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Linhua Lu,[a] Prinessa Chellan,[b] Gregory S. Smith, *[b] Xiang Zhang,[a] Hong Yan,[a] and Jincheng Mao*[a]
[a]*Key Laboratory of Organic Synthesis of Jiangsu Province, College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou 215123, P. R. China*
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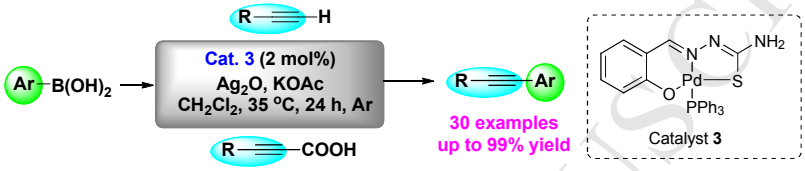

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ABSTRACT

An efficient catalytic system has been developed for the synthesis of unsymmetrical substituted alkynes *via* the thiosemicarbazone salicylaldiminato palladium(II)-catalyzed alkynylation couplings between arylboronic acids and alkynes or alkynyl carboxylic acids under mild conditions.

1. Introduction

Cross-coupling reactions are set of palladium catalyzed reactions that have proven useful for the syntheses of polymers,[1,2] natural products,[3] agrochemicals[4,5] and pharmaceuticals.[6,7] Generally, a Pd(II) complex is employed from which the active Pd(0) species is generated *in situ*. A drawback of many currently used palladium catalyst systems is decomposition of the catalyst giving rise to poor recyclability and impurities in the products.[8] Thus, it is of great importance to find a catalytic system that is stable while maintaining high chemo- and regio-selectivity and recyclability.

The study of thiosemicarbazone metal complexes has been mainly concerned with their biological activities [9-11] but in the last two decades increasing interest in their catalytic applications has arisen. Recent examples of their catalytic evaluations include a hydroxyquinoline thiosemicarbazone Ru(II) complex for the conversion of aldehydes to amides and oxidation of alkanes to alcohols and ketones [12] and dioxomolybdenum(VI) thiosemicarbazone complexes demonstrated activity in the epoxidation of olefins using *tert.*-butyl hydrogen peroxide.[13] Several mononuclear Pd(II) tridentate thiosemicarbazone complexes have been studied as pre-catalysts for a variety of cross-coupling reactions.[14-23] There are several factors that have contributed to this burgeoning interest including, the tridentate coordination of the thiosemicarbazone ligand is similar to pincer type Pd(II) complexes which have shown high efficiency as precatalysts for coupling reactions[24-27] and their high thermal stability in solution and in the solid state makes them ideal for high temperature homogenous catalysis.

It is well known that the Sonogashira reaction of terminal alkynes with aryl or alkenyl halides is the most powerful and straightforward approach for the formation of C(sp)–C(sp^2) bonds. In the past decades, various modifications on this coupling have been developed. For example, Pd-catalyzed cross-coupling reaction of arylboronic reagents with terminal alkynes was disclosed by several groups.[28-30] Very recently, Loh and co-workers successfully reported the first example of Pd-catalyzed decarboxylative cross-coupling of arylboronic acids and alkynyl carboxylic acids for the synthesis of unsymmetrical substituted alkynes.[31] Although the great progress has been made on alkynylations, the development of a general and efficient catalytic system remains highly desirable.

We have shown that the [O,N,S] tridentate salicylaldiminato thiosemicarbazone palladium catalysts **1**-**4** (Figure 1) were able to catalyse the Mizoroki-Heck coupling of methylacrylate and iodobenzene.[18] The best activity was observed for catalyst **2** and its use for the Heck coupling of other aryl halides and olefins gave yields of between 90 and 100%. Herein, we report the further evaluation of **1**-**4** as catalyst precursors for the

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alkynylation coupling of different various boronic acids and alkynes.

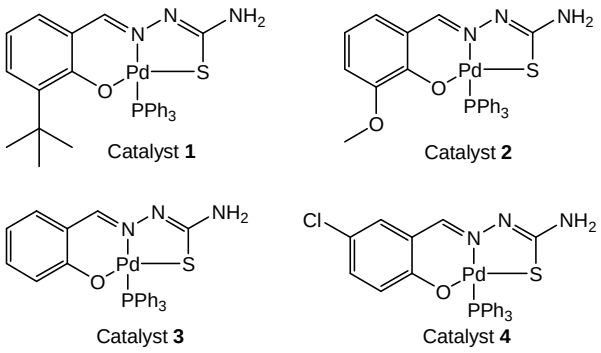


Figure 1. Pd(II) thiosemicarbazone catalysts **1-4.**

2. Results and discussion

Catalysts **1-4** were first evaluated for activity for the alkynylation coupling of 4-methoxy-phenylboronic acid and phenylacetylene in air (Entries 1-4, Figure 2) in order to determine the most active catalyst for further study. Catalysts **1** and **2**, which contain electron donating groups in the 3'-position, yielded moderate product yields of 47 and 45% respectively. Catalyst **4** gave a higher yield of 59% and catalyst **3** showed the best activity. The coupling reaction was repeated using catalyst **3** but under argon (Entry 5) and this led to a significant increase in the product yield to 76%. Thus, catalyst **3** was chosen for further analysis. Figure 3 contains the percent yields obtained while investigating different catalytic condition for catalyst **3**.

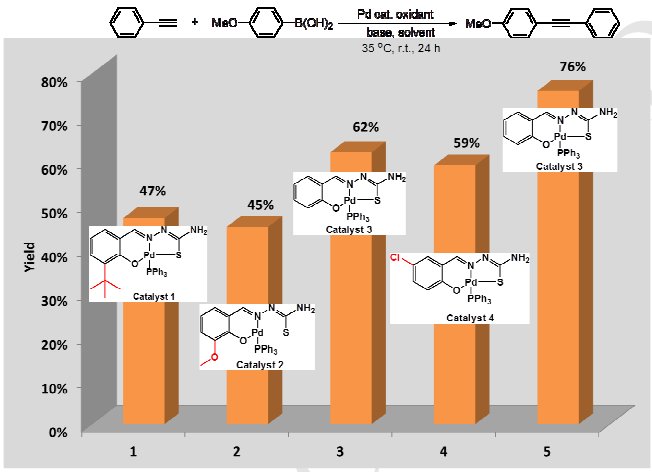


Figure 2. Screening of catalysts **1-4** for the alkynylation coupling of phenylacetylene and 4-methoxy(phenylacetylene). Reaction conditions: boronic acid (0.5 mmol), alkyne (0.6 mmol), Pd cat. (1 mol%), Ag_2O (2 equiv), NaOAc (2 equiv), CH_2Cl_2 (2 mL), 35 °C, 24 h, air (Entries 1-4) or argon (Entry 5). Isolated yield based on arylboronic acid.

A 2 mol% loading of catalyst was used and the reaction was carried out in DCM at 35 °C. When the catalyst loading of **3** was increased from 1 mol % (Entry 5, Figure 2) to 2 mol% (Entry 1, Figure 3) the total yield of product increases to 82%. Changing the oxidant (Entries 2-7) for the catalytic reactions revealed that no product was formed when silver nitrate, 1,4-benzoquinone (BQ), $K_2S_2O_4$ or *tert*-butyl hydroperoxide (TBHP) were used. When silver acetate (Entry 4) was used as oxidant a low yield of 46 % was obtained. A product yield of 70% is observed when silver carbonate was used (Entry 3) but this yield was still lower than that obtained for the catalytic reaction using silver oxide (Entry 1). Thus, silver oxide was identified as the best oxidant and the catalytic reaction was repeated using a 1 mol equivalent (Entry 8) to see if a decrease in oxidant effects the catalyst activity.

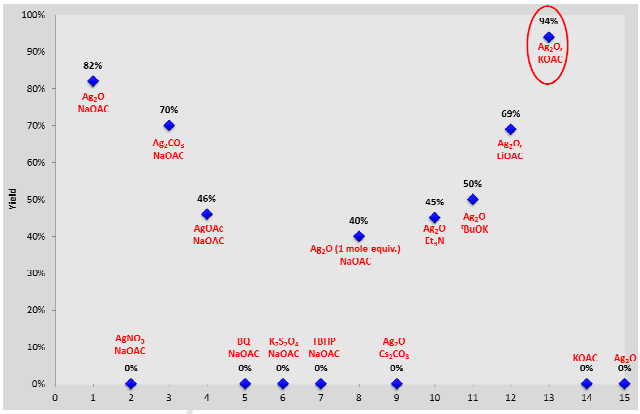
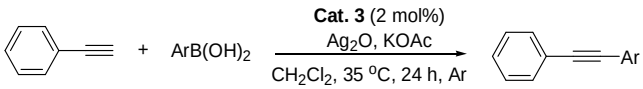
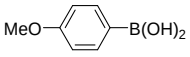
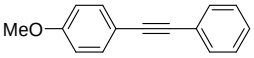
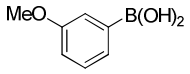
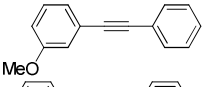
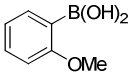
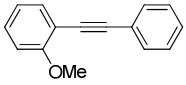
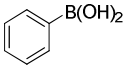
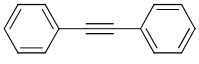
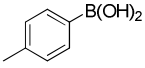
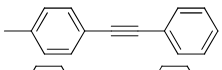
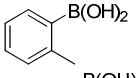
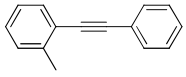
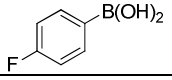
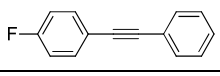


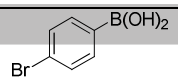
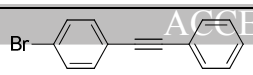
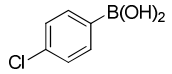
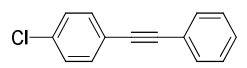
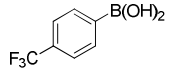
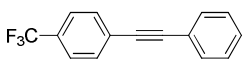
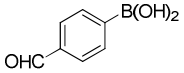
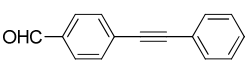
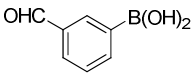
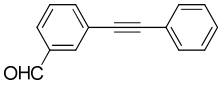
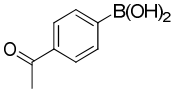
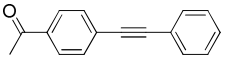
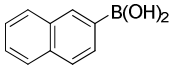
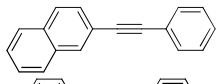
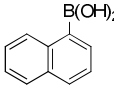
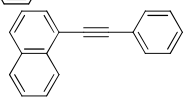
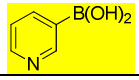
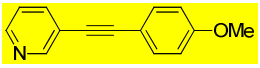
Figure 3. Screening of various bases and additives for the alkynylation coupling of phenylacetylene and 4-methoxy(phenylacetylene). Reaction conditions: boronic acid (0.5 mmol), alkyne (0.6 mmol), Pd cat.**3** (2 mol%), additive (2 equiv), base (2 equiv), CH_2Cl_2 (2 mL), 35 °C, 24 h. Isolated yield based on arylboronic acid.

Only 40% of product was obtained, less than half of what is obtained using 2 mol equivalents (Entry 1). Varying the base led to no product formation when cesium carbonate was used (Entry 9) and only moderate yields were obtained for potassium *tert*-butoxide, triethylamine and lithium acetate (Entries 10-12). When potassium acetate was used as base, the product yield increased to 94%. Overall, the best activity was observed when a 2 mol% catalyst loading was used with 2 mol equivalents of silver oxide and potassium acetate.

Table 1. Yields obtained for the alkynylation coupling reaction between phenylacetylene and different aryl boronic acids using catalyst **3**. [a]



Entry	Arylboronic acid	Product	Yield (%)[b]
1			94
2			90
3			63
4			99
5			85
6			64
7			92

8			96
9			93
10			73
11			96
12			93
13			83
14			92
15			30
16			40

[a] Catalytic conditions: arylboronic acid (0.5 mmol), phenylacetylene (0.6 mmol), Pd cat. (2 mol%), Ag_2O (2 equiv), KOAc (2 equiv), DCM (2 mL), 35 °C, 24 h, Ar. [b] Isolated yield based on arylboronic acid.

The optimal reactions conditions and reagents were then applied to the alkynylation coupling of phenylacetylene and different aryl bromides using catalyst **3** (Table 1). Similar product yields were obtained when 4-methoxyphenyl boronic acid or 3-methoxyphenylboronic acid was used (Entries 1 and 2), however when the methoxy substituent is in the 2'-position (Entry 3) a significant decrease in the yield was evident. A similar observation was noted for the coupling reactions using methylphenyl boronic acid, the yields decreased when the methyl substituent is in the 2'-position of the ring compared to the 4'-position (Entries 5 and 6). This large decrease in activity may be a consequence of steric effects imposed by the substituents in the 2'-positon hindering coordination of the boronic acid substrate to palladium. A decrease in percent yield from 96 to 92% was observed with an increase in electronegativity of the halide substituent (Entries 7 and 8). The trifluoromethyl substituent is a highly electron withdrawing group and a product yield of only 73% is observed for 4-trifluoromethyl-phenyl boronic acid (Entry 10). High product yields were also observed for the coupling reactions using formylphenyl boronic acid (Entries 11 and 12). For the two reactions using naphthyl boronic acid, large differences in the yields were noted depending on the position of the boronic acid substituent. A yield of 92% is obtained when the acid is in the 2'-position (Entry 14) and this decreases to 30% when it is in the 1'-position (Entry 15). When pyridin-3-yl-3-boronic acid was used as the substrate, the desired product was obtained in 40% yield (Entry 16).

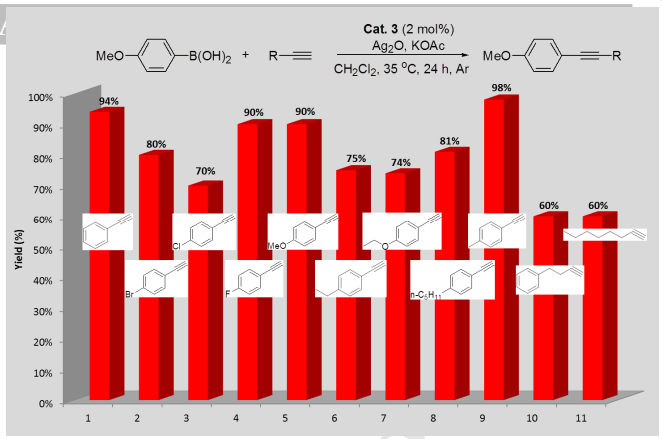
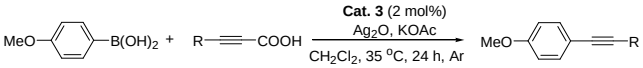
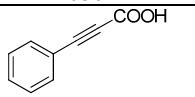
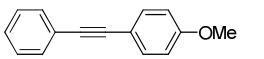
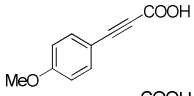
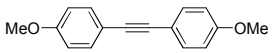
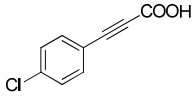
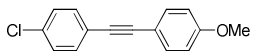
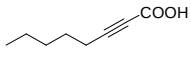
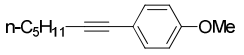


Figure 4. Yields obtained for alkynylation coupling of 4-methoxy(phenylboronic acid) with different terminal alkynes using catalyst **3**. Reaction conditions: 4-methoxyphenylboronic acid (0.5 mmol), terminal alkyne (0.6mmol), Pd cat. (2 mol%), Ag_2O (2 equiv), KOAc (2 equiv), DCM (2 mL), 35 °C, 24 h, argon, isolated yield based on arylboronic acid.

Evaluation of catalyst **3** for the coupling of 4-methoxy phenyl boronic acid and different alkynes revealed the best product yield was obtained for the substrate 4-ethynyl-toluene (Entry 9, Figure 4). Moderate to high yields were observed of all of the alkynylation reactions. A slightly lower yield is obtained when there is no substituent on the aromatic ring of the alkyne substrate (Entry 1) and increasing the chain length between the phenyl ring and the alkyne bond leads to a decrease in activity (Entry 10), a similar yield is observed when 1-octyne is the substrate. This suggests that the presence and proximity of the phenyl ring influences the catalytic activity of **3**. The reactions using halo-aryl-alkynes (Entries 2-4) gave yields ranging from 70 – 90%. A similar range in activity was obtained for the alkynyl substrates containing electron donating substituents (Entries 5-7). This observation proposes that catalyst **3** displays no selectivity toward electron-donating or withdrawing substituents.

Table 2. Yields obtained for the alkynylation coupling of 4-methoxy(phenylboronic acid) and different alkynyl carboxylic acids using catalyst **3** [a]



Entry	alkynyl carboxylic acid	product	Yield (%)[b]
1			80
2			95
3			70
4			81

[a] Catalytic conditions: 4-methoxyphenylboronic acid (0.5 mmol), terminal alkynyl carboxylic acid (0.6mmol), Ag_2O (2 equiv), KOAc (2 equiv), DCM (2 mL), 35 °C, 24h, Ar. [b] Isolated yield based on 4-methoxyphenylboronic acid.

The encouraging results obtained for the coupling reactions using boronic acids and alkynes led us to carry out a preliminary screen of catalyst **3** for the decarboxylative cross-coupling of several alkynyl carboxylic acids with arylboronic acids (Table 2). The results obtained show that catalyst **3** is able to catalyze these reactions with high product yields, particularly for the reactions using alkynyl carboxylic acids containing electron-donating substituents.

3. Conclusions

In summary, we have demonstrated that tridentate Pd(II) salicylaldiminato-thiosemicarbazone complexes are able to efficiently catalyze the alkynylation couplings of a variety of aryl boronic acids with alkynes or alkynyl carboxylic acids under mild conditions. In addition, this catalytic system is also suitable for the decarboxylative coupling of alkynyl carboxylic acids with arylboronic acids. This will result in this method for the speical application in some cases. These preliminary studies suggest that the easily prepared and stable Pd(II) catalysts of this type may be efficient for the synthesis of substituted alkynes. We are currently exploring these complexes' use for other palladium catalyzed coupling reactions.

4. Experiment

4.1 General information

All manipulations were carried out under argon atmosphere. Terminal alkynes were purchased from Acros Organics and used without further purification. Palladium complexes were prepared according to the literature.[18] Column chromatography was generally performed on silica gel (300-400 mesh) and reactions were monitored by thin layer chromatography (TLC) using UV light to monitor the course of the reactions. The ^{1}H (400 MHz) and ^{13}C NMR (100 MHz) data were recorded on Varian 400 M spectrometers using $CDCl_3$ as solvent. The chemical shifts (δ) are reported in ppm and coupling constants (*J*) in Hz. ^{1}H NMR spectra was recorded with tetramethylsilane (δ= 0.00 ppm) as internal reference; ^{13}C NMR spectra was recorded with $CDCl_3$ (δ = 77.00 ppm) as internal reference. MS were performed by the State-authorized Analytical Center in Soochow University.

4.2 General procedure for Pd-catalyzed coupling reaction between arylboronic acid and terminal alkyne or alkynyl carboxylic acid:

A mixture of arylboronic acid (0.5 mmol), terminal alkyne or alkynyl carboxylic acid (0.6 mmol), DCM (2 mL), catalyst **3** (2 mol%), Ag_2O (1.0 mmol), KOAc (1.0 mmol) in a Schlenk tube was stirred under an argon atmosphere at 35^{o}C for 24 h. The excess DCM was then removed by rotary evaporation and the residue was directly purified by flash column chromatography (petroleum ether or petroleum ether/ethyl acetate) to afford the corresponding coupling products.

1-Methoxy-4-(phenylethynyl)benzene[31] (Table 1, entry 1) (98 mg, 94% yield): White solid, mp: 80-81^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, *J* = 6.2 Hz, 2H), 7.49 (d, *J* = 8.7 Hz, 2H), 7.34 (d, *J* = 6.9 Hz, 3H), 6.89 (d, *J* = 8.4 Hz, 2H), 3.84 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.6, 133.0, 131.4, 128.3, 127.9, 123.6, 115.3, 114.0, 89.4, 88.1, 55.2.

1-Methoxy-3-(phenylethynyl)benzene[31] (Table 1, entry 2) (94 mg, 90% yield): White solid, mp: 77–78 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (dd, *J* = 4.6, 2.8 Hz, 2H), 7.38 (d, *J* = 5.2 Hz, 3H), 7.29 (t, *J* = 7.9 Hz, 1H), 7.18 (d, *J* = 7.6 Hz, 1H), 7.11 (s, 1H), 6.93 (d, *J* = 8.3 Hz, 1H), 3.84 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.3, 131.6, 129.4, 128.3, 128.3, 124.2, 124.2, 123.2, 116.3, 114.9, 89.3, 89.2, 55.2.

1-Methoxy-2-(phenylethynyl)benzene[32a] (Table 1, entry 3) (66 mg, 63% yield): Pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (dd, *J* = 24.5, 6.8 Hz, 3H), 7.33 (dd, *J* = 14.0, 6.0 Hz, 4H), 6.99–6.89 (m, 2H), 3.93 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.9, 133.6, 131.7, 129.8, 128.2, 128.0, 123.5, 120.4, 112.4, 110.6, 93.4, 85.7, 55.8.

Diphenyl acetylene[31] (Table 1, entry 4) (88 mg, 99% yield): White solid, mp: 60–61 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65–7.58 (m, 4H), 7.44–7.36 (m, 6H).^{13}C NMR (100 MHz, $CDCl_3$) δ 131.6, 128.4, 128.3, 123.3, 89.5.

1-(2-*p*-Tolylethynyl)benzene[31] (Table 1, entry 5) (82 mg, 85% yield): White solid, mp: 73–74 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (s, 2H), 7.51 (d, *J* = 7.3 Hz, 2H), 7.39 (s, 3H), 7.21 (d, *J* = 6.7 Hz, 2H), 2.42 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.4, 131.5, 131.5, 129.1, 128.3, 128.1, 123.5, 120.2, 89.6, 88.8, 21.5.

1-(2-*o*-Tolylethynyl)benzene[31] (Table 1, entry 6) (61 mg, 64% yield): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (dd, *J* = 15.1, 7.2 Hz, 3H), 7.44–7.35 (m, 3H), 7.28 (d, *J* = 3.7 Hz, 2H), 7.23 (dd, *J* = 6.8, 4.7 Hz, 1H), 2.58 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.2, 131.9, 131.5, 129.5, 128.4, 128.3, 128.2, 125.6, 123.6, 123.1, 93.4, 88.4, 20.8.

1-(2-(4-Fluorophenyl)ethynyl)benzene[31] (Table 1, entry 7) (90 mg, 92% yield): White solid, mp: 109–111 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58–7.53 (m, *J* = 11.7, 5.9, 3.2 Hz, 4H), 7.37 (dd, *J* = 12.0 Hz, 10.0Hz, 3H), 7.07 (dd, *J* = 8.6, 7.8 Hz, 2H).;^{13}C NMR (75 MHz, $CDCl_3$) δ 161.5 (d, *J* = 248.2 Hz), 132.5 (d, *J* = 8.3 Hz), 130.6, 127.4, 127.4, 122.1, 118.4 (d, *J* = 3.0 Hz), 114.7 (d, *J* = 22.5 Hz), 88.1, 87.3.

1-Bromo-4-(phenylethynyl)benzen[32b] (Table 1, entry 8) (123 mg, 96% yield): White solid, mp: 82–83 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56–7.50 (m, 2H), 7.48 (d, *J* = 8.1 Hz, 2H), 7.42–7.31 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.1, 131.6, 131.6, 128.5, 128.4, 122.9, 122.5, 122.3, 90.5, 88.3.

1-Chloro-4(phenylethynyl)benzene[32c] (Table 1, entry 9) (99 mg, 93% yield): White solid, mp: 81–82 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (dd, *J* = 6.1, 2.6 Hz, 2H), 7.48 (d, *J* = 8.3 Hz, 2H), 7.41–7.30 (m, 5H).^{13}C NMR (100 MHz, $CDCl_3$) δ 134.2, 132.8, 131.6, 128.7, 128.5, 128.4, 122.9, 121.7, 90.3, 88.2.

1-(Phenylethynyl)-4-(trifluoromethyl)benzene[32b] (Table 1, entry 10) (90 mg, 73% yield): White solid, mp: 101–103 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67–7.59 (m, 4H), 7.56 (dd, *J* = 4.4, 1.9 Hz, 2H), 7.42–7.31 (m, 3H).^{13}C NMR (75 MHz, $CDCl_3$)) δ 131.8, 131.7, 130.0 (d, *J* = 33.0 Hz), 128.8, 128.4, 127.1 (d, *J* = 1.5 Hz), 125.3 (q, *J* = 3.8 Hz), 123.9 (d, *J* = 270. 0 Hz), 122.5, 91.7, 88.0.

4-(Phenylethynyl)benzaldehyde[32d] (Table 1, entry 11) (99 mg, 96% yield): White solid, mp: 98–100 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.99 (s, 1H), 7.84 (d, *J* = 7.8 Hz, 2H), 7.66 (d, *J* = 8.0 Hz, 2H), 7.56 (dd, *J* = 3.4, 2.9 Hz, 2H), 7.37 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.6, 135.3, 132.0, 131.7, 129.6, 128.9, 128.43, 128.41, 122.4, 93.5, 88.5.

3-(Phenylethynyl)benzaldehyde[32b] (Table 1, entry 12) (96 mg, 93% yield): yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.00 (s,

1H), 8.02 (s, 1H), 7.82 (d, *J* = 7.7 Hz, 1H), 7.76 (d, *J* = 7.7 Hz, 1H), 7.55 (dd, *J* = 4.0, 1.8 Hz, 2H), 7.50 (t, *J* = 7.7 Hz, 1H), 7.39–7.34 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.5, 137.0, 136.4, 132.9, 131.6, 129.0, 128.8, 128.6, 128.4, 124.4, 122.6, 90.9, 87.8.

1-(4-(Phenylethynyl)phenyl)ethanone[32d] (Table 1, entry 13) (91 mg, 83% yield): White solid, mp: 98–99 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, *J* = 7.9 Hz, 2H), 7.63–7.51 (m, 4H), 7.36 (s, 3H), 2.59 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.2, 136.1, 131.7, 131.6, 128.8, 128.4, 128.2, 128.1, 122.6, 92.7, 88.6, 26.5.

2-(2-Phenylethynyl)naphthalene[31] (Table 1, entry 14) (105 mg, 92% yield): White solid, mp: 113–115 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (s, 1H), 7.86 (dd, *J* = 8.6, 4.5 Hz, 3H), 7.66 (d, *J* = 7.0 Hz, 3H), 7.59–7.49 (m, 2H), 7.42 (d, *J* = 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.0, 132.8, 131.7, 131.5, 128.43, 128.41, 128.3, 128.0, 127.8, 126.7, 126.6, 123.3, 120.6, 89.9, 89.8.

1-(2-Phenylethynyl)naphthalene[31] (Table 1, entry 15) (34 mg, 30% yield): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.50 (d, *J* = 8.3 Hz, 1H), 7.89 (t, *J* = 9.0 Hz, 2H), 7.81 (dd, *J* = 7.1, 1.1 Hz, 1H), 7.73–7.67 (m, 2H), 7.64 (dd, *J* = 8.2, 6.9 Hz, 1H), 7.60 – 7.55 (m, 1H), 7.50 (d, *J* = 8.2 Hz, 1H), 7.46–7.37 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.23, 133.18, 131.6, 130.3, 128.7, 128.41, 128.37, 128.3, 126.8, 126.4, 126.2, 125.3, 123.4, 120.9, 94.3, 87.5.

4-Phenylethynylpyridine[32c] (Table 1, entry 16) (36 mg, 40% yield): Yellow solid, mp: 50–51 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.77 (s, 1H), 8.54 (d, *J* = 4.3 Hz, 1H), 7.80 (d, *J* = 7.7 Hz, 1H), 7.54 (d, *J* = 2.8 Hz, 2H), 7.36 (s, 3H), 7.31–7.23 (m, 1H);^{13}C NMR (75 MHz, $CDCl_3$) δ 151.2, 147.5, 137.5, 130.7, 128.0, 127.4, 122.0, 121.5, 119.5, 91.7, 84.9.

1-Bromo-4-(2-(4-methoxyphenyl)ethynyl)benzene[31] (Figure 4, entry 2) (114 mg, 80% yield): White solid, mp: 154–156 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 (d, *J* = 8.8 Hz, 4H), 7.37 (d, *J* = 8.4 Hz, 2H), 6.88 (d, *J* = 8.5 Hz, 2H), 3.82 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.8, 133.1, 132.9, 131.6, 122.6, 122.1, 115.0, 114.1, 90.6, 87.1, 55.3.

1-Chloro-4-((4-methoxyphenyl)ethynyl)benzene[32e] (Figure 4, entry 3) (85 mg, 70% yield): White solid, mp: 114–116 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (dd, *J* = 13.6, 8.5 Hz, 4H), 7.31 (d, *J* = 8.5 Hz, 2H), 6.89 (d, *J* = 8.7 Hz, 2H), 3.82 (s, 3H).^{13}C NMR (75 MHz, $CDCl_3$) δ 158.8, 132.8, 132.1, 131.6, 127.6, 121.1, 114.0, 113.1, 89.4, 86.0, 54.3.

1-Fluoro-4-((4-methoxyphenyl)ethynyl)benzene[32e] (Figure 4, entry 4) (102 mg, 90% yield): White solid, mp: 83–85 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55–7.45 (m, 4H), 7.04 (t, *J* = 8.6 Hz, 2H), 6.89 (d, *J* = 8.6 Hz, 2H), 3.81 (s, 3H).^{13}C NMR (75 MHz, $CDCl_3$) δ 161.3 (d, ^1J = 247.5 Hz), 158.7, 132.3 (d, ^3J = 8.3 Hz), 132.0, 118.7 (d, ^4J = 3.0 Hz), 114.7, 114.3 (d, ^2J = 20.3 Hz), 113.0, 88.1, 86.0, 54.2.

1,2-Bis(4-methoxyphenyl)ethyne[31] (Figure 4, entry 5) (107 mg, 90% yield): White solid, mp: 140–142 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 8.5 Hz, 4H), 6.87 (d, *J* = 8.6 Hz, 4H), 3.82 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 159.3, 134.0, 115.6, 113.9, 87.9, 55.2.

1-Ethyl-4-((4-methoxyphenyl)ethynyl)benzene (Figure 4, entry 6) (89 mg, 75% yield): Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 (t, *J* = 8.8 Hz, 4H), 7.20 (d, *J* = 7.6 Hz, 2H), 6.90 (d, *J* = 8.6 Hz, 2H), 3.82 (s, 3H), 2.68 (q, *J* = 7.4 Hz, 2H), 1.27 (t, *J* = 7.6 Hz, 3H).^{13}C NMR (100 MHz, $CDCl_3$) δ 159.4, 144.3, 132.9, 131.4, 127.9, 120.7, 115.5, 113.9, 88.7, 88.2, 55.2, 28.8, 15.4. MS ESI$^+$ (m/z): $[M+H]^+$ calcd for $[C_{17}H_{17}O]^+$ requires 237.1, found 237.1.

1-Ethoxy-4-((4-methoxyphenyl)ethynyl)benzene (Figure 4, entry 7) (93 mg, 74% yield): White solid, mp: 138–139 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53–7.39 (m, 4H), 6.87 (dd, *J* = 8.8, 5.3 Hz, 4H), 4.03 (q, *J* = 7.0 Hz, 2H), 3.81 (s, 3H), 1.42 (t, *J* = 7.0 Hz, 3H).^{13}C NMR (75 MHz, $CDCl_3$) δ 158.3, 157.8, 133.0, 131.9, 114.7, 114.5, 113.5, 112.9, 87.0, 86.9, 62.5, 54.3, 13.8. MS (ESI$^+$): calcd. for $[C_{17}H_{17}O_2]^+$ requires m/z 253.1, found $[M+H]^+$: 253.2.

1-Methoxy-4-((4-pentylphenyl)ethynyl)benzene[32g] (Figure 4, entry 8) (113 mg, 81% yield): White solid, mp: 44–45°C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 (dd, *J* = 13.4, 8.2 Hz, 4H), 7.17 (d, *J* = 7.9 Hz, 2H), 6.89 (d, *J* = 8.5 Hz, 2H), 3.83 (s, 3H), 2.66 – 2.58 (m, 2H), 1.68–1.58 (m, 2H), 1.42–1.28 (m, 4H), 0.92 (t, *J* = 6.8 Hz, 3H).^{13}C NMR (100 MHz, $CDCl_3$) δ 159.4, 143.0, 132.9, 131.3, 128.4, 120.7, 115.6, 113.9, 88.7, 88.2, 55.2, 35.8, 31.4, 30.9, 22.5, 14.0.

1-Methoxy-4-(p-tolylethynyl)benzene[32e] (Figure 4, entry 9) (109 mg, 98% yield): White solid, mp: 126–130 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 8.8 Hz, 2H), 7.41 (d, *J* = 8.1 Hz, 2H), 7.14 (d, *J* = 7.9 Hz, 2H), 6.87 (d, *J* = 8.8 Hz, 2H), 3.82 (s, 3H), 2.17 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.4, 137.1, 131.9, 130.3, 128.0, 119.4, 114.6, 112.9, 87.6, 87.2, 54.3, 20.5.

1-Methoxy-4-(4-phenylbut-1-yn-1-yl)benzene[32e] (Figure 4, entry 10) (71 mg, 60% yield): Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44–7.25 (m, 7H), 6.86 (d, *J* = 8.6 Hz, 2H), 3.82 (d, *J* = 1.0 Hz, 3H), 2.97 (t, *J* = 7.5 Hz, 2H), 2.73 (t, *J* = 7.6 Hz, 2H).^{13}C NMR (100 MHz, $CDCl_3$) δ 159.1, 140.8, 132.8, 128.5, 128.3, 126.3, 116.0, 113.8, 87.9, 81.0, 55.2, 35.3, 21.7.

1-Hexyl-4-((4-methoxyphenyl)ethynyl)benzene[32f] (Figure 4, entry 11) (65 mg, 60% yield): Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.6 Hz, 2H), 6.82 (d, *J* = 8.6 Hz, 2H), 3.79 (s, 3H), 2.39 (t, *J* = 7.1 Hz, 2H), 1.65–1.55 (m, 2H), 1.51–1.42 (m, 2H), 1.39–1.26 (m, 4H), 0.92 (t, *J* = 6.9 Hz, 3H).^{13}C NMR (100 MHz, $CDCl_3$) δ 158.9, 132.7, 116.2, 113.7, 88.7, 80.2, 55.1, 31.3, 28.8, 28.6, 22.5, 19.34, 14.0.

1-(Hept-1-ynyl)-4-methoxybenzene[31] (Table 3, entry 4) (82 mg, 81% yield): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.7 Hz, 2H), 6.81 (d, *J* = 8.7 Hz, 2H), 3.78 (s, 3H), 2.39 (t, *J* = 7.1 Hz, 2H), 1.67–1.56 (m, 2H), 1.49–1.31 (m, 4H), 0.94 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.9, 132.8, 116.2, 113.7, 88.7, 80.2, 55.1, 31.1, 28.5, 22.2, 19.3, 13.9.

Acknowledgments

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Supporting Information

Thiosemicarbazone Salicylaldiminato Palladium(II)-Catalyzed Alkynylation Couplings between Arylboronic Acids and Alkynes or Alkynyl Carboxylic Acids

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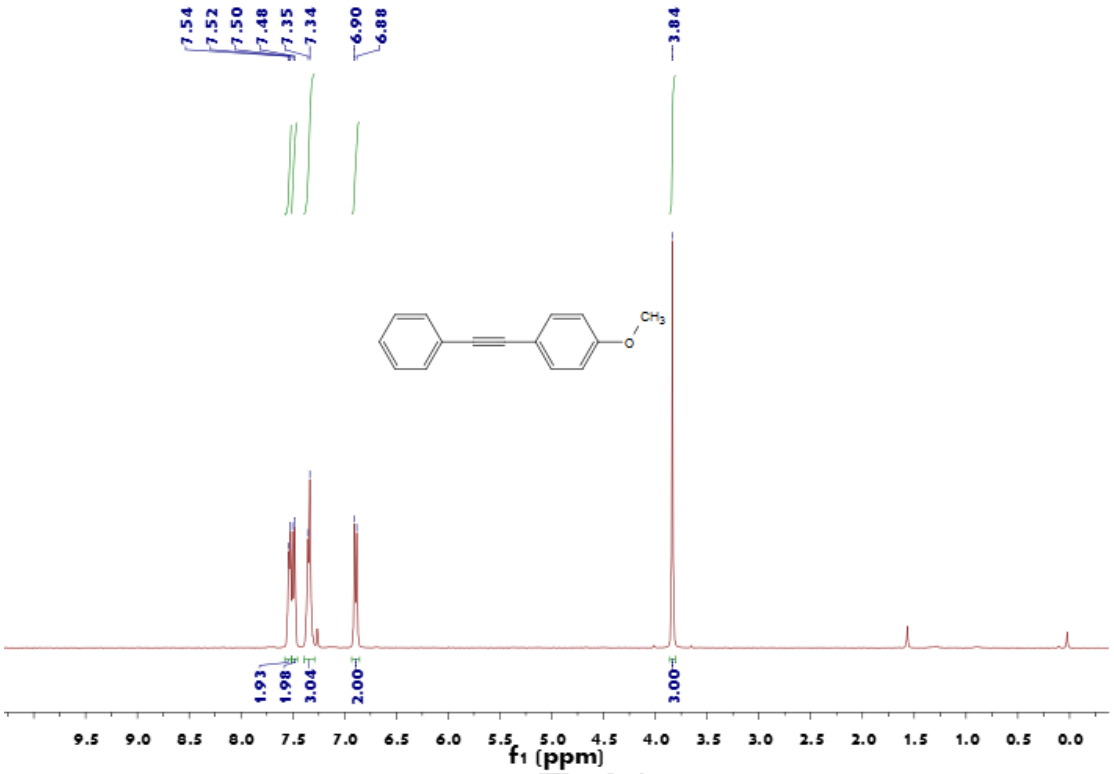
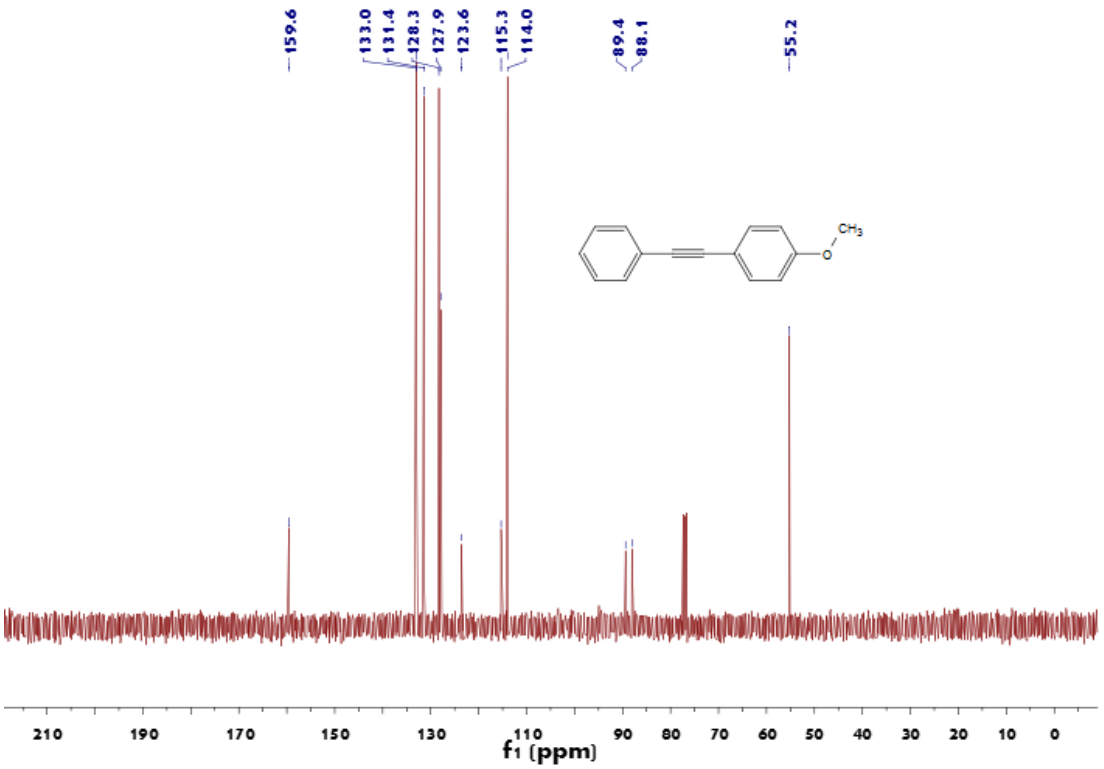
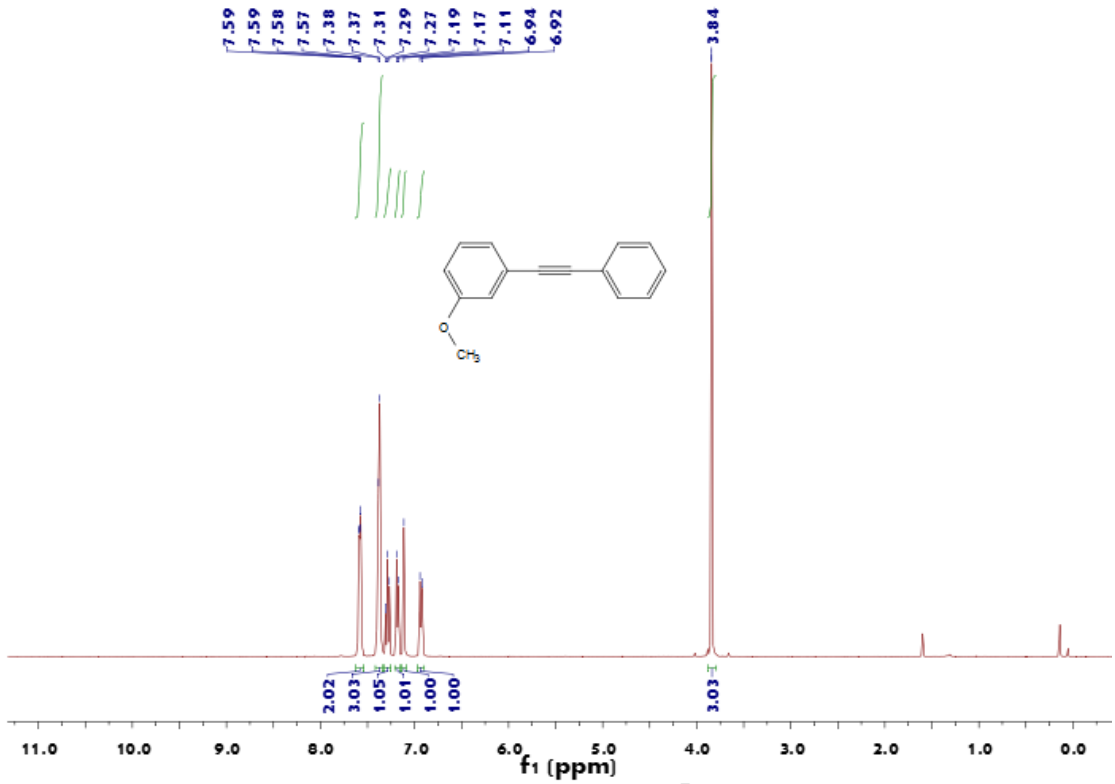
Content

Copies of ^{1}H and ^{13}C NMR Spectra for desired products



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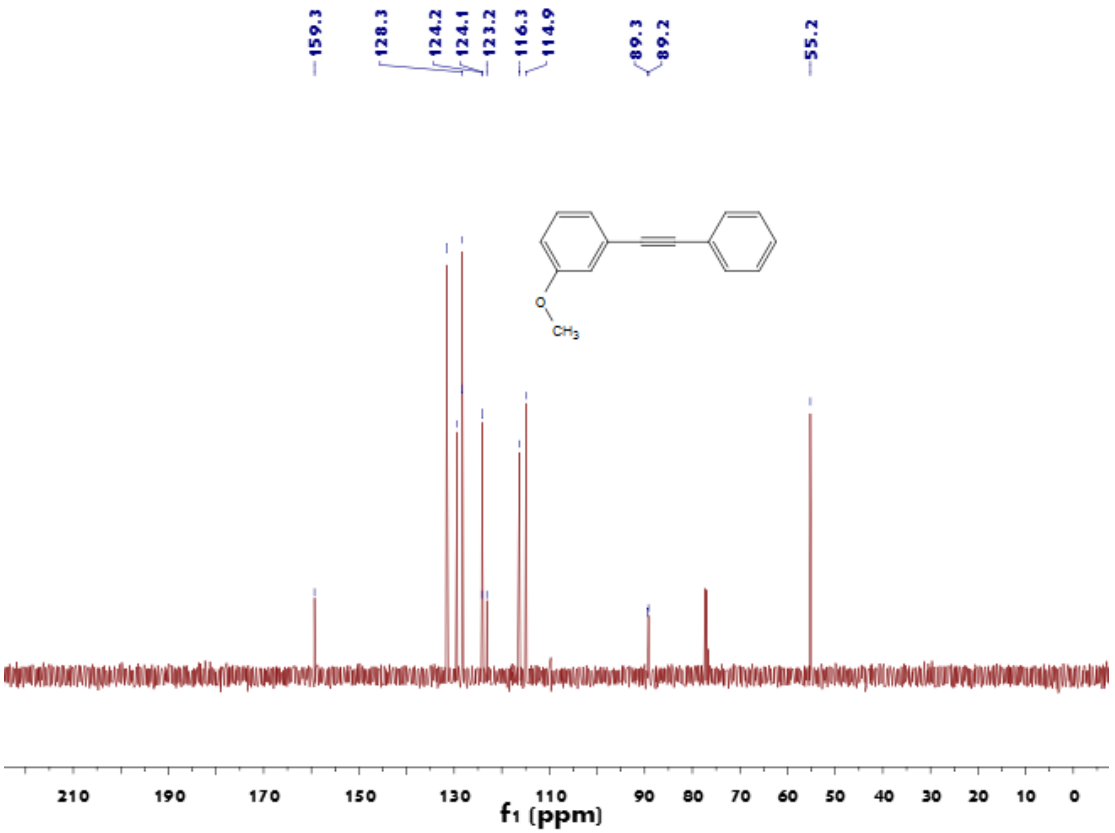
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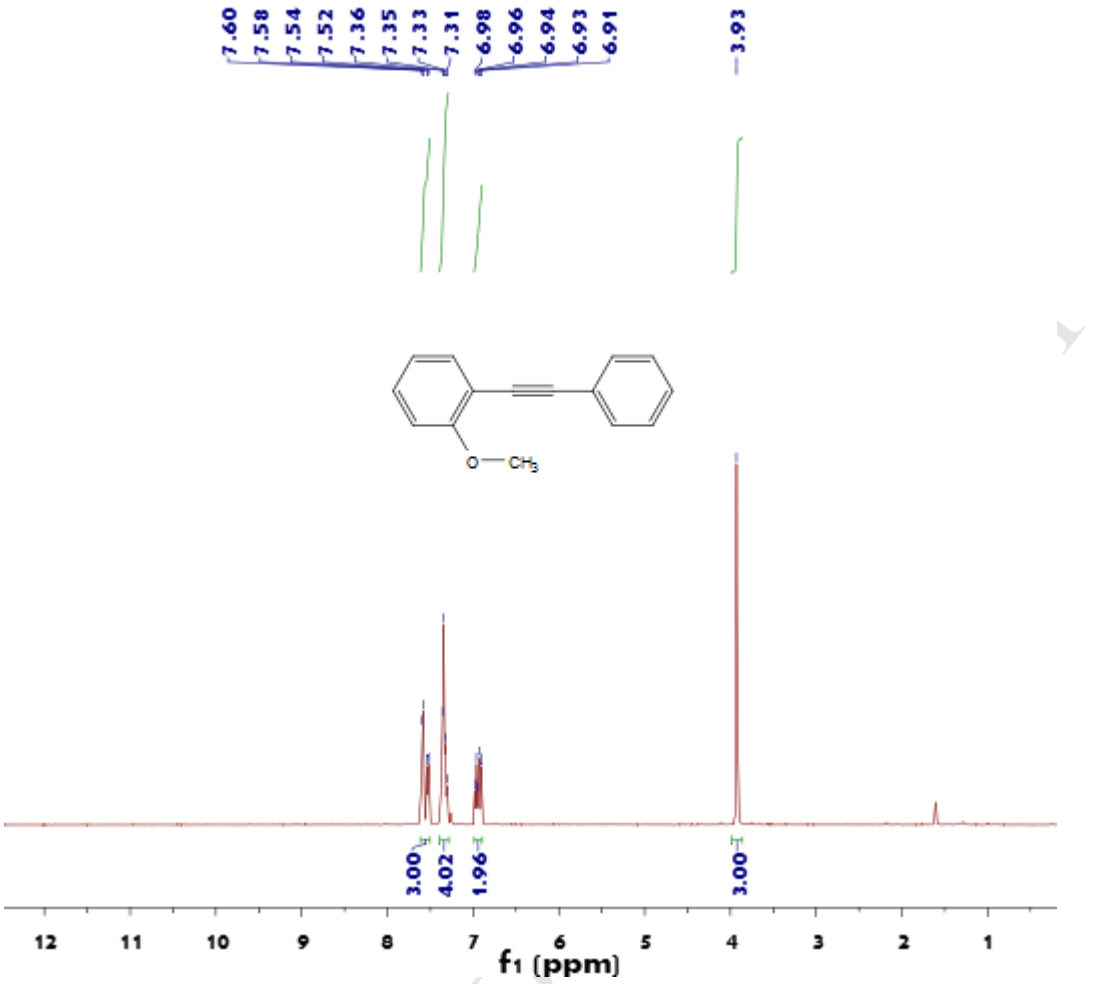
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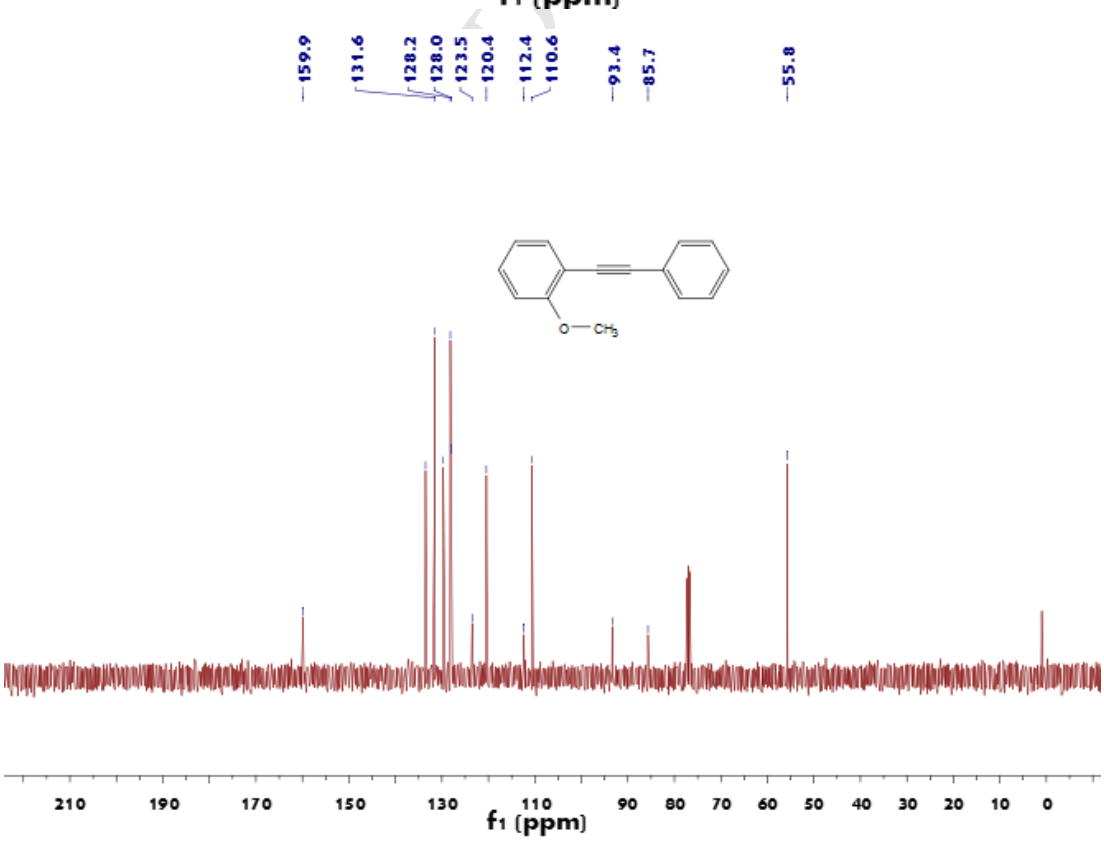
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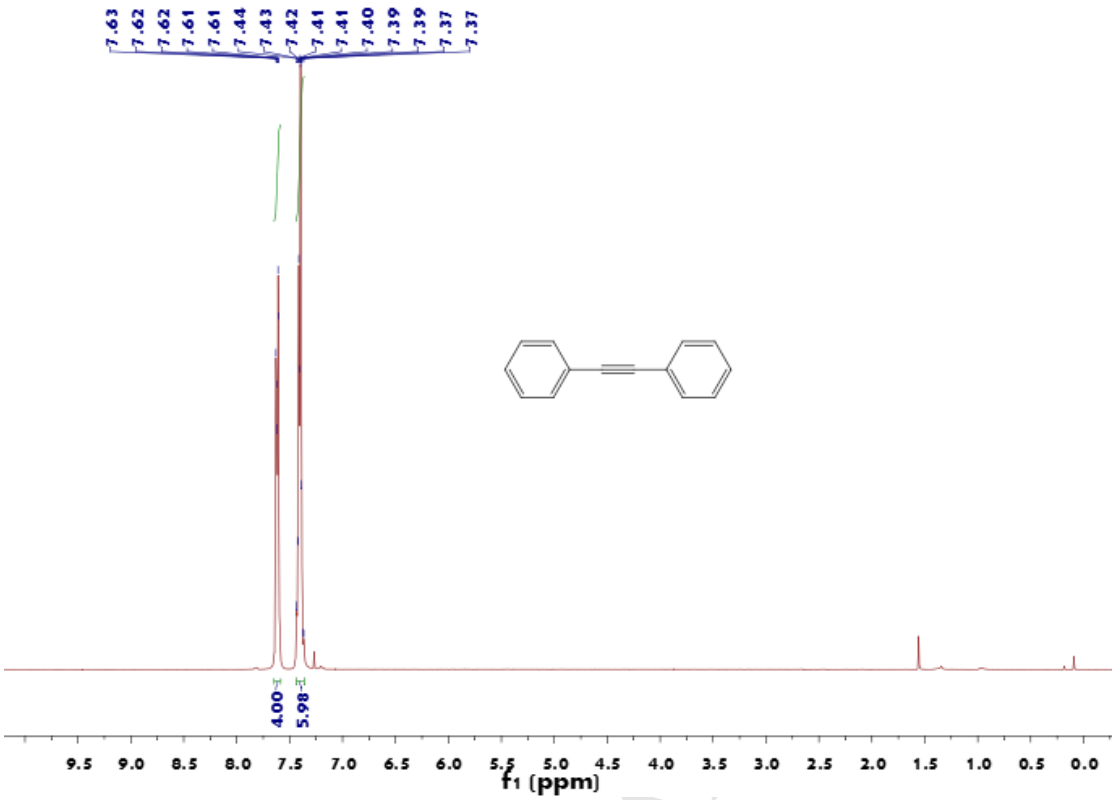
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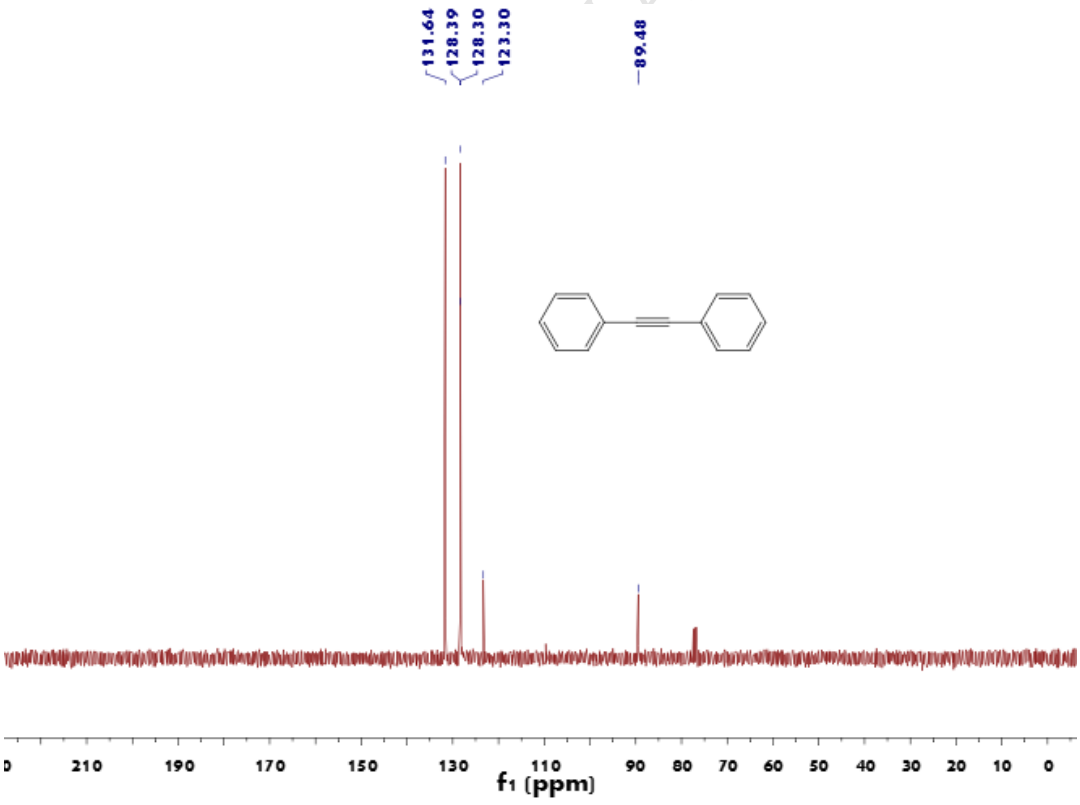
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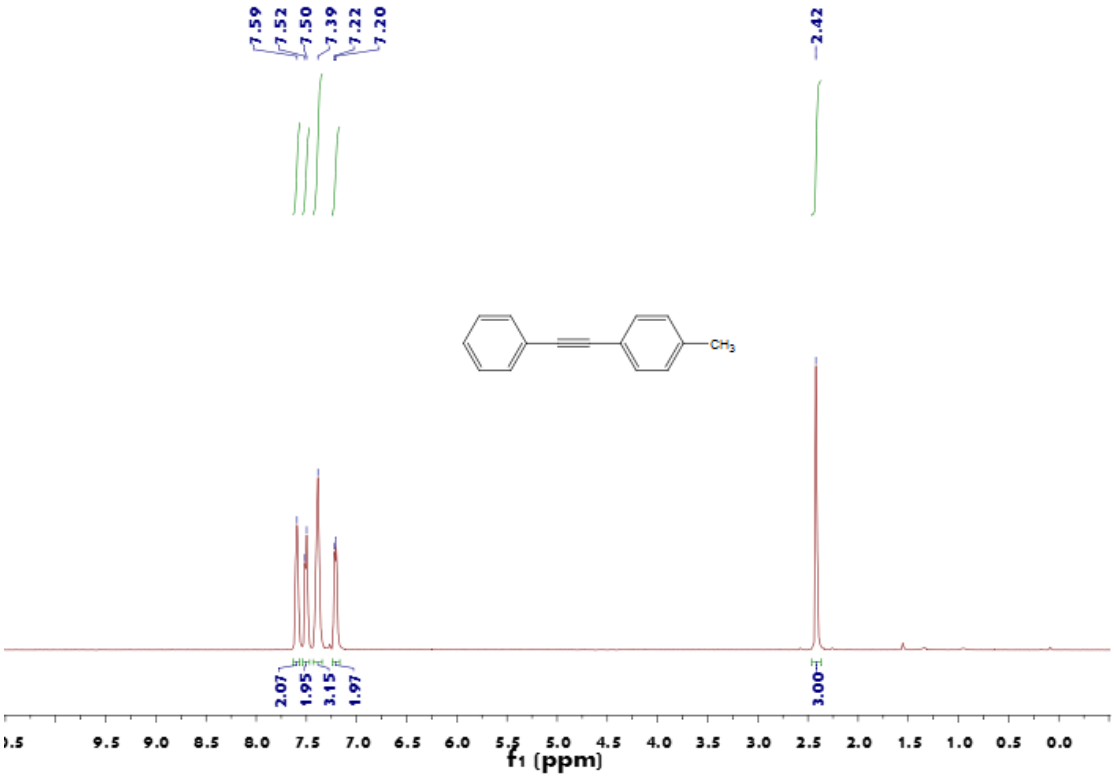
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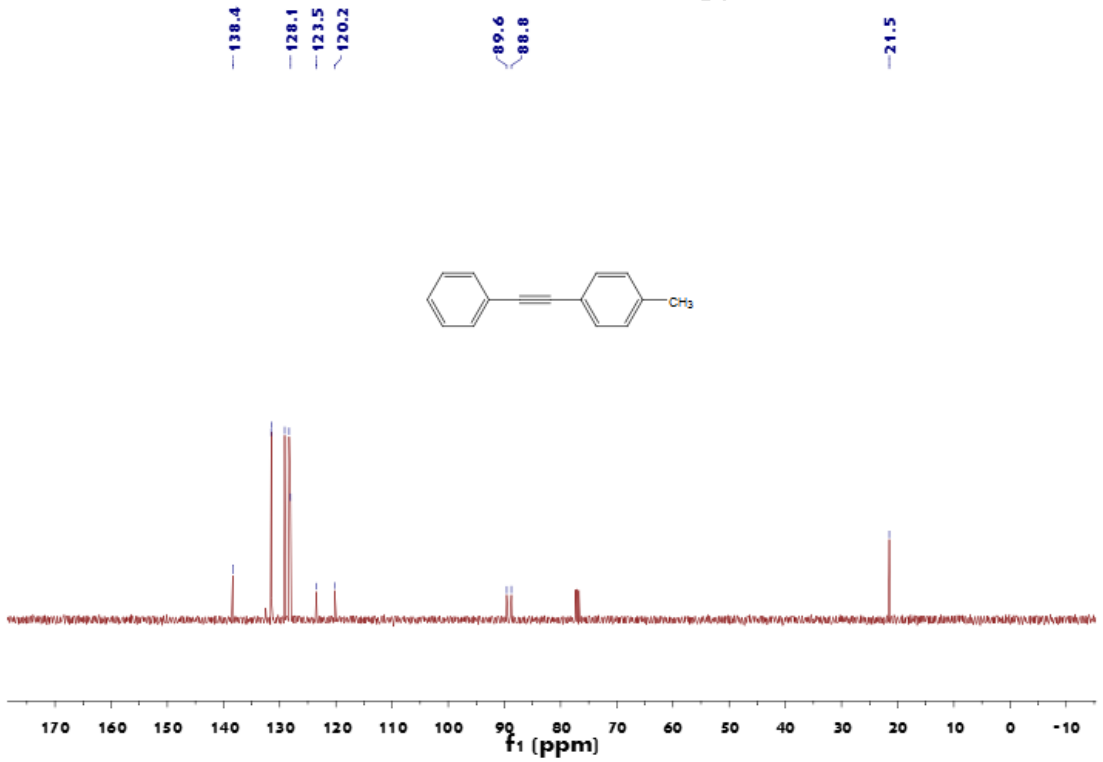
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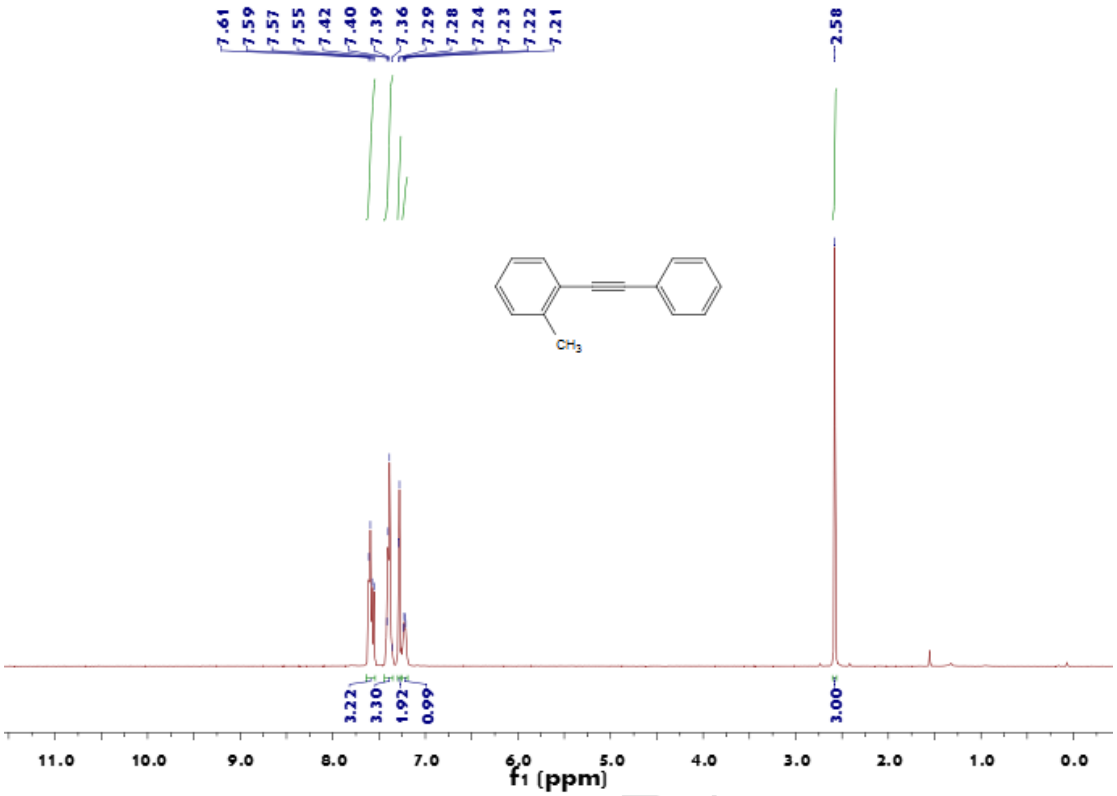
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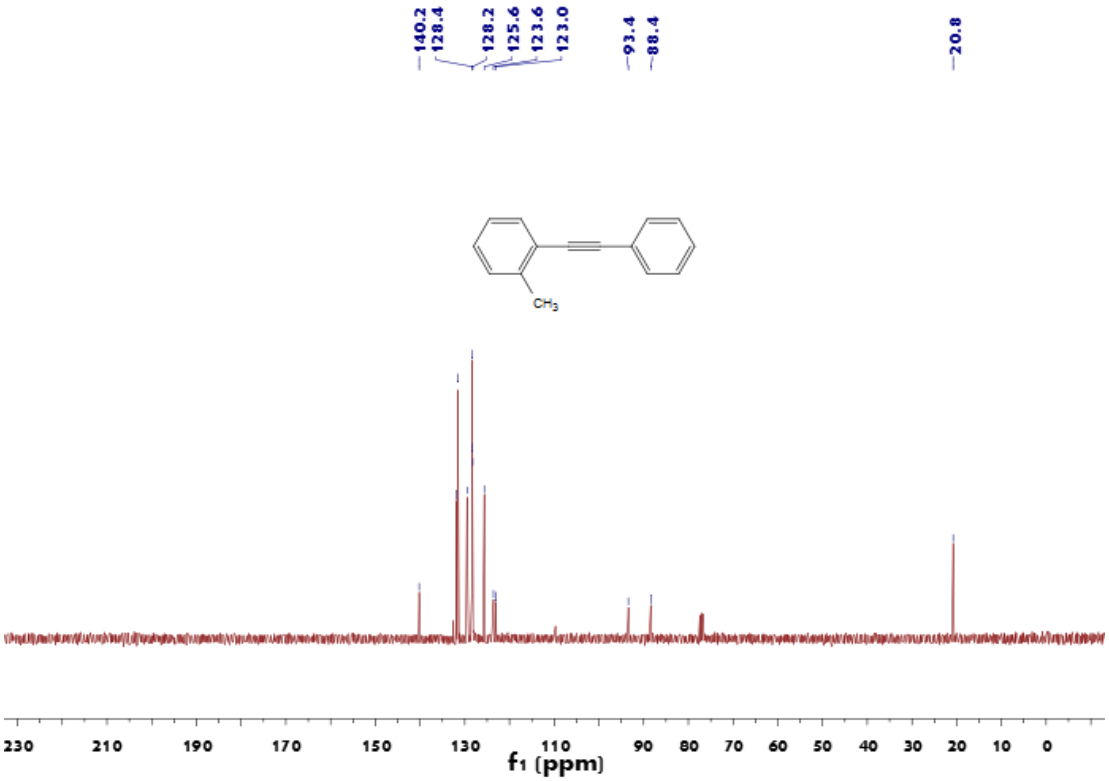
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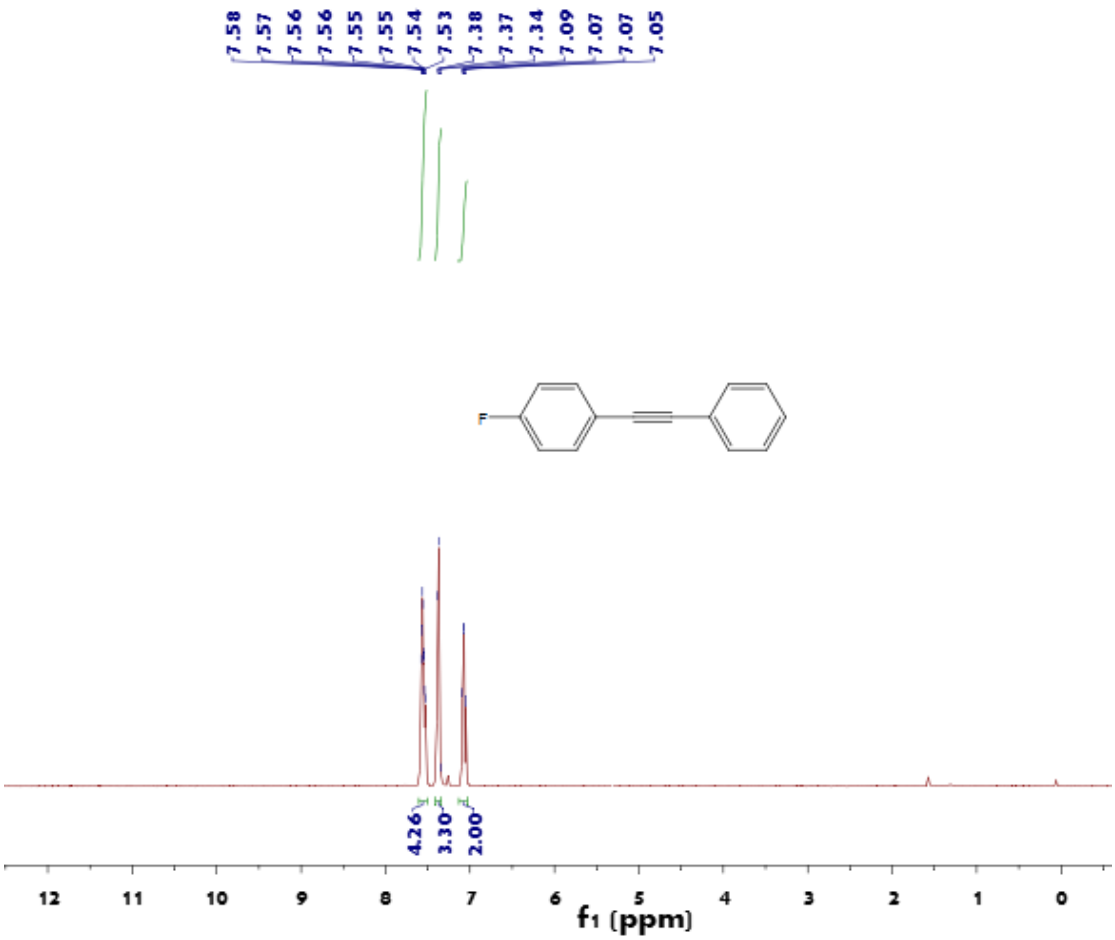
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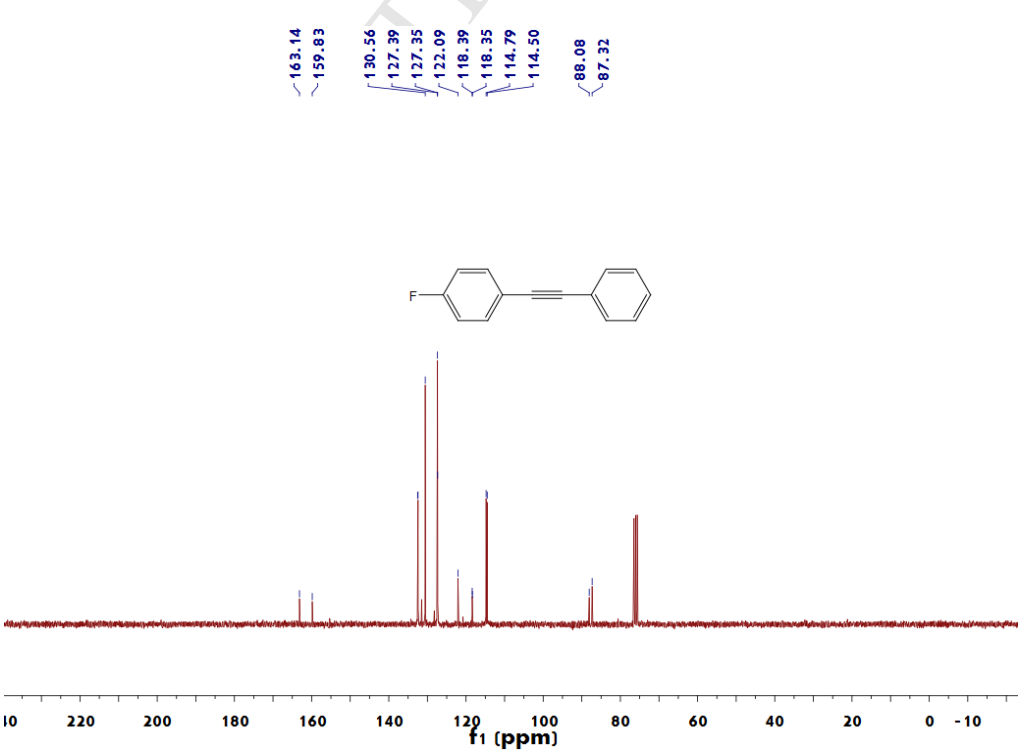
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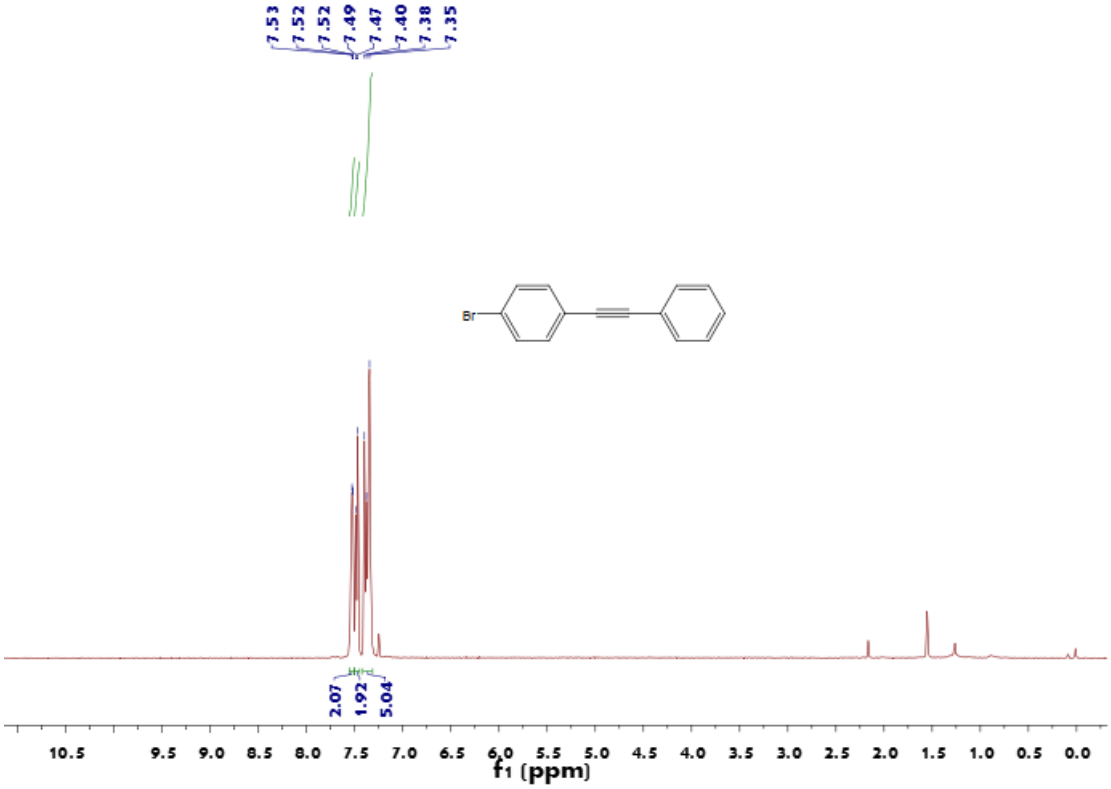
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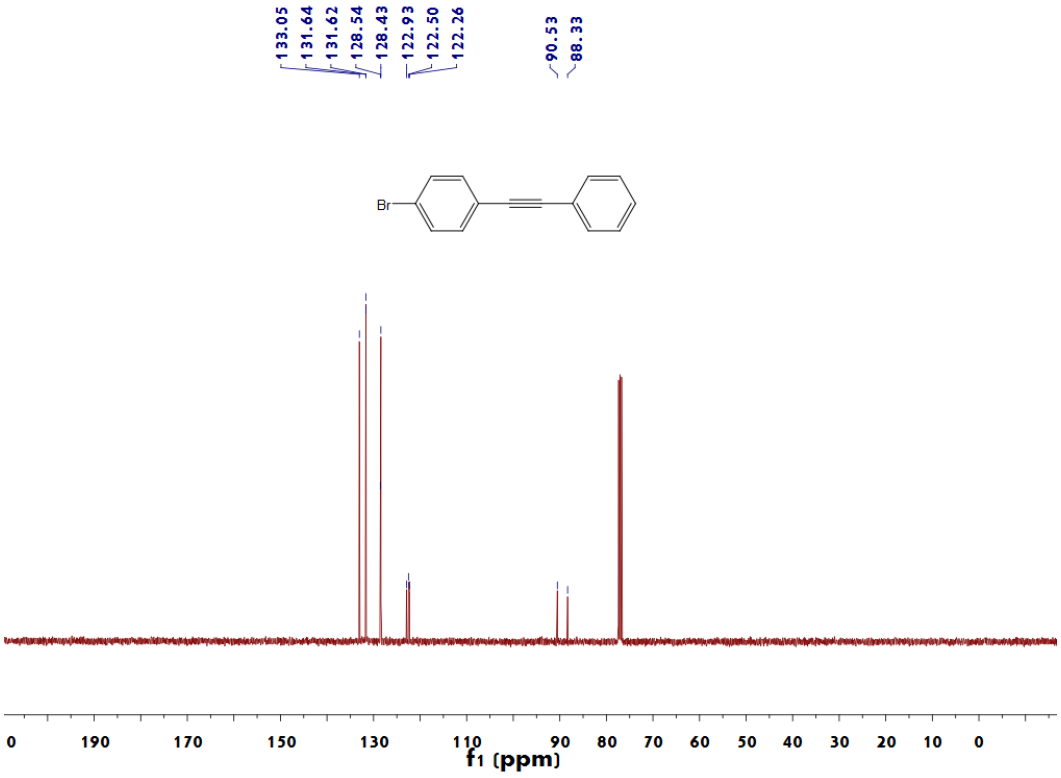
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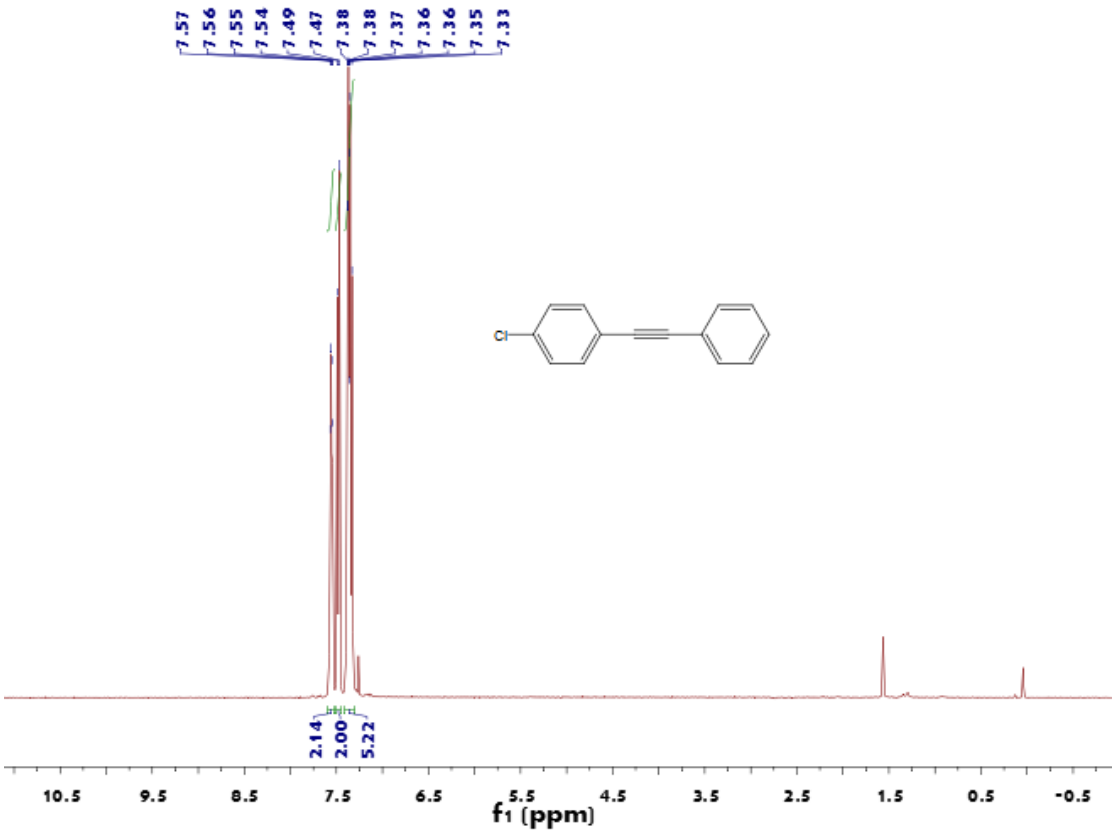
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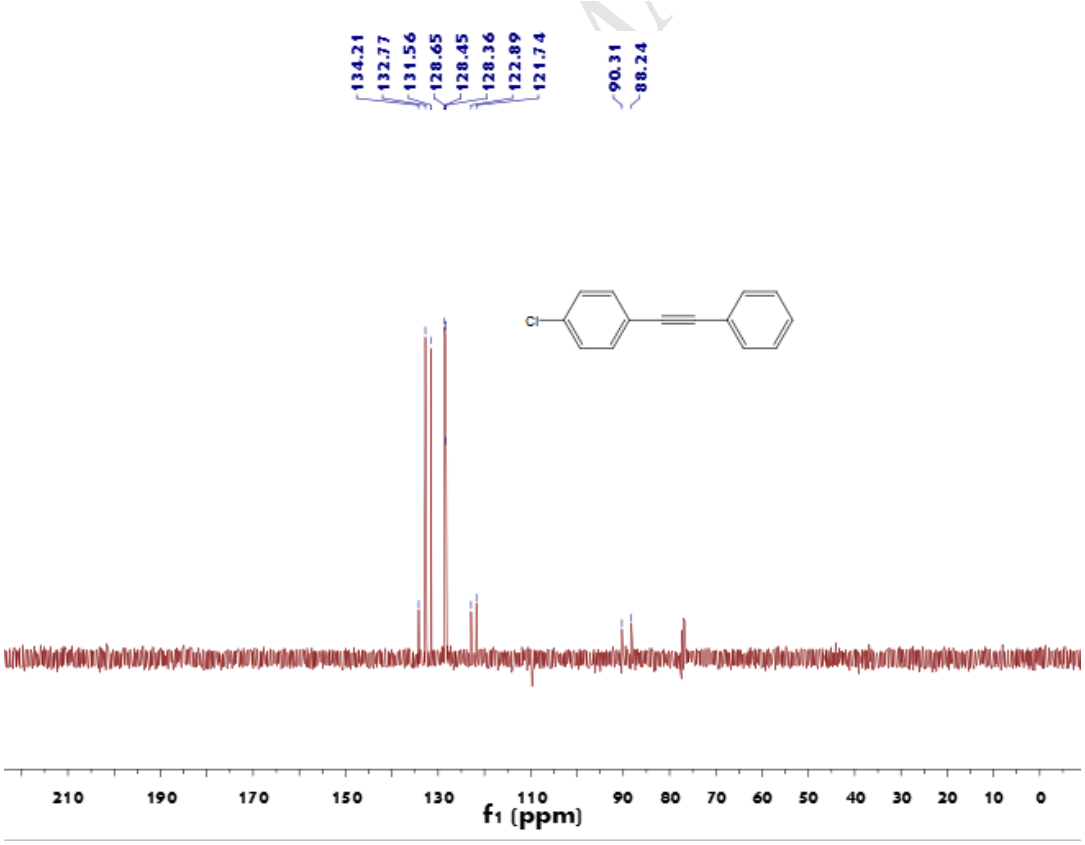
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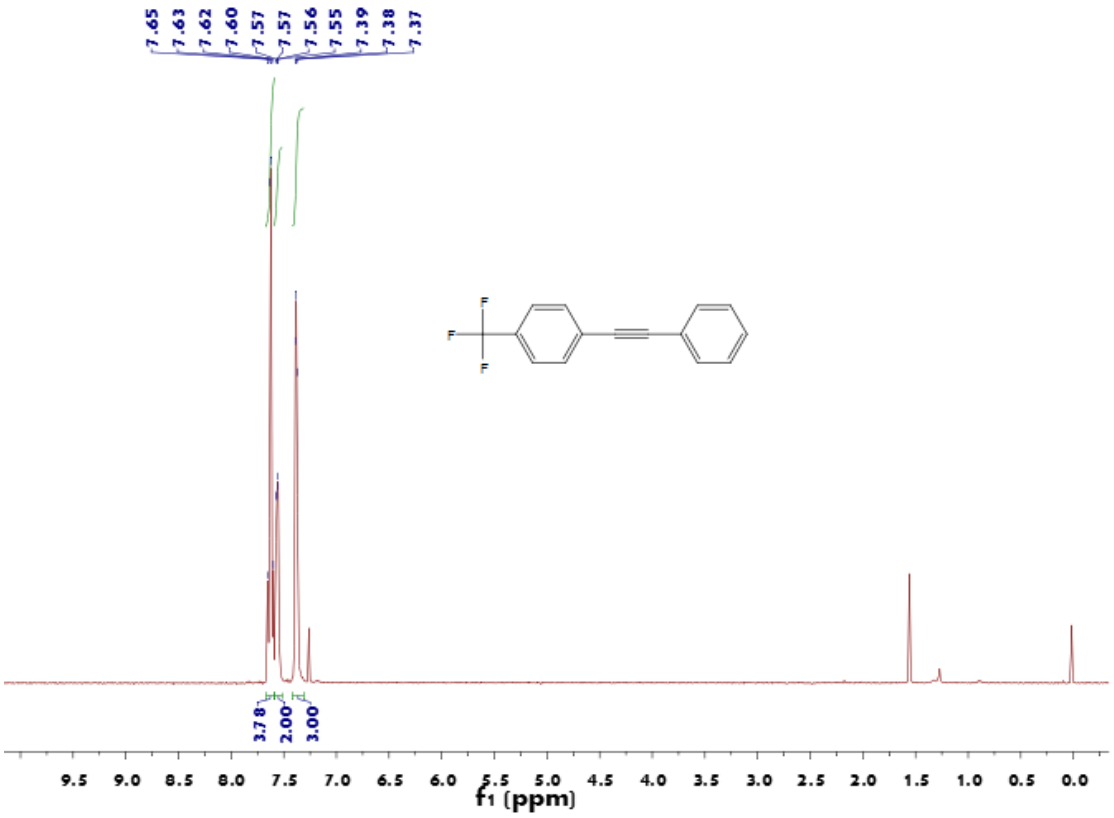
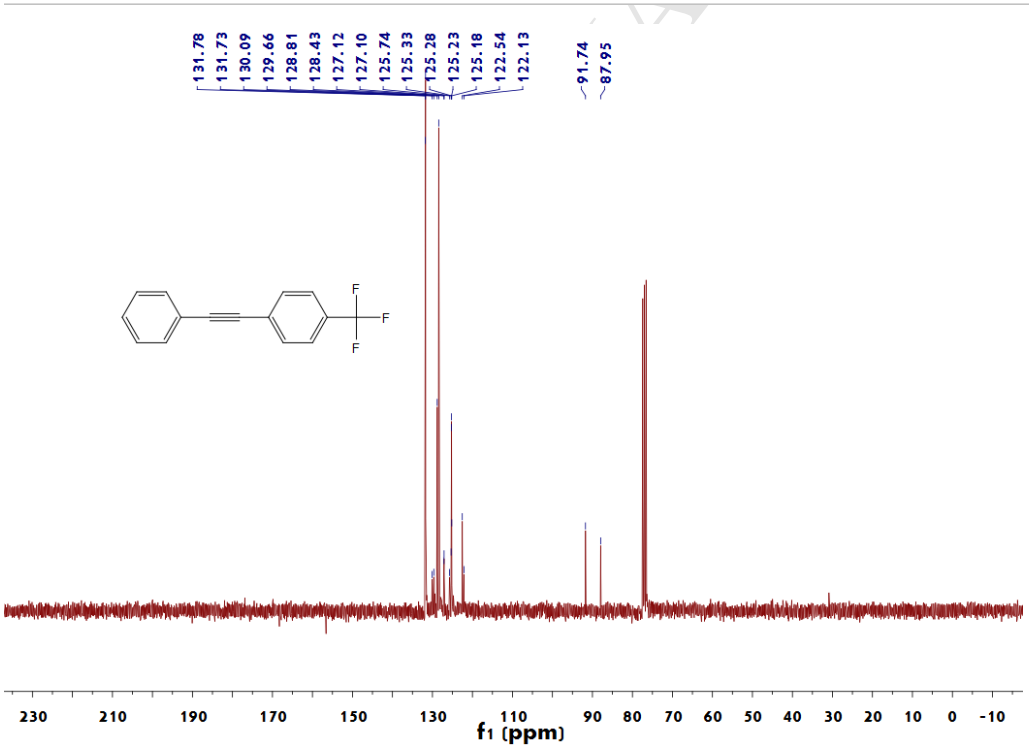
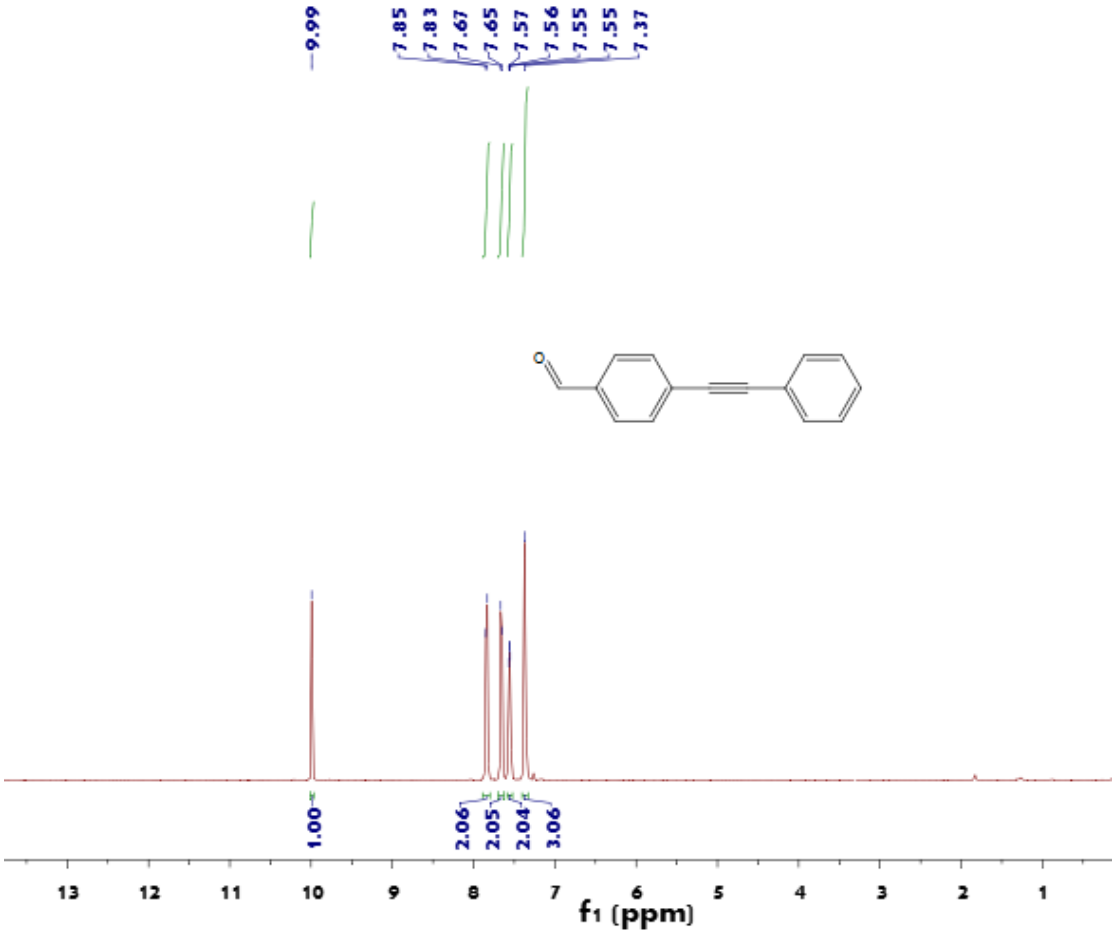
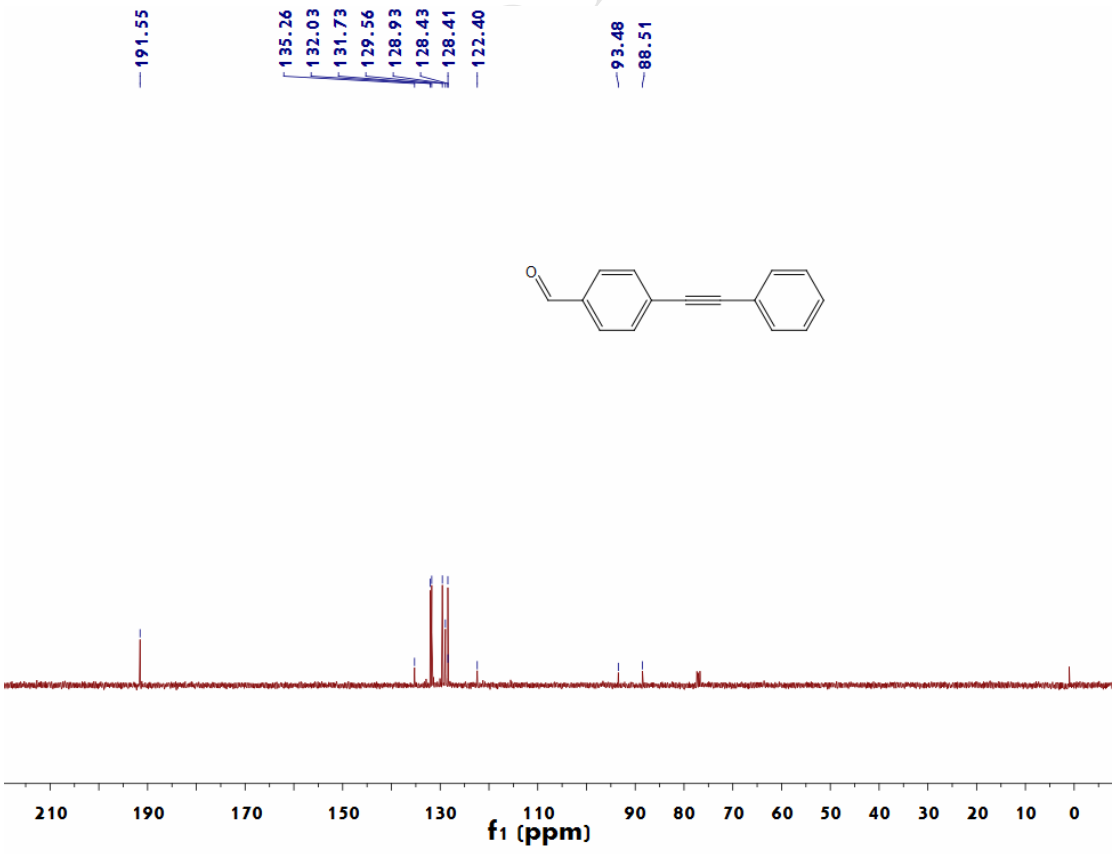
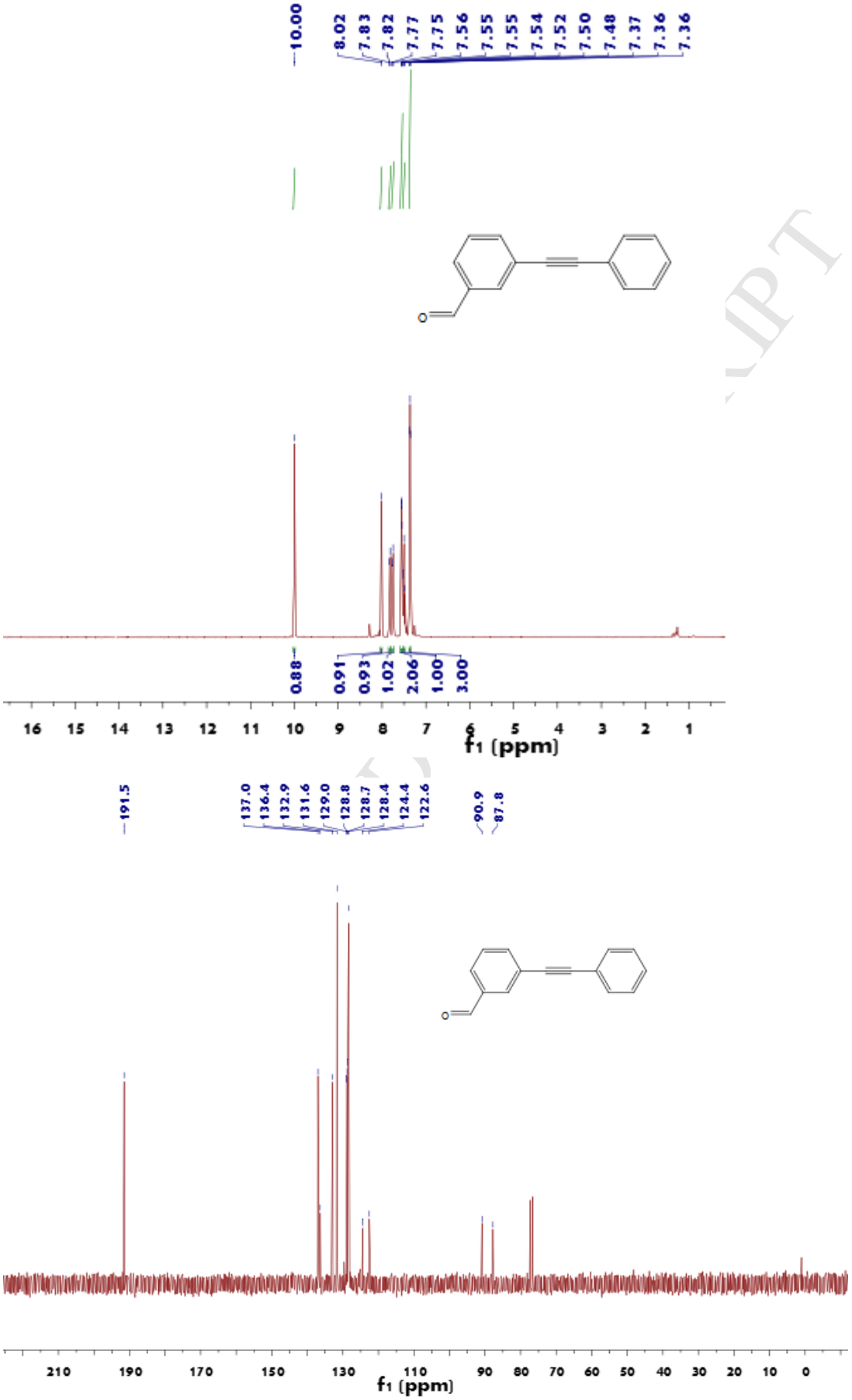
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

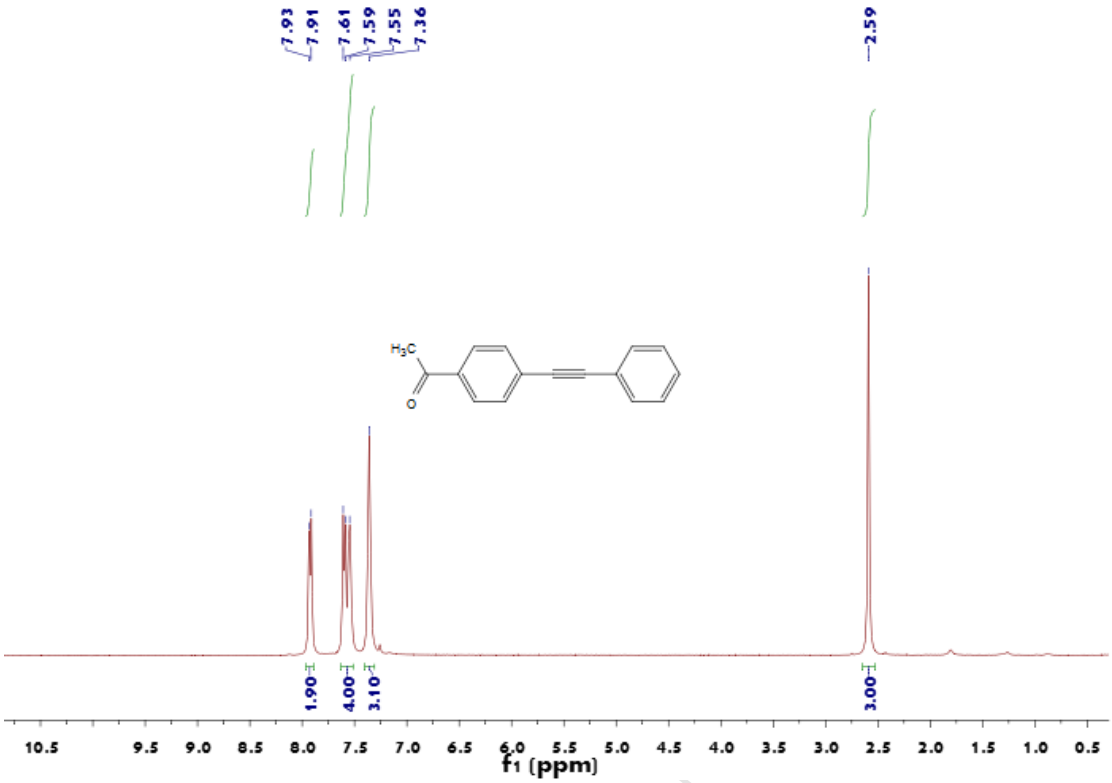

7.65
7.63
7.62
7.60
7.57
7.57
7.56
7.55
7.39
7.38
7.37
F
F
F
3.78
2.00
3.00
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)

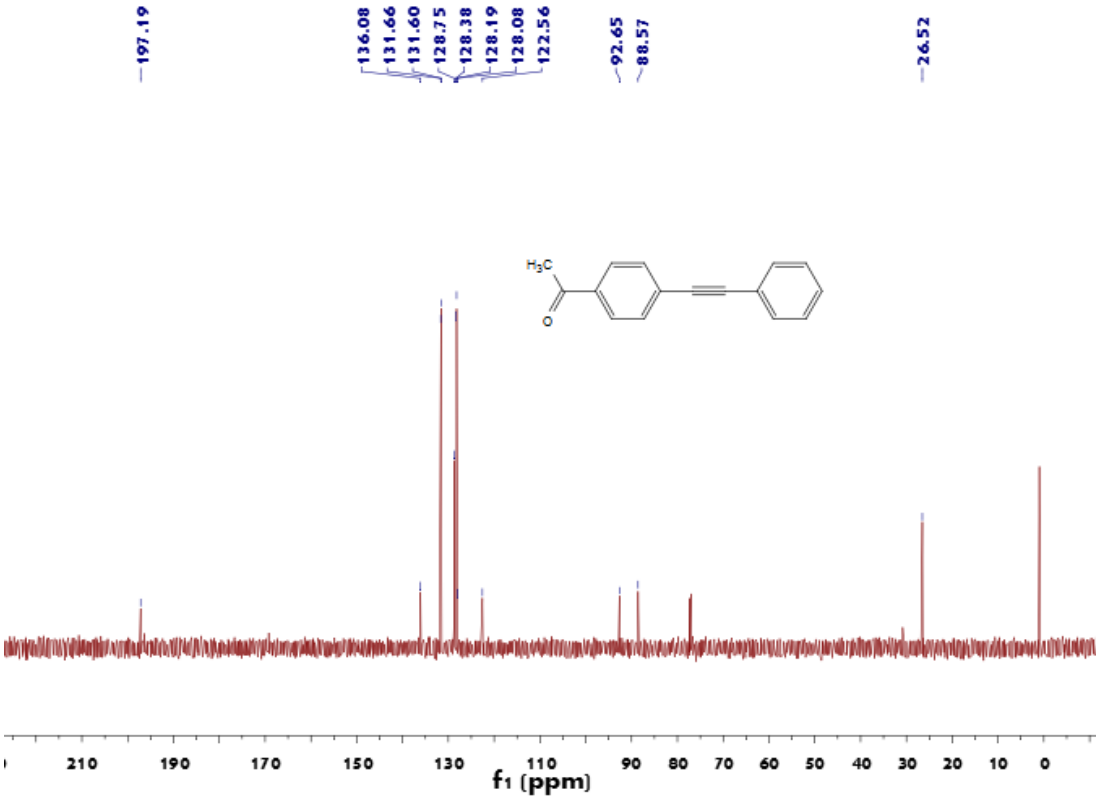

131.78
131.73
130.09
129.66
128.81
128.43
127.12
127.10
125.74
125.33
125.28
125.23
125.18
122.54
122.13
91.74
87.95
F
F
F
230 210 190 170 150 130 110 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

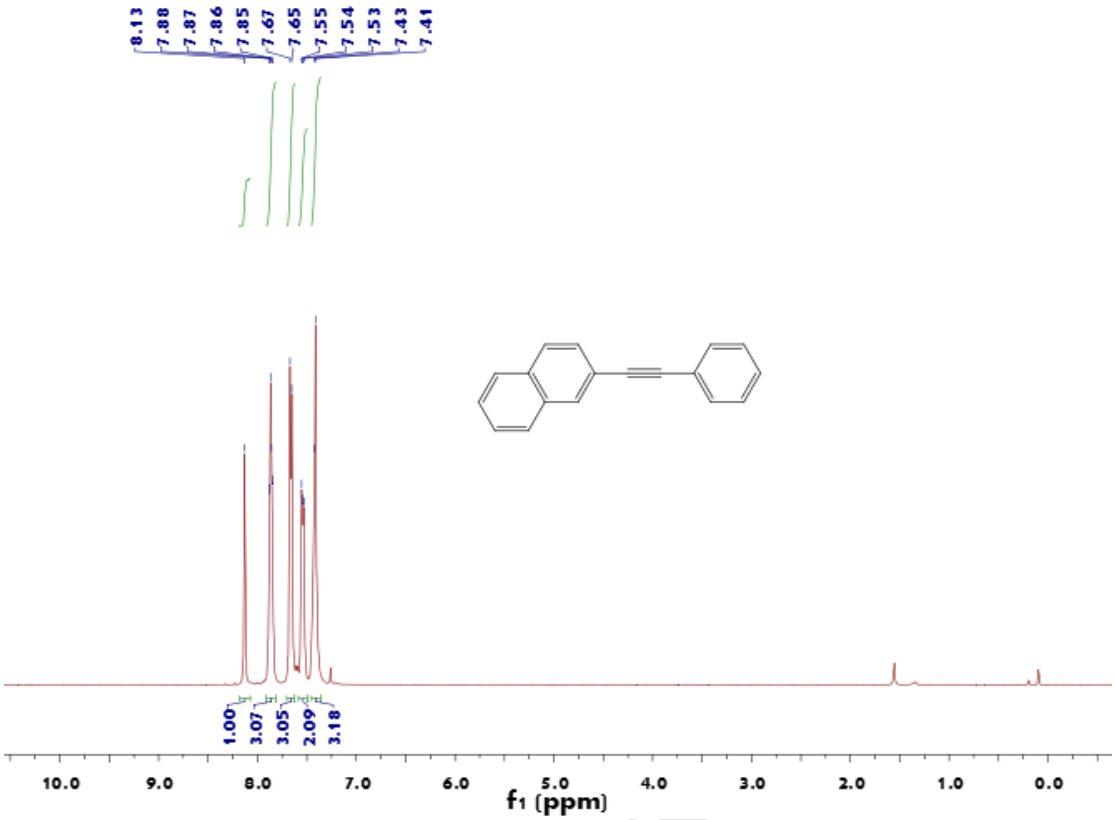

9.99
7.85
7.83
7.67
7.65
7.57
7.56
7.55
7.55
7.37
1.00
2.06
2.05
2.04
3.06
13
12
11
10
9
8
7
6
5
4
3
2
1
f1 (ppm)

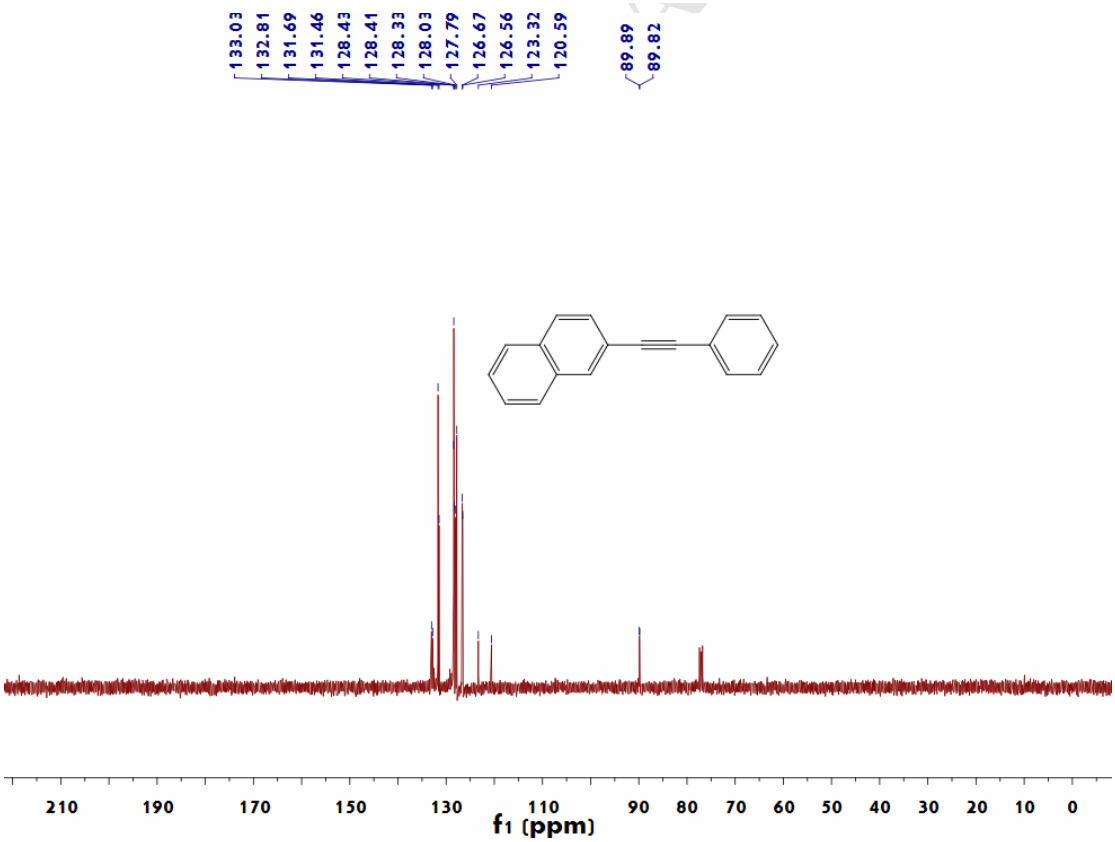

191.55
135.26
132.03
131.73
129.56
128.93
128.43
128.41
122.40
93.48
88.51
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

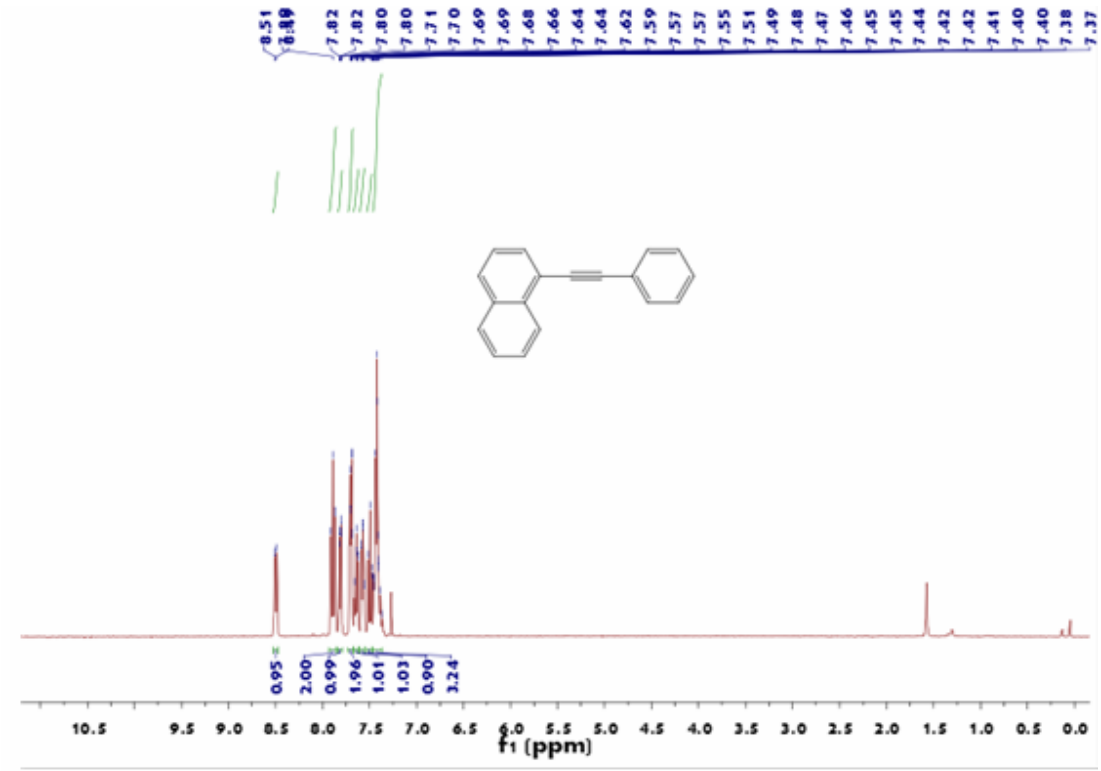

10.00
8.02
7.83
7.82
7.77
7.75
7.56
7.55
7.55
7.54
7.52
7.50
7.48
7.37
7.36
7.36
O
0.88
0.91
0.93
1.02
2.06
1.00
3.00
16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
f1 (ppm)
191.5
137.0
136.4
132.9
131.6
129.0
128.8
128.7
128.4
124.4
122.6
90.9
87.8
O
210 190 170 150 130 110 90 80 70 60 50 40 30 20 10 0
f1 (ppm)

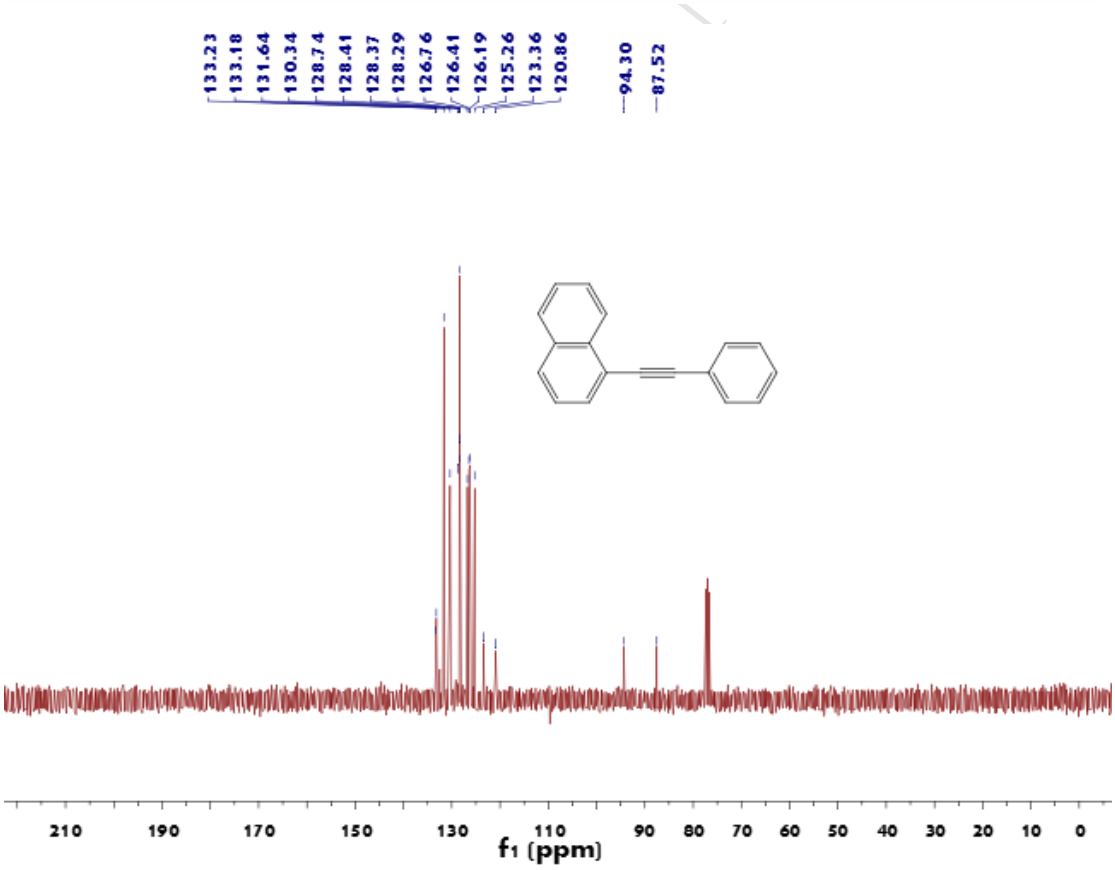

7.93
7.91
7.61
7.59
7.55
7.36
2.59
H3C
O
1.90
4.00
3.10
3.00
10.5 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
f1 (ppm)

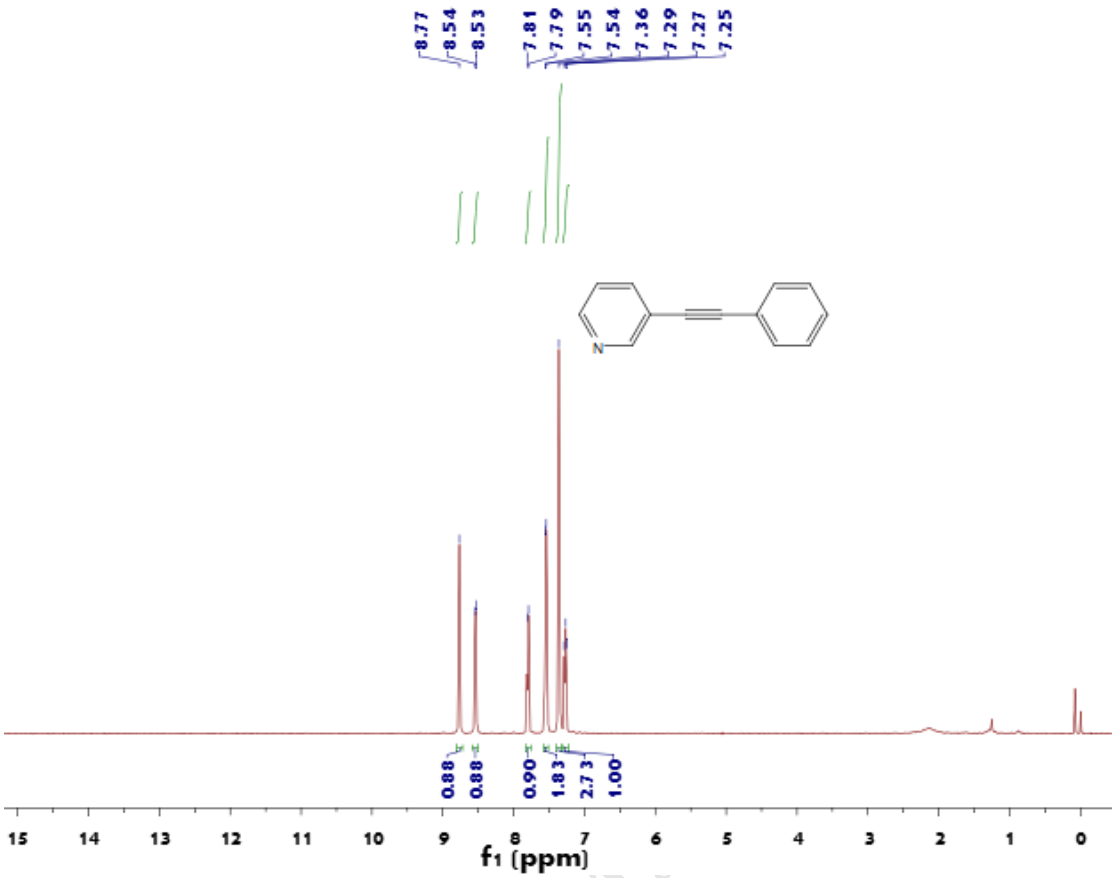

197.19
136.08
131.66
131.60
128.75
128.38
128.19
128.08
122.56
92.65
88.57
26.52
H3C
O
210 190 170 150 130 110 90 80 70 60 50 40 30 20 10 0
f1 (ppm)

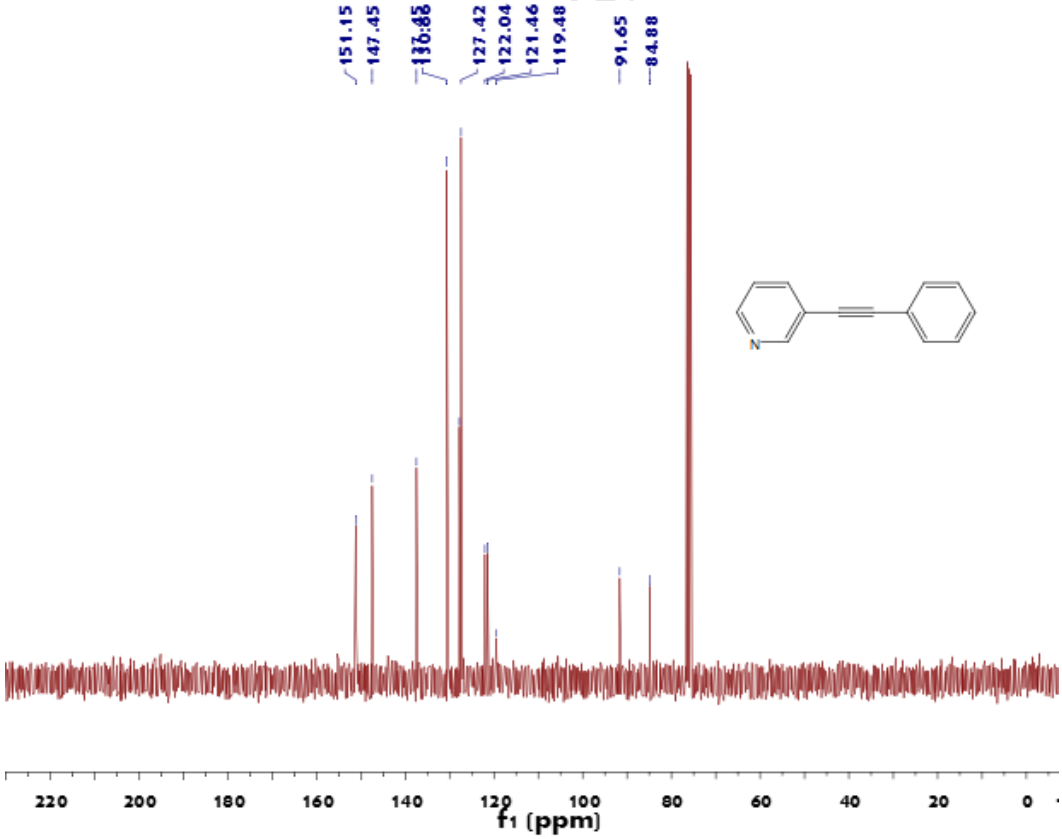

8.13
7.88
7.87
7.86
7.85
7.67
7.65
7.55
7.54
7.53
7.43
7.41
1.00
3.07
3.05
2.09
3.18
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

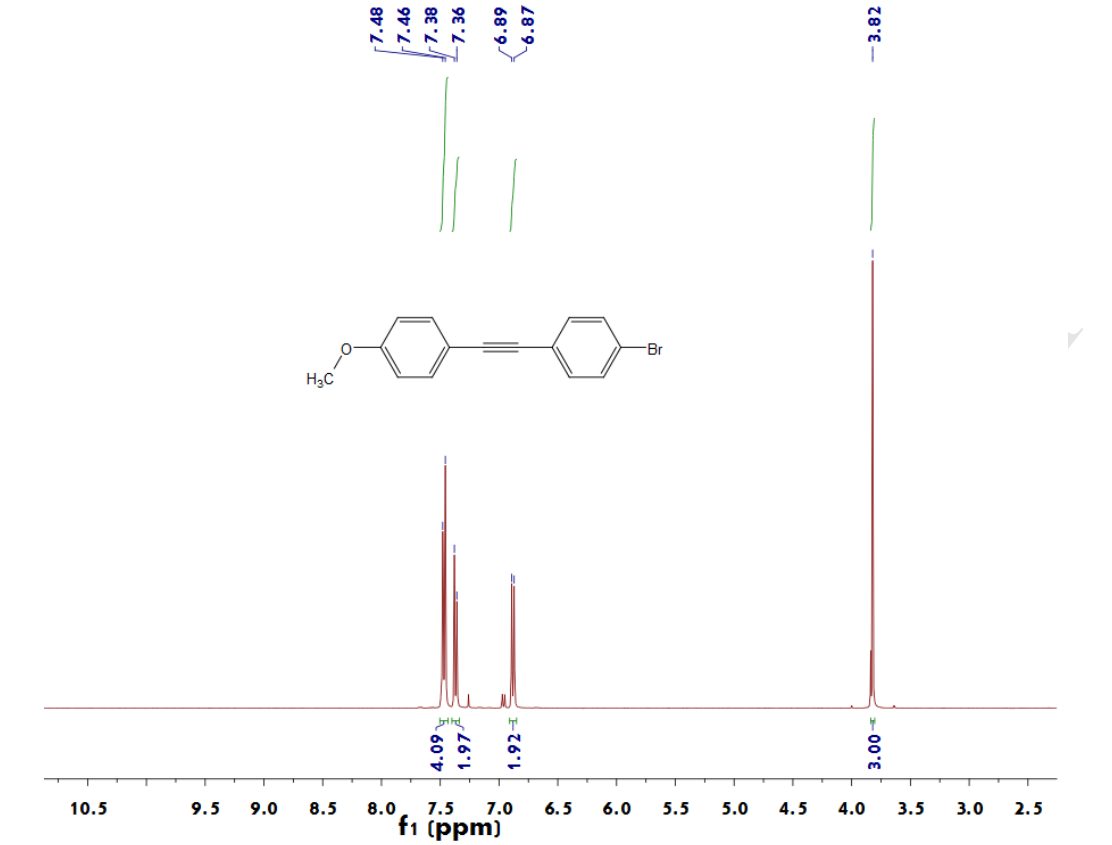

133.03
132.81
131.69
131.46
128.43
128.41
128.33
128.03
127.79
126.67
126.56
123.32
120.59
89.89
89.82
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

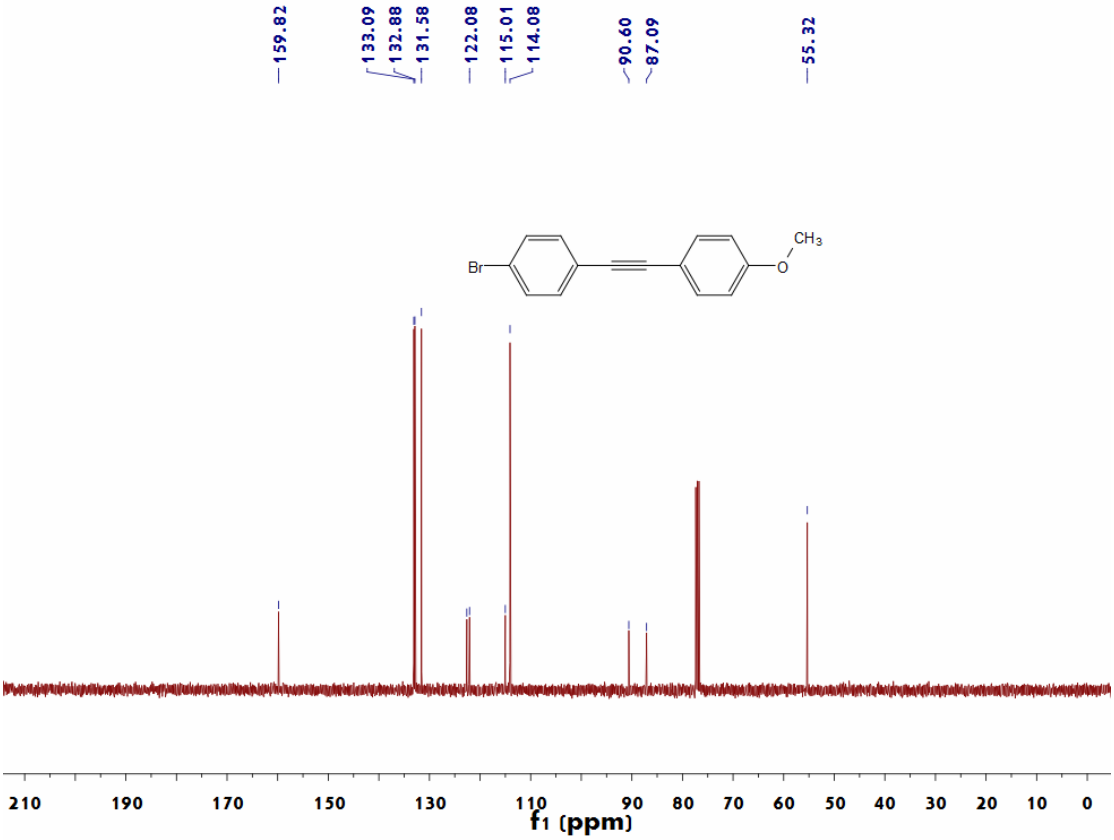

8.51
8.49
7.82
7.82
7.80
7.80
7.71
7.70
7.69
7.69
7.68
7.66
7.64
7.64
7.62
7.59
7.57
7.57
7.55
7.51
7.49
7.48
7.47
7.46
7.45
7.45
7.44
7.42
7.42
7.41
7.40
7.40
7.38
7.37
0.95
2.00
0.99
1.96
1.01
1.03
0.90
3.24
10.5
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

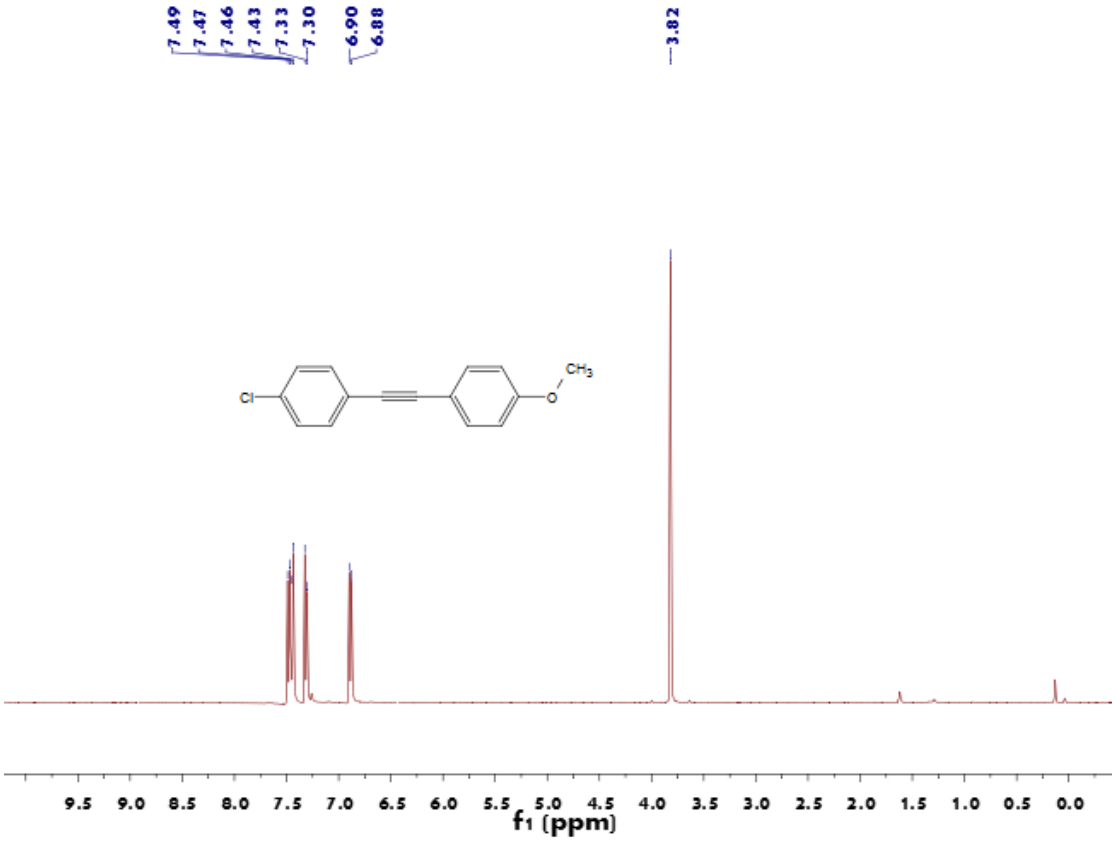

133.23
133.18
131.64
130.34
128.74
128.41
128.37
128.29
126.76
126.41
126.19
125.26
123.36
120.86
94.30
87.52
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

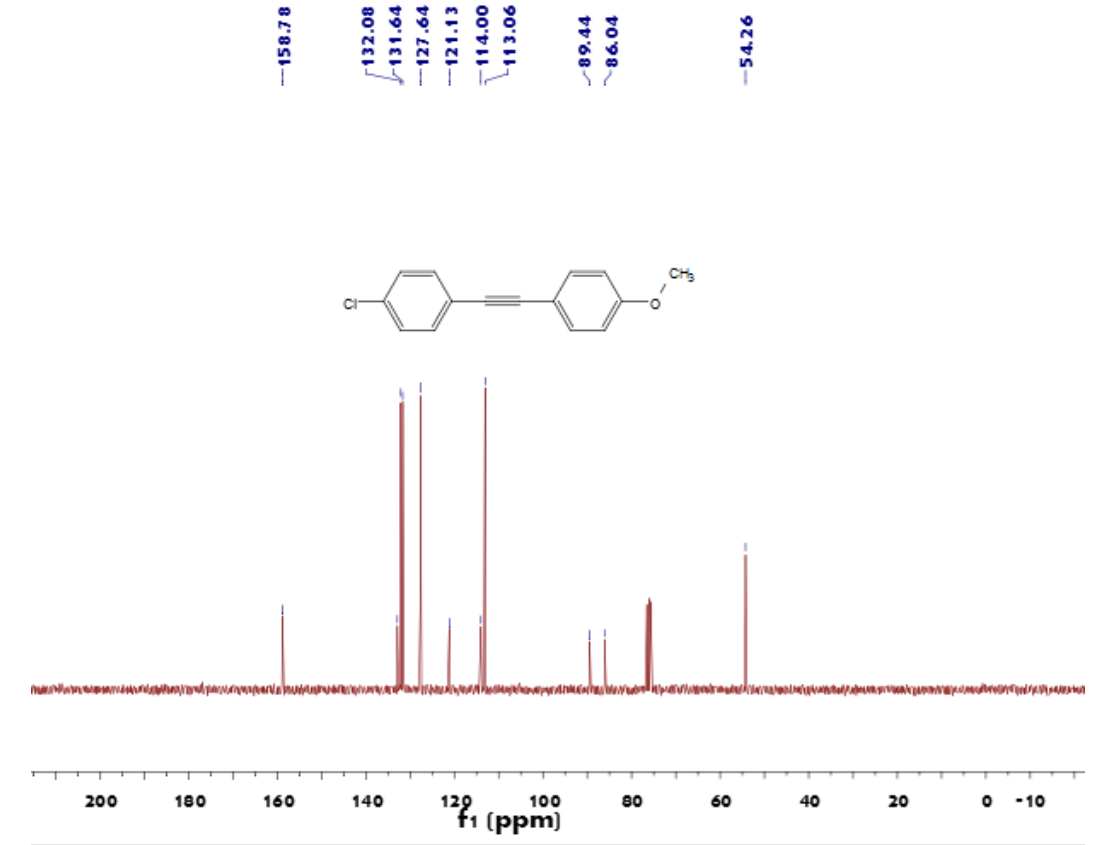

8.77
8.54
8.53
7.81
7.79
7.55
7.54
7.36
7.29
7.27
7.25
0.88
0.88
0.90
1.83
2.73
1.00
f1 (ppm)

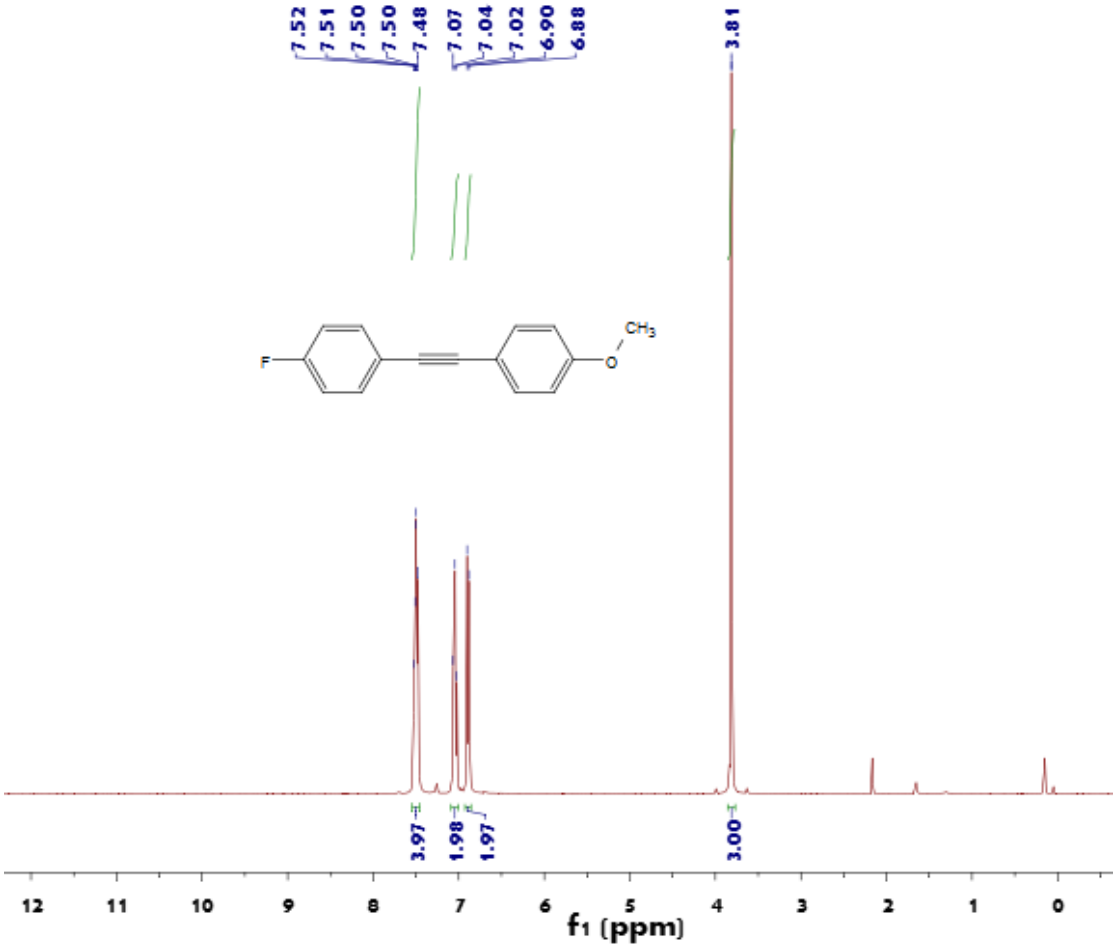

151.15
147.45
136.88
127.42
122.04
121.46
119.48
91.65
84.88
f1 (ppm)

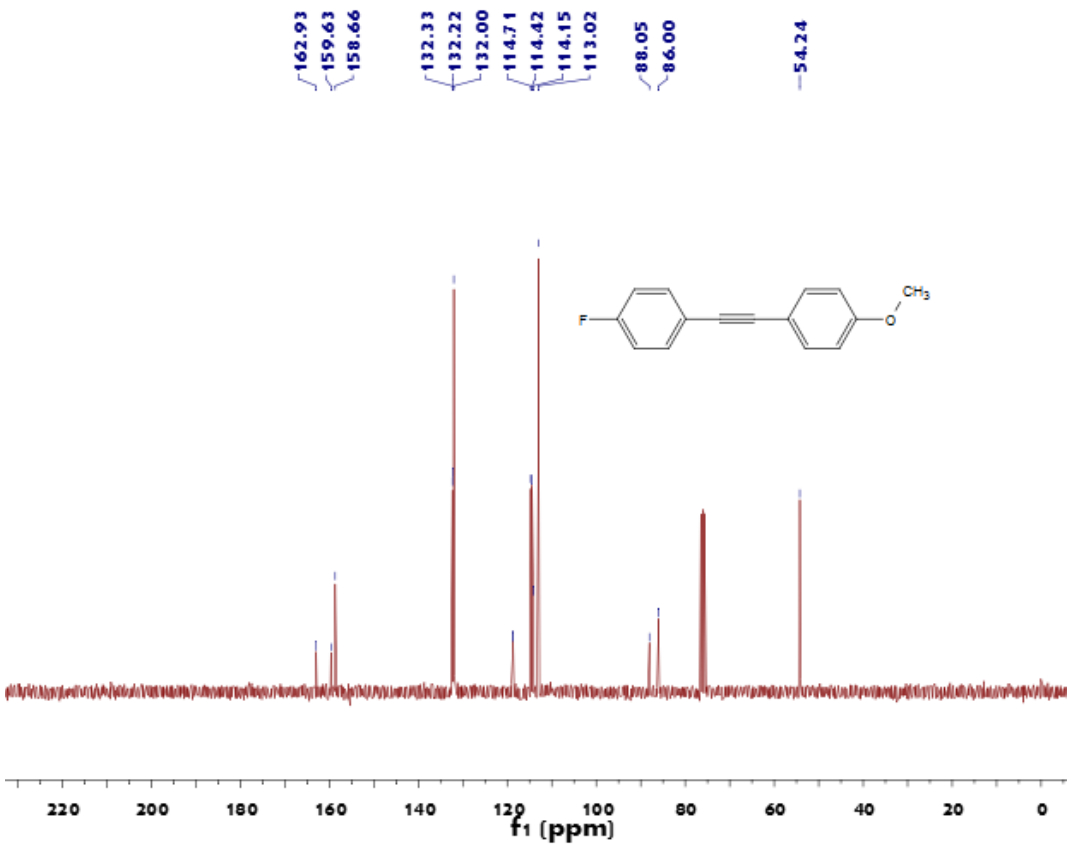

7.48
7.46
7.38
7.36
6.89
6.87
3.82
O
H3C
Br
4.09
1.97
1.92
3.00
10.5
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
f1 (ppm)

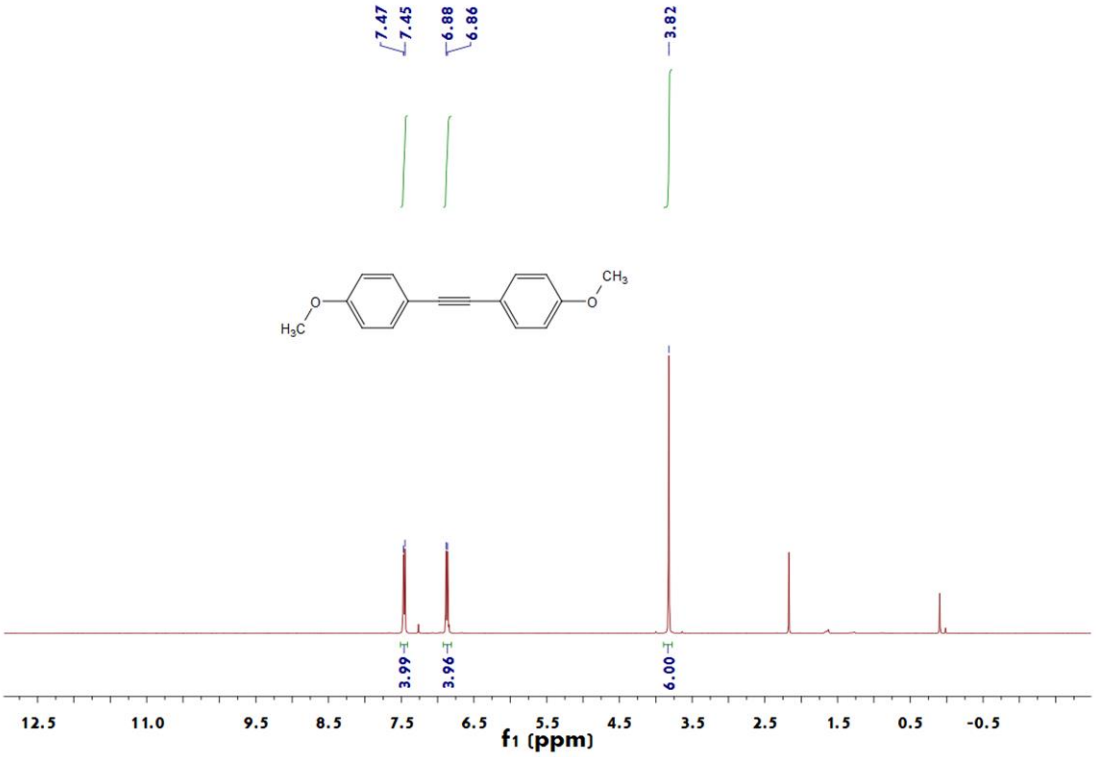

159.82
133.09
132.88
131.58
122.08
115.01
114.08
90.60
87.09
55.32
Br
CH3
O
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

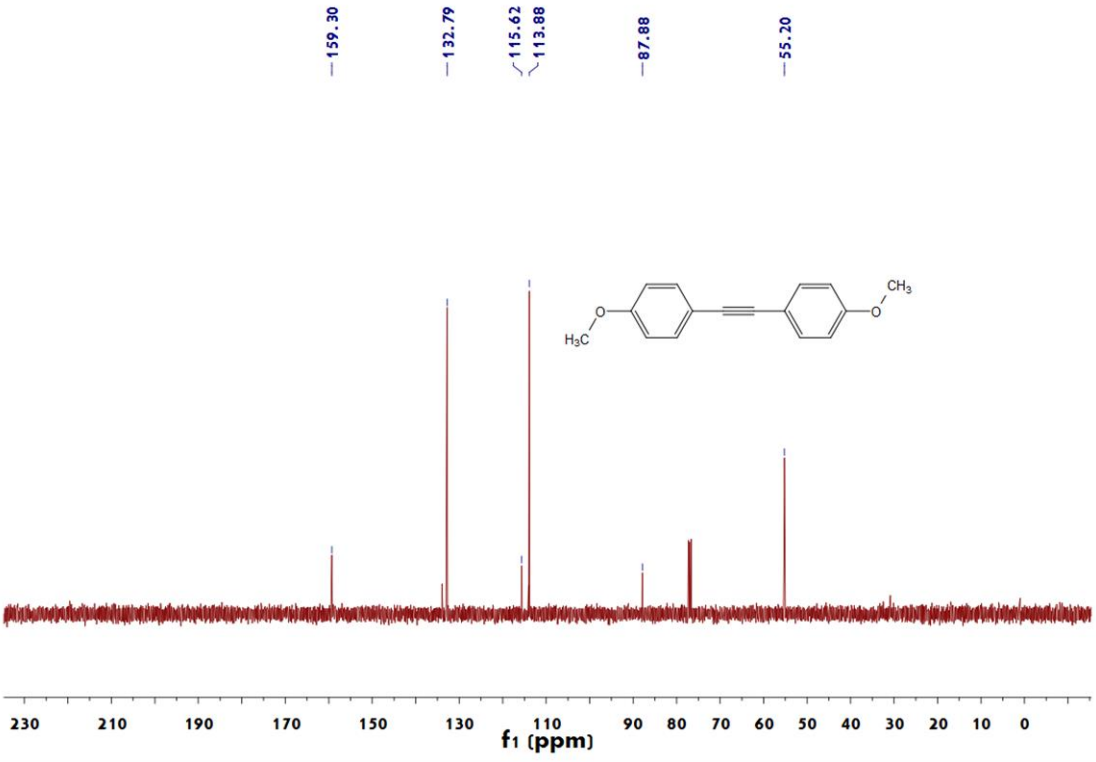

7.49
7.47
7.46
7.43
7.33
7.30
6.90
6.88
3.82
Cl
CH3
O
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)

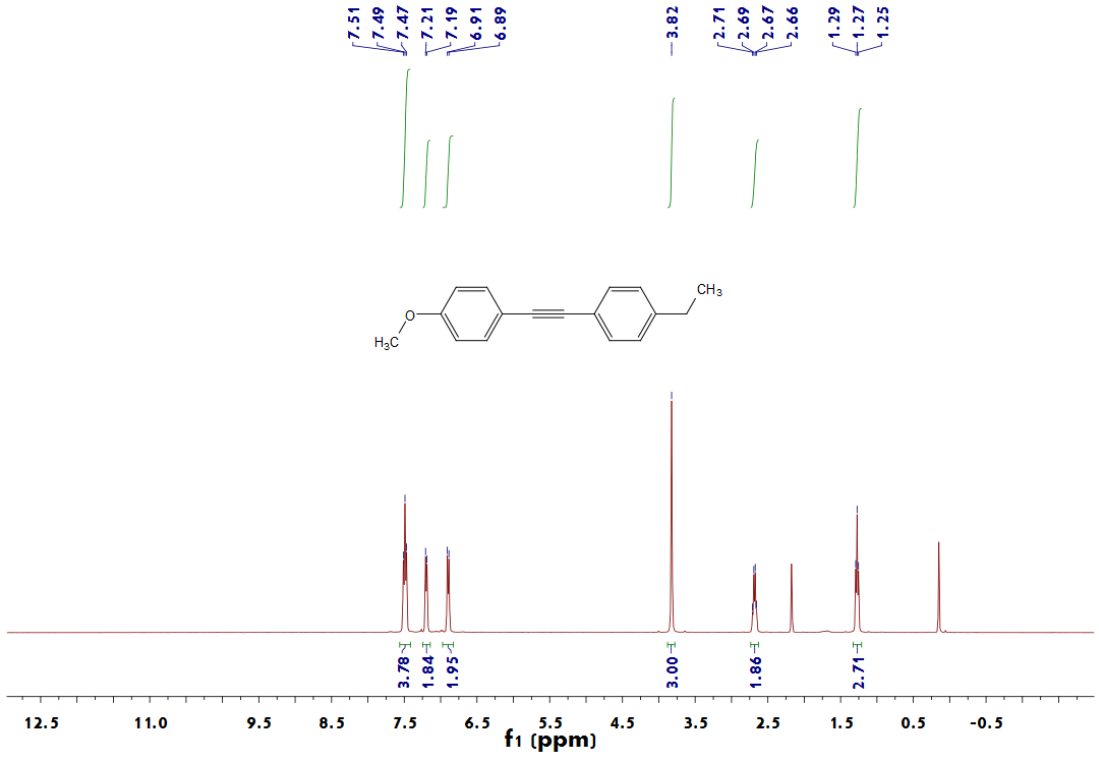

158.78
132.08
131.64
127.64
121.13
114.00
113.06
89.44
86.04
54.26
Cl
CH3
O
200 180 160 140 120 100 80 60 40 20 0 -10
f1 (ppm)

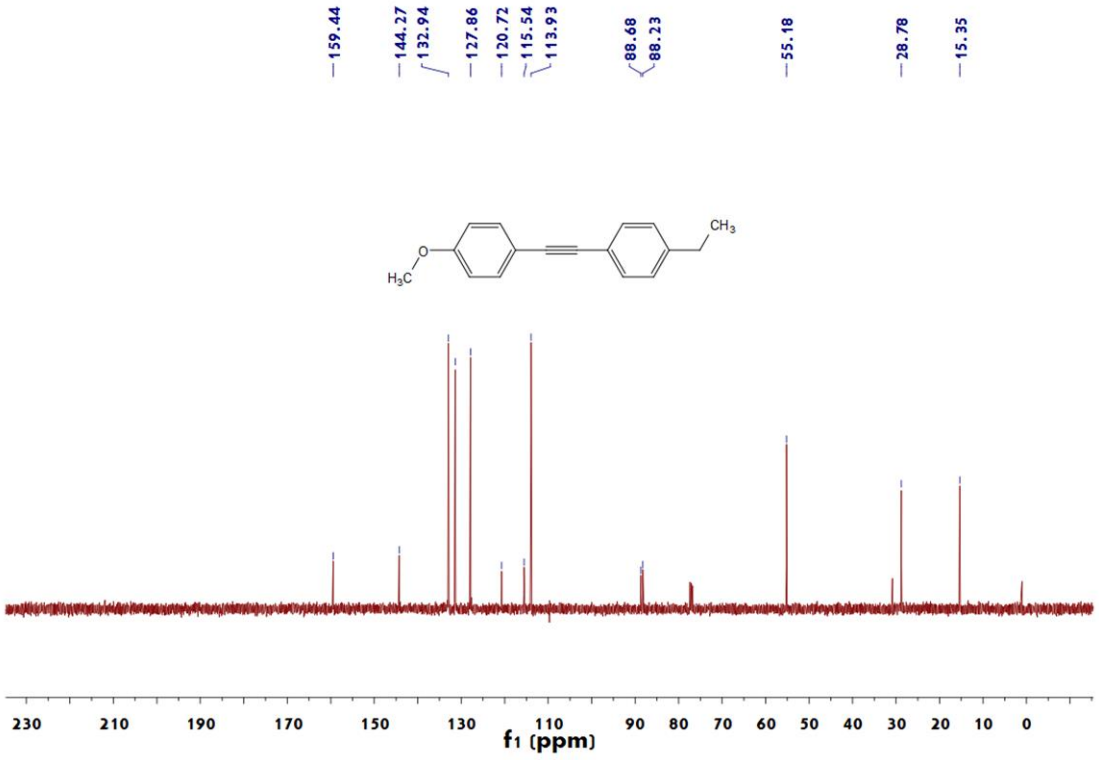

7.52
7.51
7.50
7.50
7.48
7.07
7.04
7.02
6.90
6.88
3.81
F
O
CH3
3.97
1.98
1.97
3.00
12
11
10
9
8
7
6
5
4
3
2
1
0
f1 (ppm)


162.93
159.63
158.66
132.33
132.22
132.00
114.71
114.42
114.15
113.02
88.05
86.00
54.24
F
O
CH3
220
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)


7.47
7.45
6.88
6.86
3.82
O
H3C
CH3
O
3.99
3.96
6.00
12.5
11.0
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)


159.30
132.79
115.62
113.88
87.88
55.20
O
H3C
CH3
O
230
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


7.51
7.49
7.47
7.21
7.19
6.91
6.89
3.82
2.71
2.69
2.67
2.66
1.29
1.27
1.25
CH3
O
H3C
3.78
1.84
1.95
3.00
1.86
2.71
12.5
11.0
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)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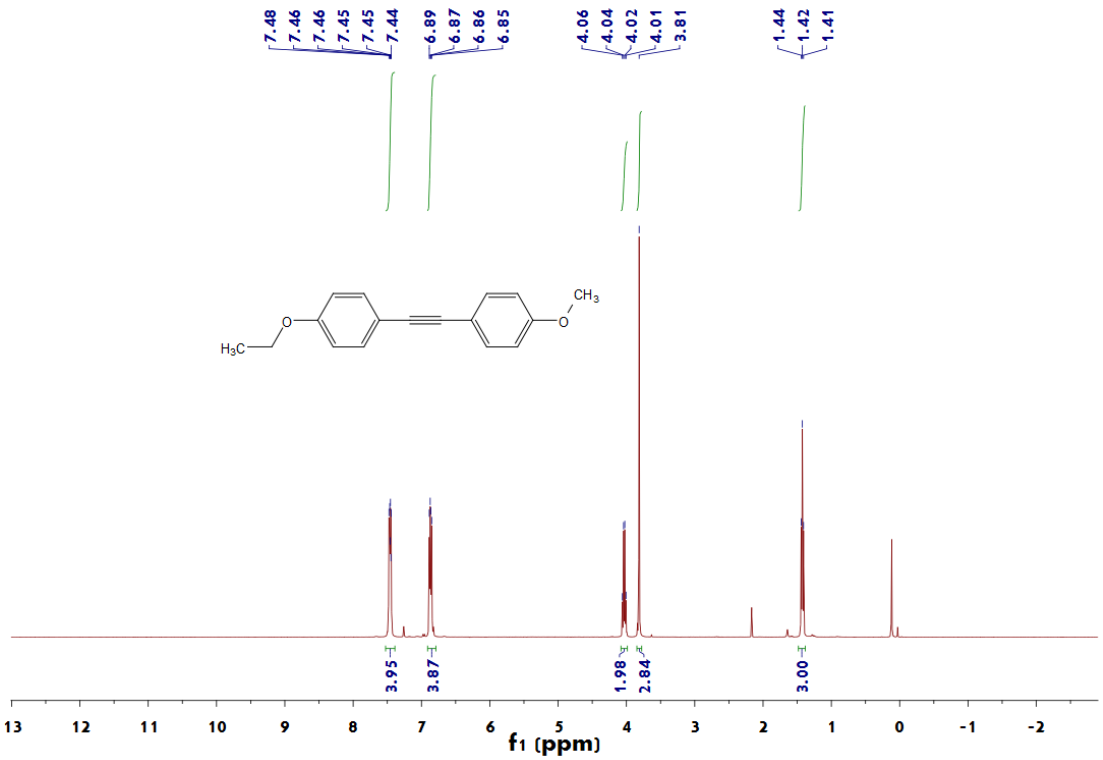
144.27
132.94
127.86
120.72
115.54
113.93
88.68
88.23
55.18
28.78
15.35
CH3
O
H3C
230
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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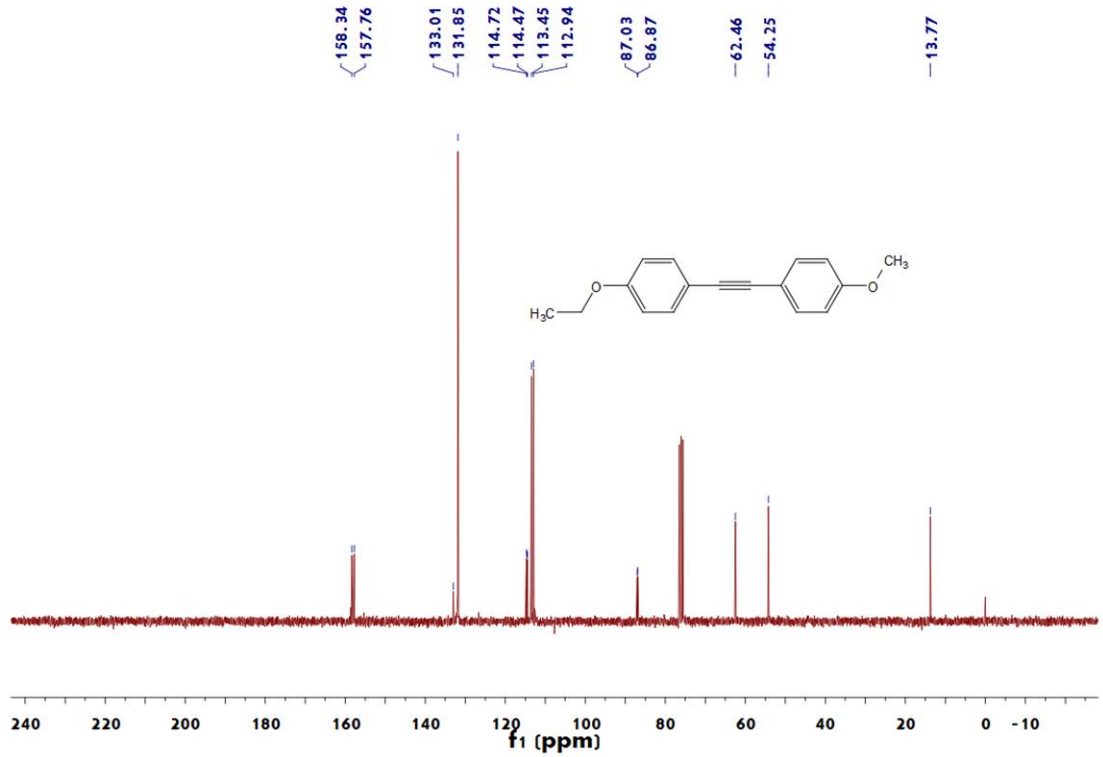
7.46
7.46
7.45
7.45
7.44
6.89
6.87
6.86
6.85
4.06
4.04
4.02
4.01
3.81
1.44
1.42
1.41
CH3
O
H3C
O
3.95
3.87
1.98
2.84
3.00
13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2
f1 (ppm)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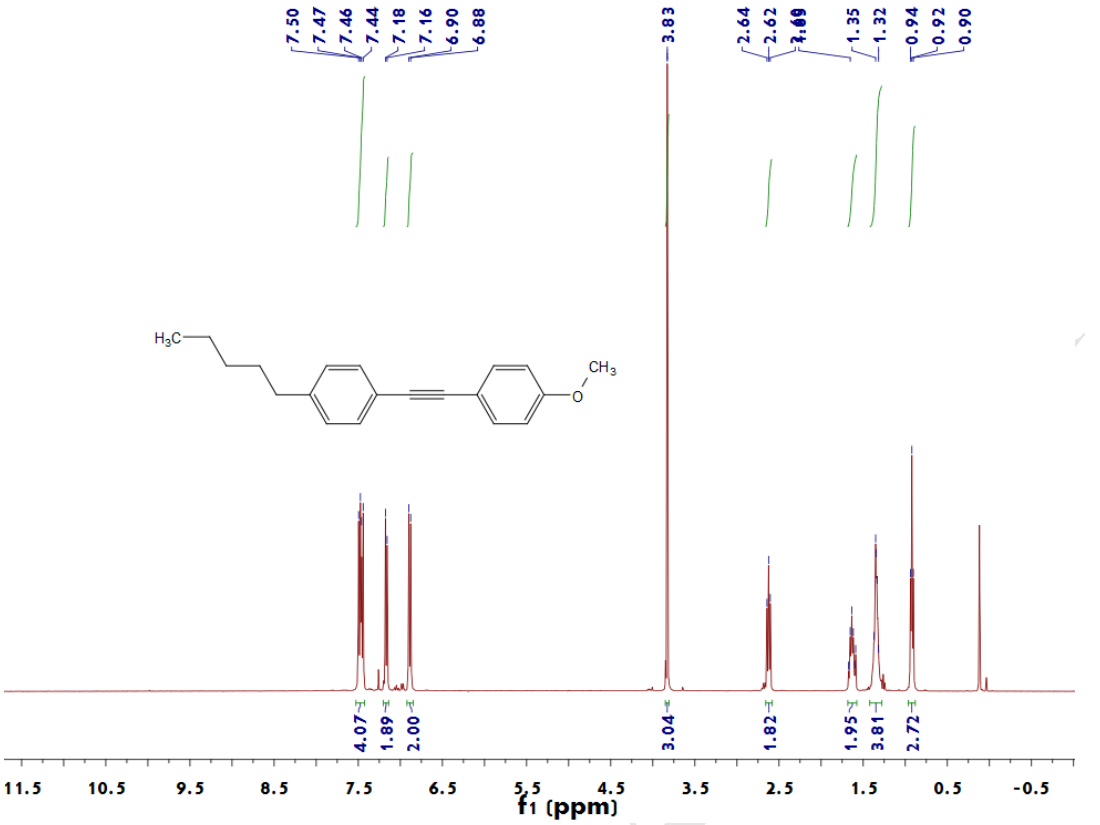
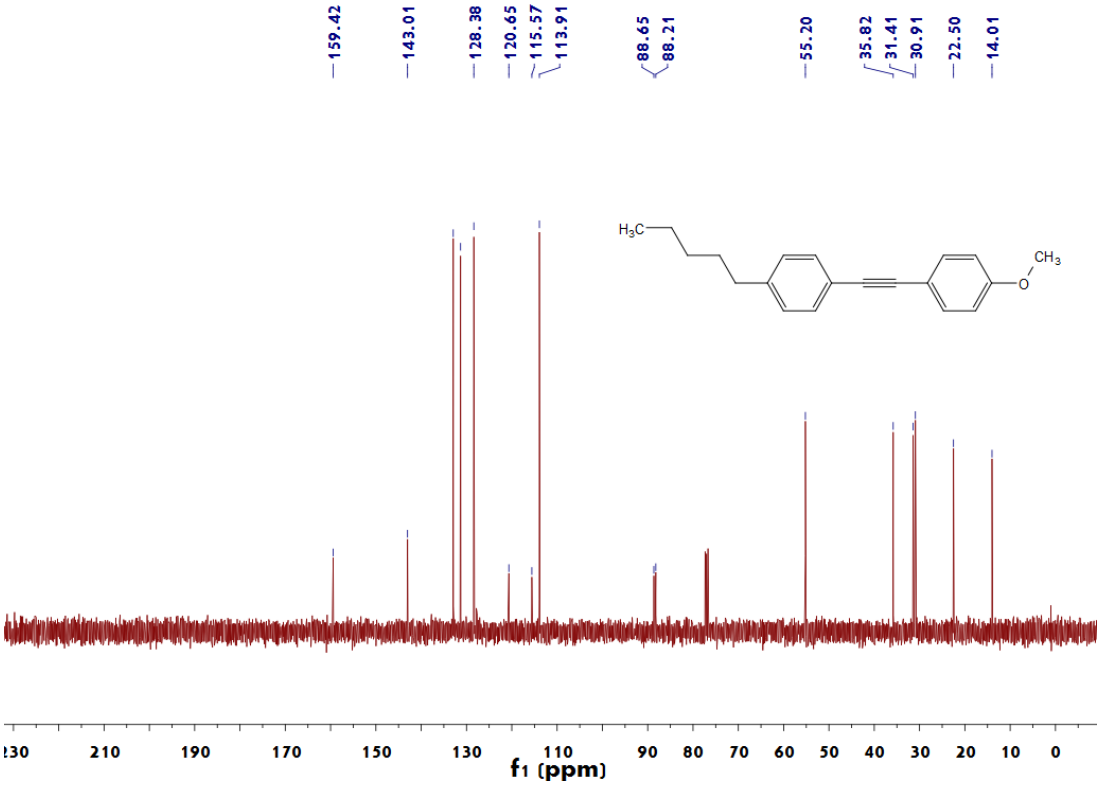
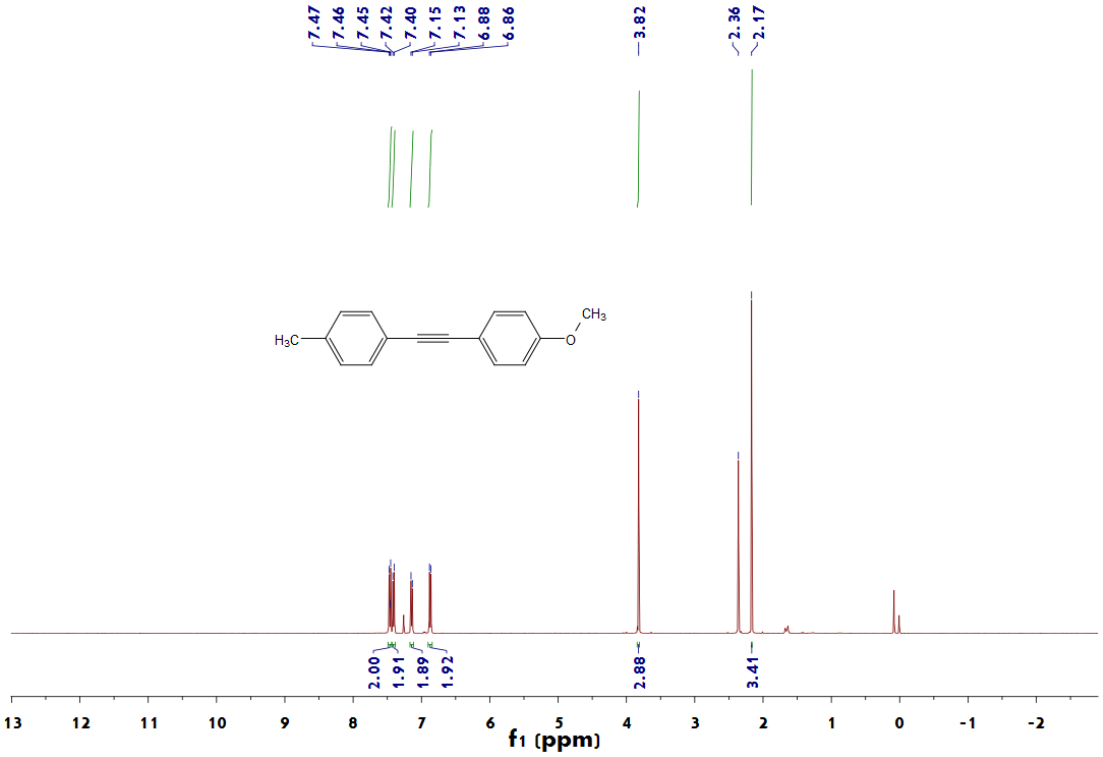
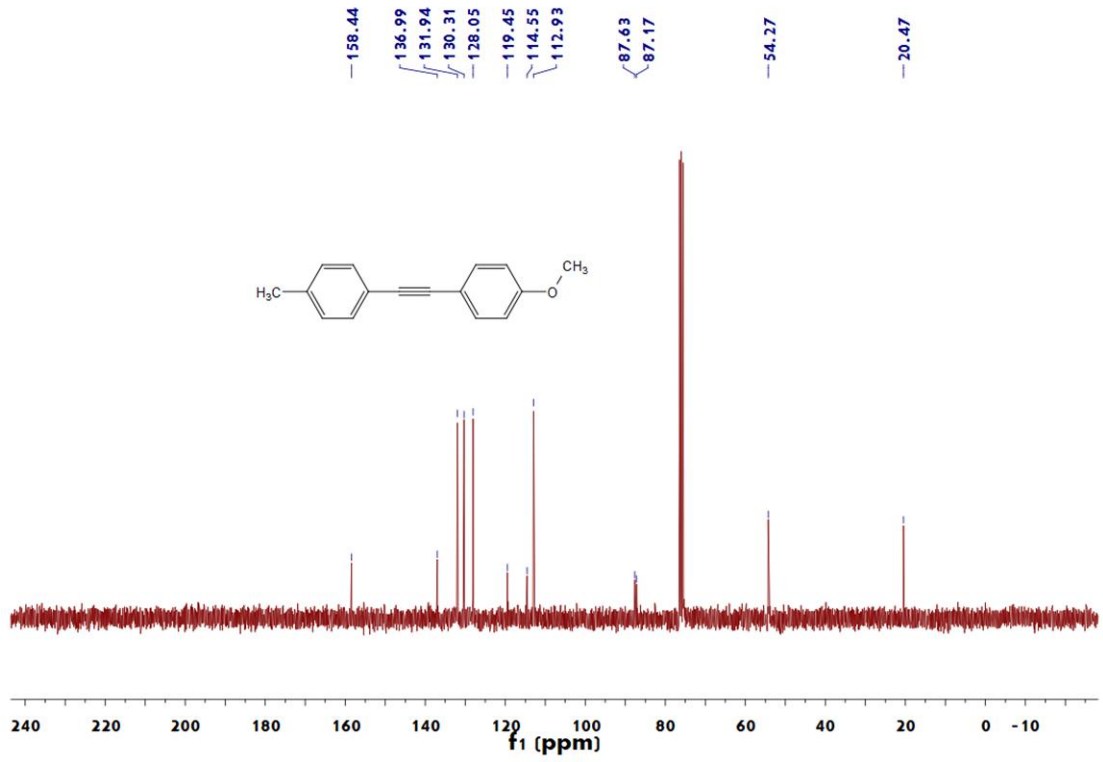
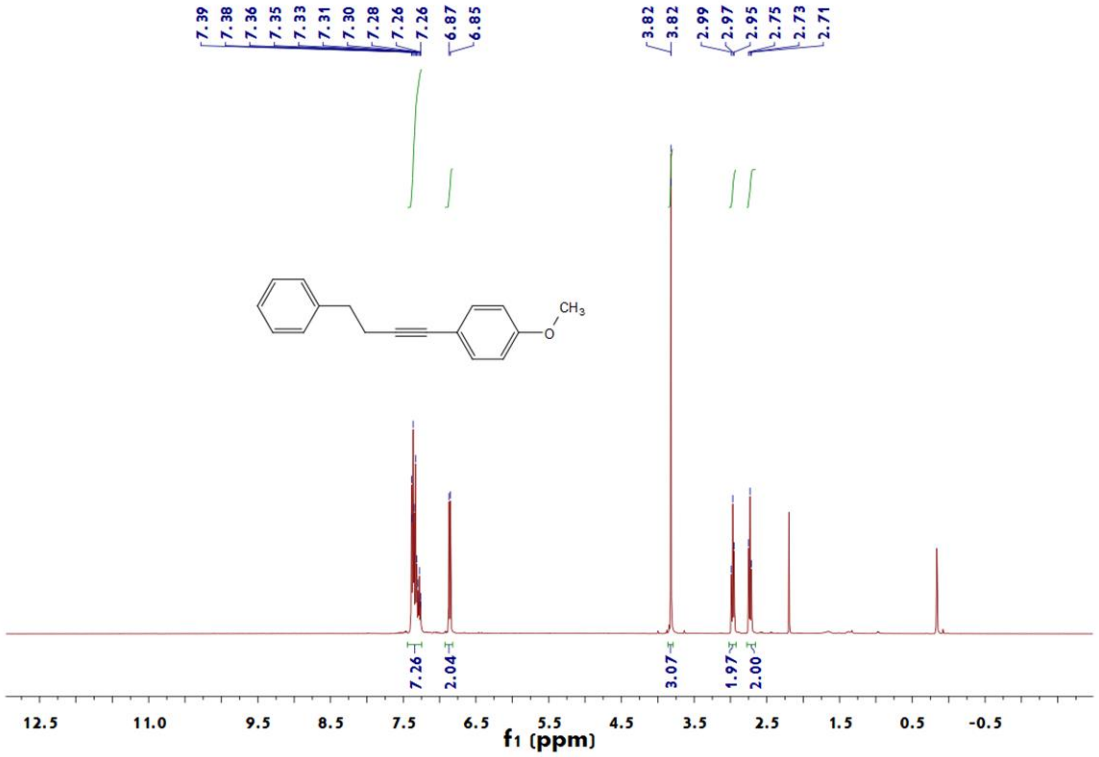
157.76
133.01
131.85
114.72
114.47
113.45
112.94
87.03
86.87
62.46
54.25
13.77
CH3
O
H3C
O
240 220 200 180 160 140 120 100 80 60 40 20 0 -10
f1 (ppm)

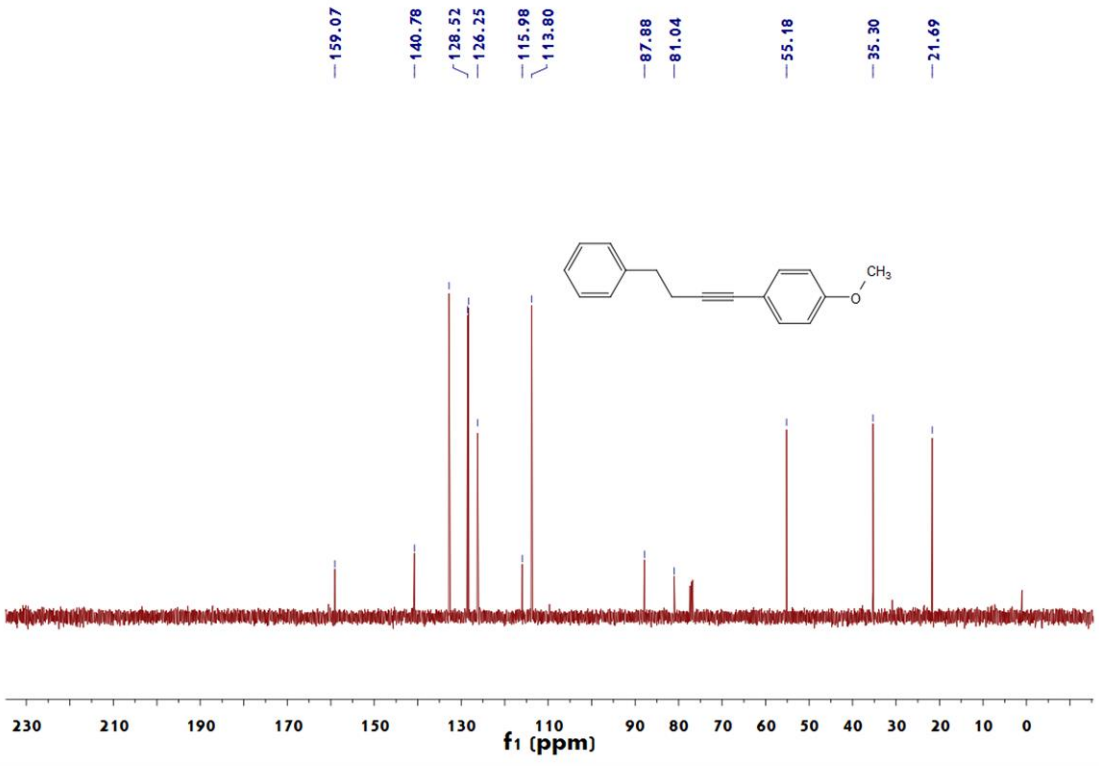

7.50
7.47
7.46
7.44
7.18
7.16
6.90
6.88
3.83
2.64
2.62
1.35
1.32
0.94
0.92
0.90
H3C
CH3
O
4.07
1.89
2.00
3.04
1.82
1.95
3.81
2.72
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)

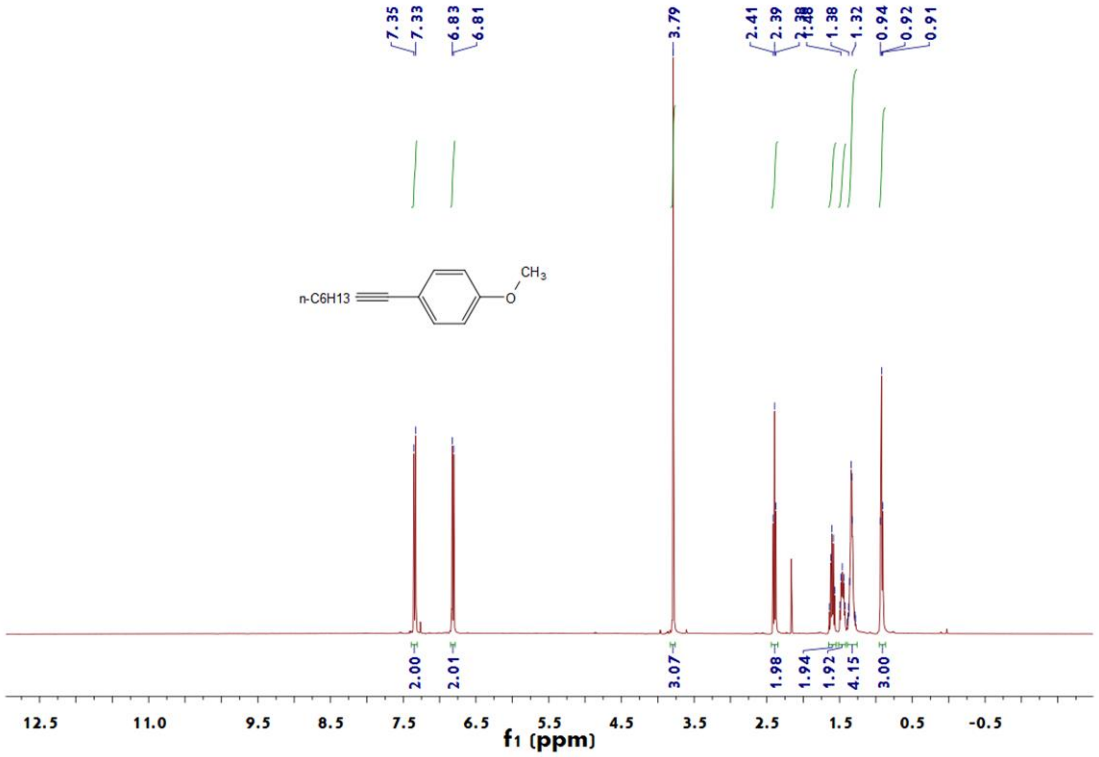

159.42
143.01
128.38
120.65
115.57
113.91
88.65
88.21
55.20
35.82
31.41
30.91
22.50
14.01
H3C
CH3
O
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

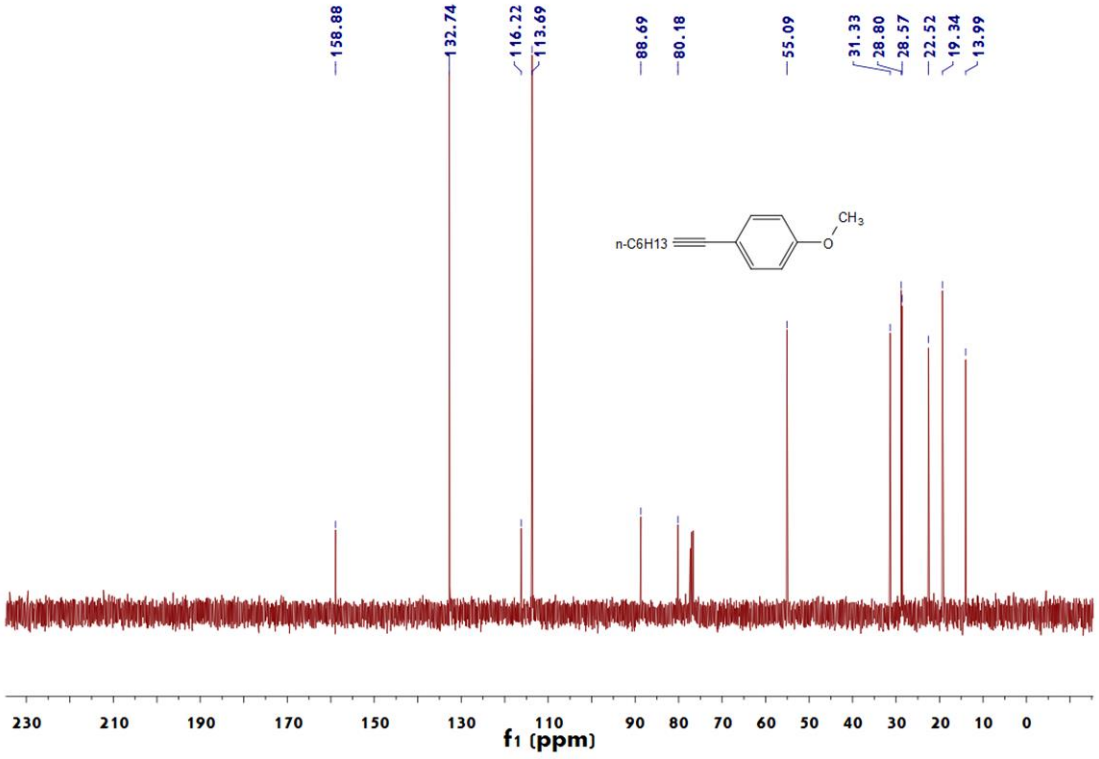

7.47
7.46
7.45
7.42
7.40
7.15
7.13
6.88
6.86
3.82
2.36
2.17
H3C
CH3
O
2.00
1.91
1.89
1.92
2.88
3.41
13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2
f1 (ppm)


158.44
136.99
131.94
130.31
128.05
119.45
114.55
112.93
87.63
87.17
54.27
20.47
H3C
CH3
O
240 220 200 180 160 140 120 100 80 60 40 20 0 -10
f1 (ppm)


7.39
7.38
7.36
7.35
7.33
7.31
7.30
7.28
7.26
7.26
6.87
6.85
3.82
3.82
2.99
2.97
2.95
2.75
2.73
2.71
CH3
O
7.26
2.04
3.07
1.97
2.00
12.5
11.0
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)


159.07
140.78
128.52
126.25
115.98
113.80
87.88
81.04
55.18
35.30
21.69
CH3
O
230
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


7.35
7.33
6.83
6.81
3.79
2.41
2.39
1.38
1.32
0.94
0.92
0.91
n-C6H13
CH3
O
2.00
2.01
3.07
1.98
1.94
1.92
4.15
3.00
12.5
11.0
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)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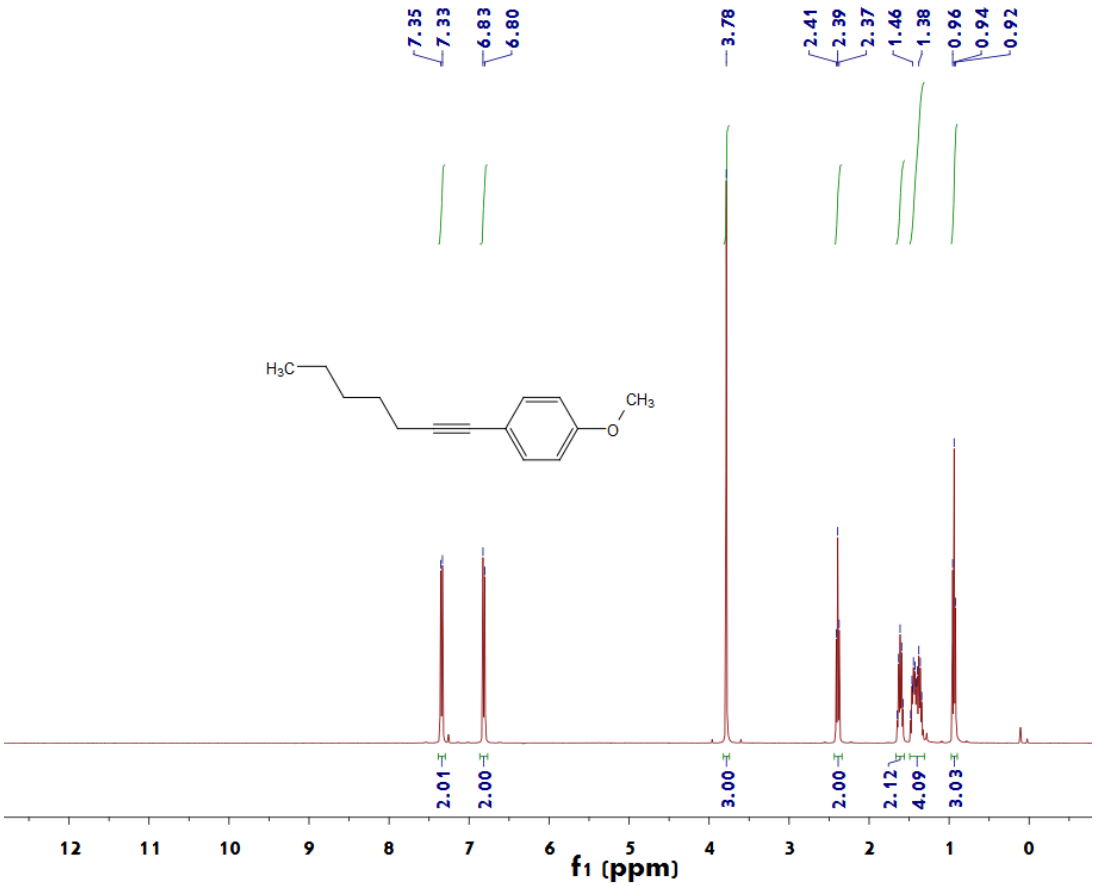
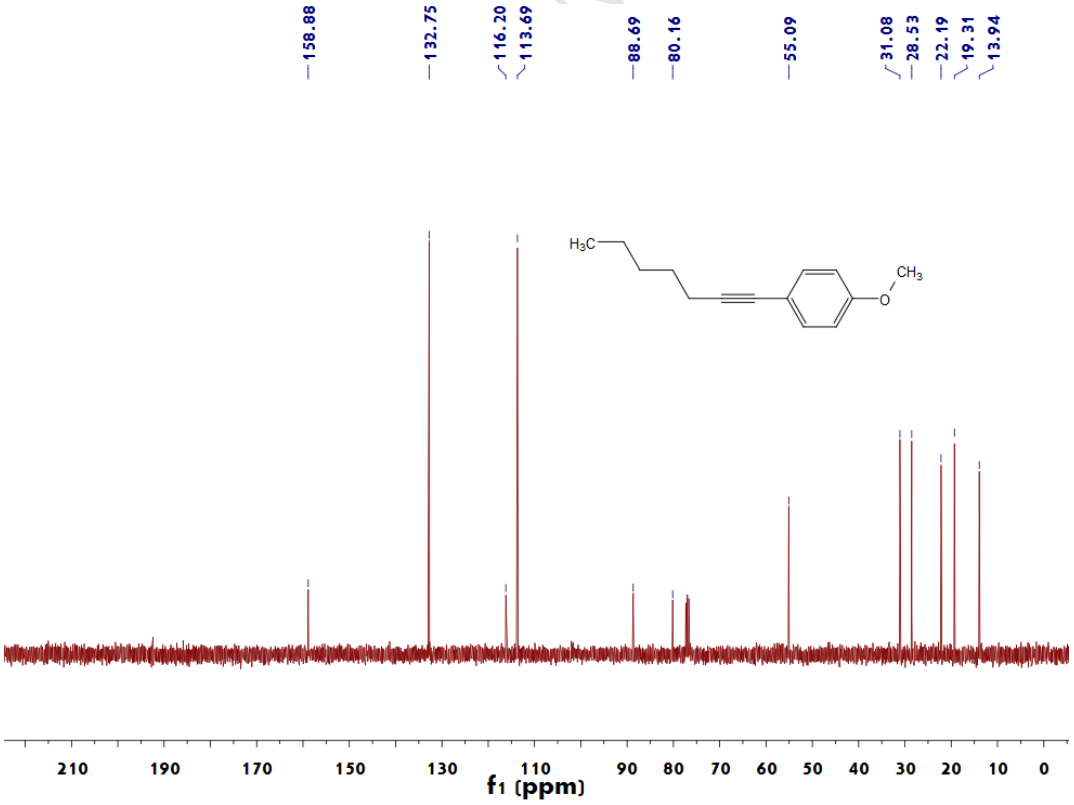
132.74
116.22
113.69
88.69
80.18
55.09
31.33
28.80
28.57
22.52
19.34
13.99
n-C6H13
CH3
O
230
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


7.35
7.33
6.83
6.80
3.78
2.41
2.39
2.37
1.46
1.38
0.96
0.94
0.92
H3C
CH3
O
2.01
2.00
3.00
2.00
2.12
4.09
3.03
12 11 10 9 8 7 6 5 4 3 2 1 0
f1 (ppm)


158.88
132.75
116.20
113.69
88.69
80.16
55.09
31.08
28.53
22.19
19.31
13.94
H3C
CH3
O
210 190 170 150 130 110 90 80 70 60 50 40 30 20 10 0
f1 (ppm)