An Efficient Process for Pd-Catalyzed C–N Cross-Coupling Reactions of Aryl Iodides: Insight Into Controlling Factors

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Supporting Information

General Reagent Information

All reactions were carried out under an argon atmosphere. The 1,4-dioxane, DME, and *tert*-butanol were purchased from Aldrich Chemical Co. in Sure-Seal bottles and were used as received. Toluene was purchased from J.T. Baker in CYCLE-TAINER® solvent-delivery kegs and vigorously purged with argon for 2 h. The solvent was further purified by passing it under argon pressure through two packed columns of neutral alumina and copper (II) oxide. Aryl halides and amines were purchased from Aldrich Chemical Co., Alfa Aesar, Acros Organics or TCI America. All amines, aryl bromides, and aryl iodides that were liquids were distilled from calcium hydride and stored under argon. Amines and aryl halides that were a solid were used as purchased without further purification. Cesium carbonate (fine) was a gift from Chemetall and sodium *tert*-butoxide was purchased from Aldrich Chemical Co. The bulk of the bases were stored in an N_2 glovebox. Small portions were taken outside the box in glass vials and weighed in the air. Anhydrous sodium iodide was purchased from Aldrich Chemical Co. and stored in an N_2 glovebox. Ligands **1**,[1] **2**,[2] and **4**[3] were synthesized using literature procedures. Ligand **3** was purchased from Strem Chemicals. Precatalysts **5**,[1] **6**, **7**, and **8**[5] were synthesized using literature procedures. Flash chromatography was performed using a Biotage SP4 instrument with prepacked silica cartridges.

General Analytical Information

All compounds were characterized by ^{1}H NMR, ^{13}C NMR, IR spectroscopy, as well as, in most instances, elemental analysis. Copies of the ^{1}H and ^{13}C spectra can be found at the end of the Supporting Information. Nuclear Magnetic Resonance spectra were recorded on a Varian 300 MHz instrument and Varian 500 MHz instruments. All ^{1}H NMR

experiments are reported in δ units, parts per million (ppm), and were measured relative to the signals for residual chloroform (7.26 ppm) in the deuterated solvent, unless otherwise stated. All ^{13}C NMR spectra are reported in ppm relative to deuterochloroform (77.23 ppm), unless otherwise stated, and all were obtained with ^{1}H decoupling. All IR spectra were taken on a Perkin – Elmer 2000 FTIR. All GC analyses were performed on a Agilent 6890 gas chromatograph with an FID detector using a J & W DB-1 column (10 m, 0.1 mm I.D.). Elemental analyses were performed by Atlantic Microlabs Inc., Norcross, GA.

General Procedure for Figure 1

An oven-dried test tube, which was equipped with a magnetic stir bar and fitted with a teflon septum, was charged with the precatalyst (1 mol%), 4-iodoanisole (234 mg, 1.0 mmol), and NaO*t*-Bu (115 mg, 1.2 mmol). The vessel was evacuated and backfilled with argon (this process was repeated a total of 3 times) and then the aniline (110 μL, 1.2 mmol) and toluene (1 mL) were added via syringe. The solution was stirred at room temperature for 10 min, diluted with Ethyl acetate, and washed with water. Dodecane was then added as an internal standard and the reaction was analyzed by GC.

General Procedure for Table 1

An oven-dried 16 mL vial was equipped with a magnetic stir bar, fitted with a screw-cap Teflon septum, and taken into the glovebox. Once in the glovebox, the vial was charged with 4-haloanisole (1.0 mmol), aniline (55 μL, 0.6 mmol), NaO*t*-Bu (58 mg, 0.6 mmol), and solvent (1.7 mL). The reaction was then taken out of the glovebox and placed in an Omnical CRC reaction calorimeter along with a syringe containing a solution of the Pd source in the solvent (300 μL solvent, 1 mol% Pd precatalyst). The calorimeter was set to 22.4 °C and allowed to thermally equilibrate. After equilibration, the solution of Pd precatalyst was injected and the reaction was stirred until the heat flow on the calorimeter returned to the baseline. A correction was then applied to the raw data due to the delay between the moment that the heat is given off of the reaction and the moment that it is detected. The corrected heat flow curve was then converted to fractional conversion by

dividing the area under the curve to any point by the total area under the curve (equation 1). Dodecane was then added as to the reaction as an internal standard and it was analyzed by GC.

Equation 1

$$\text{fractional conversion} = \frac{\int_0^t q \bullet dt}{\int_0^{t(f)} q \bullet dt}$$

General Procedure for Figure 2

An oven-dried 16 mL vial was equipped with a magnetic stir bar, fitted with a screw-cap Teflon septum, and taken into the glovebox. Once in the glovebox, the vial was charged with 2 mL of a solution of 4-bromoanisole (63 μL, 0.5 mmol), aniline (55 μL, 0.6 mmol), NaO*t*-Bu (58 mg, 0.6 mmol), and NaI (0 – 20 mol%) in DME, which was prepared in a 2 mL volumetric flask. The reaction was then taken out of the glovebox and placed in an Omnical CRC reaction calorimeter along with a syringe containing a solution of **8** (4 mg, 1 mol%) in 1,4-dioxane (300 μL). The calorimeter was set to 22.4 °C and allowed to thermally equilibrate. After equilibration, the solution containing **8** was injected and the reaction was stirred until the heat flow on the calorimeter returned to the baseline. A correction was then applied to the raw data due to the delay between the moment that the heat is given off of the reaction and the moment that it is detected. The corrected heat flow curve was then converted to rate by using the equation $q = \Delta H_{rxn} \bullet V \bullet r$, where q is the heat flow, ΔH_{rxn} is the heat of reaction, V is the reaction volume, and r is the reaction rate. The heat of reaction was found by integrating the heat flow vs. time curves.

General Procedure for Figure 3

An oven-dried 16 mL vial was equipped with a magnetic stir bar, fitted with a screw-cap Teflon septum, and taken into the glovebox. Once in the glovebox, the vial was charged with 4-iodoanisole (117 mg, 0.5 mmol), aniline (55 μL, 0.6 mmol), NaO*t*-Bu (58 mg, 0.6

mmol), NaI or tetrahexylammonium iodide (0 – 20 mol%), and toluene (1.7 mL). The reaction was then taken out of the glovebox and placed in an Omnical CRC reaction calorimeter along with a syringe containing a solution of **8** (4 mg, 1 mol%) in toluene (300 μL). The calorimeter was set to 22.4 °C and allowed to thermally equilibrate. After equilibration, the solution containing **8** was injected and the reaction was stirred until the heat flow on the calorimeter returned to the baseline. A correction was then applied to the raw data due to the delay between the moment that the heat is given off of the reaction and the moment that it is detected. The corrected heat flow curve was then converted to rate by using the equation $q = \Delta H_{rxn} \bullet V \bullet r$, where q is the heat flow, ΔH_{rxn} is the heat of reaction, V is the reaction volume, and r is the reaction rate. The heat of reaction was found by integrating the heat flow vs. time curves.

General Procedure for Figure 4

An oven-dried test tube, which was equipped with a magnetic stir bar and fitted with a teflon septum, was charged with the precatalyst (1 mol%), 4-iodoanisole (234 mg, 1.0 mmol), and NaO*t*-Bu (115 mg, 1.2 mmol). The vessel was evacuated and backfilled with argon (this process was repeated a total of 3 times) and then the morpholine (105 μL, 1.2 mmol) and toluene (1 mL) were added via syringe. The solution was heated to 80 °C for 3 min, then cooled to room temperature, diluted with Ethyl acetate, and washed with water. Dodecane was then added as an internal standard and the reaction was analyzed by GC.

General Procedures for Tables 2, 3, and 4

General Procedure A: An oven-dried test tube, which was equipped with a magnetic stir bar and fitted with a teflon septum, was charged with NaO*t*-Bu (1.2 equiv). The vessel was evacuated and backfilled with argon (this process was repeated a total of 3 times) and then the aryl iodide (1 equiv), amine (1.2 equiv), and toluene (0.3 – 1.0 mL/mmol) were added via syringe (aryl iodides or amines that were solids at room temperature were added with the and base). A solution of the ligand and precatalyst in toluene (0.002 M, 0.005 – 0.2 mol% **1**, 0.005 – 0.2 mol% **5**) was added and the reaction was heated to 110

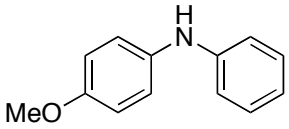
°C until the starting material was completely consumed as monitored by GC. The reaction mixture was then cooled to room temperature, diluted with ethyl acetate, washed with water, concentrated in vacuo, and purified via the Biotage SP4 (silica-packed 50 or100 g snap cartridge).

General Procedure B: An oven-dried test tube, which was equipped with a magnetic stir bar and fitted with a teflon septum, was charged with the ligand (0.05 – 0.2 mol%), the precatalyst (0.05 – 0.2 mol%), and NaO*t*-Bu (1.2 – 1.4 equiv). The vessel was evacuated and backfilled with argon (this process was repeated a total of 3 times) and then the aryl iodide (1 equiv), amine (1.2 – 1.4 equiv), and toluene (0.3 mL/mmol) were added via syringe (aryl iodides or amines that were solids at room temperature were added with the precatalyst and base). The solution was heated to 85 °C until the starting material was completely consumed as monitored by GC. The reaction mixture was then cooled to room temperature, diluted with ethyl acetate, washed with water, concentrated in vacuo, and purified via the Biotage SP4 (silica-packed 50 or100 g snap cartridge).

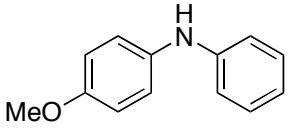
General Procedure C: General procedure A was used with the following modification: 1.4 equiv of Cs_2CO_3 was used as the base.

General Procedure D: An oven-dried test tube, which was equipped with a magnetic stir bar and fitted with a teflon septum, was charged with the ligand (0.5 – 1 mol%), the precatalyst (0.5 – 1 mol%), and K_2CO_3 (1.4 equiv). The vessel was evacuated and backfilled with argon (this process was repeated a total of 3 times) and then the aryl iodide (1 equiv), amine (1.4 equiv), and *t*-BuOH (2 mL/mmol) were added via syringe (aryl iodides or amines that were solids at room temperature were added with the precatalyst and base). The solution was heated to 110 °C until the starting material was completely consumed as monitored by GC. The reaction mixture was then cooled to room temperature, diluted with ethyl acetate, washed with water, concentrated in vacuo, and purified via the Biotage SP4 (silica-packed 50 g snap cartridge).

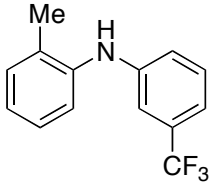
Experimental Procedures for Examples Described in Table 2



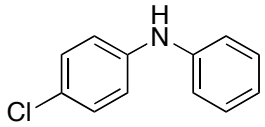
4-methoxy-*N*-phenylaniline[4] (Table 2) Following general procedure A, a mixture of 4-iodoanisole (468 mg, 2.0 mmol), aniline (256 μL, 2.8 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **5** and **1** (50 μL, 0.002 M in toluene, 0.005 mol%), and toluene (2 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-45% EtOAc/hexanes) to provide the title compound as a white solid (390 mg, 98%), mp 104 – 105 °C (lit. 104 – 106 °C). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.31 (t, *J* = 7.5 Hz, 2H), 7.15 (d, *J* = 9.0 Hz, 2H), 6.97 (m, 5H), 5.58 (bs, 1H), 3.87 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 155.5, 145.5, 136.1, 129.7, 122.5, 119.9, 115.9, 115.0, 55.9 ppm. IR (neat, cm^{-1}): 3384, 2837, 1597, 1513, 1298, 1250, 1182, 1034, 752, 696. Anal. Calcd. for $C_{13}H_{13}NO$: C, 78.36; H, 6.58. Found: C, 78.07; H, 6.62.



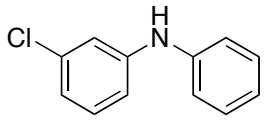
4-methoxy-*N*-phenylaniline[4] (Table 2) Following general procedure A, a mixture of 4-iodoanisole (468 mg, 2.0 mmol), aniline (256 μL, 2.8 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **5** and **1** (100 μL, 0.002 M in toluene, 0.01 mol%), and toluene (900 μL) was heated to 110 °C for 5 min. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-45% EtOAc/hexanes) to provide the title compound as a white solid (388 mg, 97%), mp 104 – 105 °C (lit. 104 – 106 °C). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.31 (t, *J* = 7.5 Hz, 2H), 7.15 (d, *J* = 9.0 Hz, 2H), 6.97 (m, 5H), 5.58 (bs, 1H), 3.87 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 155.5, 145.5, 136.1, 129.7, 122.5, 119.9, 115.9, 115.0, 55.9 ppm. IR (neat, cm^{-1}): 3384, 2837, 1597, 1513, 1298, 1250, 1182, 1034, 752, 696. Anal. Calcd. for $C_{13}H_{13}NO$: C, 78.36; H, 6.58. Found: C, 78.38; H, 6.68.



2-methyl-*N*-(3-(trifluoromethyl)phenyl)aniline (Table 2) Following general procedure A, a mixture of 2-iodotoluene (350 μL, 2.0 mmol), 3-aminobenzotrifluoride (350 μL, 2.8 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **5** and **1** (100 μL, 0.002 M in toluene, 0.01 mol%), and toluene (900 μL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-45% EtOAc/hexanes) to provide the title compound as a yellow oil (438 mg, 87%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.42 – 7.28 (m, 4H), 7.23 – 7.10 (m, 4H), 5.58 (bs, 1H), 2.35 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 145.4, 140.1, 132.1, 131.9, 131.6, 130.5, 130.1, 127.3, 125.7, 124.0, 123.5, 121.2, 119.4, 116.6, 116.5, 116.5, 113.0, 112.9, 112.9, 18.1 ppm (observed complexity due to C–F splitting). IR (neat, cm^{-1}): 3398, 3034, 2926, 1585, 1496, 1338, 1165, 1124, 1069, 699. Anal. Calcd. for $C_{14}H_{12}F_3N$: C, 66.93; H, 4.81. Found: C, 66.98; H, 4.80.

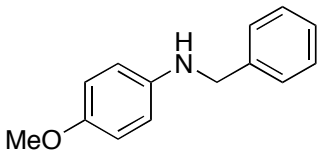


4-chloro-*N*-phenylaniline[5] (Table 2) Following general procedure A, a mixture of 4-chloroiodobenzene (477 mg, 2.0 mmol), aniline (182 μL, 2.0 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **5** and **1** (500 μL, 0.002 M in toluene, 0.05 mol%), and toluene (500 μL) was heated to 80 °C for 2 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-25% EtOAc/hexanes) to provide the title compound as a white solid (397 mg, 97%), mp 67 – 68 °C (lit. 72 °C). ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.38 (t, J = 7.5 Hz, 2H), 7.29 (d, J = 6.5 Hz, 2H), 7.12 (d, J = 7.5 Hz, 2H), 7.05 (m, 3H), 5.70 (bs, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 143.0, 142.2, 129.8, 129.6, 125.7, 121.8, 119.1, 118.4 ppm. IR (neat, cm^{-1}): 3403, 1590, 1505, 1485, 1384, 1312, 1090, 750, 692, 504. Anal. Calcd. for $C_{12}H_{10}ClN$: C, 70.77; H, 4.95. Found: C, 70.57; H, 5.03.

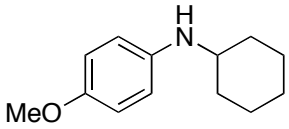


3-chloro-*N*-phenylaniline (Table 2) Following general procedure A, a mixture of 3-chloroiodobenzene (247 μL, 2.0 mmol), aniline (182 μL, 2.0 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **5** and **1** (500 μL, 0.002 M in toluene, 0.05 mol%), and toluene (500 μL) was heated to 80 °C for 2 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-25% EtOAc/hexanes) to provide the title compound as a

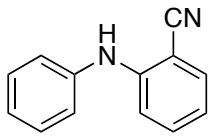
yellow oil (395 mg, 96%). ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.38 (t, *J* = 7.5 Hz, 2H), 7.22 (t, *J* = 8.0 Hz, 1H), 7.15 (d, *J* = 7.5 Hz, 2H), 7.09 (m, 2H), 6.95 (dd, *J* = 8.0 Hz, *J* = 2.0 Hz, 2H), 5.73 (bs, 1H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$) δ: 145.1, 142.2, 135.3, 130.7, 129.8, 122.4, 120.8, 119.3, 117.0, 115.4 ppm. IR (neat, cm^{-1}): 3403, 3059, 1589, 1496, 1480, 1314, 993, 916, 752, 681. Anal. Calcd. for $C_{12}H_{10}ClN$: C, 70.77; H, 4.95. Found: C, 71.05; H, 4.91.



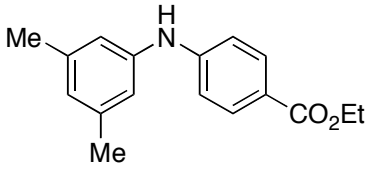
***N*-benzyl-4-methoxyaniline**[1] (Table 2) Following general procedure B, a mixture of 4-iodoanisole (2.33 g, 10 mmol), benzylamine (1.31 mL, 12 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **5** (4 mg, 0.05 mol%) and **1** (2.5 mg, 0.05 mol%), and toluene (3 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a yellow oil (1.761 g, 83%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.46 (m, 5H), 6.91 (d, *J* = 9.0 Hz, 2H), 6.71 (d, *J* = 9.0 Hz, 2H), 4.37 (s, 2H), 3.90 (bs, 1H), 3.84 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 152.5, 142.9, 140.2, 129.0, 127.9, 127.5, 115.3, 114.5, 56.1, 49.5 ppm. IR (neat, cm^{-1}): 3415, 3028, 2831, 1511, 1452, 1234, 1036, 819, 742, 697.



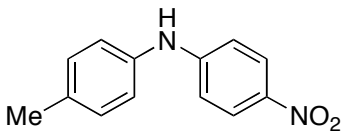
***N*-cyclohexyl-4-methoxyaniline**[6] (Table 2) Following general procedure B, a mixture of 4-iodoanisole (2.33 g, 10 mmol), cyclohexylamine (1.603 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **5** (8 mg, 0.1 mol%) and **1** (5 mg, 0.1 mol%), and toluene (3 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-50% EtOAc/hexanes) to provide the title compound as a white solid (1.875 g, 92%), mp 44 – 46 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.80 (d, *J* = 9.0 Hz, 2H), 6.60 (*J* = 9.0 Hz, 2H), 3.76 (s, 3H), 3.26 (bs, 1H), 3.20 (m, 1H), 2.07 (m, 2H), 1.78 (m, 2H), 1.68 (m, 1H), 1.48 – 1.05 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 152.1, 141.9, 115.1, 115.0, 56.0, 53.0, 33.9, 26.3, 25.4 ppm. IR (neat, cm^{-1}): 3388, 2929, 2852, 1511, 1450, 1240, 1040, 819, 756, 515.



2-(phenylamino)benzonitrile (Table 2) Following general procedure C, a mixture of iodobenzene (112 μL, 1.0 mmol), 2-aminobenzonitrile (165 mg, 1.2 mmol), Cs_2CO_3 (456 mg, 1.4 mmol), and **5** and **1** (1 mL, 0.002 M in toluene, 0.2 mol%) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-45% EtOAc/hexanes) to provide the title compound as a white solid (175 mg, 90%), mp 50 – 51 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.51 (d, J = 7.8 Hz, 1H), 7.39 (m, 3H), 7.21 (m, 3H), 7.15 (t, J = 7.2 Hz, 1H), 6.85 (t, J = 7.5 Hz, 1H), 6.54 (bs, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 147.6, 140.3, 134.2, 133.4, 129.9, 124.4, 121.9, 119.5, 118.0, 114.5, 98.8 ppm. IR (neat, cm^{-1}): 3338, 2217, 1592, 1575, 1517, 1457, 1319, 1293, 745, 695. Anal. Calcd. for $C_{13}H_{10}N_2$: C, 80.39; H, 5.19. Found: C, 80.09; H, 5.12.

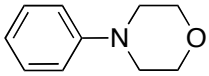


Ethyl 4-(3,5-dimethylphenylamino)benzoate[7] (Table 2) Following general procedure C, a mixture of 3,5-dimethyliodobenzene (144 μL, 1.0 mmol), ethyl 4-aminobenzoate (231 mg, 1.4 mmol), Cs_2CO_3 (456 mg, 1.4 mmol), **5** and **1** (500 μL, 0.002 M in toluene, 0.1 mol%), and toluene (0.5 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-50% EtOAc/hexanes) to provide the title compound as a white solid (244 mg, 91%), mp 117 – 119 °C (lit. 119 °C). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.94 (d, J = 8.4 Hz, 2H), 6.99 (d, J = 8.4, 2H), 6.81 (s, 2H), 6.73 (s, 1H), 6.12 (bs, 1H), 4.36 (q, J = 7.2 Hz, 2H), 2.32 (s, 6H), 1.40 (t, J = 7.2 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 166.9, 148.5, 141.1, 139.4, 131.7, 125.0, 121.3, 118.3, 114.9, 60.7, 21.6, 14.7 ppm. IR (neat, cm^{-1}): 3343, 1698, 1595, 1510, 1352, 1282, 1170, 1109, 831, 769. Anal. Calcd. for $C_{17}H_{19}NO_2$: C, 75.81; H, 7.11. Found: C, 75.54; H, 7.13.

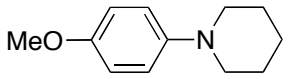


4-methyl-*N*-(4-nitrophenyl)aniline (Table 2) Following general procedure C, a mixture of 4-iodotoluene (218 mg, 1.0 mmol), 4-nitroaniline (193 mg, 1.4 mmol), Cs_2CO_3 (456 mg, 1.4 mmol), **5** and **1** (500 μL, 0.002 M in toluene, 0.1 mol%), and toluene (0.5 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as an orange solid (220 mg, 96%), mp 138 – 139 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.09 (d, *J* = 9.0 Hz, 2H), 7.20 (d, *J* = 7.8 Hz, 2H), 7.12 (d, *J* = 7.8 Hz, 2H), 6.88 (d, *J* = 9.0 Hz, 2H), 6.38 (bs, 1H), 2.37 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 151.2, 139.4, 136.9, 135.0, 130.5, 126.6, 122.9, 113.4, 21.2 ppm. IR (neat, cm^{-1}): 3342, 1595, 1524, 1481, 1298, 1187, 1111, 829, 749, 499. Anal. Calcd. for $C_{13}H_{12}N_2O_2$: C, 68.41; H, 5.30. Found: C, 68.35; H, 5.22.

Experimental Procedures for Examples Described in Table 3

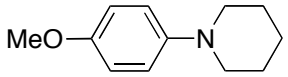


4-phenylmorpholine[8] (Table 3) Following general procedure A, a mixture of iodobenzene (1.119 mL, 10 mmol), morpholine (1.223 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **4** and **8** (1.25 mL, 0.002 M in toluene, 0.025 mol%), and toluene (1.75 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-50% EtOAc/hexanes) to provide the title compound as a white solid (1.632 g, 99%), mp 53 – 55 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.39 (t, *J* = 7.0 Hz, 2H), 7.00 (m, 3H), 3.91 (t, *J* = 5.0 Hz, 4H), 3.19 (t, *J* = 5.0 Hz, 4H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$) δ: 151.7, 129.6, 120.3, 116.0, 67.2, 49.6 ppm. IR (neat, cm^{-1}): 2888, 2856, 2826, 1599, 1496, 1449, 1231, 1120, 926, 773. Anal. Calcd. for $C_{10}H_{13}NO$: C, 73.59; H, 8.03. Found: C, 73.53; H, 8.19.

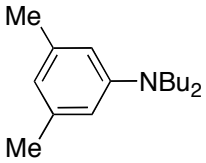


1-(4-methoxyphenyl)piperidine[8] (Table 3) Following general procedure B, a mixture of 4-iodoanisole (2.33 g, 10 mmol), piperidine (1.381 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **8** (3.5 mg, 0.05 mol%) and **4** (2.5 mg, 0.05 mol%), and toluene (3 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a

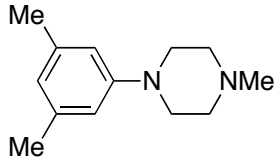
yellow oil (1.633 g, 85%). ^{1}H NMR (500 MHz, $CDCl_3$) δ: 6.96 (d, J = 9.0 Hz, 2H), 6.88 (d, J = 9.0 Hz, 2H), 3.79 (s, 3H), 3.07 (t, J = 5.5 Hz, 4H), 1.77 (m, 4H), 1.59 (m, 2H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$) δ: 153.8, 147.2, 119.0, 114.6, 55.7, 52.6, 26.5, 24.5 ppm. IR (neat, cm^{-1}): 2934, 2792, 1511, 1453, 1244, 1041, 919, 823, 700, 539.



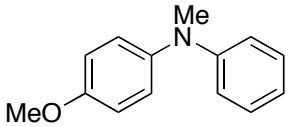
1-(4-methoxyphenyl)piperidine[8] (Table 3) Following general procedure B, a mixture of 4-iodoanisole (2.33 g, 10 mmol), piperidine (1.381 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **8** (3.5 mg, 0.05 mol%) and **4** (2.5 mg, 0.05 mol%), and dioxane (3 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a yellow oil (1.711 g, 89%). ^{1}H NMR (500 MHz, $CDCl_3$) δ: 6.96 (d, J = 9.0 Hz, 2H), 6.88 (d, J = 9.0 Hz, 2H), 3.79 (s, 3H), 3.07 (t, J = 5.5 Hz, 4H), 1.77 (m, 4H), 1.59 (m, 2H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$) δ: 153.8, 147.2, 119.0, 114.6, 55.7, 52.6, 26.5, 24.5 ppm. IR (neat, cm^{-1}): 2934, 2792, 1511, 1453, 1244, 1041, 919, 823, 700, 539.



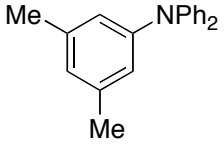
***N*,*N*-dibutyl-3,5-dimethylaniline** (Table 3) Following general procedure A, a mixture of 3,5-dimethyliodobenzene (1.44 mL, 10 mmol), dibutylamine (2.35 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **4** and **8** (2.50 mL, 0.002 M in toluene, 0.05 mol%), and toluene (0.5 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 0-50% EtOAc/hexanes) to provide the title compound as a yellow oil (2.127 g, 91%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.66 (s, 3H), 3.60 (t, J = 7.5 Hz, 4H), 2.64 (s, 6H), 1.93 (pentet, J = 8.1 Hz, 4H), 1.72 (sextet, J = 7.5 Hz, 4H), 1.33 (t, J = 7.5 Hz, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 148.9, 139.1, 117.9, 110.3, 51.4, 30.1, 22.5, 21.0, 14.6 ppm. IR (neat, cm^{-1}): 2957, 2872, 1597, 1486, 1367, 1304, 1196, 1064, 814, 691. Anal. Calcd. for $C_{16}H_{27}N$: C, 82.34; H, 11.66. Found: C, 82.17; H, 11.91.



1-(3,5-dimethylphenyl)-4-methylpiperazine (Table 3) Following general procedure B, a mixture of 3.5-dimethyliodobenzene (1.443 mL, 10 mmol), *N*-methylpiperazine (1.550 mL, 14 mmol), NaO*t*-Bu (1.34 g, 14 mmol), **8** (7 mg, 0.1 mol%) and **4** (4.5 mg, 0.1 mol%), and toluene (3 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 100 g snap column; 75-100% EtOAc/hexanes) to provide the title compound as a yellow oil (1.808 g, 89%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.61 (s, 2H), 6.56 (s, 1H), 3.22 (t, J = 5.1 Hz, 4H), 2.59 (t, J = 5.1 Hz, 4H), 2.38 (s, 3H), 2.32 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 151.7, 138.8, 121.9, 114.3, 55.5, 49.5, 46.5, 22.0 ppm. IR (neat, cm^{-1}): 2937, 2794, 1597, 1452, 1376, 1291, 1265, 1143, 1009, 828.

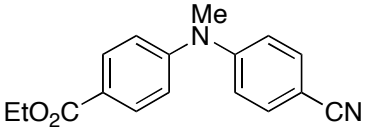


4-methoxy-*N*-methyl-*N*-phenylaniline (Table 3) Following general procedure A, a mixture of 4-iodoanisole (468 mg, 2.0 mmol), *N*-methylaniline (303 μL, 2.8 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **4** and **8** (100 μL, 0.002 M in toluene, 0.01 mol%), and toluene (0.9 mL) was heated to 85 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a yellow oil (342 mg, 80%). ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.25 (t, J = 9.0 Hz, 2H), 7.15 (d, J = 9.0 Hz, 2H), 6.95 (d, J = 9.5 Hz, 2H), 6.85 (m, 3H), 3.86 (s, 3H), 3.31 (s, 3H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$) δ: 156.6, 150.0, 142.5, 129.2, 126.6, 118.6, 116.0, 115.0, 55.8, 40.8, 39.8 ppm. IR (neat, cm^{-1}): 2951, 2834, 1597, 1508, 1344, 1244, 1035, 835, 751, 695. Anal. Calcd. for $C_{14}H_{15}NO$: C, 78.84; H, 7.09. Found: C, 79.07; H, 7.24.



3,5-dimethyl-*N*,*N*-diphenylaniline (Table 3) Following general procedure A, a mixture

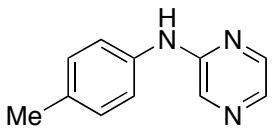
of 3.5-dimethyliodobenzene (289 μL, 2.0 mmol), diphenylamine (473 mg, 2.8 mmol), NaO*t*-Bu (269 mg, 2.8 mmol), **4** and **8** (500 μL, 0.002 M in toluene, 0.05 mol%), and toluene (0.5 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a white solid (489 mg, 90%), mp 135 – 136 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.34 (t, *J* = 7.2 Hz, 4H), 7.20 (*J* = 7.5 Hz, 4H), 7.09 (t, *J* = 7.2 Hz, 2H), 6.86 (s, 2H), 6.80 (s, 1H), 2.34 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 148.4, 148.1, 139.2, 129.5, 125.2, 125.2, 124.4, 122.7, 21.7 ppm. IR (neat, cm^{-1}): 3035, 1589, 1492, 1338, 1294, 1273, 1230, 1029, 753, 693. Anal. Calcd. for $C_{20}H_{19}N$: C, 87.87; H, 7.01. Found: C, 87.62; H, 7.11.



3,5-dimethyl-*N*,*N*-diphenylaniline (Table 3) Following general procedure C, a mixture of ethyl 4-iodobenzoate (152 μL, 1.0 mmol), 4-cyano-*N*-methylaniline (185 mg, 1.4 mmol), Cs_2CO_3 (456 mg, 1.4 mmol), **4** and **8** (500 μL, 0.002 M in toluene, 0.1 mol%), and toluene (0.5 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-30% EtOAc/hexanes) to provide the title compound as a clear oil (266 mg, 95%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.99 (d, *J* = 8.4 Hz, 2H), 7.45 (d, *J* = 9.0 Hz, 2H), 7.15 (d, *J* = 8.7 Hz, 2H), 6.96 (d, *J* = 8.7 Hz, 2H), 4.33 (q, *J* = 6.9 Hz, 2H), 3.38 (s, 3H), 1.36 (t, *J* = 7.2 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 166.2, 151.4, 151.0, 133.6, 131.5, 125.9, 122.6, 119.9, 118.0, 102.7, 61.1, 40.2, 14.6 ppm. IR (neat, cm^{-1}): 2982, 2218, 1710, 1595, 1508, 1347, 1278, 1179, 1107, 773. Anal. Calcd. for $C_{17}H_{16}N_2O_2$: C, 72.84; H, 5.75. Found: C, 72.90; H, 5.76.

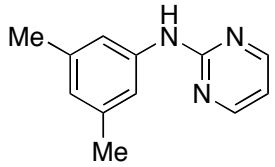
Experimental Procedures for Examples Described in Table 4

Note: All heteroaryliodides that were not commercially available were synthesized using literature procedures.[9]

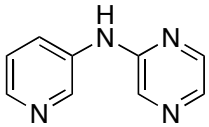


***N*-*p*-tolylpyrazin-2-amine** (Table 4) Following general procedure D, a mixture of 4-

iodotoluene (218 mg, 1.0 mmol), aminopyrazine (133 mg, 1.4 mmol), K_2CO_3 (197 mg, 1.4 mmol), **5** (4 mg, 0.5 mol%) and **1** (2.5 mg, 0.5 mol%), and *t*-BuOH (2 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-50% EtOAc/hexanes) to provide the title compound as a white solid (167 mg, 95%), mp 112 – 113 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.19 (s, 1H), 8.06 (s, 1H), 7.92 (d, J = 2.7 Hz, 1H), 7.62 (bs, 1H), 7.30 (d, J = 8.4 Hz, 2H), 7.14 (J = 8.1 Hz, 2H), 2.33 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 153.2, 142.2, 136.9, 134.3, 133.6, 133.0, 130.2, 121.2, 21.1 ppm. IR (neat, cm^{-1}): 3289, 3100, 1626, 1524, 1385, 1142, 1004, 814, 506, 413. Anal. Calcd. for $C_{11}H_{11}N_3$: C, 71.33; H, 5.99. Found: C 71.06; H, 6.03.

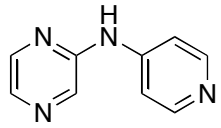


***N*-(3,5-dimethylphenyl)pyrimidin-2-amine** (Table 4) Following general procedure D, a mixture of 3,5-dimethyliodobenzene (144 μL, 1.0 mmol), 2-aminopyrimidine (133 mg, 1.4 mmol), K_2CO_3 (197 mg, 1.4 mmol), **5** (8 mg, 1 mol%) and **1** (5 mg, 1 mol%), and *t*-BuOH (2 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-40% EtOAc/hexanes) to provide the title compound as a yellow oil (161 mg, 81%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.44 (d, J = 4.8 Hz, 2H), 8.26 (s, 1H), 7.28 (s, 2H), 6.74 (s, 1H), 6.69 (t, J = 4.8 Hz, 1H), 2.53 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$) δ: 160.8, 158.3, 139.6, 138.8, 125.0, 118.0, 112.3, 21.8 ppm. IR (neat, cm^{-1}): 3274, 3014, 1580, 1539, 1449, 1404, 1246, 838, 797, 631. Anal. Calcd. for $C_{12}H_{13}N_3$: C, 72.33; H, 6.58. Found: C 72.23; H, 6.65.

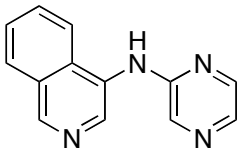


***N*-(pyridin-3-yl)pyrazin-2-amine** (Table 4) Following general procedure D, a mixture of 3-iodopyridine (205 mg, 1.0 mmol), aminopyrazine (133 mg, 1.4 mmol), K_2CO_3 (197 mg, 1.4 mmol), **5** (8 mg, 1 mol%) and **1** (5 mg, 1 mol%), and *t*-BuOH (2 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-10% MeOH/EtOAc) to provide the title compound as a white solid

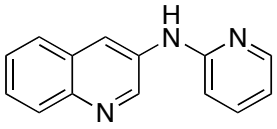
(160 mg, 93%), mp 181 – 182 °C. ^{1}H NMR (300 MHz, DMSO) δ: 9.70 (s, 1H), 8.61 (s, 1H), 8.25 (s, 1H), 8.15 (m, 3H), 7.95 (s, 1H), 7.30 (m, 1H) ppm. ^{13}C NMR (75 MHz, DMSO) δ: 152.7, 142.8, 141.7, 140.8, 138.0, 135.8, 134.9, 125.3, 124.2 ppm. IR (neat, cm^{-1}): 3305, 2317, 1643, 1585, 1528, 1485, 1462, 1359, 1006, 702. Anal. Calcd. for $C_9H_8N_4$: C, 62.78; H, 4.68. Found: C 62.54; H, 4.72.



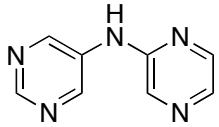
***N*-(pyridin-4-yl)pyrazin-2-amine** (Table 4) Following general procedure D, a mixture of iodopyrazine (98 μL, 1.0 mmol), 4-amnopyridine (132 mg, 1.4 mmol), K_2CO_3 (197 mg, 1.4 mmol), **5** (8 mg, 1 mol%) and **1** (5 mg, 1 mol%), and *t*-BuOH (2 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-10% MeOH/EtOAc) to provide the title compound as a brown solid (155 mg, 90%), decomposed above 200 °C. ^{1}H NMR (500 MHz, DMSO) δ: 9.97 (s, 1H), 8.33 (m, 3H), 8.23 (s, 1H), 8.06 (s, 1H), 7.66 (m, 2H) ppm. ^{13}C NMR (125 MHz, DMSO) δ: 152.2, 150.7, 147.8, 141.8, 136.3, 136.0, 112.7 ppm. IR (neat, cm^{-1}): 3444, 1617, 1522, 1425, 1400, 1356, 1145, 1008, 815, 517.



***N*-(pyrazin-2-yl)isoquinolin-4-amine** (Table 4) Following general procedure D, a mixture of 4-iodoisoquinoline (128 mg, 0.5 mmol), aminopyrazine (67 mg, 0.7 mmol), K_2CO_3 (99 mg, 0.7 mmol), **5** (4 mg, 1 mol%) and **1** (2.5 mg, 1 mol%), and *t*-BuOH (1 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-10% MeOH/EtOAc) to provide the title compound as a white solid (88 mg, 80%), mp 214 – 216 °C. ^{1}H NMR (300 MHz, DMSO) δ: 9.42 (s, 1H), 9.07 (s, 1H), 8.97 (s, 1H), 8.41 (s, 1H), 8.14 (t, J = 8.4 Hz, 2H), 8.05 (s, 1H), 7.95 (s, 1H), 7.77 (t, J = 7.2 Hz, 1H), 7.69 (t, J = 7.2 Hz, 1H) ppm. ^{13}C NMR (75 MHz, DMSO) δ: 153.9, 148.3, 141.9, 137.0, 135.3, 135.0, 131.1, 130.7, 130.6, 129.3, 128.5, 128.1, 122.6 ppm. IR (neat, cm^{-1}): 3391, 1628, 1580, 1521, 1477, 1384, 784, 762, 446, 436.



***N*-(pyridin-2-yl)quinolin-3-amine** (Table 4) Following general procedure D, a mixture of 3-iodoquinoline (128 mg, 0.5 mmol), 2-aminopyridine (66 mg, 0.7 mmol), K_2CO_3 (99 mg, 0.7 mmol), **5** (4 mg, 1 mol%) and **1** (2.5 mg, 1 mol%), and *t*-BuOH (1 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-10% MeOH/EtOAc) to provide the title compound as a white solid (80 mg, 73%), mp 224 – 226 °C. ^{1}H NMR (300 MHz, DMSO) δ: 9.60 (bs, 1H), 8.92 (s, 2H), 8.27 (s, 1H), 7.86 (m, 1H), 7.64 (t, J = 7.2 Hz, 1H), 7.50 (m, 2H), 6.96 (d, J = 8.1 Hz, 1H), 6.84 (t, J = 6.0 Hz, 1H) ppm. ^{13}C NMR (75 MHz, DMSO) δ: 156.2, 148.0, 145.6, 143.4, 138.2, 136.2, 129.2, 127.8, 127.5, 126.8, 118.4, 115.9, 112.1 ppm. IR (neat, cm^{-1}): 3285, 2919, 1633, 1580, 1483, 1431, 1384, 1349, 1156, 768.



***N*-(pyrazin-2-yl)pyrimidin-5-amine** (Table 4) Following general procedure D, a mixture of 5-iodopyrimidine (103 mg, 0.5 mmol), aminopyrazine (67 mg, 0.7 mmol), K_2CO_3 (99 mg, 0.7 mmol), **5** (4 mg, 1 mol%) and **1** (2.5 mg, 1 mol%), and *t*-BuOH (1 mL) was heated to 110 °C for 24 h. The crude product was purified via the Biotage SP4 (silica-packed 50 g snap column; 0-10% MeOH/EtOAc) to provide the title compound as a white solid (76 mg, 88%), sublimed above 200 °C. ^{1}H NMR (300 MHz, DMSO) δ: 9.88 (s, 1H), 9.11 (s, 2H), 8.76 (s, 1H), 8.27 (s, 1H), 8.18 (s, 1H), 8.02 (s, 1H) ppm. ^{13}C NMR (75 MHz, DMSO) δ: 152.1, 151.8, 146.5, 141.7, 136.7, 135.8, 135.6 ppm. IR (neat, cm^{-1}): 3388, 2918, 1579, 1529, 1443, 1384, 1055, 1005, 833, 716.

References

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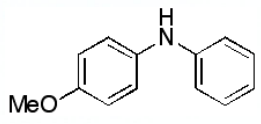
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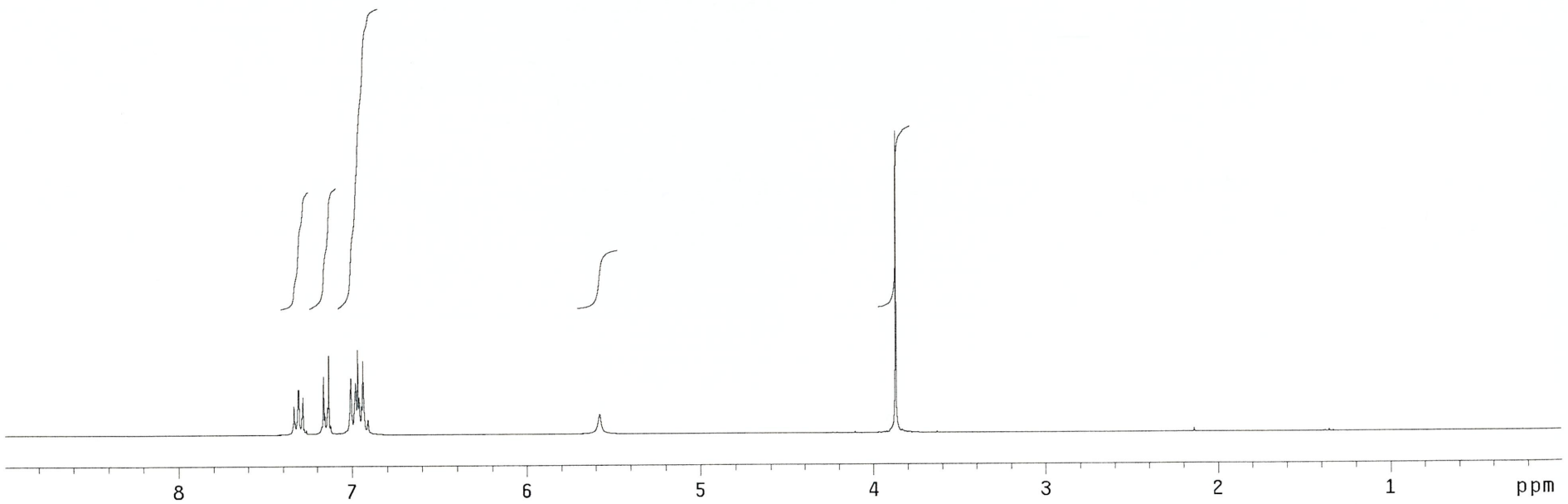
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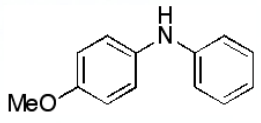
7
6
5
4
3
2
1
ppm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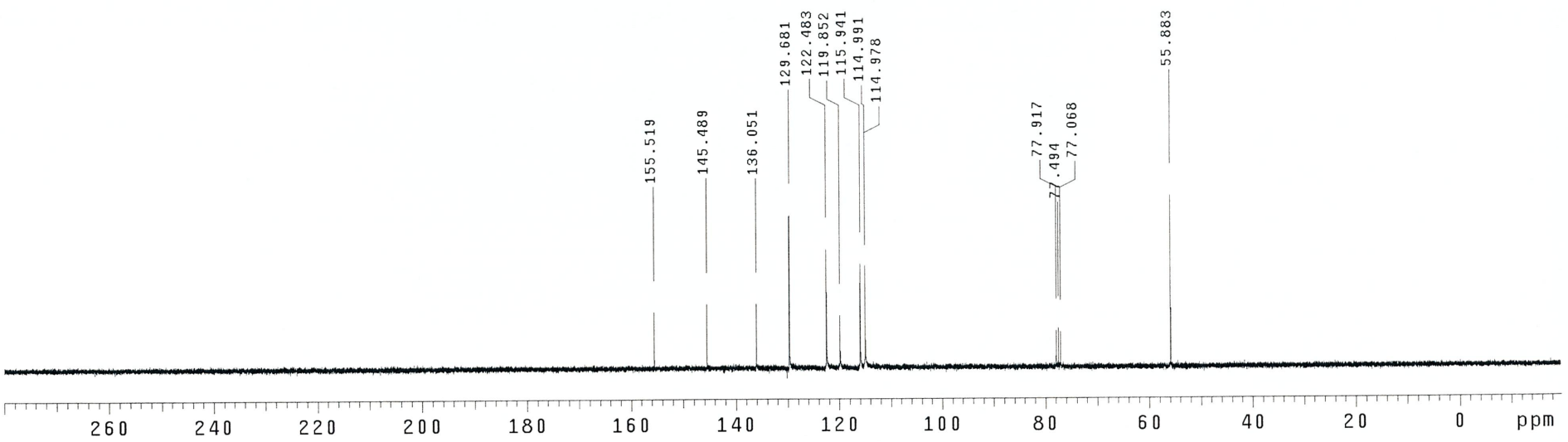
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129.681
122.483
119.852
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114.991
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77.917
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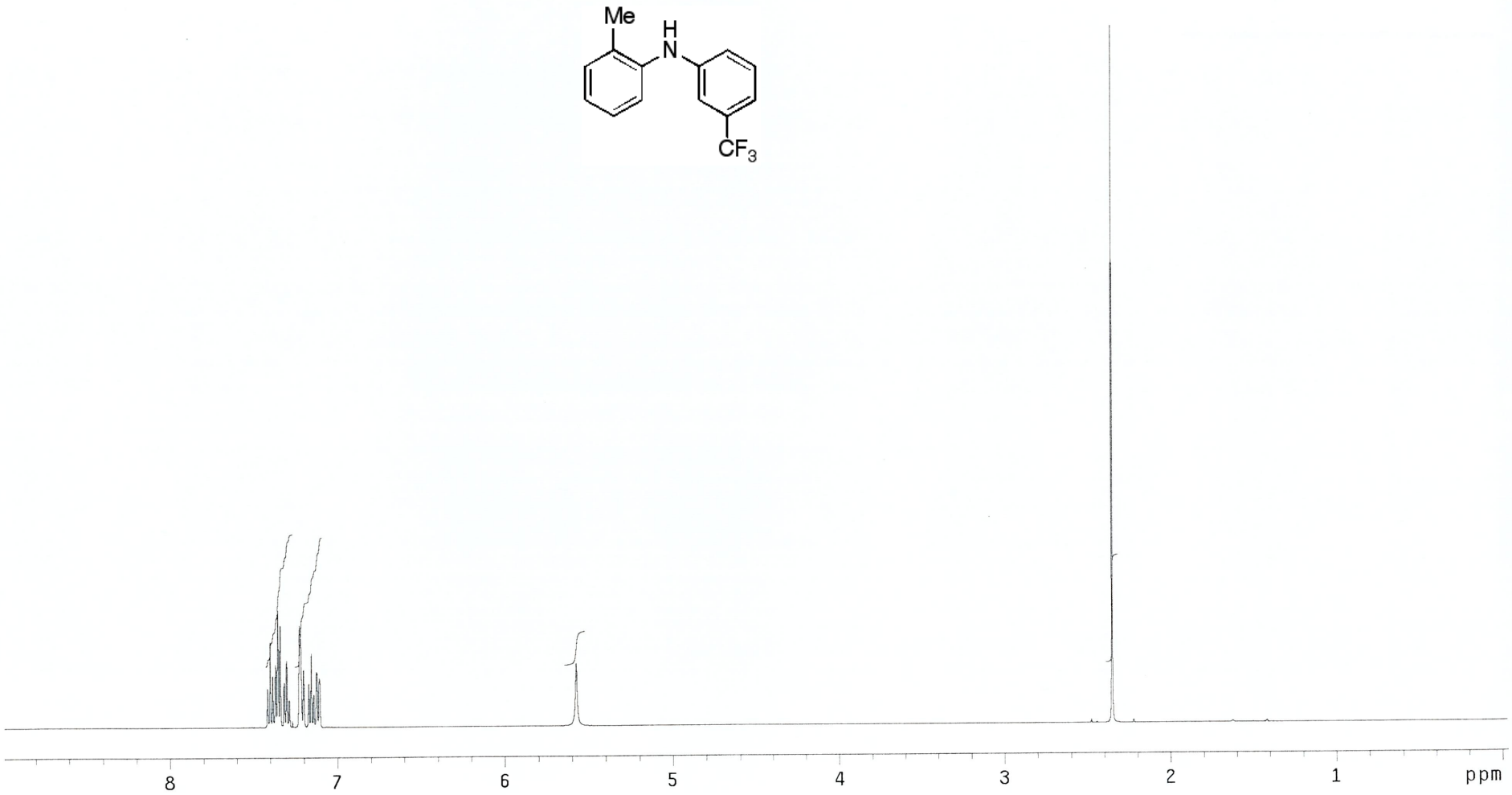
220
200
180
160
140
120
100
80
60
40
20
0
ppm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N
CF3
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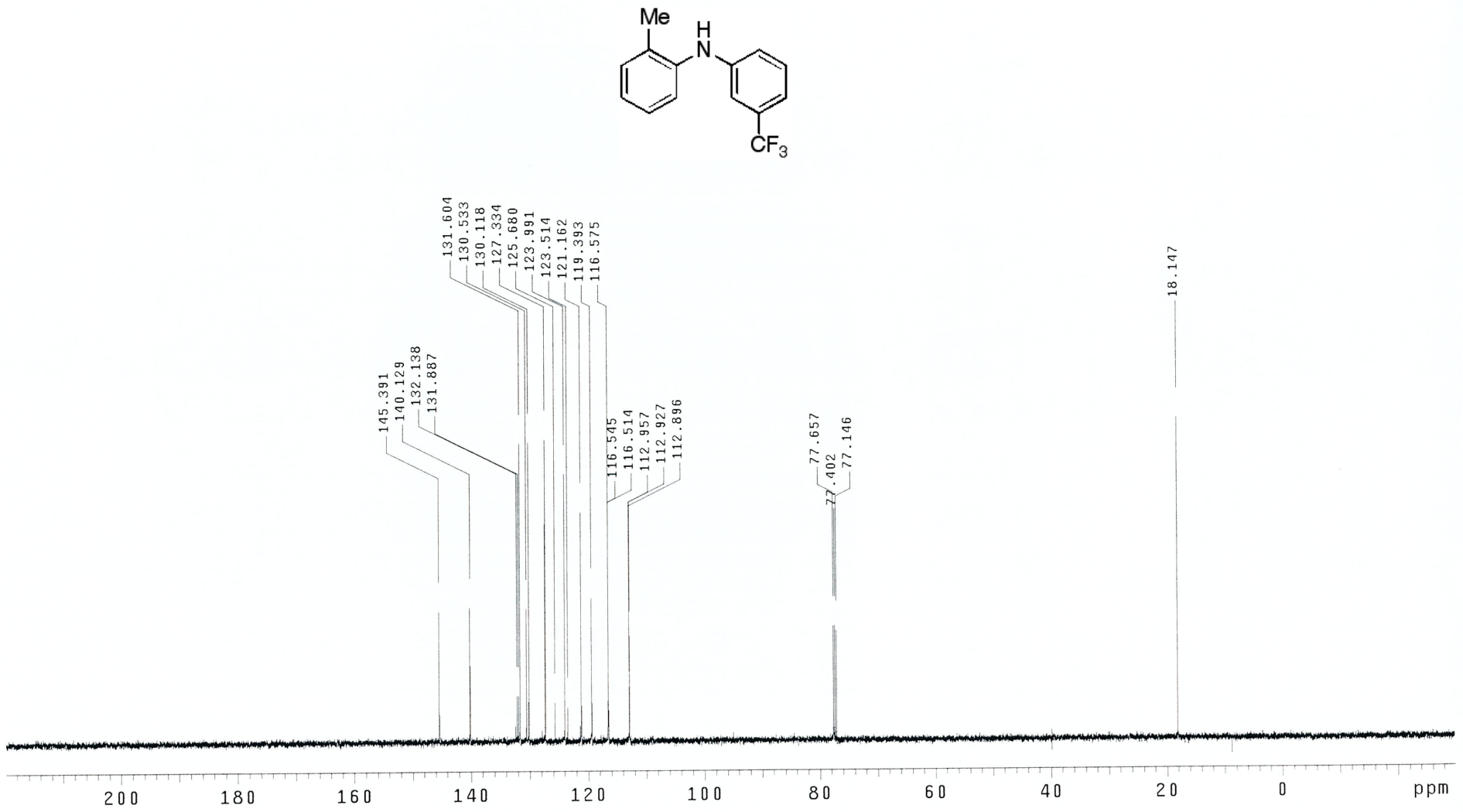
7
6
5
4
3
2
1
ppm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145.391
140.129
132.138
131.887
116.545
116.514
112.957
112.927
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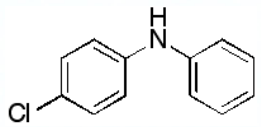
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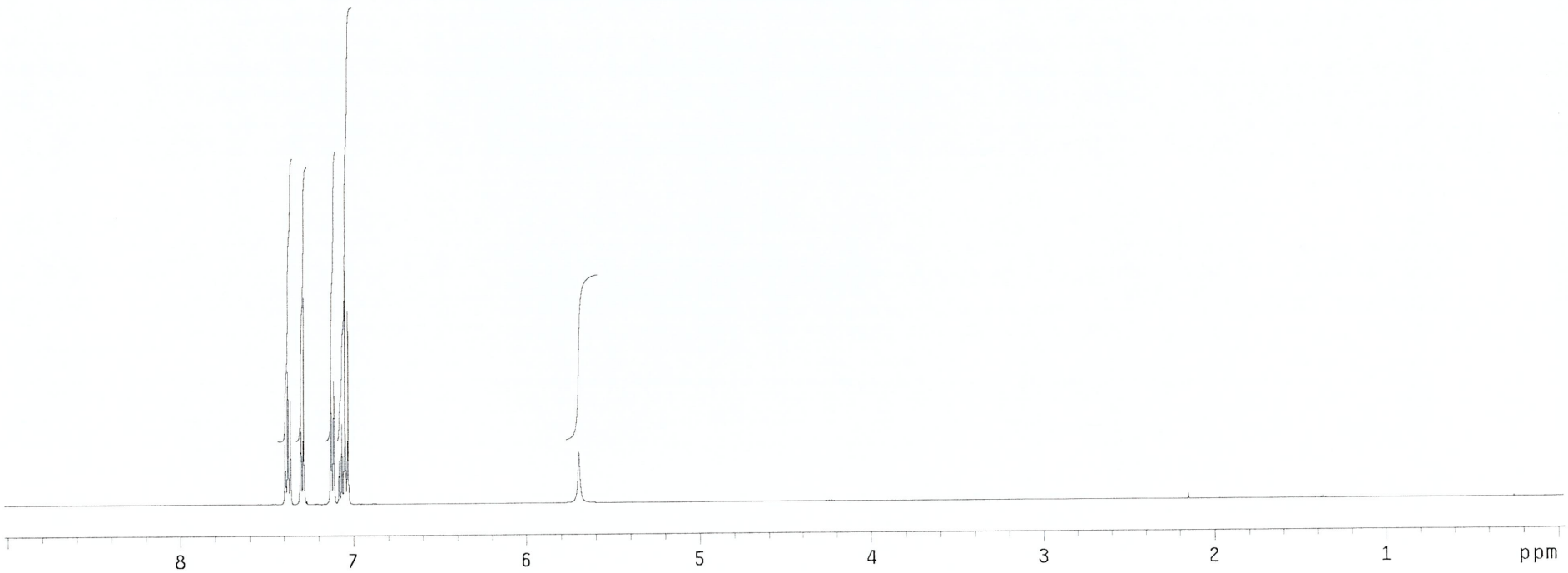
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6
5
4
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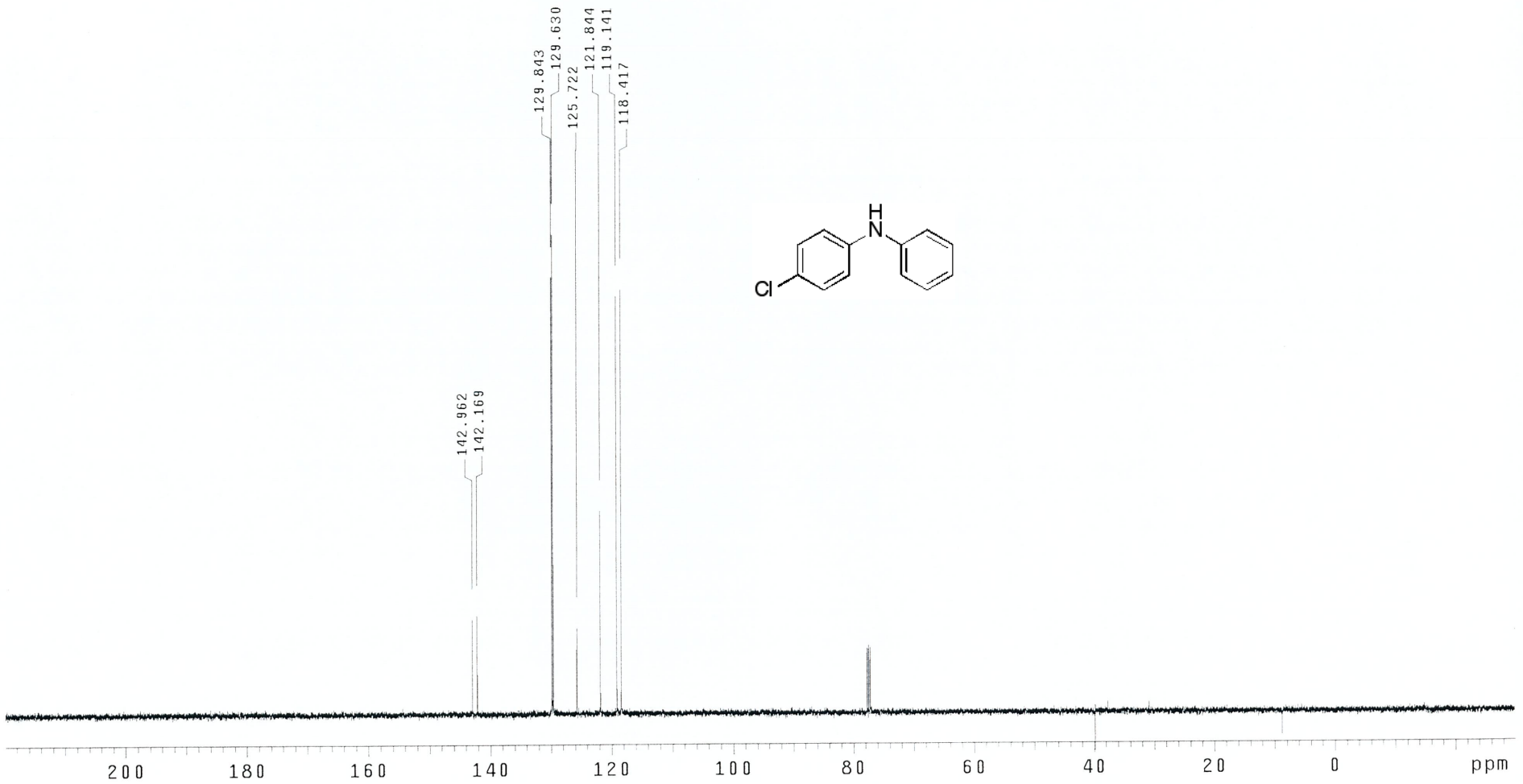
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Cl
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0
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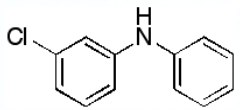
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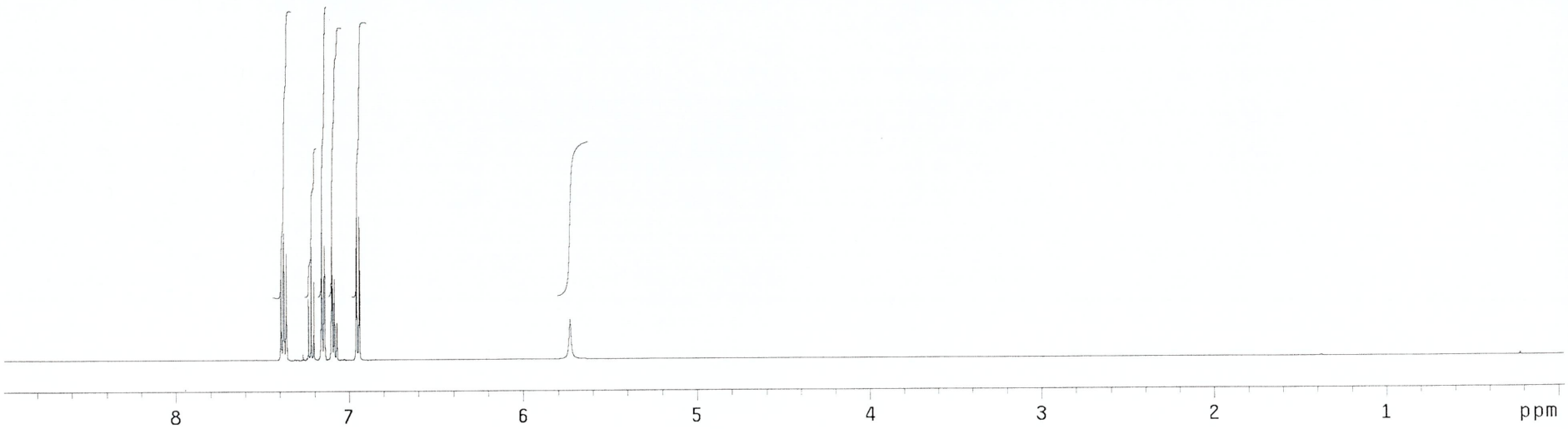
H
N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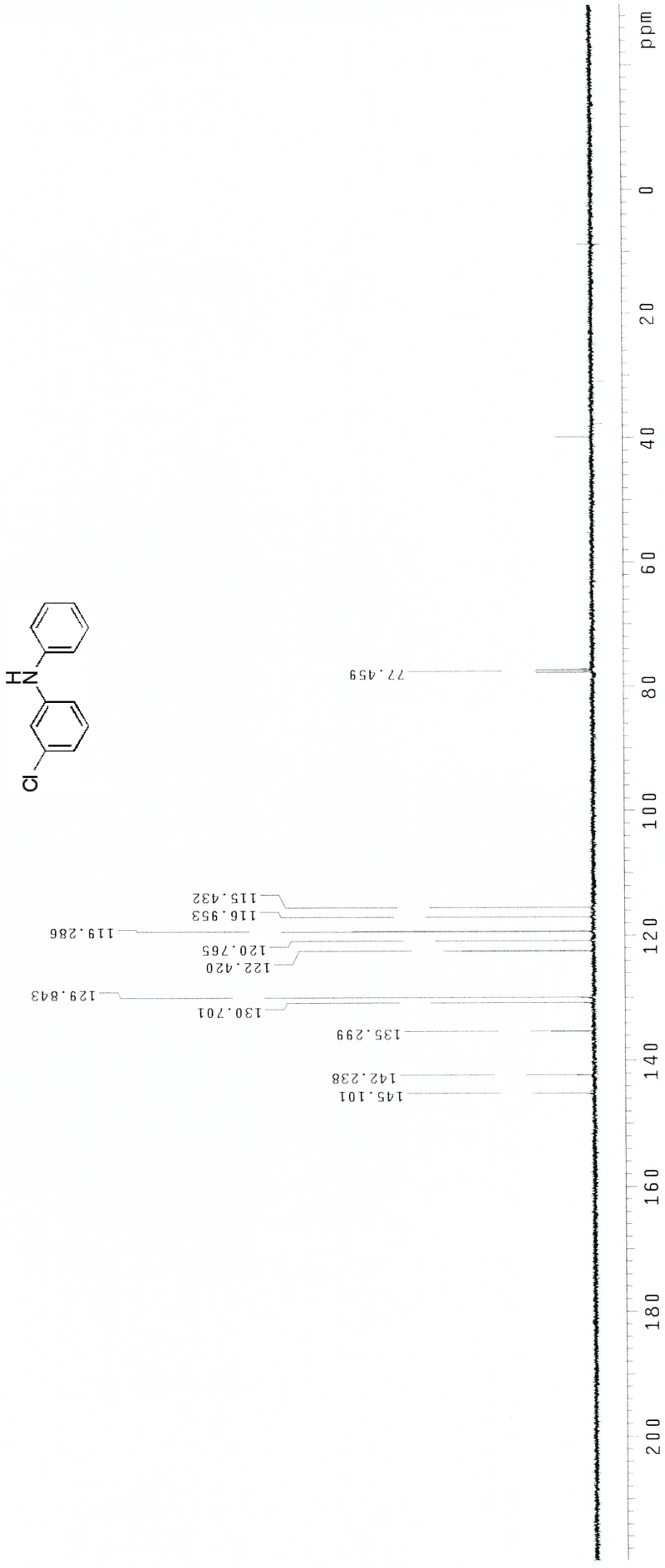
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180
200
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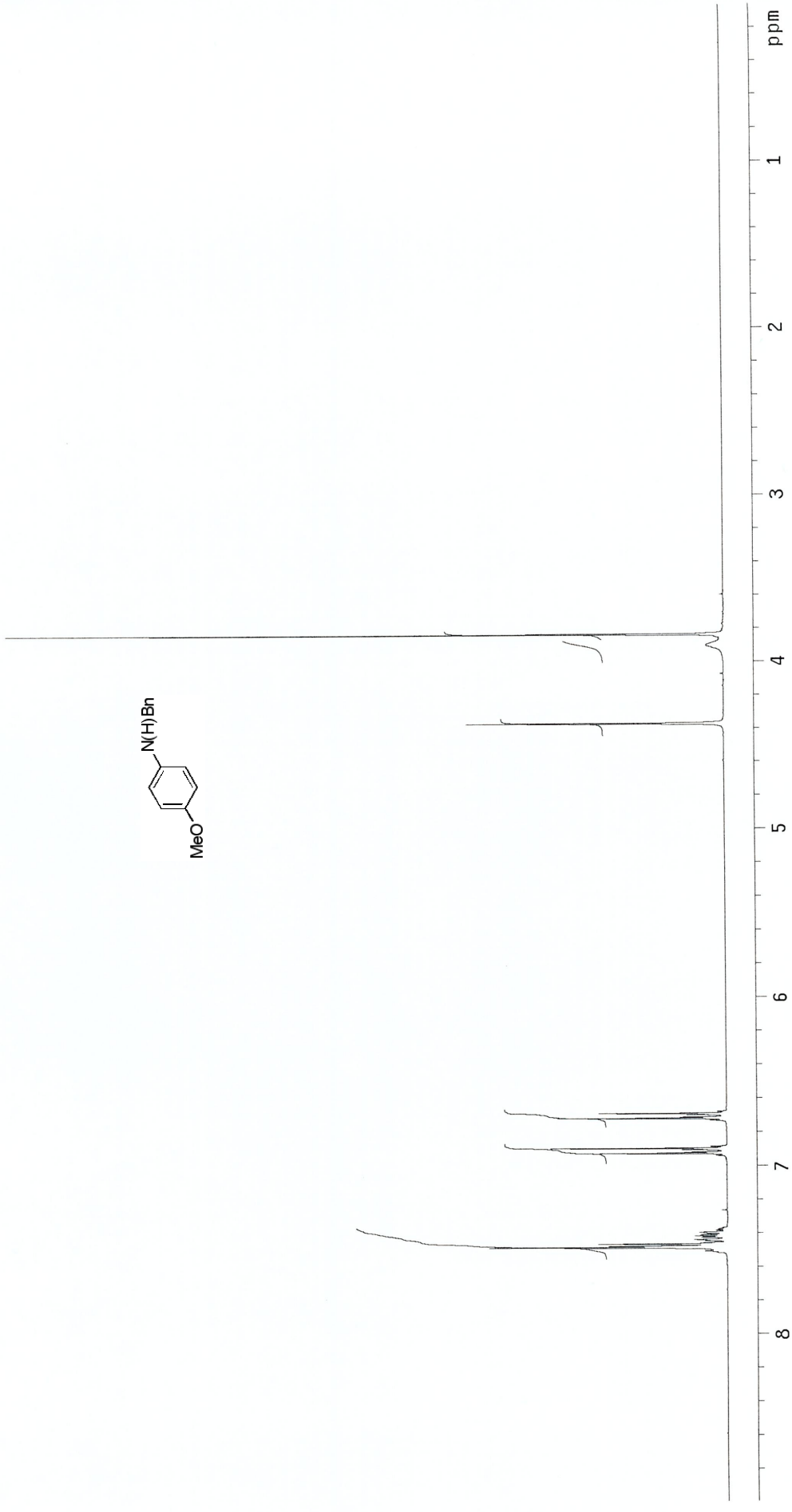
145.101
NH
Cl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ppm
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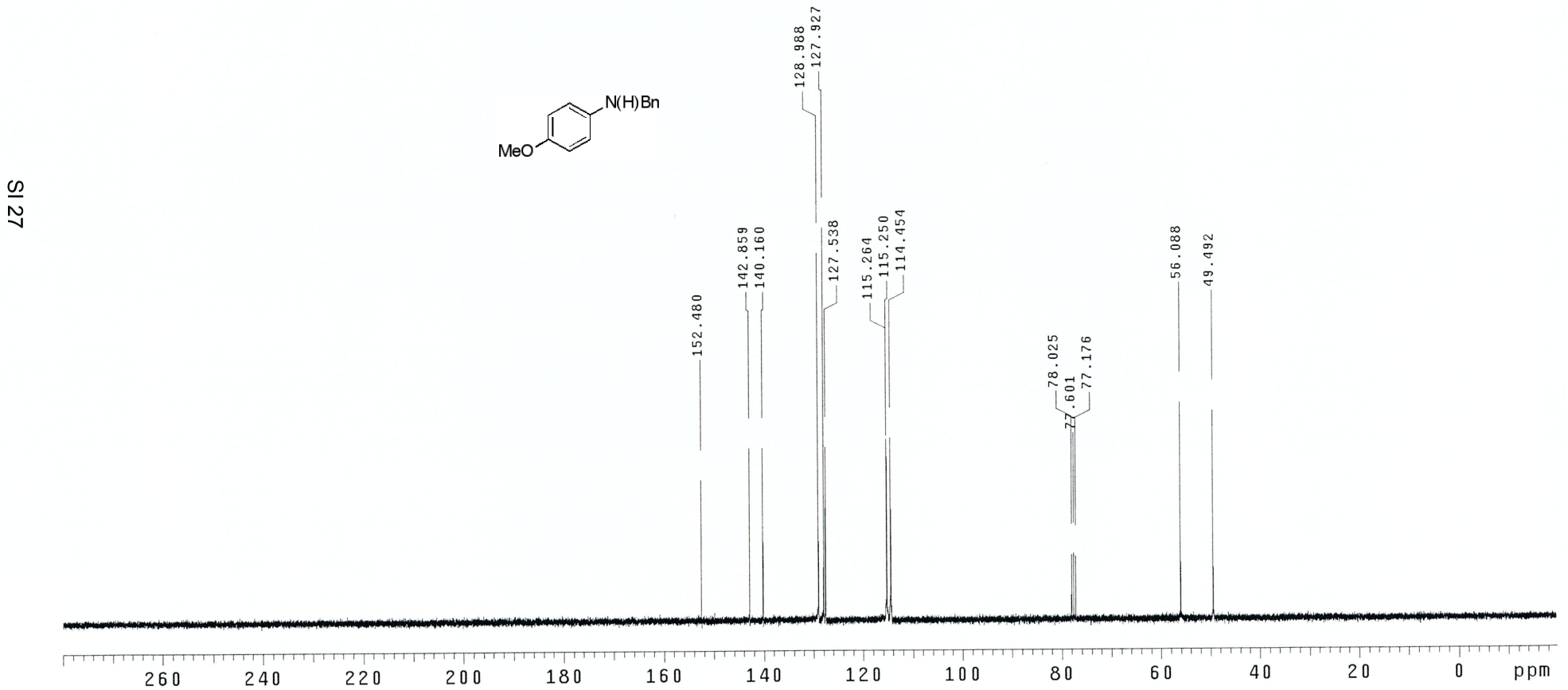
2
3
4
5
6
7
8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77.601
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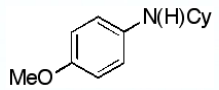
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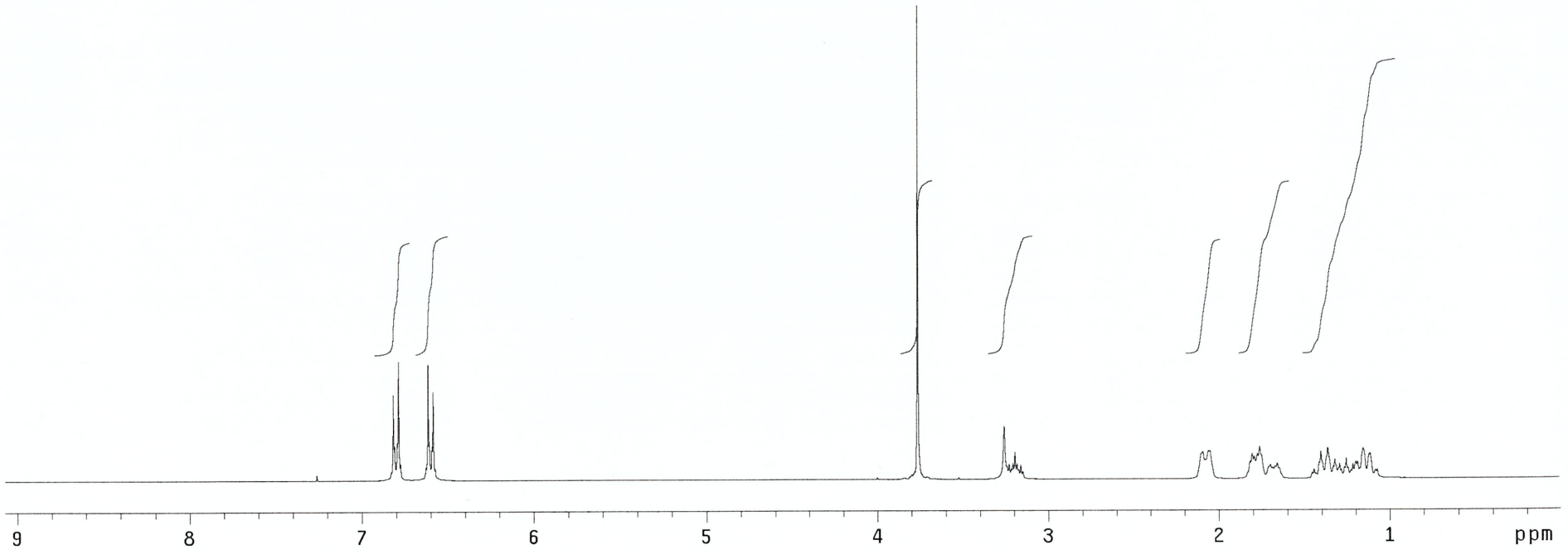
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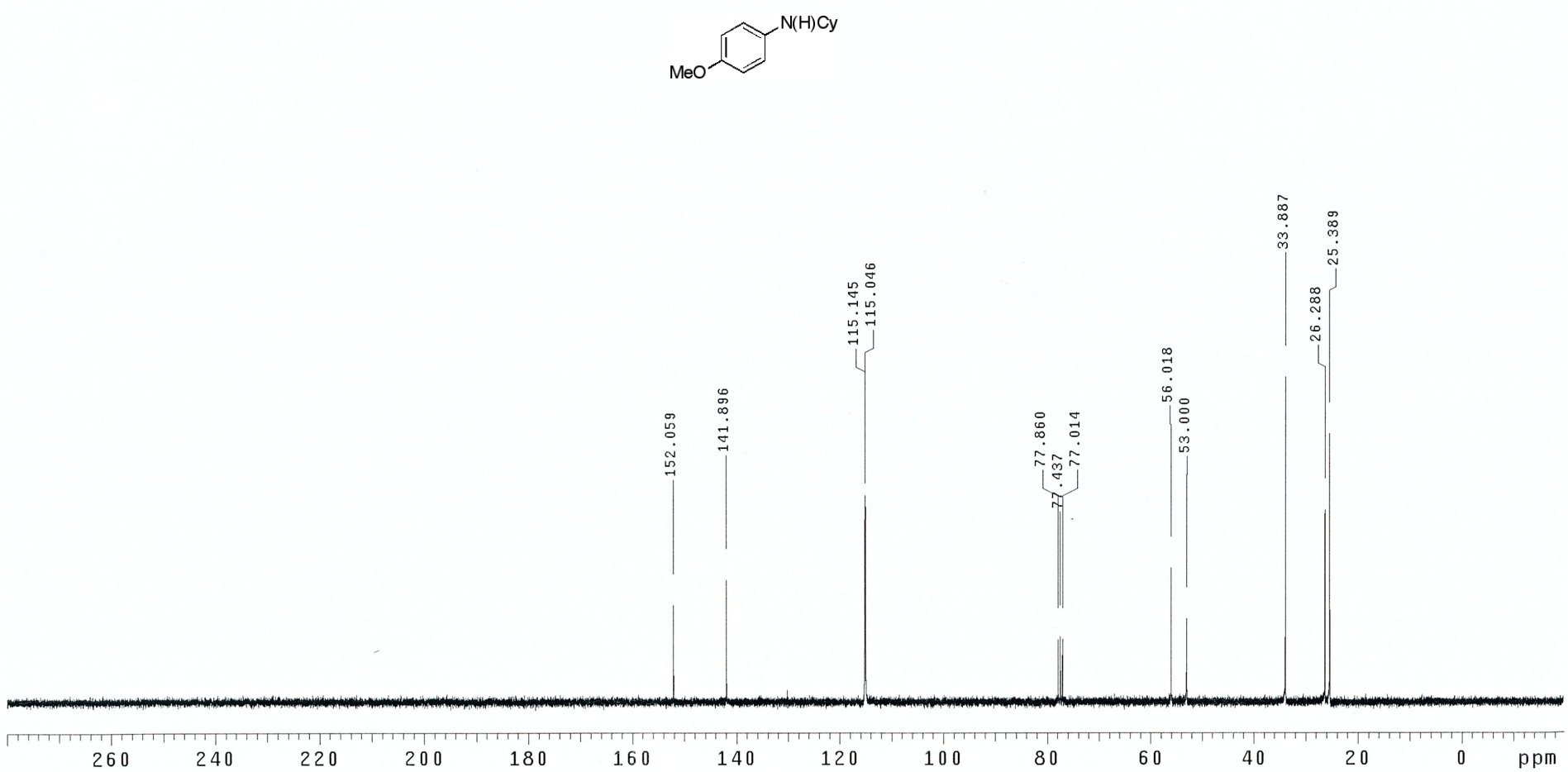
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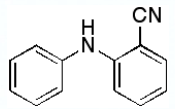
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N
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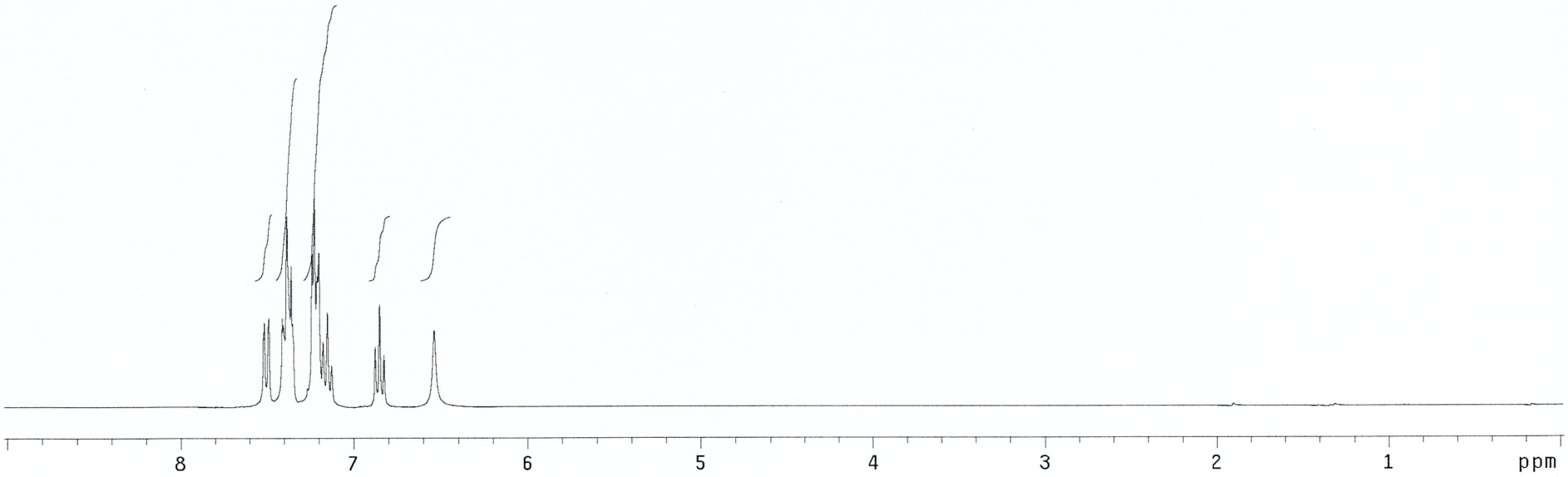
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2
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ppm

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114.509
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200
220
240
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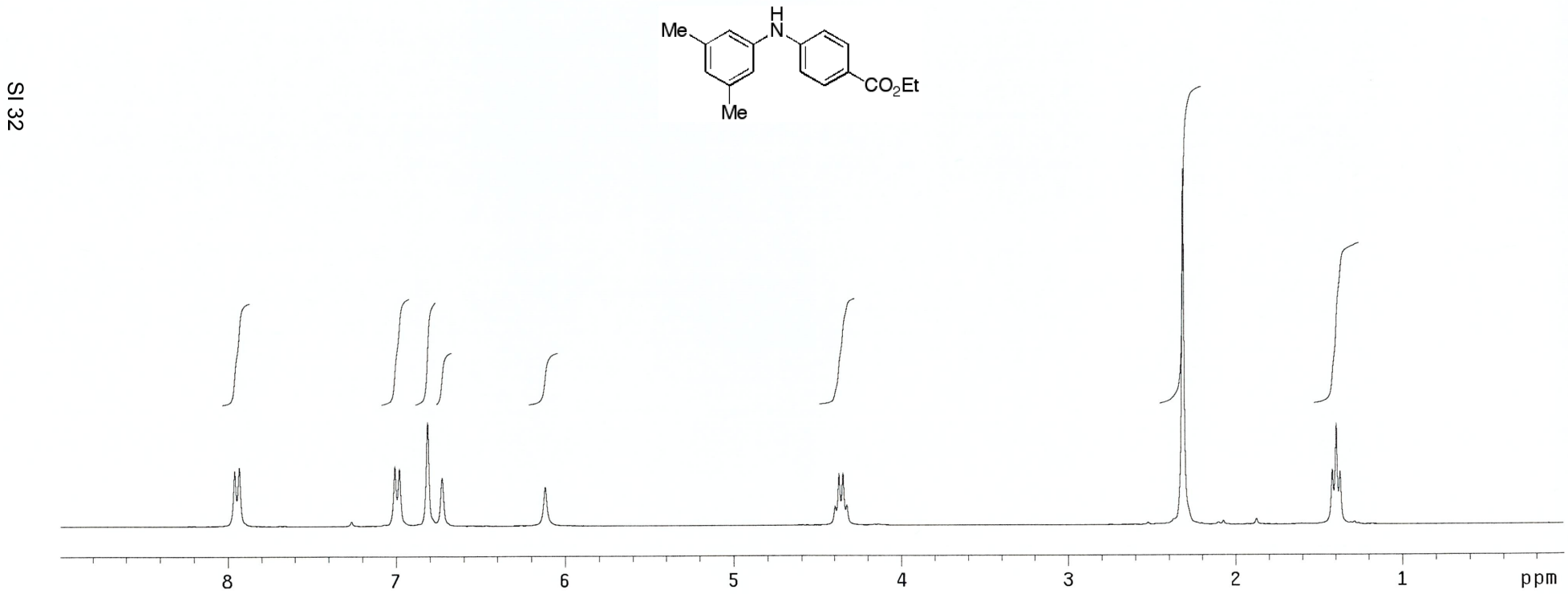
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CO2Et
Me
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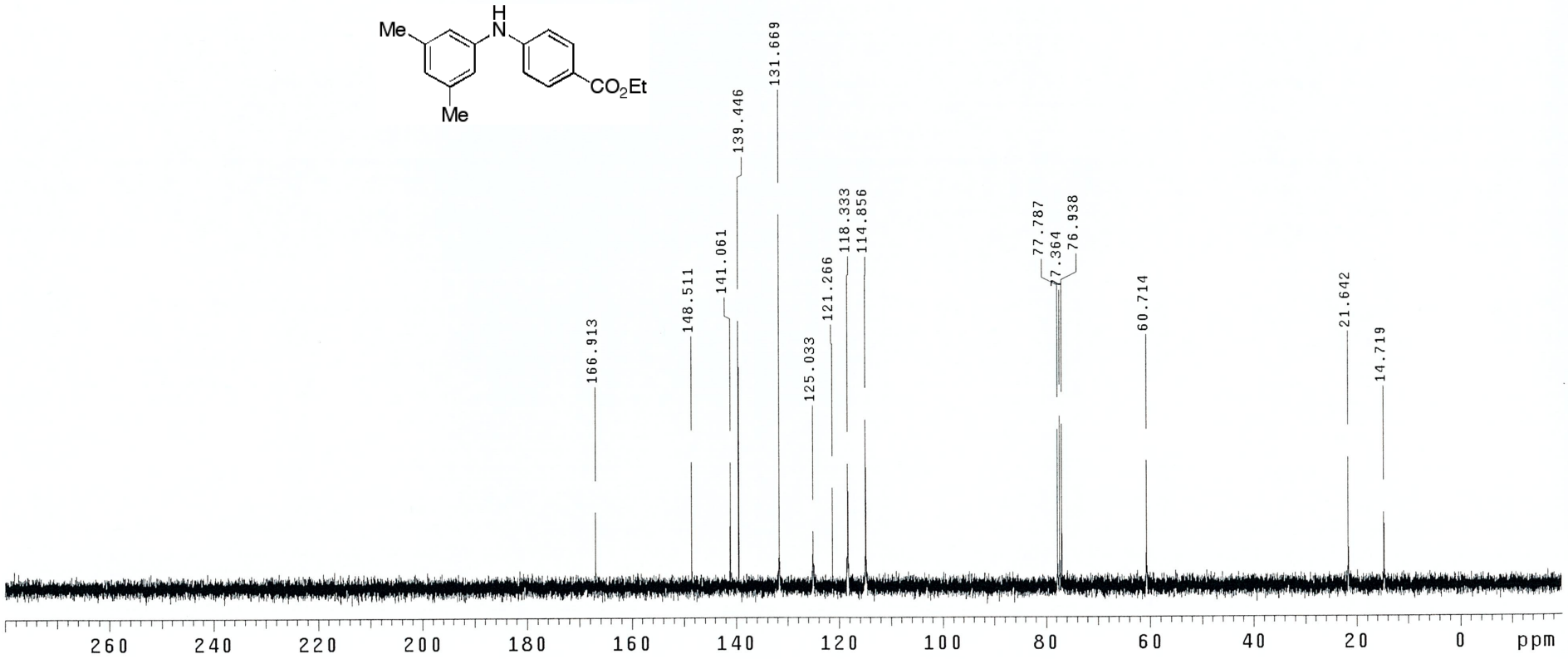
7
6
5
4
3
2
1
ppm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N
CO2Et
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125.033
121.266
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114.856
77.787
77.364
76.938
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120
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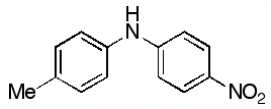
80
60
40
20
0
ppm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N
Me
NO2

8
7
6
5
4
3
2
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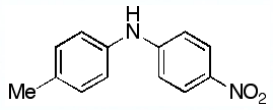
ppm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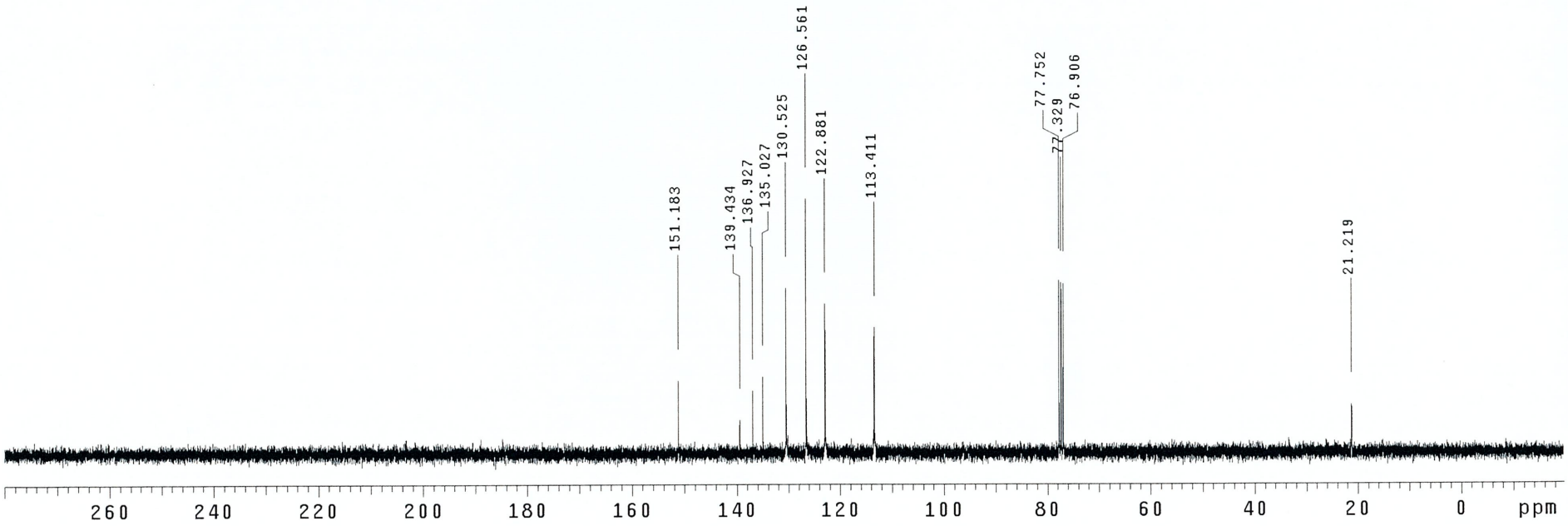
N
Me
NO2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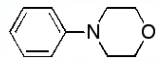
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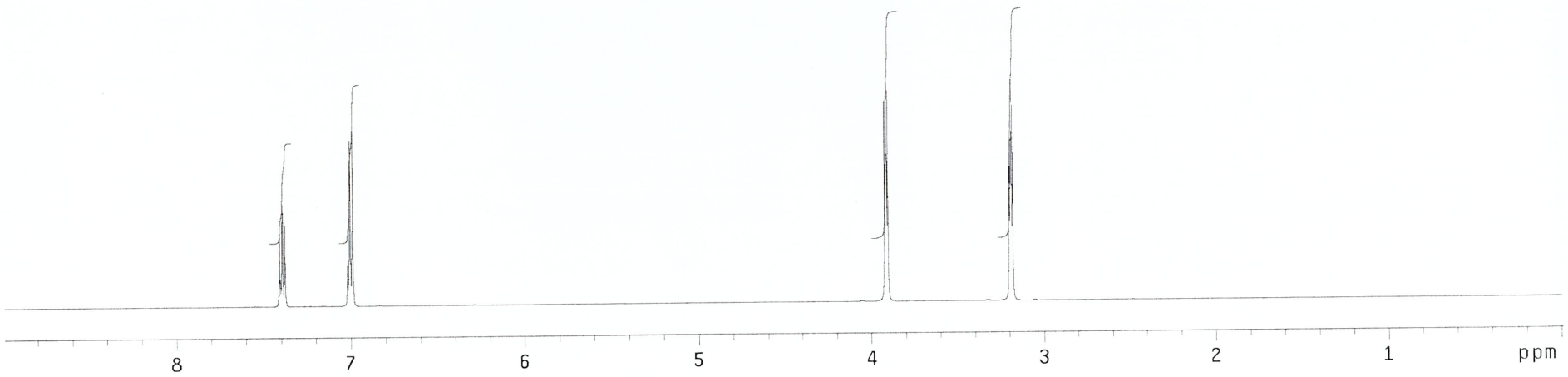
O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7
6
5
4
3
2
1
ppm

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49.605
ppm
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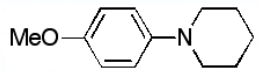
60
40
20
0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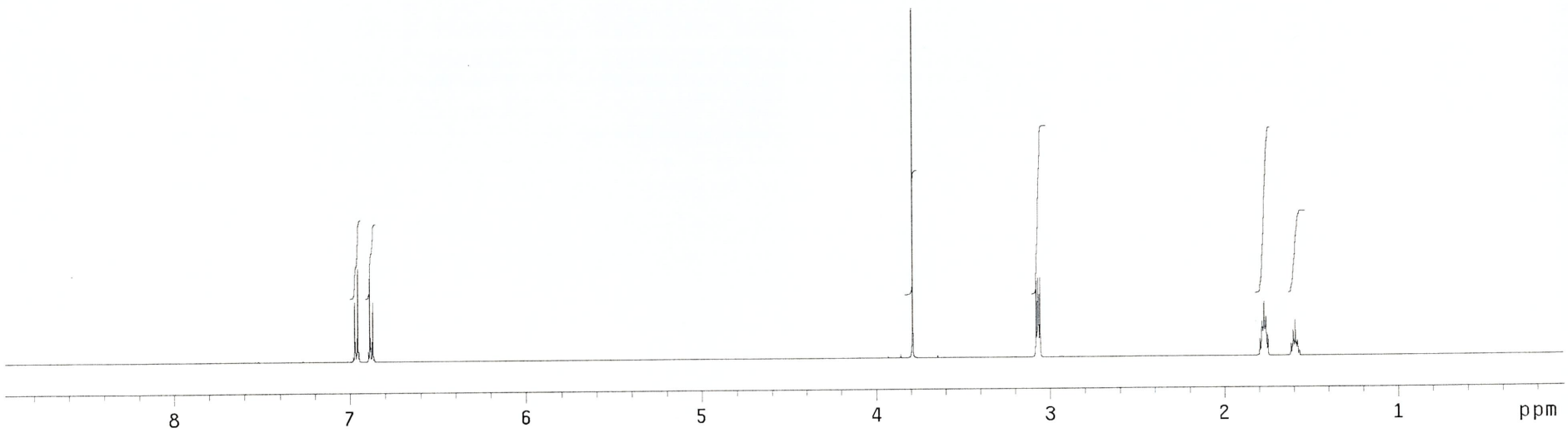
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7
6
5
4
3
2
1
ppm

ppm
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20
40
60
80
100
120
140
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200
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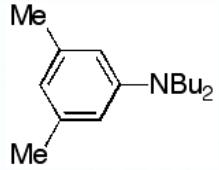
N
MeO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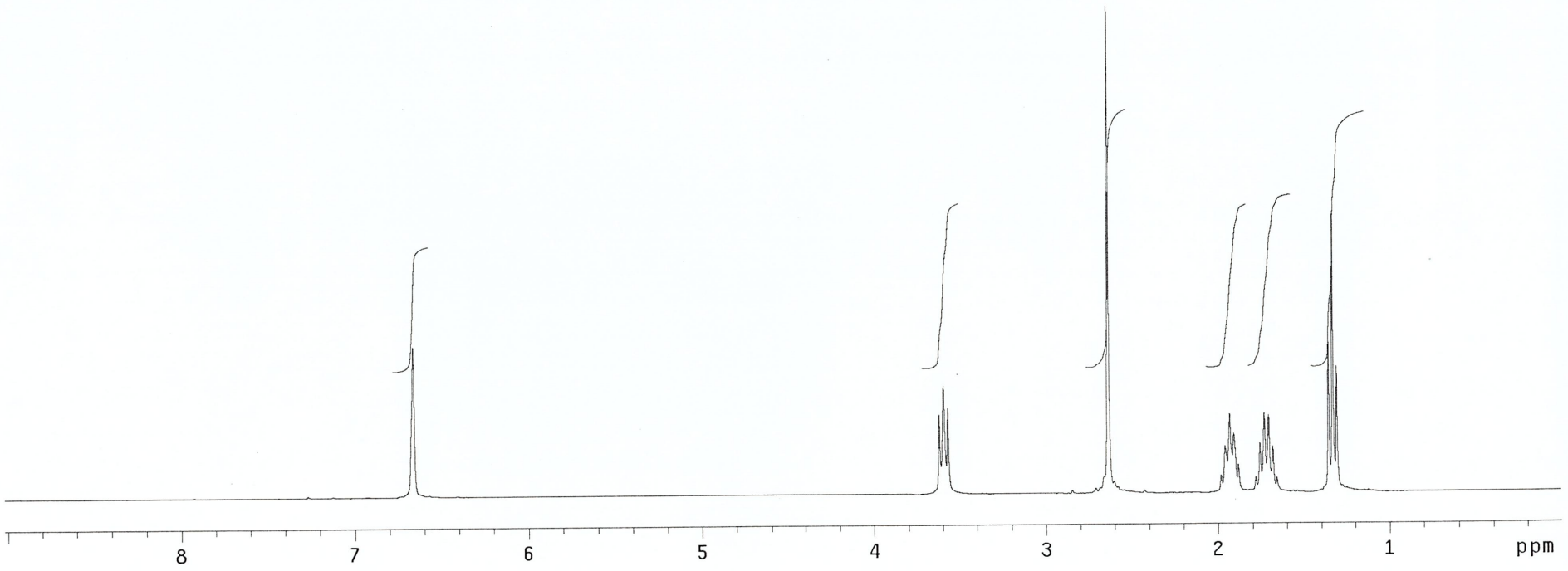
NBu2
Me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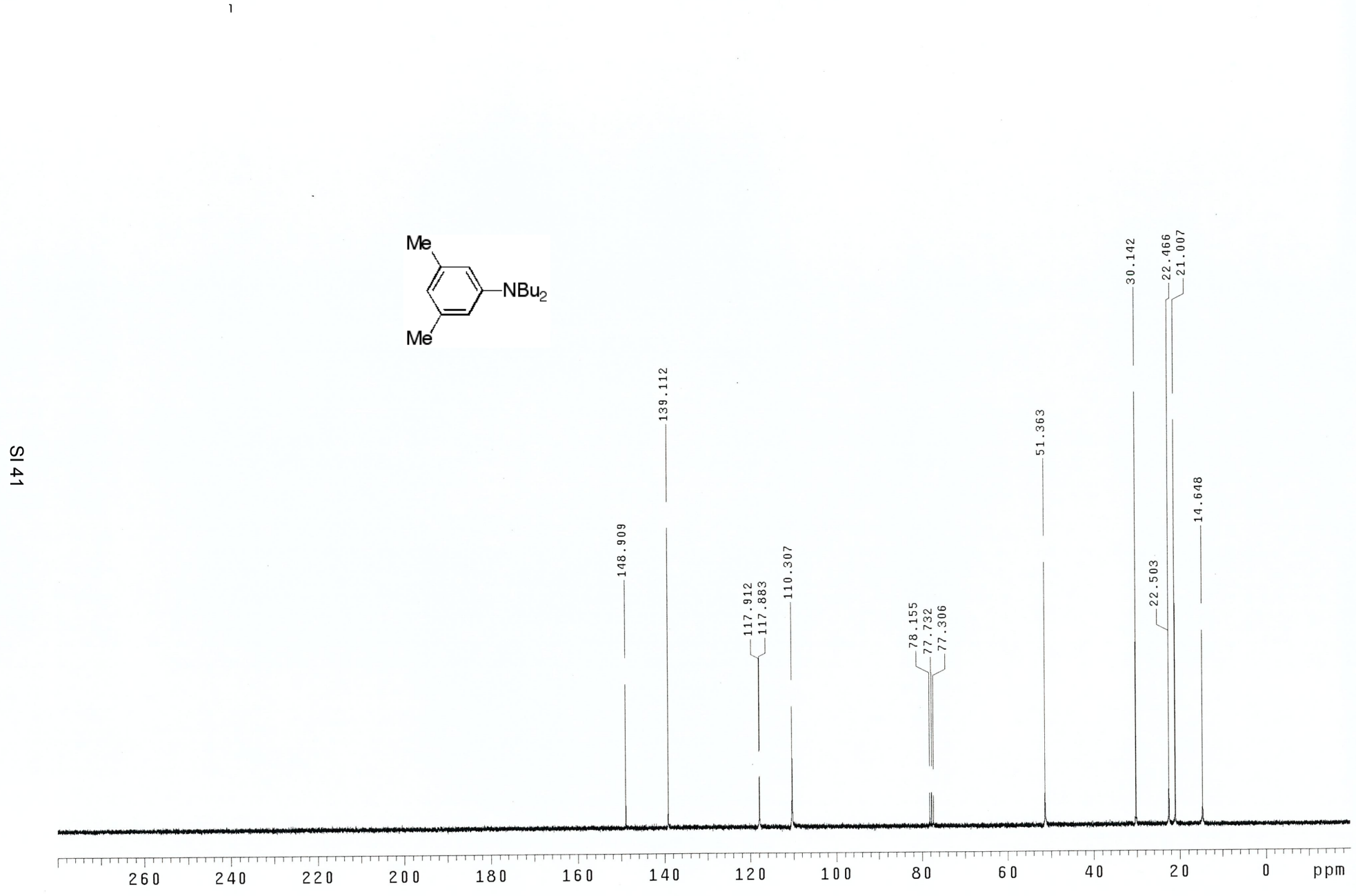
7
6
5
4
3
2
1
ppm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NBu2
Me
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77.306
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22.503
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40
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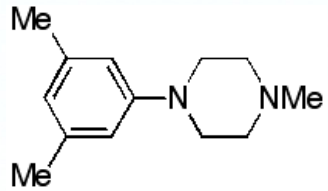
ppm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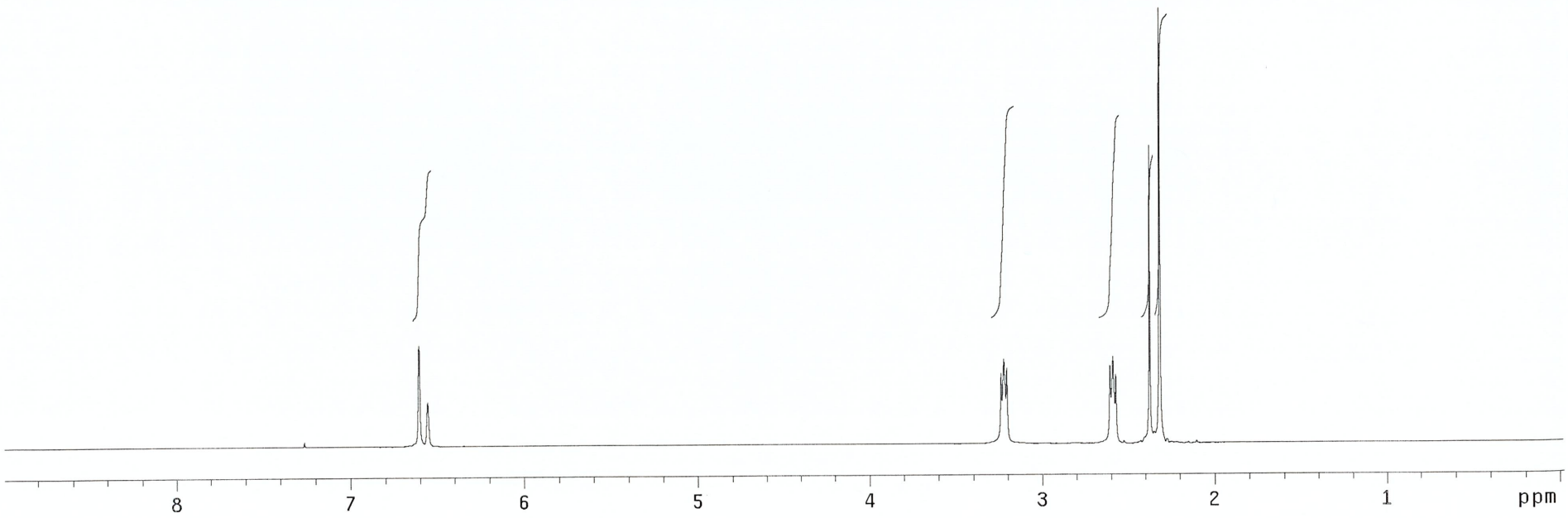
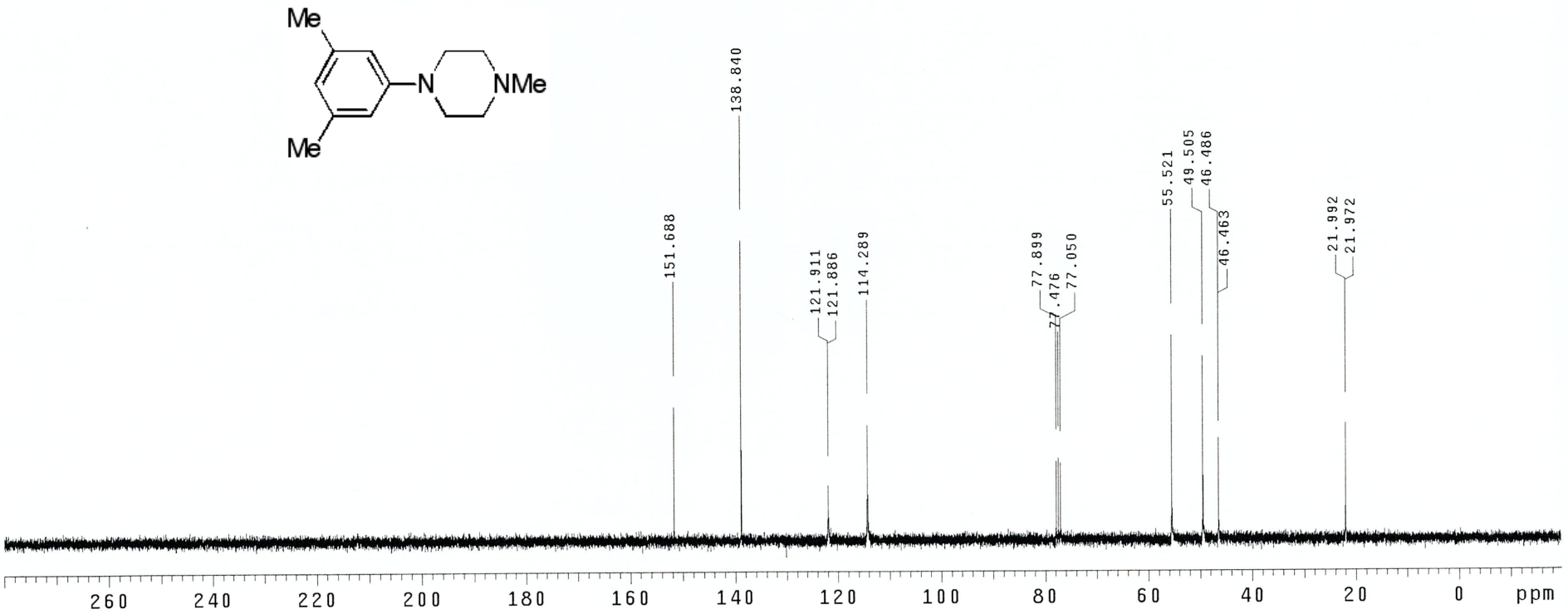
NMe
Me


8
7
6
5
4
3
2
1
ppm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49.505
46.486
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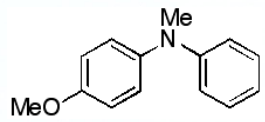
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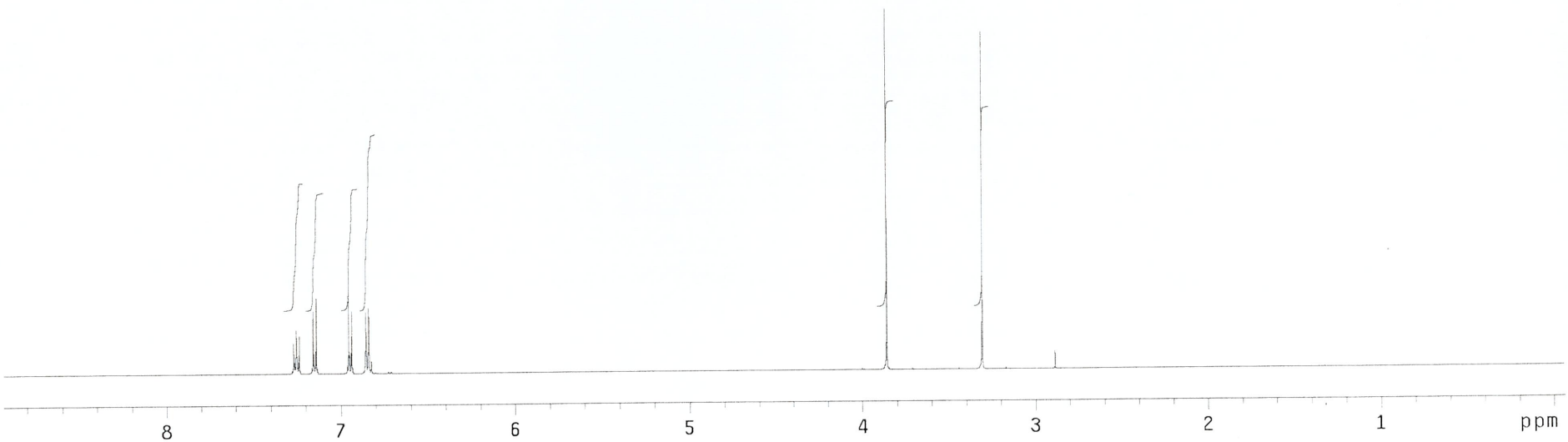
8
7
6
5
4
3
2
1
ppm

ppm
0
20
40
60
80
100
120
140
160
180
200
39.829
40.775
55.781
77.104
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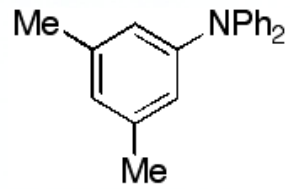
N
MeO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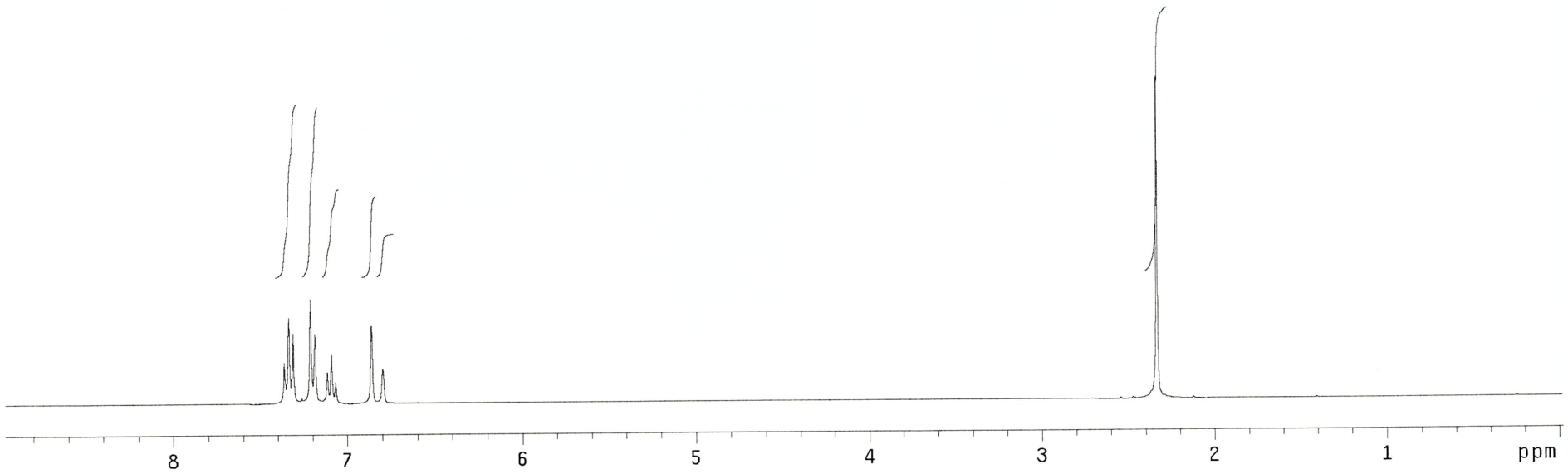
Me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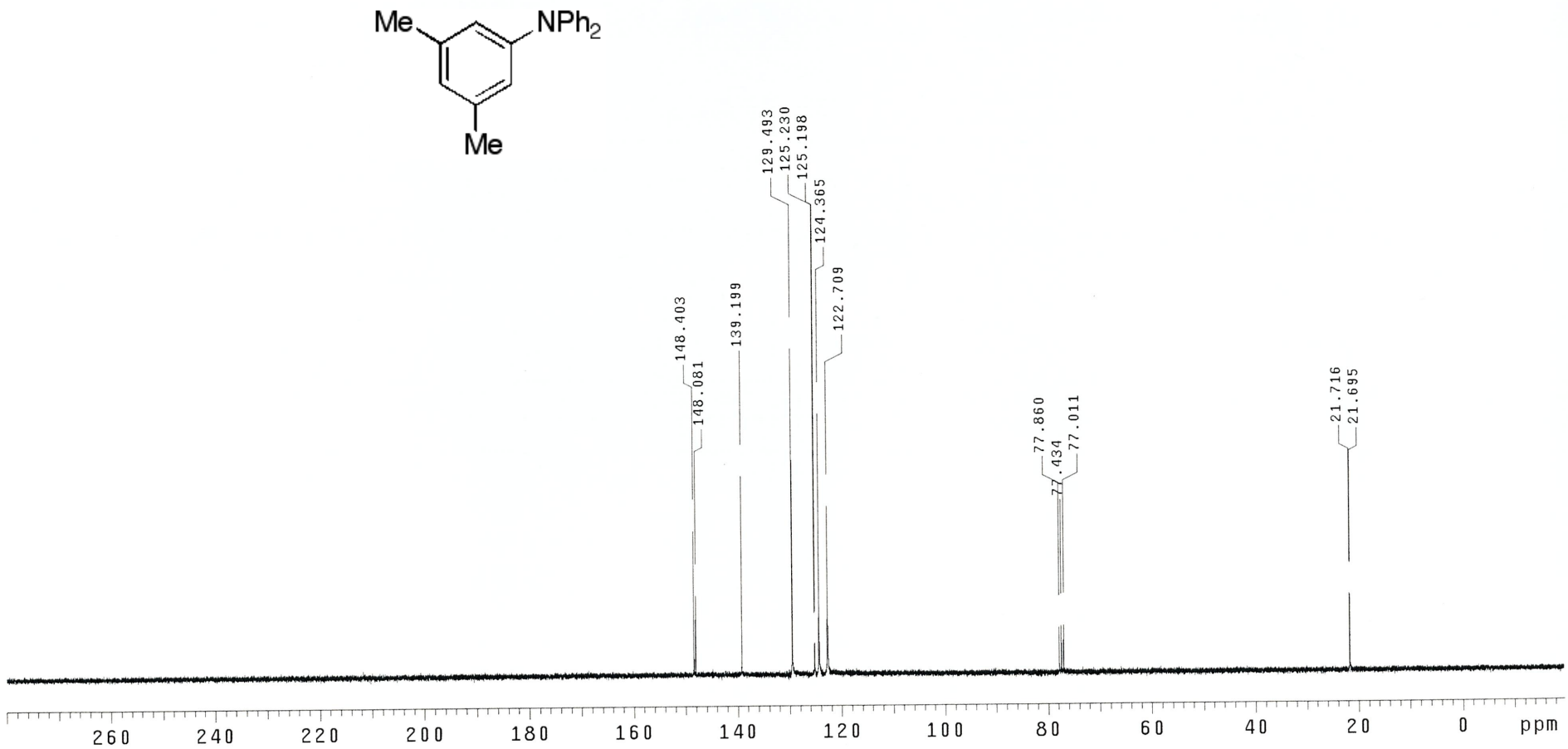
7
6
5
4
3
2
1
ppm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NPh2
Me
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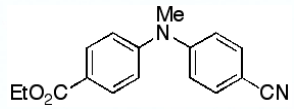
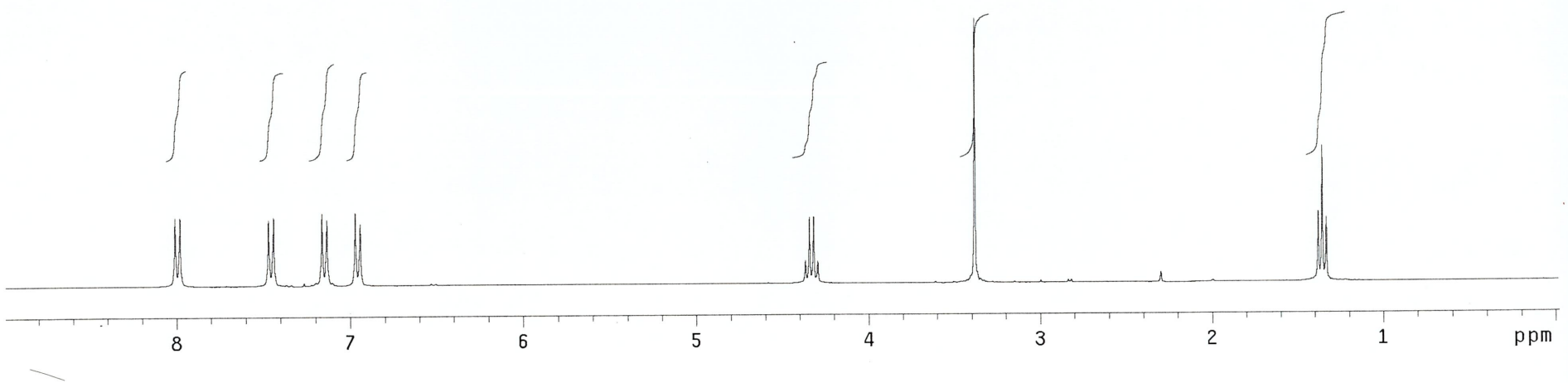
77.011
21.716
21.695
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm


Me
N
EtO2C
CN


8
7
6
5
4
3
2
1
ppm

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61.125
77.068
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77.917
102.674
118.002
119.886
122.631
125.861
131.499
133.606
151.043
151.370
166.195
ppm
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60
80
100
120
140
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200
220
240
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CN
Me
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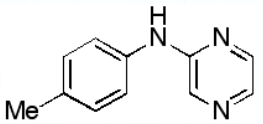
EtO2C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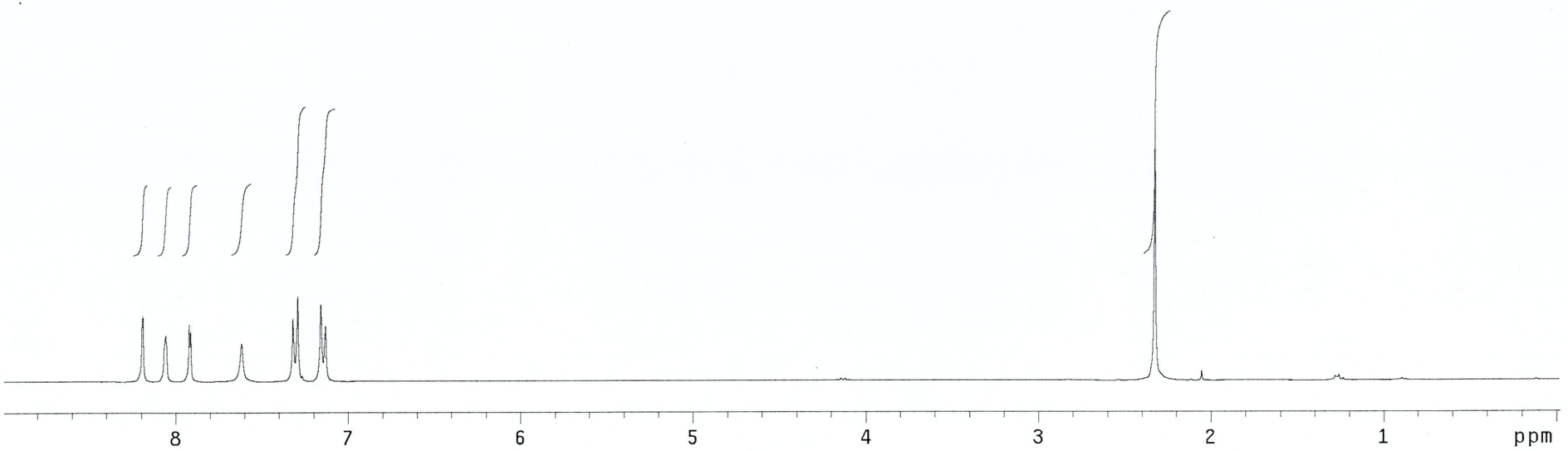
N
N
Me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7
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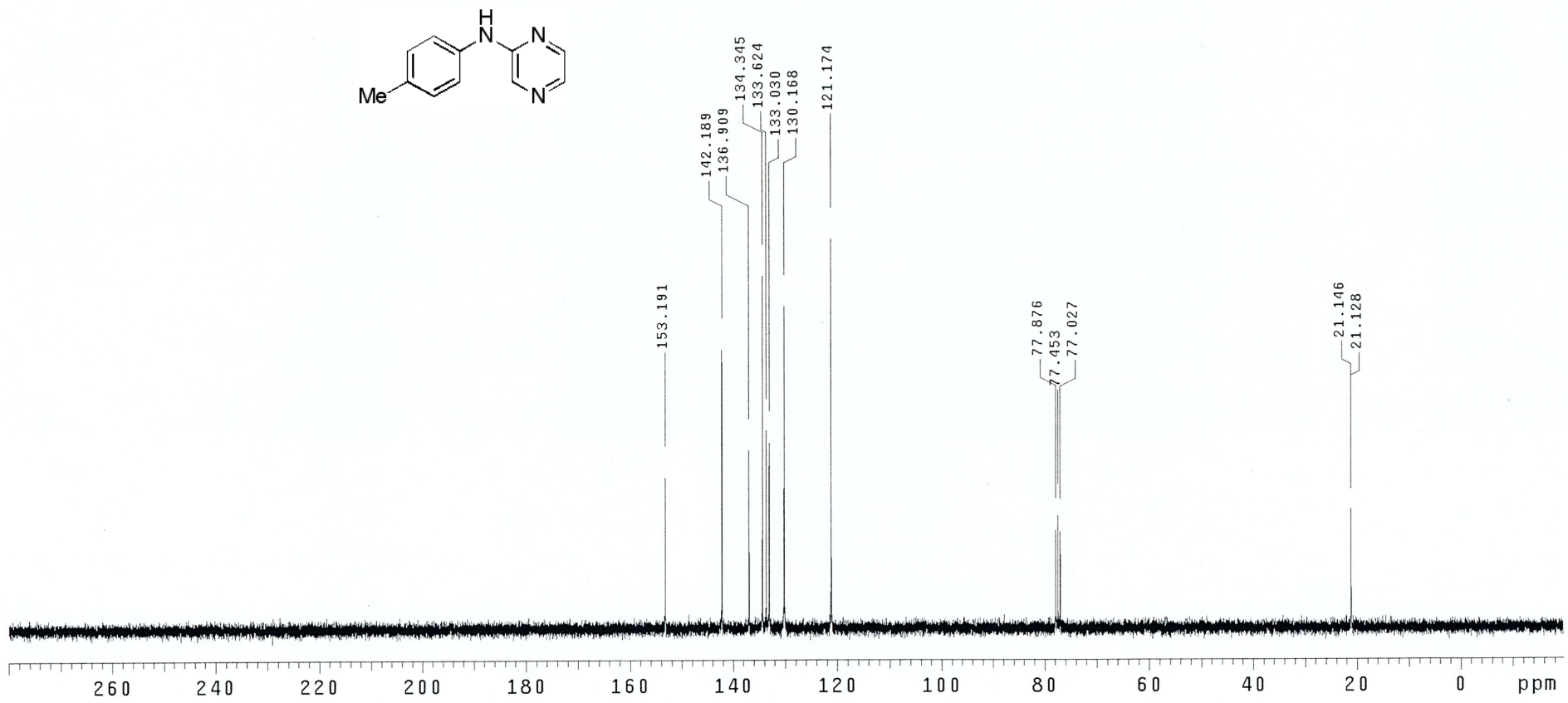
5
4
3
2
1
ppm


H
N
N
N
Me
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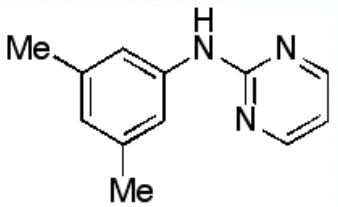
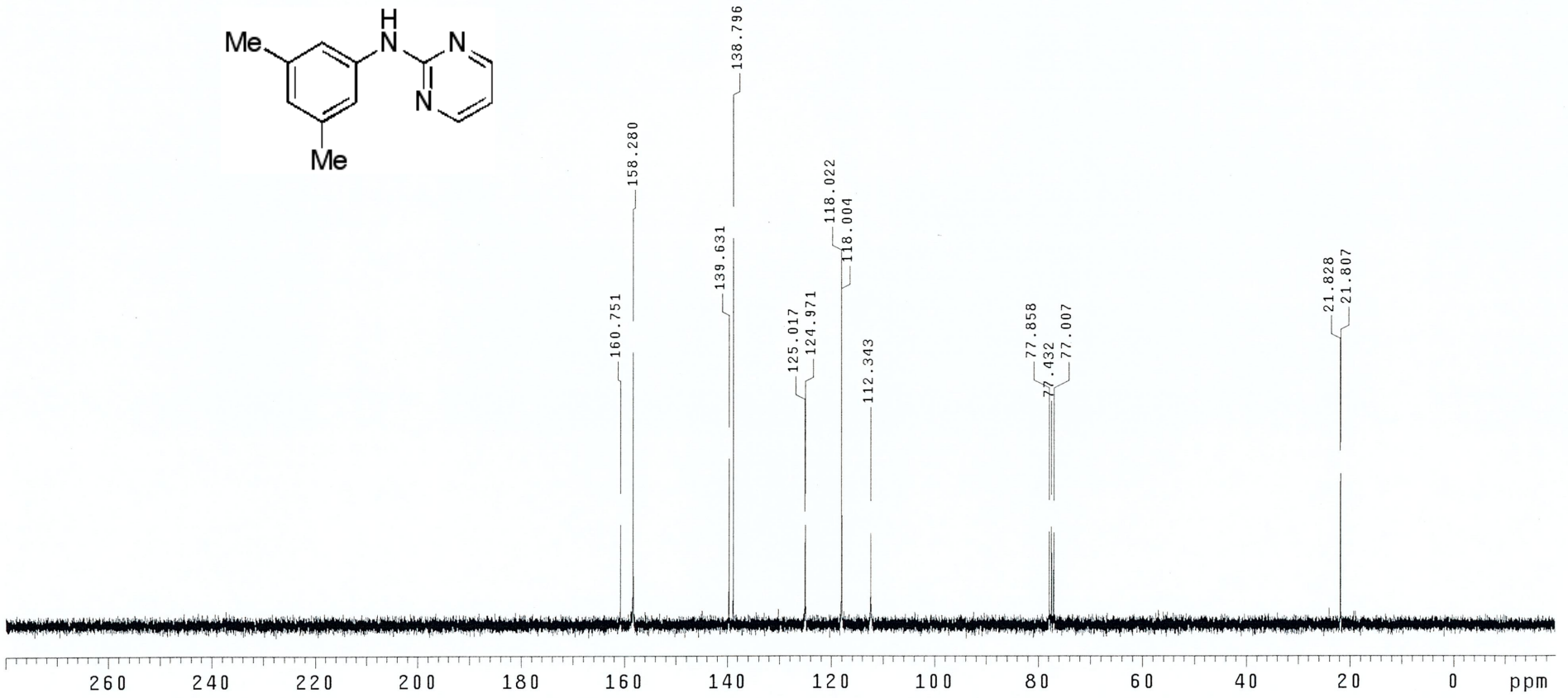
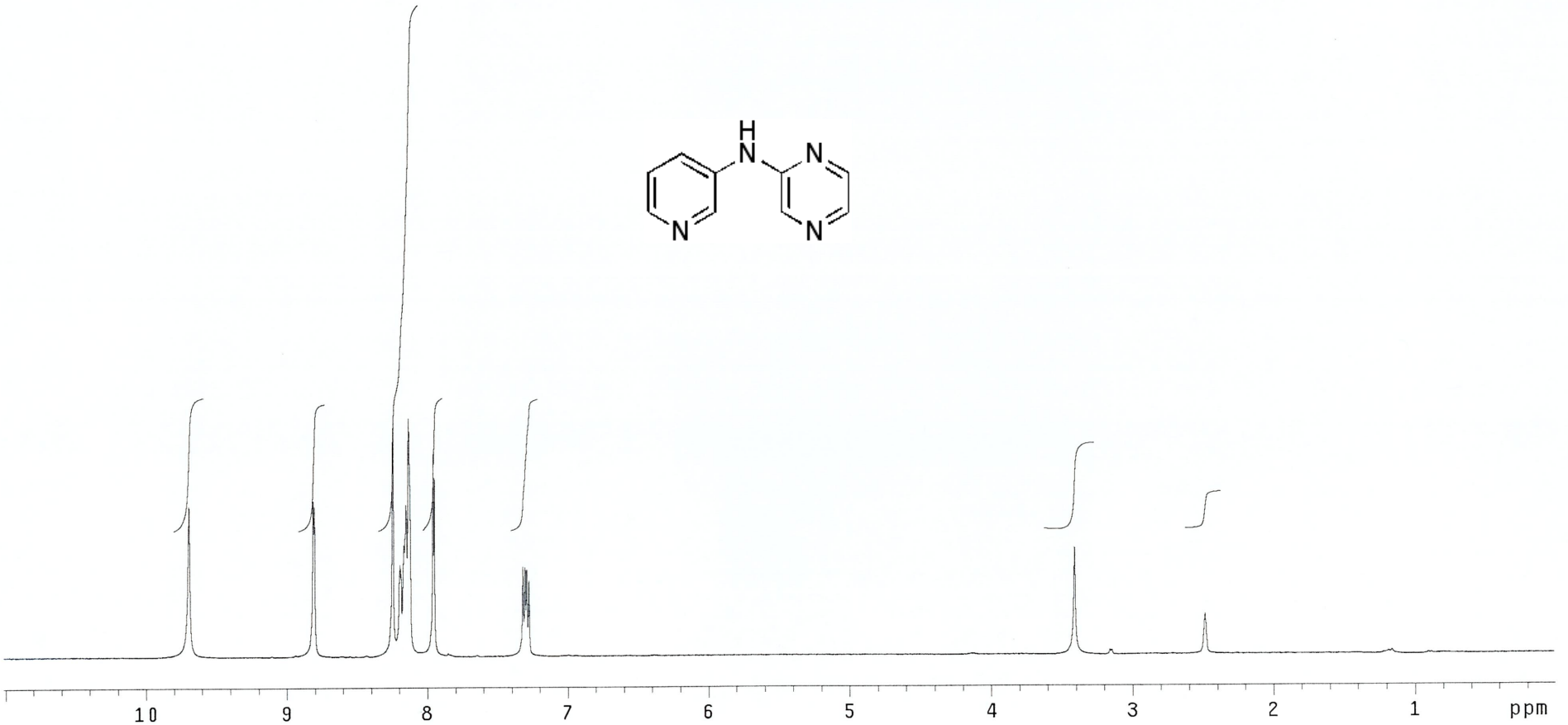
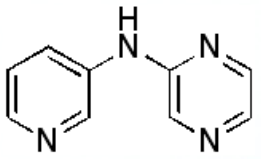
142.189
136.909
134.345
133.624
133.030
130.168
121.174
77.876
77.453
77.027
21.146
21.128
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm

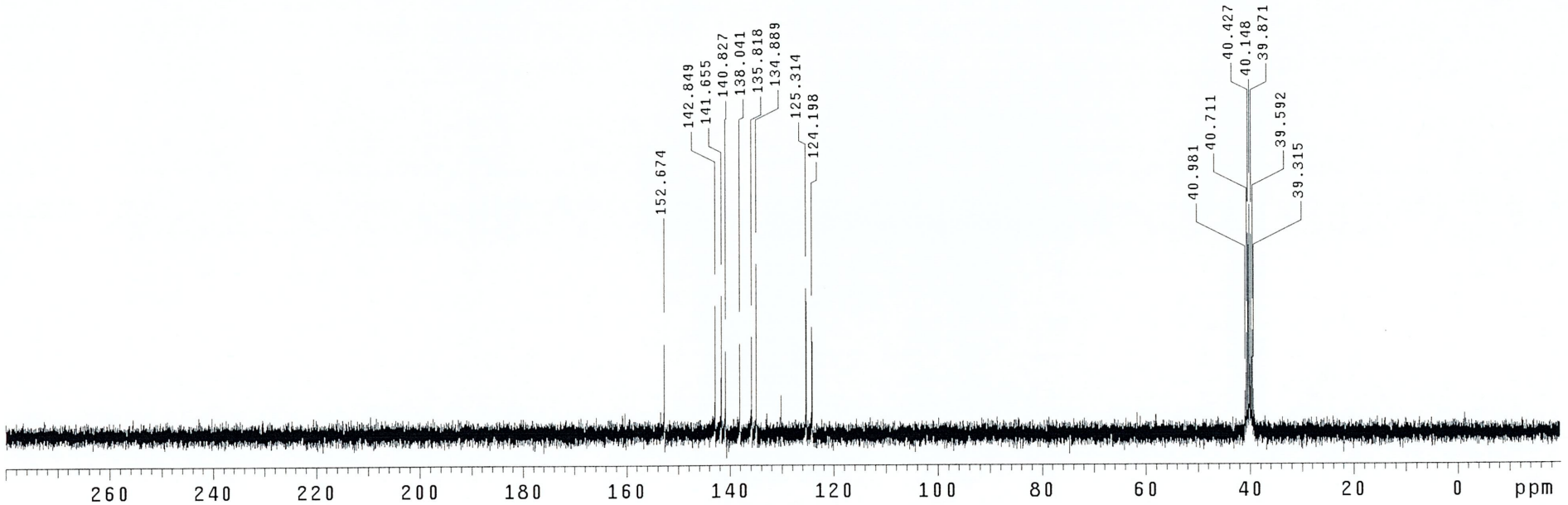

Me
H
N
N
N
Me

9
8
7
6
5
4
3
2
1
ppm


Me
H
N
N
N
Me
160.751
158.280
139.631
138.796
125.017
124.971
118.022
118.004
112.343
77.858
77.432
77.007
21.828
21.807
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm


H
N
N
N
N
10
9
8
7
6
5
4
3
2
1
ppm

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138.041
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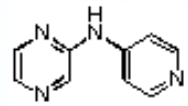
125.314
124.198
40.981
40.711
40.427
40.148
39.871
39.592
39.315
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm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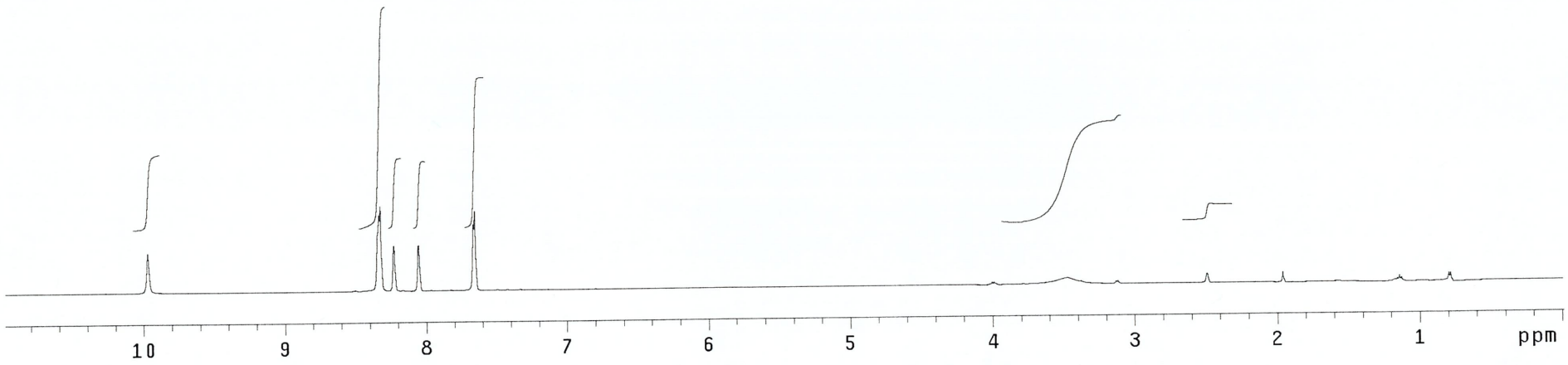
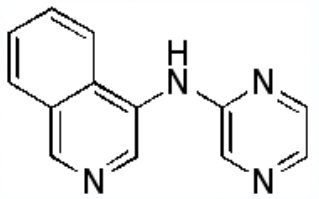

10
9
8
7
6
5
4
3
2
1
ppm

ppm
0
20
40
60
80
100
120
140
160
180
200
39.678
39.841
40.009
40.173
40.341
40.509
40.676
112.714
136.020
136.325
141.784
147.797
150.702
152.234
N
H
N
N
N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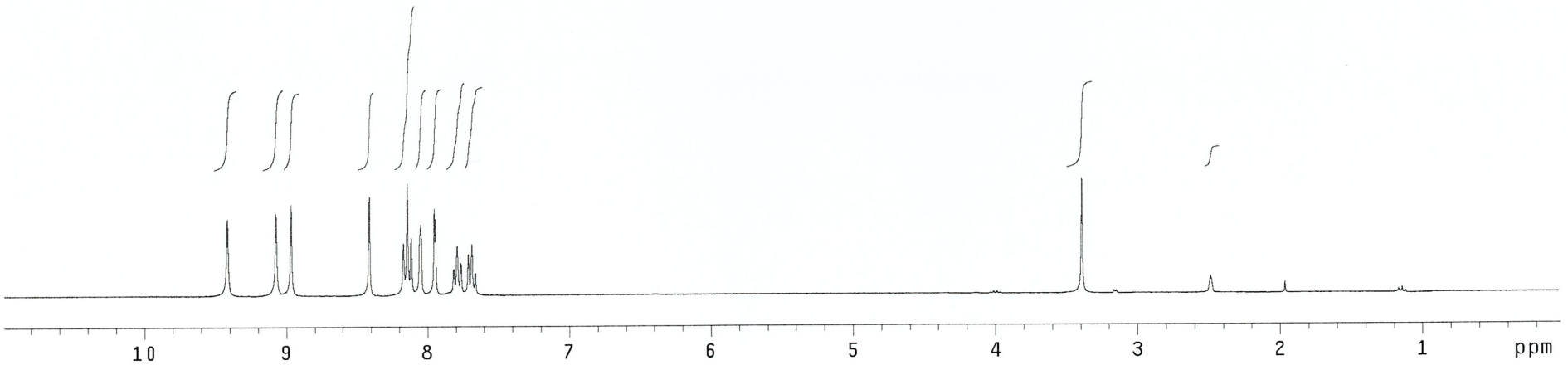
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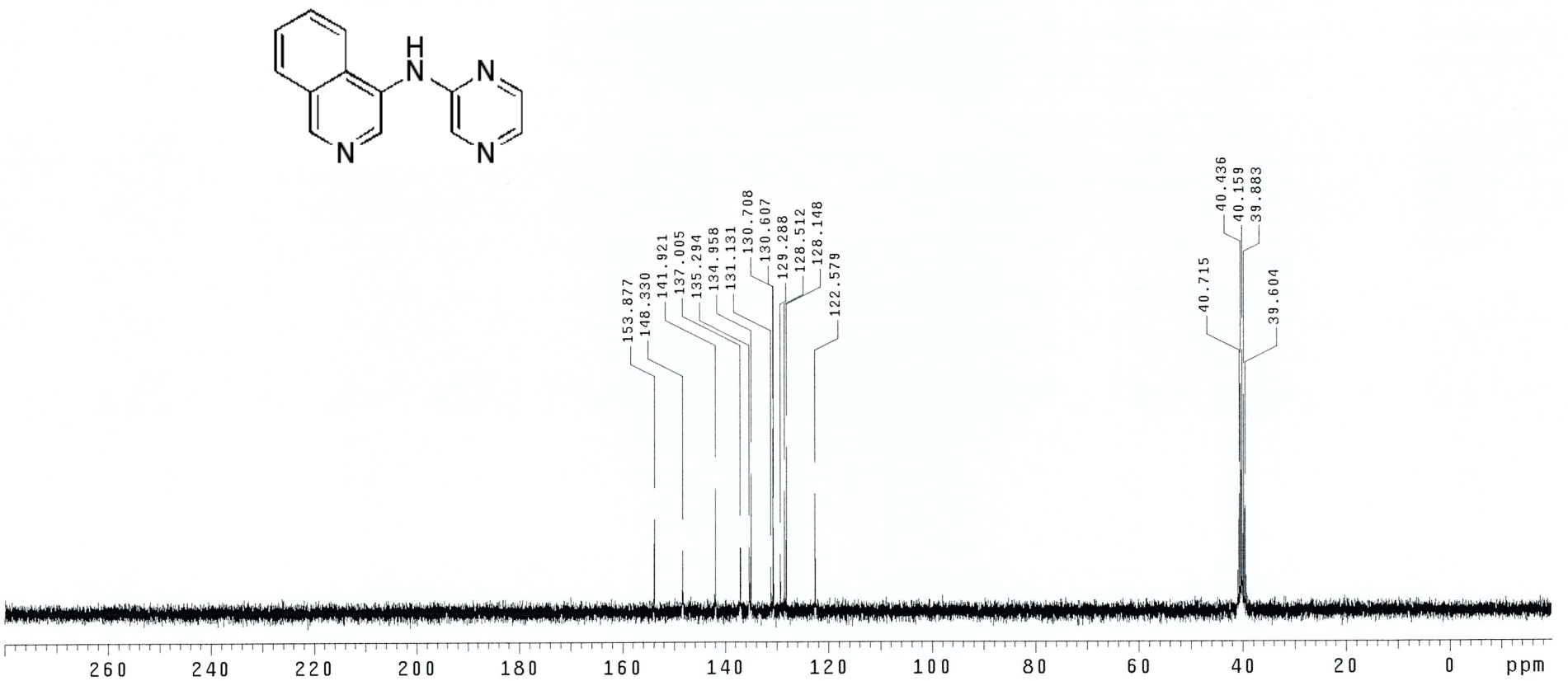
8
7
6
5
4
3
2
1
ppm


H
N
N
N
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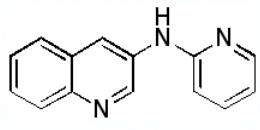
141.921
137.005
135.294
134.958
131.131
130.708
130.607
129.288
128.512
128.148
122.579
40.715
40.436
40.159
39.883
39.604
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm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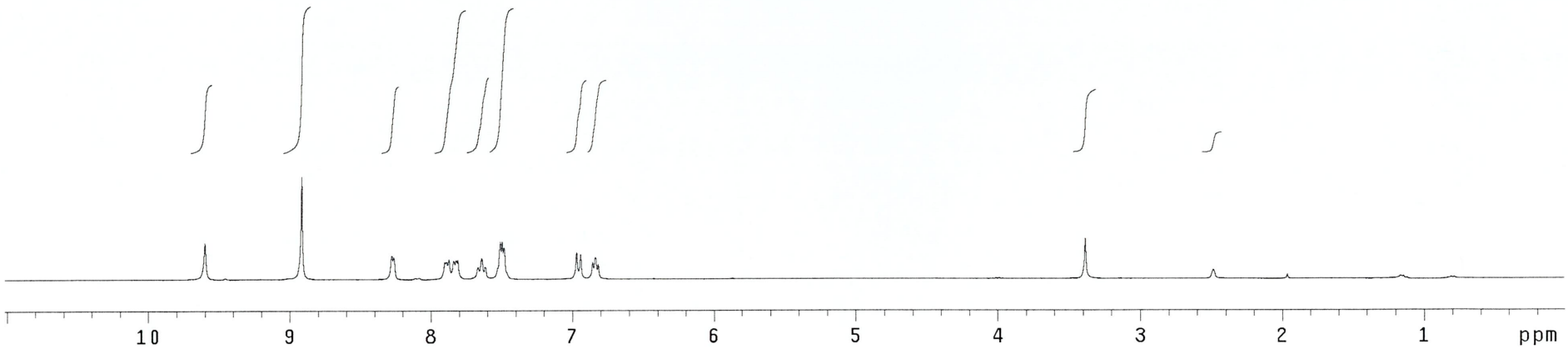
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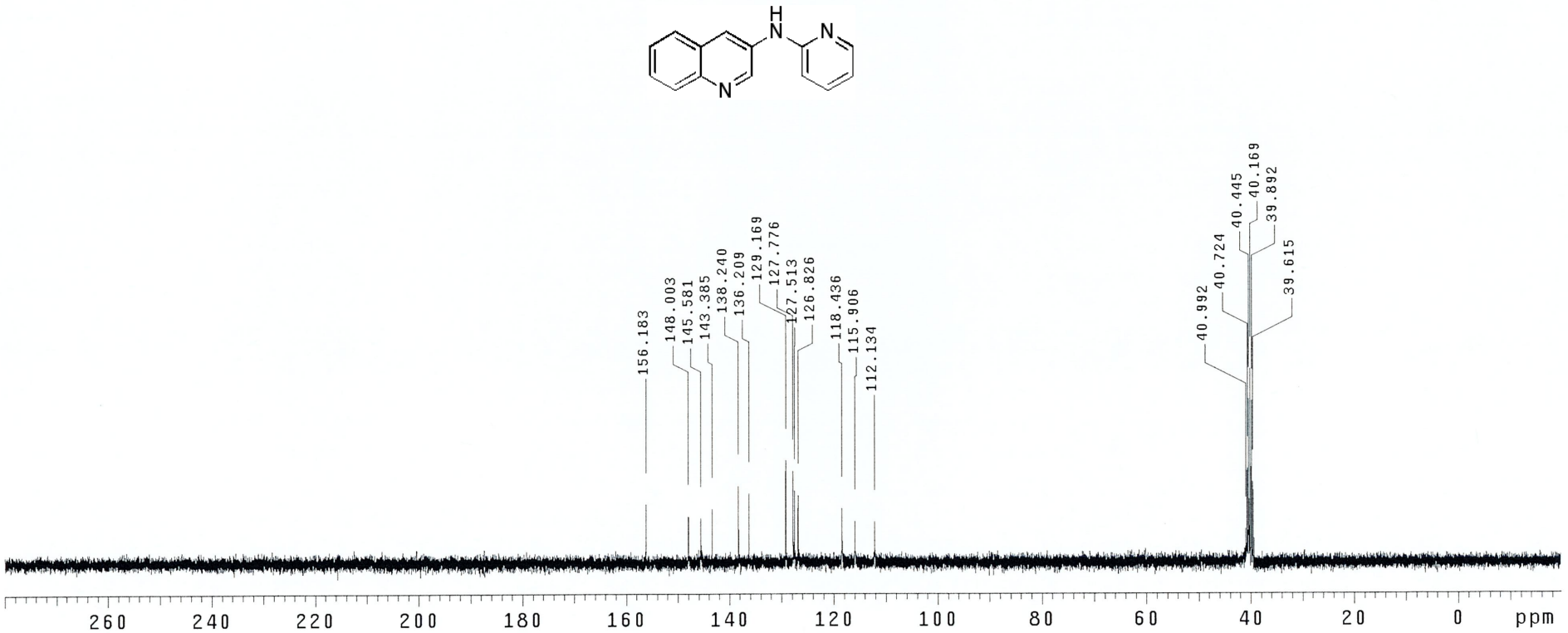
9
8
7
6
5
4
3
2
1
ppm


H
N
N
N
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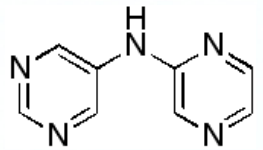
145.581
143.385
138.240
136.209
129.169
127.776
127.513
126.826
118.436
115.906
112.134
40.992
40.724
40.445
40.169
39.892
39.615
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm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N
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N
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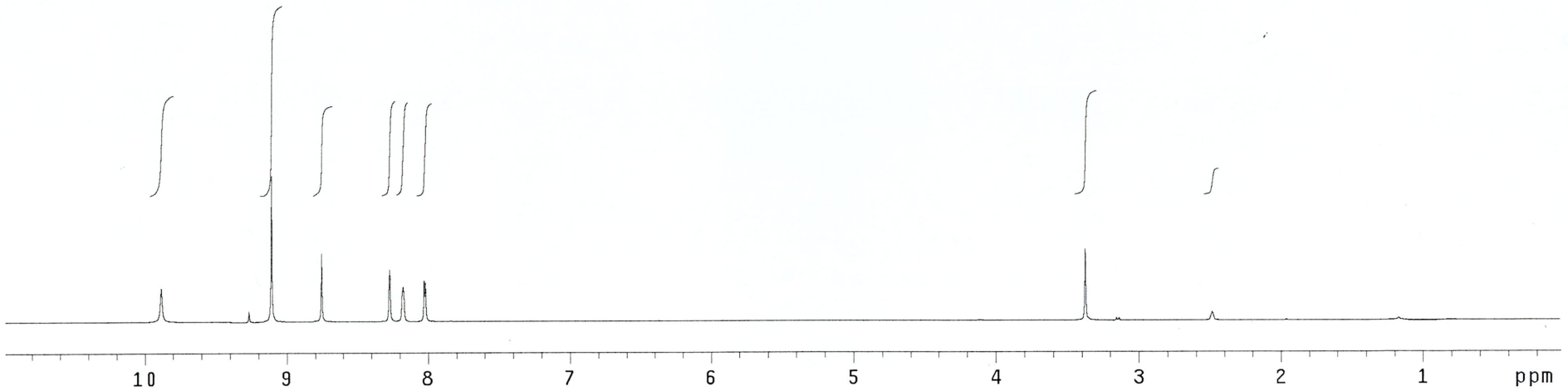
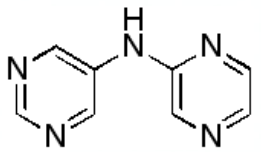

10
9
8
7
6
5
4
3
2
1
ppm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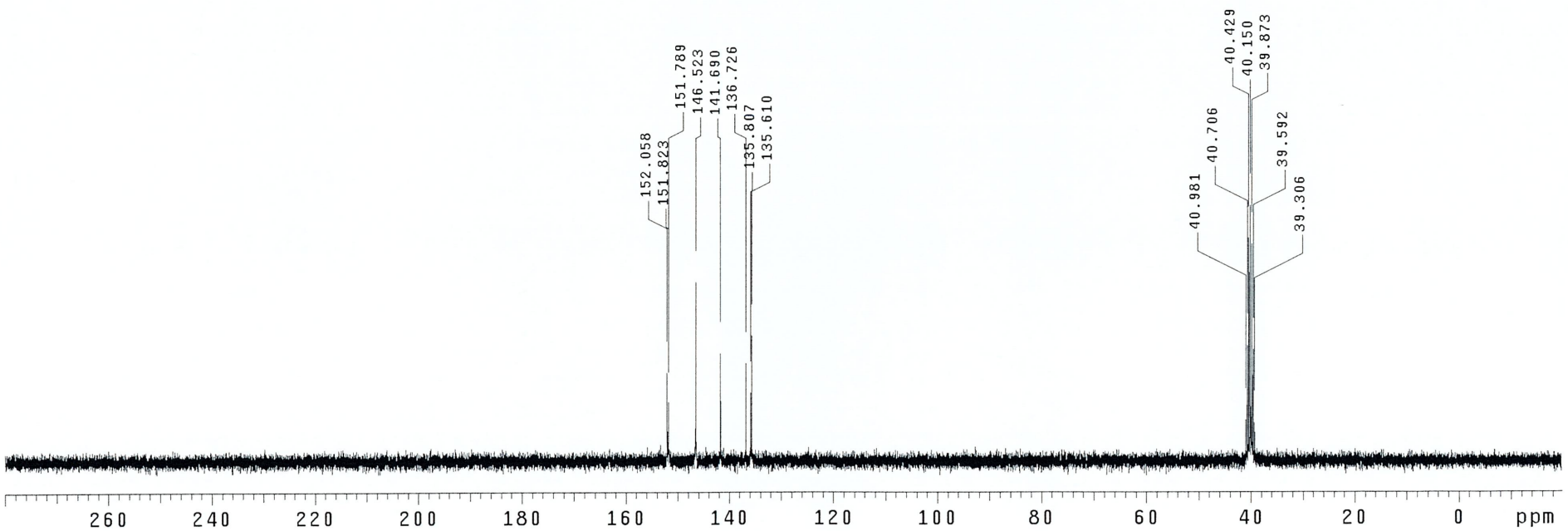
N
N
N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136.726
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135.610
40.981
40.706
40.429
40.150
39.873
39.592
39.306
260
240
220
200
180
160
140
120
100
80
60
40
20
0
ppm