Electronic Supplementary Information

An aerobic and green C-H cyanation of terminal alkynes

Peng-Fei Zhu, Yi-Xin Si and Song-Lin Zhang*

Key Laboratory of Synthetic and Biological Colloids, Ministry of Education, School of Chemical and Material Engineering, Jiangnan University, Wuxi, Jiangsu 214122, China

E-mail: slzhang@jiangnan.edu.cn

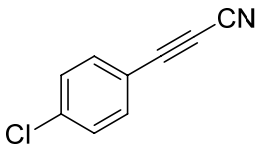
Table of Contents

1. General experimental details

All the reactants/reagents were used as received commercially (purchased from energy chemicals corp. with >98% purity,) without further purification, except compound **5** which was prepared according to a literature method.[S1,S2] All the reactions were carried out under O_2 atmosphere using an oxygen balloon which was realized through evacuation/backfill techniques. NMR spectra were recorded on a Bruker Advance III HD 400 MHz spectrometer (400 MHz for ^{1}H, 101 MHz for ^{13}C; 376 MHz for ^{19}F NMR). Chemical shifts are reported in ppm and referenced to residual solvent peak. Coupling constants are reported in Hertz where available. All the ^{13}C and ^{19}F NMR spectra were obtained with complete proton decoupling. High resolution mass spectra (HRMS) were determined on Thermo Scientific LTQ Orbitrap XL with ESI ionization mode. FT-IR spectra were recorded on an IRTracer-100 spectrometer.

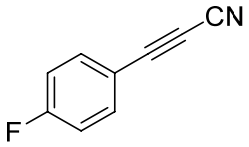
2. General procedure for copper-mediated aerobic cyanation of terminal alkynes (or halides or boronic acids)

Into an oven-dried 25-mL Schlenk tube equipped with a stir bar were added terminal alkynes (or halides or boronic acids) (0.5 mmol), CuI (0.5 mmol), phenanthroline (0.5 mmol) and $K_2S_2O_8$ (0.5 mmol). The tube was then sealed, evacuated and backfilled with dry O_2 using an O_2 balloon. An NMP solution (3 mL) of ethyl cyanoacetate (1.5 mmol) was then added into the tube by syringe. The reaction mixture was stirred under O_2 at 130 ^oC (oil bath) for 12 hours. The reaction mixture was then cooled to room temperature, diluted with dichloromethane, and separated by filtration. The filtrates were washed with a large amount of water for 3 times. The solvent was removed by vacuum evaporation. The resulting residual was purified by column chromatography on silica gel eluting with *n*-hexane (or other eluents as noted) to provide cyanation products.



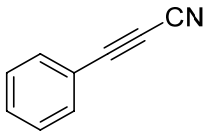
3-(4-chlorophenyl)propiolonitrile (**3a**; 48 mg, 60%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 – 7.53 (m, 2H), 7.42 – 7.38 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.6, 134.7, 129.4, 116.0, 105.2, 81.7, 64.0.

These data are in good agreement with literature report.[S3]

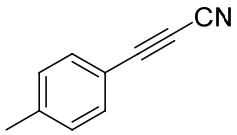


3-(4-fluorophenyl)propiolonitrile (**3b**; 35 mg, 49%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 – 7.59 (m, 2H), 7.15 – 7.08 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 164.6 (d, J = 256.1 Hz), 135.9 (d, J = 9.1 Hz), 116.6 (d, J = 22.6 Hz), 113.7 (d, J = 3.6 Hz), 105.4 (s), 81.9 (s), 63.2 (s).

These data are in good agreement with literature report.[S3]

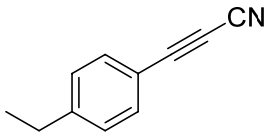


3-phenylpropiolonitrile (**3c**; 15 mg, 24%). Eluted with hexane. Colorless oil; ^{1}H NMR (400 MHz, CDCl3) δ 7.66 – 7.60 (m, 2H), 7.57 – 7.50 (m, 1H), 7.42 (t, *J* = 7.6 Hz, 2H). ^{13}C NMR (101 MHz, CDCl3) δ 133.5, 131.9, 128.9, 117.6, 105.5, 83.0, 63.1. These data are in good agreement with literature report.[S3]



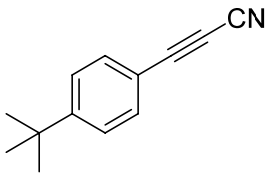
3-(*p*-tolyl)propiolonitrile (**3d**; 40 mg, 69%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (d, *J* = 8.2 Hz, 2H), 7.22 (d, *J* = 8.0 Hz, 2H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.9, 133.5, 129.7, 114.4, 105.7, 83.5, 62.7, 21.9.

These data are in good agreement with literature report.[S3]



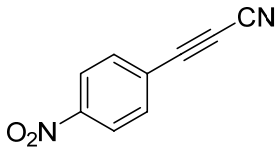
3-(4-ethylphenyl)propiolonitrile (**3e**; 51 mg, 66%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, *J* = 8.2 Hz, 2H), 7.27 (d, *J* = 8.1 Hz, 2H), 2.72 (q, *J* = 7.6 Hz, 2H), 1.28 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.0, 133.6, 128.5, 114.6, 105.6, 83.5, 62.7, 29.1, 15.0.

These data are in good agreement with literature report.[S3]



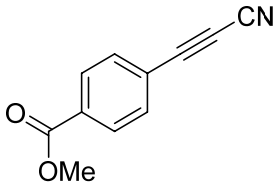
3-(4-(tert-butyl)phenyl)propiolonitrile (**3f**; 46 mg, 61%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, *J* = 8.4 Hz, 2H), 7.43 (d, *J* = 8.4 Hz, 2H), 1.33 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.8, 133.4, 126.0, 114.4, 105.7, 83.5, 62.7, 35.2, 31.0.

These data are in good agreement with literature report.[S4]



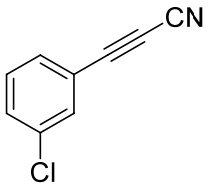
3-(4-nitrophenyl)propiolonitrile (**3g**; 21 mg, 25%). Eluted with petroleum ether/ethyl acetate 10:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.32 – 8.26 (m, 2H), 7.87 – 7.76 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.3, 134.5, 124.0, 104.7, 79.9, 66.7.

These data are in good agreement with literature report.[S3]



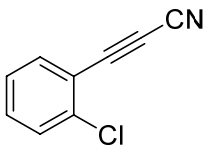
Methyl 4-(cyanoethynyl)benzoate (**3h**; 41 mg, 44%). Eluted with petroleum ether/ethyl acetate 10:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, J = 8.5 Hz, 2H), 7.68 (d, J = 8.5 Hz, 2H), 3.95 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.7, 133.5, 132.9, 129.8, 121.8, 105.1, 81.6, 65.1, 52.6.

These data are in good agreement with literature report.[S4]



3-(3-chlorophenyl)propiolonitrile (**3i**; 38 mg, 56%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (t, J = 1.5 Hz, 1H), 7.54 – 7.48 (m, 2H), 7.36 (t, J = 7.9 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 134.9, 133.1, 132.3, 131.6, 130.2, 119.3, 105.1, 81.1, 64.0.

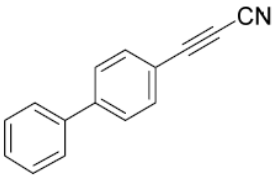
These data are in good agreement with literature report.[S5]



3-(2-chlorophenyl)propiolonitrile (**3j**; 42 mg, 62%). Eluted with hexane. White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 (d, J = 7.6 Hz, 1H), 7.49 – 7.45 (m, 2H),

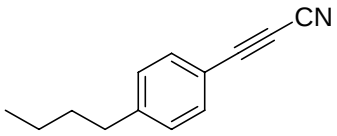
7.36 – 7.29 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.3, 135.3, 132.8, 130.0, 127.0, 118.2, 105.2, 79.3, 67.3.

These data are in good agreement with literature report.[S5]



3-([1,1'-biphenyl]-4-yl)propiolonitrile (**3k**; 61 mg, 61%). Eluted with petroleum ether/ethyl acetate 20:1 (v/v). Yellow solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 – 7.58 (m, 6H), 7.53 – 7.46 (m, 2H), 7.46 – 7.39 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.7, 139.4, 134.0, 129.1, 128.6, 127.5, 127.2, 116.1, 105.6, 83.1, 63.7.

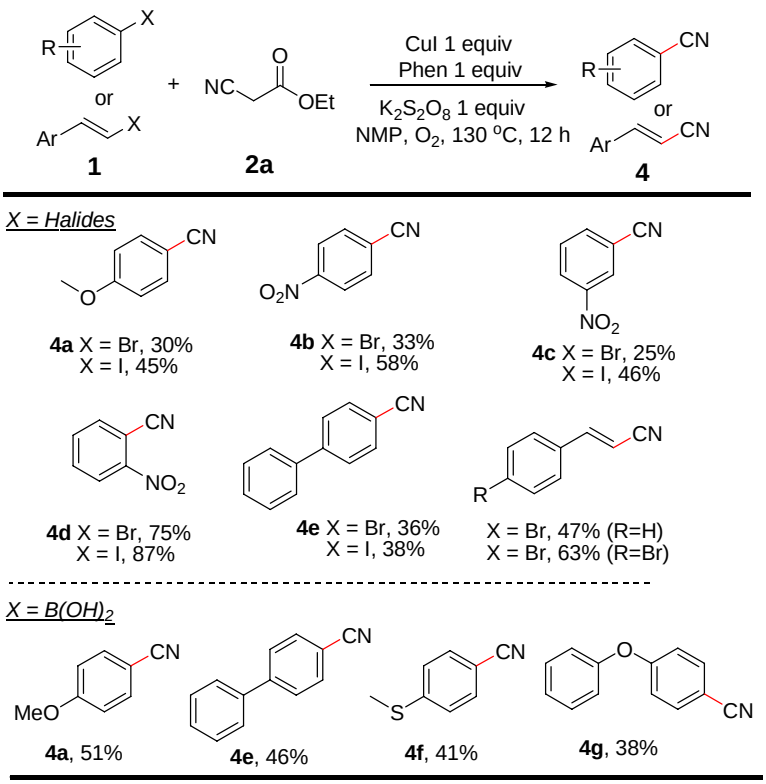
These data are in good agreement with literature report.[S5]

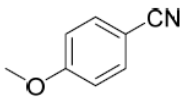


3-(4-butylphenyl)propiolonitrile (**3p**; 49 mg, 54%). Eluted with hexane. Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (d, *J* = 8.2 Hz, 2H), 7.22 (d, *J* = 8.2 Hz, 2H), 2.68 – 2.62 (m, 2H), 1.62 – 1.57 (m, 2H), 1.34 (dd, *J* = 15.5, 6.9 Hz, 2H), 0.93 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.7 (s), 132.5 (s), 128.0 (s), 113.5 (s), 104.7 (s), 82.5 (s), 61.7 (s), 34.8 (s), 32.1 (s), 21.2 (s), 12.8 (s).

These data are in good agreement with literature report.[S9]

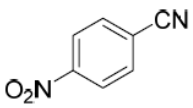
Scheme S1. Extension to cyanation of aryl/vinyl halides and boronic acids





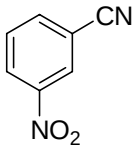
4-methoxybenzonitrile (**4a**; 30 mg, 45%). Eluted with petroleum ether/ethyl acetate 10:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 – 7.55 (m, 2H), 6.98 – 6.91 (m, 2H), 3.86 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.9, 134.0, 119.2, 114.8, 104.0, 55.6.

These data are in good agreement with literature report.[S6]



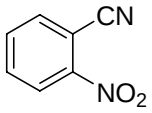
4-nitrobenzonitrile (**4b**; 43 mg, 58%). Eluted with petroleum ether/ethyl acetate 20:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.39 – 8.32 (m, 2H), 7.92 – 7.86 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.8, 131.3, 122.1, 116.1, 114.6.

These data are in good agreement with literature report.[S6]



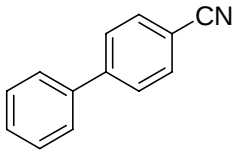
3-nitrobenzonitrile (**4c**; 34 mg, 46%). Eluted with petroleum ether/ethyl acetate 10:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.56 – 8.52 (m, 1H), 8.48 (ddd, *J* = 8.3, 2.1, 1.0 Hz, 1H), 8.05 – 7.95 (m, 1H), 7.74 (t, *J* = 8.0 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.3, 137.6, 130.7, 127.5, 127.2, 116.5, 114.2.

These data are in good agreement with literature report.[S6]



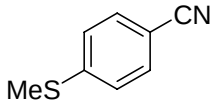
2-nitrobenzonitrile (**4d**; 64 mg, 87%). Eluted with petroleum ether/ethyl acetate 10:1 (v/v). Yellow solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.37 – 8.30 (m, 1H), 7.96 – 7.91 (m, 1H), 7.89 – 7.83 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.6, 135.7, 134.5, 133.9, 125.6, 115.1, 107.9.

These data are in good agreement with literature report.[S6]



[1,1'-biphenyl]-4-carbonitrile (**4e**; 34 mg, 38%). Eluted with petroleum ether/ethyl acetate 20:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 – 7.67 (m, 4H), 7.62 – 7.57 (m, 2H), 7.52 – 7.46 (m, 2H), 7.46 – 7.39 (m, 1H).^{13}C NMR (101 MHz, $CDCl_3$) δ 145.7, 139.2, 132.6, 129.1, 128.7, 127.8, 127.3, 119.0, 110.9.

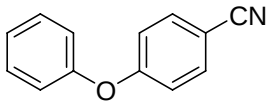
These data are in good agreement with literature report.[S6]



4-(methylthio)benzonitrile (**4f**; 30 mg, 41%). Eluted with petroleum ether/ethyl acetate 30:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (d, *J* = 8.6 Hz, 2H),

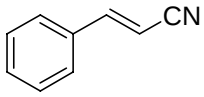
7.28 (d, J = 8.6 Hz, 2H), 2.53 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.1, 132.2, 125.5, 119.0, 107.7, 14.7.

These data are in good agreement with literature report.[S7]



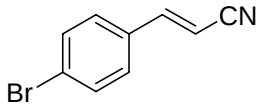
4-phenoxybenzonitrile (**4g**; 38 mg, 38%). Eluted with petroleum ether/ethyl acetate 40:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 – 7.56 (m, 2H), 7.46 – 7.37 (m, 2H), 7.26 – 7.20 (m, 1H), 7.09 – 7.04 (m, 2H), 7.03 – 6.98 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 161.7, 154.8, 134.2, 130.3, 125.2, 120.4, 118.9, 117.9, 105.8.

These data are in good agreement with literature report.[S8]



(E)-Cinnamonitrile (**4h**; 30 mg, 47%). Eluted with petroleum ether/ethyl acetate 30:1 (v/v). Colorless oil; a mixture of E/Z isomers in a ratio of 1:0.3. Major (E-isomer): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.35 (m, 6H), 5.88 (d, J = 16.7 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.6, 133.5, 131.2, 129.1, 127.4, 118.2, 96.4.

These data are in good agreement with literature report.[S8]



(E)-3-(4-bromophenyl)acrylonitrile (**4i**; 65 mg, 63%). Eluted with petroleum ether/ethyl acetate 30:1 (v/v). White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 – 7.49 (m, 2H), 7.34 – 7.26 (m, 3H), 5.88 (d, J = 16.7 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.2, 138.4, 132.4, 128.8, 125.7, 117.9, 97.2.

These data are in good agreement with literature report.[S8]

References

S1. J.-Y. Hu.; B. Gao and L.-C. Li, et al. *Org. Lett*. **2015**, *17*, 3086-3089.

S2. S. Gao.; H. Liu and Z.-J. Wu, et al. *Green Chemistry*, **2017**, *19*, 1861-1865.

S3. G.-W. Rong, J.-C. Mao, Y. Zheng, R.-W. Yao and X.-F. Xu, *Chem. Comm*, **2015**, *51*, 13822.

S4. H.-N. Wang.; P.-B. Mi.; W.-J. Zhao.; Kumar, R and X.-H. Bi, *Org. Lett.* **2017**, *19*, 5613.

S5. P. Liu, R. J. Clark and L. Zhu, *J. Org. Chem.* **2018**, *83*, 5092.

S6. S.-L. Zhang and L. Huang, *Org. Biomol. Chem.*, **2015**, *13*, 9963.

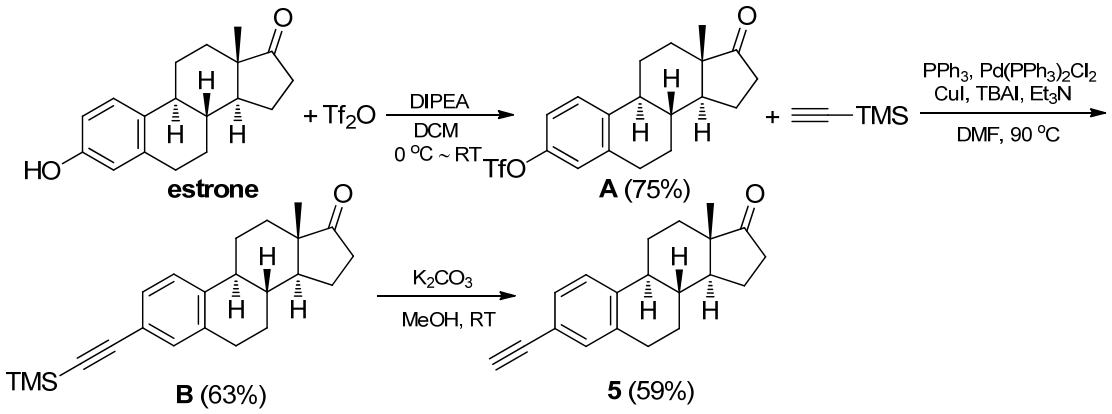
S7. C.-Y. Zhang.; Y. Zhou.; J.-T. Huang.; C.-H. Tu.; X.-A. Zhou and G.-D. Yin, *Org. Biomol. Chem.*, **2018**, *16*, 6316.

S8. X.-J. Wang and S.-L. Zhang, *New. J. Chem.*, **2017**, *41*, 14826.

S9. Y. Du and Z. Li, *Tetrahedron Letters* **2018**, *59*, 4622.

3. Application to the modification of estrone derivative

Scheme S1. Preparation of precursor **5**



Compound **5** was prepared according to the literature procedures.[S1,S2]

Step 1: Into an oven-dried 100-mL Schlenk tube equipped with a stir bar were added estrone (5 mmol) and diisopropylethylamine (DIPEA) (5.5 mmol). The tube was evacuated and refilled with dry nitrogen. The dichloromethane (DCM) solution (20 mL) of Tf_2O (5.5 mmol) was added into the tube by syringe at 0 °C. The reaction mixture was warmed to and stirred at room temperature for 30 min. The resulting mixture was diluted with DCM and separated by filtration. The solvent was removed by vacuum evaporation. The resulting residual was purified by column chromatography on silica gel eluting with petroleum ether/ethyl acetate = 4:1 (v/v) to provide triflated product **A** (white solid, 1508 mg, 75%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.6 Hz, 1H), 7.03 (dd, *J* = 8.6, 2.7 Hz, 1H), 6.99 (d, *J* = 2.6 Hz, 1H), 2.94 (dd, *J* = 8.7, 4.1 Hz, 2H), 2.52 (dd, *J* = 18.8, 8.7 Hz, 1H), 2.44 – 2.36 (m, 1H), 2.30 (td, *J* = 10.7, 4.1 Hz, 1H), 2.21 – 1.93 (m, 4H), 1.70 – 1.43 (m, 6H), 0.92 (s, 3H).

Step 2: Into an oven-dried 100-mL Schlenk tube equipped with a stir bar were added triflated estrone **A** (4 mmol), PPh_3 (0.24 mmol), $Pd(PPh_3)_2Cl_2$ (0.2 mmol), tetrabutylammonium iodide (TBAI) (8 mmol), and CuI (0.14 mmol). The tube was evacuated and refilled with dry nitrogen. The DMF solution (30 mL) of trimethylsilylacetylene (12 mmol) and Et_3N (52 mmol) was added into the tube by syringe. The reaction mixture was stirred at 90 °C for 12 h. The reaction mixture was

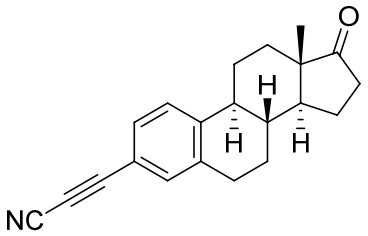
cooled to room temperature. The resulting mixture was diluted with DCM and separated by filtration. The organic layers were washed with a large amount of water for 3 times. The solvent was removed by vacuum evaporation. The resulting residual was purified by column chromatography on silica gel eluting with petroleum ether/ethyl acetate = 10:1 (v/v) to provide estrone derivative **B** (white solid, 878 mg, 63%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25 – 7.18 (m, 3H), 2.92 – 2.83 (m, 2H), 2.50 (dd, *J* = 18.8, 8.6 Hz, 1H), 2.43 – 2.35 (m, 1H), 2.33 – 2.23 (m, 1H), 2.19 – 1.93 (m, 4H), 1.67 – 1.36 (m, 6H), 0.90 (s, 3H), 0.24 (s, 9H).

Step 3: Into an oven-dried 100-mL Schlenk tube equipped with a stir bar were added **B** (2.28 mmol) and K_2CO_3 (13.37 mmol). The tube was evacuated and refilled with dry nitrogen. With MeOH (40 mL) as solvent, the reaction mixture was stirred at room temperature for 3 h. The resulting mixture was diluted with DCM and separated by filtration. The solvent was removed by vacuum evaporation. The resulting residual was purified by column chromatography on silica gel eluting with petroleum ether/ethyl acetate = 10:1 (v/v) to provide **5** (white solid, 375 mg, 59%).

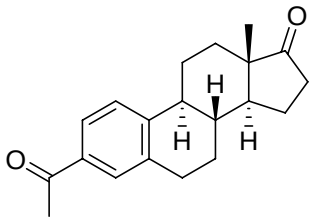
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 – 7.19 (m, 3H), 3.01 (s, 1H), 2.94 – 2.83 (m, 2H), 2.51 (dd, *J* = 18.7, 8.6 Hz, 1H), 2.45 – 2.35 (m, 1H), 2.29 (td, *J* = 10.6, 4.4 Hz, 1H), 2.20 – 1.93 (m, 4H), 1.69 – 1.36 (m, 6H), 0.91 (s, 3H).

Following the general procedure described in Section 2, estrone derivative **5** was cyanated at the terminal alkyne to give product **6**.



3-((8*R*,9*S*,13*S*,14*S*)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6*H*-cyclopenta[*a*]phenanthren-3-yl)propiolonitrile (**6**; 22 mg, 33%). Eluted with petroleum ether/ethyl acetate 20:1 (v/v). Light yellow solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 – 7.32 (m, 3H), 3.02 – 2.88 (m, 2H), 2.54 (dd, *J* = 18.8, 8.7 Hz, 1H), 2.48 – 2.40 (m, 1H), 2.39 – 2.30 (m, 1H), 2.28 – 1.97 (m, 4H), 1.72 – 1.45 (m, 6H),

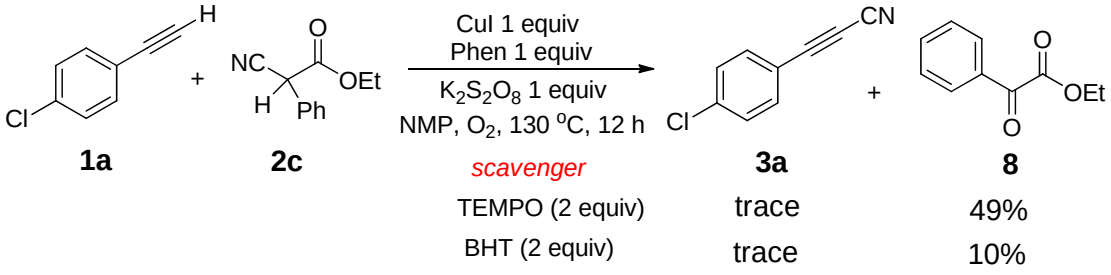
0.94 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 220.3, 144.6, 137.6, 133.9, 130.8, 126.0, 114.7, 105.7, 83.5, 62.7, 50.5, 47.8, 44.6, 37.7, 35.8, 31.5, 29.0, 26.1, 25.5, 21.6, 13.8.



(8*R*,9*S*,13*S*,14*S*)-3-acetyl-13-methyl-7,8,9,11,12,13,15,16-octahydro-6*H*-cyclopent a[*a*]phenanthren-17(14*H*)-one (**7**, 45 mg, 30%). Eluted with petroleum ether/ethyl acetate 20:1 (v/v). Yellow solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 – 7.66 (m, 2H), 7.38 (d, *J* = 8.1 Hz, 1H), 3.03 – 2.89 (m, 2H), 2.57 (s, 3H), 2.55 – 2.47 (m, 1H), 2.47 – 2.41 (m, 1H), 2.38 – 2.29 (m, 1H), 2.21 – 1.94 (m, 4H), 1.71 – 1.22 (m, 6H), 0.91 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 220.3, 198.1, 145.5, 136.9, 134.9, 128.9, 125.8, 125.6, 50.6, 47.9, 44.7, 37.9, 35.8, 31.6, 29.3, 26.6, 26.3, 25.6, 21.6, 13.8.

4. Radical trapping experiments

Scheme S2. Radical scavenger effect study

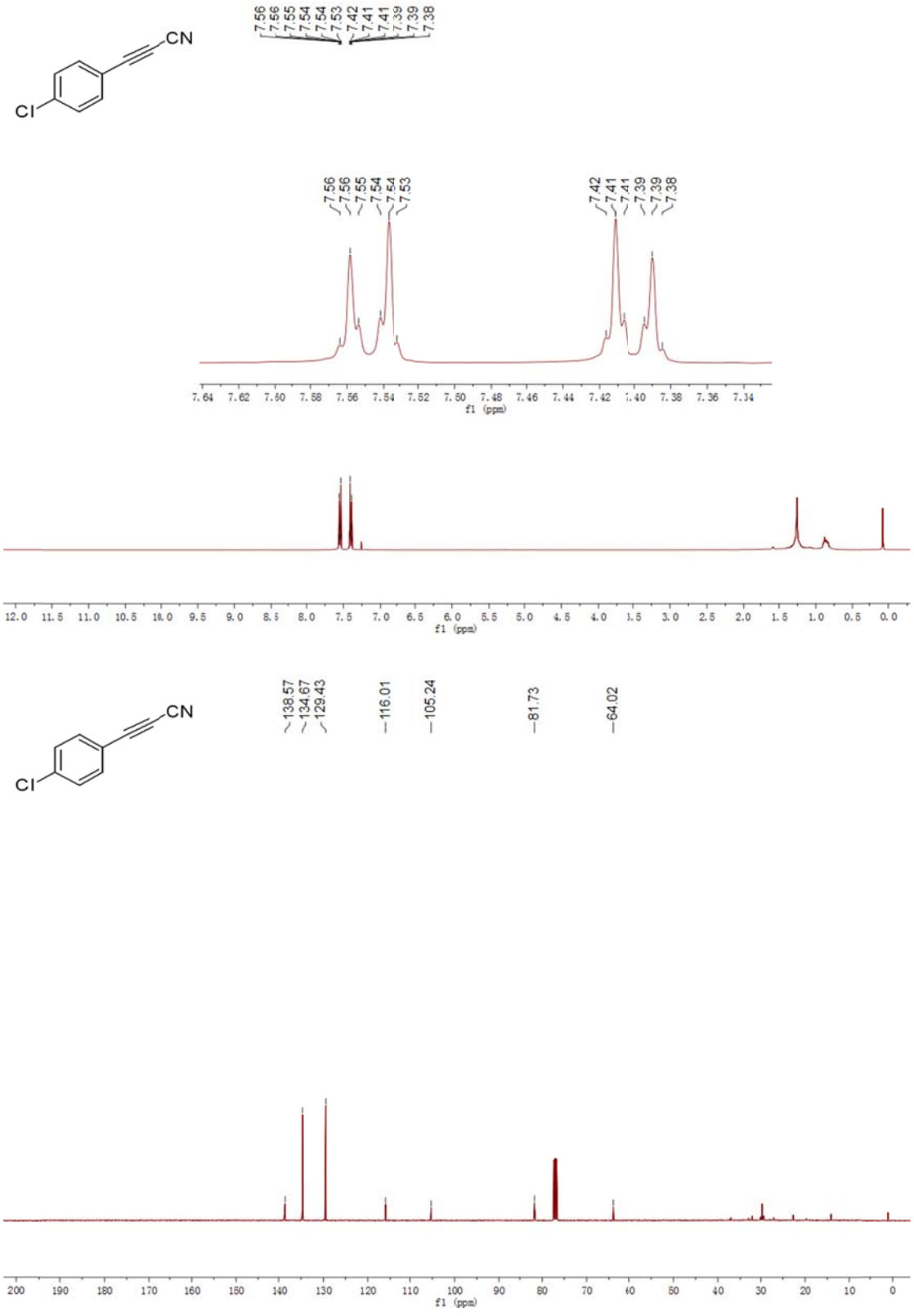


When two equivalents of TEMPO or BHT were added to the standard reaction solutions, the yield of **3a** is greatly reduced to trace amounts, suggesting the involvement of radical species during the reaction course. It is more exciting to isolated oxalate monoester product **8** in the crude reaction mixture in 49% and 10% yield, respectively, implying the occurring of b-C elimination of a hydroxylated intermediate of **2c**.

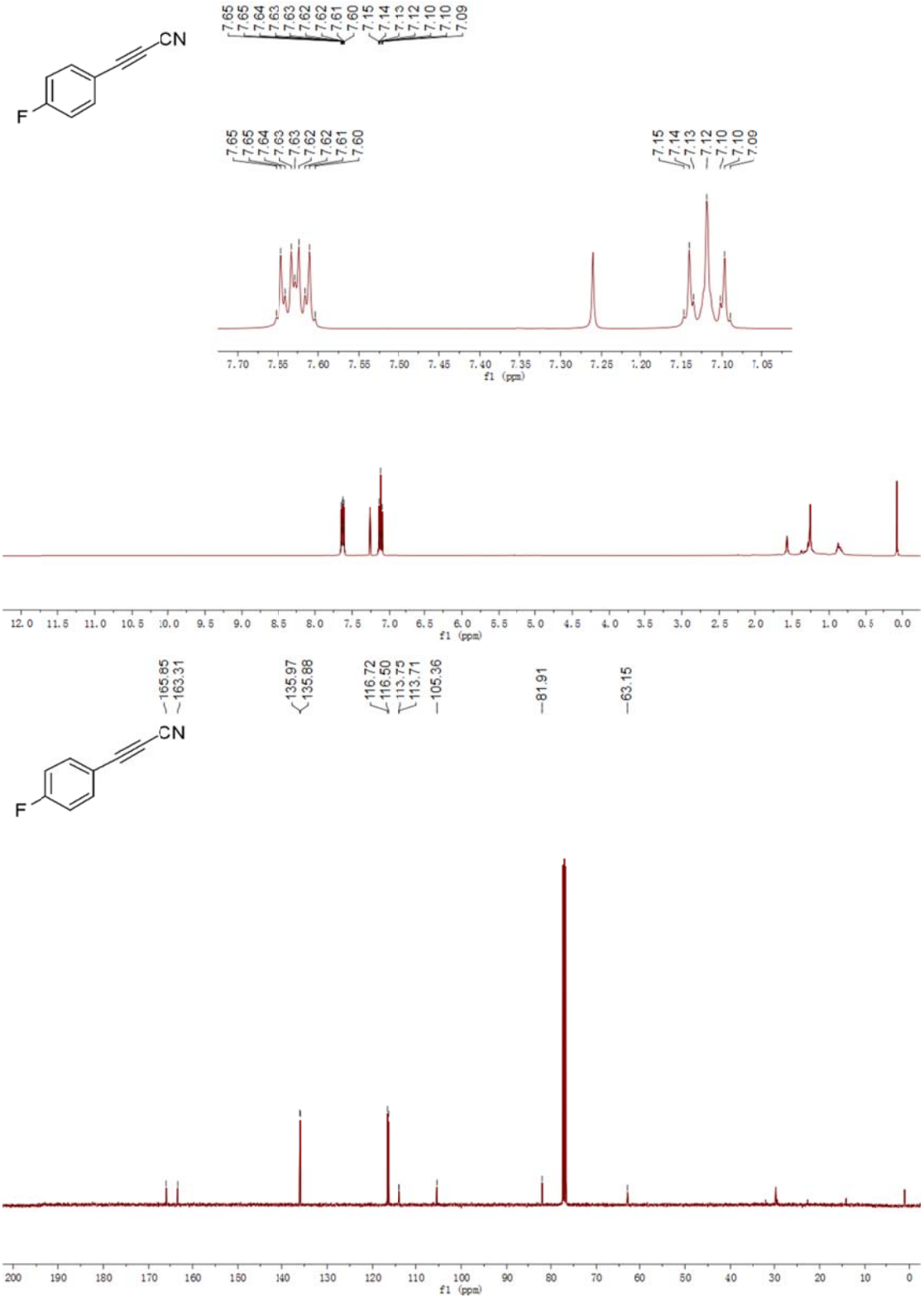
8. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 – 7.98 (m, 2H), 7.68 – 7.62 (m, 1H), 7.54 – 7.48 (m, 2H), 4.45 (q, *J* = 7.1 Hz, 2H), 1.42 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 186.4, 163.8, 134.9, 132.5, 130.0, 128.9, 62.3, 14.1.

5. NMR spectra for all the products

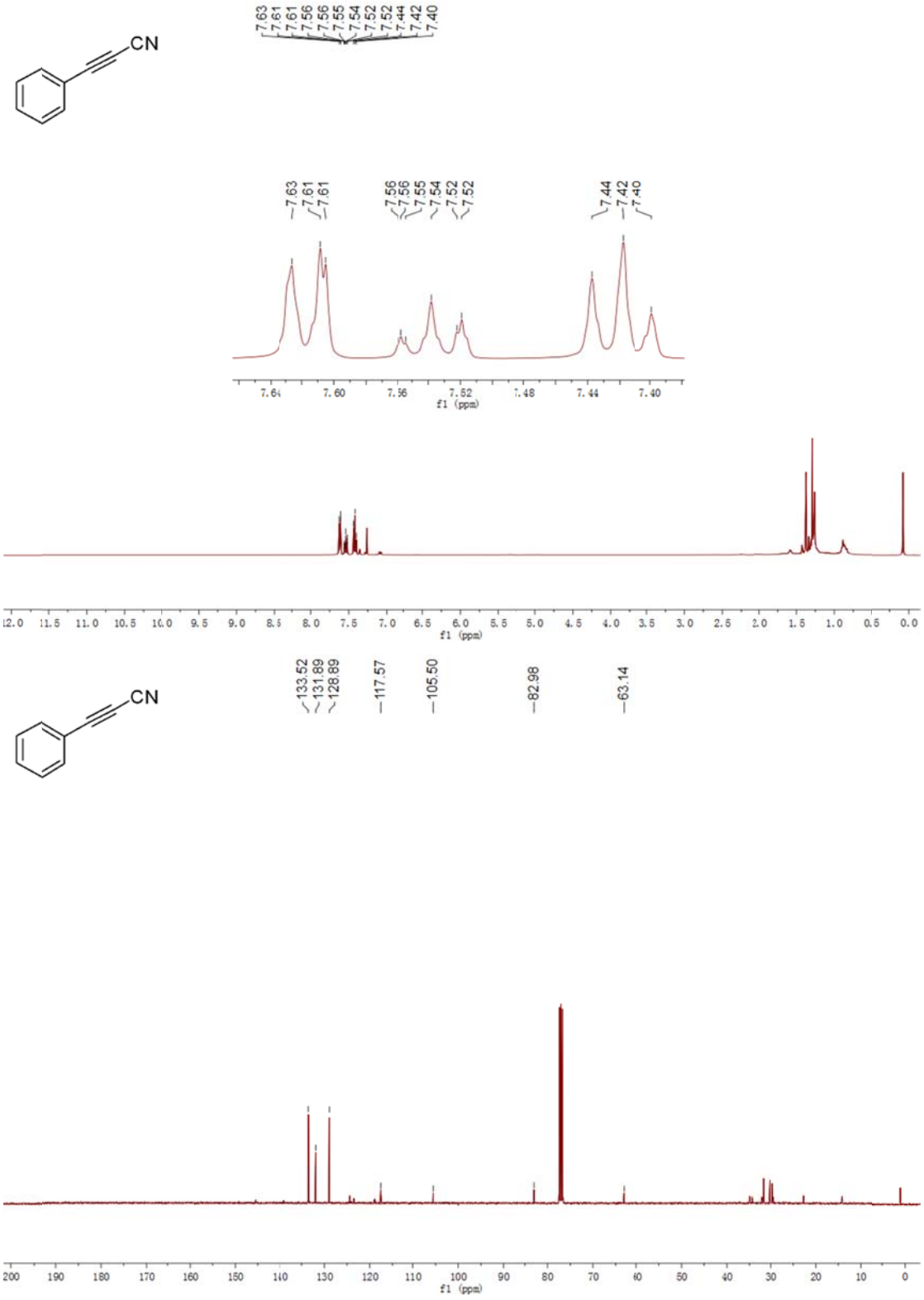
3-(4-chlorophenyl)propiolonitrile (**3a**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



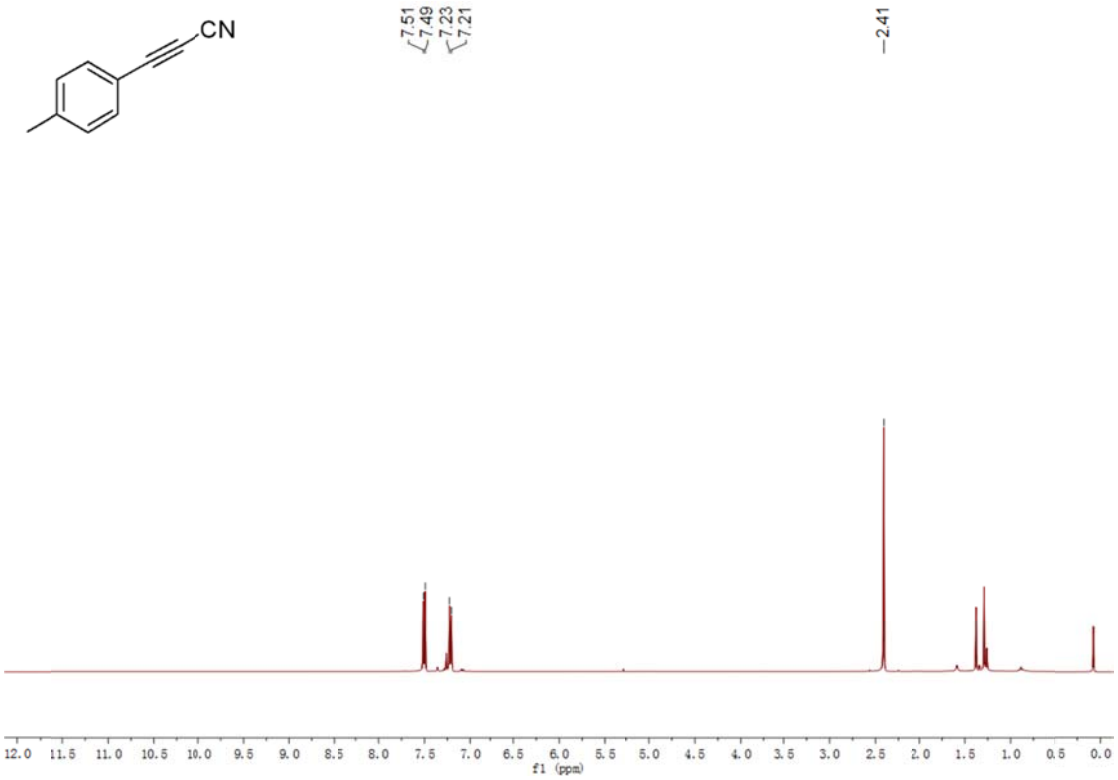
3-(4-fluorophenyl)propiolonitrile (**3b**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

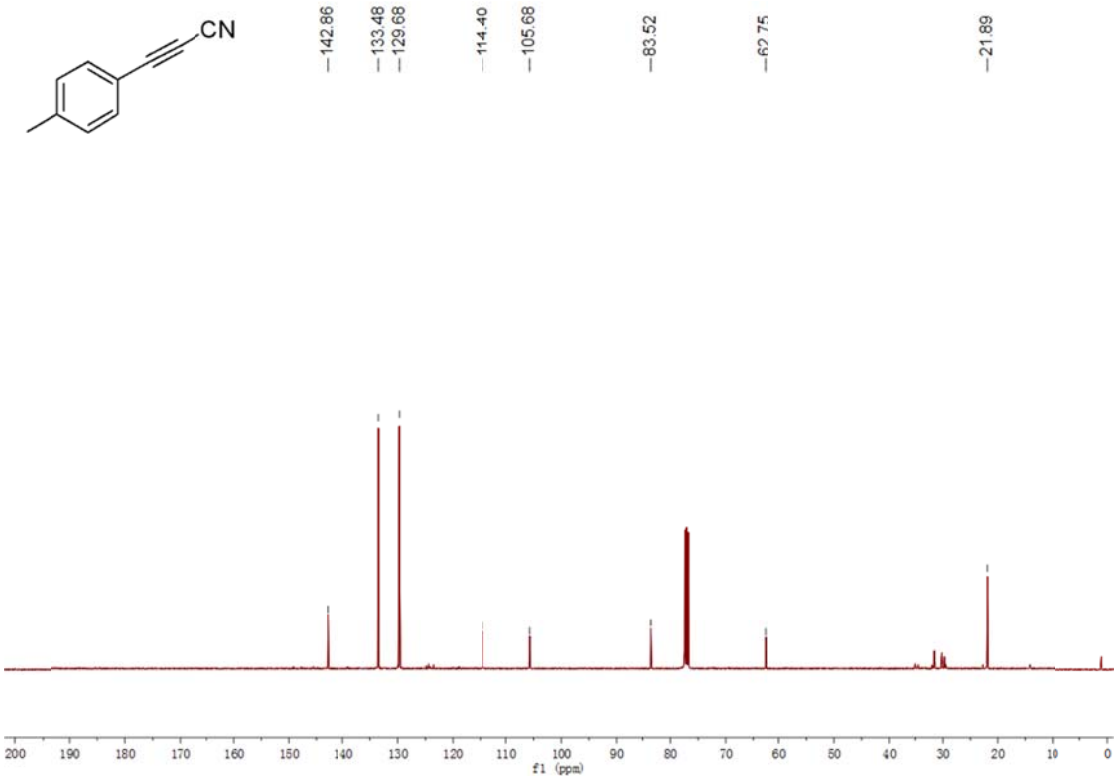


3-phenylpropiolonitrile (**3c**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

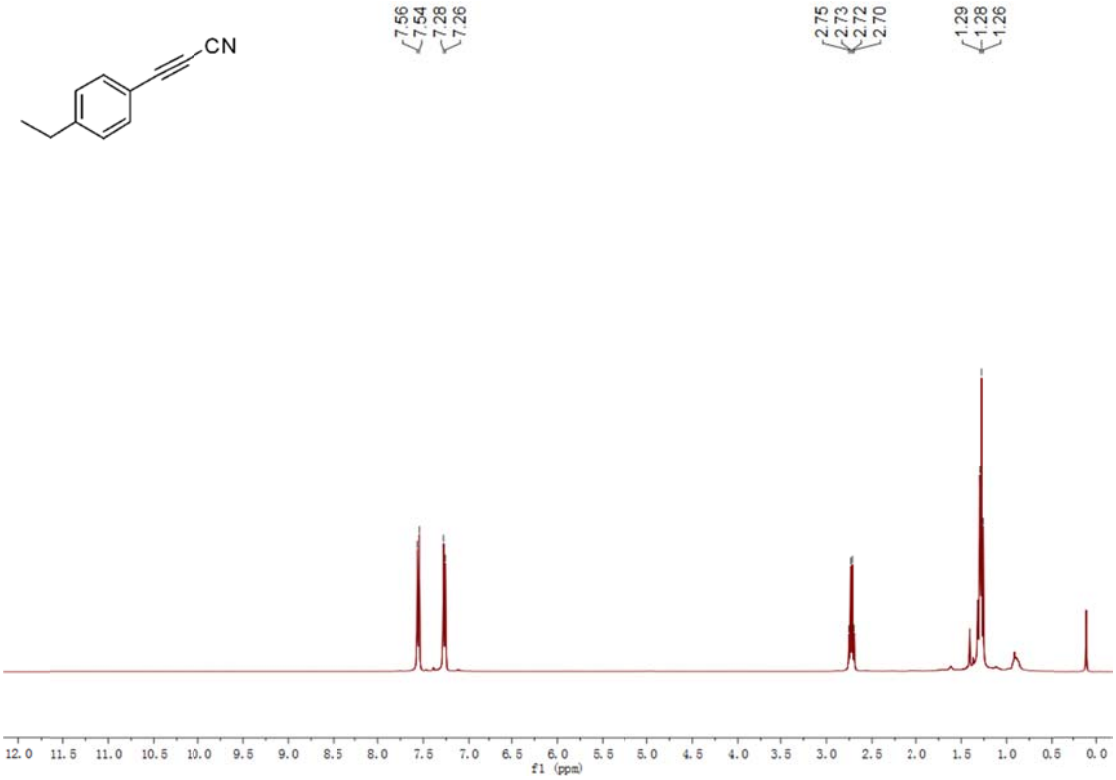


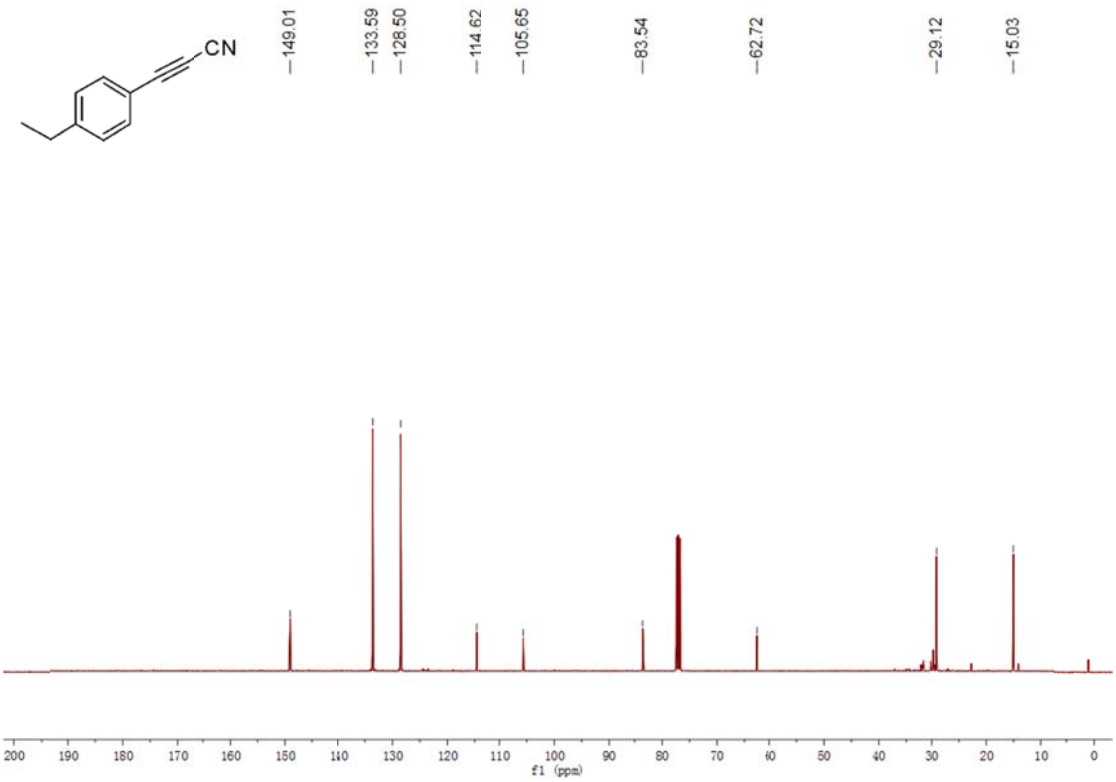
3-(p-tolyl)propiolonitrile (**3d**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



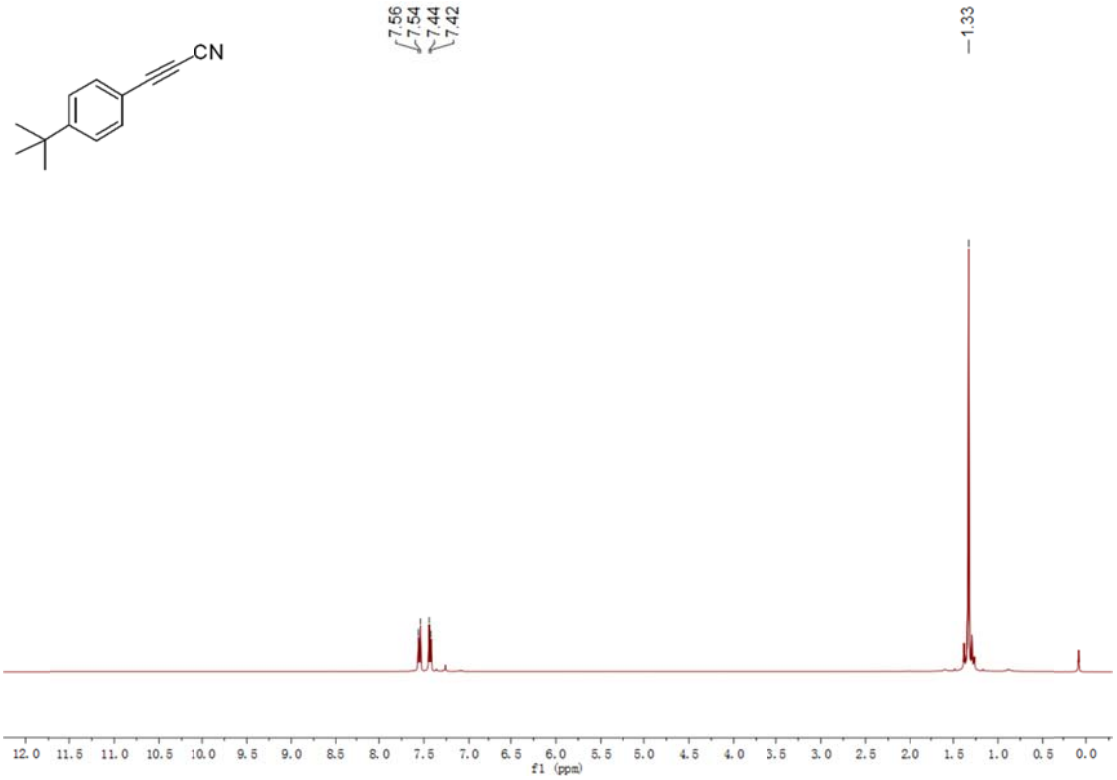


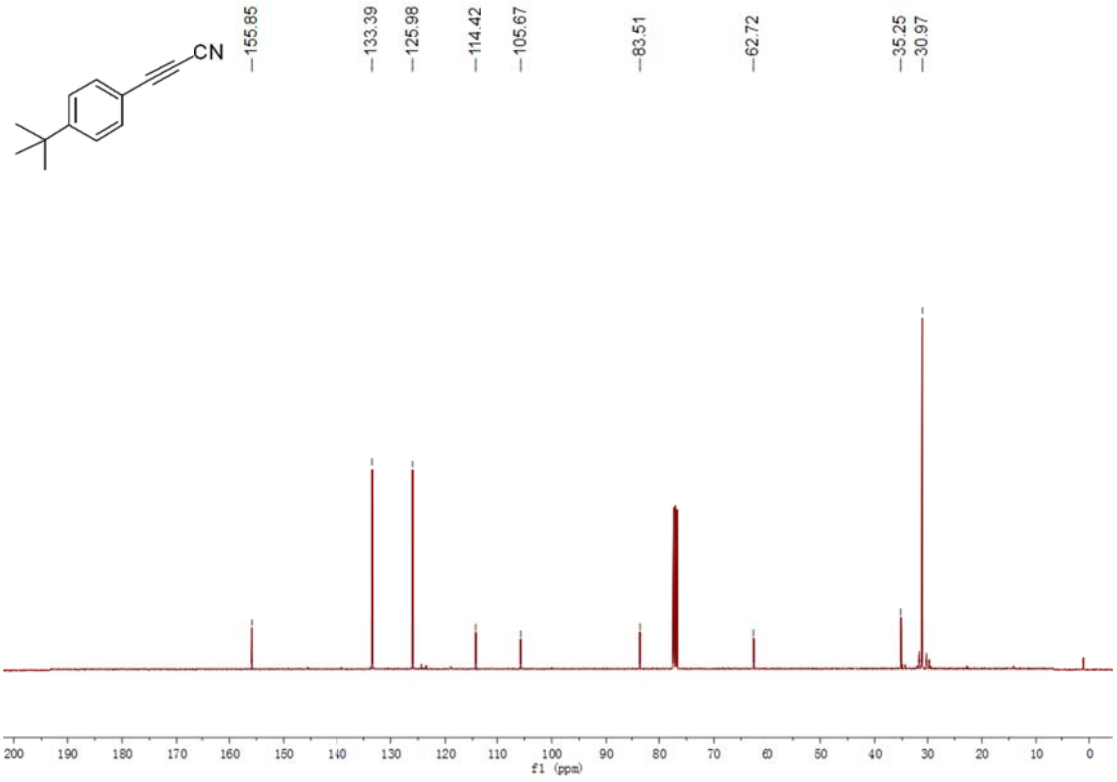
3-(4-ethylphenyl)propiolonitrile (**3e**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



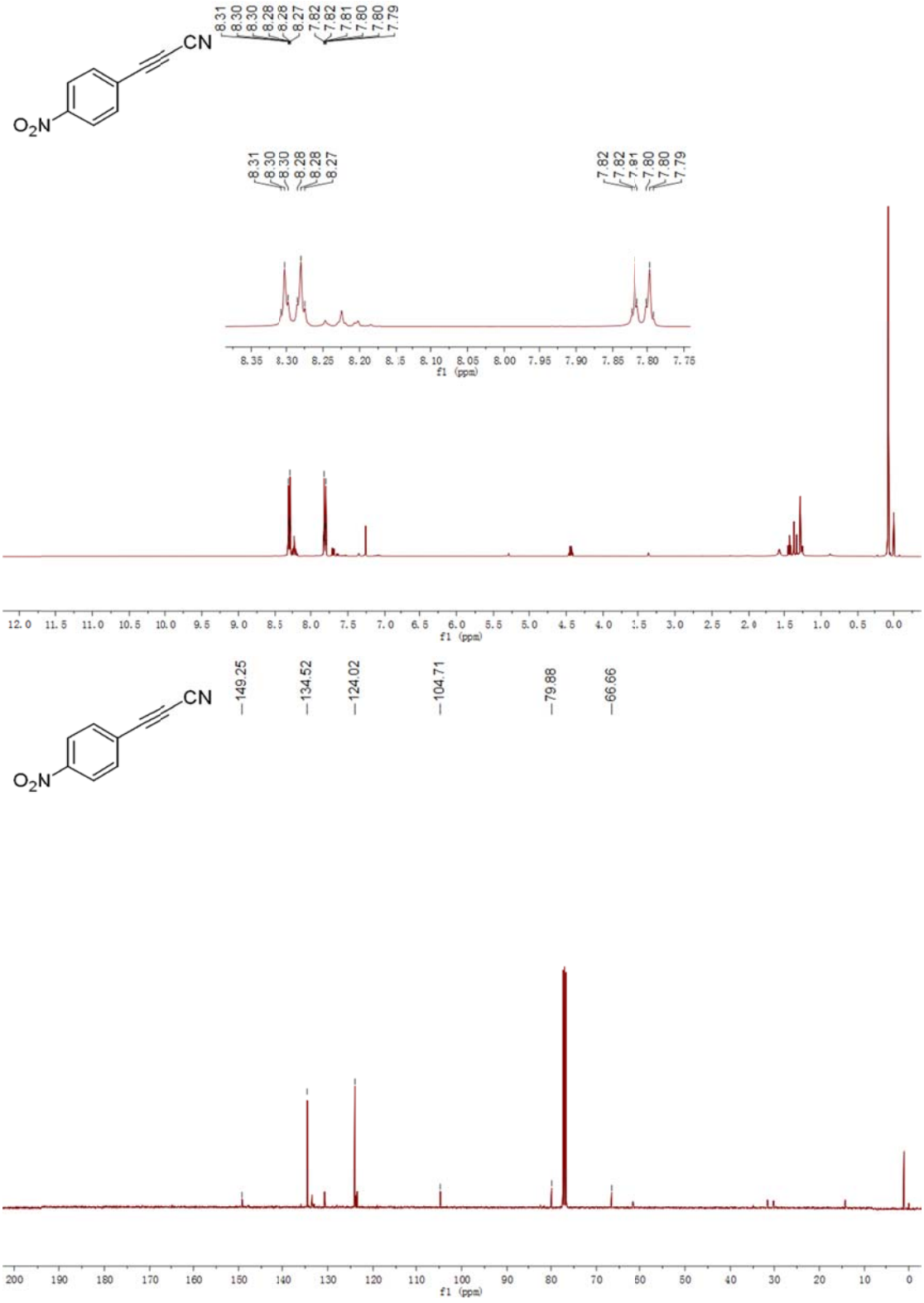


3-(4-(tert-butyl)phenyl)propiolonitrile (**3f**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

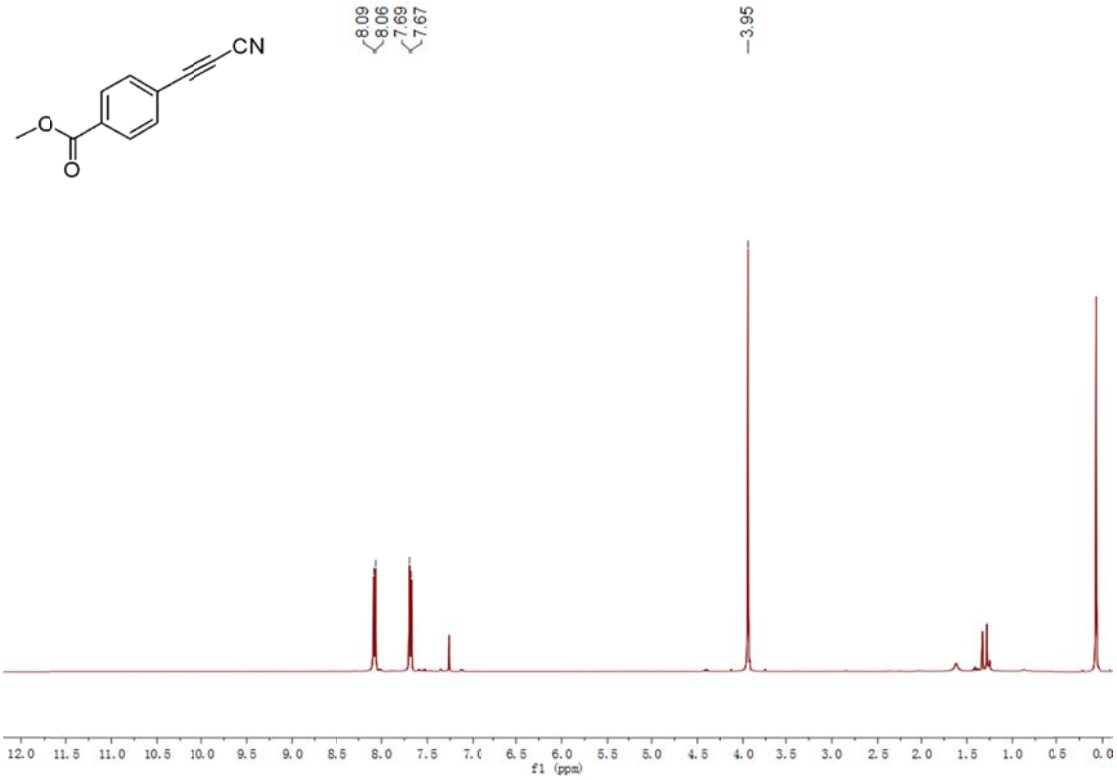


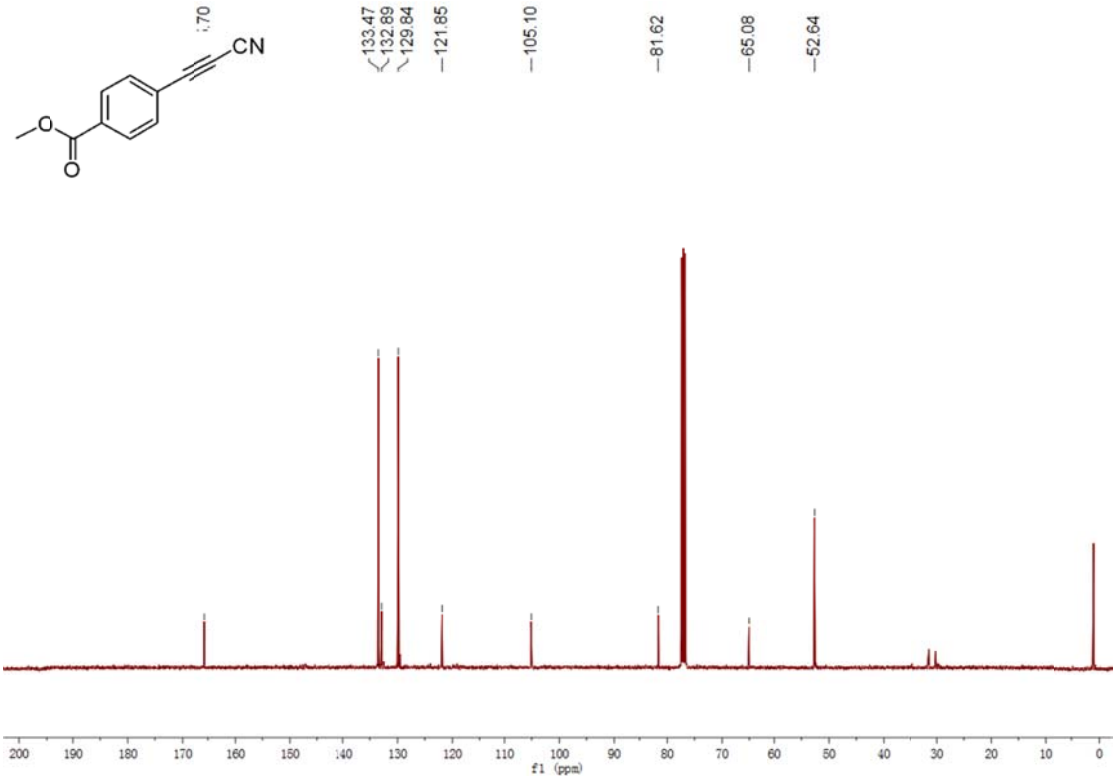


3-(4-nitrophenyl)propiolonitrile (**3g**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

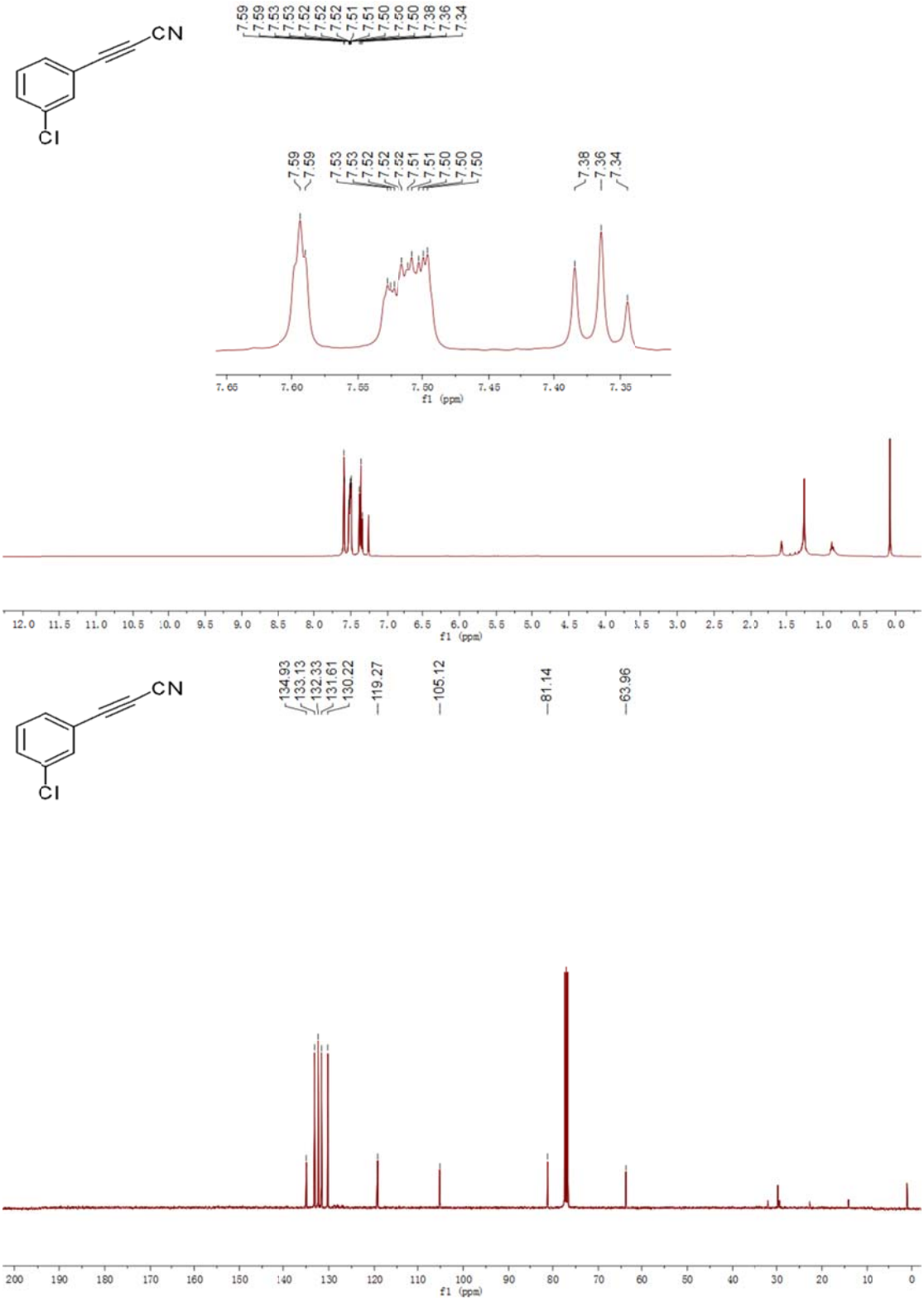


Methyl 4-(cyanoethynyl)benzoate (3h. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

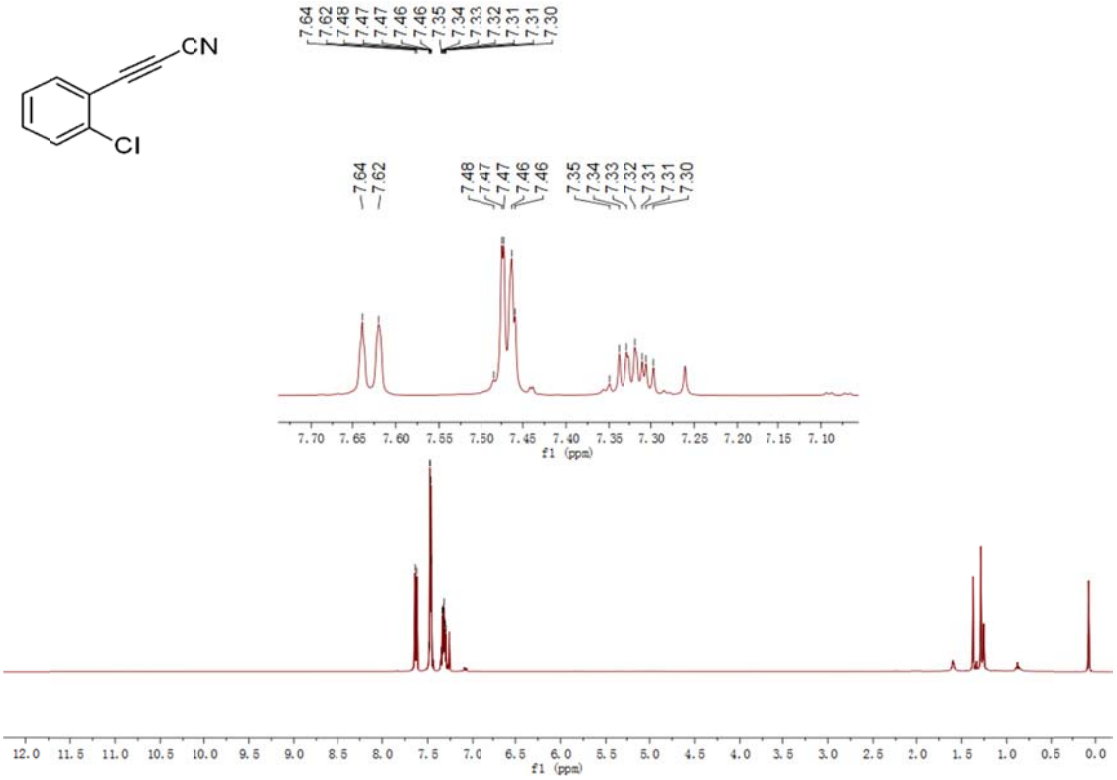


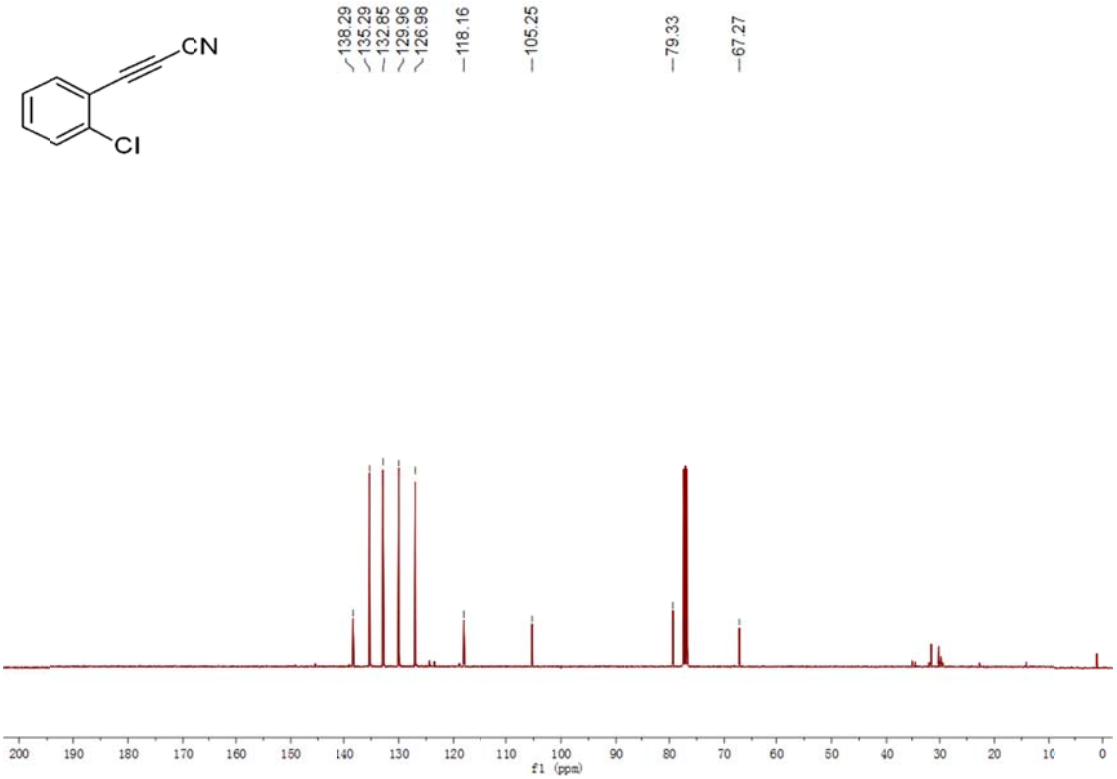


3-(3-chlorophenyl)propiolonitrile (**3i**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

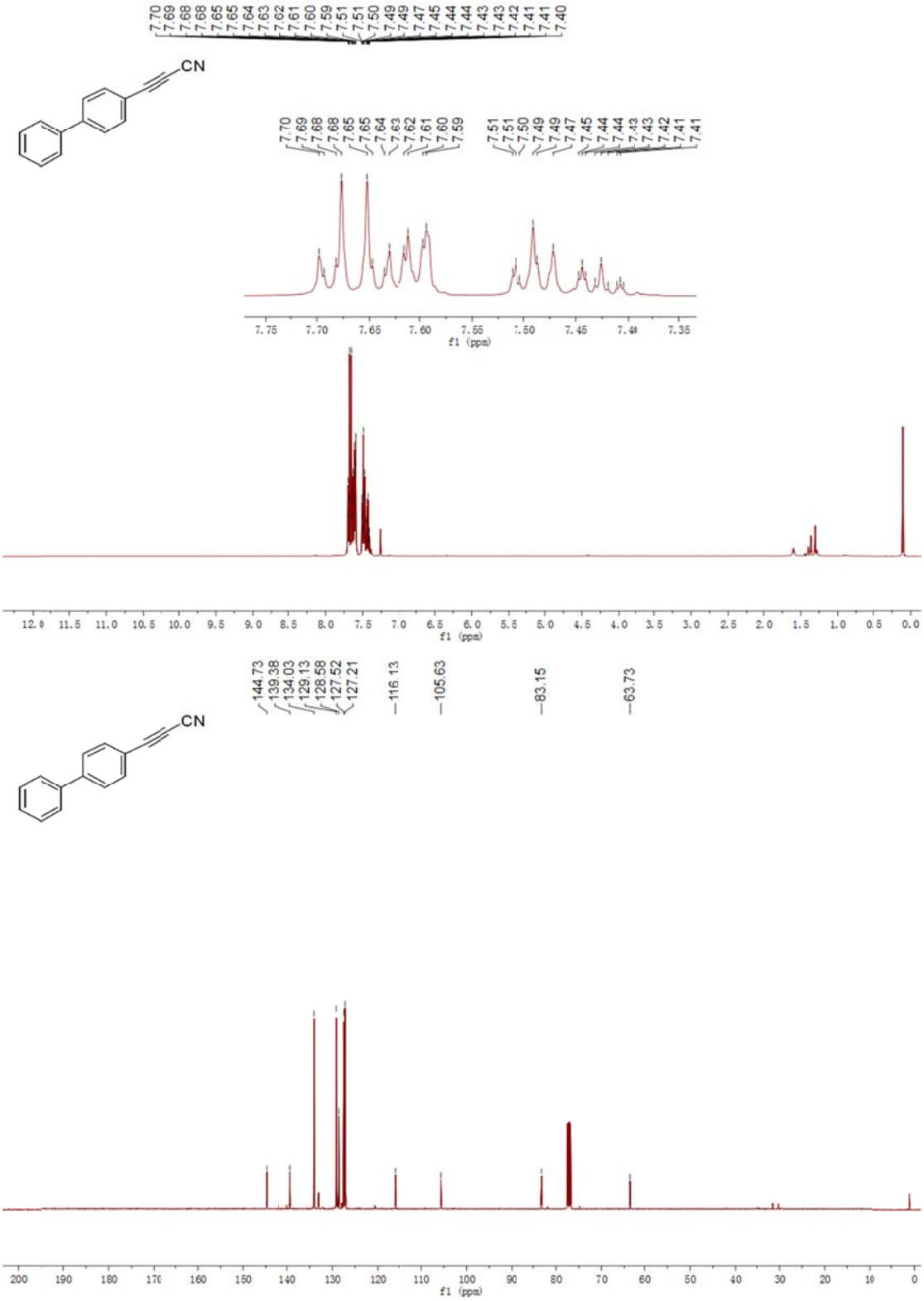


3-(2-chlorophenyl)propiolonitrile (**3j**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

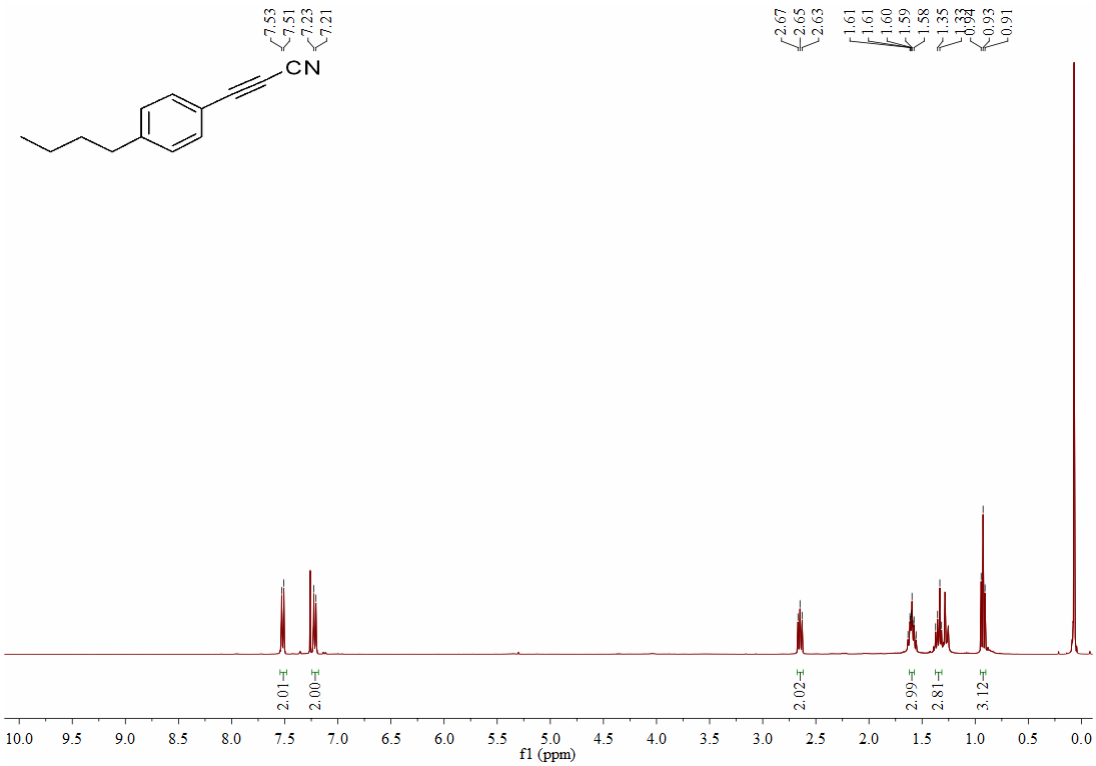


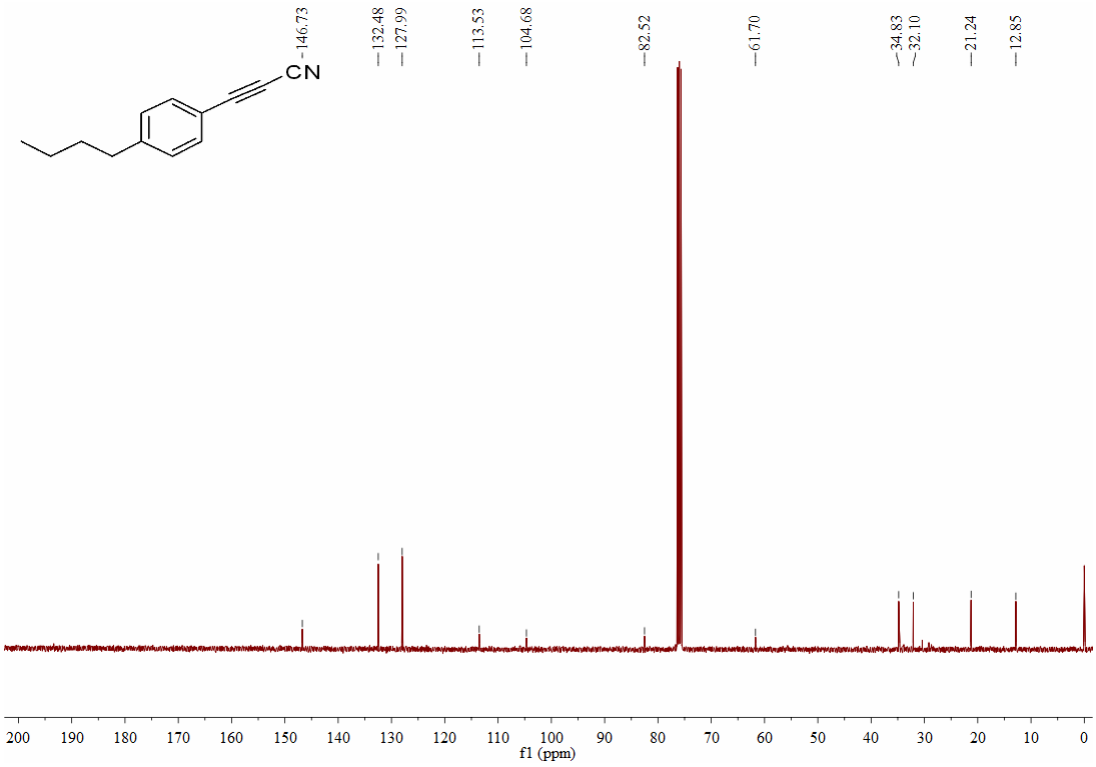


3-([1,1'-biphenyl]-4-yl)propiolonitrile (**3k**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

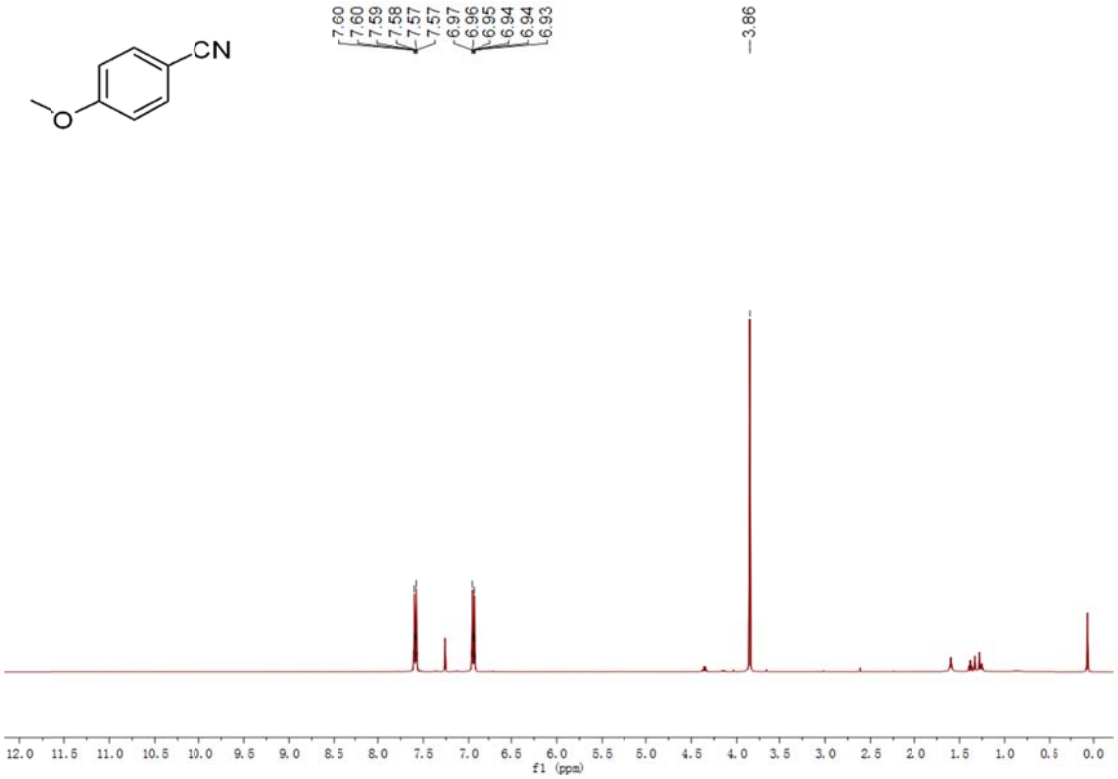


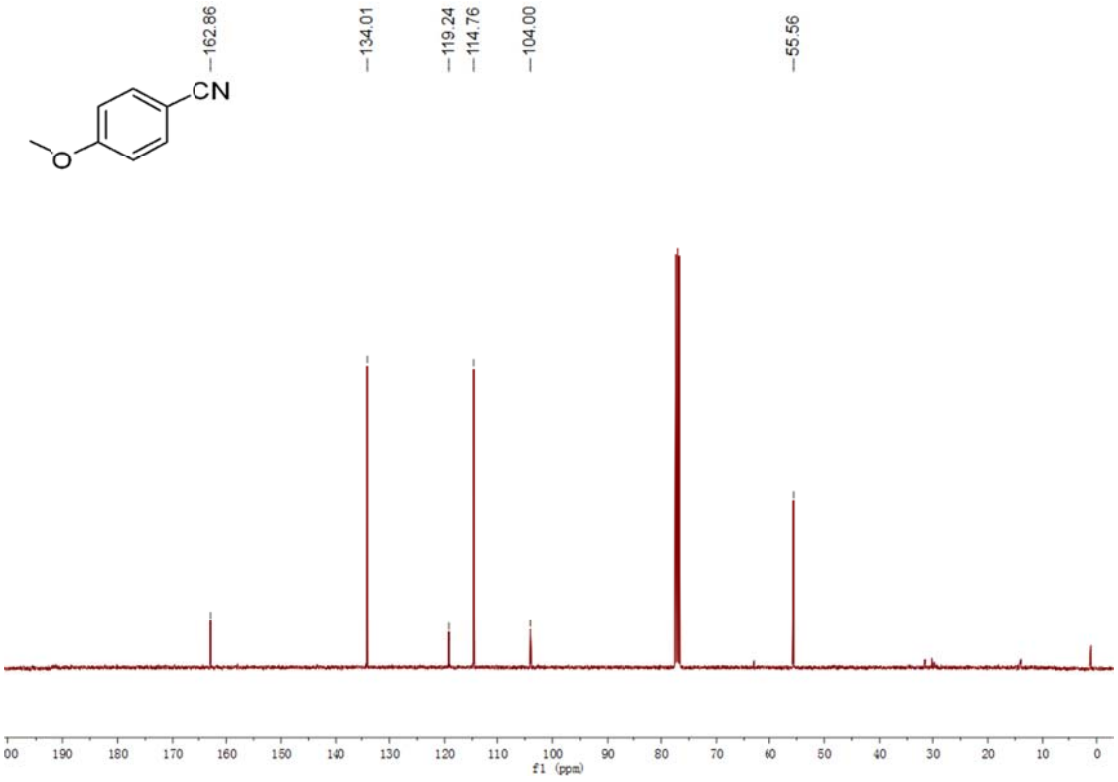
3-(4-butylphenyl)propiolonitrile (**3p**, ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



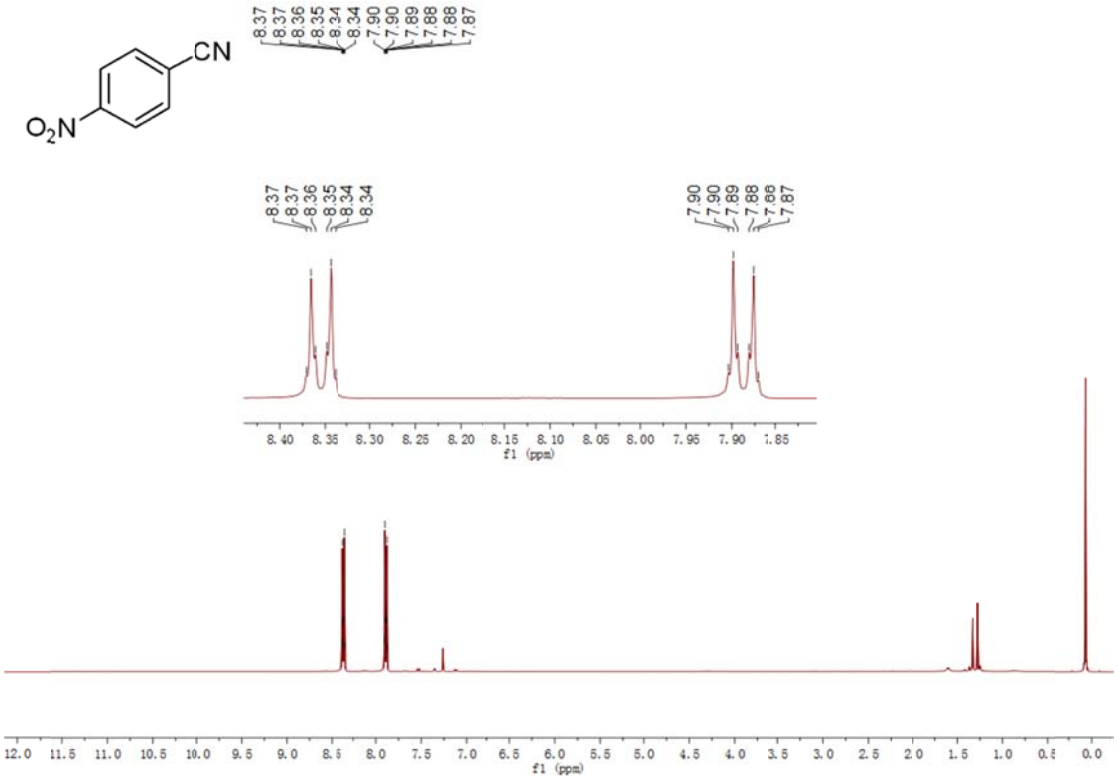


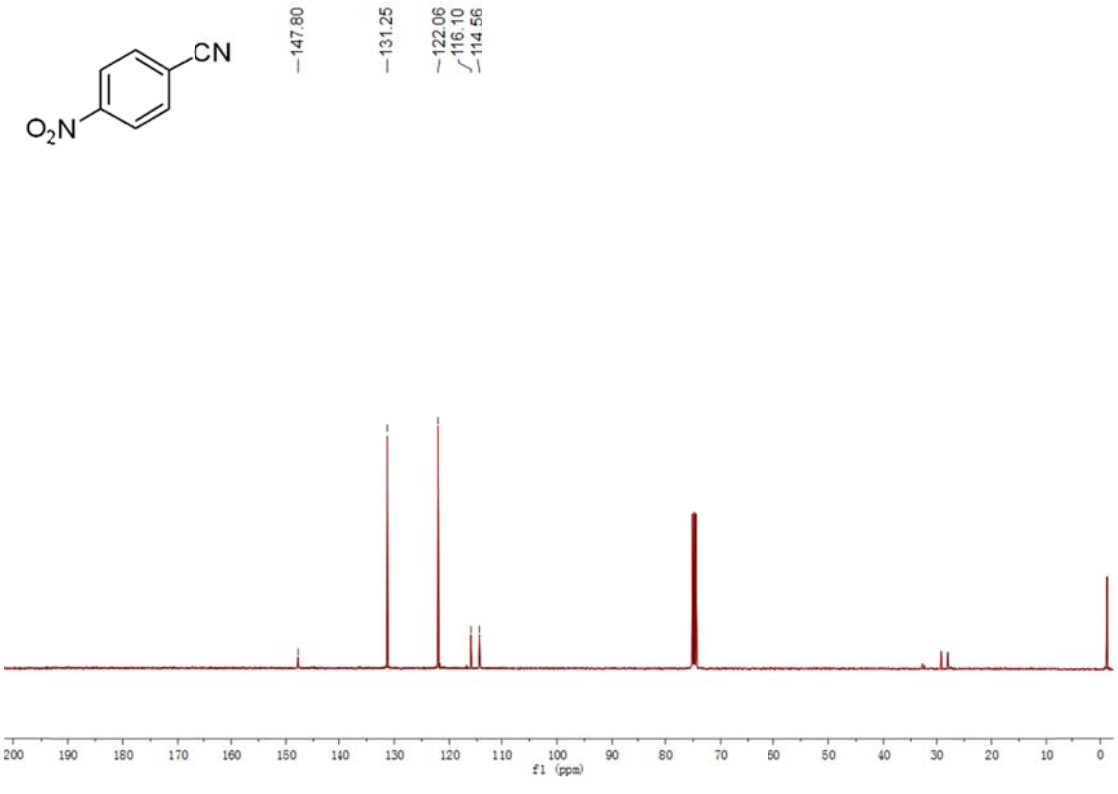
4-methoxybenzonitrile (**4a**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



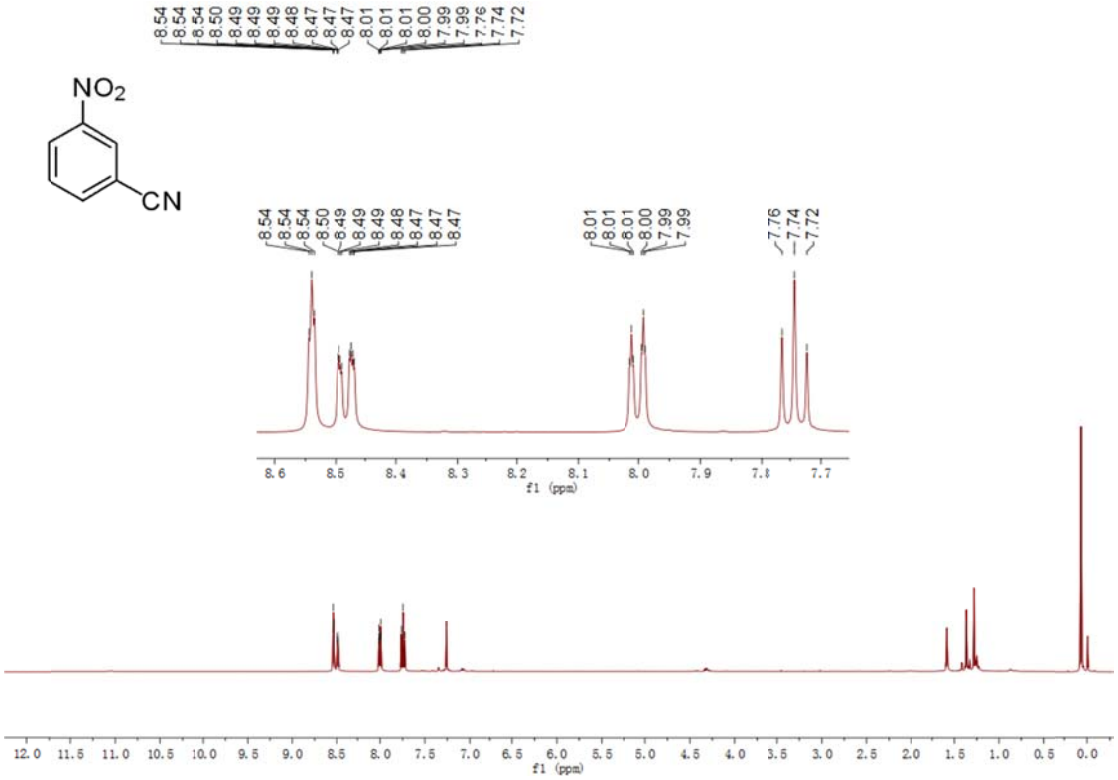


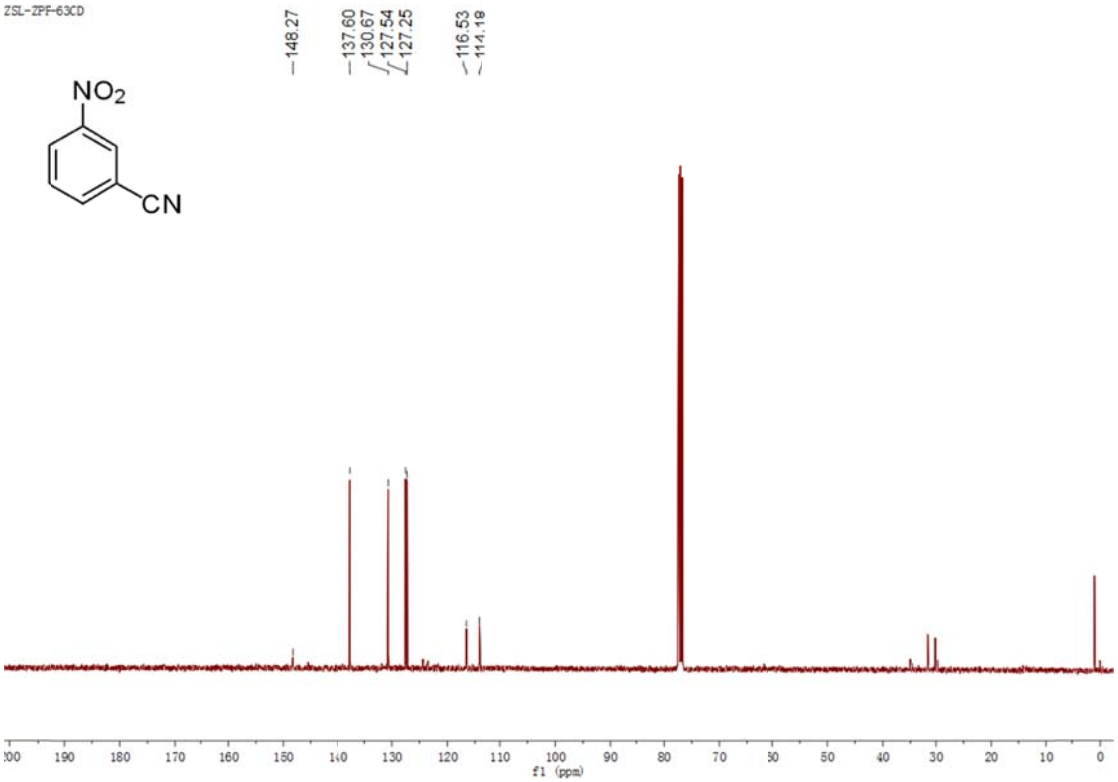
4-nitrobenzonitrile (**4b**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



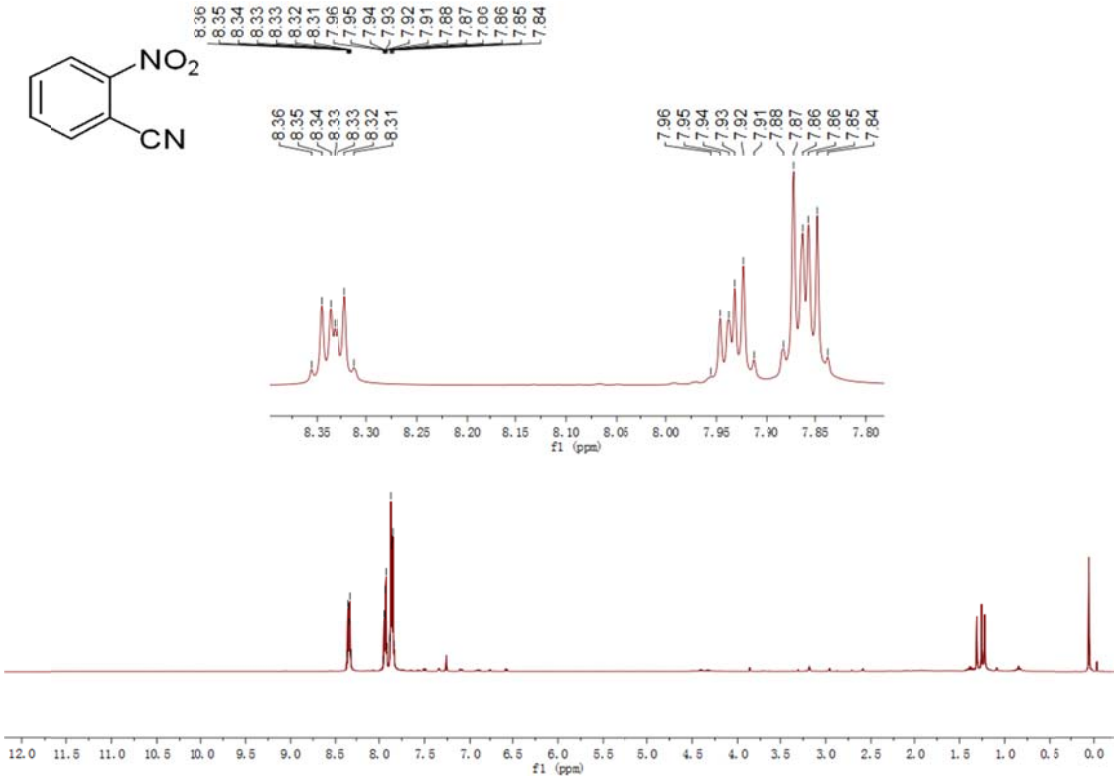


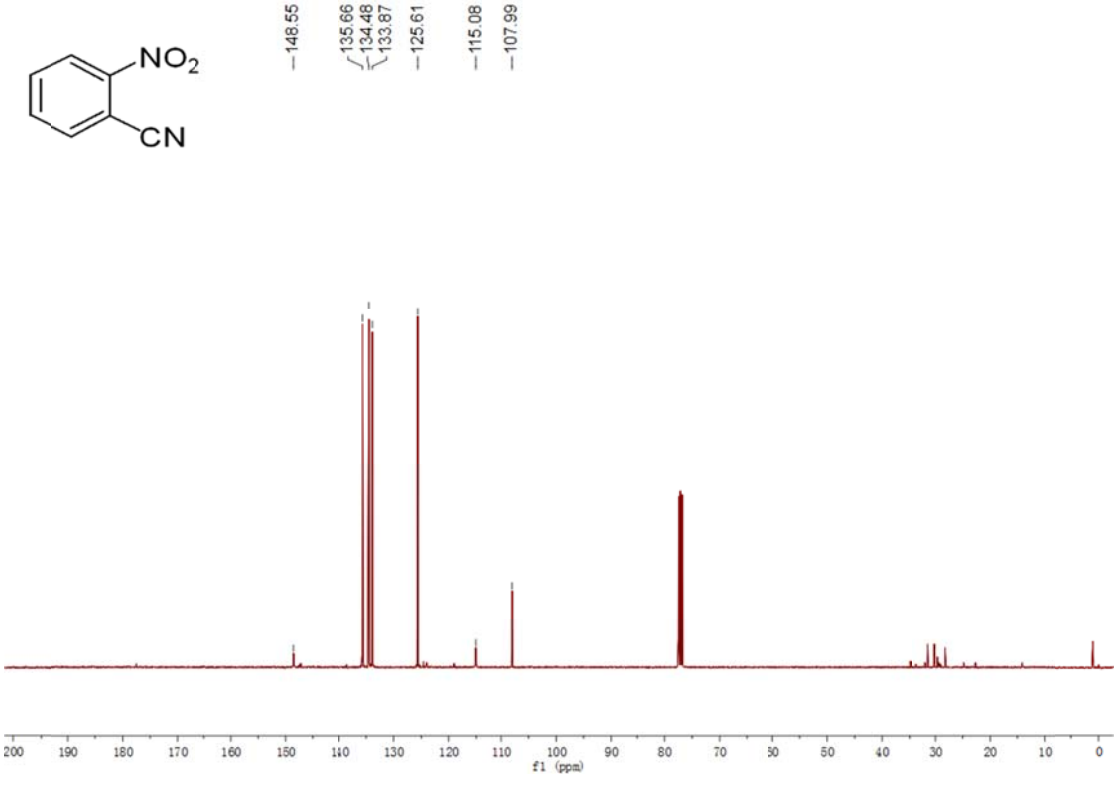
3-nitrobenzonitrile (**4c**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



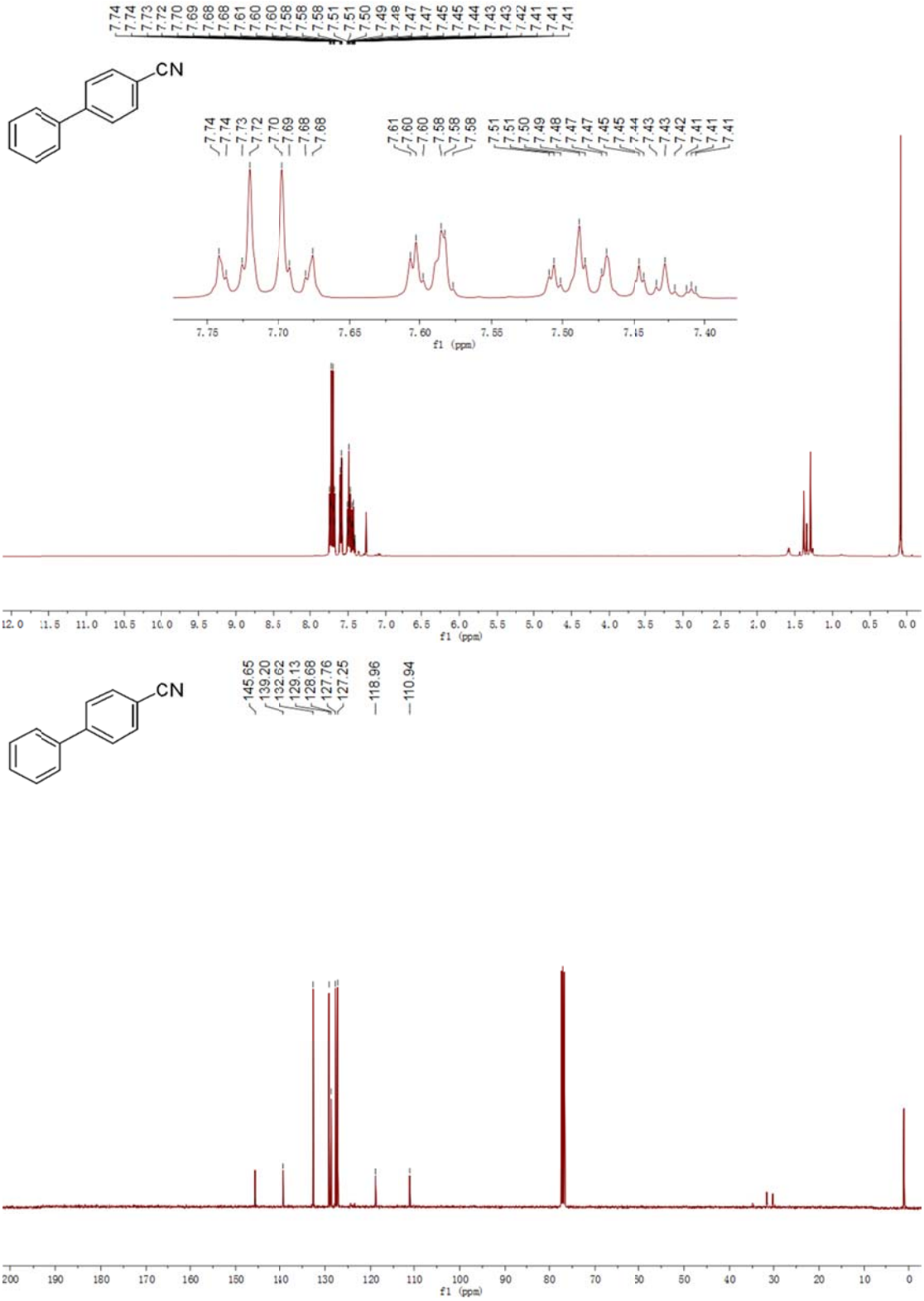


2-nitrobenzonitrile (**4d**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

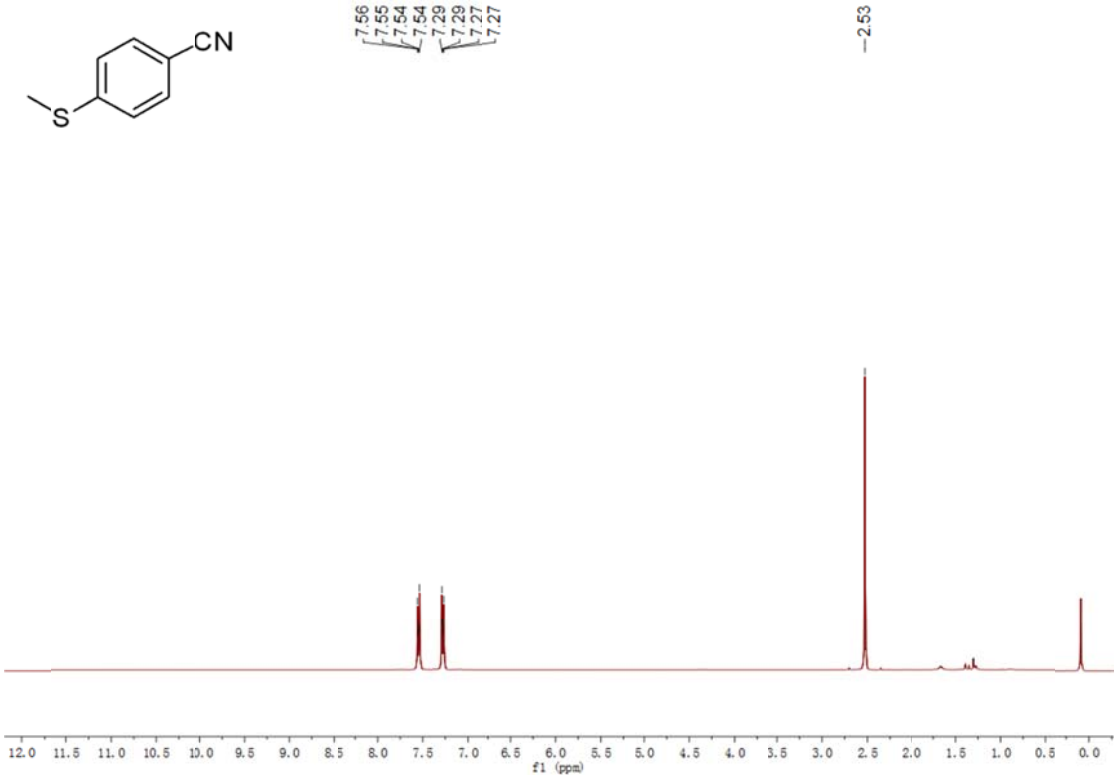


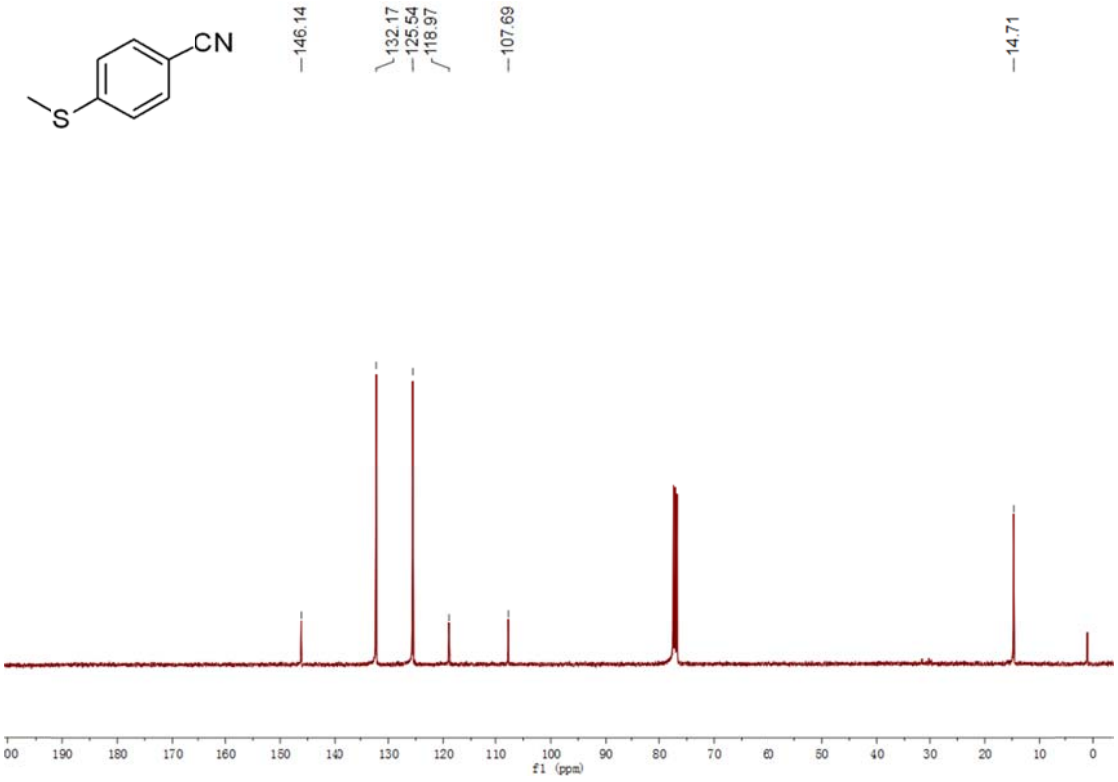


[1,1'-biphenyl]-4-carbonitrile (**4e**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

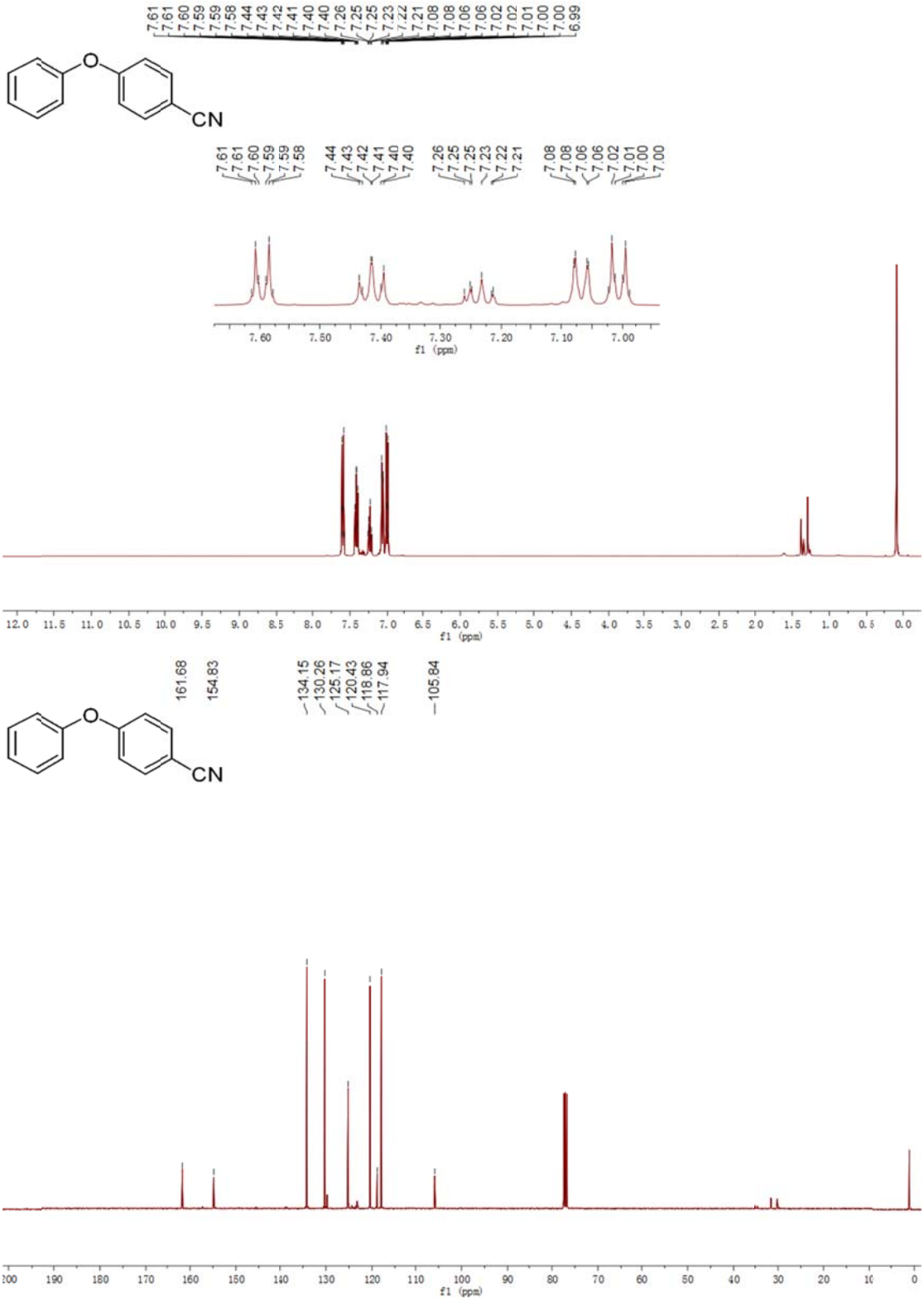


4-(methylthio)benzonitrile (**4f**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

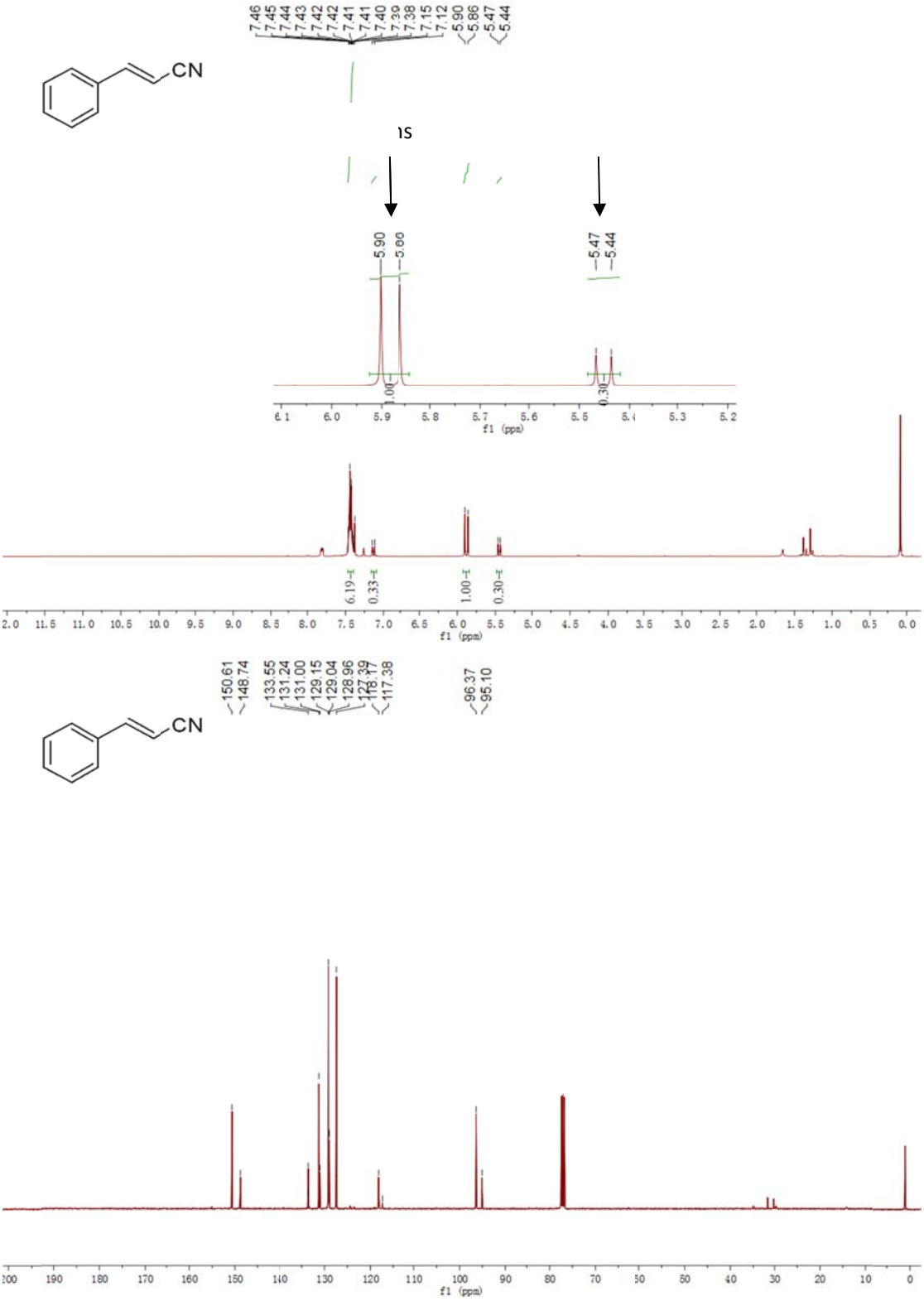




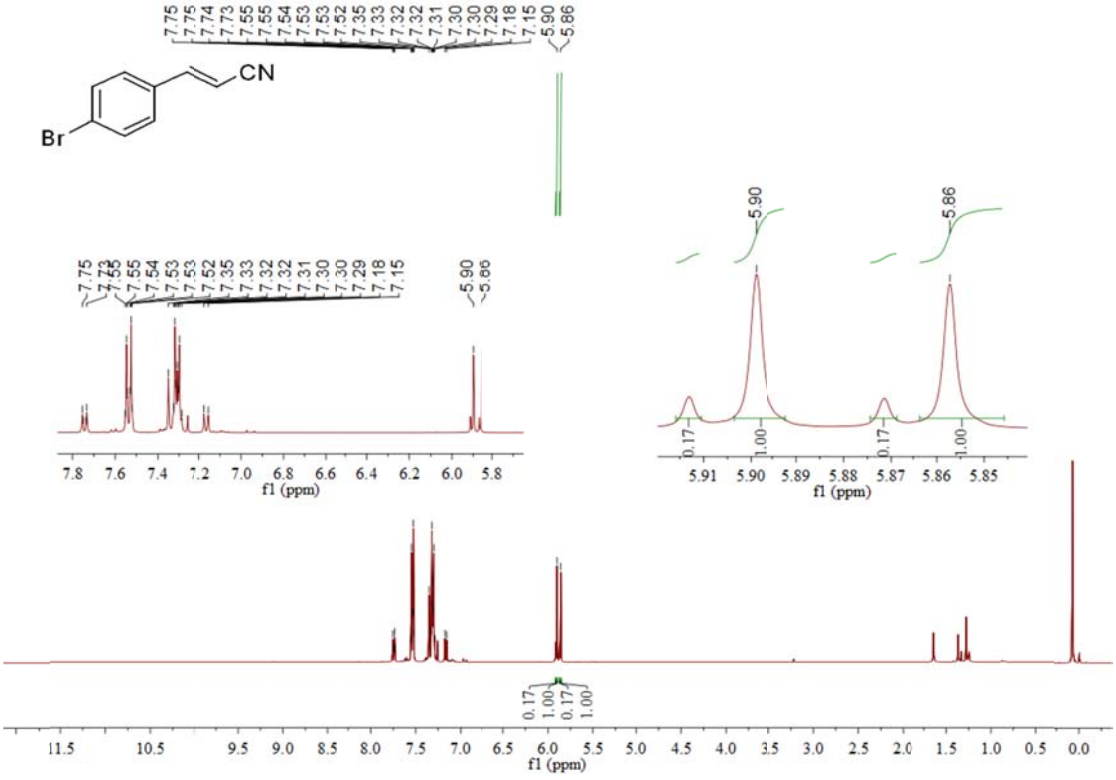
4-phenoxybenzonitrile (**4g**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).

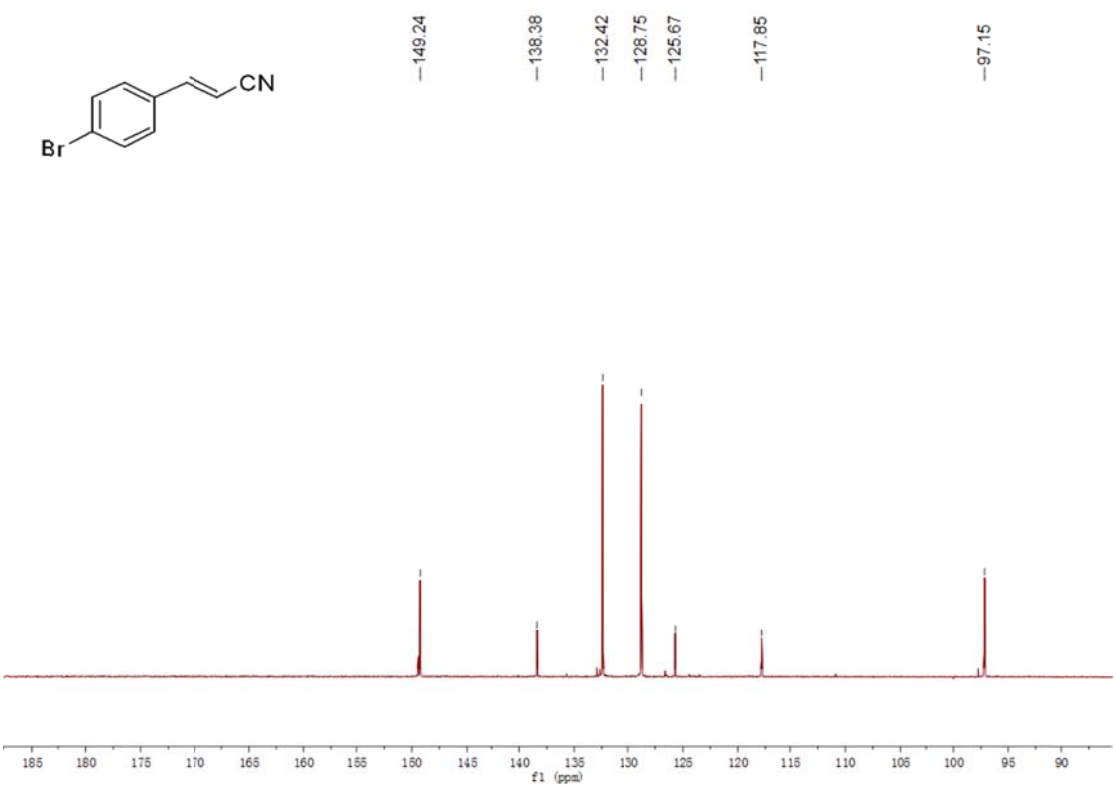


(E)-Cinnamonitrile (**4h**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$). (E/Z = 1:0.3)

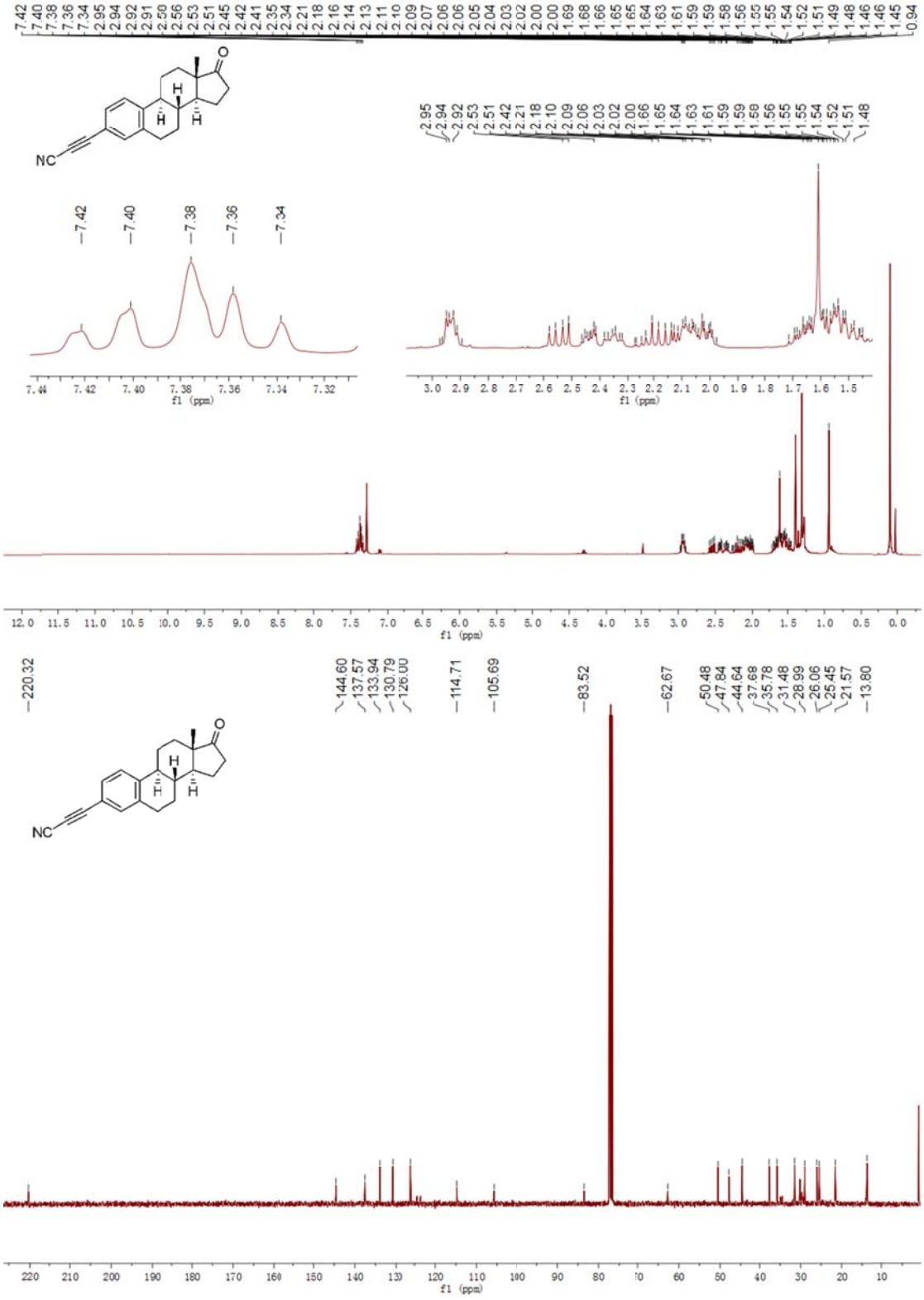


(E)-3-(4-bromophenyl)acrylonitrile (**4i**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$). (Contain minor amount of bis-cyanation byproduct in a ratio of ca 1:0.2)





3-((8*R*,9*S*,13*S*,14*S*)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6*H*-cyclopenta[*a*]phenanthren-3-yl)propiolonitrile (**6**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$).



(8*R*,9*S*,13*S*,14*S*)-3-acetyl-13-methyl-7,8,9,11,12,13,15,16-octahydro-6*H*-cyclopenta[*a*]phenanthren-17(14*H*)-one (**7**. ^{1}H NMR 400 MHz, $CDCl_3$; ^{13}C NMR 101 MHz, $CDCl_3$)