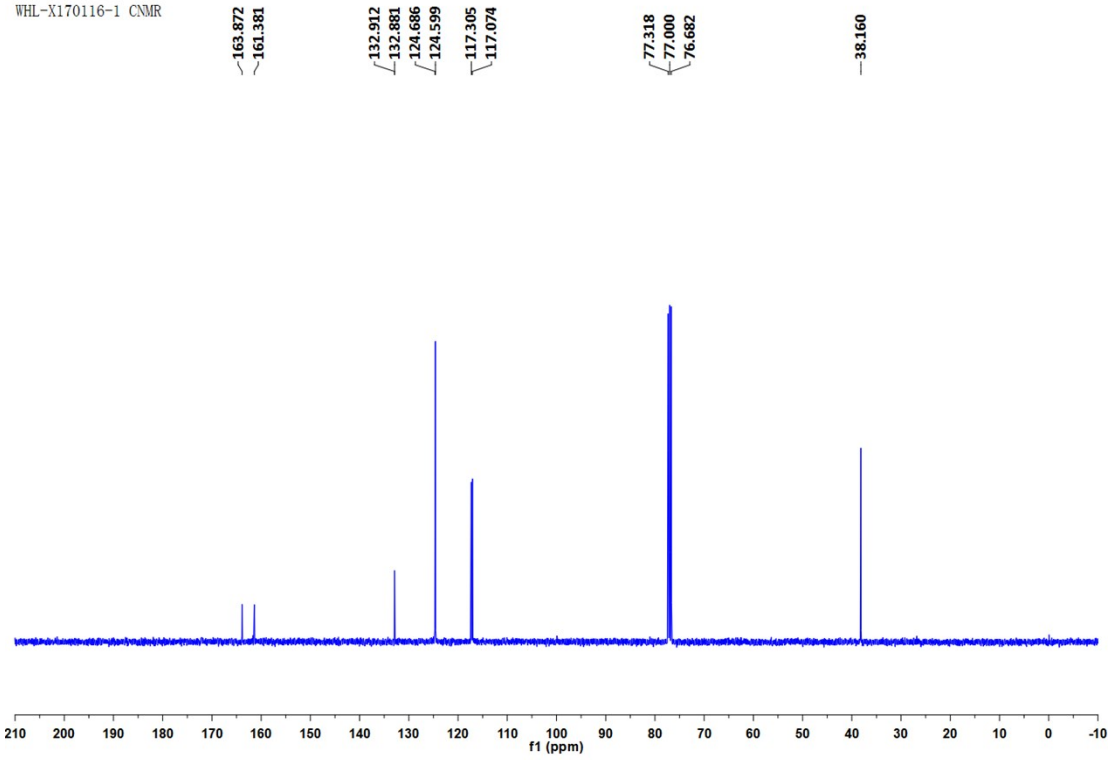


WHL-X170116-1 FNMR




H
N
Me
HCl
F

3g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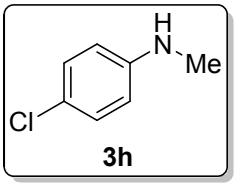
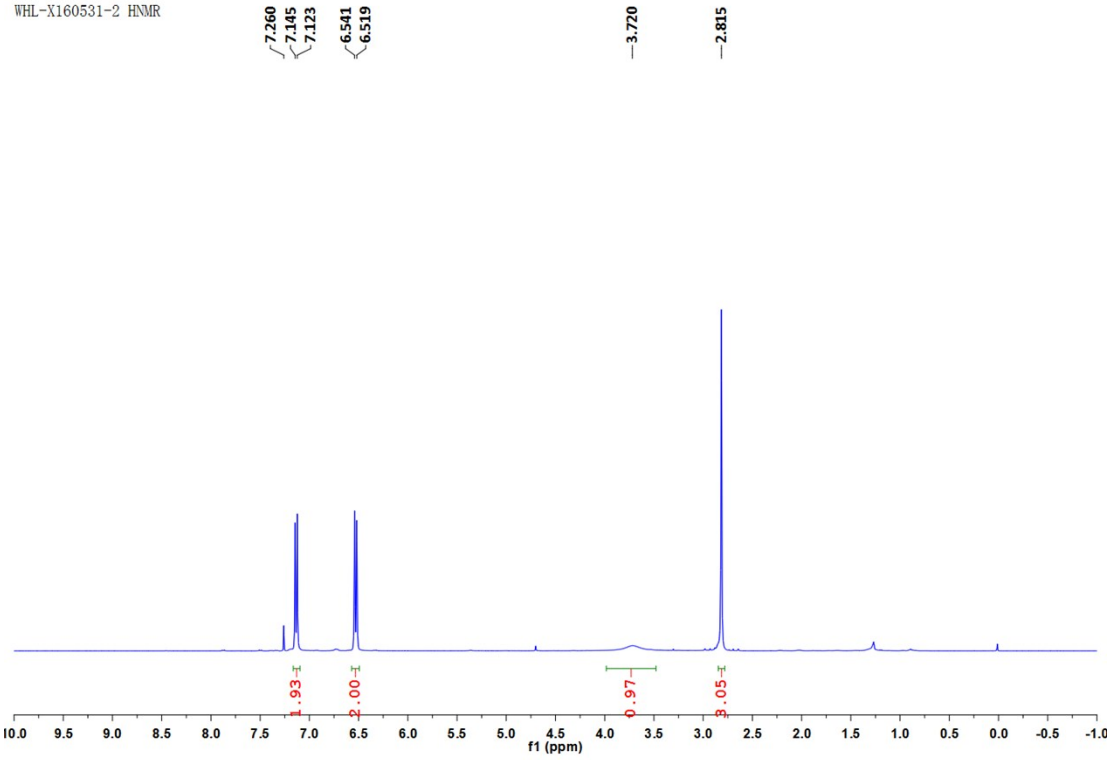
132.912
132.881
124.686
124.599
117.305
117.074
77.318
77.000
76.682
38.160
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

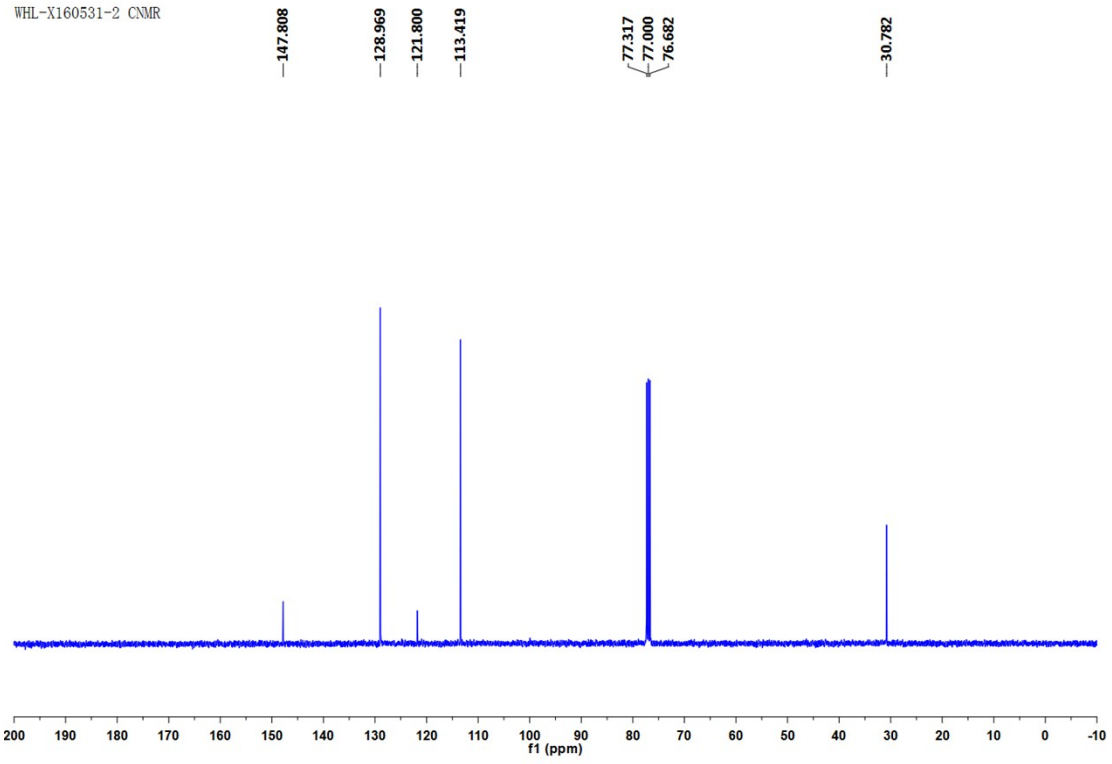


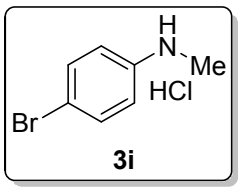
3h

WHL-X160531-2 HNMR

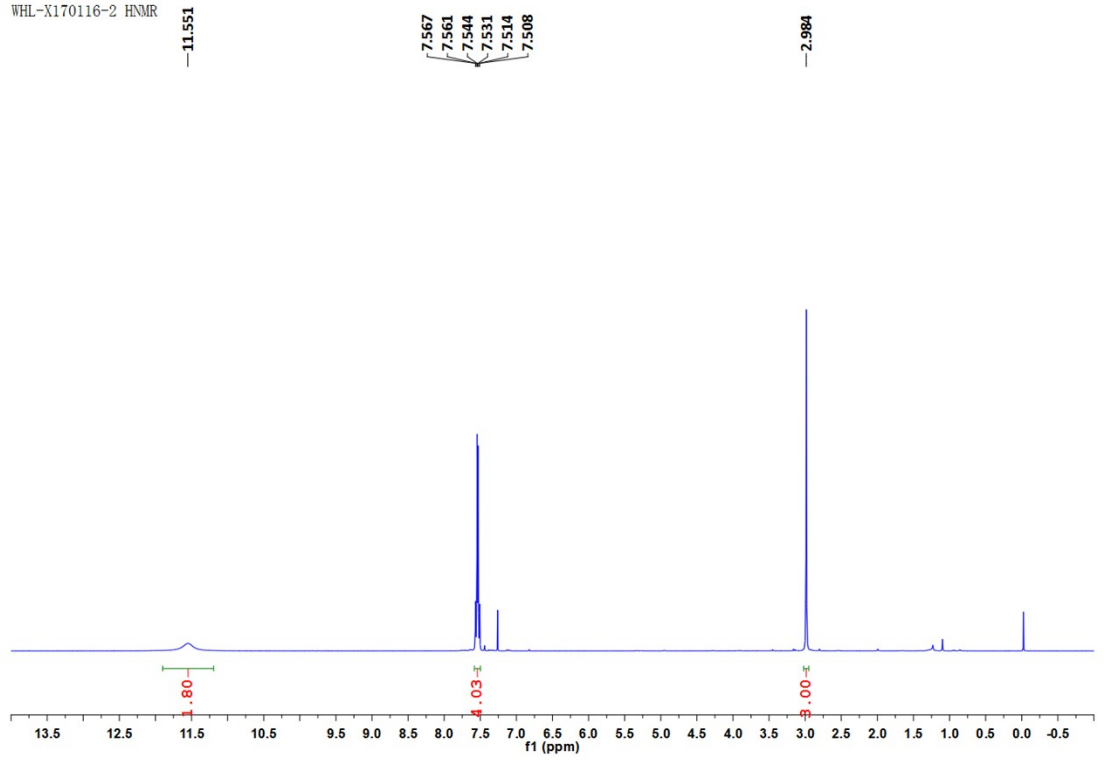


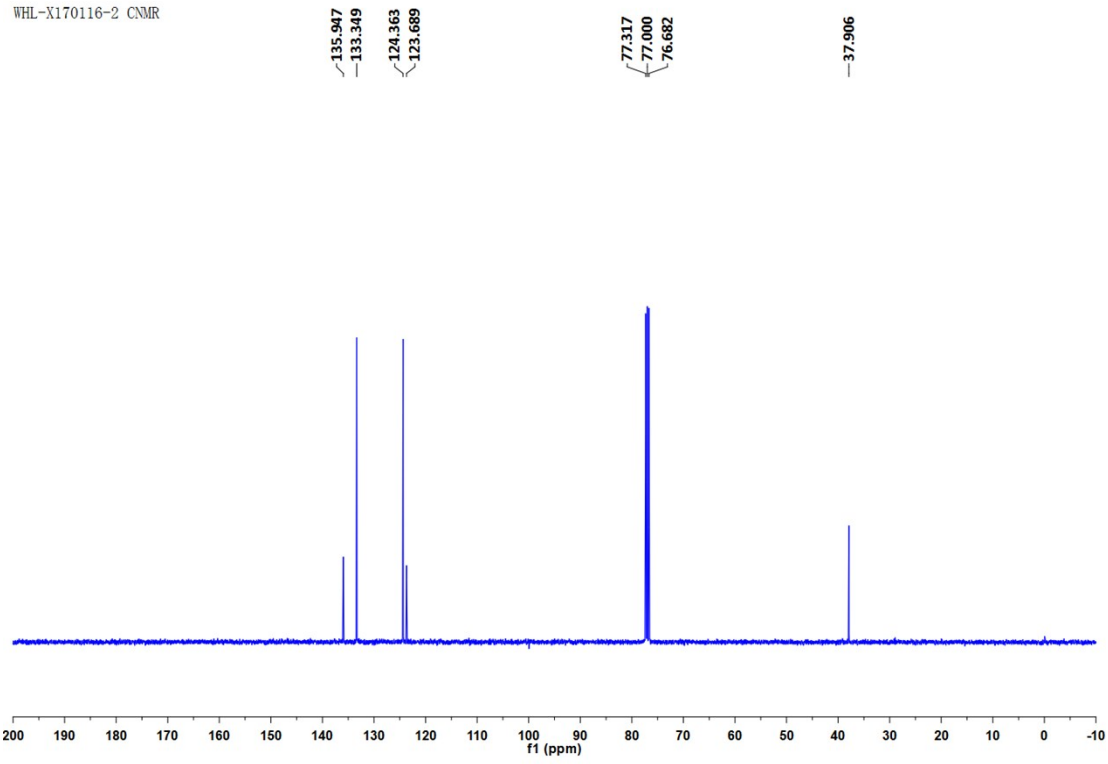
WHL-X160531-2 CNMR




H
N
Me
HCl
Br

3i


WHL-X170116-2 HNMR
11.551
7.567
7.561
7.544
7.531
7.514
7.508
2.984
1.80
4.03
3.00
13.5 12.5 11.5 10.5 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)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133.349
124.363
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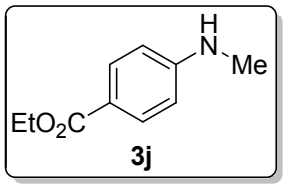
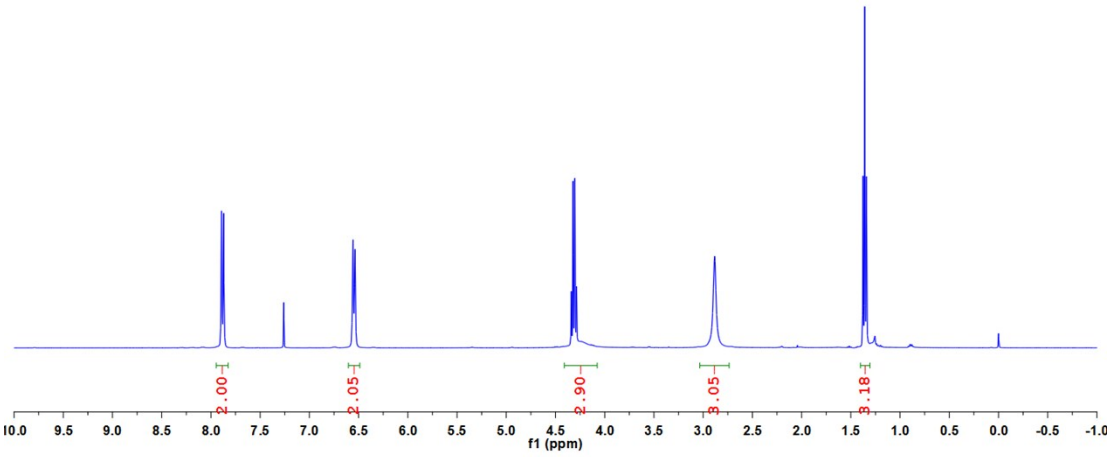
77.317
77.000
76.682
37.906
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)



3j

WHL-X160601-4 HNMR

7.892
7.870
7.260
6.557
6.536
4.339
4.321
4.304
4.286
4.238
2.883
1.376
1.358
1.341



WHL-X160601-4 CNMR

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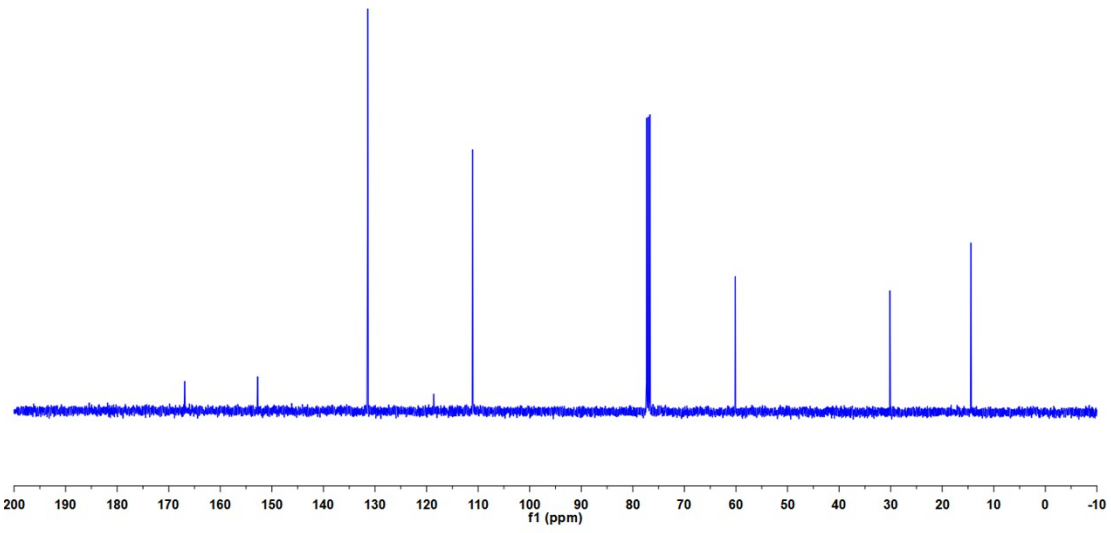
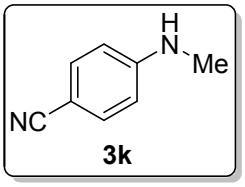
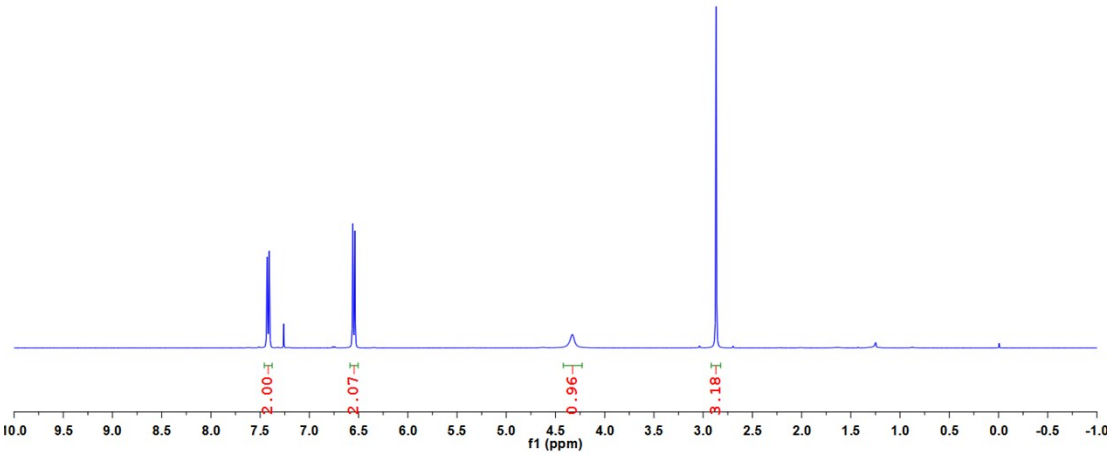
152.762
131.421
118.602
111.060
77.318
77.000
76.682
60.126
30.144
14.424



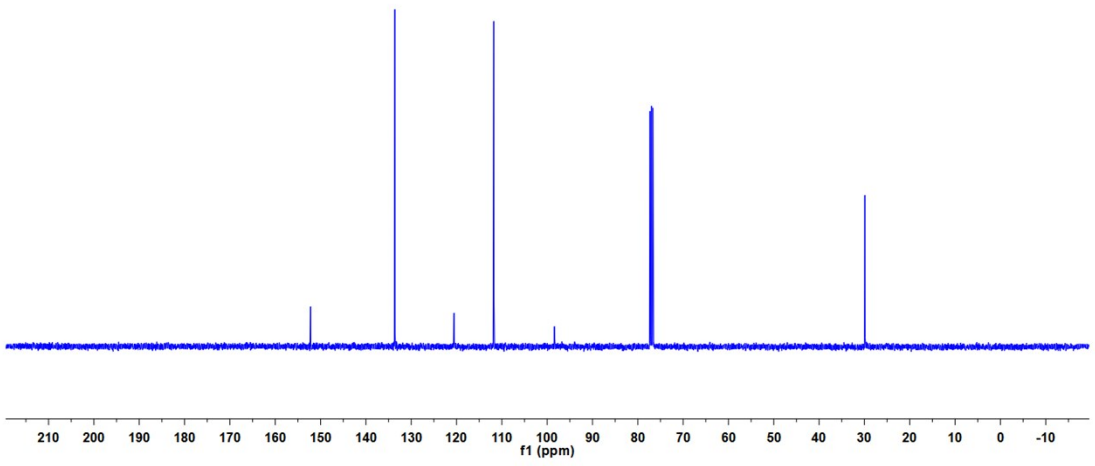


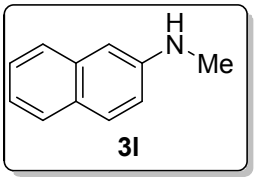
3k

WHL-X170105-2 HNMR

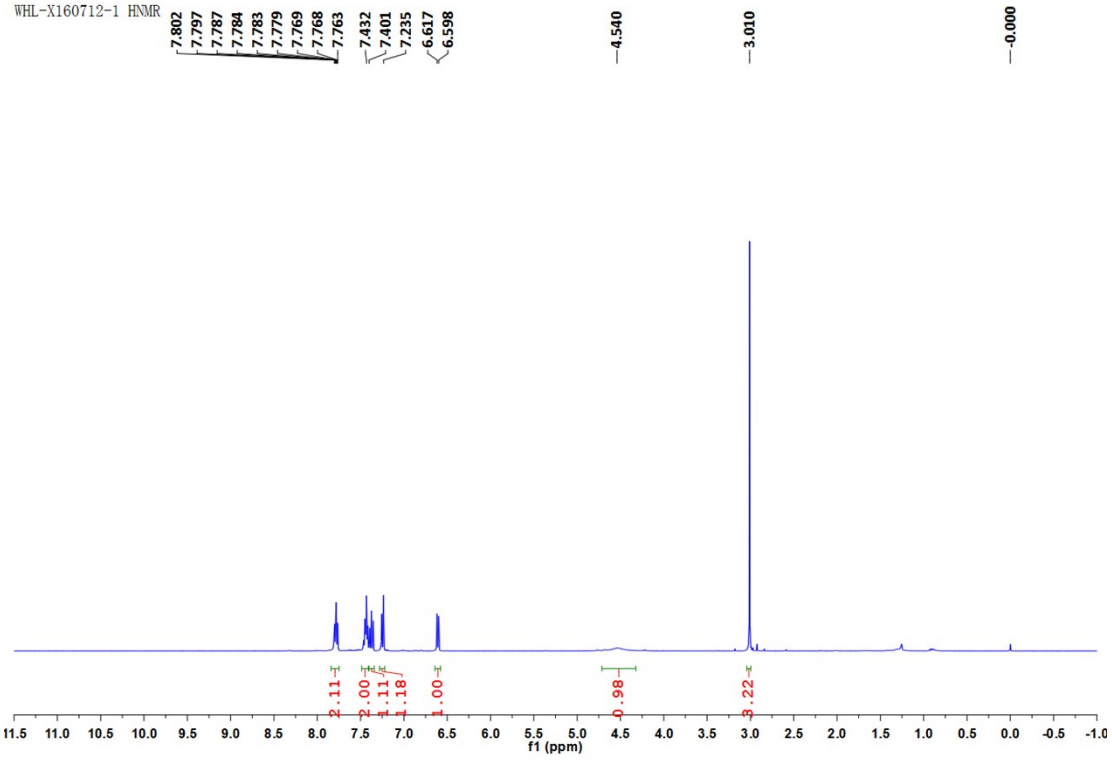


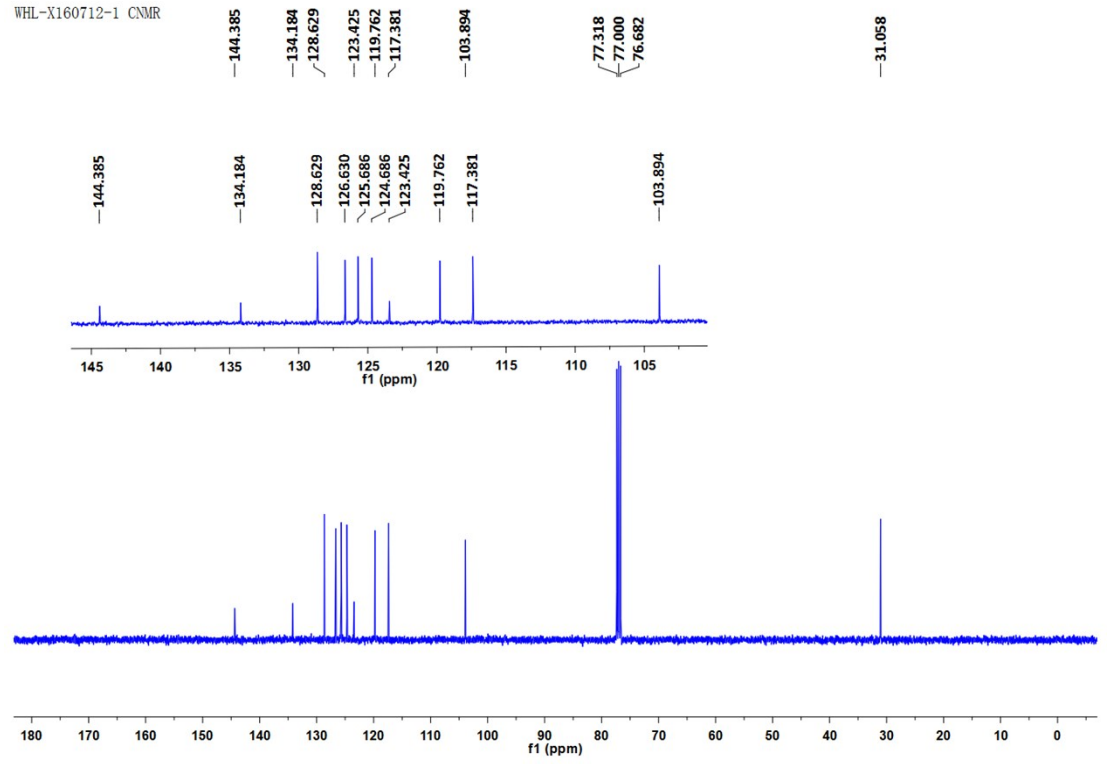
WHL-X170105-2 CNMR

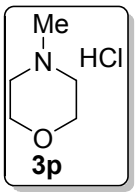



H
N
Me

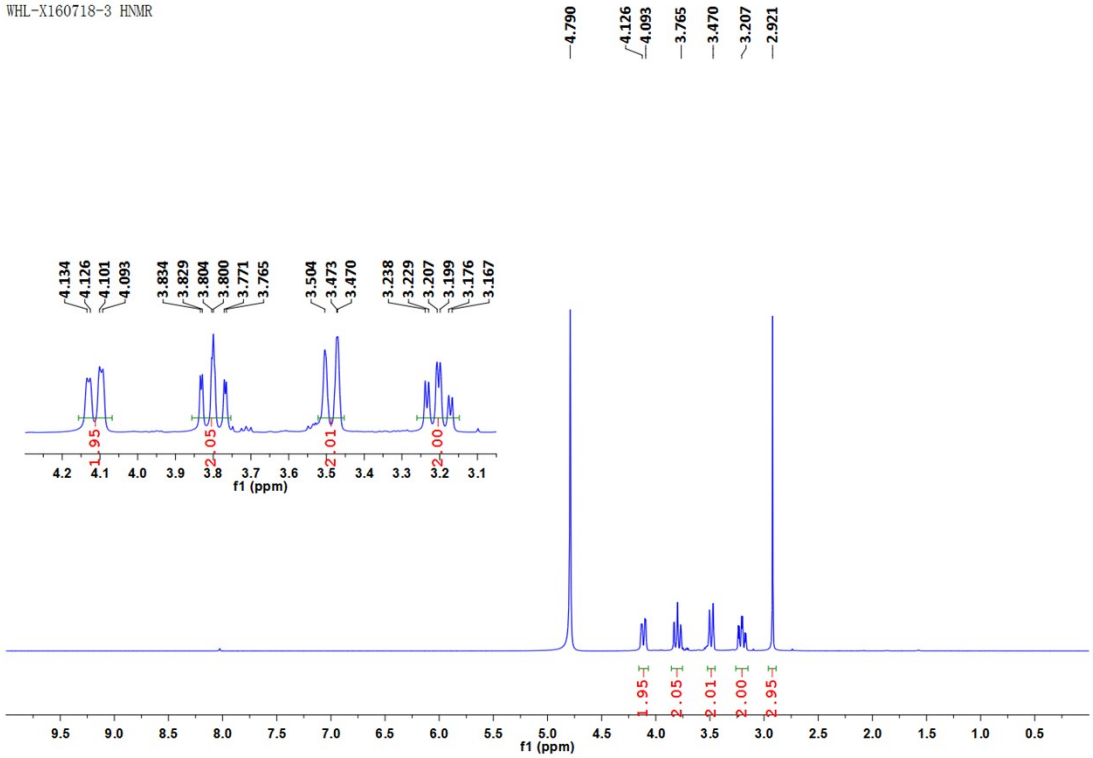
3l


WHL-X160712-1 HNMR
7.802
7.797
7.787
7.784
7.783
7.779
7.769
7.768
7.763
7.432
7.401
7.235
6.617
6.598
4.540
3.010
0.000
2.11
2.00
1.11
1.18
1.00
0.98
3.22
f1 (ppm)

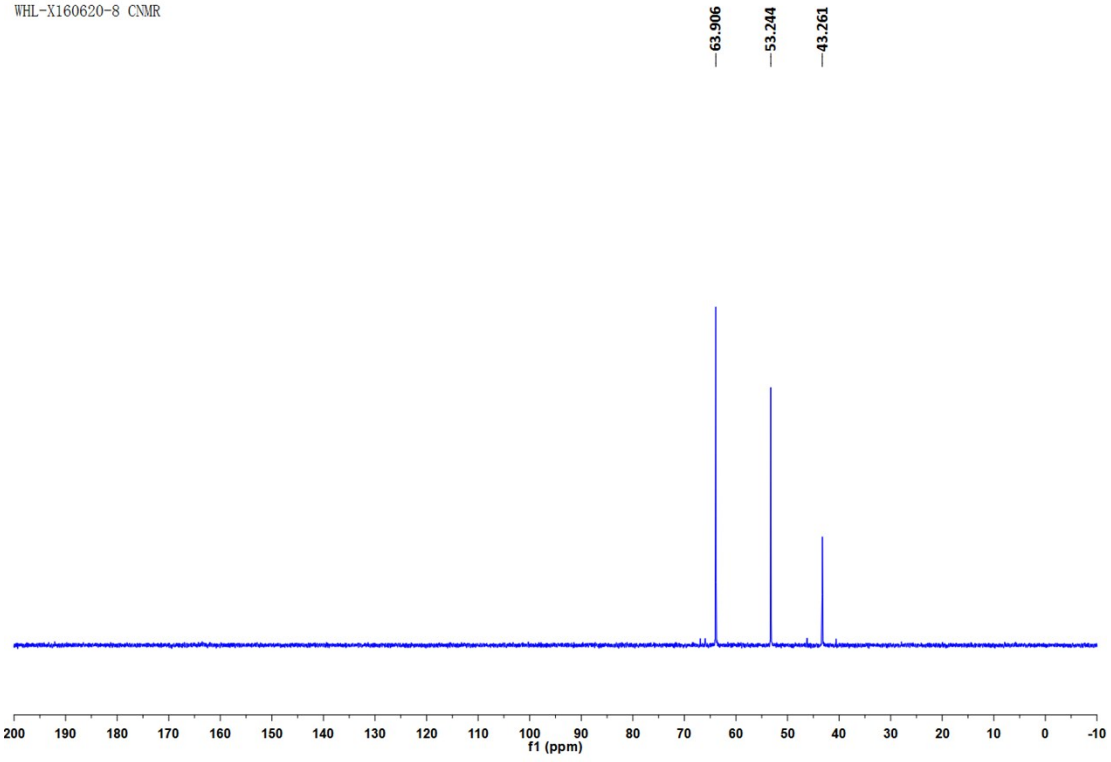

WHL-X160712-1 CNMR
144.385
134.184
128.629
123.425
119.762
117.381
103.894
77.318
77.000
76.682
31.058
126.630
125.686
124.686
f1 (ppm)

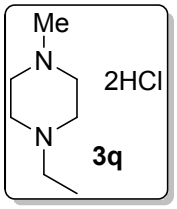


WHL-X160718-3 HNMR

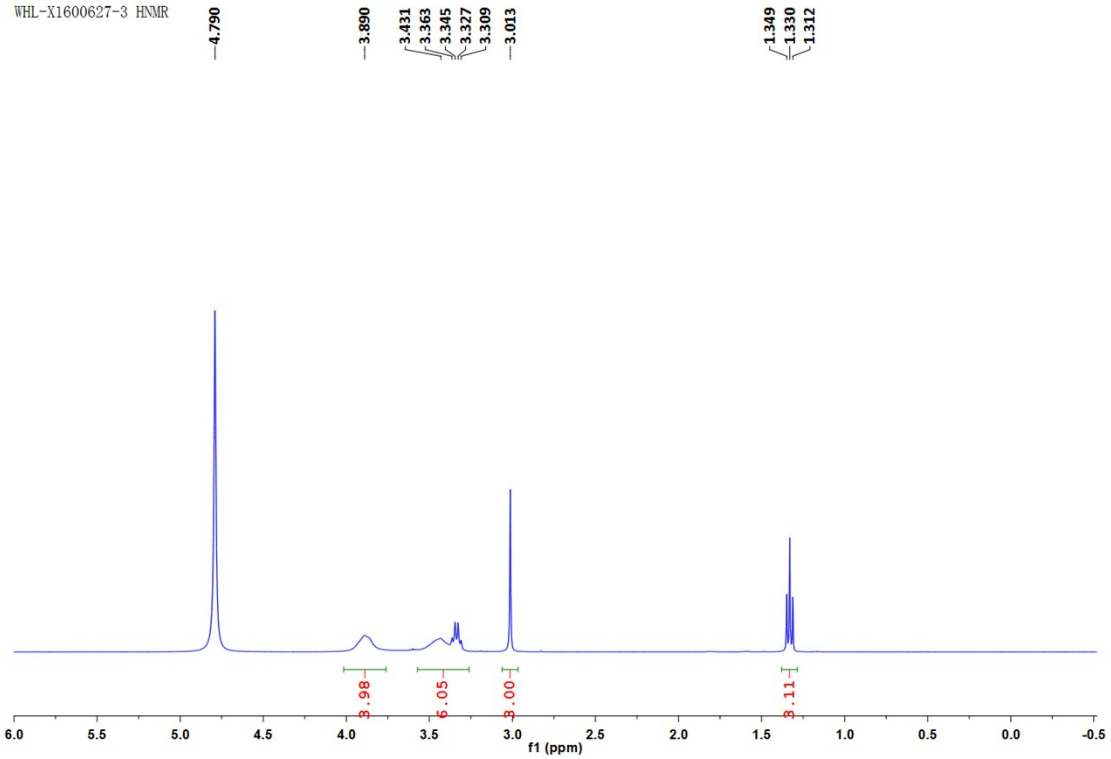


WHL-X160620-8 CNMR

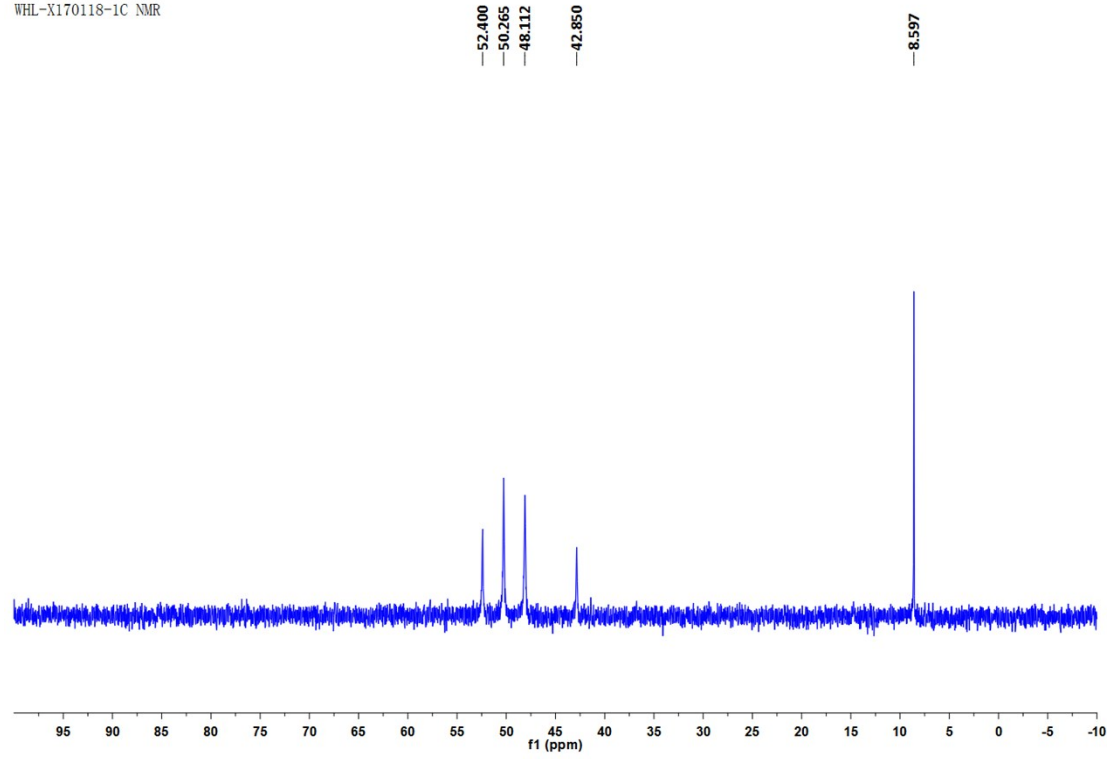


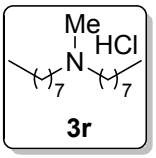


WHL-X1600627-3 HNMR

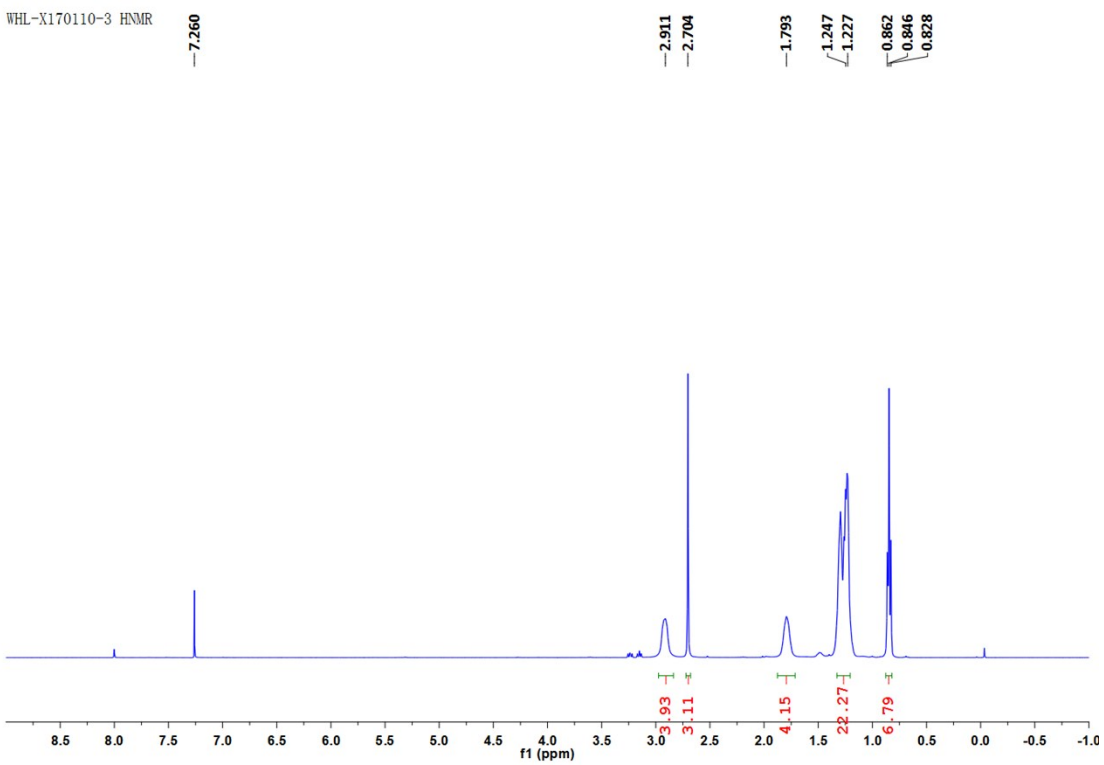


WHL-X170118-1C NMR

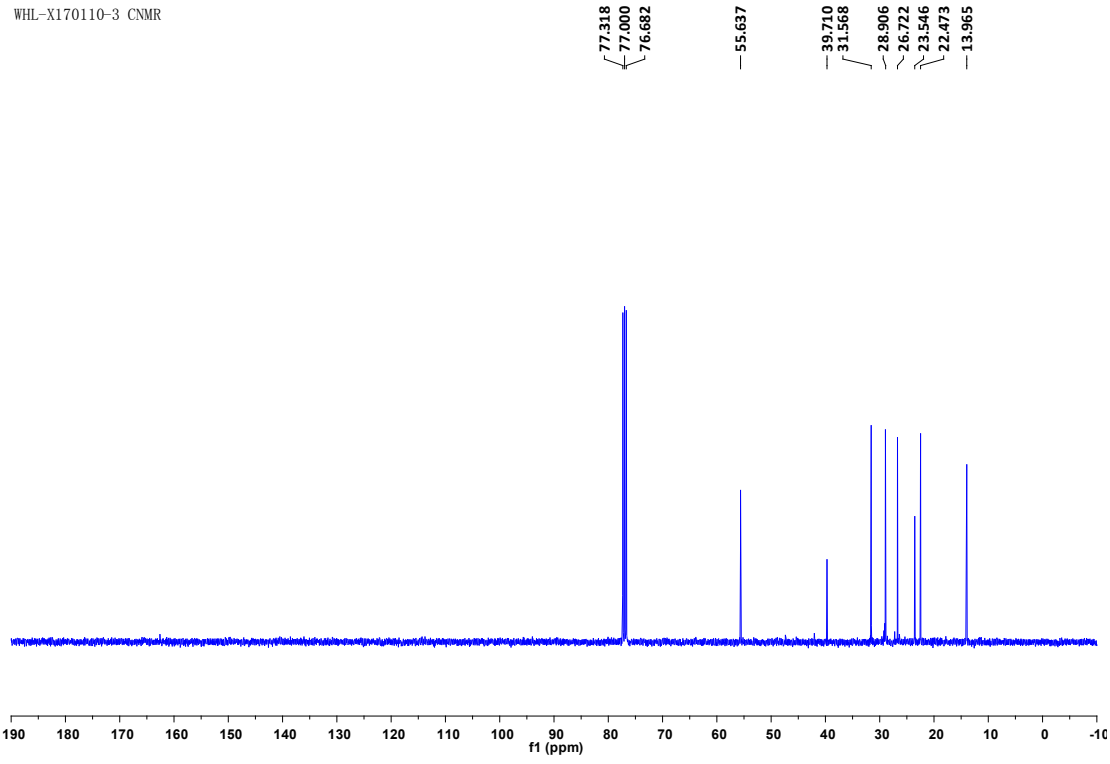


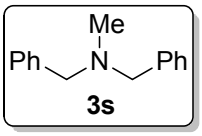


WHL-X170110-3 HNMR

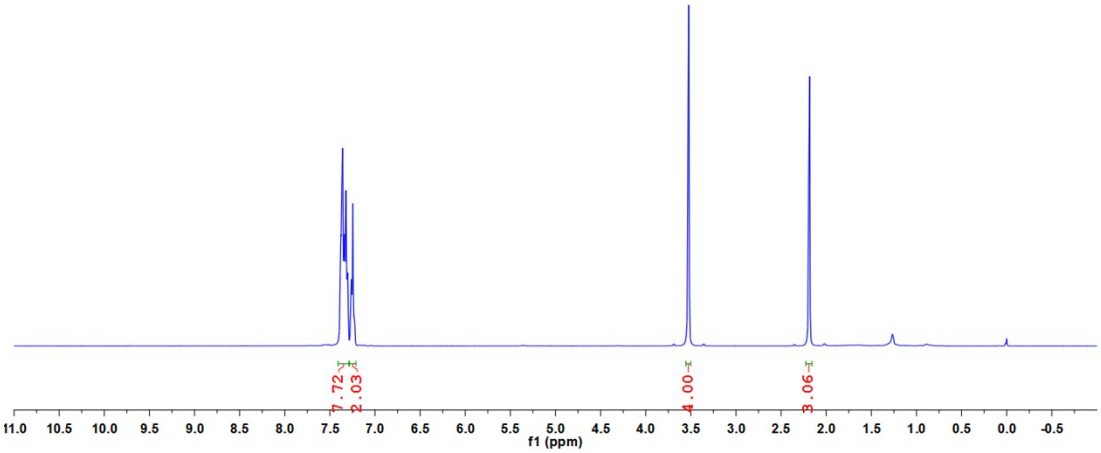


WHL-X170110-3 CNMR

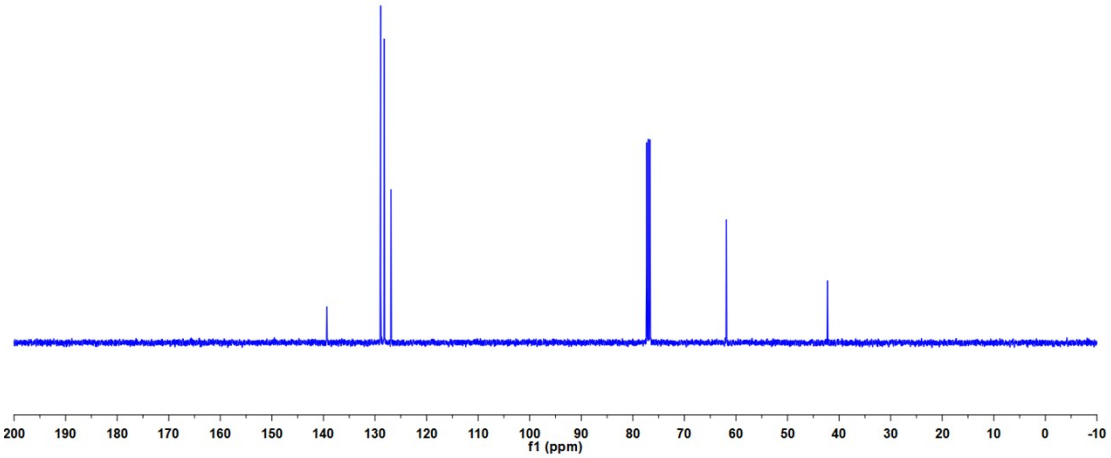


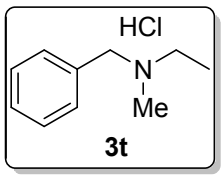


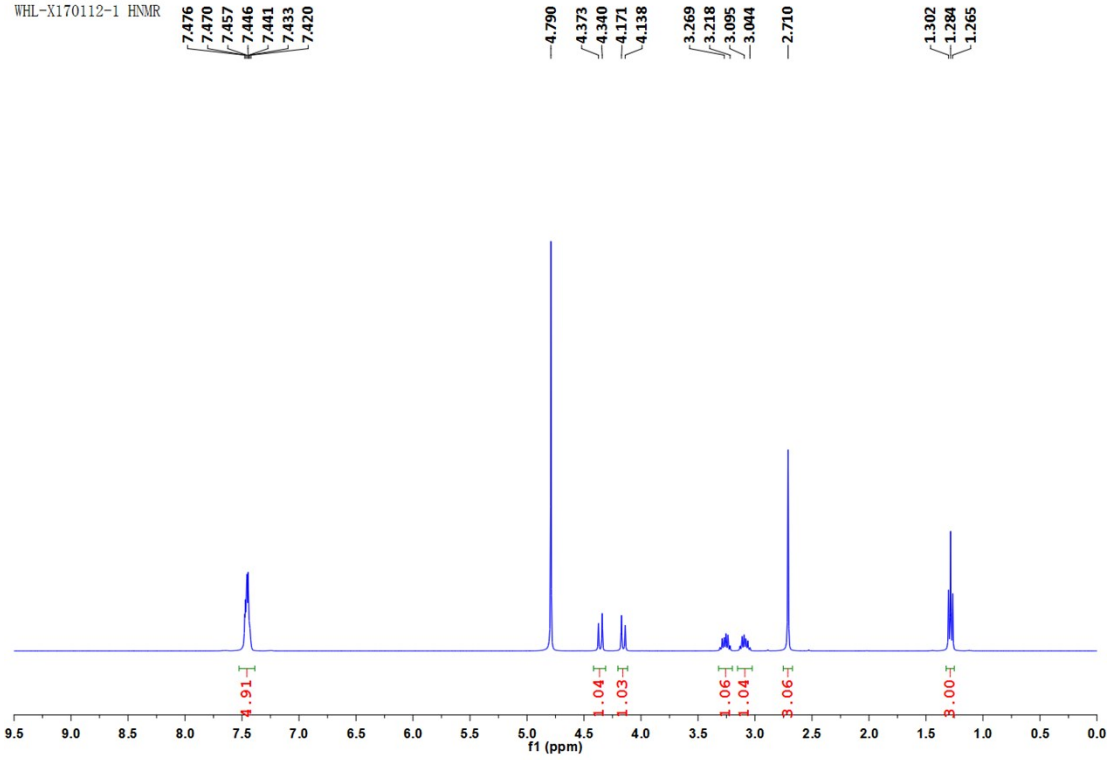
WHL-X160620 HNMR

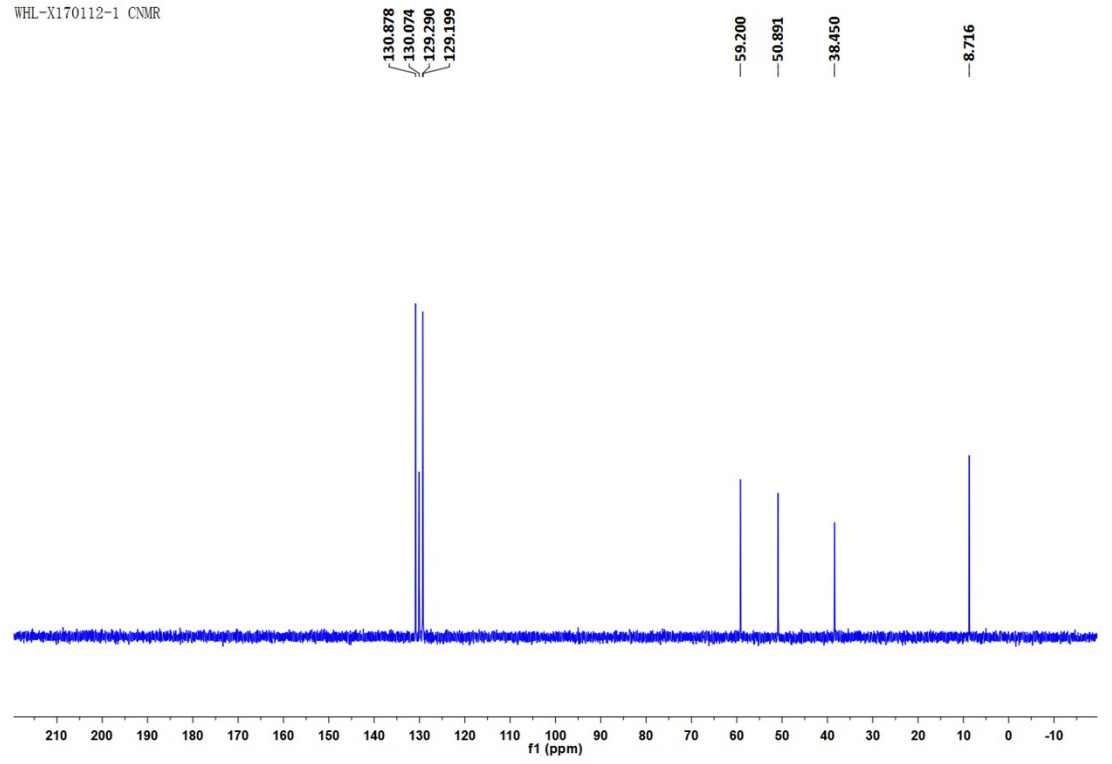


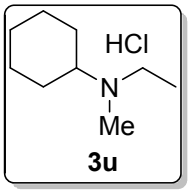
WHL-X160620-2 CNMR

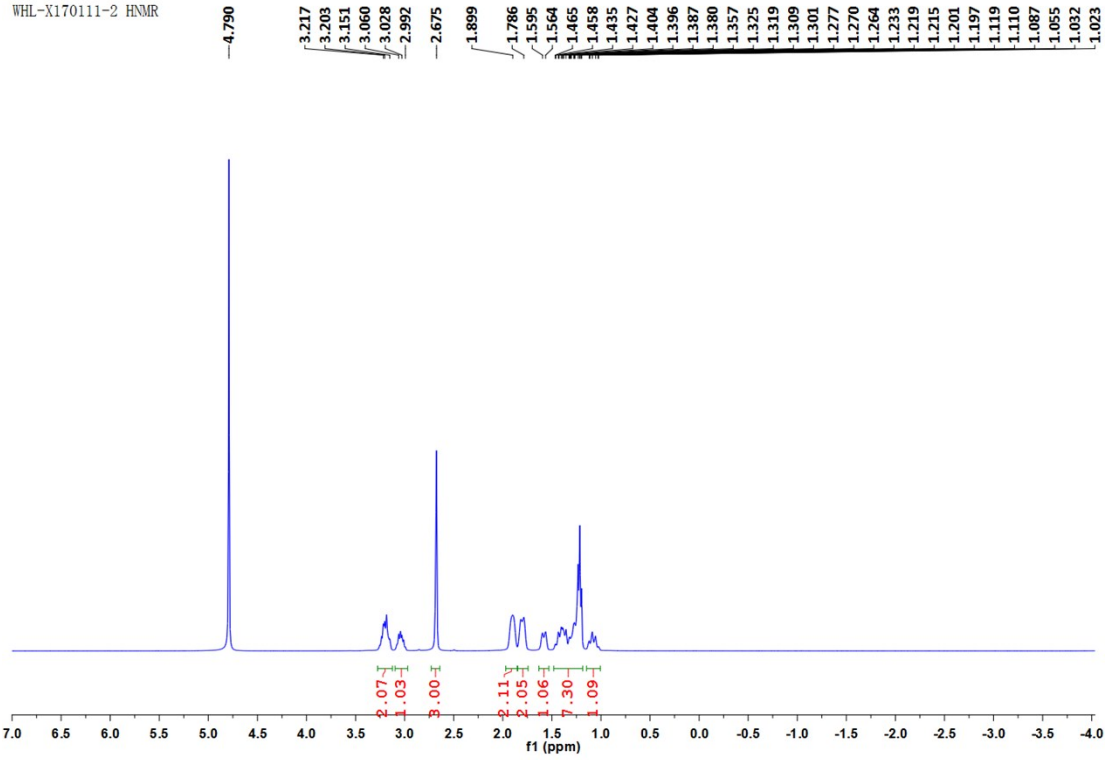


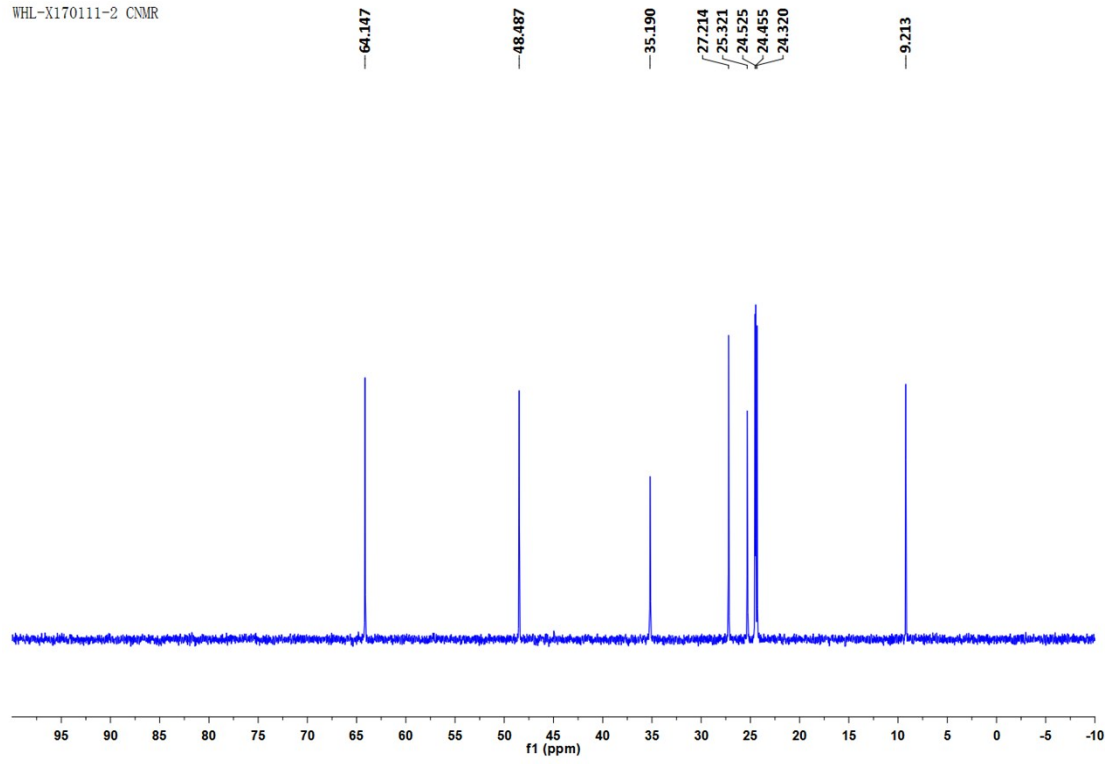

HCl
N
Me
3t

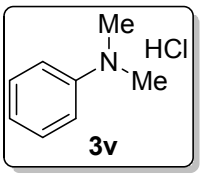

WHL-X170112-1 HNMR
7.476
7.470
7.457
7.446
7.441
7.433
7.420
4.790
4.373
4.340
4.171
4.138
3.269
3.218
3.095
3.044
2.710
1.302
1.284
1.265
4.91
1.04
1.03
1.06
1.04
3.06
3.00
f1 (ppm)

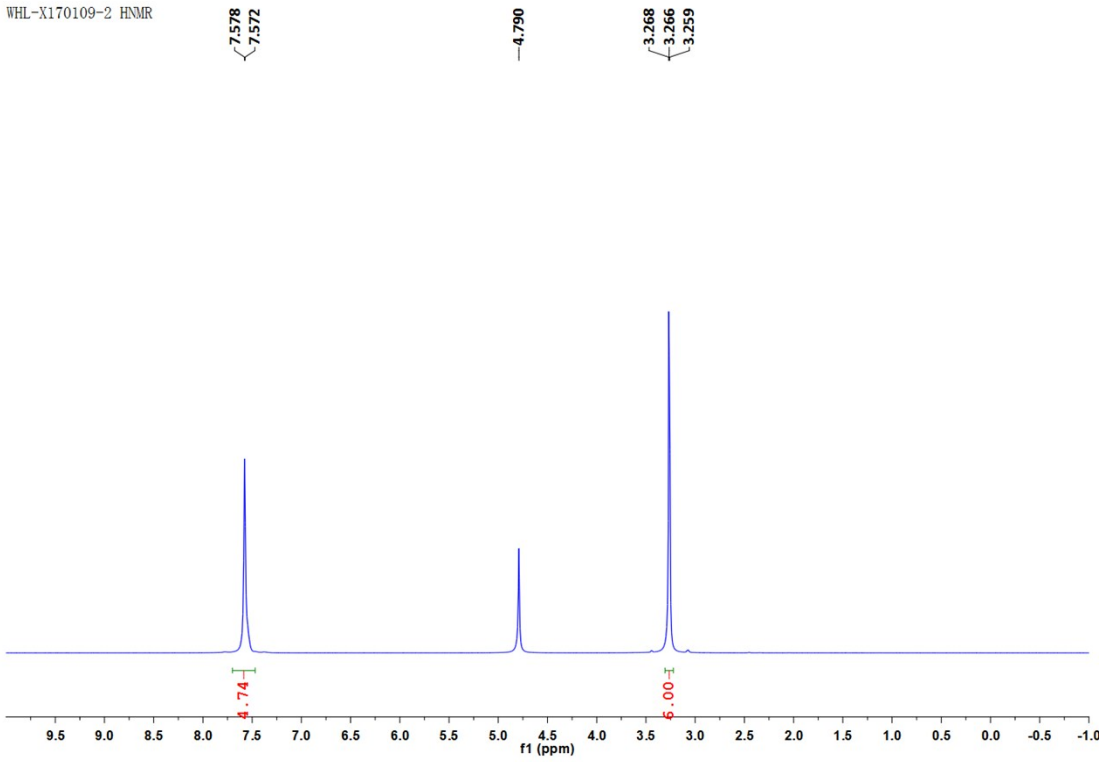

WHL-X170112-1 CNMR
130.878
130.074
129.290
129.199
59.200
50.891
38.450
8.716
f1 (ppm)

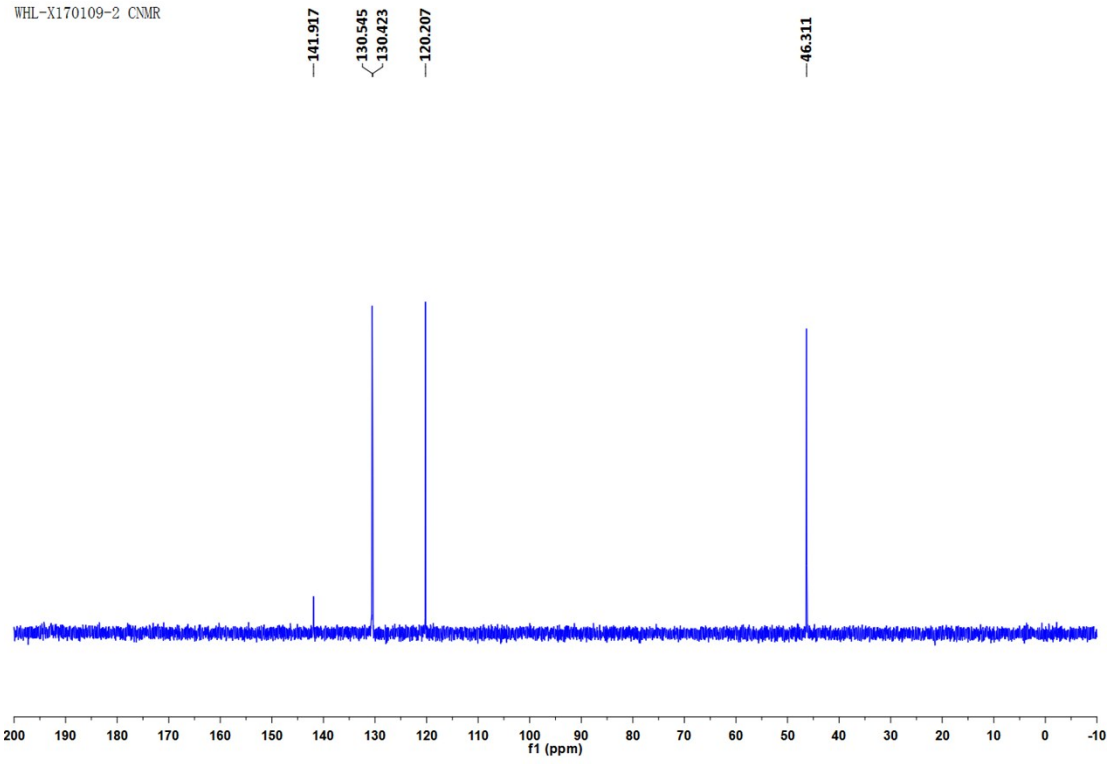

HCl
N
Me
3u


WHL-X170111-2 HNMR
4.790
3.217
3.203
3.151
3.060
3.028
2.992
2.675
1.899
1.786
1.595
1.564
1.465
1.458
1.435
1.427
1.404
1.396
1.387
1.380
1.357
1.325
1.319
1.309
1.301
1.277
1.270
1.264
1.233
1.219
1.215
1.201
1.197
1.119
1.110
1.087
1.055
1.032
1.023
2.07
1.03
3.00
2.11
2.05
1.06
7.30
1.09
f1 (ppm)


WHL-X170111-2 CNMR
64.147
48.487
35.190
27.214
25.321
24.525
24.455
24.320
9.213
f1 (ppm)


Me
N
HCl
Me
3v


WHL-X170109-2 HNMR
7.578
7.572
4.790
3.268
3.266
3.259
4.74
6.00
f1 (ppm)


WHL-X170109-2 CNMR
141.917
130.545
130.423
120.207
46.311
f1 (ppm)