

Supporting Information

Asymmetric synthesis of axially chiral 1-aryl-5,6,7,8-tetrahydroquinolines by cobalt-catalyzed [2+2+2] cycloaddition reaction of 1-aryl-1,7-octadiynes and nitriles

Marko Hapke, Karolin Kral, Christine Fischer, Anke Spannenberg, Andrey Gutnov, Dmitry*

Redkin and Barbara Heller

Leibniz-Institut für Katalyse e.V. an der Universität Rostock (LIKAT)

Albert-Einstein-Str. 29a, 18059 Rostock, Germany

E-mail: marko.hapke@catalysis.de

1. General Methods _____	S-2
2. Synthesis of CpCo(bpy) _____	S-3
3. Photochemical Experiments _____	S-4 – 7
4. NMR Spectra _____	S-8 – S-35
5. Dynamic HPLC Spectra of 45 and 46 _____	S-36
6. X-ray Crystallographic Study of CpCo(bipy) _____	S-37
7. References _____	S. 38

1. General Methods

The NMR spectra were in general recorded at 298 K and the individual measurement conditions given with the data. Chemical shifts are reported in ppm relative to the ^1H and ^{13}C residue signals of the deuterated solvent (deuteriochloroform: δ 7.26 ppm for ^1H and δ 77.16 ppm for ^{13}C) or to an external standard for the hetero nuclei (^{19}F , ^{11}B). Mass spectra were obtained with a mass spectrometer at an ionizing voltage of 70 eV for EI. Only characteristic fragments containing the isotopes of highest abundance are listed. Relative intensities in percentages are given in parentheses. Melting points were not corrected. In all cases the enantiomeric excesses of pyridines were analyzed by HPLC using appropriate chiral columns. For the photochemistry two halogen lamps (460 W each) have been used for irradiation of the thermostated Schlenk-type reaction vessel.

All reactions were carried out in an argon atmosphere, using standard techniques in dry, oxygen-free solvents. All liquid reagents were distilled under argon prior to use. All solid compounds used for the photo-catalyzed reactions were recrystallized from degassed solvents and the liquid starting materials were dried over and distilled from molecular sieves under argon before use. Chromatographic purifications were done with 240-400 mesh silica gel or on an automated flash chromatography system.

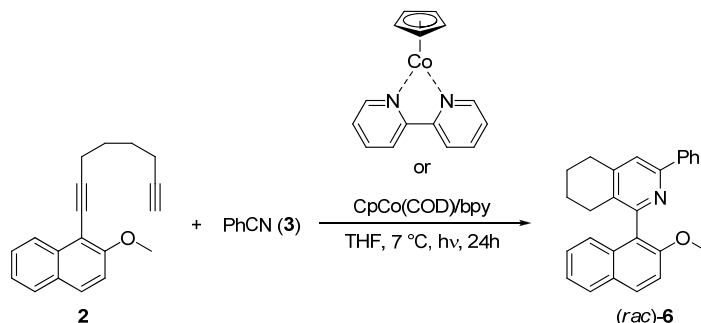
Chiral $\text{Cp}^*\text{Co}(\text{COD})$,¹ CpCoCOD ,² $\text{Pd}(\text{PPh}_3)_4$,³ and $\text{Pd}_2\text{dba}_3\cdot\text{CHCl}_3$,³ were synthesized according to known procedures. All other compounds not referenced were commercially available and have been purchased.

2. Synthesis of CpCo(bpy)

Synthesis of CpCo(bpy) from Cp₂Co.⁴ The CpCo(bipy) complex was prepared from cobaltocene (500 mg, 2.65 mmol), 2,2'-bipyridine (414 mg, 2.65 mmol) and lithium metal (18.6 mg, 2.65 mmol). The three solids were weighted into a Schlenk flask and dissolved in THF (ca. 5 mL) at -15 °C. The dark red reaction mixture was stirred at this temperature for 2 h before it was allowed to warm to 0 °C and stirred additional 2 h followed by warm-up to rt. After 24 h the reaction was finished and the solvent was removed. Toluene (20 mL) was added to the residue and the solution was filtered 2 times. The volume of the solvent was reduced to half and 10 mL *n*-hexane was added. The product was stored in the freezer to be crystallized at -35°C and yield dark violet crystals were obtained (124 mg (17%). ¹H NMR (300 MHz, CD₂Cl₂): δ = 8.66 (s, 2H), 8.43 (s, 2H), 7.82 (s, 2H), 7.32 (s, 2H), 4.76 (bs, 5H) ppm. ¹³C NMR (100 MHz, CD₂Cl₂): δ = 151.2, 138.9, 125.8, 122.8, 81.0 ppm (the signal for C-2 was not observed). MS (EI, 70 eV), m/z (%): 280 (25) [M⁺], 215 (22), 156 (100), 128 (29), 78 (16). Anal. Calcd for C₁₅H₁₃CoN₂ (280.04): C 64.29, H 4.68, N 10.00. Found: C 64.24, H 4.81, N 10.20.

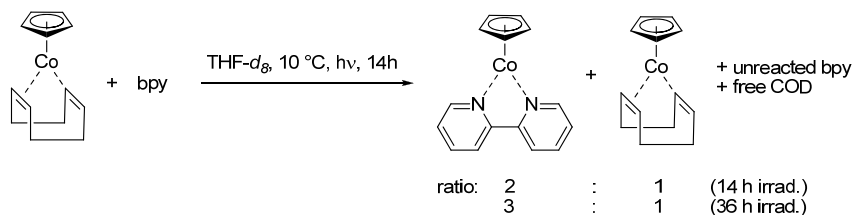
3. Photochemical Experiments

Reaction of diyne 2 and PhCN (3) using either CpCo(bpy) or CpCo(COD)/bpy as the catalysts:



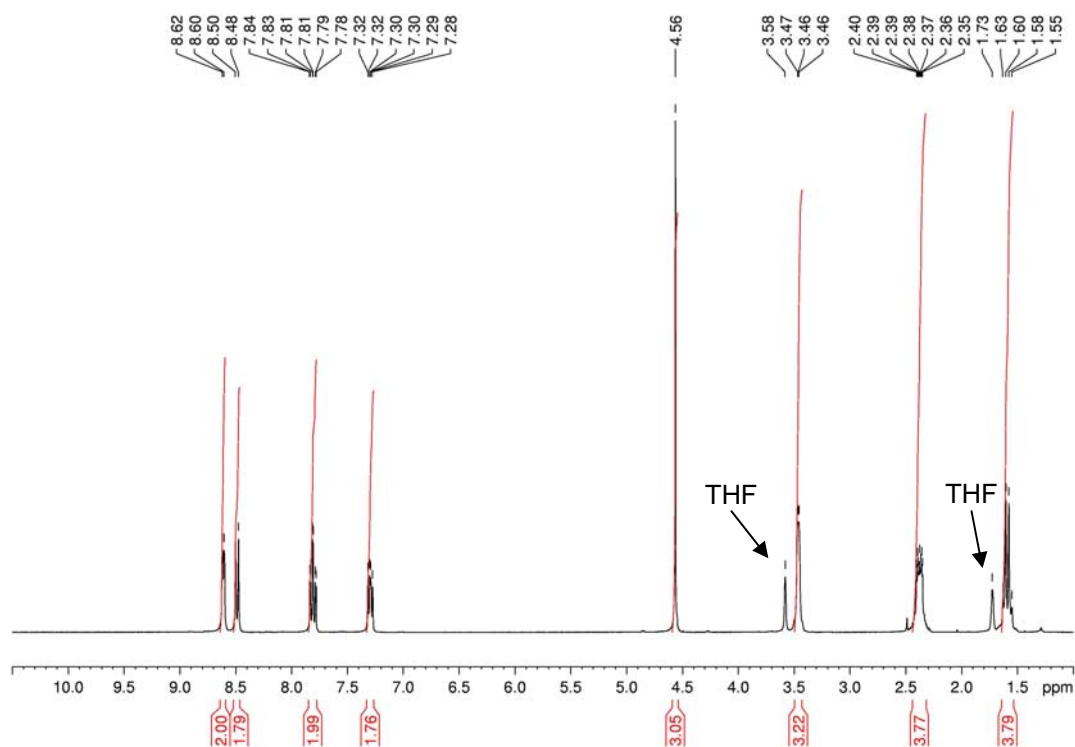
For the inhibition experiments the General Procedure described above for the performance of the photochemical reactions was applied. In a typical experiment diyne **2** (170 mg, 0.65 mmol) and CpCo(bpy) (18.2 mg, 0.065 mmol, 10 mol%) were weighted into a secured Schlenk flask used for the photoreactions under Argon. THF (10 mL) and benzonitrile (**3**, 0.14 ml, 1.3 mmol) were added via syringe, the solution was thermostated to 7–10 °C and the reaction mixture stirred for 24 h. While the reaction using CpCo(bpy) was turning dark-violet immediately, in case of the use of CpCo(COD)/bpy (1:1.25 or 1:6 mixture) the solution turned dark-violet shortly after starting the irradiation. After turning off the lights and exposing the reaction mixture to air, the mixture was analyzed by GC.

Reaction of CpCo(COD) and bpy under photochemical conditions:

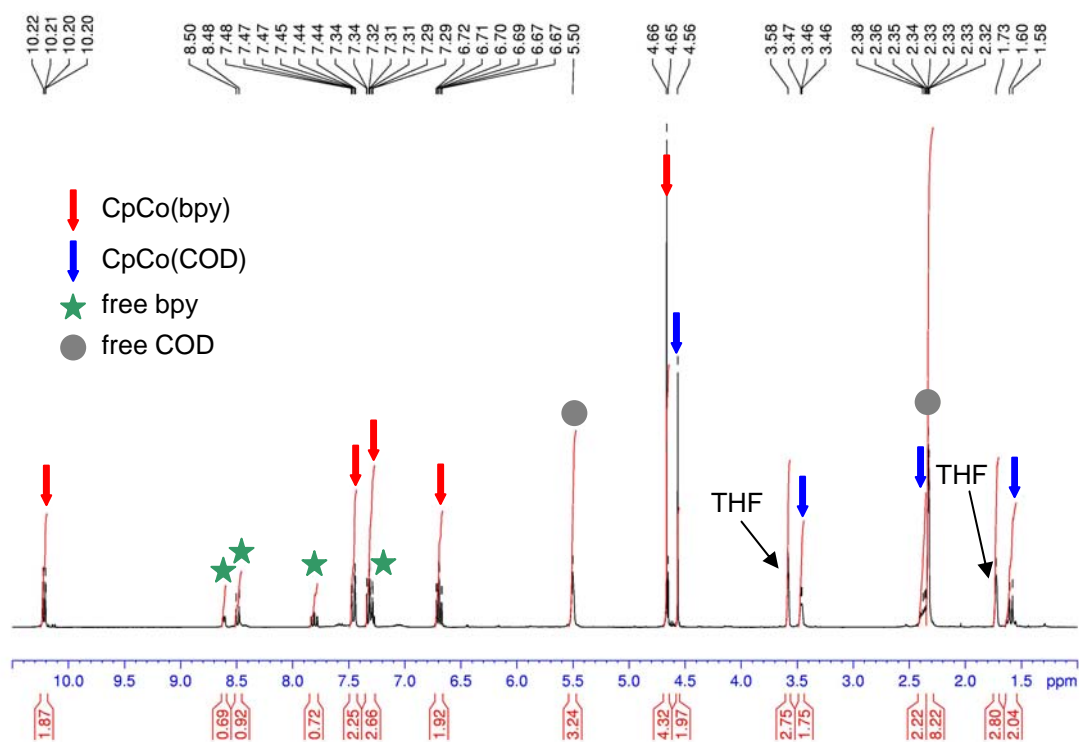


In the dry box CpCo(COD) (20 mg, 0.086 mmol) and 2,2'-bipyridine (13.5 mg, 0.086 mmol) were weighted into a NMR tube. The solids were dissolved in thoroughly dried THF-*d*₈ (1 mL) yielding a yellow solution. The tube was carefully flame-sealed in vacuo. A ¹H NMR spectra was taken before the reaction and the tube then irradiated under the same conditions as described above while thermostating the solution at 10 °C for 36 h totally. Already after a short time the solution turned intensively purple. Comparison of the data showed, that most of the starting CpCo(COD) was transformed to CpCo(bpy) after 14 h, giving a ratio of 1:2 [CpCo(COD):CpCo(bpy)]. In addition free COD as well as unreacted bpy was observed. After 36 h of irradiation a yield of 75% for CpCo(bpy) was determined.

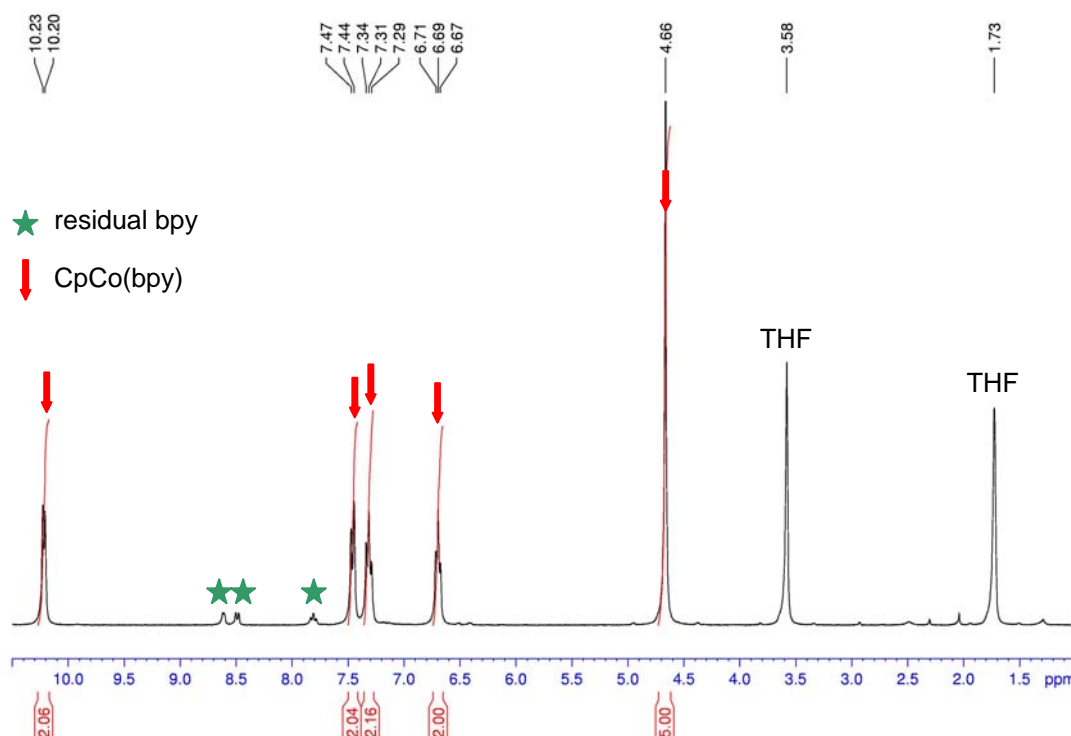
^1H NMR of the reaction of $\text{CpCo}(\text{COD})$ with bpy in $\text{THF-}d_8$ before irradiation:



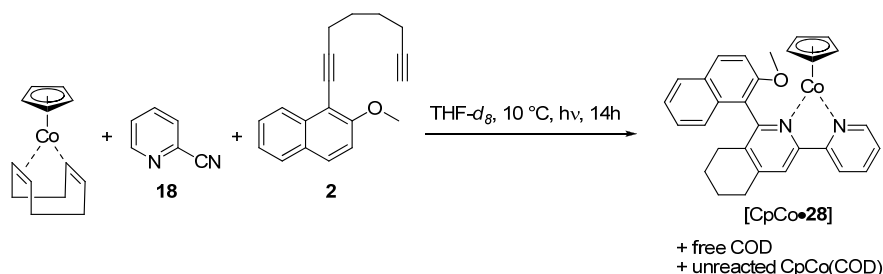
^1H NMR of the reaction of $\text{CpCo}(\text{COD})$ with bpy $\text{THF-}d_8$ after irradiation:



^1H NMR of pure $\text{CpCo}(\text{bpy})$ dissolved in $\text{THF-}d_8$:



Reaction of $\text{CpCo}(\text{COD})$ with diyne **2 and 2-cyanopyridine (**18**) under photochemical conditions:**

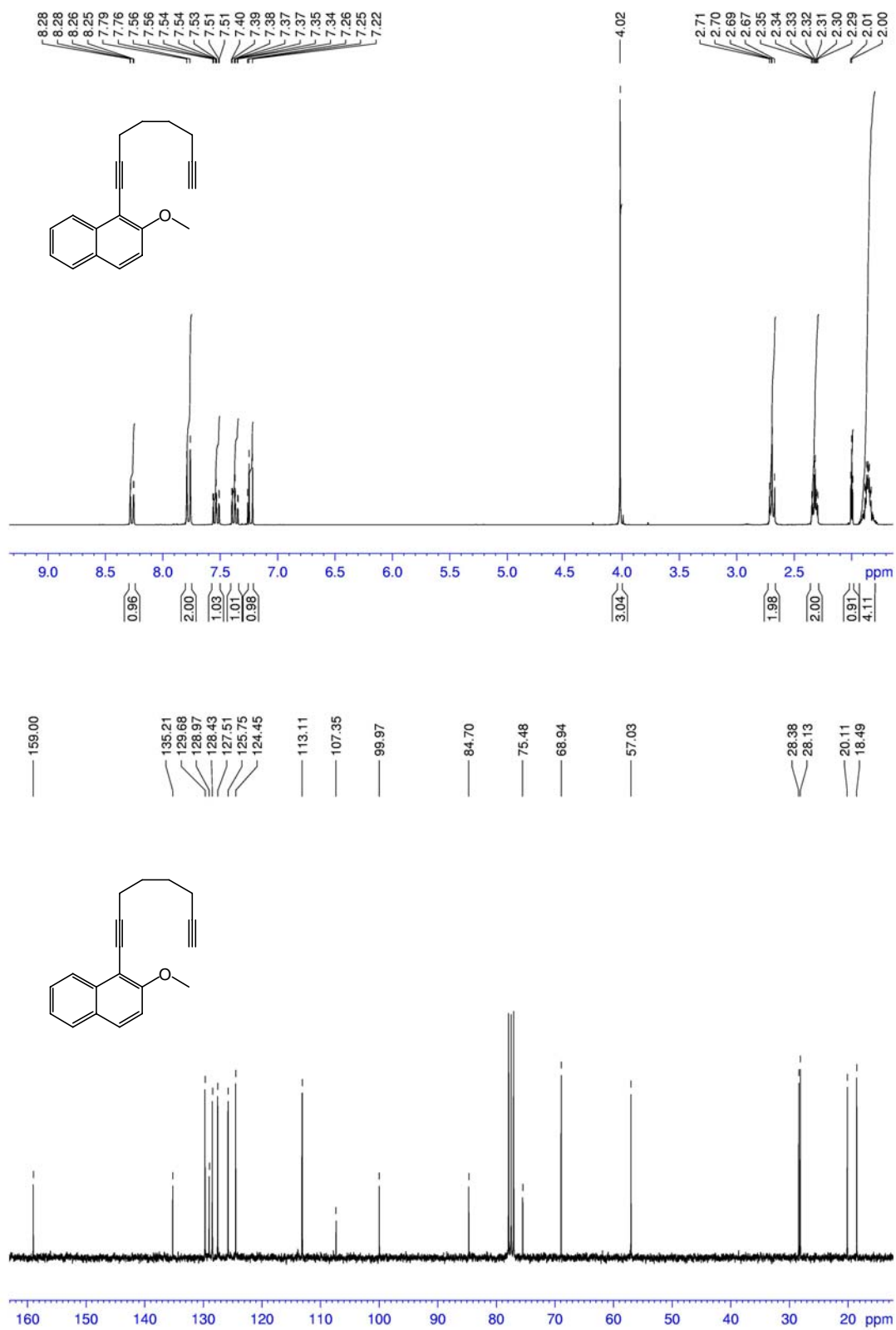


In the dry box $\text{CpCo}(\text{COD})$ (23.2 mg, 0.1 mmol), diyne **2** (26.2 mg, 0.1 mmol) and 2-cyanopyridine (**18**) (10.4 mg, 0.1 mmol) were weighted into a NMR tube. The solids were dissolved in thoroughly dried $\text{THF-}d_8$ (0.1 mL) yielding a yellow solution. The tube was carefully flame-sealed in vacuo. A ^1H NMR spectra was taken before the reaction and the tube then irradiated under the same conditions as described above while thermostating the solution at 10 °C for 14 h. Already after a short time the solution turned intensively dark blue-purple. After the end of irradiation another proton NMR spectra was observed and showed, that according to the integration of COD protons from $\text{CpCo}(\text{COD})$ and free COD about 36% of the $\text{CpCo}(\text{COD})$ have reacted while the rest was found to be intact. On the other hand, the signals for **2** have nearly completely disappeared and characteristically shifted signals for a

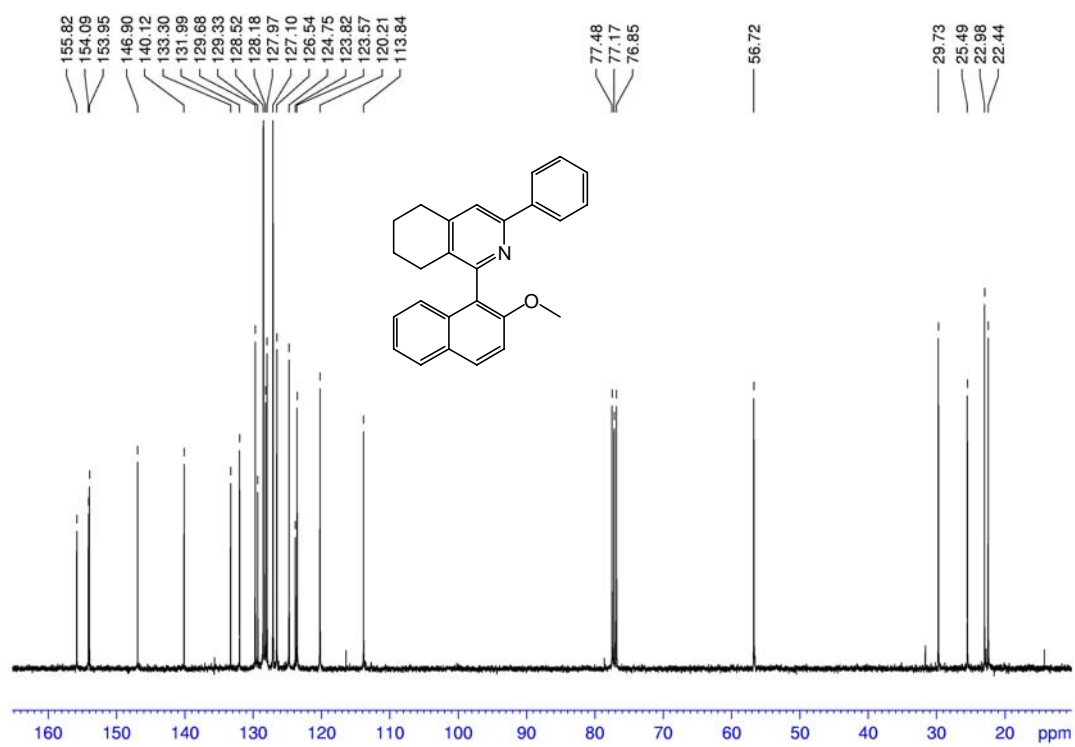
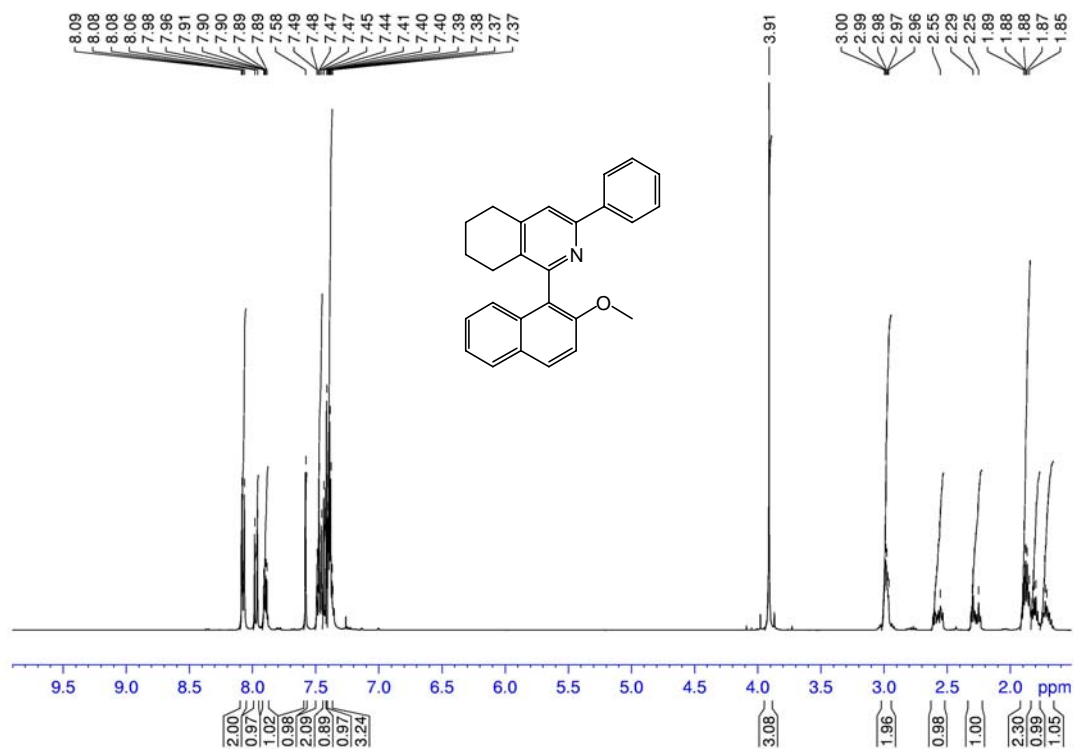
newly formed, Co-bipyridine [CpCo•**28**] were found at 10.1 and 6.56 ppm. However, these latter signals are comparably small. The formation of **28** was corroborated by high-resolution ESI mass spectroscopy of the sample after unsealing the NMR tube on air and removal of the solvent (HRMS (ESI) for C₂₅H₂₃N₂O: calcd 367.1805, found 367.1808).

4. NMR Spectra

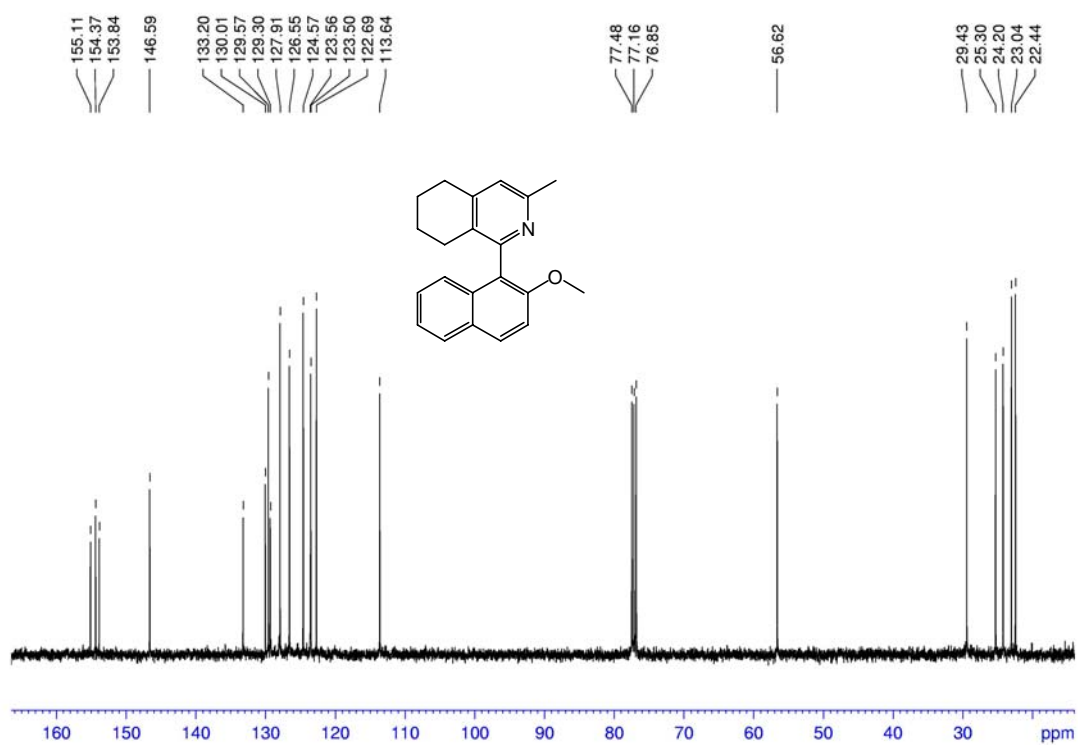
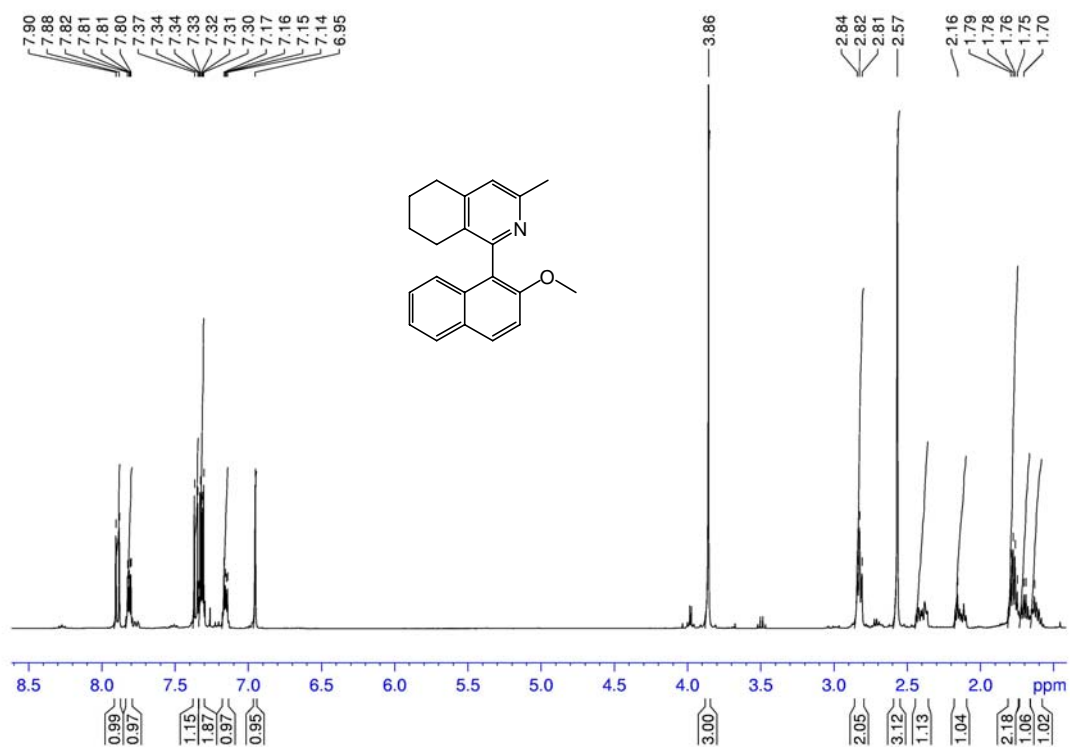
Compound 2:



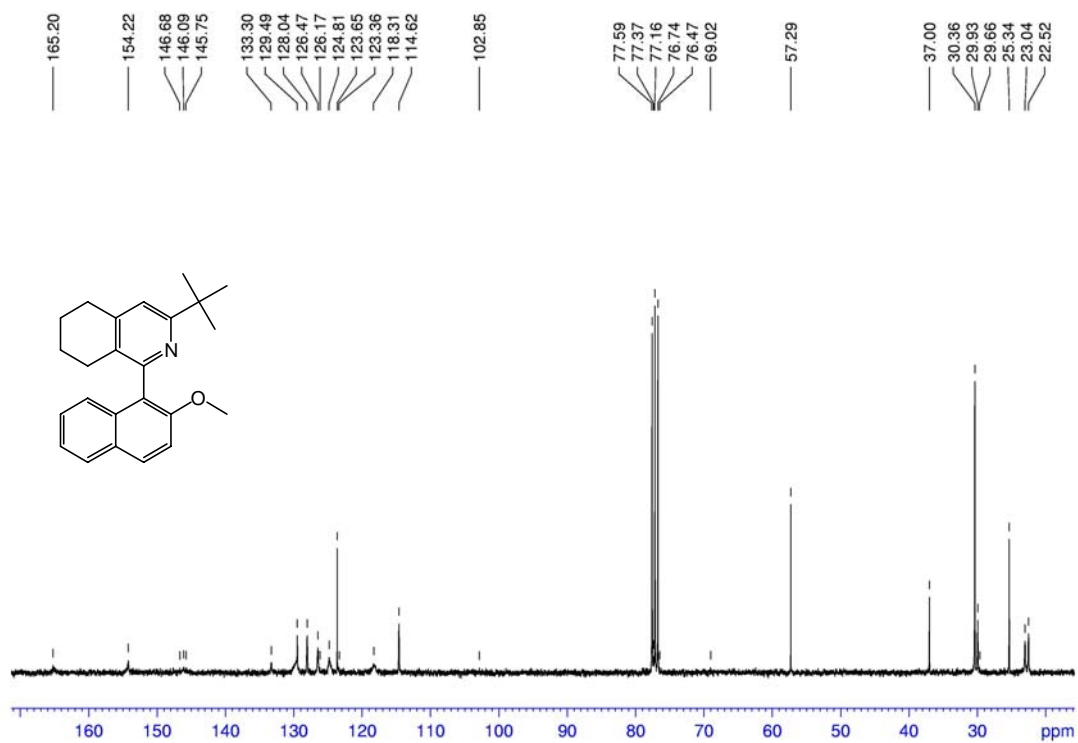
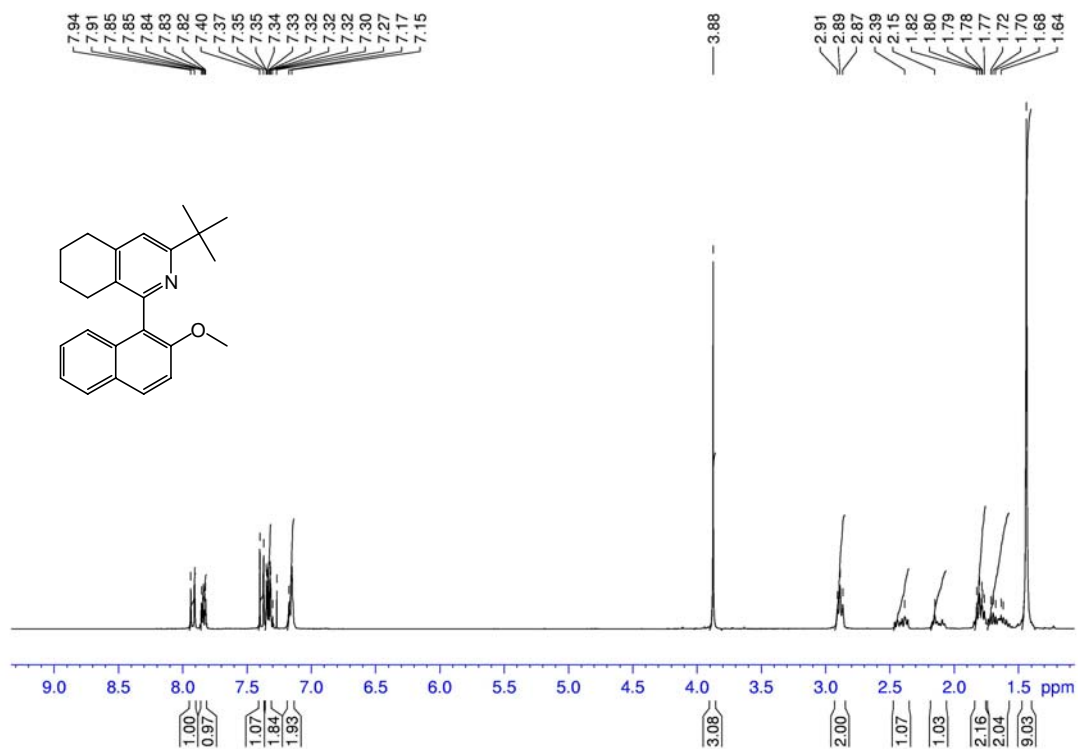
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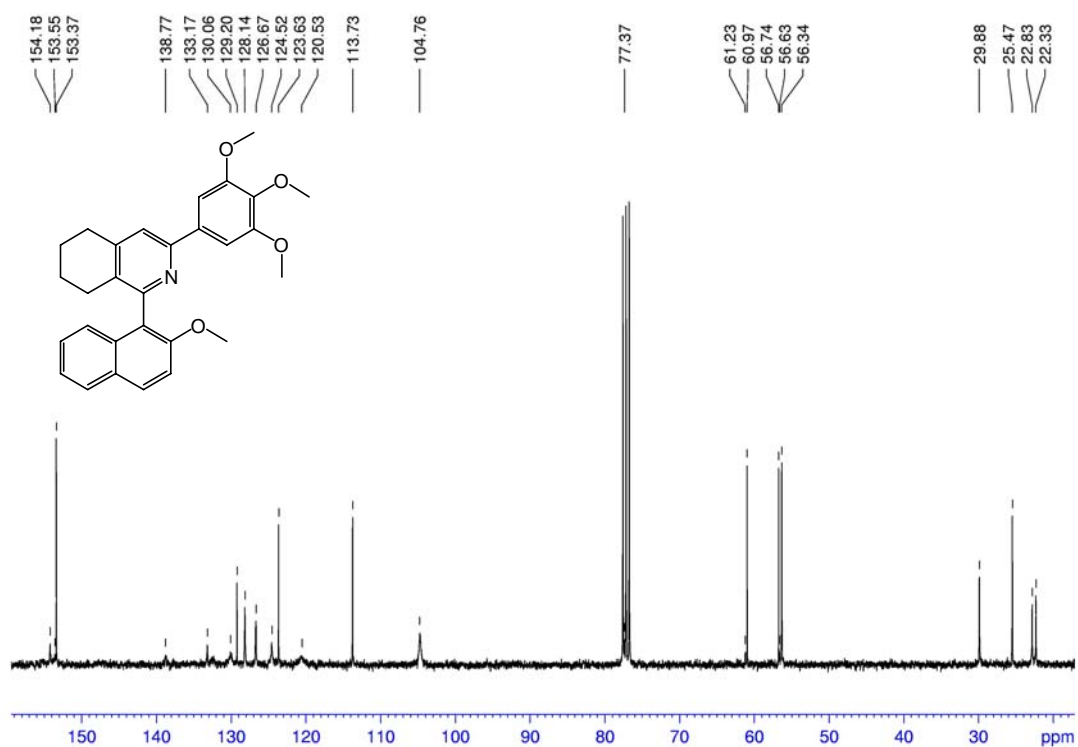
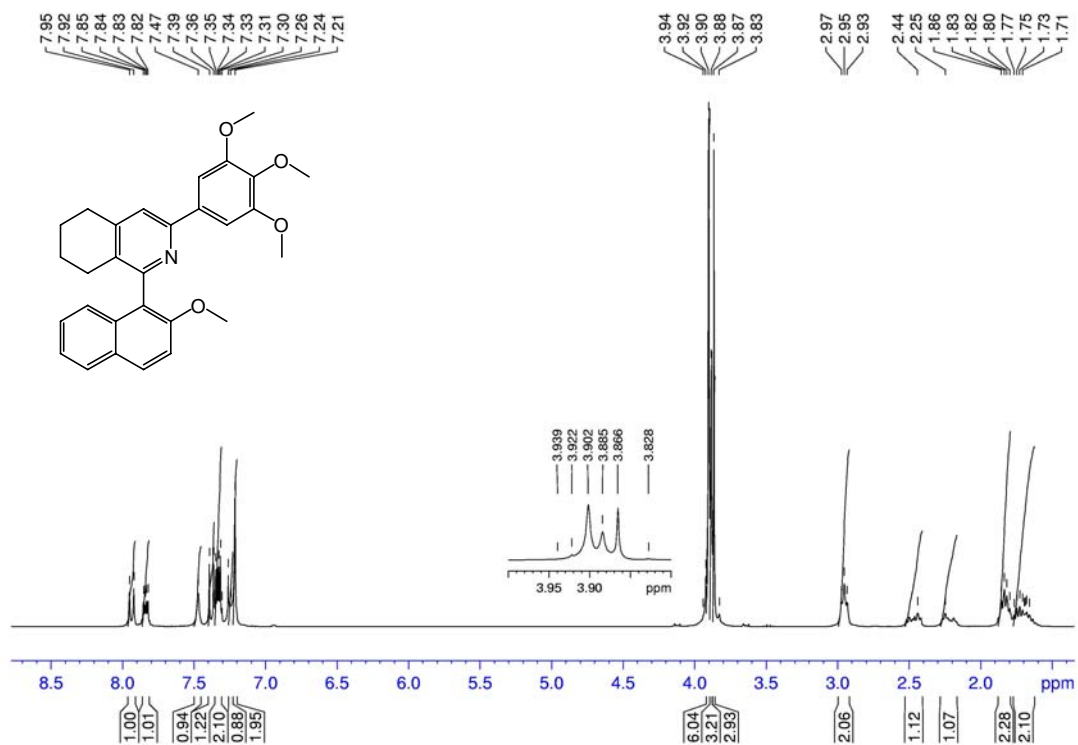
Compound 7:



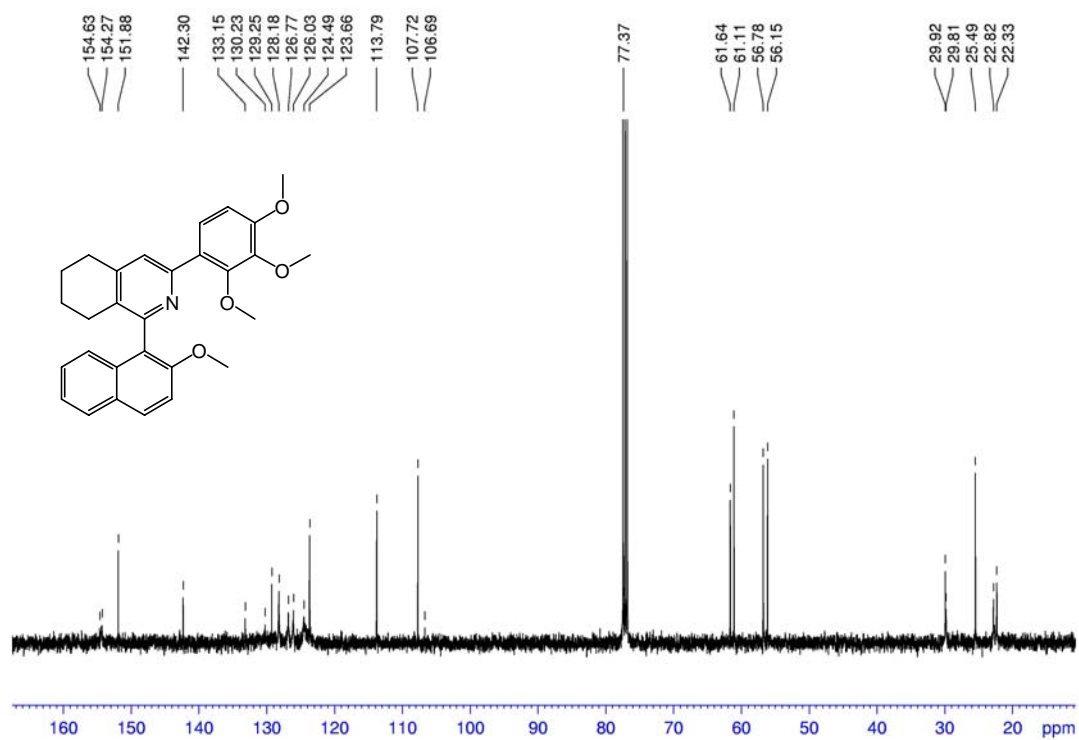
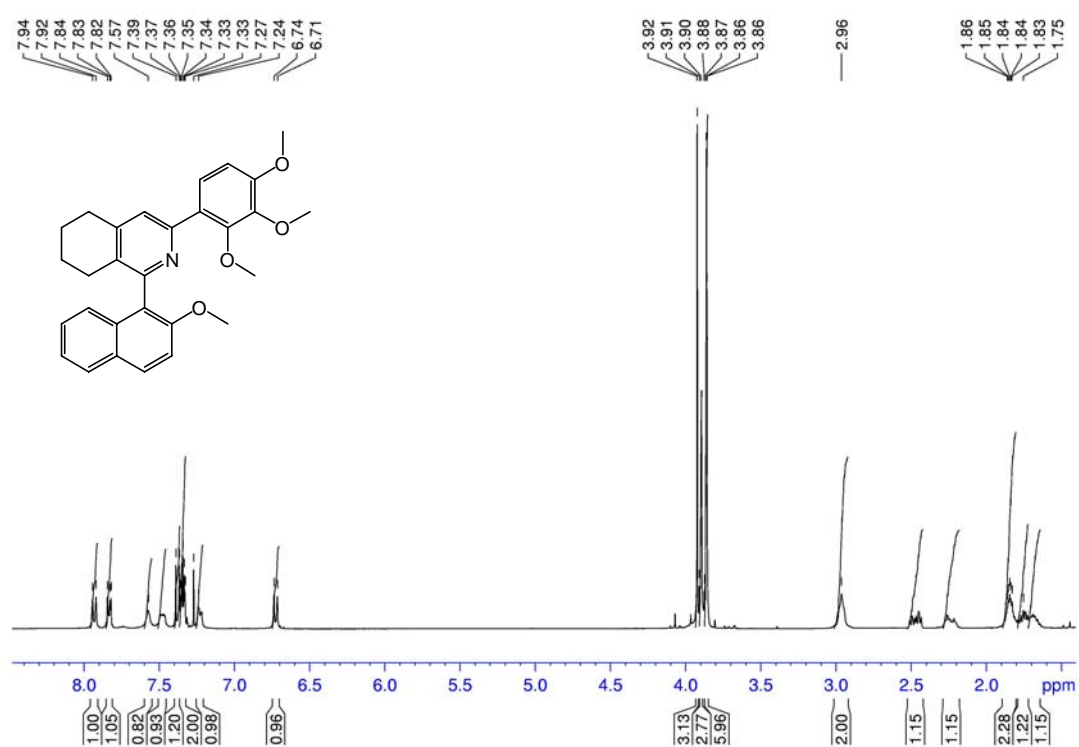
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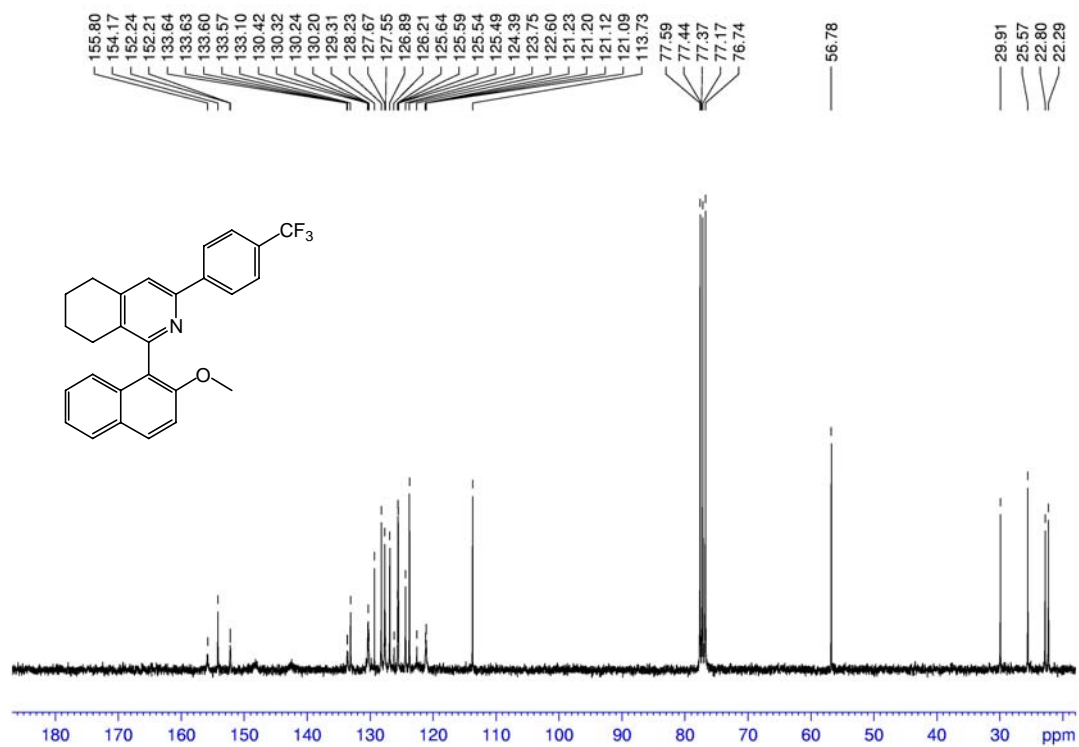
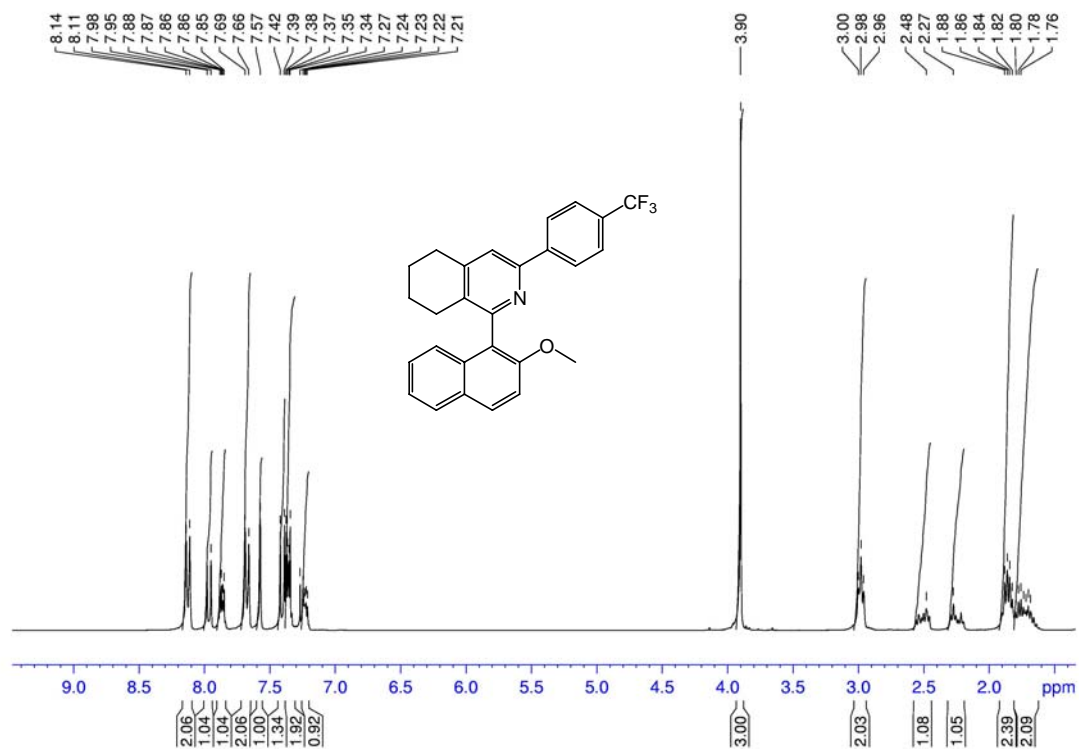
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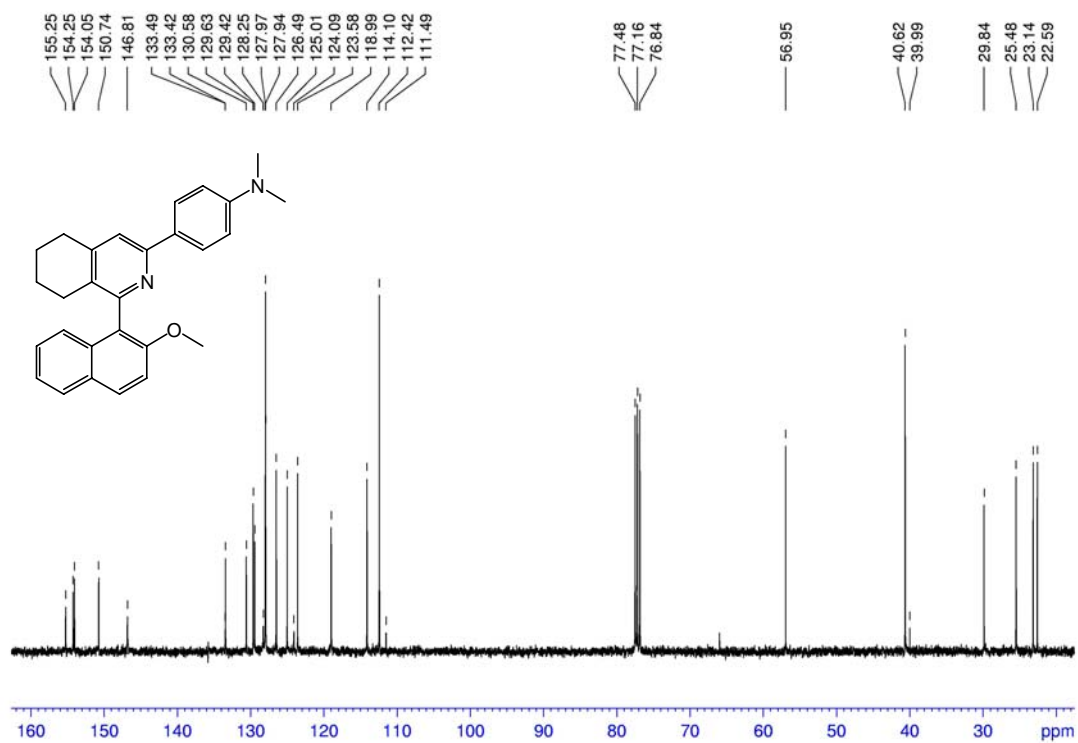
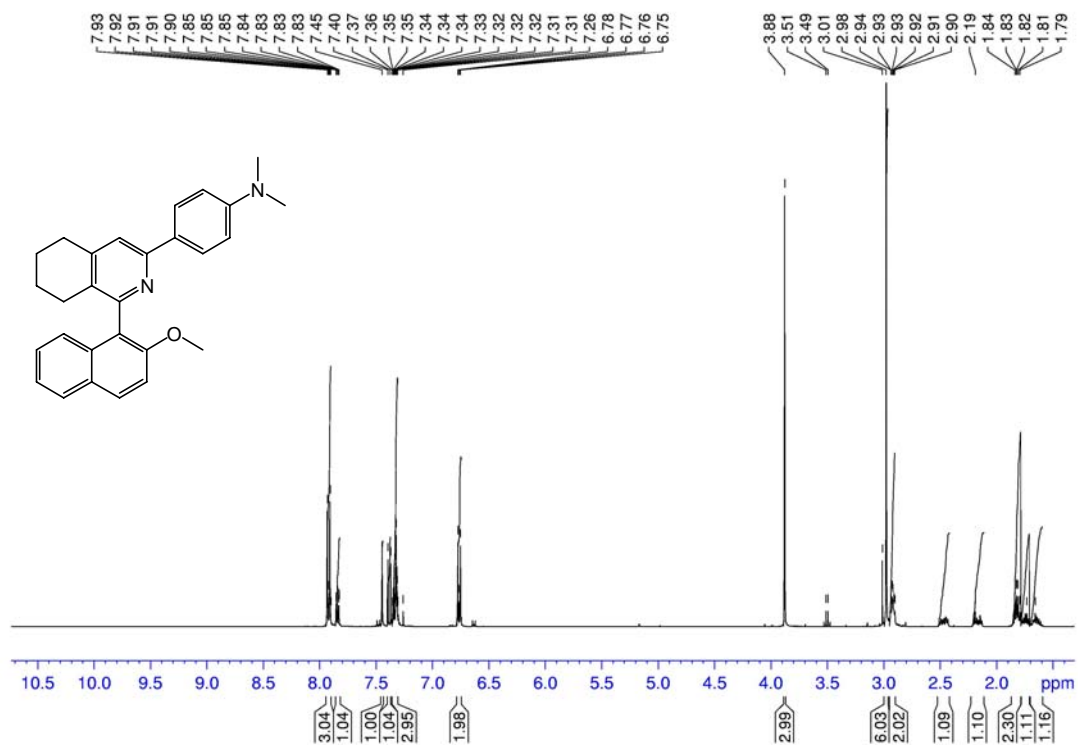
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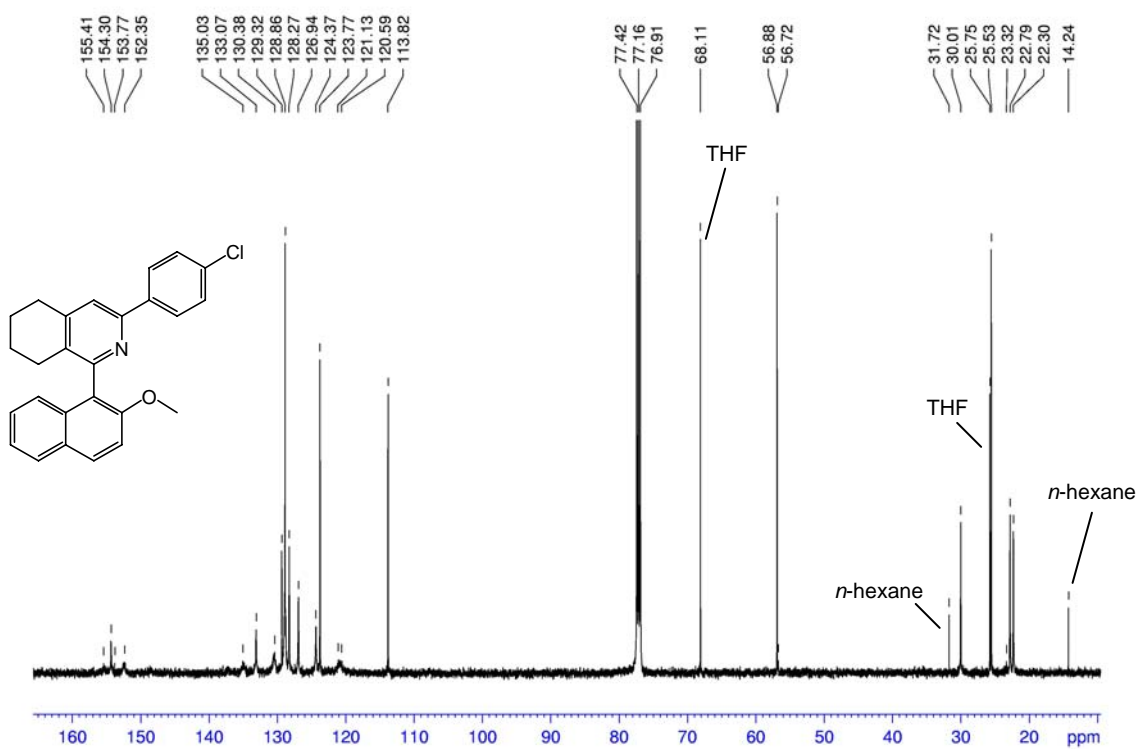
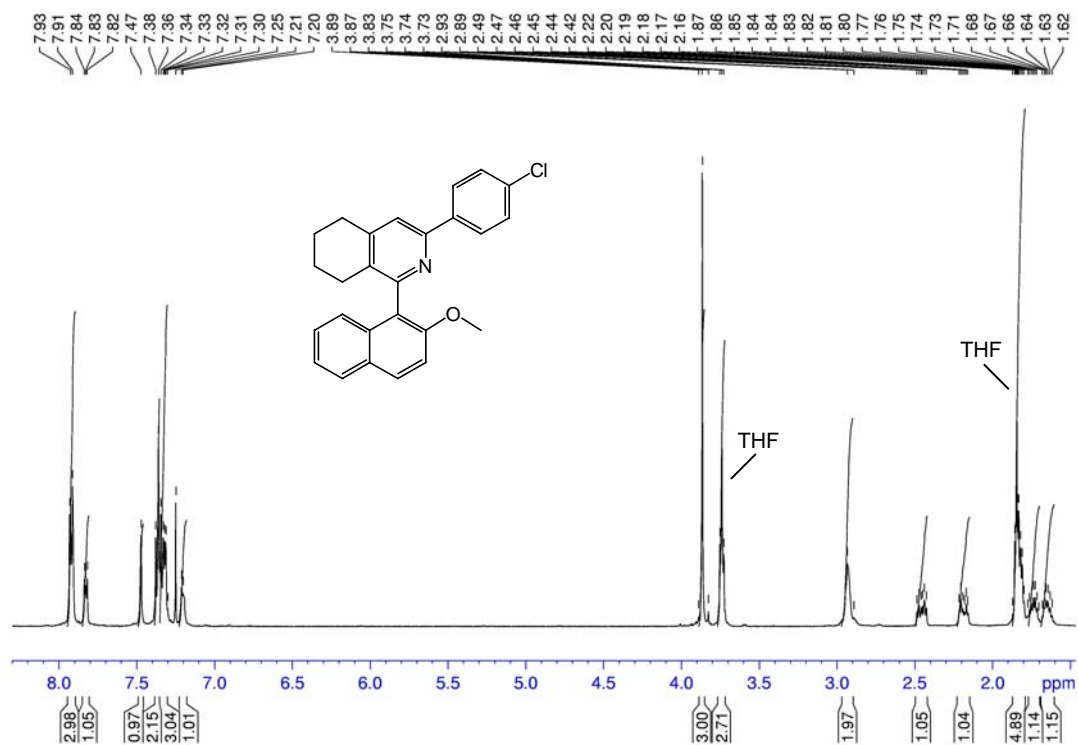
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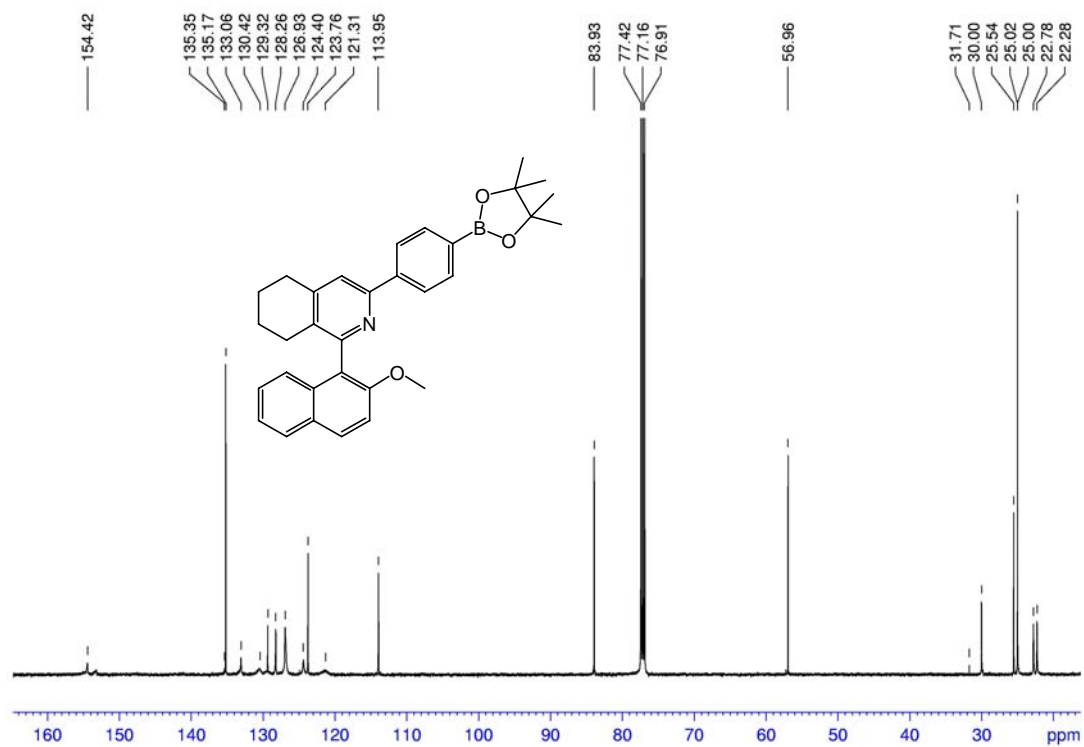
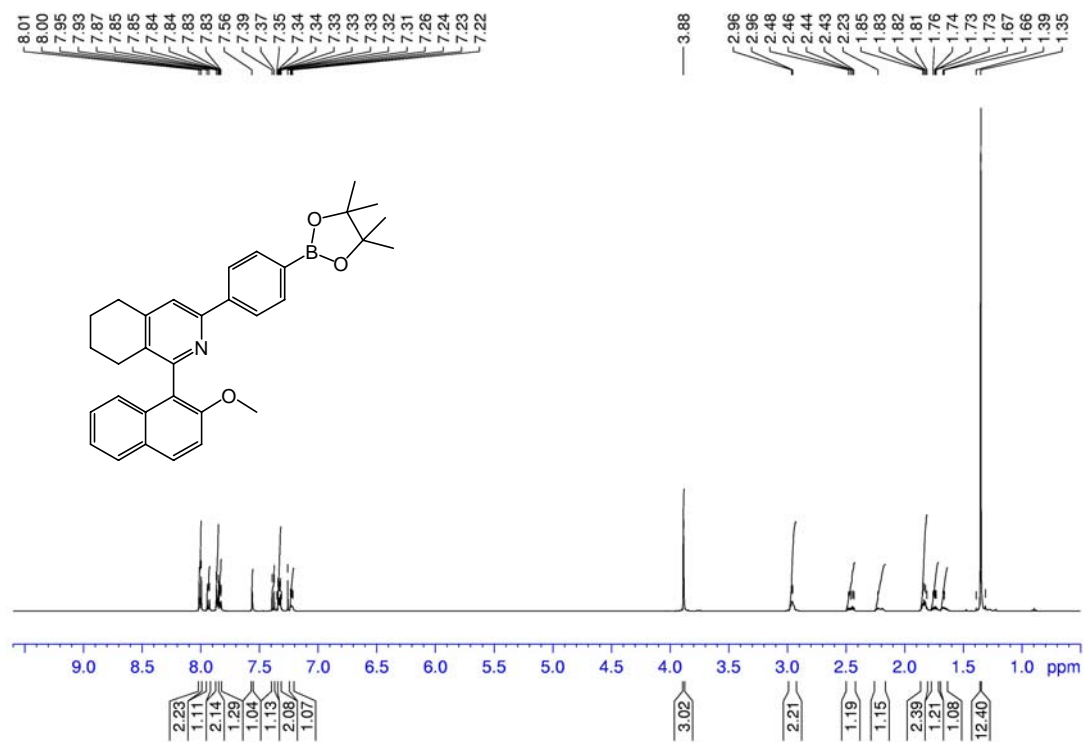
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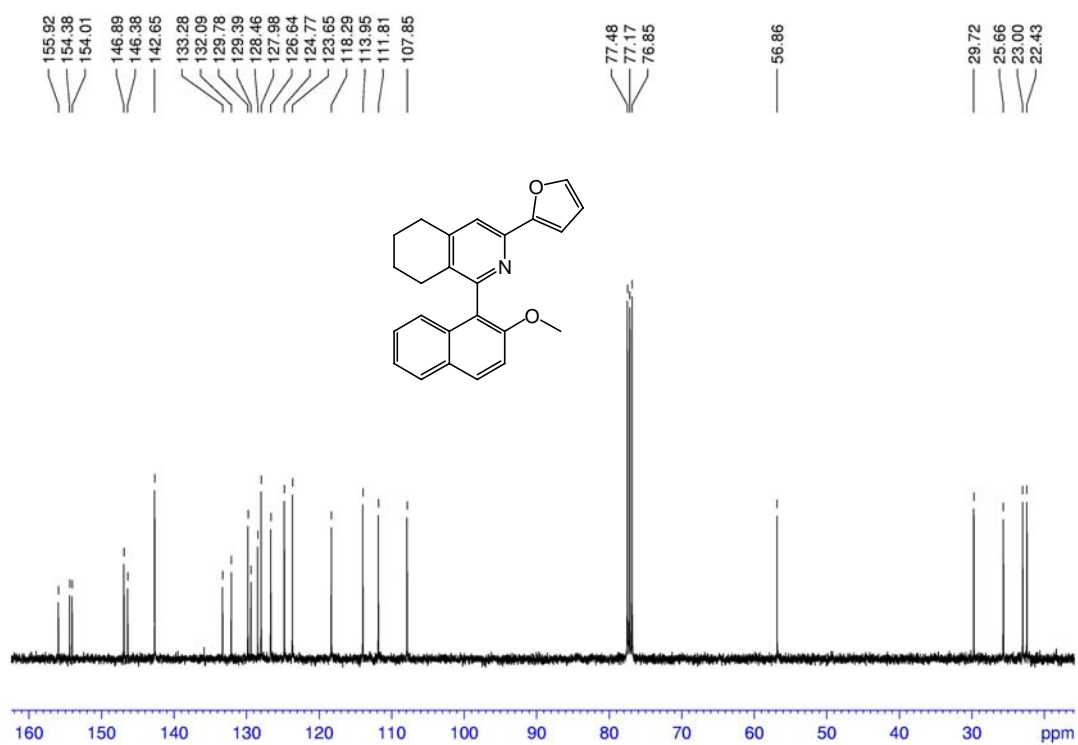
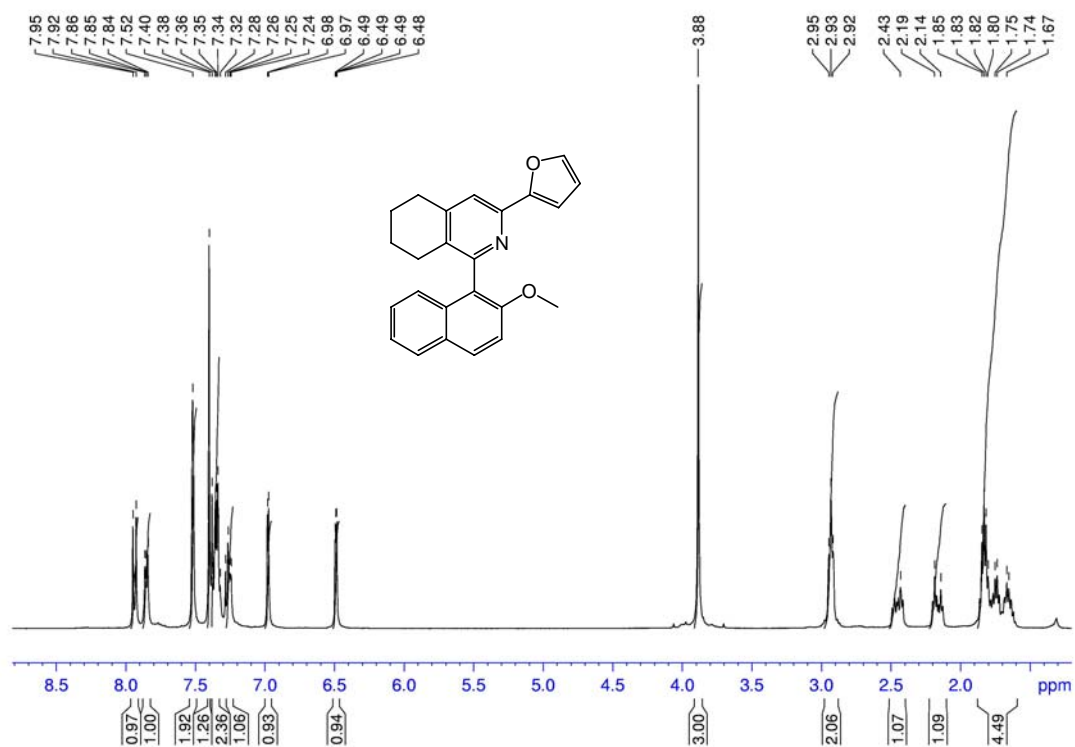
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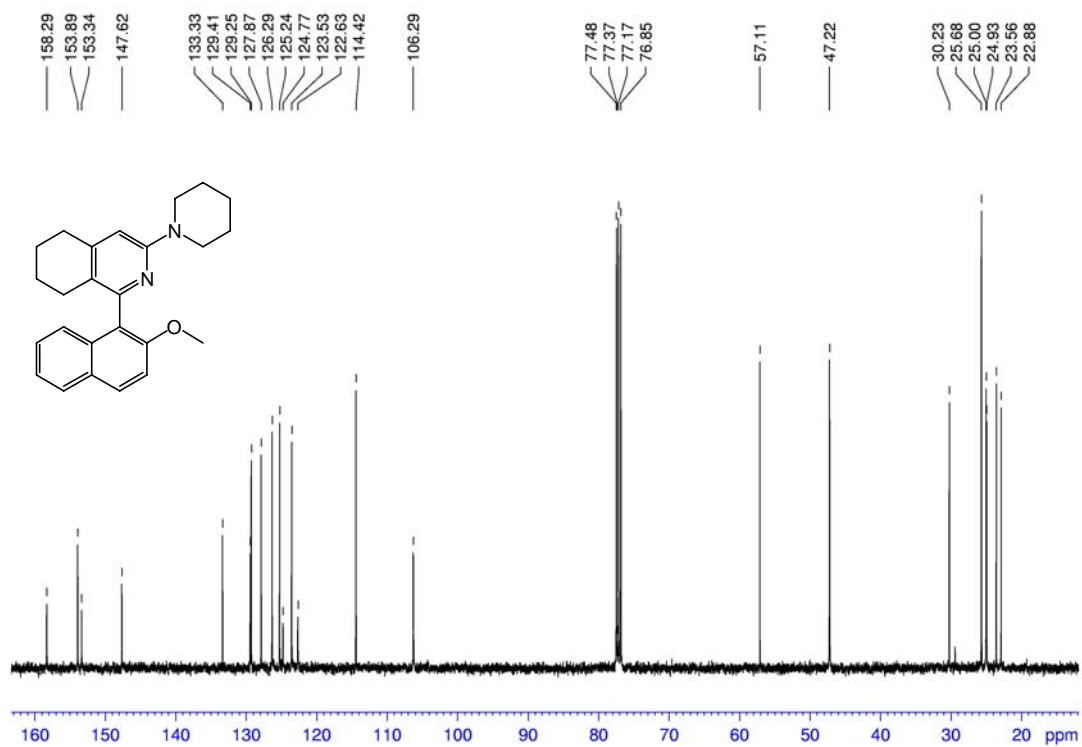
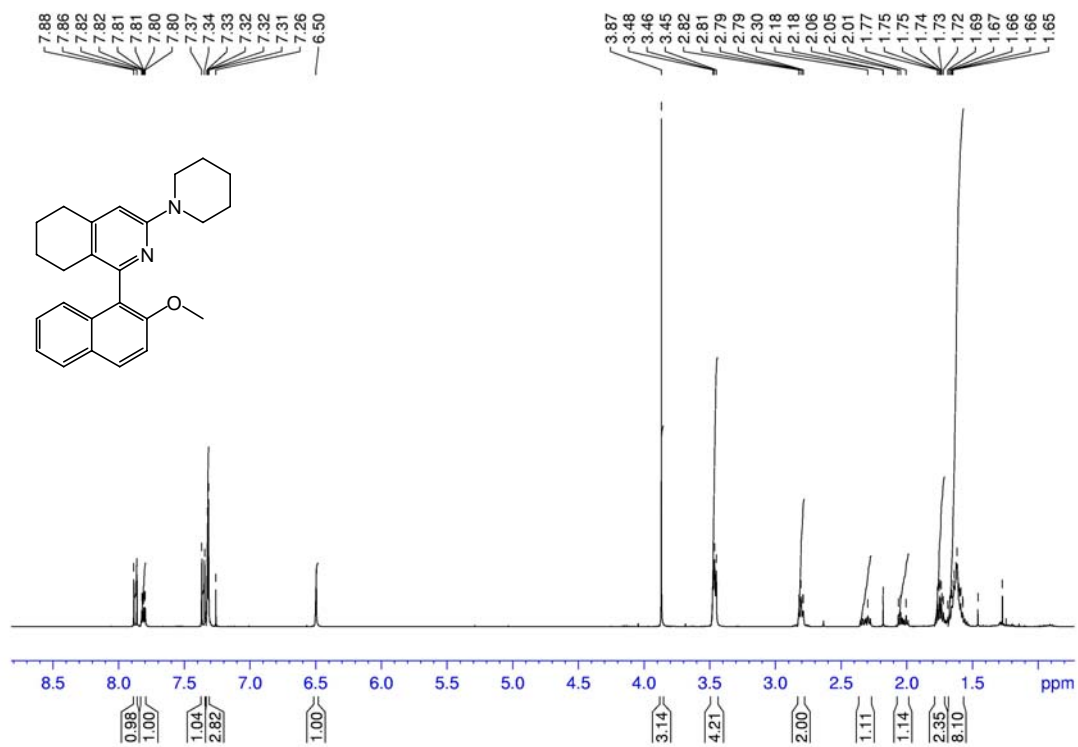
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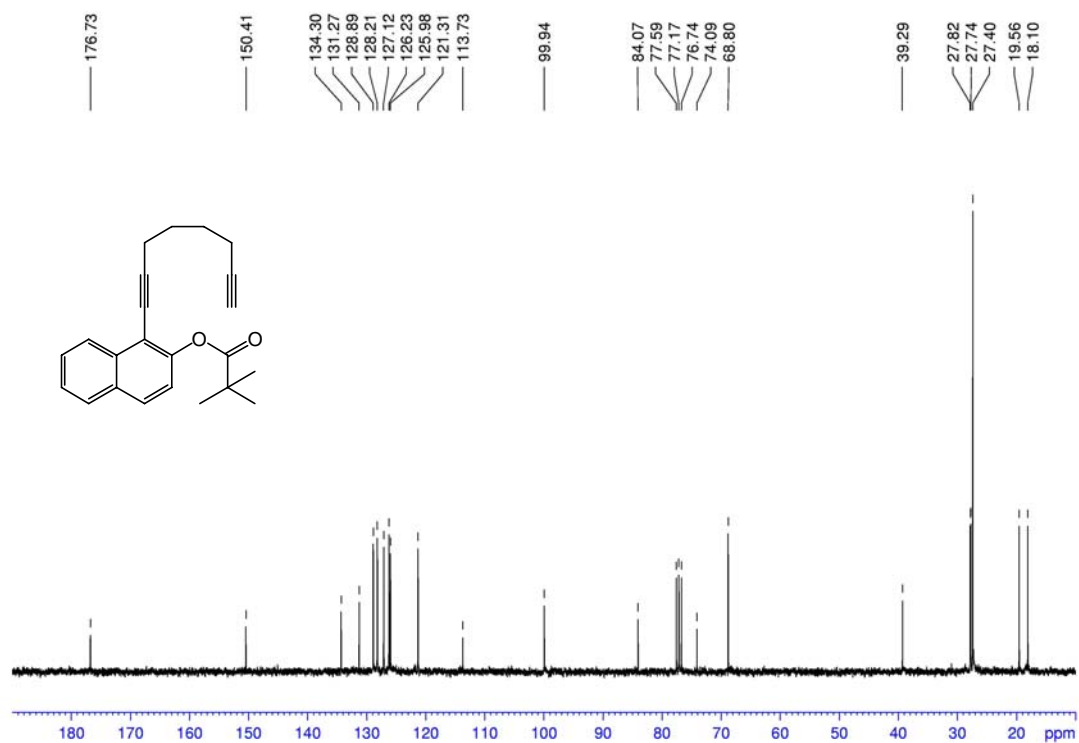
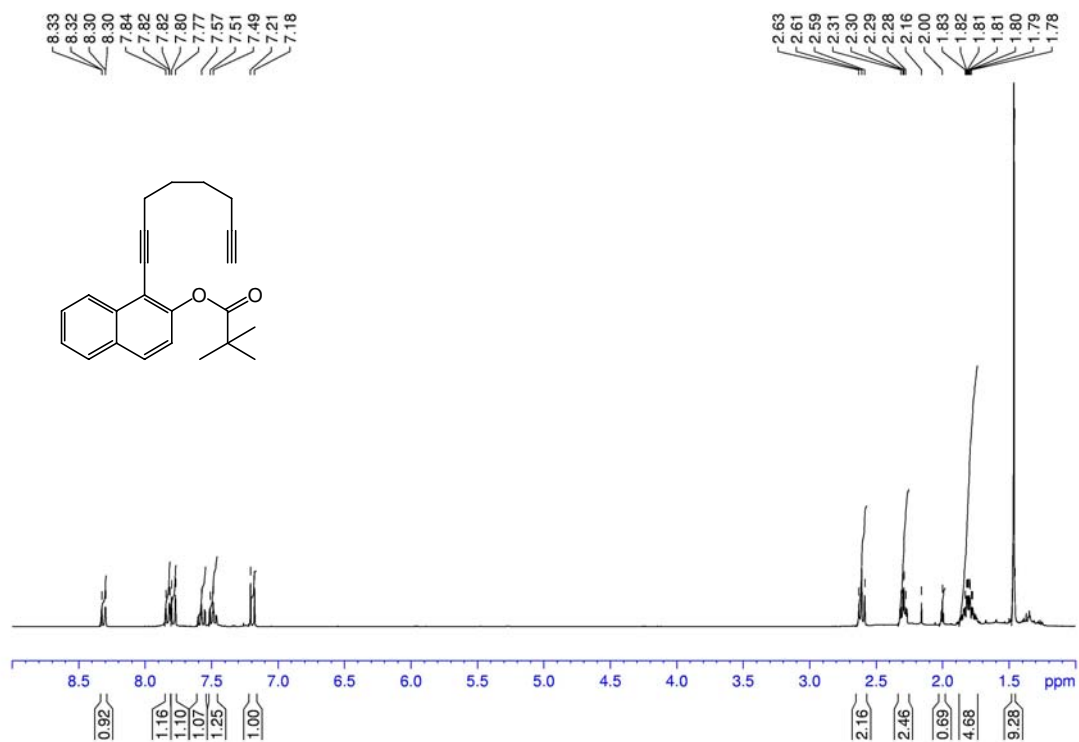
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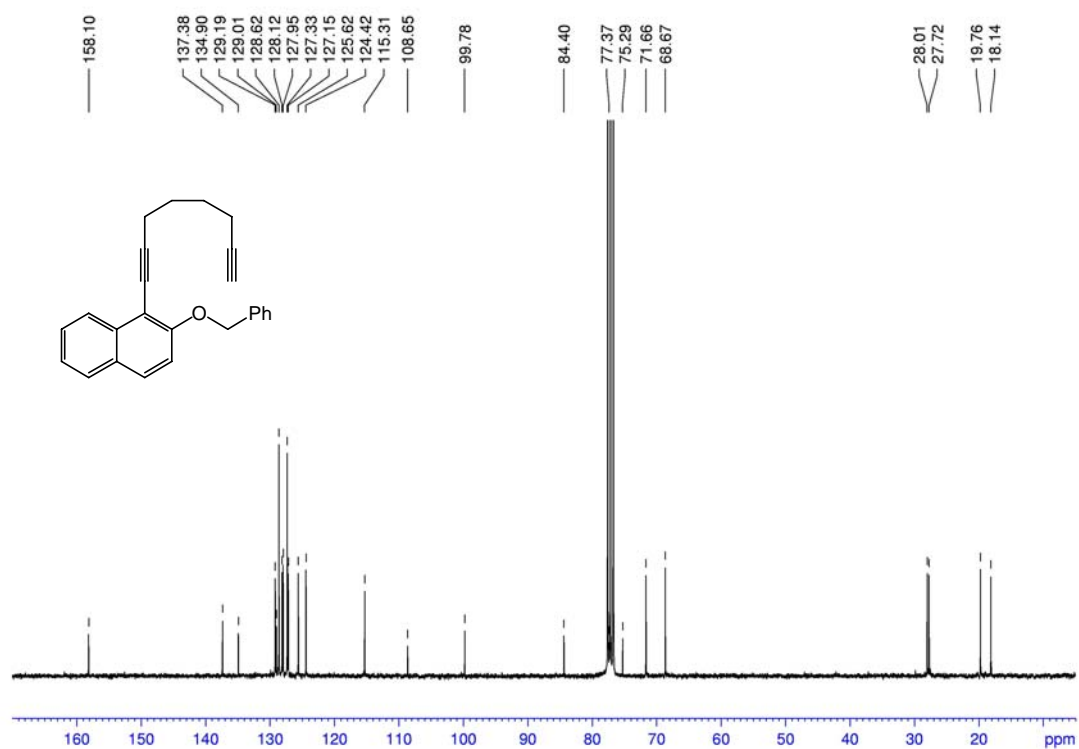
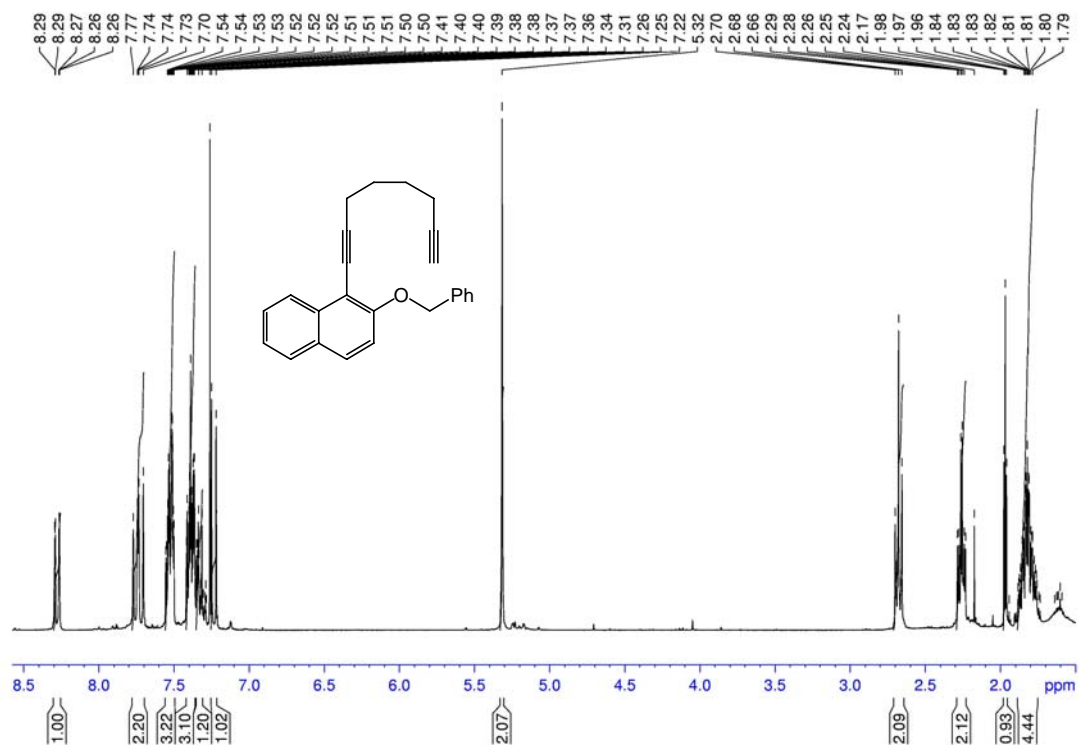
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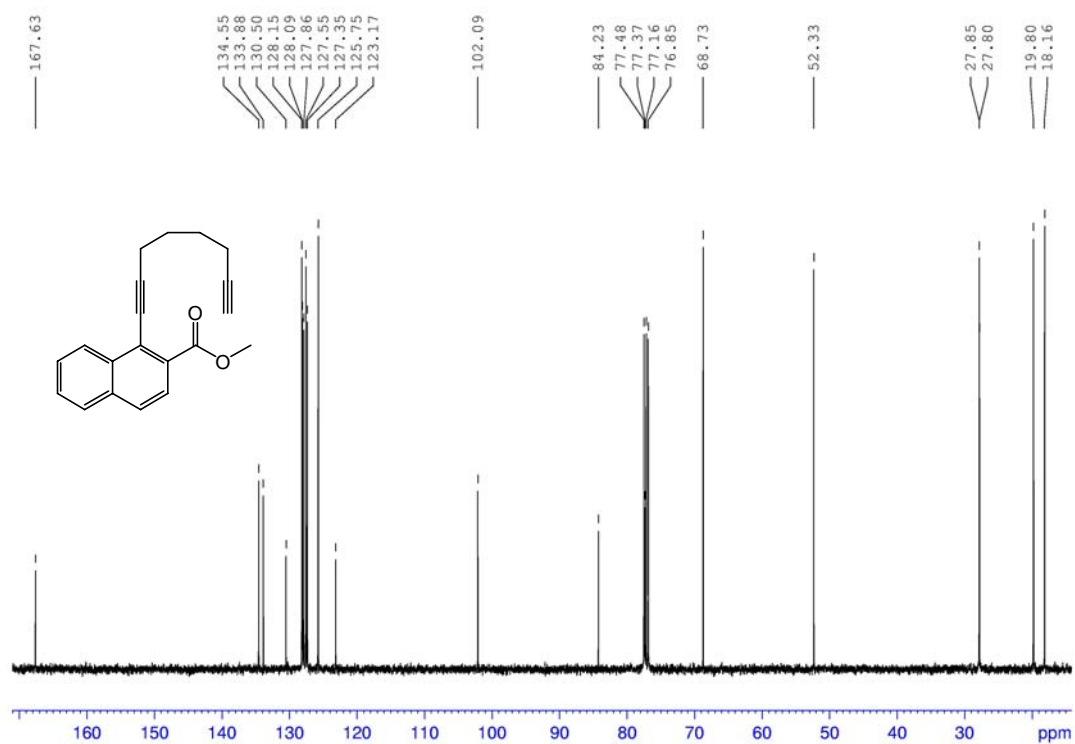
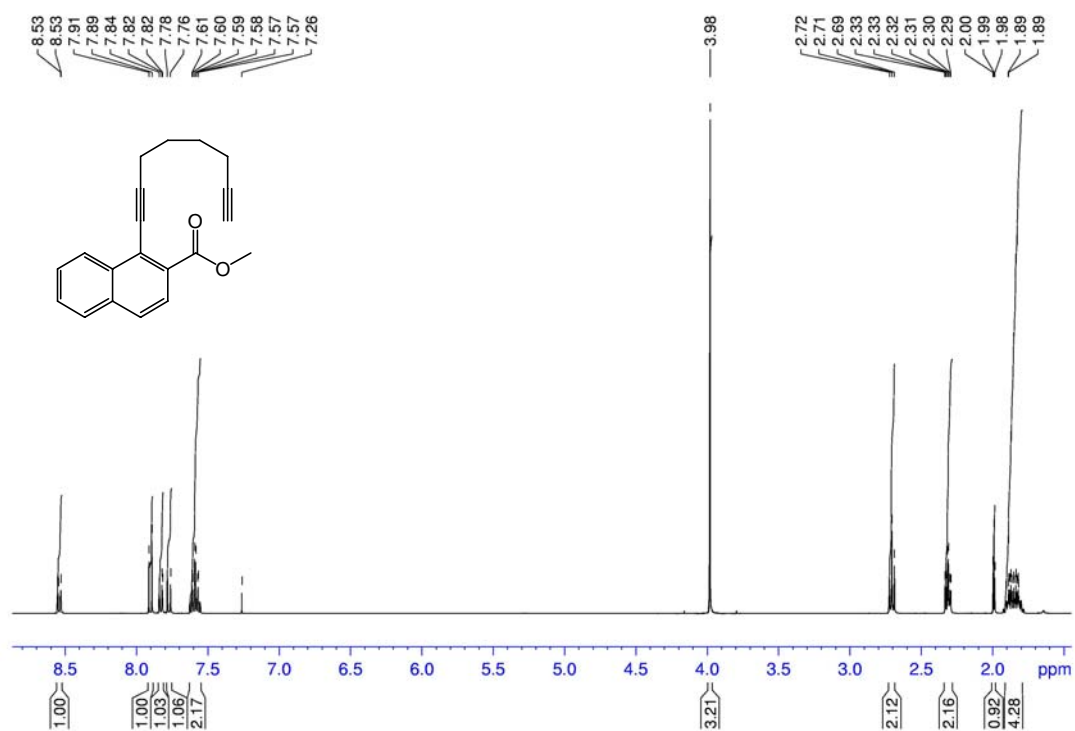
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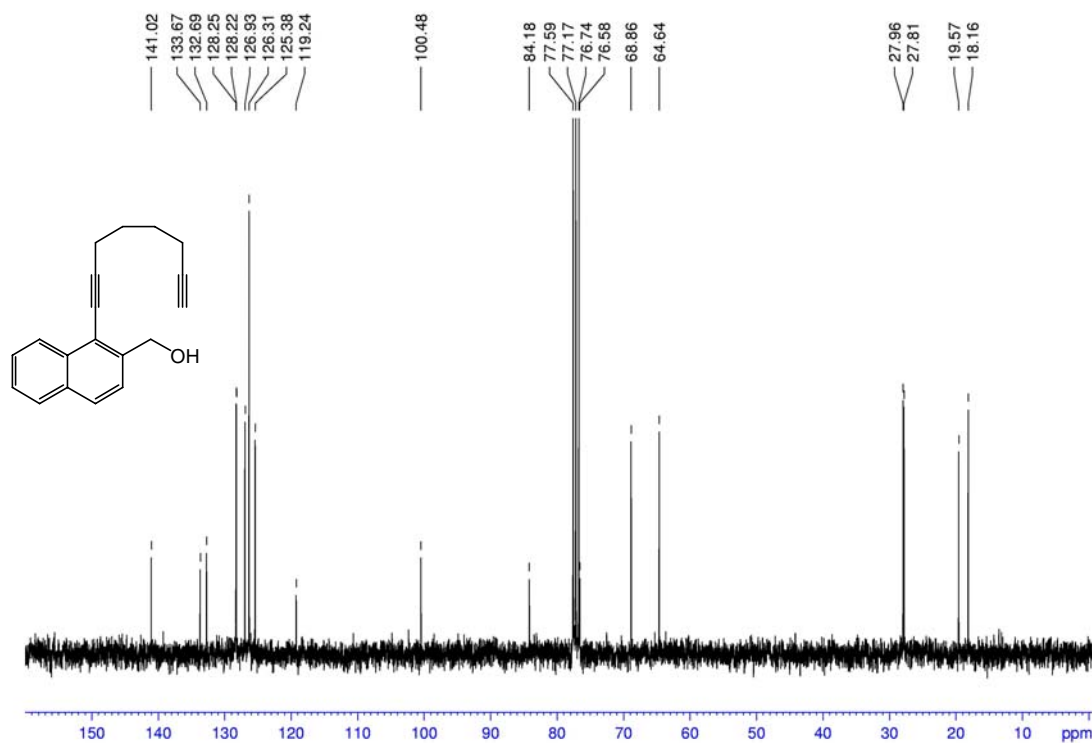
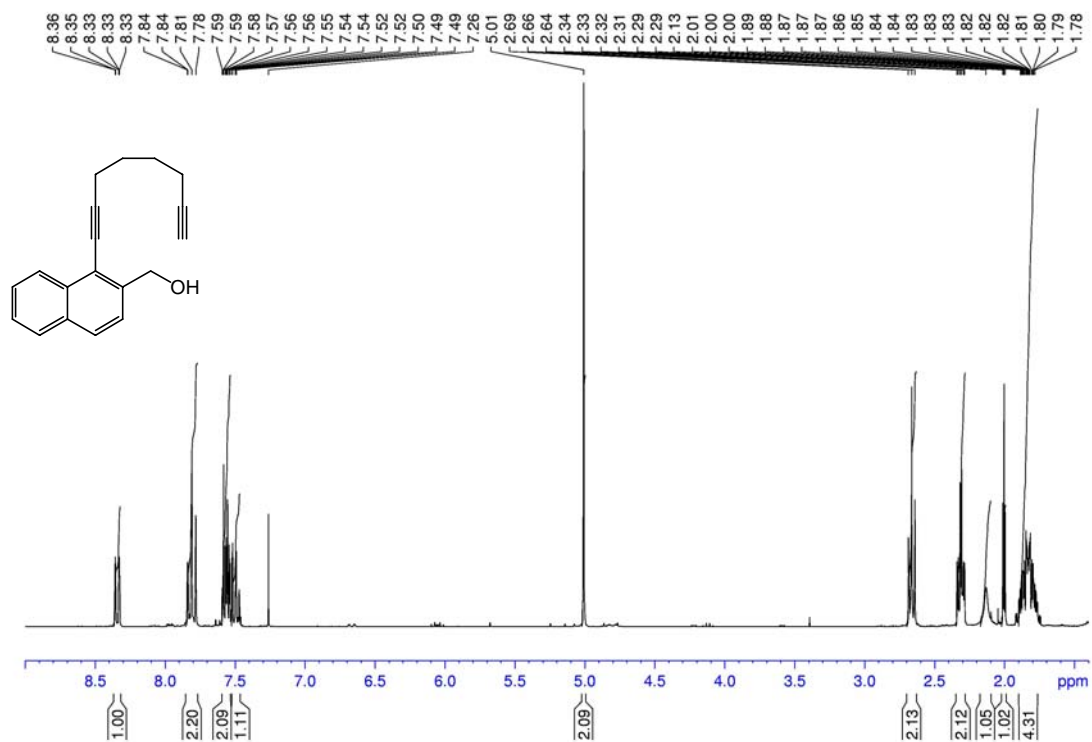
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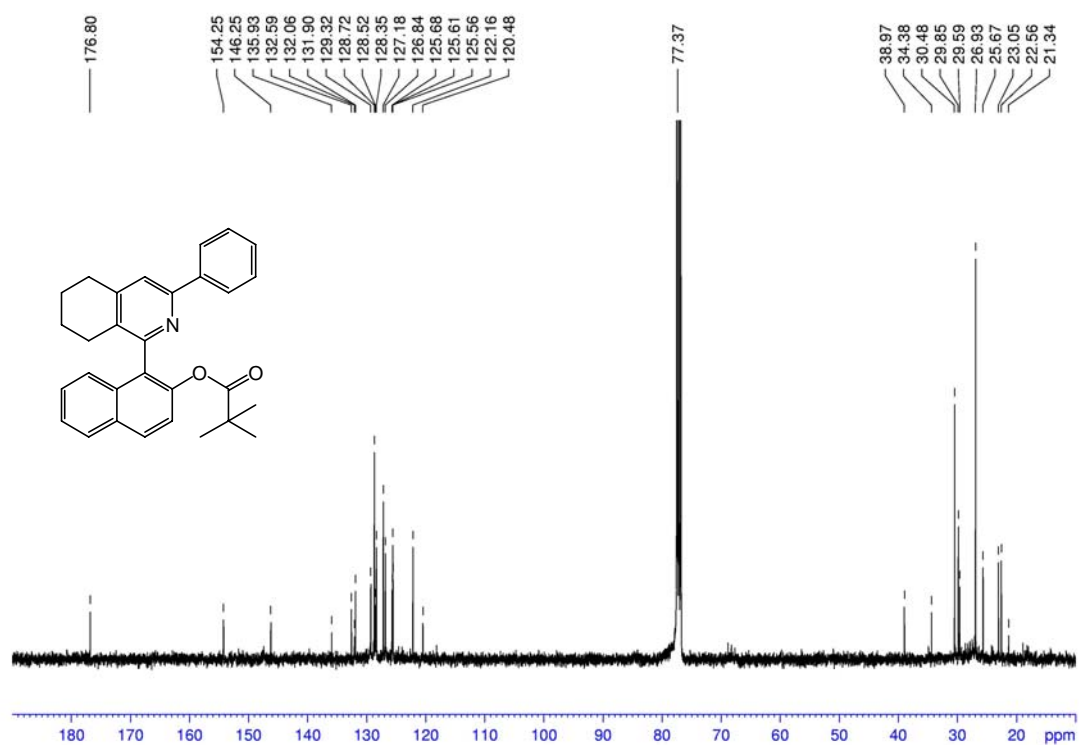
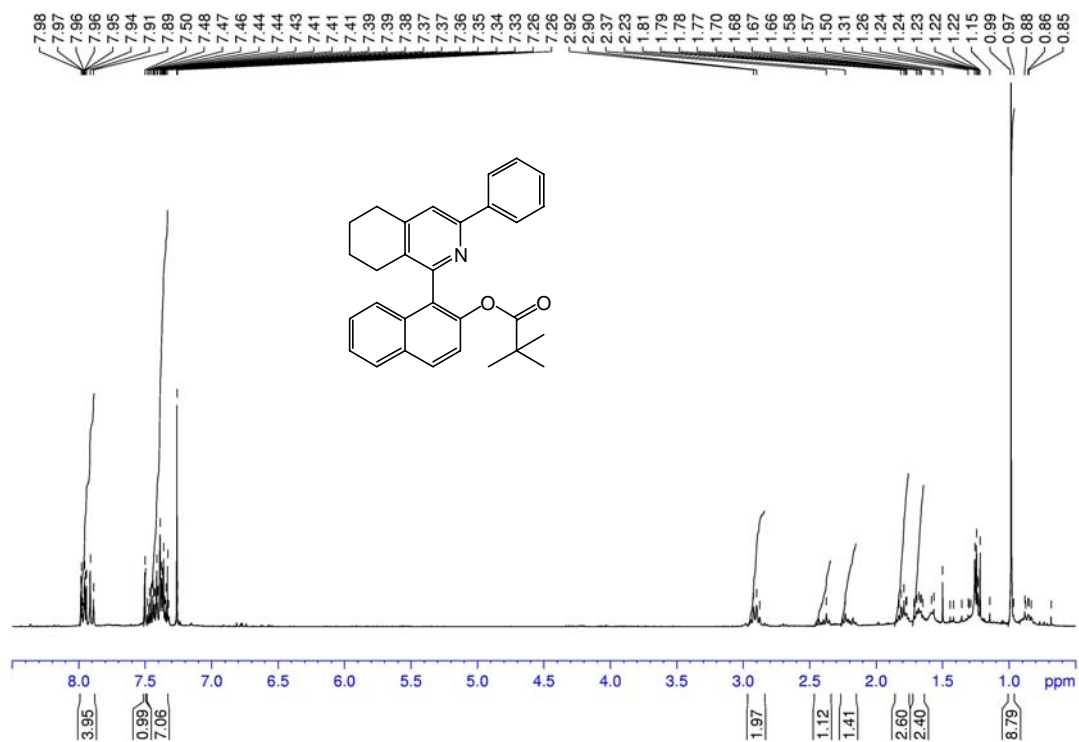
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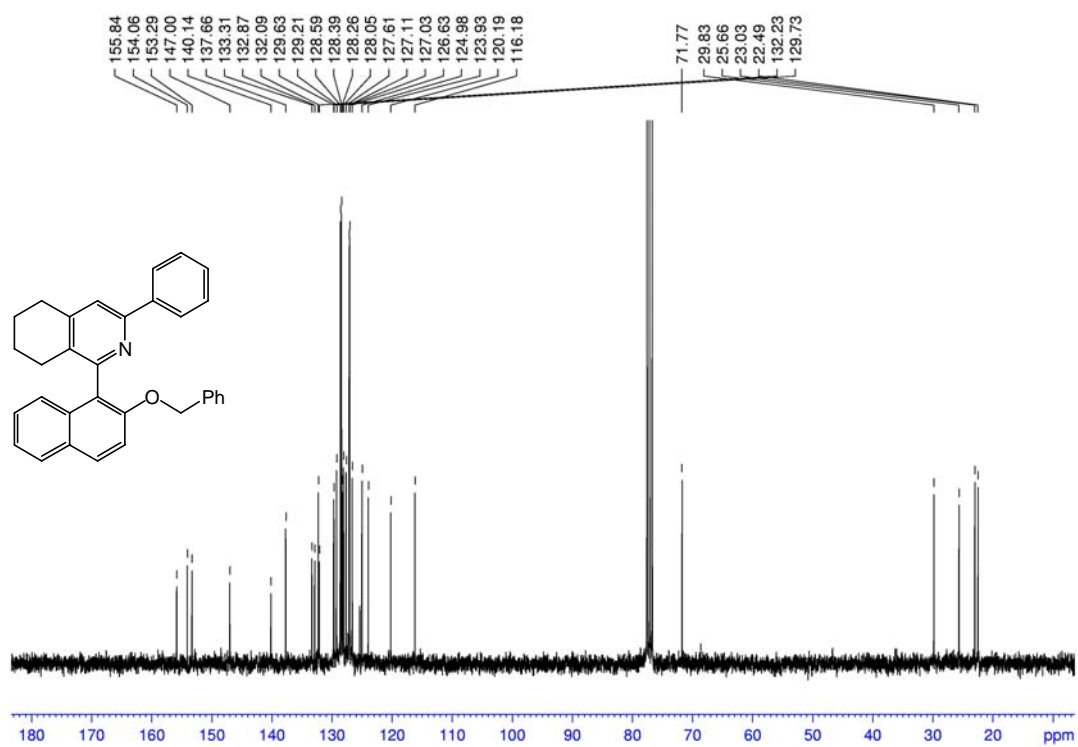
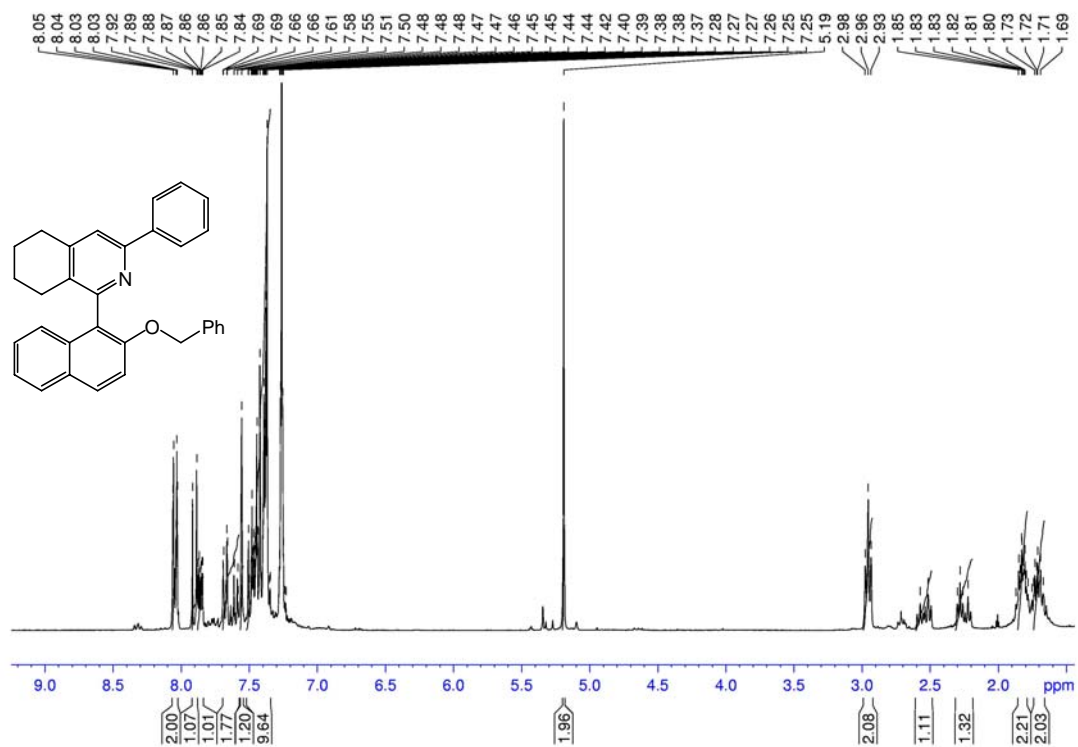
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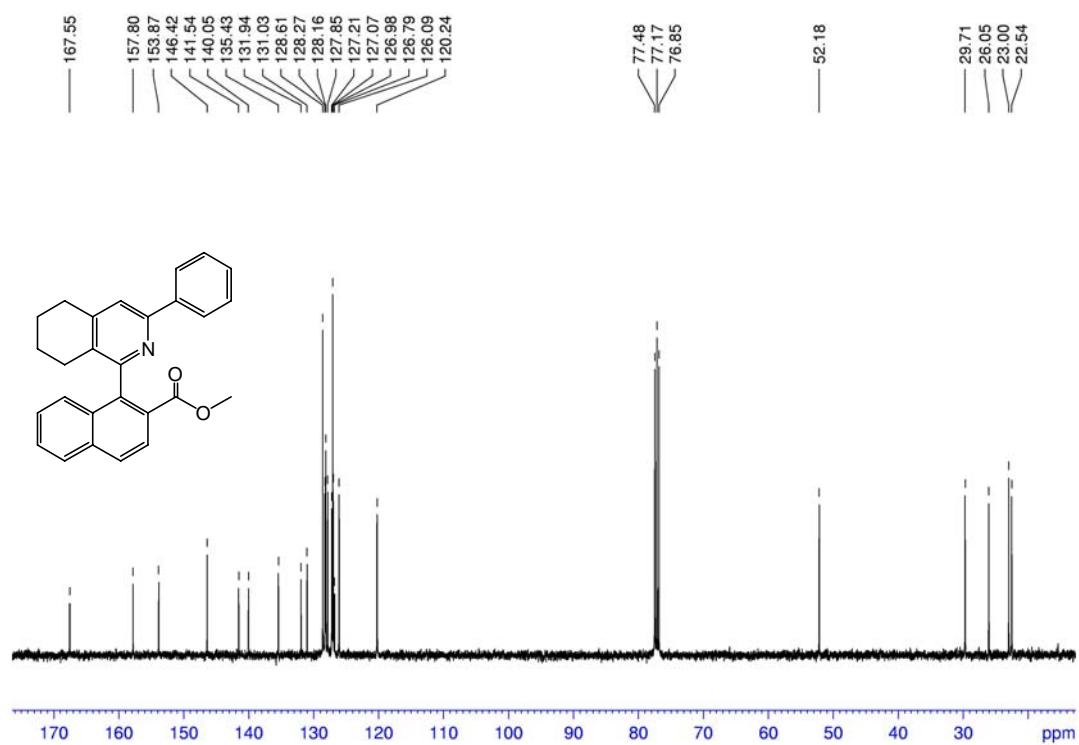
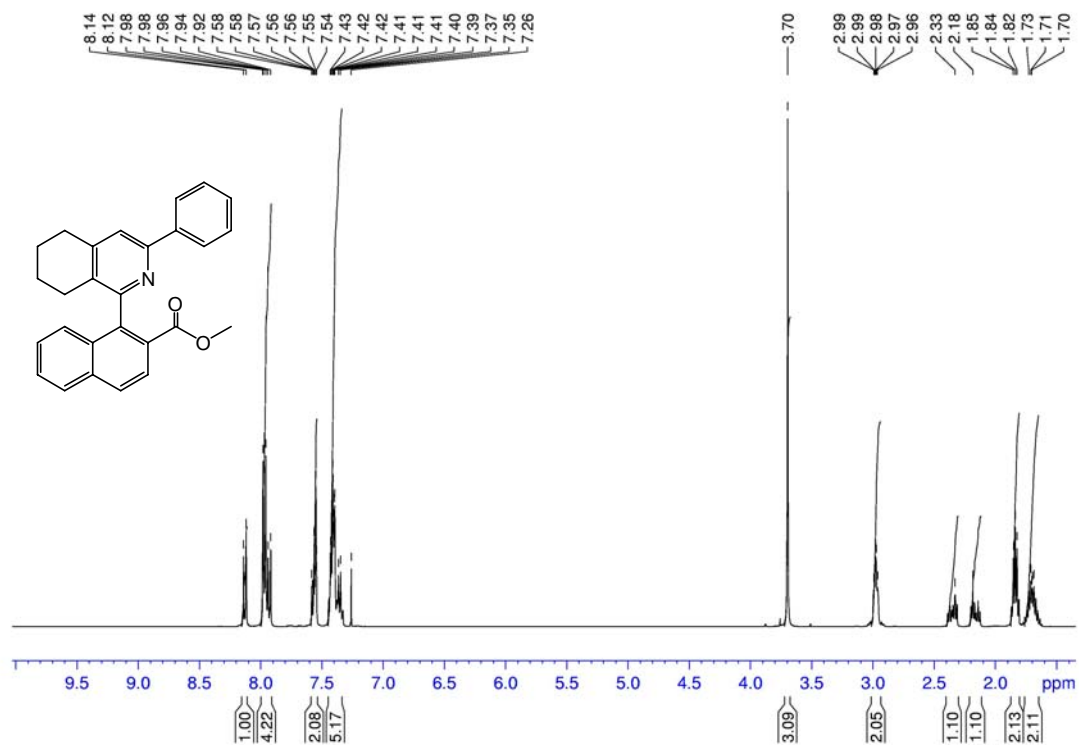
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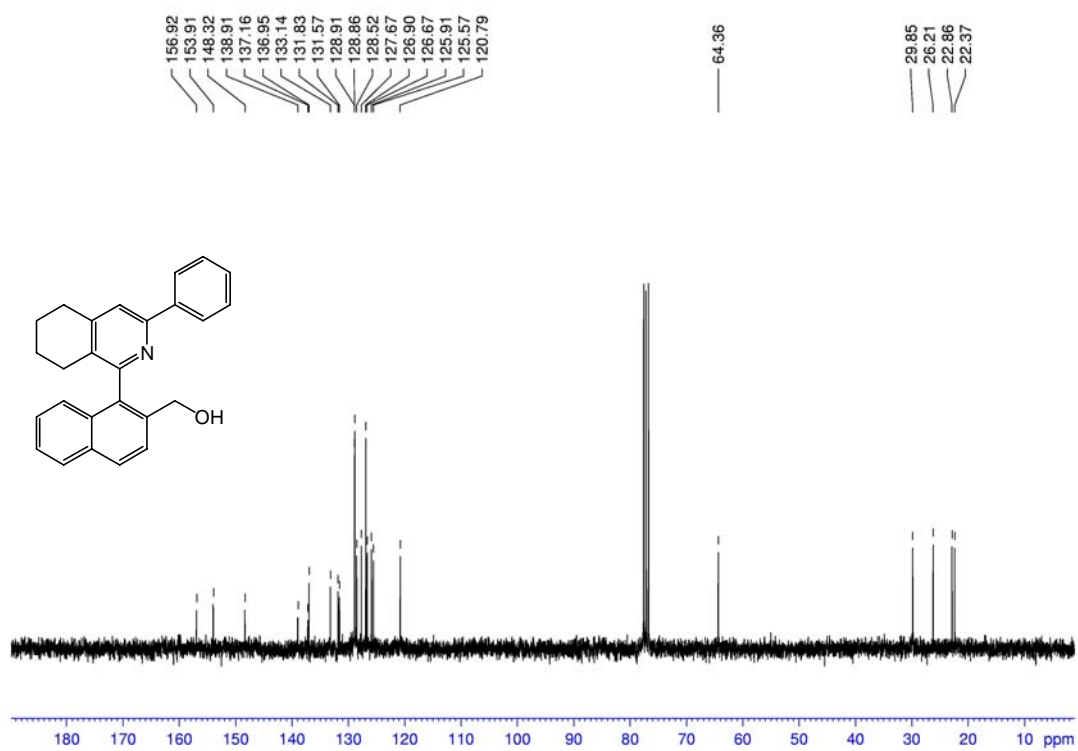
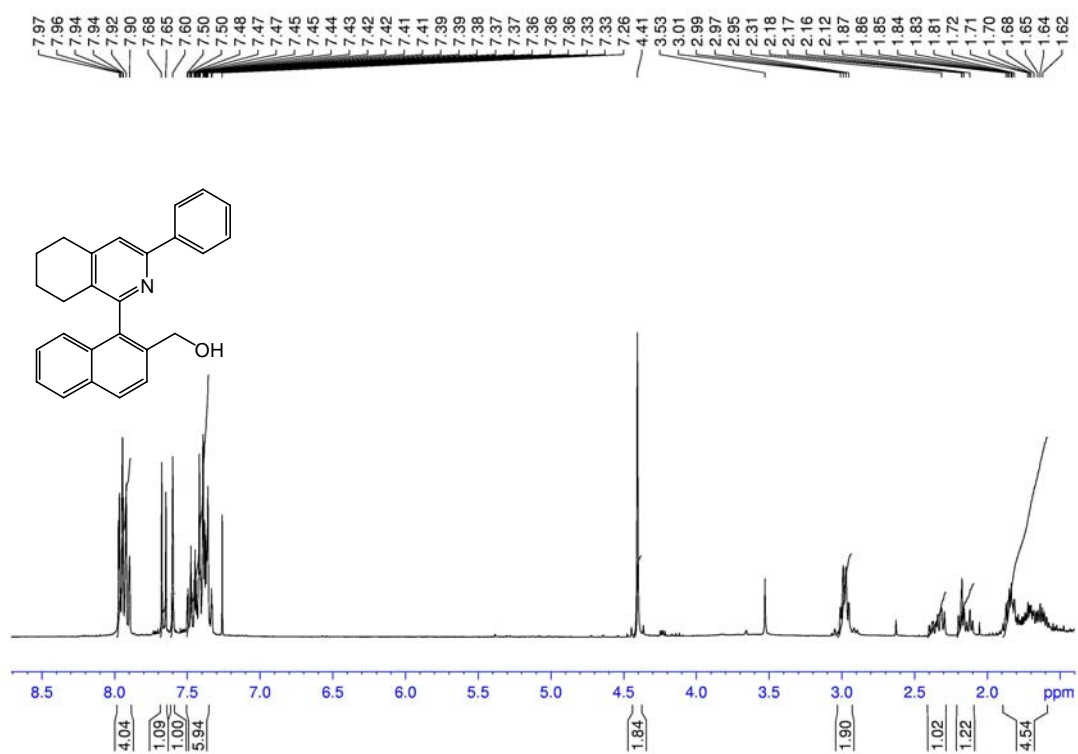
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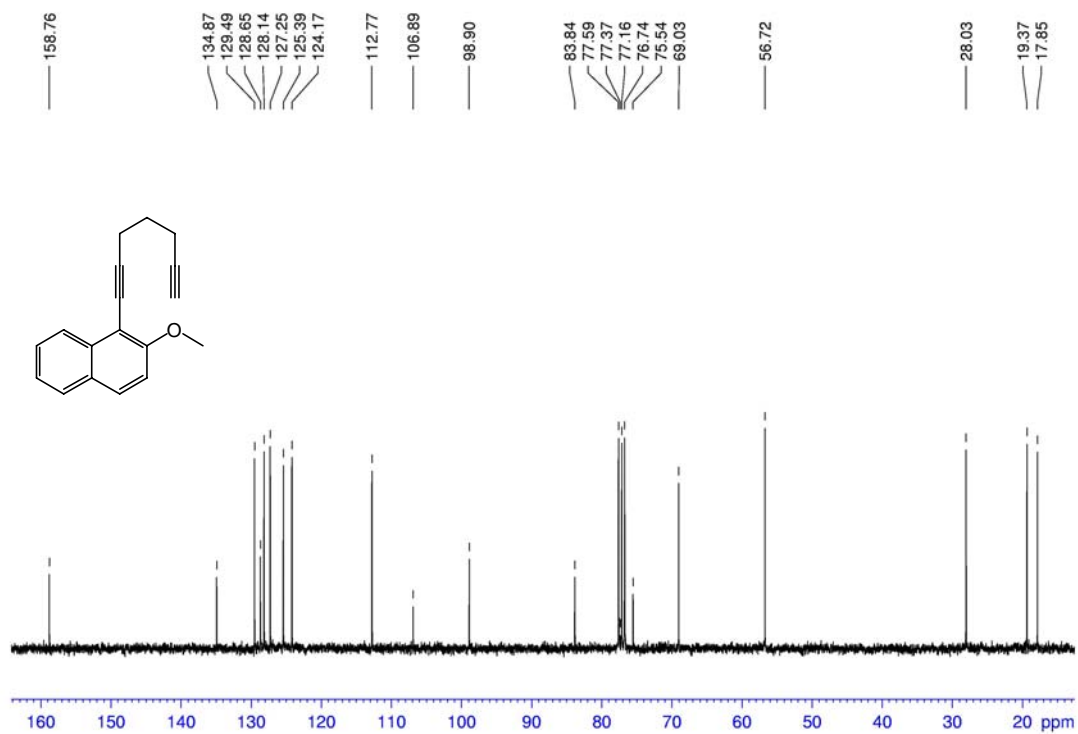
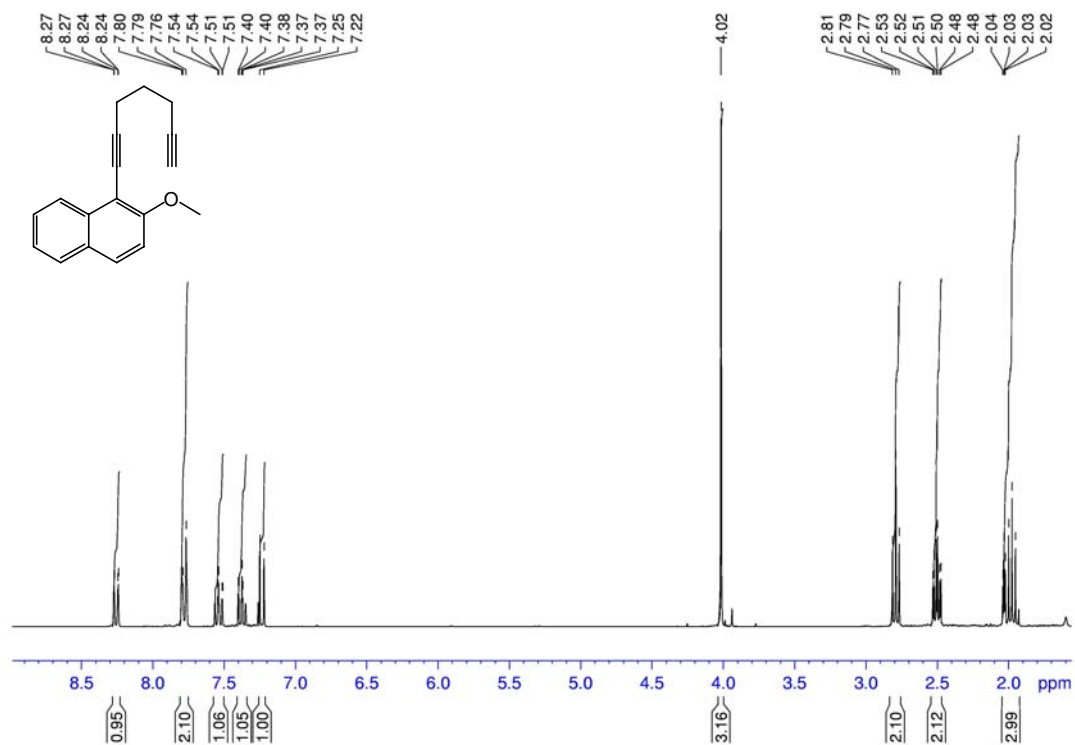
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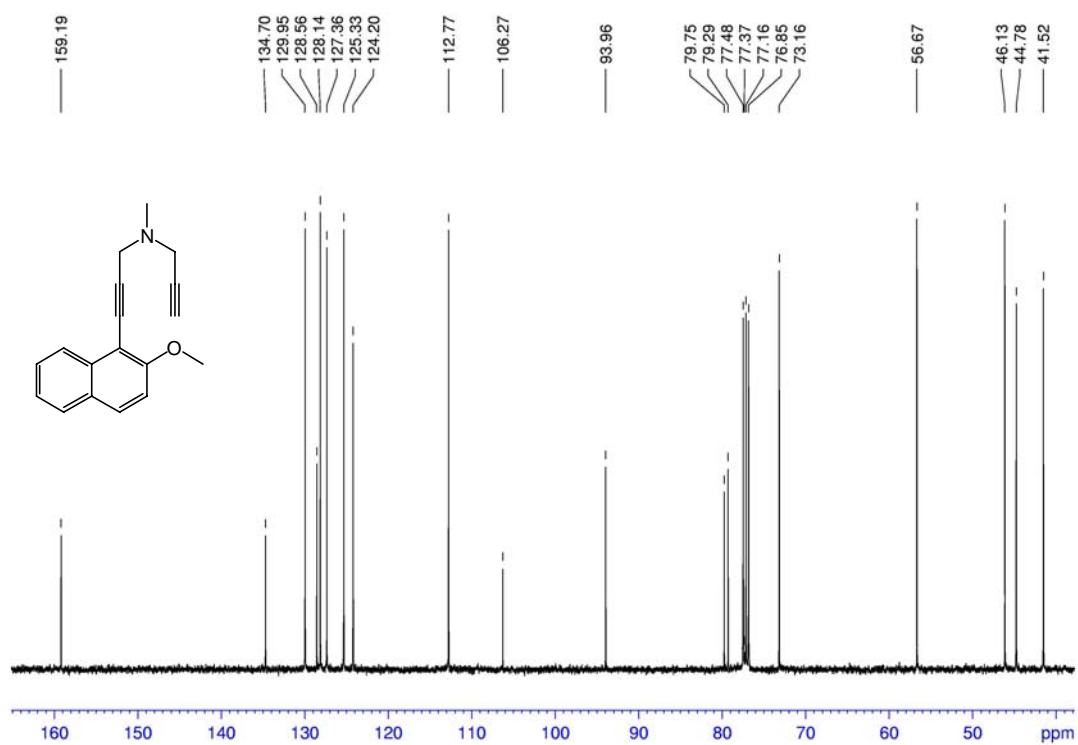
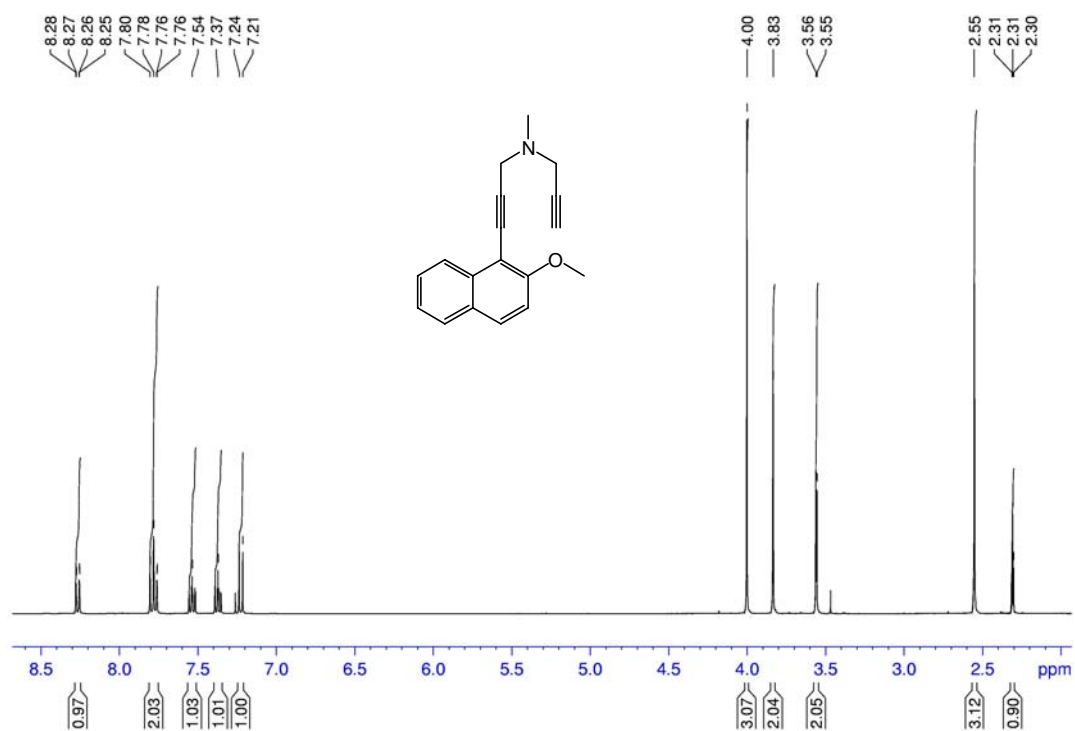
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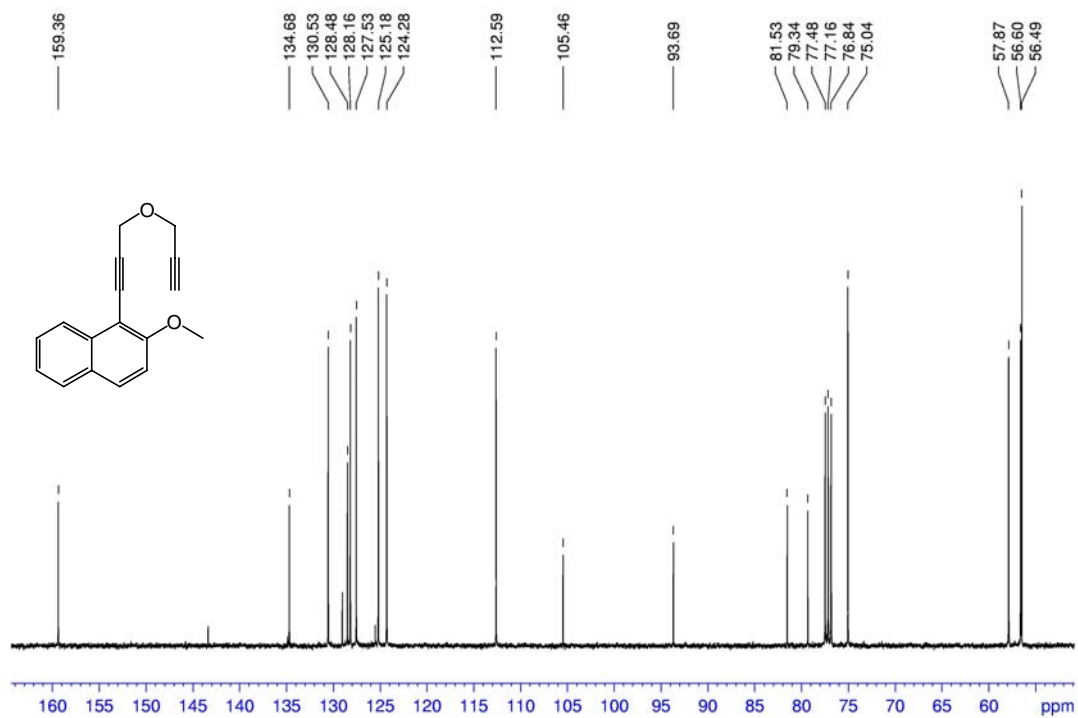
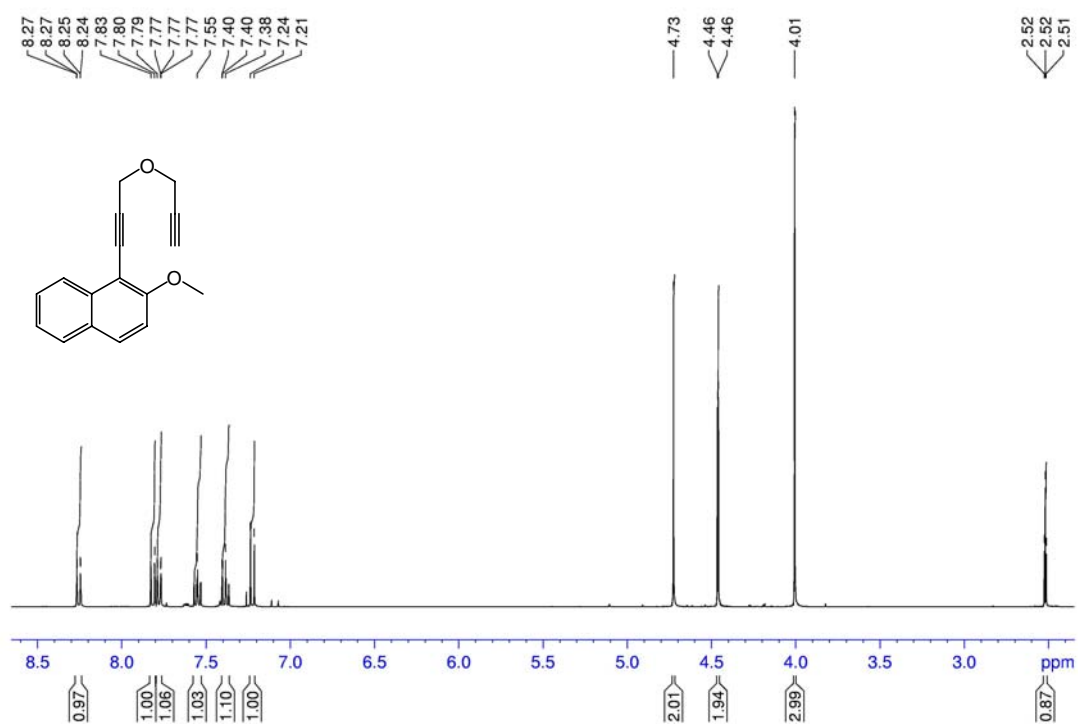
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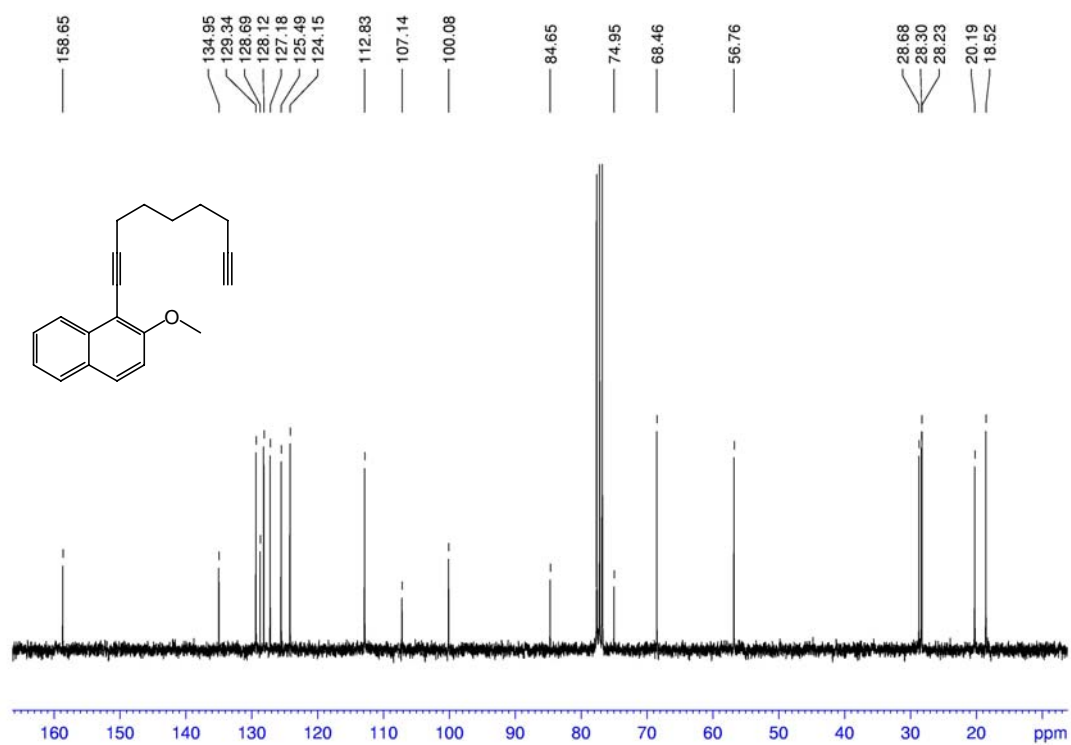
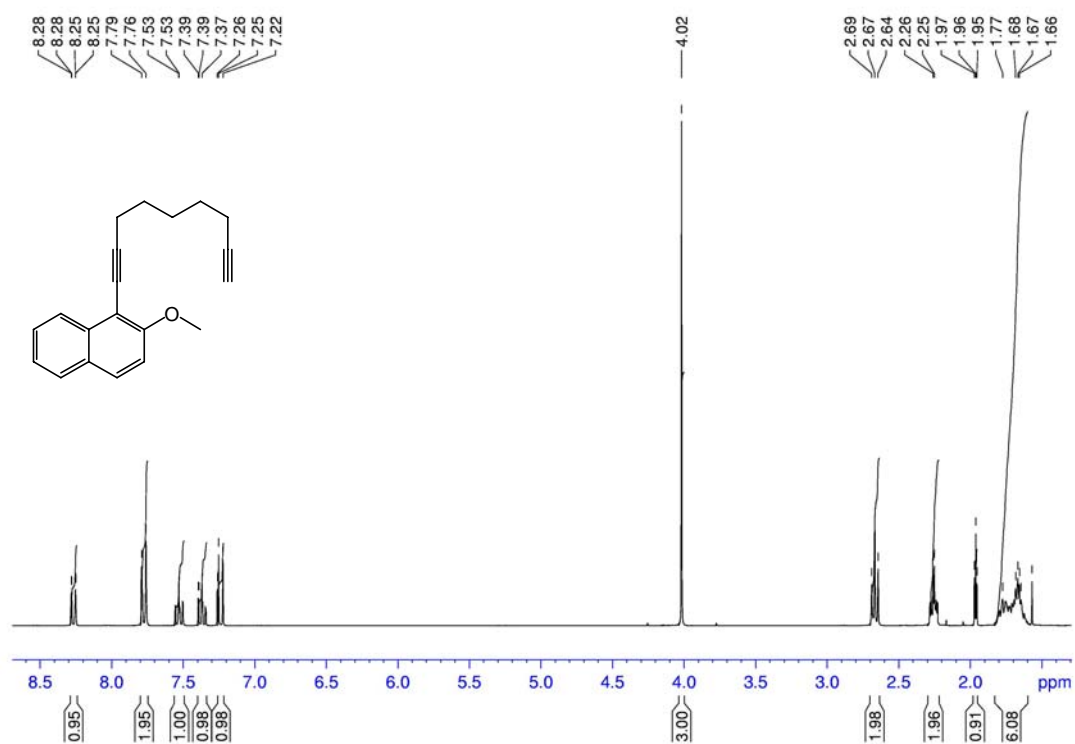
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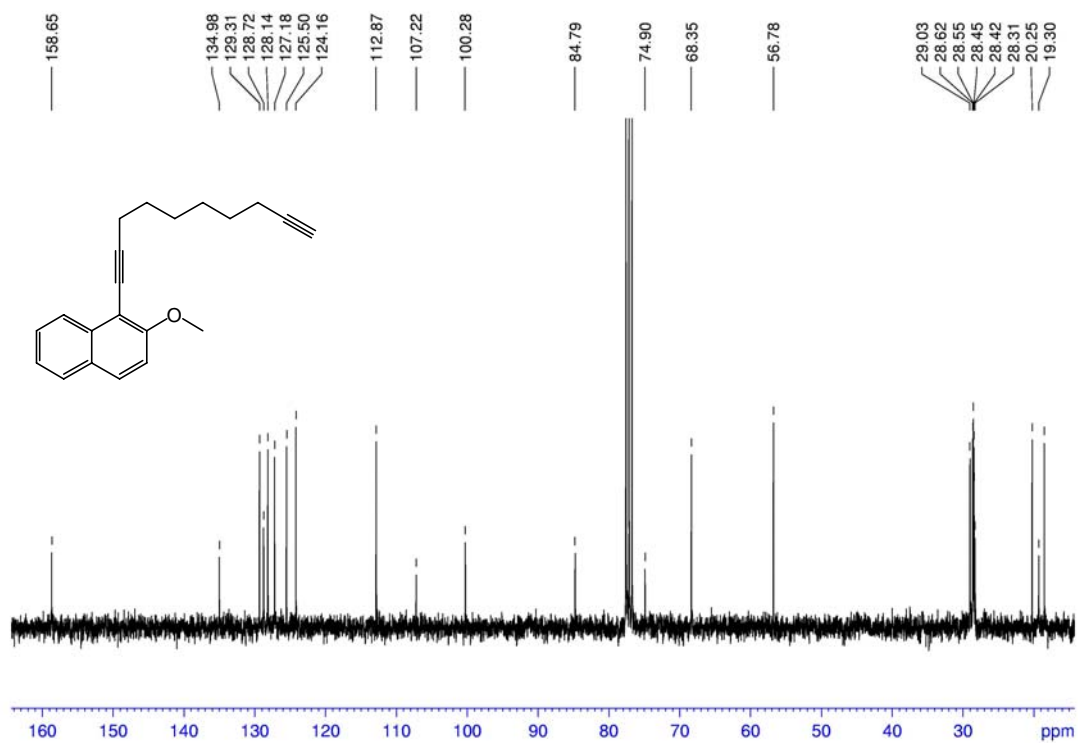
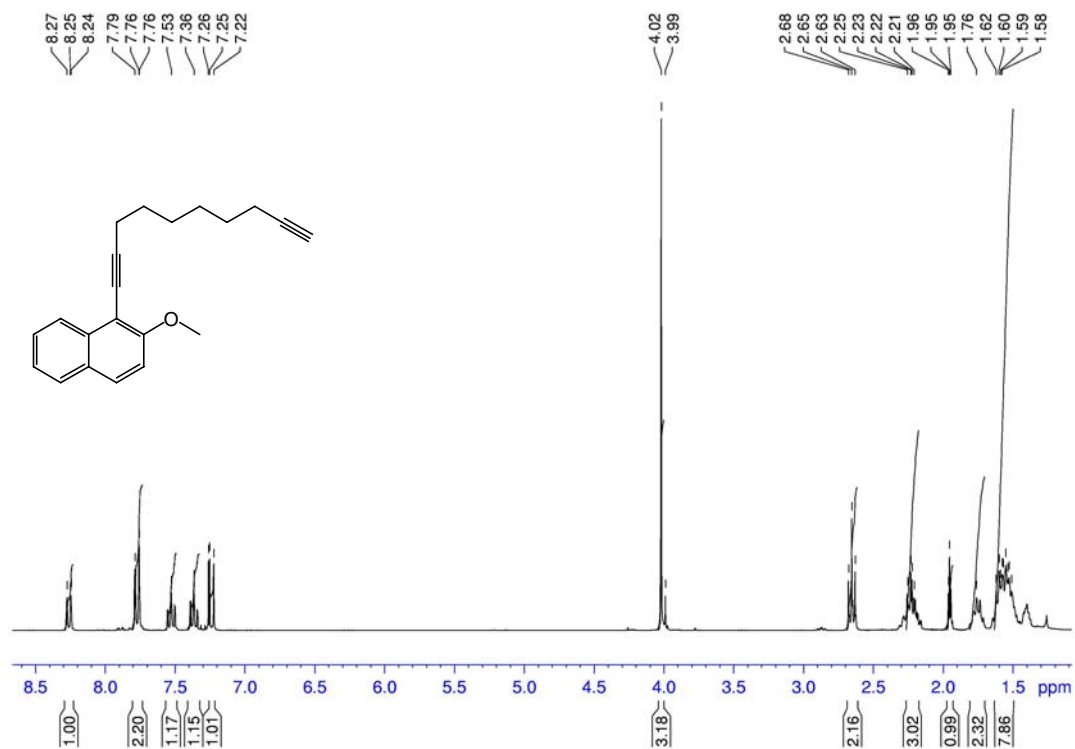
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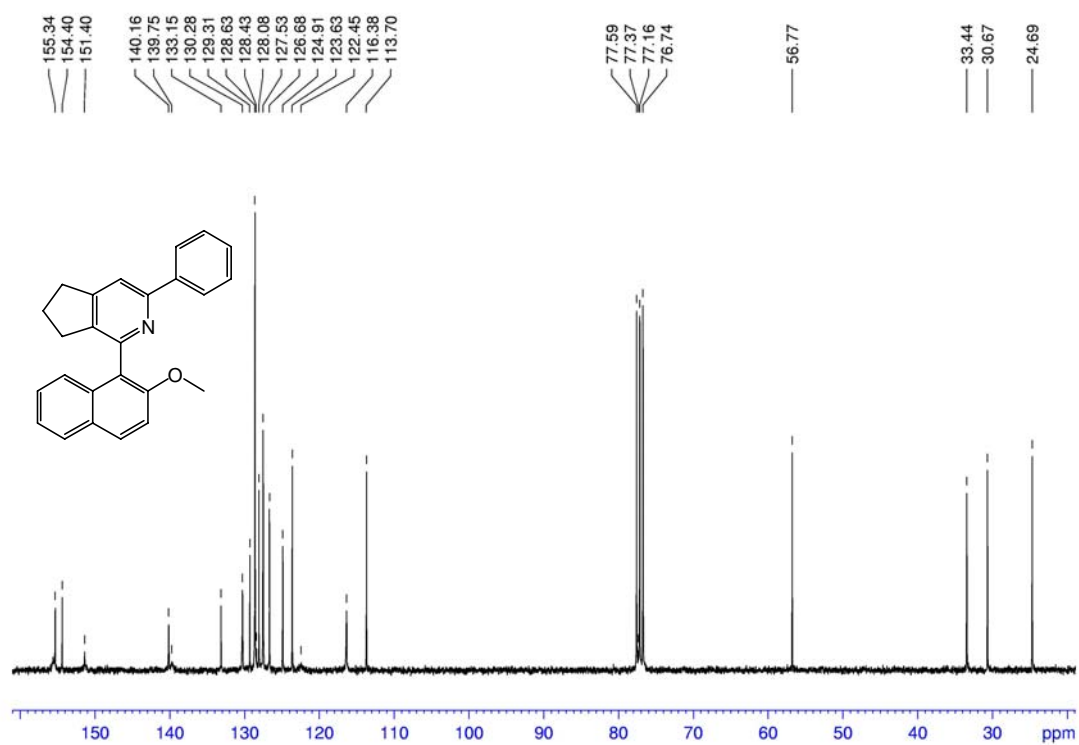
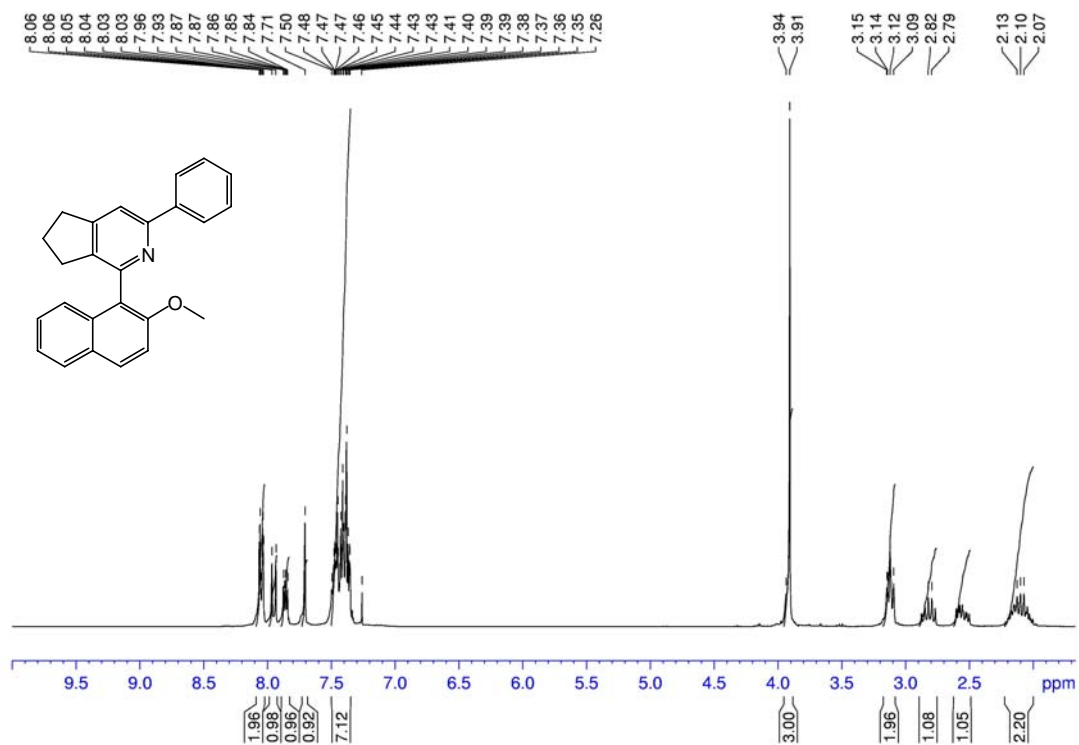
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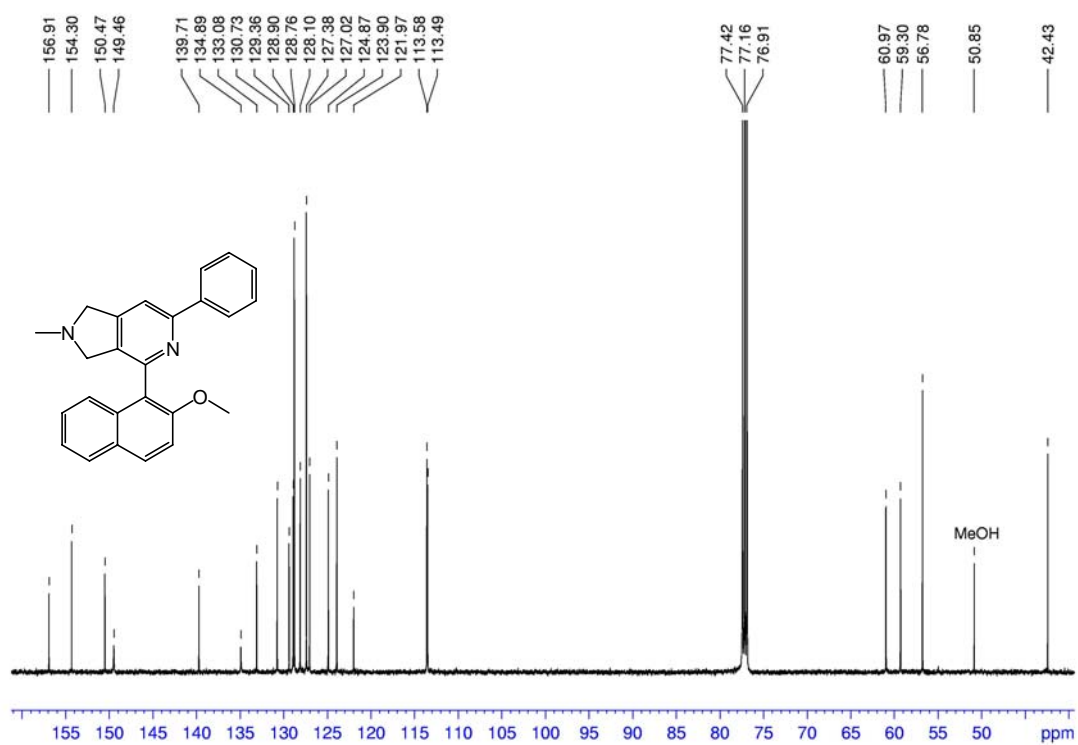
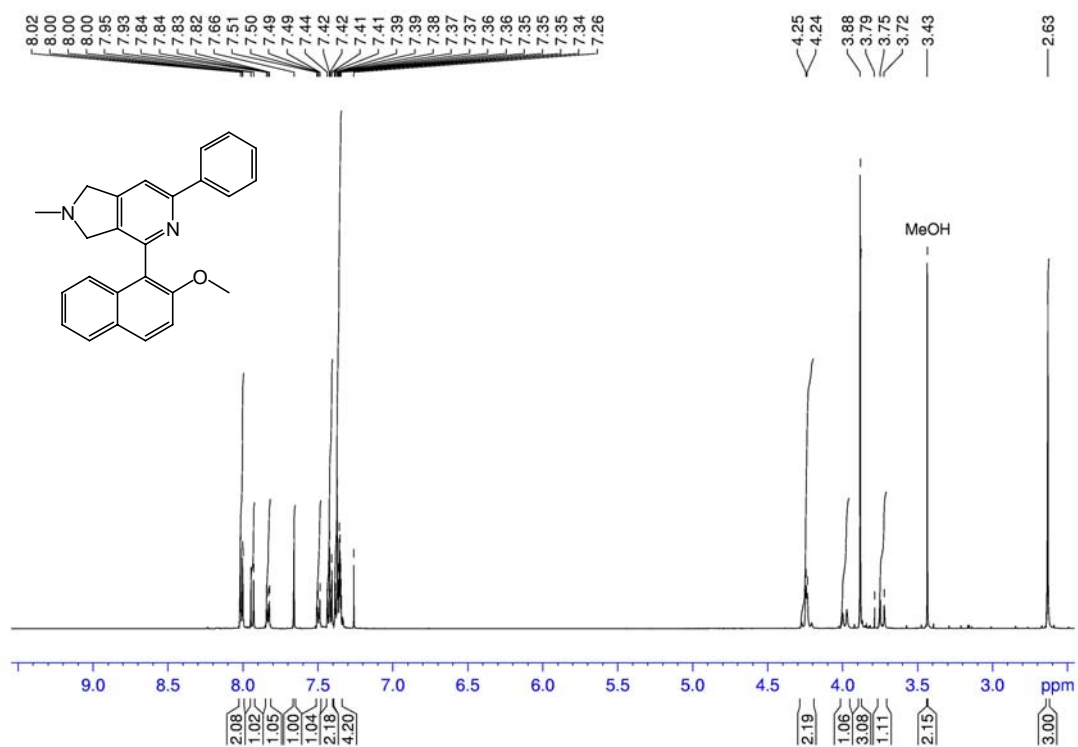
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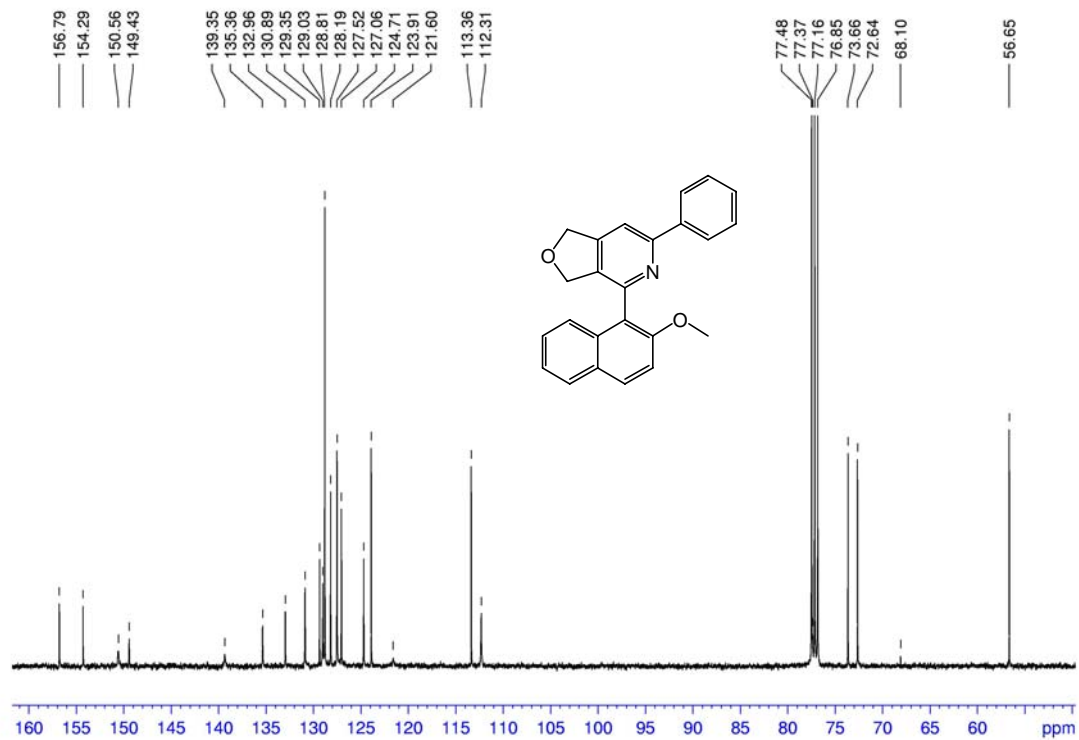
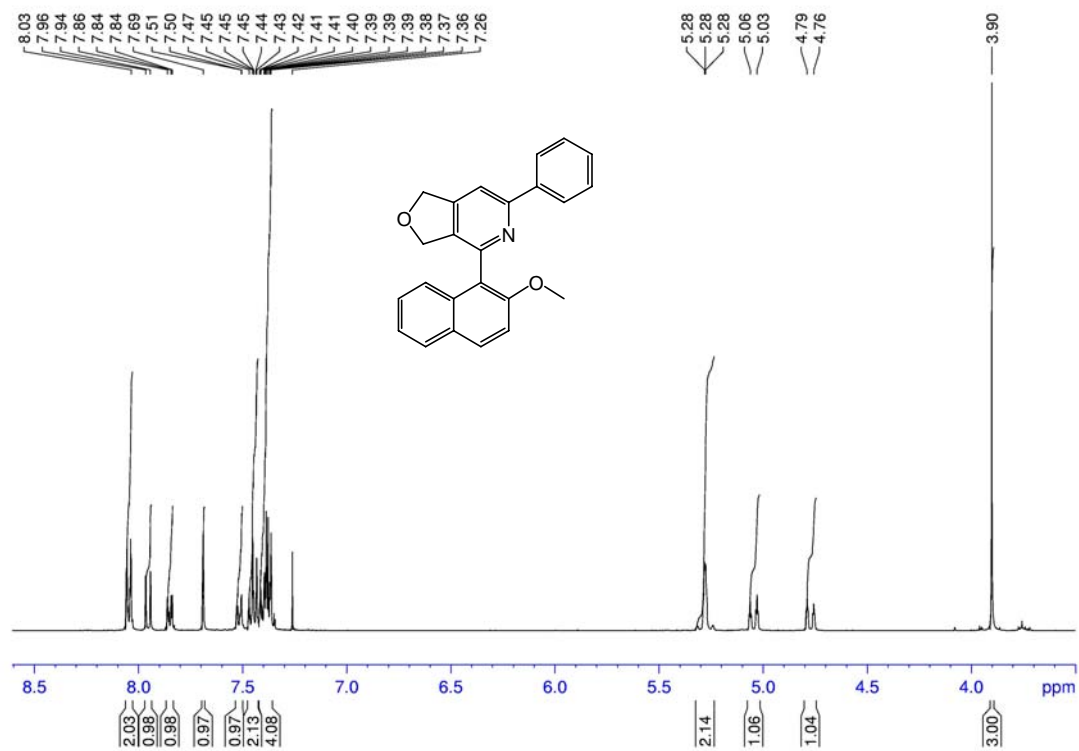
Compound **44**:



Compound **45**:

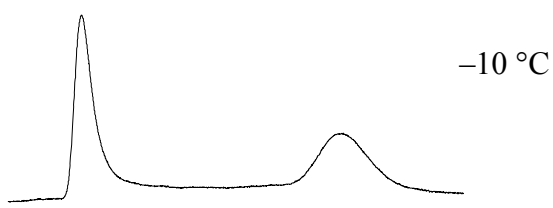
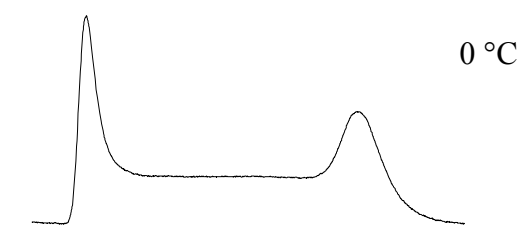
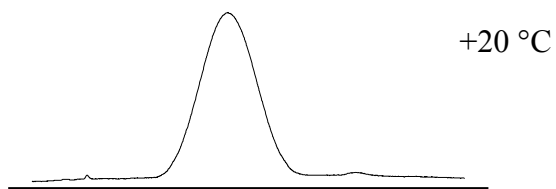


Compound **46**:

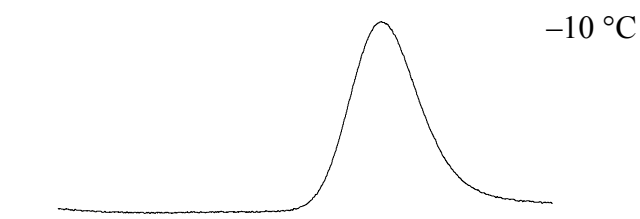


5. Dynamic HPLC Spectra

Dynamic HPLC for Compound **45** (HPLC conditions: Chiralpak AD-H, *n*-hexane/ethanol 99:1, 1.0 mL/min; $T_1 = 9.9$ min, $T_2 = 13.9$ min für -20 °C):



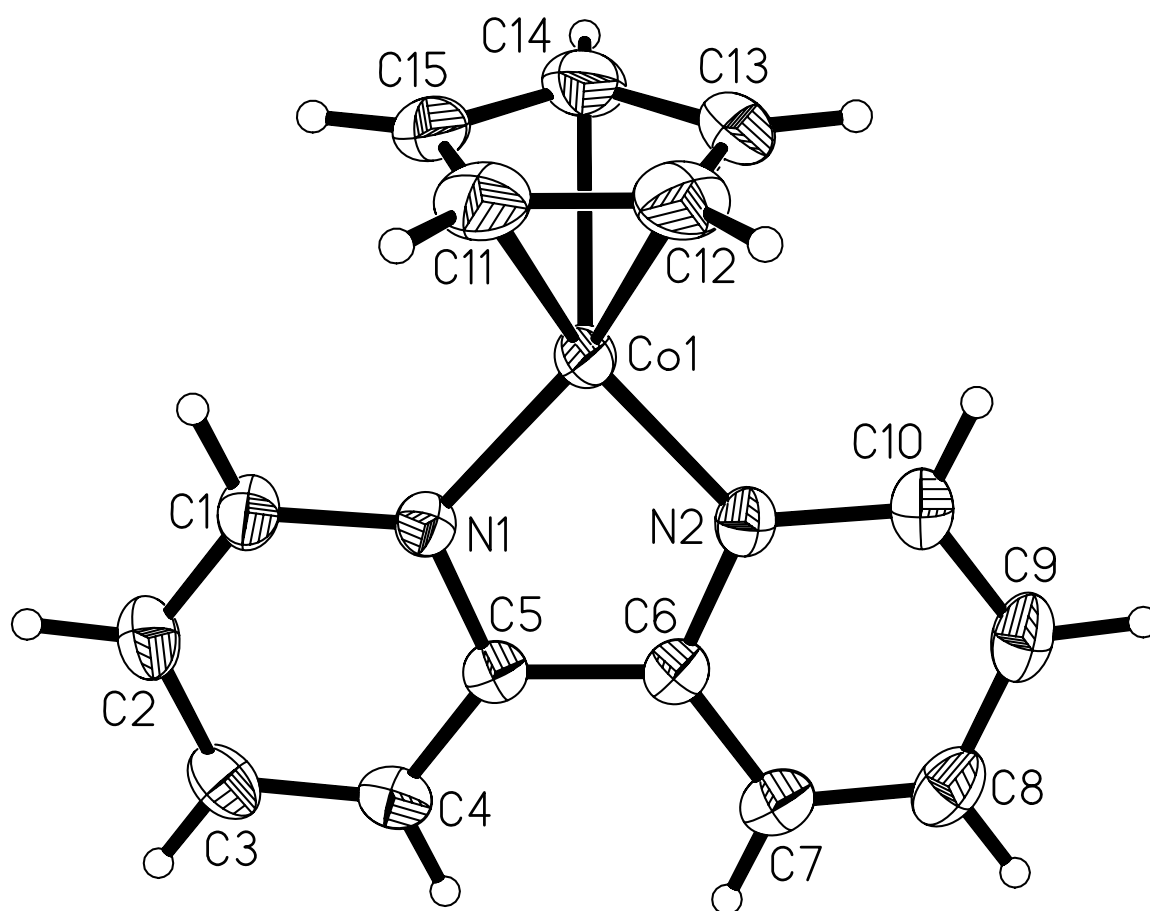
Dynamic HPLC for Compound **46** (HPLC conditions: see above):



6. X-ray Crystallographic study of CpCo(bipy)

Data were collected on a STOE IPDS II diffractometer using graphite-monochromated $\text{MoK}\alpha$ radiation. The structure was solved by direct methods (SHELXS-97)⁵ and refined by full-matrix least-squares techniques on F^2 (SHELXL-97).⁵ Schakal-99 (E. Keller, Universität Freiburg, 1999) and XP (Bruker AXS) were used for graphical representation.

$\text{C}_{15}\text{H}_{13}\text{CoN}_2$, $M_r = 280.20$, monoclinic, space group $P2_1/c$, $a = 9.7530(5)$, $b = 10.7244(4)$, $c = 12.2426(6)$ Å, $\beta = 112.171(4)^\circ$, $V = 1185.8(1)$ Å³, $Z = 4$, $\rho_{\text{calcd}} = 1.569$ g · cm⁻³, $\mu = 1.427$ mm⁻¹, $T = 200$ K, 17565 reflections measured, 2834 independent reflections ($R_{\text{int}} = 0.0465$), of which 2388 were observed [$I > 2\sigma(I)$], final R indices [$I > 2\sigma(I)$]: $R_1 = 0.0250$, $wR_2 = 0.0635$, R indices (all data): $R_1 = 0.0327$, $wR_2 = 0.0654$, 163 refined parameters.



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- (1) (a) Gutnov, A.; Drexler, H.-J.; Oehme, G. Spannenberg, A.; Heller, B. *Organometallics* **2004**, 23, 1002. (b) Gutnov, A.; Heller, B.; Drexler, H.-J.; Spannenberg, A.; Oehme, G. *Organometallics* **2003**, 22, 1550.
- (2) H. Bönnemann, H.; Bogdanovič, B.; Brinkmann, R.; Spliethoff, B.; He, D. *J. Organomet. Chem.* **1993**, 451, 23.
- (3) Brandsma, L.; Vasilevsky, S. F.; Verkruijsse, S. F. *Application of Transition Metal Catalysts in Organic Synthesis*, Springer Verlag, Berlin, Heidelberg, Germany, 1999.
- (4) (a) General reference: Jonas, K.; Deffense, E.; Habermann, D. *Angew. Chem., Int. Ed. Engl.* **1983**, 22, 716. Exemplified procedure: (b) Hapke, M.; Spannenberg, A. *Acta Cryst.* **2009**, E65, m93.
- (5) Sheldrick, G. M. *Acta Cryst.* **2008**, A64, 112.