Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers

Palladium-Catalyzed Base-accelerated Direct C-H Bond Alkenylation of Phenols to Syntheize Coumarin Derivatives

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Contents

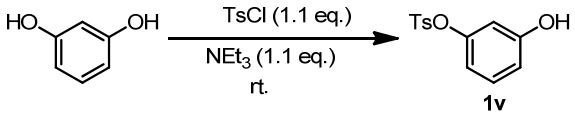
General:

$Pd(CH_3CN)_4(BF_4)_2$ was purchased from Alfa, phenol derivatives (**1**) were purchased from J&K or Alfa. Other reagents were commercially available and used directly without further purification unless otherwise specified. All the solvents were directly used unless otherwise specified (HPLC grade). NMR data were collected on Bruker 400 M or Bruker 500 M nuclear resonance spectrometers in the solvents indicated unless otherwise specified. Chemical shifts are reported in units (ppm) by assigning TMS resonance in the ^1H spectrum as 0.00 ppm and the central peak of $CDCl_3$ resonance in the ^{13}C spectrum as 77.0 ppm. When $CD_3C(O)CD_3$ was used as solvent, the central peak of CD_3 in $CD_3C(O)CD_3$ was assigned as 2.05 ppm in ^1H spectrum and 29.8 ppm in ^{13}C spectrum. The data of ^1H NMR was reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet and br = broad), coupling constant (*J* values) in Hz and integration. Column chromatography was performed on 200-300 mesh silica gels with the indicated solvent systems. Analytical thin-layer chromatography (TLC) was performed on pre-coated, glass-backed silica gel plates. Visualization of the developed chromatogram was performed by UV absorbance (254 nm). HRMS (ESI) were performed on Fourier Transform Ion Cyclotron Resonance Mass Spectrometer by Analytical Instrumentation Center, Peking University.

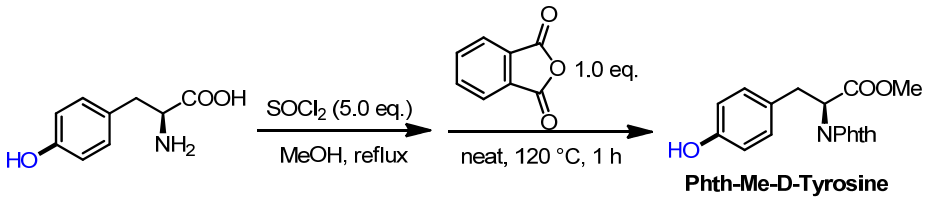
Synthetic Procedures:

1. Procedure for the synthesis of selected starting materials

Synthesis of **1v:** To a mixture of resorcinol (20 mmol) and NEt_3 (22 mmol, 1.1 eq, 2.2 g) in DCM, solution of TsCl (22 mmol, 1.1 eq., 4.2 g) in DCM was added dropwise at room temperature. After the reaction, the solid was filtrated and the product was purified by column chromatography. (0.72 g, 14 % yield)



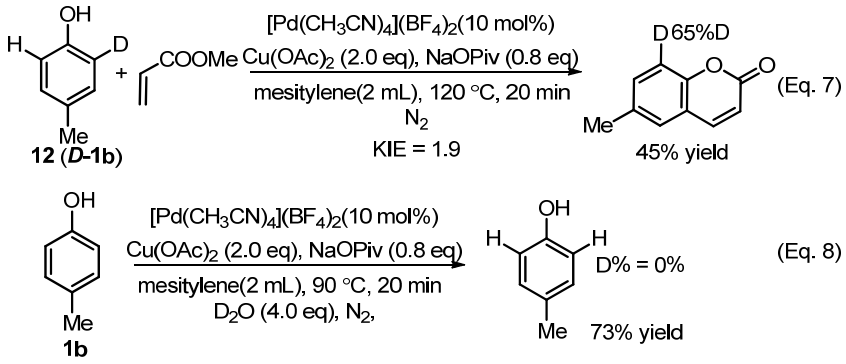
Synthesis of **Phth-Me-D-Tyrosine**: The protection of the carboxylic acid to ester was according to the literature.[1] After this step, the crude product was directly added 1.0 equivalent of isobenzofuran-1,3-dione and heated at 120 ℃ for 1 h without solvent under air atmosphere. After the reaction, the product was purified by column chromatography in 11% yield.



2. Procedure for the C-H alkenylation of phenol to synthesize coumarins

The procedure to synthesis **3aa**: To a 50 mL of Wattcs reaction tube with a stirring bar was added 4-(tert-butyl)phenol **1a** (0.2 mmol, 1.0 equiv, 30.0 mg), $Cu(OAc)_2$ (0.4 mmol, 2.0 equiv, 72.5 mg) and NaOPiv (0.16 mmol, 0.8 equiv, 19.9 mg) at air atmosphere. After adding $Pd(CH_3CN)_4(BF_4)_2$ (0.02 mmol, 8.9 mg) in glove box, methyl acrylate **2a** (0.4 mmol, 2.0 equiv, 34.4 mg) and solvent (mesitylene, 2 mL) were added and the tube was sealed and conducted to 120 ℃ for 12 h. After cooling to room temperature, the system was purified by column chromatography with Hexane:EtOAc (6:1) to afford the product as white solid in 70% yield (28.5 mg).

3. Procedure for the deuterium labeling experiment (Scheme 5)



Scheme 5. Deuterium labeling experiments

3.1 Synthesis of the deuterium labeled material (12)

The deuterium labeled substrate **12** was synthesized according to the literature.[2] The characterization data was as follows:δ = ^{1}H NMR (400MHz, $CDCl_3$): δ = 7.03 (d, J = 8.0 Hz, 2H), 6.73 (d, J = 8.0 Hz, 1.08H), 4.99 (s, 1H), 2.27 (s, 3H). D%>90%. ^{13}C NMR (126 MHz, $CDCl_3$) δ = 153.23, 130.10, 130.02, 129.95, 115.25, 20.47.

3.2 Procedure for the deuterium labeling experiment (Eq. 7)

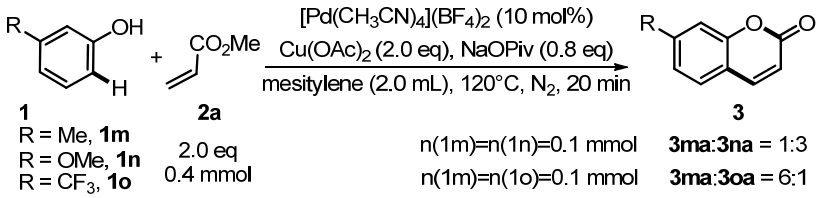
The reaction was conducted according to the standard procedure except that the reaction temperature was lowed 90 ℃ and the reaction time was reduced to 20 min, in order to make sure a proper conversion. After the reaction, the product was isolated and characterized by ^{1}HNMR. The ^{1}HNMR of the product was: ^{1}H NMR (300MHz, $CDCl_3$): δ = 7.66 (d, J = 9.5 Hz, 1H), 7.33 (s, 1H), 7.24-7.22 (m, 0.35 H), 6.40 (d, J = 9.3 Hz, 1H), 2.41 (s, 3H). D% = 65%, KIE = 1.9.

3.3 Procedure for the deuterium exchange reaction (Eq. 8)

The reaction was conducted according to the standard procedure except that the reaction temperature was lowed 90 ℃ and the reaction time was reduced to 20 min, and 4.0 equivalent of D_2O was added as a deuterium source. After the reaction, the starting material was recovered and the ^{1}HNMR detection showed that no deuterium exchange was present.

4. Procedure for the competing experiments (Scheme 6)

Scheme 6. Competing reaction



1
R = Me, **1m**
R = OMe, **1n**
R = CF_3, **1o**

2a
2.0 eq
0.4 mmol

3
n(1m)=n(1n)=0.1 mmol **3ma**:**3na** = 1:3
n(1m)=n(1o)=0.1 mmol **3ma**:**3oa** = 6:1

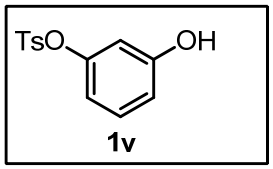
The competing experiments were conducted according to the standard procedure with two different electron characteristic phenol derivatives in the same reaction system. Take the mixture of **1m** and **1n** for example: To a 50 mL of Wattcs reaction tube with a stirring bar was added **1m** (0.1 mmol, 1.0 equiv), **1n** (0.1 mmol, 1.0 equiv), $Cu(OAc)_2$ (0.4 mmol, 2.0 equiv, 72.5 mg) and NaOPiv (0.16 mmol, 0.8 equiv, 19.9 mg) at air atmosphere. After adding $Pd(CH_3CN)_4(BF_4)_2$ (0.02 mmol, 8.9 mg) in glove box, methyl acrylate **2a** (0.4 mmol, 2.0 equiv, 34.4 mg) and solvent (mesitylene, 2 mL) were added and the tube was sealed and conducted to 120 ℃ for 20min. After cooling to room temperature, the solvent was removed under reduced pressure and the yield and ratio of the products (**3**) were determined by crude NMR with CH_2Br_2 as internal standard.

The characteristic peaks in the crude NMR of the mixture of **3ma** and **3na**: ^{1}H NMR(400MHz, $CDCl_3$): δ = 4.928 (s, 1.00H, CH_2 of CH_2Br_2), 6.36 (d, J = 9.6 Hz, 0.11H, alkenyl CH of **3ma**), 6.26 (d, J = 9.2 Hz, 0.33H, alkenyl CH of **3na**).

The characteristic peaks in the crude NMR of the mixture of **3ma** and **3oa**: ^{1}H NMR(400MHz, $CDCl_3$): δ = 4.932 (s, 1.00H, CH_2 of CH_2Br_2), 6.36 (d, J = 9.6 Hz, 0.35H, alkenyl CH of **3ma**), 6.56 (d, J = 9.6 Hz, 0.06H, alkenyl CH of **3oa**).

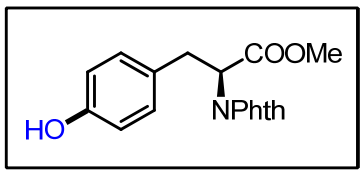
Characterization Data

1 Characterization data of phenol derivatives (1)



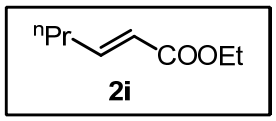
1v

1v. Colorless oil. **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.70 (d, J = 8.2 Hz, 2H), 7.29 (d, J =8.2 Hz, 2H), 7.08 (t, J= 8.2 Hz, 1H), 6.72 (dd, J = 2.0, 8.2 Hz, 1H), 6.57 (t, J = 2.0 Hz, 1H), 6.49-6.47 (m, 1H), 6.36 (br, 1H), 2.42 (s, 3H). **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{13}H_{13}O_4S$: 265.05291, found: 265.05266.



Phth-Me-D-Tyrosine. White solid. **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.77-7.79 (m, 2H), 7.68-7.70 (m, 2H), 7.01 (d, J = 8 Hz, 2H), 6.64 (d, J = 8 Hz, 2H), 5.10 (dd, J = 4 Hz, 8 Hz, 1H), 3.78 (s, 3H), 3.43-3.55 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ = 169.40, 167.64, 154.64, 134.16, 131.46, 129.95, 128.39, 123.52, 115.46, 53.47, 52.86, 33.78. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{18}H_{16}NO_5$: 326.10230, found: 326.10196.

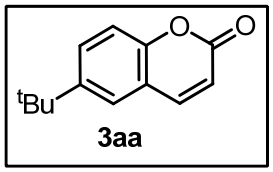
2 Characterization data of alkenes (2)



2i

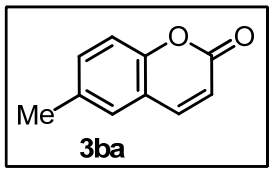
(E)-ethyl hex-2-enoate. Colorless oil. **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 6.92-7.00 (m, 1H), 5.82 (d, J = 12 Hz, 1H), 4.16-4.21 (m, 2H), 2.18 (q, J = 8 Hz, 2H), 1.43-1.54 (m, 3H), 1.29 (t, J = 8 Hz, 3H), 0.94 (t, J = 8 Hz, 3H). **^{13}C NMR (100MHz, $CDCl_3$)**: δ = 166.71, 149.10, 121.37, 60.05, 34.14, 21.23, 14.21, 13.58.

3 Characterization data of coumarin products (3)



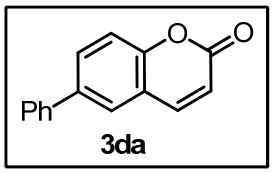
3aa

6-(tert-butyl)-2H-chromen-2-one. According to the general procedure, **3aa** was obtained as a White solid in 70% yield (28.5 mg) by column chromatography (Petroleum ether: Ethyl acetate : Toluene= 2 : 1 : 0.33). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.71 (d, J = 9.5 Hz, 1H), 7.58 (dd, J = 8.7, 2.2 Hz, 1H), 7.50 (d, J = 2.1 Hz, 1H), 7.27 (d, J = 9.5 Hz, 1H), 1.36 (s, 9H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 161.09, 152.05, 147.55, 143.83, 129.45, 124.09, 118.25, 116.40, 116.38, 34.49, 31.30. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{13}H_{15}O_2$: 203.10666, found: 203.10677.



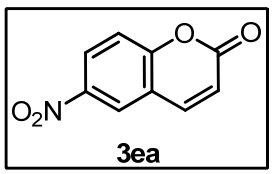
3ba

6-methyl-2H-chromen-2-one. According to the general procedure, **3ba** was obtained as a White solid in 68% yield (19.4 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.60 (d, J = 12 Hz, 1H), 7.34 (dd, J = 2.0, 8.0 Hz, 1H), 7.27-7.22 (m, 2H), 2.41 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 161.03, 152.21, 143.35, 134.10, 132.80, 127.65, 118.59, 116.61, 20.69. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_8O_2$: 161.05971, found: 161.05974.



3da

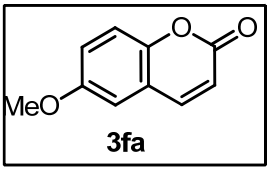
6-phenyl-2H-chromen-2-one. According to the general procedure, **3da** was obtained as a yellow solid in 67% yield (29.9 mg) by column chromatography (Petroleum ether: Ethyl acetate : Toluene= 20 : 1 : 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.78-7.74 (m, 2H), 7.67 (d, J = 2 Hz, 1H), 7.59-7.57 (m, 2H), 7.47 (t, J = 8 Hz, 2H), 7.42-7.37 (m, 2H), 6.47 (d, J = 8.0 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 160.67, 153.43, 143.44, 139.40, 137.84, 130.74, 129.01, 127.79, 127.04, 126.04, 119.04, 117.26, 117.05.



3ea

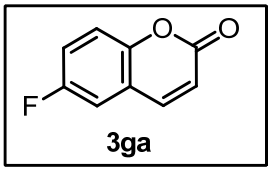
6-nitro-2H-chromen-2-one. According to the general procedure, **3ea** was obtained as a white solid in 62% yield (23.8 mg) by column chromatography (Petroleum ether: Ethyl acetate :

Toluene= 20 : 1 : 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 8.45-8.40 (m, 2H), 7.81 (d, J = 8.0Hz, 1H), 7.47 (d, J = 12 Hz, 1H), 6.59 (d, J = 12 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 158.76, 157.55, 144.06, 142.16, 126.58, 123.72, 118.82, 118.06. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_9H_5NO_4$: 192.02913, found: 192.02947.



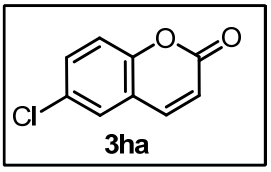
3fa

6-methoxy-2H-chromen-2-one. According to the general procedure, **3fa** was obtained as a white solid in 22% yield (7.8 mg) by column chromatography (Petroleum ether: Ethyl acetate : Toluene= 20 : 1 : 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.66 (d, J = 8 Hz, 1H), 7.28 (d, J = 4 Hz, 1H), 7.12 (dd, J = 4, 8 HZ, 1H), 6.92 (d, J = 4 Hz, 1H), 6.43 (d, J = 8 Hz, 1H), 3.85 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 160.96, 156.07, 148.45, 143.16, 119.43, 119.15, 117.87, 117.08, 110.01, 55.82. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for: $C_{10}H_9O_3$: 177.05462, found: 177.05457.



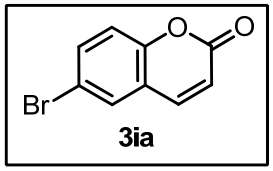
3ga

6-fluoro-2H-chromen-2-one. According to the general procedure, **3ga** was obtained as a White solid in 59% yield (19.4 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.66 (d, J = 8 Hz, 1H), 7.33 (dd, J = 4, 8 Hz, 1H), 7.28-7.23 (m, 1H), 7.19 (dd, J = 2, 8Hz, 1H), 6.48 (d, J = 12 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ 160.27, 158.74 (d, J = 243 Hz), 150.23, 142.38 (d, J = 3 Hz), 119.47 (d, J = 9 Hz), 119.20 (d, J = 24 Hz), 118.50 (d, J = 9 Hz), 117.92, 113.15 (d, J = 24 Hz). **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_9H_6FO_2$: 165.03463, found: 165.03465.



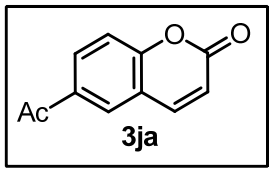
3ha

6-chloro-2H-chromen-2-one. According to the general procedure, **3ha** was obtained as a White solid in 72% yield (25.9 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10).. **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.64 (d, J = 12 Hz, 1H), 7.50-7.48 (m, 2H), 7.30-7.28 (m, 1H), 6.48 (d, J = 12 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 159.95, 152.44, 142.13, 131.73, 129.68, 127.10, 119.80, 118.30, 117.87. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_9H_6ClO_2$: 181.00508, found: 181.00515.



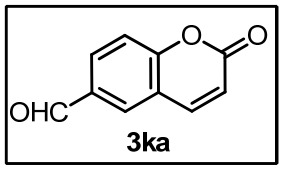
3ia

6-bromo-2H-chromen-2-one. According to the general procedure, **3ia** was obtained as a White solid in 56% yield (25.3 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.65-7.61 (m, 3H), 7.23 (d, J = 9.2 Hz, 1H), 6.46 (d, J = 9.6 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 159.85, 152.90, 142.03, 134.54, 130.13, 120.30, 118.59, 117.83, 116.93. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_9H_6BrO_2$: 224.95457, found: 224.95434.



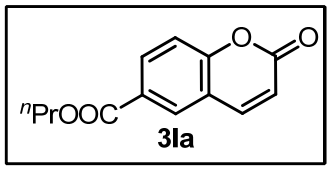
3ja

6-acetyl-2H-chromen-2-one. According to the general procedure, **3ja** was obtained as a White solid in 64% yield (24.0 mg) by column chromatography (Petroleum ether: Ethyl acetate = 5). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 8.15-8.12 (m, 2H), 7.78 (d, J = 8 Hz, 1H), 7.40 (d, J = 12 Hz, 1H), 6.50 (d, J = 12 Hz, 1H), 2.65 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 195.91, 159.76, 156.91, 143.12, 133.54, 131.68, 128.59, 118.63, 117.67, 117.28, 26.53. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{11}H_9O_3$: 189.05462, found: 189.05447.



3ka

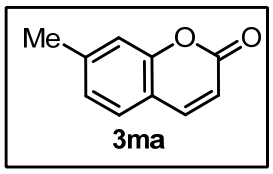
2-oxo-2H-chromene-6-carbaldehyde. According to the general procedure, **3ka** was obtained as a White solid in 73% yield (25.4 mg) by column chromatography (Petroleum ether: Ethyl acetate = 5). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 10.05 (s, 1H), 8.08-8.05 (m, 2H), 7.81 (d, J = 8 Hz, 1H), 7.48 (d, J = 8 Hz, 1H), 6.54 (d, J = 12 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 189.93, 159.46, 157.77, 142.80, 132.84, 132.43, 129.98, 119.11, 117.95, 115.92. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_7O_3$: 175.03897, found: 175.03942.



3la

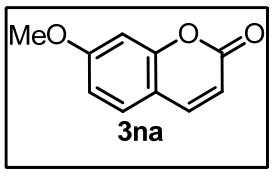
isopropyl 2-oxo-2H-chromene-6-carboxylate. According to the general procedure, **3la** was obtained as a White solid in 49% yield (22.9 mg) by column chromatography (Petroleum ether: Ethyl acetate = 5). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 8.21-8.19 (m, 2H), 7.77 (d, J = 12 Hz, 1H),

7.38 (d, J = 8 Hz, 1H), 4.32 (t, J = 8 Hz, 2H), 1.86-1.78 (m, 2H), 1.05 (t, J = 8 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 165.19, 159.89, 156.81, 143.08, 132.76, 129.82, 126.95, 118.52, 117.45, 117.07, 67.03, 22.07, 10.47. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{13}H_{13}O_4$: 233.08084, found: 233.08072.



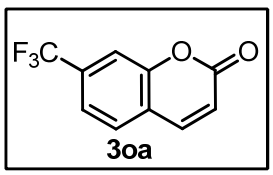
3ma

7-methyl-2H-chromen-2-one. According to the general procedure, **3ma** was obtained as a White solid in 71% yield (22.9 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.67 (d, J = 8 Hz, 1H), 7.36 (d, J = 8 Hz, 1H), 7.14 (s, 1H), 7.09 (d, J = 8 Hz, 1H), 6.36 (d, J = 12 Hz, 1H), 2.46 (s, 3H). **^{13}C NMR (101MHz, $CDCl_3$)**: δ = 161.07, 154.21, 143.33, 143.10, 127.49, 125.58, 117.09, 116.49, 115.49, 21.75. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_9O_2$: 161.05971, found: 161.05949.



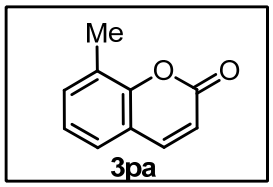
3na

7-methoxy-2H-chromen-2-one. According to the general procedure, **3na** was obtained as a White solid in 39% yield (13.6 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10 to 5). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.64 (d, J = 8 Hz, 1H), 7.38(d, J = 12 Hz, 1H), 6.82-6.86(m, 2H), 6.25(d, J = 8 Hz, 1H), 3.88(s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)**: δ = 162.84, 161.14, 155.92, 143.36, 128.72, 113.09, 112.56, 112.52, 100.85, 55.74. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_9O_3$: 177.05462, found: 177.05460.



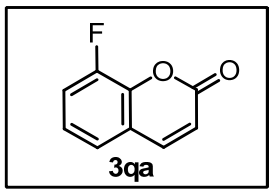
3oa

7-(trifluoromethyl)-2H-chromen-2-one. According to the general procedure, **3oa** was obtained as a White solid in 21% yield (9.2 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10 to 5). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.75 (d, J = 8 Hz, 1H), 7.64-7.59 (m, 2H), 7.54 (d, J = 8 Hz, 1H), 6.55 (d, J = 8 Hz, 1H). **^{13}C NMR (126MHz, $CDCl_3$)**: δ = 159.52, 153.75, 142.13, 133.55 (q, J = 32.5 Hz), 128.56, 123.2 (q, J = 271.3 Hz), 121.35, 121.02 (q, J = 3.8 Hz), 119.03, 114.40 (q, J = 3.8 Hz). **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_6F_3O_2$: 215.03144, found: 215.03107.



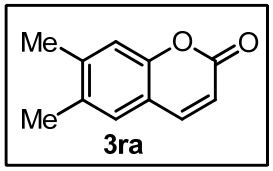
3pa

8-methyl-2H-chromen-2-one. According to the general procedure, **3pa** was obtained as a White solid in 22.2% yield (21.8 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.70 (d, J = 8 Hz, 1H), 7.39 (d, J = 8 Hz, 1H), 7.32 (d, J = 8 Hz, 1H), 7.18 (t, J = 8 Hz, 1H), 6.42 (d, J = 12 Hz, 1H), 2.46 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)**: δ = 161.02, 152.39, 143.79, 133.15, 126.35, 125.55, 123.97, 118.56, 116.31, 15.38. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_9O_2$: 161.05971, found: 161.05960.



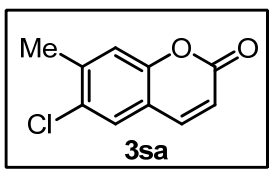
3qa

8-fluoro-2H-chromen-2-one. According to the general procedure, **3qa** was obtained as a White solid in 46% yield (15.0 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, CD_3COCD_3)**: δ = 8.04 (dd, J = 4.0, 12.0 Hz, 1H), 7.53-7.45 (m, 2H), 7.37-7.33 (m, 1H), 6.51 (d, J = 8Hz, 1H). **^{13}C NMR (126 MHz, CD_3COCD_3)** δ 159.32, 150.05 (d, J = 243 Hz), 144.27 (d, J = 2.5 Hz), 143.08 (d, J = 11.3 Hz), 125.30 (d, J = 7.5 Hz), 124.62 (d, J = 3.8 Hz), 121.97, 118.80 (d, J = 17.5 Hz), 118.18. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_9H_6FO_2$: 165.03463, found: 165.03481.



3ra

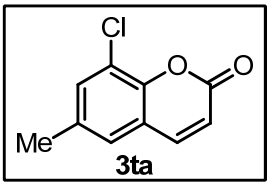
6,7-dimethyl-2H-chromen-2-one. According to the general procedure, **3ra** was obtained as a White solid in 63% yield (21.9 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.63 (d, J = 8 Hz, 1H), 7.21 (s, 1H), 7.11 (s, 1H), 6.33 (d, J = 8 Hz, 1H), 2.35 (s, 3H), 2.30 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)**: δ = 161.31, 152.47, 143.27, 141.88, 133.12, 127.87, 117.39, 116.60, 115.42, 20.28, 19.10. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{11}H_{11}O_2$: 175.07536, found: 175.07544.



3sa

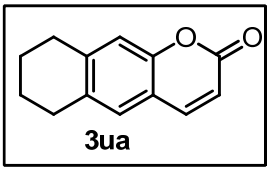
6-chloro-7-methyl-2H-chromen-2-one. According to the general procedure, **3sa** was obtained as a White solid in 70% yield (27.2 mg) by column chromatography (Petroleum ether: Ethyl acetate

= 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.62 (d, J = 12 Hz, 1H), 7.46 (s, 1H), 7.21 (s, 1H), 6.40 (d, J = 8 Hz, 1H), 2.46 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)**: δ = 160.31, 152.38, 142.09, 140.69, 130.12, 127.25, 118.82, 117.80, 116.74, 20.59. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_8ClO_2$: 195.02073, found: 195.02073.



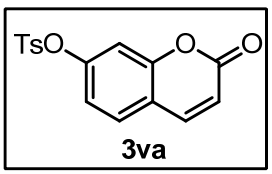
3ta

8-chloro-6-methyl-2H-chromen-2-one. According to the general procedure, **3ta** was obtained as a White solid in 57% yield (22.2 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.64 (d, J = 12 Hz, 1H), 7.42 (m, 1H), 7.18 (s, 1H), 6.45 (d, J = 12 Hz, 1H), 7.18 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)**: δ = 159.75, 147.81, 142.99, 134.72, 133.03, 126.33, 121.26, 119.78, 117.32, 20.56. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{10}H_8ClO_2$: 195.02073, found: 195.02070.



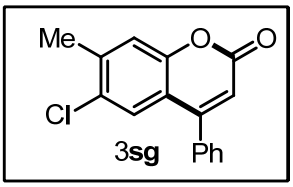
3ua

6,7,8,9-tetrahydro-2H-benzo[g]chromen-2-one. According to the general procedure, **3ua** was obtained as a White solid in 48% yield (19.2 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.62 (d, J = 8 Hz, 1H), 7.15 (s, 1H), 7.03 (s, 1H), 6.33 (d, J = 12 Hz, 1H), 2.83 (d, J = 24 Hz, 4H), 1.80-1.84 (m, 4H). **^{13}C NMR (100MHz, $CDCl_3$)**: δ = 161.34, 151.99, 143.36, 142.45, 133.73, 127.55, 116.69, 116.44, 115.48, 29.83, 28.73, 22.89, 22.62. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{13}H_{13}O_2$: 201.09101, found: 201.09087.

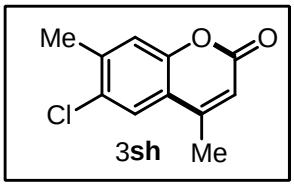


3va

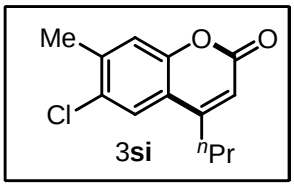
2-oxo-2H-chromen-7-yl 4-methylbenzenesulfonate. According to the general procedure, **3va** was obtained as a White solid in 47% yield (29.7 mg) by column chromatography (Petroleum ether: Ethyl acetate = 5 to 3). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.74 (d, J = 8 Hz, 2H), 7.67 (d, J = 12 Hz, 1H), 7.45 (d, J = 8 Hz, 1H), 7.35 (d, J = 8 Hz, 1H), 7.06-7.08 (m, 1H), 6.41 (d, J = 12 Hz, 1H), 2.47 (s, 3H). **^{13}C NMR (100MHz, $CDCl_3$)**: δ = 159.86, 154.34, 151.64, 146.05, 142.54, 131.88, 130.03, 128.85, 128.42, 119.09, 117.61, 116.70, 110.89, 21.73. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{16}H_{13}O_5S$: 317.04782, found: 317.04771.



6-chloro-7-methyl-4-phenyl-2H-chromen-2-one. According to the general procedure, **3sg** was obtained as a White solid in 57% yield (31.0 mg) by column chromatography (Petroleum ether: Ethyl acetate = 15). **^{1}H NMR (400MHz, CDCl$_3$)**: δ = 7.55 (t, J = 4 Hz, 3H), 7.42-7.45 (m, 3H), 7.28 (d, J = 12 Hz, 1H), 6.35 (s, 1H), 2.47 (s, 3H). **^{13}C NMR (100MHz, CDCl$_3$)**: δ = 160.40, 154.66, 152.53, 140.88, 134.79, 130.16, 129.92, 129.06, 128.30, 126.54, 119.24, 118.12, 115.10, 20.50. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{16}H_{12}ClO_2$: 271.05203, found: 271.05184.

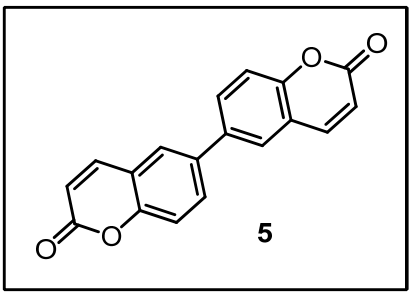


6-chloro-4,7-dimethyl-2H-chromen-2-one. According to the general procedure, **3sh** was obtained as a White solid in 37% yield (15.5 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10).**^{1}H NMR (400MHz, CDCl$_3$)**: δ = 7.55 (s, 1H), 7.21 (s, 1H), 6.27 (s, 1H), 2.46 (s, 3H), 2.41 (d, J = 4 Hz, 3H). **^{13}C NMR (100MHz, CDCl$_3$)**: δ = 160.41, 151.87, 151.29, 140.56, 130.07, 124.42, 119.12, 118.98, 115.10, 20.47, 18.51. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{11}H_{10}ClO_2$: 209.03638, found: 209.03632.

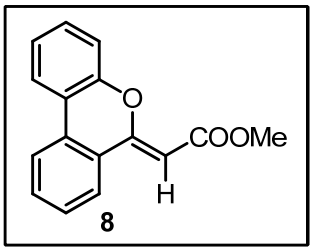


6-chloro-7-methyl-4-propyl-2H-chromen-2-one. 3si was obtained as a White solid by column chromatography (Petroleum ether: Ethyl acetate = 10), 21% yield was obtained by **^{1}H NMR** with CH_2Br_2 as internal standard. **^{1}H NMR (400MHz, CDCl$_3$)**: δ = 7.57 (s, 1H), 7.22 (s, 1H), 6.25 (s, 1H), 2.70 (t, J = 8 Hz, 2H), 2.46 (s, 3H), 1.69-1.79 (m, 2H), 1.07 (t, J = 8 Hz, 3H). **^{13}C NMR (126MHz, CDCl$_3$)**: δ = 160.67, 155.00, 152.12, 140.39, 130.07, 124.16, 119.19, 118.53, 113.93, 33.54, 21.19, 20.44, 13.86. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{13}H_{14}ClO_2$: 237.06768, found: 237.06756.

4 Characterization data of other transformations



2H,2'H-[6,6'-bichromene]-2,2'-dione. According to the general procedure, **5** was obtained as a yellow solid in 34% yield (19.6 mg) by column chromatography (Petroleum ether: Ethyl acetate = 5/1 to 1.5/1). **^{1}H NMR (400MHz, CD_3COCD_3)**: δ = 8.08(d, J = 12 Hz, 2H), 8.05-8.06(m, 2H), 7.97(dd, J = 4 Hz, 8 Hz, 2H), 6.50(d, J = 12 Hz, 2H). **^{13}C NMR (100MHz, CD_3COCD_3)**: δ = 160.31, 154.50, 144.34, 136.41, 131.03, 127.17, 120.21, 117.76, 117.72. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{18}H_{11}O_4$: 291.06519, found: 291.06502.



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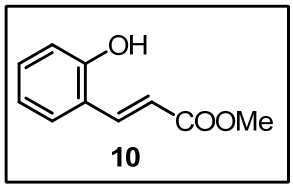
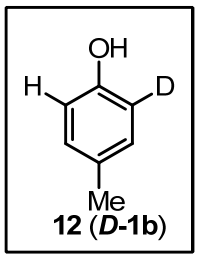
(Z)-methyl 2-(6H-benzo[c]chromen-6-ylidene)acetate. According to the general procedure, **8** was obtained as oil liquid in 28% yield (14.1 mg) by column chromatography (Petroleum ether: Ethyl acetate = 15/1). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.97 (d, J = 8Hz, 1H), 7.89 (d, J = 8Hz, 1H), 7.79 (d, J = 8Hz, 1H), 7.69-7.56 (m, 1H), 7.42-7.33 (m, 3H), 7.21-7.17 (m, 1H), 5.86 (s, 1H), 3.78 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$)** δ = 165.82, 158.96, 150.62, 131.89, 130.19, 129.50, 128.80, 124.87, 124.27, 123.69, 122.25, 121.93, 118.28, 117.43, 90.86, 50.90. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{16}H_{13}O_3$: 253.08592, found: 253.08586.

5 Characterization data of mechanistic studies



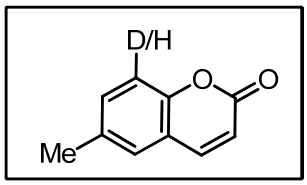
10

(E)-methyl 3-(2-hydroxyphenyl)acrylate. The **10** was synthesized according to the literature.[3] The characterization data was as follows: **^{1}H NMR (400MHz, CDCl$_3$)**: δ = 8.04 (d, J = 24 Hz, 1H), 7.47 (dd, J = 4 Hz, 8 Hz, 1H), 7.21-7.27 (m, 1H), 6.84-6.95 (m, 2H), 6.64 (d, J = 20 Hz, 1H), 6.59 (s, 1H), 3.83 (s, 3H).



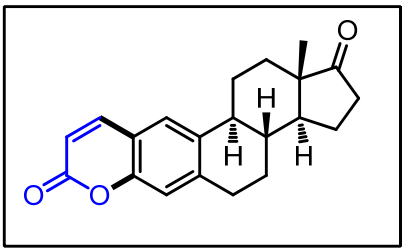
12 (*D*-1b)

12. White solid. **^{1}H NMR (400MHz, CDCl$_3$)**: δ = 7.03 (d, J = 8.0 Hz, 2H), 6.73 (d, J = 8.0 Hz, 1.08H), 4.99 (s, 1H), 2.27 (s, 3H). D%>90%. ^{13}C NMR (126 MHz, $CDCl_3$) δ = 153.23, 130.10, 130.02, 129.95, 115.25, 20.47.

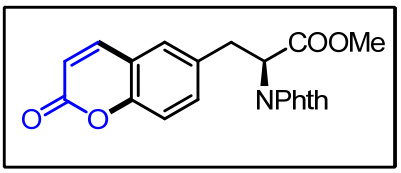


13. White solid. **^{1}H NMR (300MHz, CDCl$_3$)**: δ = 7.66 (d, J = 9.5 Hz, 1H), 7.33 (s, 1H), 7.24-7.22 (m, 0.35 H), 6.40 (d, J = 9.3 Hz, 1H), 2.41 (s, 3H). D% = 65%

6 Characterization data of synthesis of bioactive molecules



(3aS,3bR,11bS,13aS)-13a-methyl-3,3a,4,5,11b,12,13,13a-octahydrocyclopenta[5,6]naphtho[1,2-g]chromene-1,8(2H,3bH)-dione. According to the general procedure, it was obtained as white solid in 59% yield (38.2 mg) by column chromatography (Petroleum ether: Ethyl acetate = 6/1 to 4/1). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.65 (d, J = 8 Hz, 1H), 7.37 (s, 1H), 7.06 (s, 1H), 6.35 (d, J = 12 Hz, 1H), 2.99-3.05 (m, 2H), 2.43-2.57 (m, 2H), 2.30-2.36 (m, 1H), 1.98-2.22 (m, 4H), 1.45-1.73 (m, 6H), 0.93 (s, 3H). **^{13}C NMR (126MHz, $CDCl_3$)**: δ = 220.30, 161.15, 152.23, 143.54, 141.92, 136.68, 124.36, 116.75, 116.41, 115.57, 50.47, 47.83, 43.80, 37.87, 35.77, 31.44, 29.64, 26.11, 25.85, 21.56, 13.77. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{21}H_{23}O_3$: 323.16417, found: 323.16442.



(R)-2-(1,3-dioxoisoindolin-2-yl)-3-(2-oxo-2H-chromen-6-yl)propanoic acid. According to the general procedure, it was obtained as white solid in 43% yield (32.7 mg) by column chromatography (Petroleum ether: Ethyl acetate = 10/3 to 5/2). **^{1}H NMR (400MHz, $CDCl_3$)**: δ = 7.78-7.80 (m, 2H), 7.70-7.73 (m, 2H), 7.58 (d, J = 8 Hz, 1H), 7.30-7.35 (m, 2H), 7.17 (d, J = 8 Hz, 1H), 6.36 (d, J = 12 Hz, 1H), 5.15-5.19 (m, 1H), 3.79 (s, 3H), 3.56-3.69 (m, 2H). **^{13}C NMR (126MHz, $CDCl_3$)**: δ = 168.94, 167.42, 160.56, 152.99, 143.06, 134.32, 133.12, 132.34, 131.44, 127.96, 123.61, 118.85, 117.10, 116.90, 53.00, 52.90, 34.03. **HRMS (ESI)**: m/z: $[M+H]^+$ caculated for $C_{21}H_{16}NO_6$: 378.09721, found: 378.09743.

References

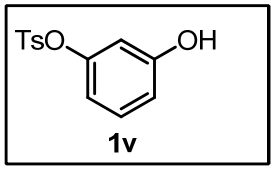
[1] S. Papst, A. F. M. Noisier, M. A. Brimble, Y. Yang, G. W. Krissansen, *Bioorg. Med. Chem.* **2012**, *20*, 5139-5149.

[2] (a) R. Zhu, J. Wei, Z. Shi, *Chem. Sci.* **2013**, *4*, 3706-3711. (b) T.-J. Gong, B. Xiao, Z.-J. Liu, J. Wan, J. Xu, D.-F. Luo, Y. Fu, L. Liu, *Org. Lett.* **2011**, *13*, 3235-3237.

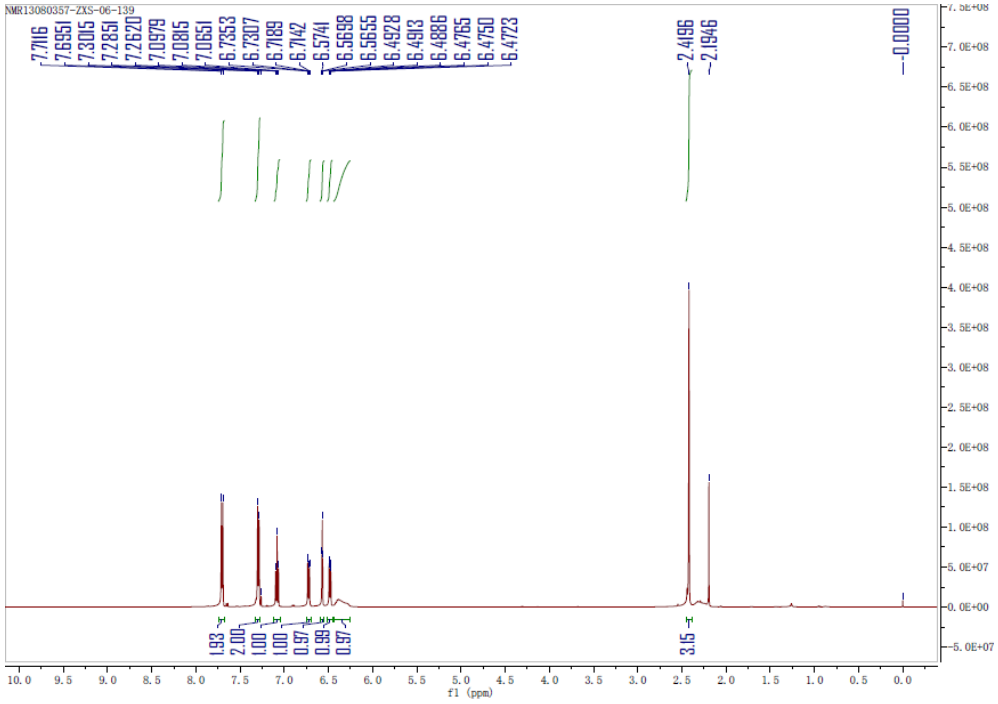
[3] Talita de A. Fernandes, Boniek Gontijo Vaz, Marcos N. Eberlin, Alcides J. M. da Silva, Paulo R. R. Costa, *J. Org. Chem*. **2010**, *75*, 7085-7091.

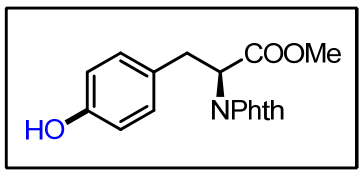
NMR spectra

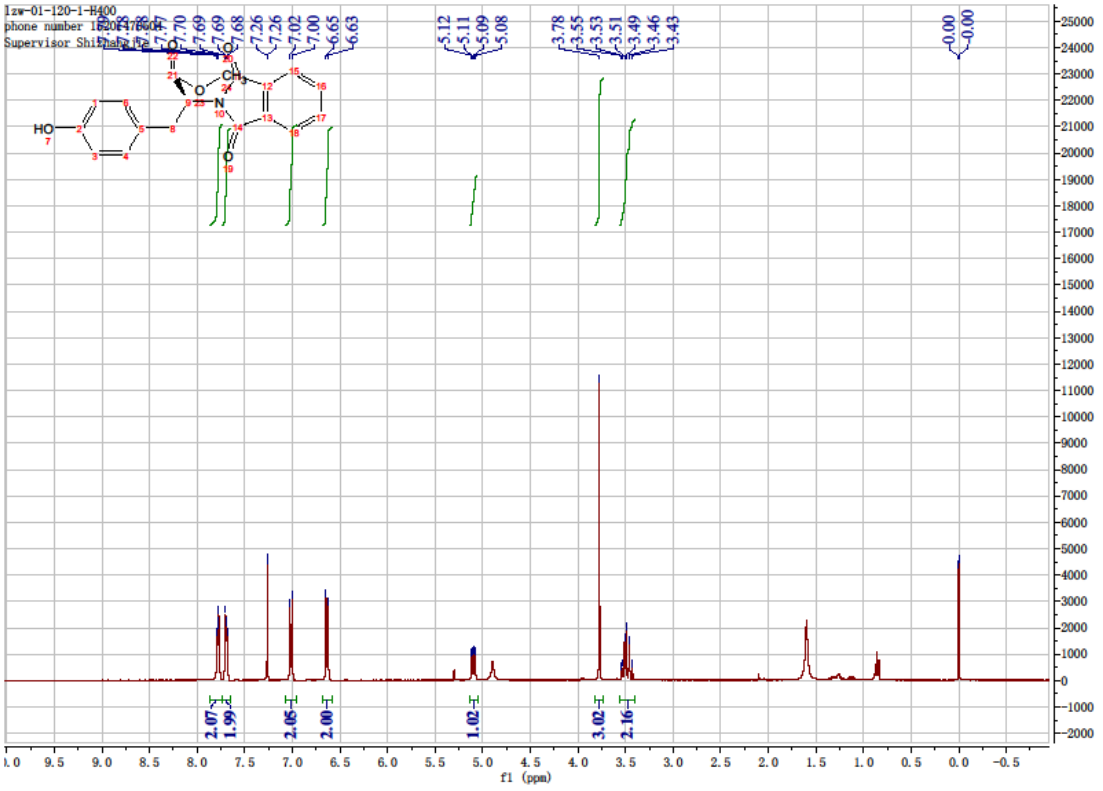
1 NMR spectra of phenol derivatives (1)

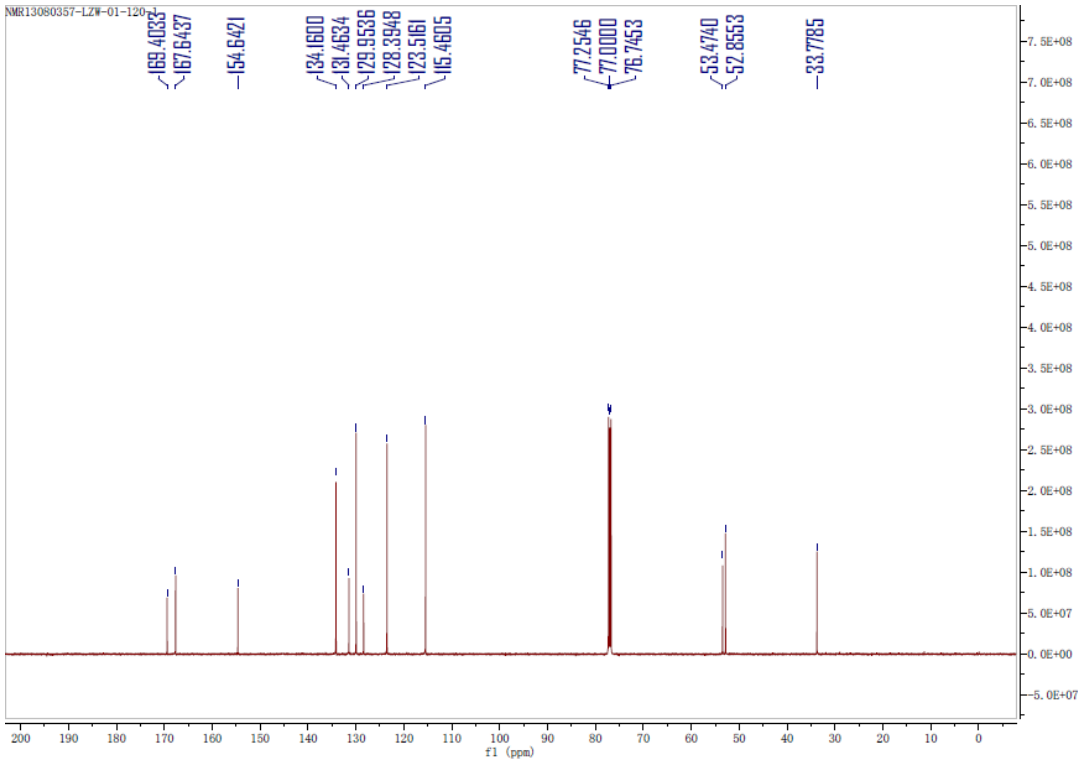


1v

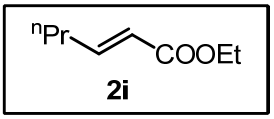




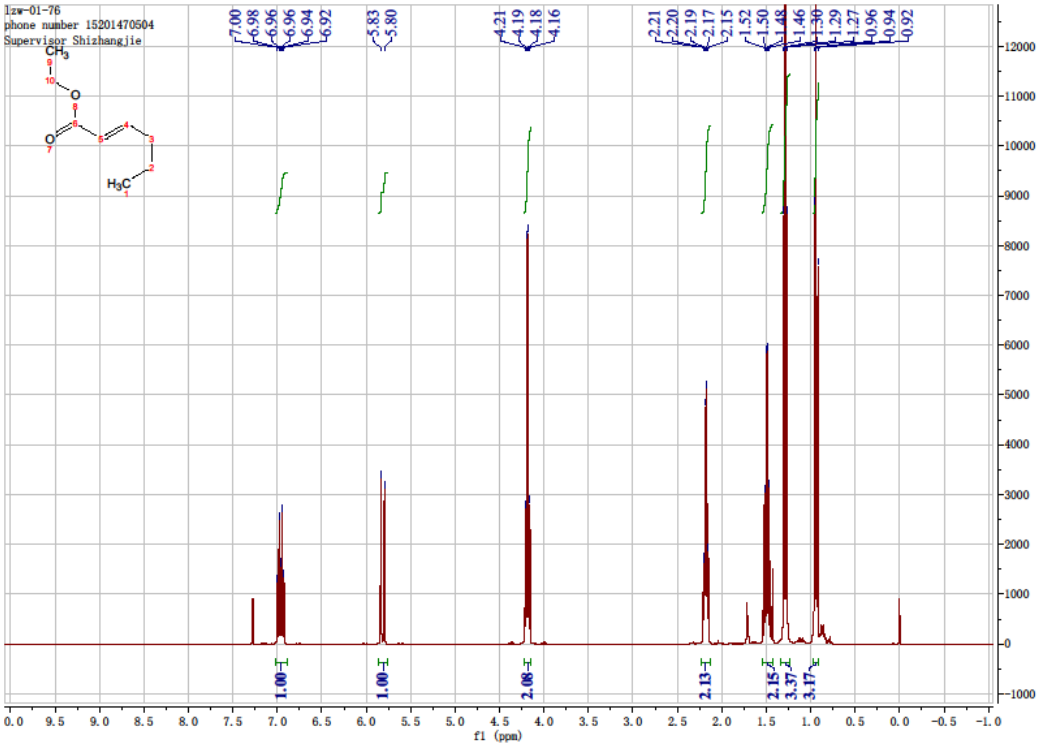


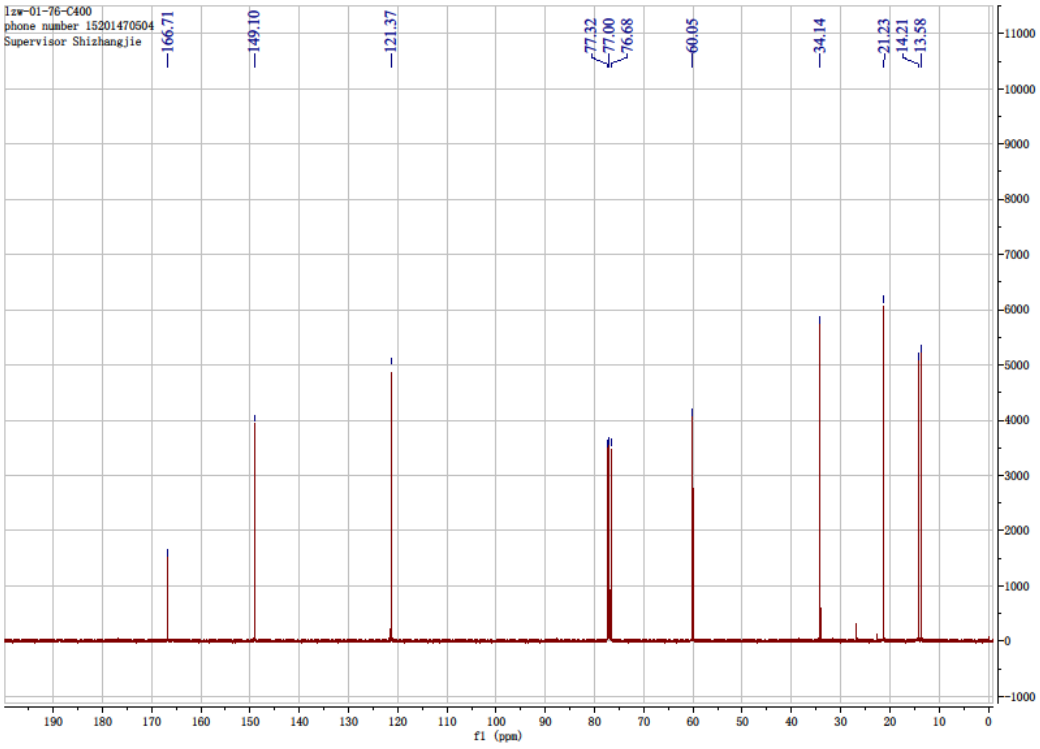


2 NMR spectra of alkenes (2)

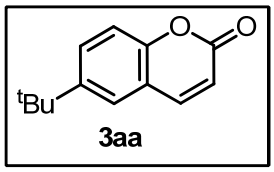


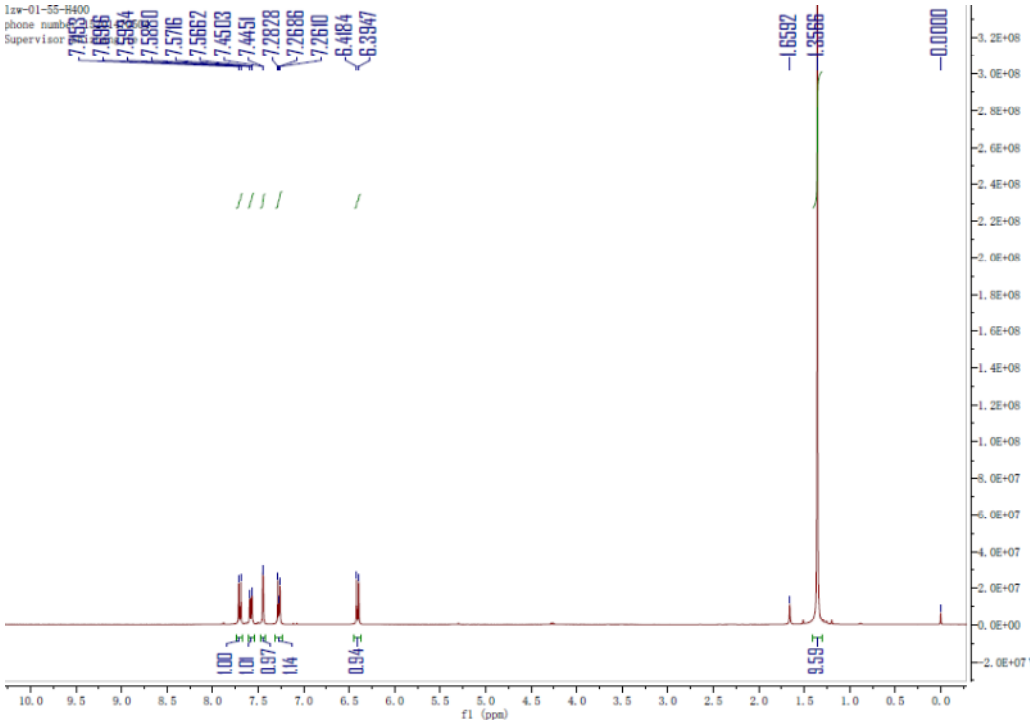
2i

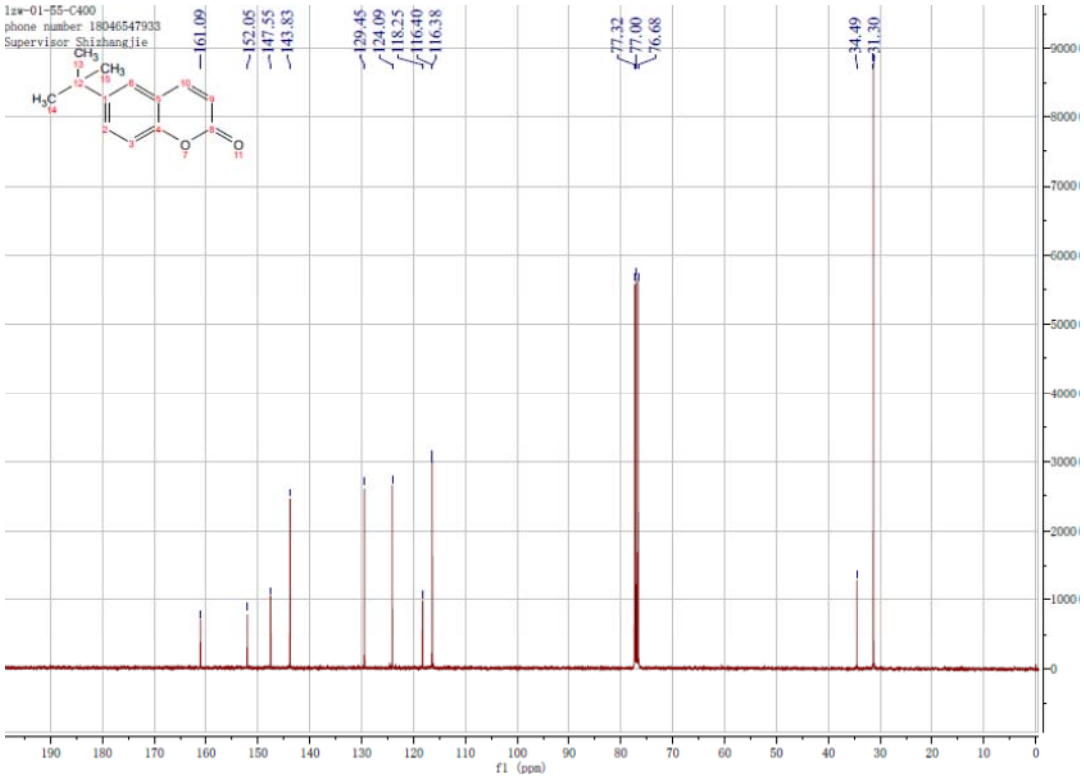


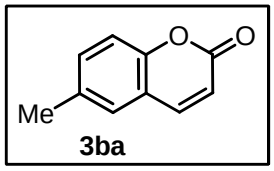


3 NMR spectra of coumarin products (3)









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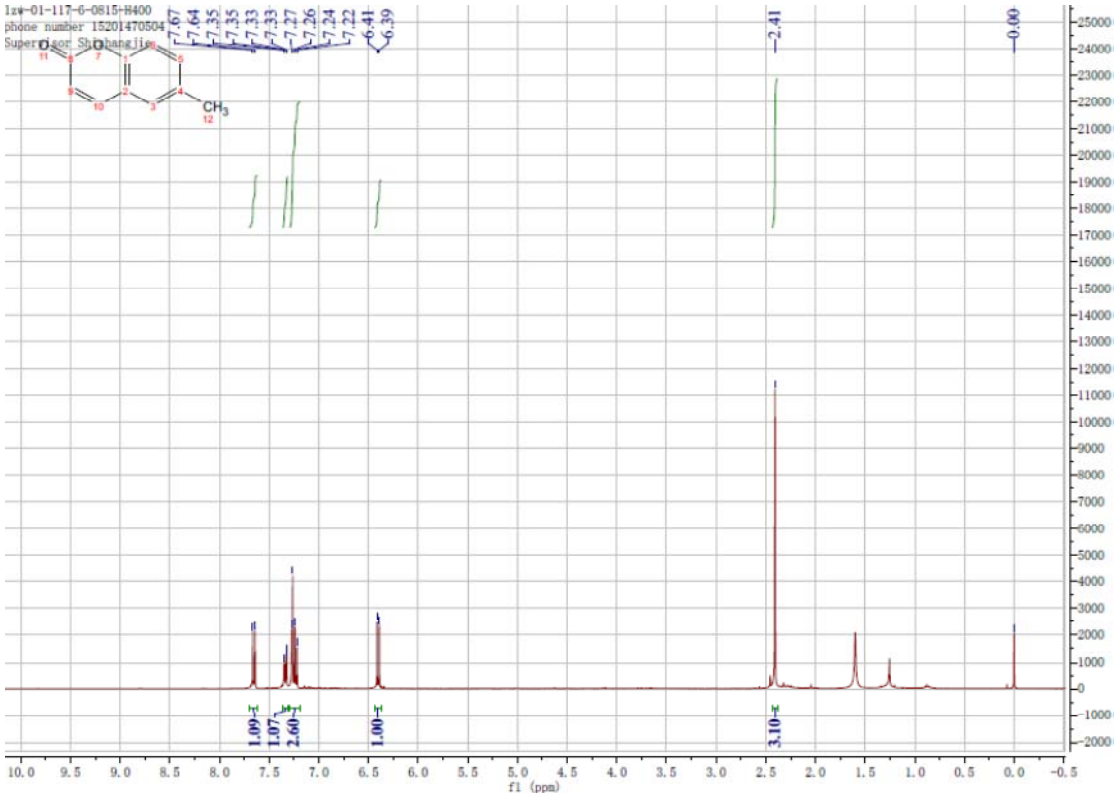

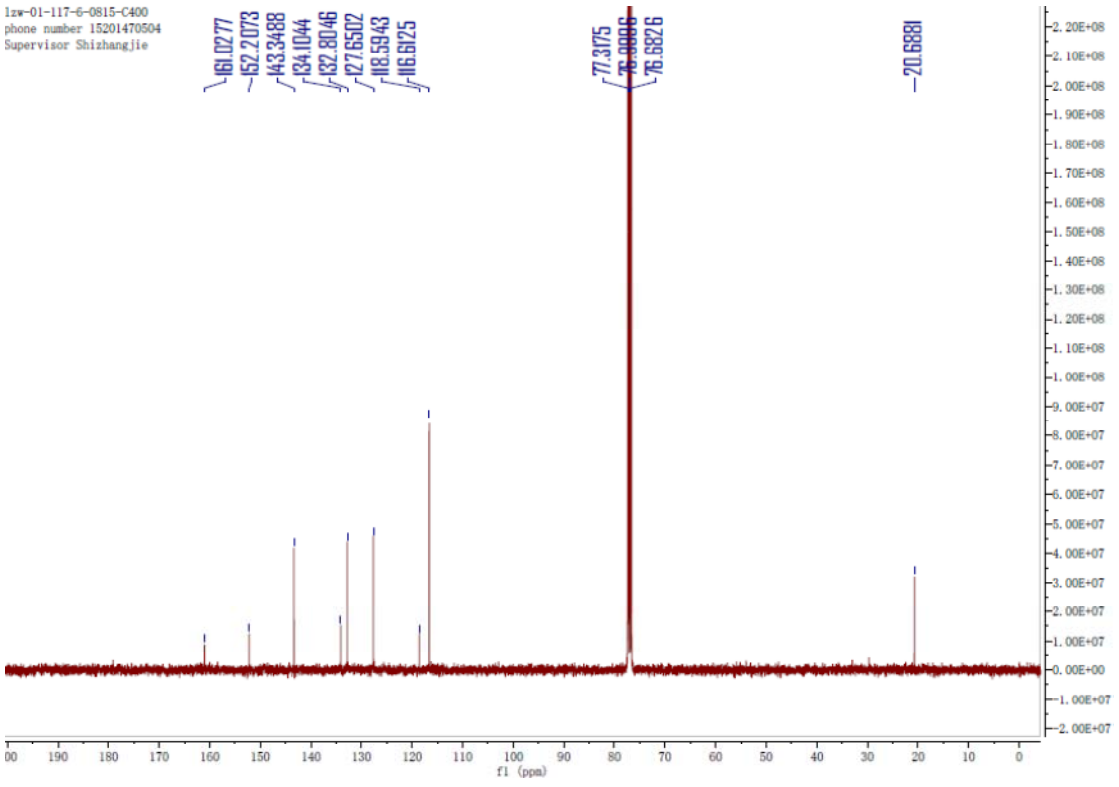

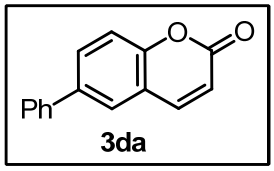

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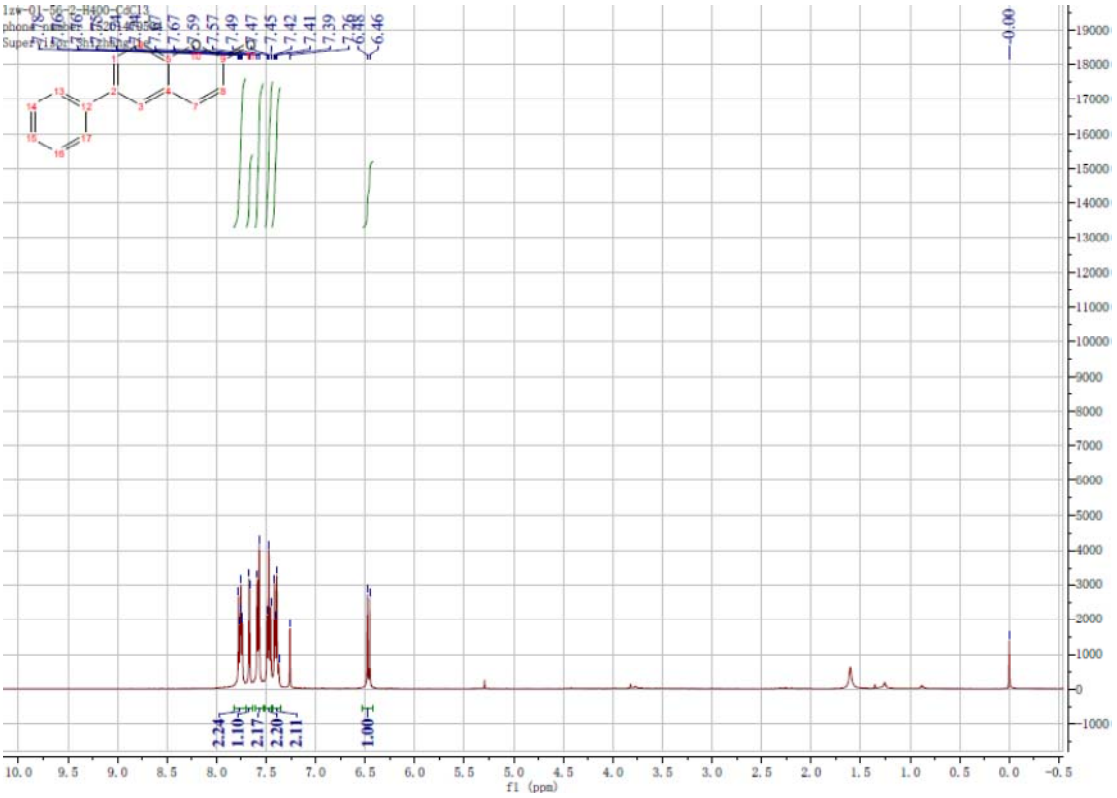

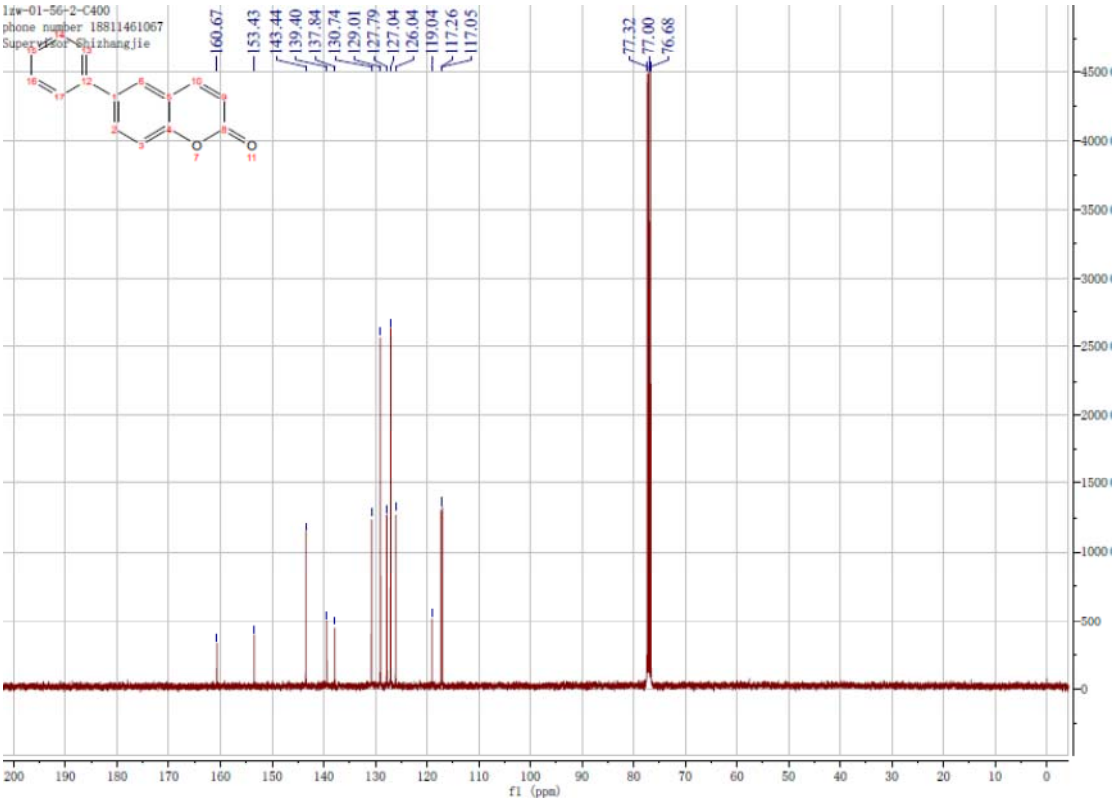

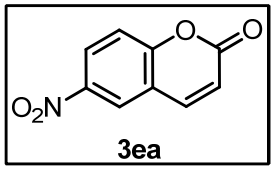

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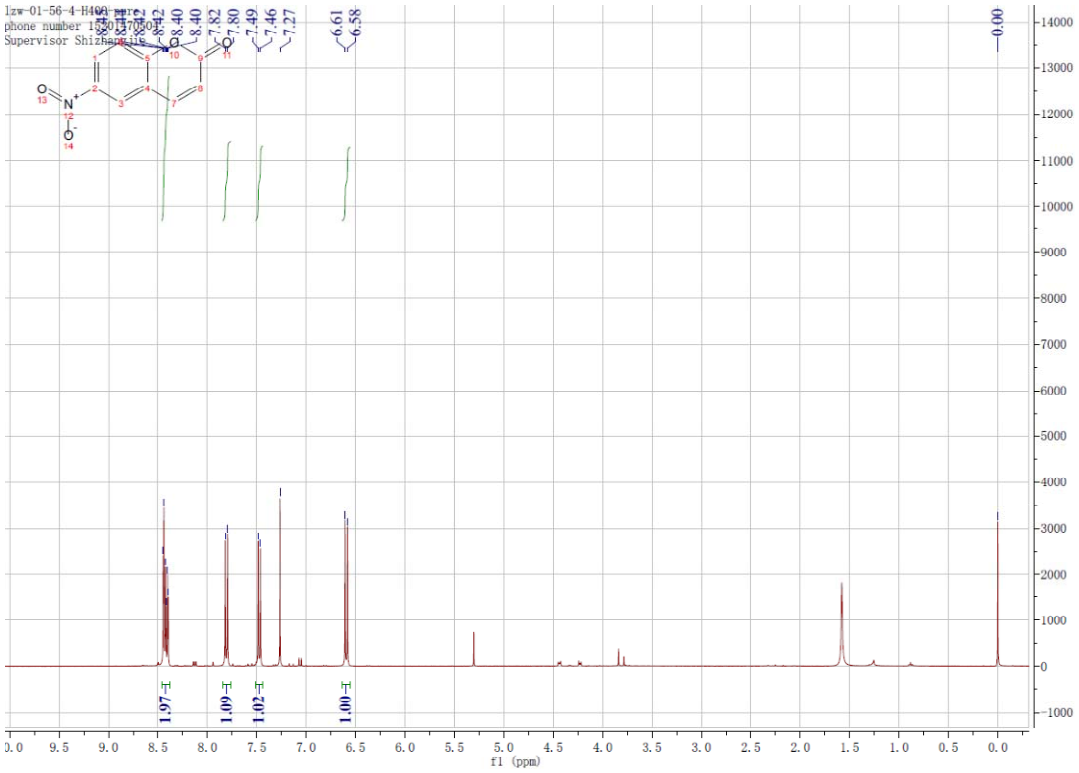

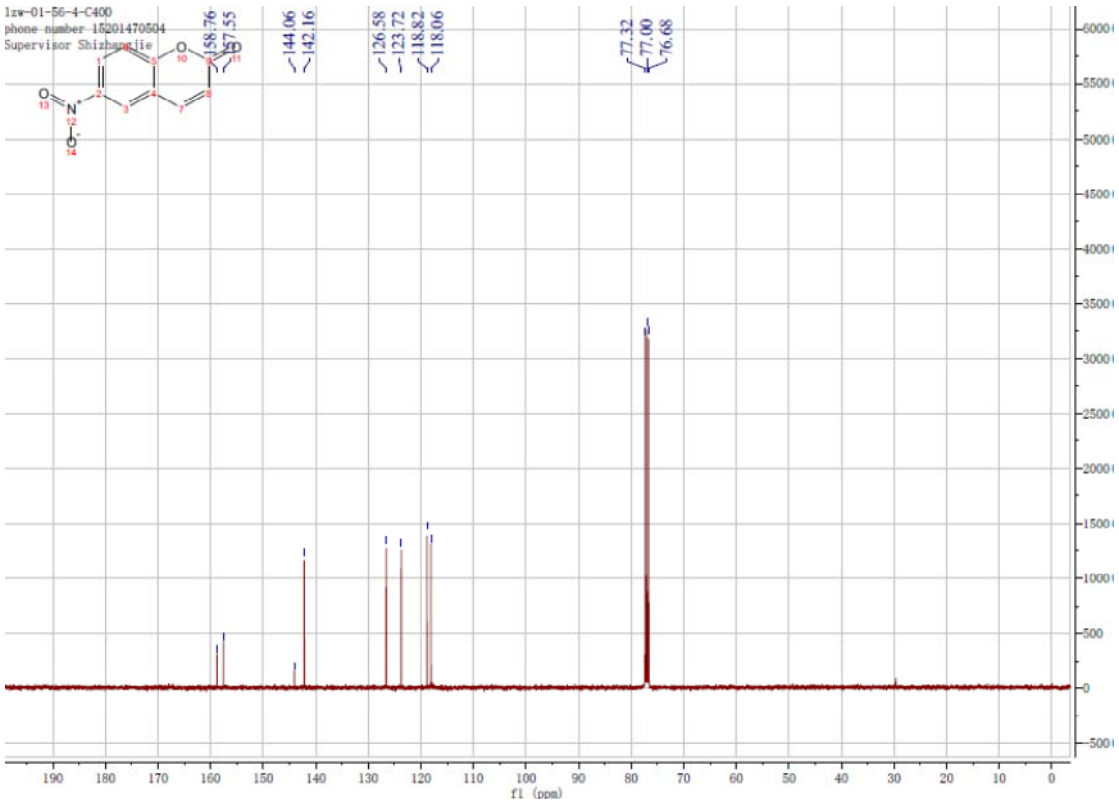

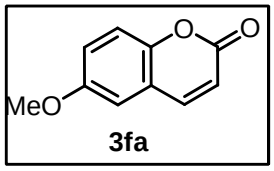

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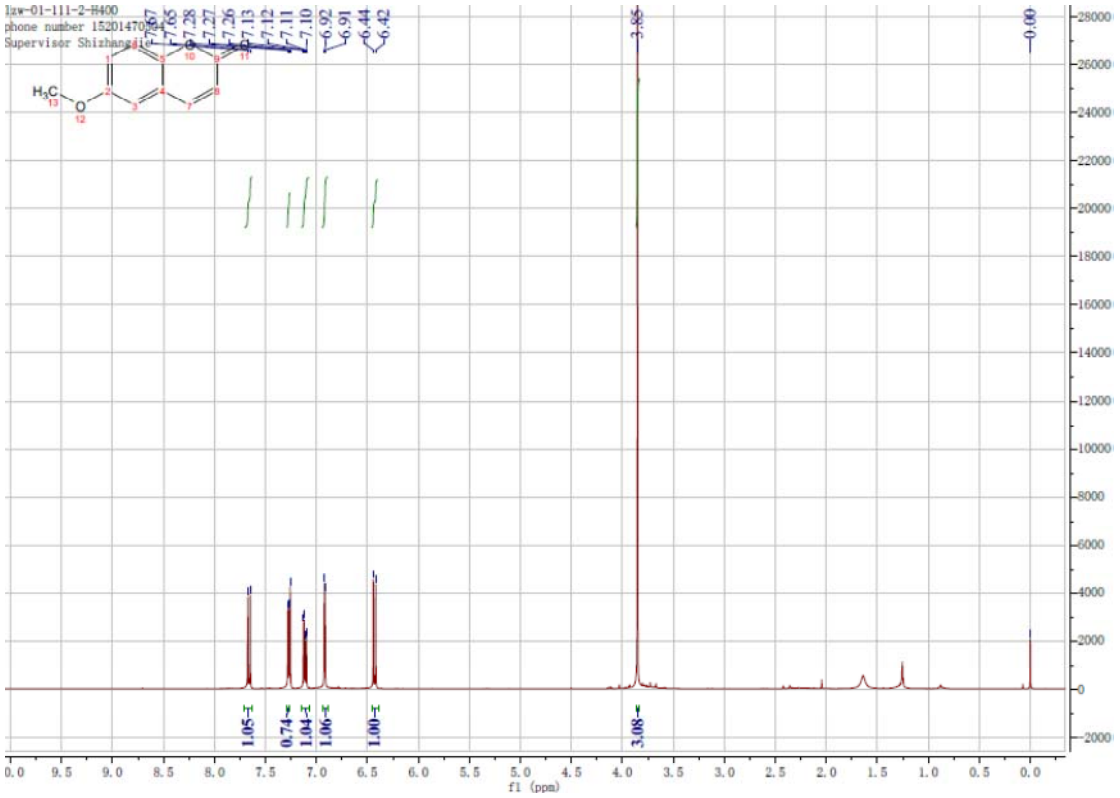

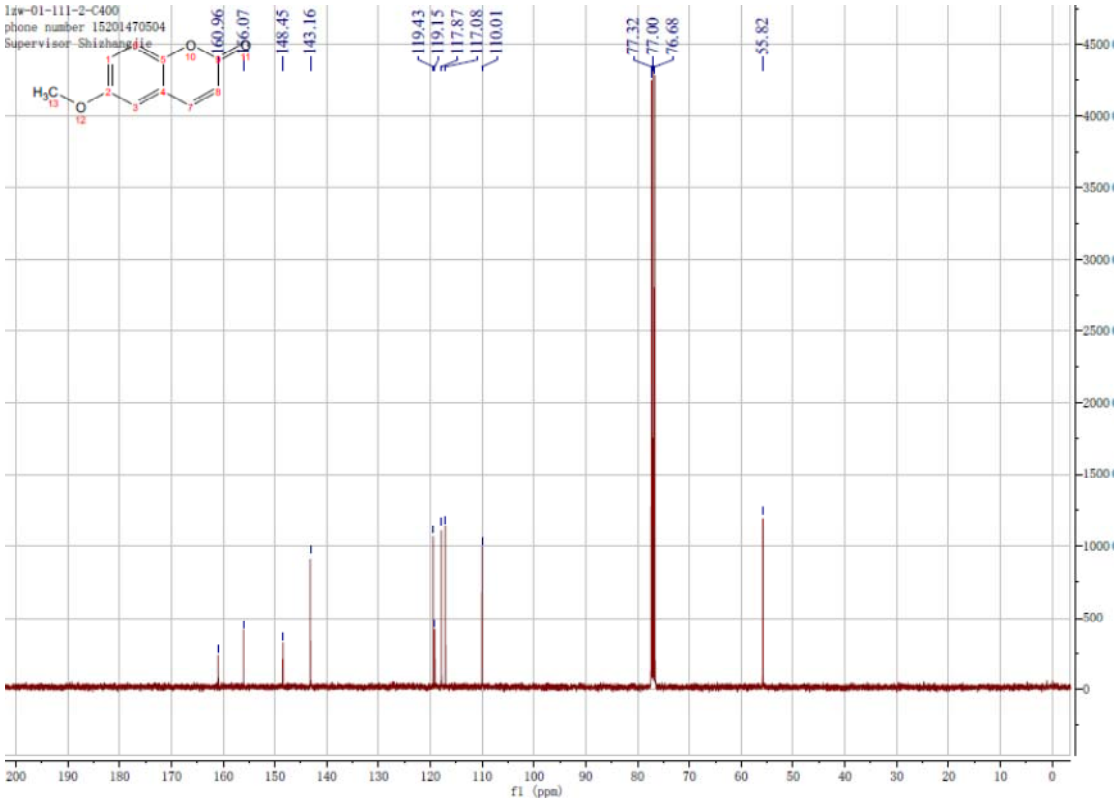

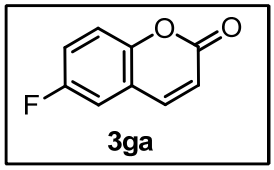

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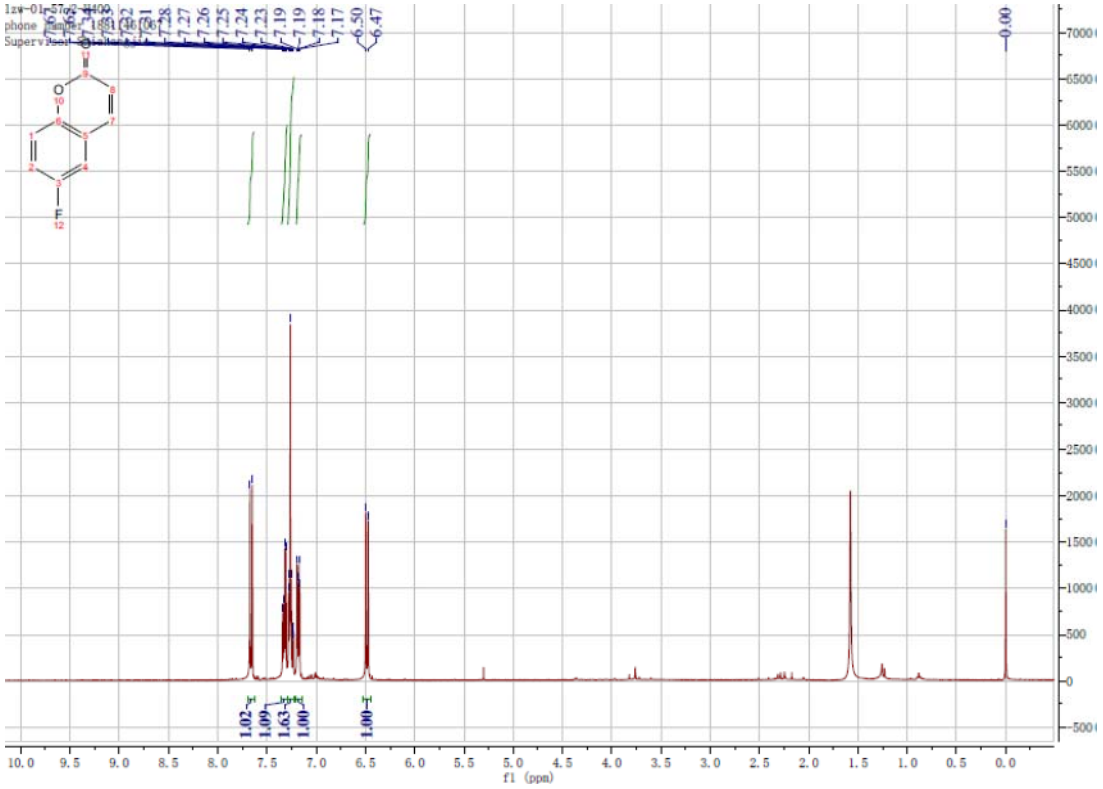

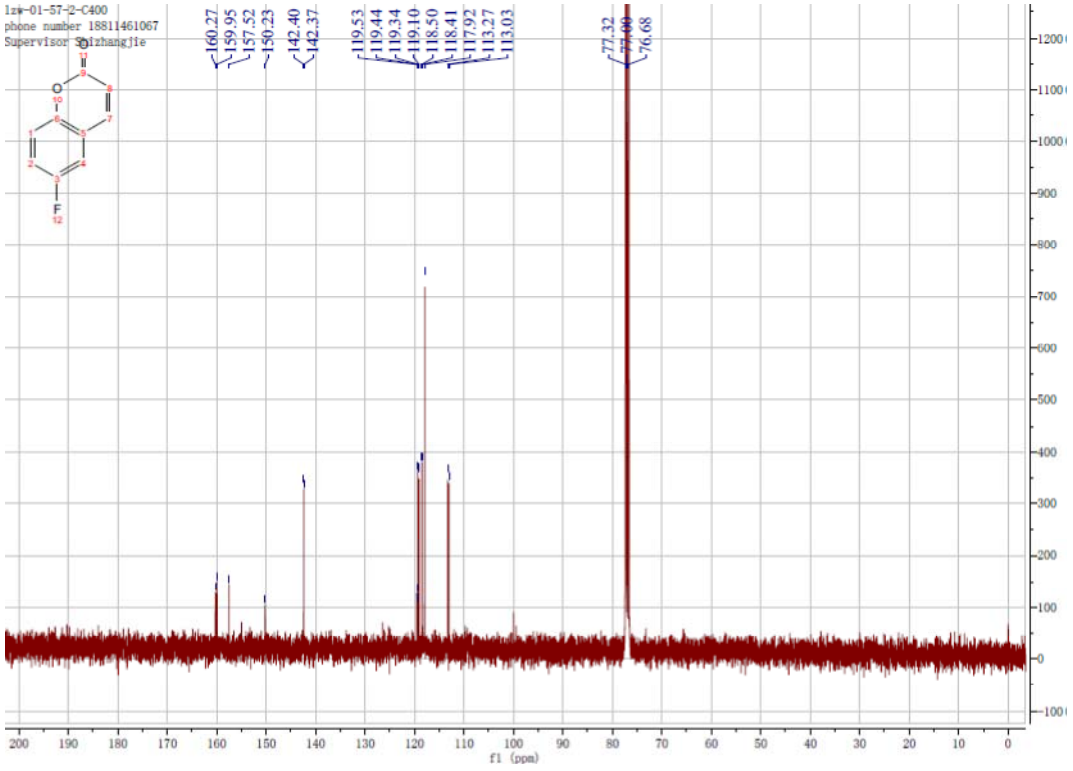

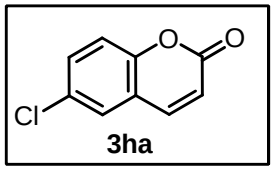

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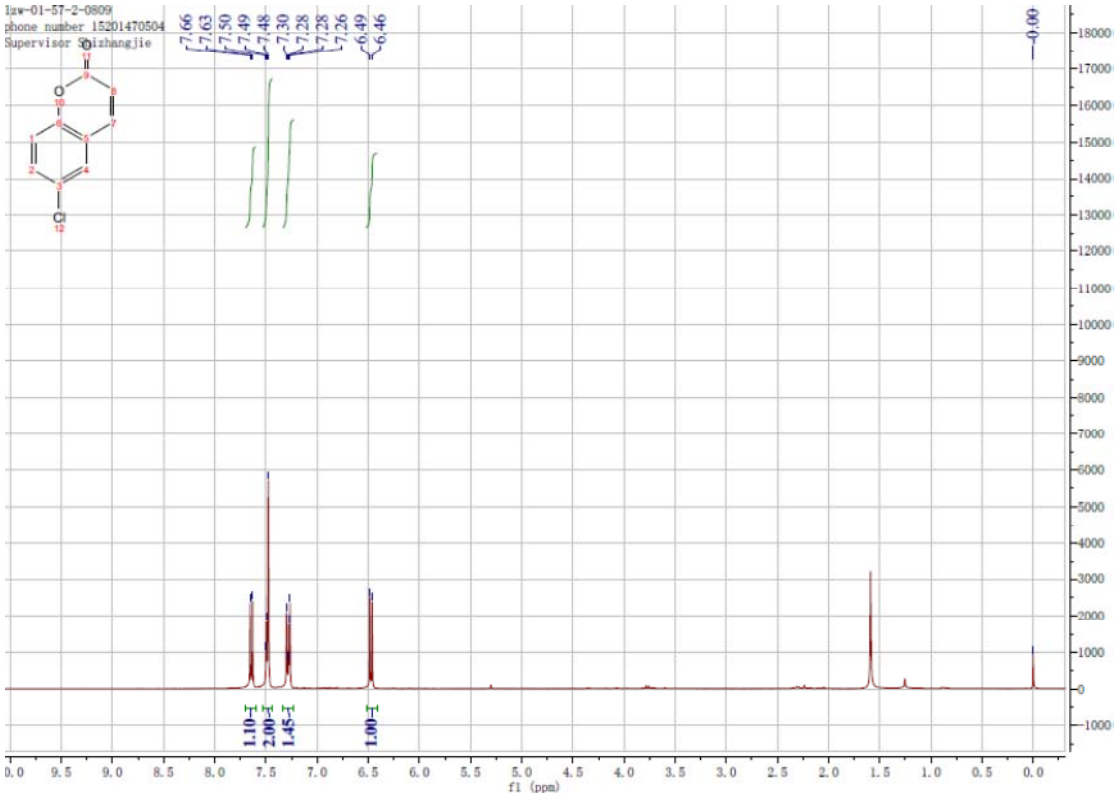

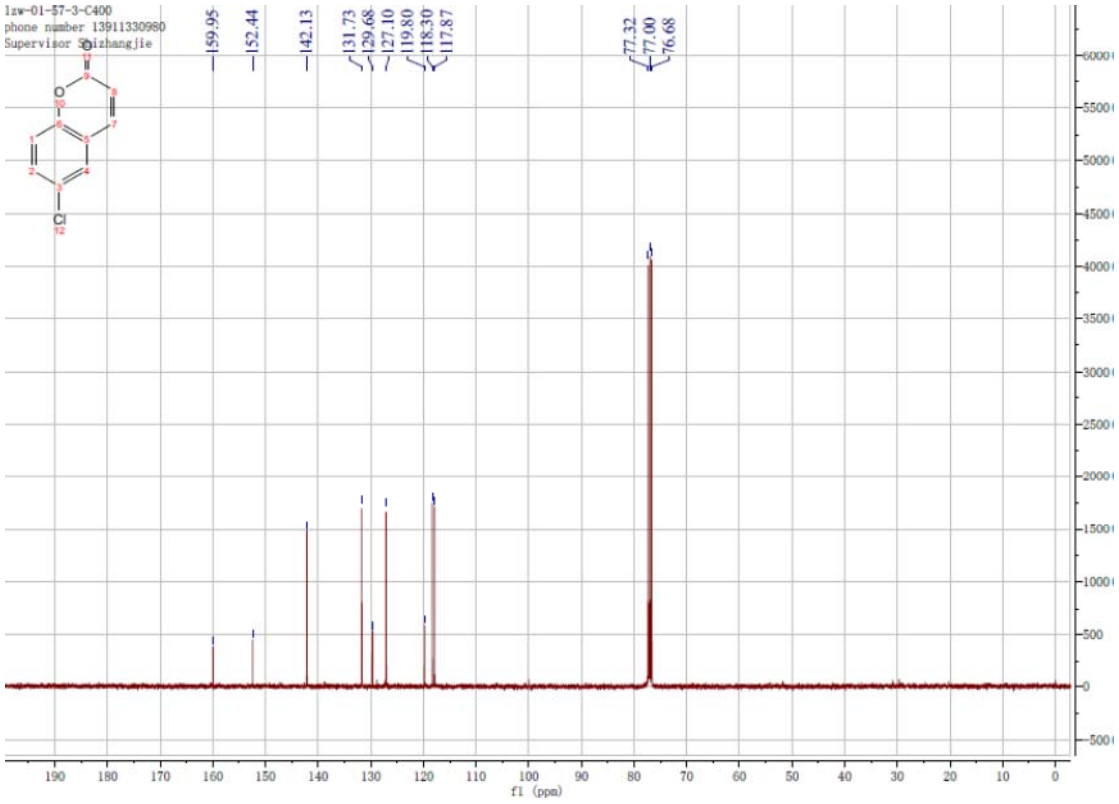

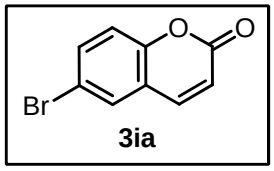

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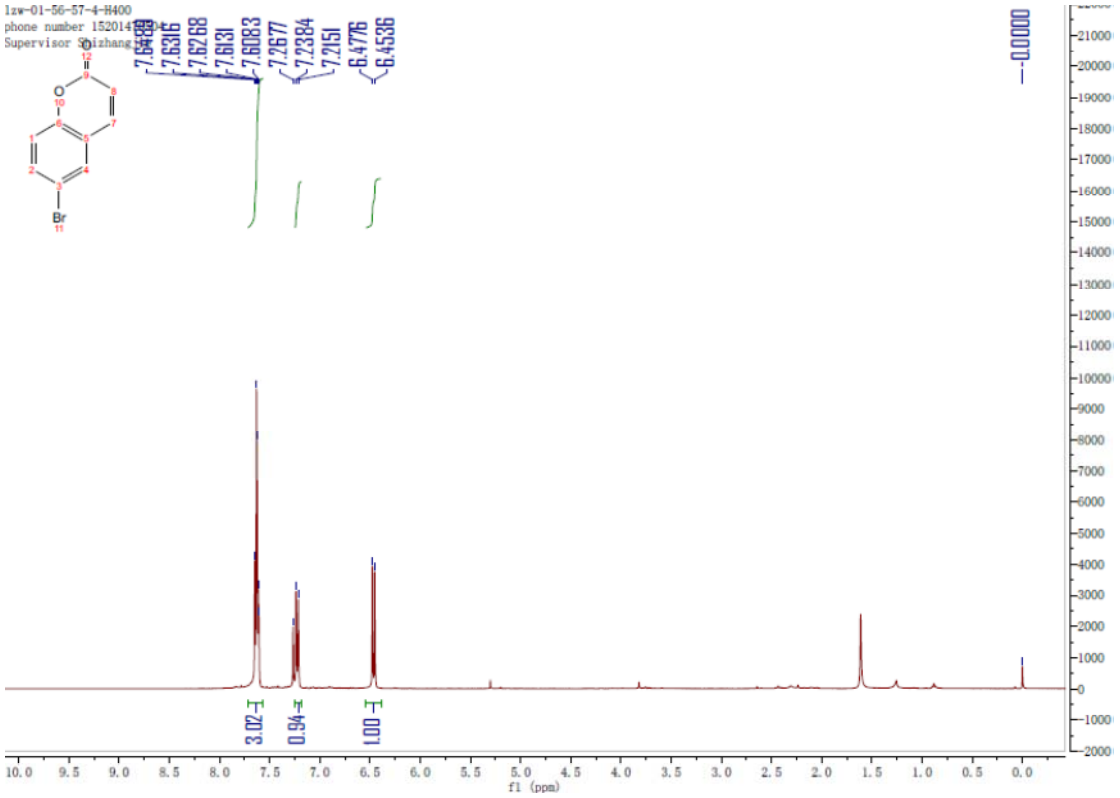

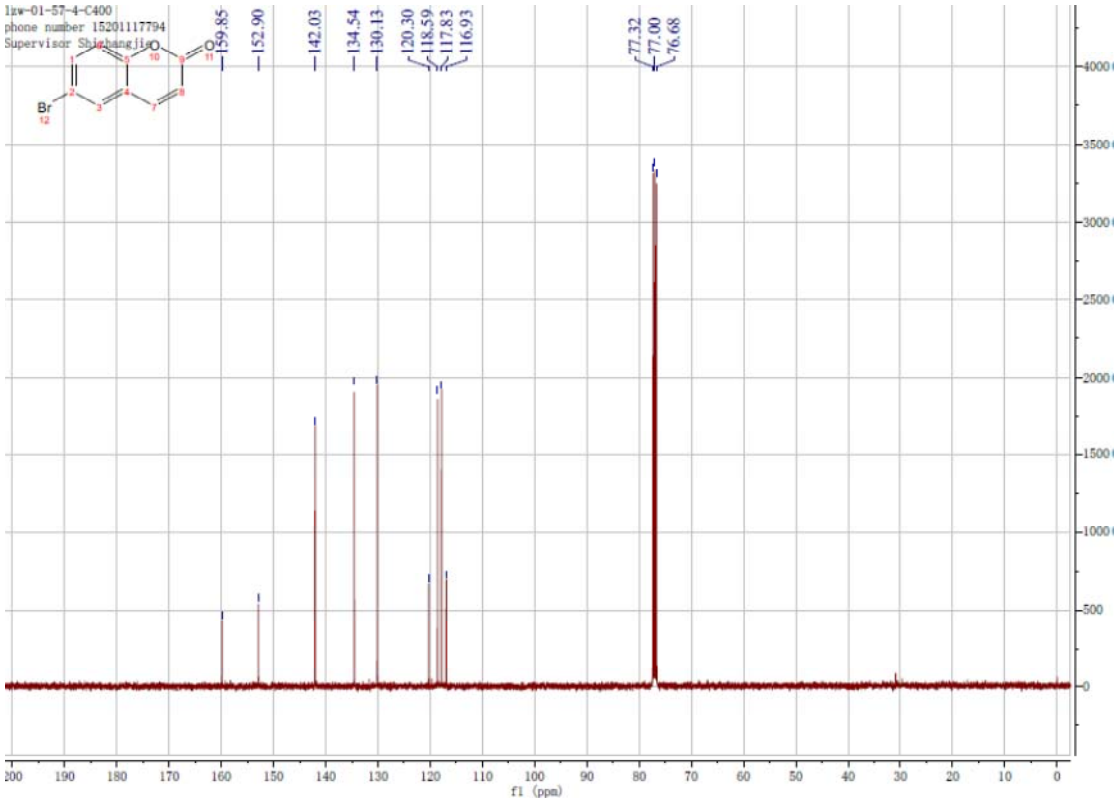

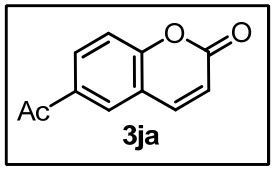

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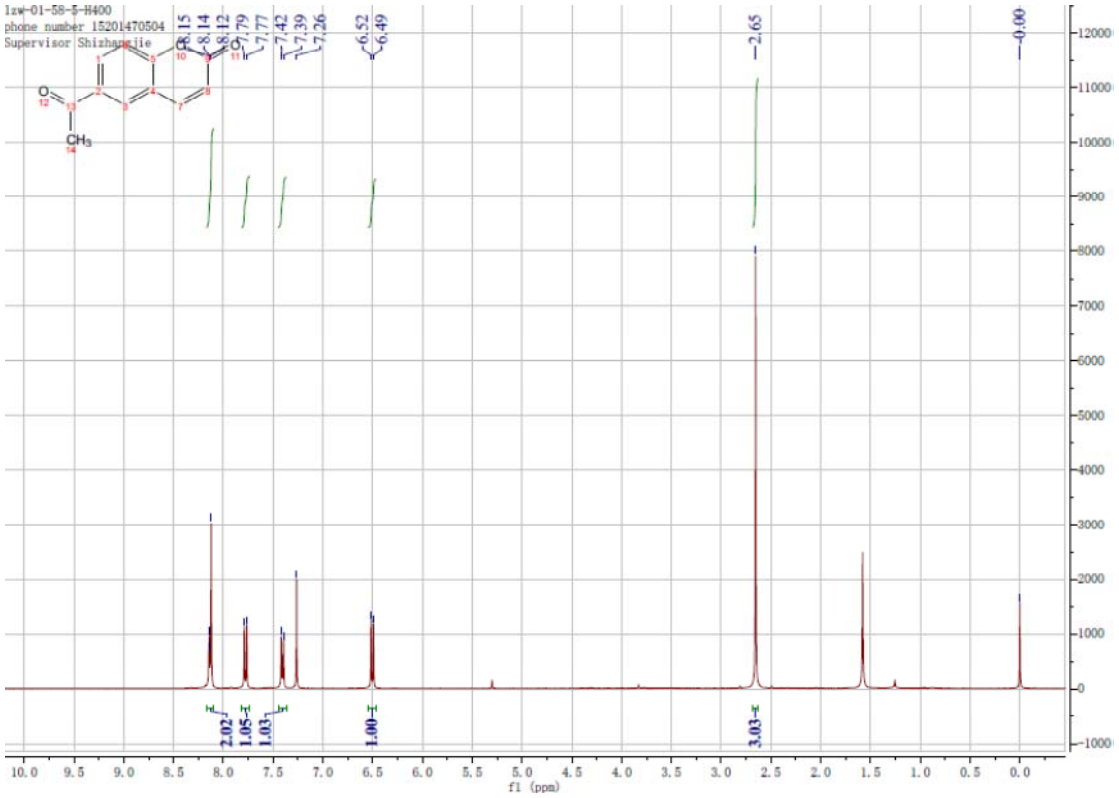

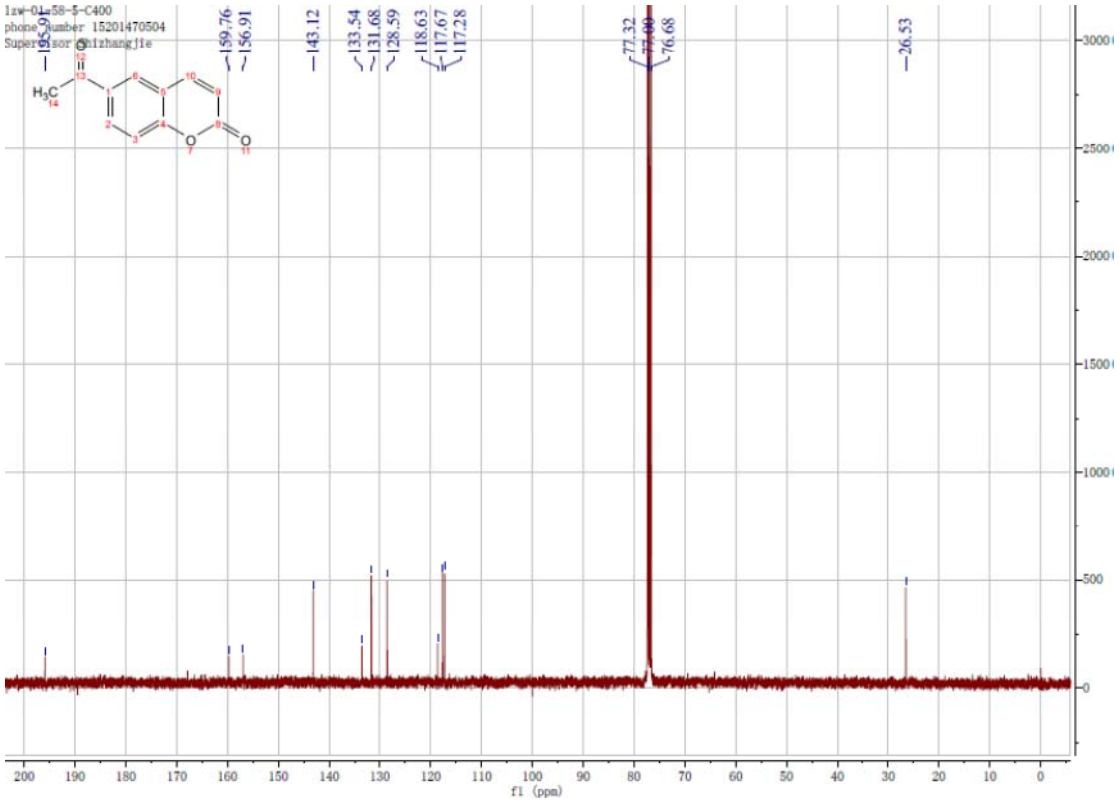

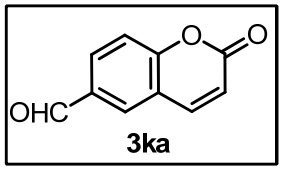

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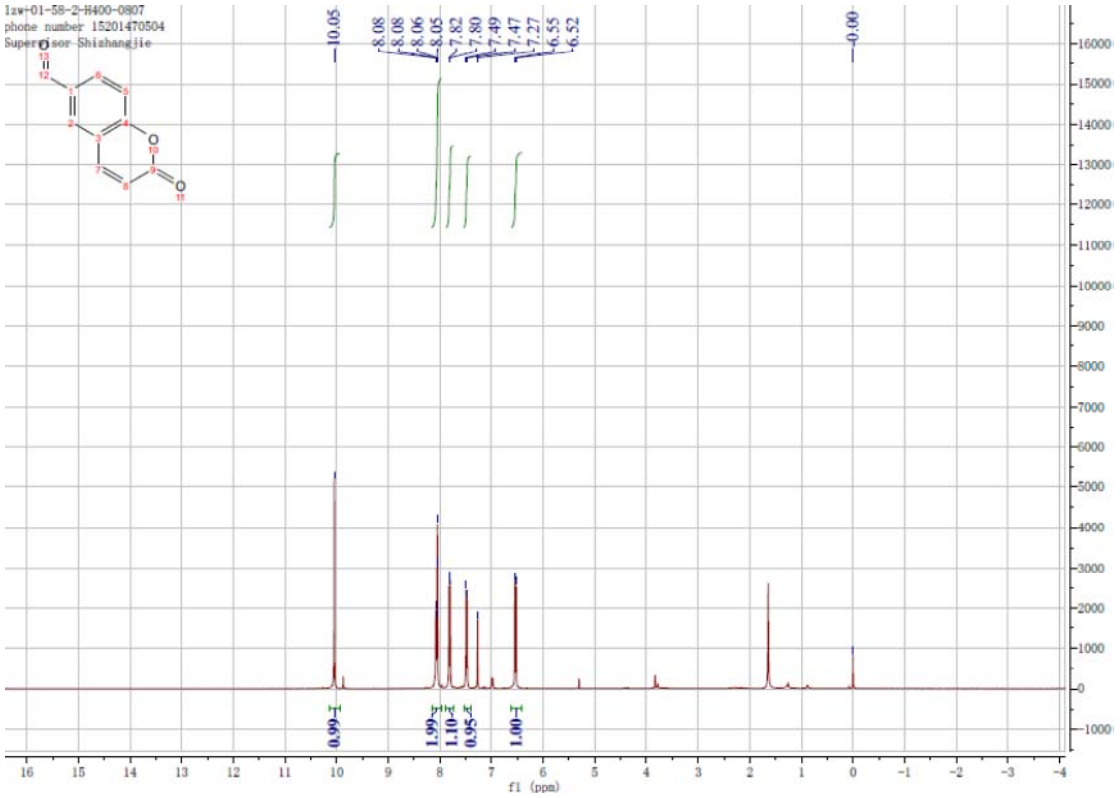

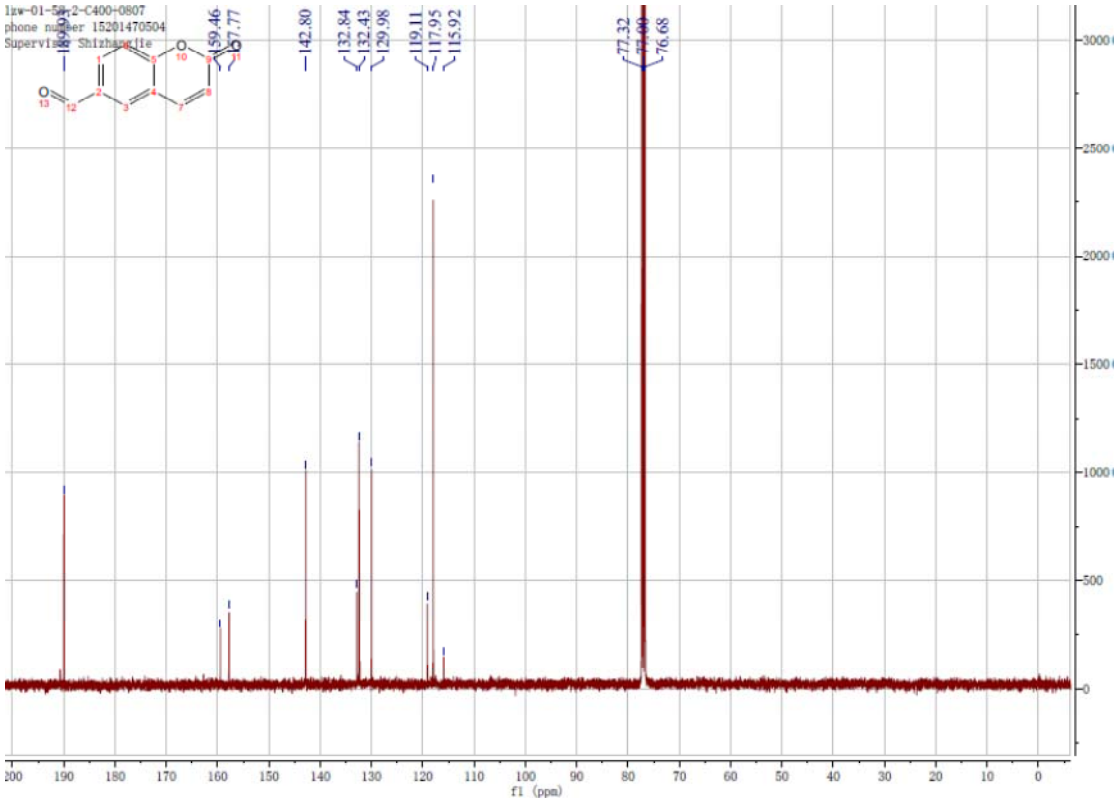

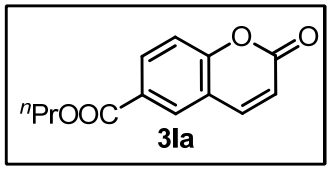

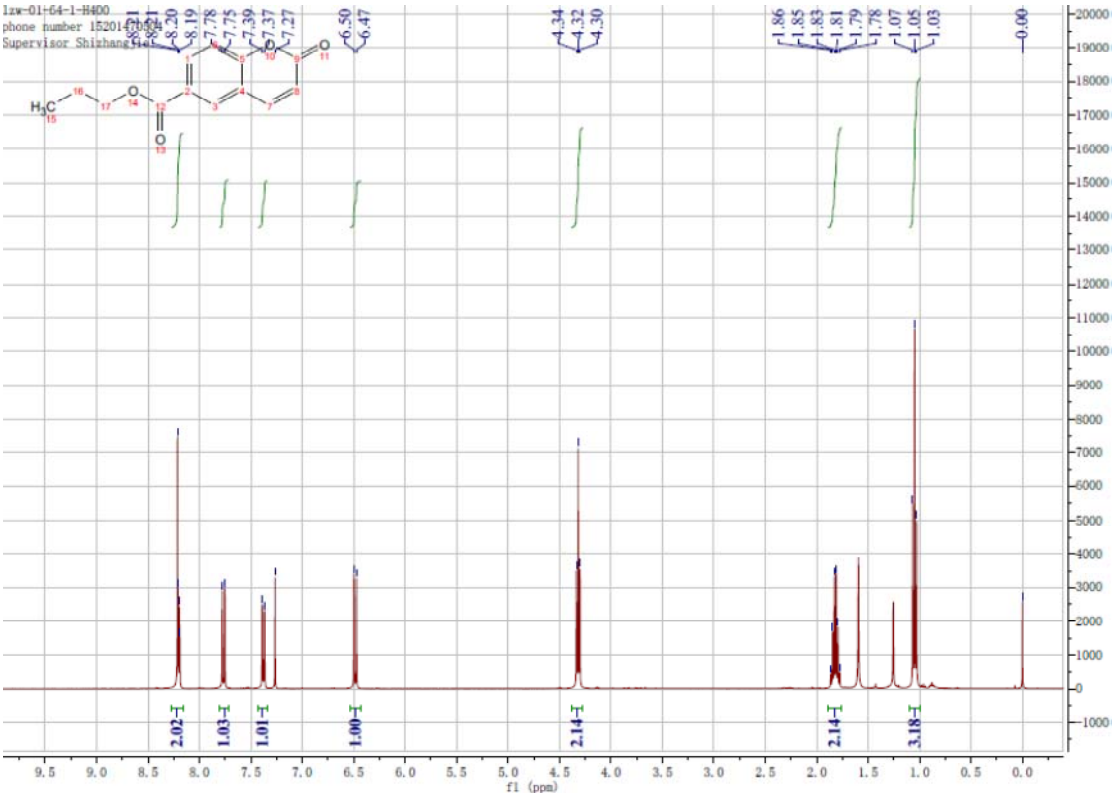

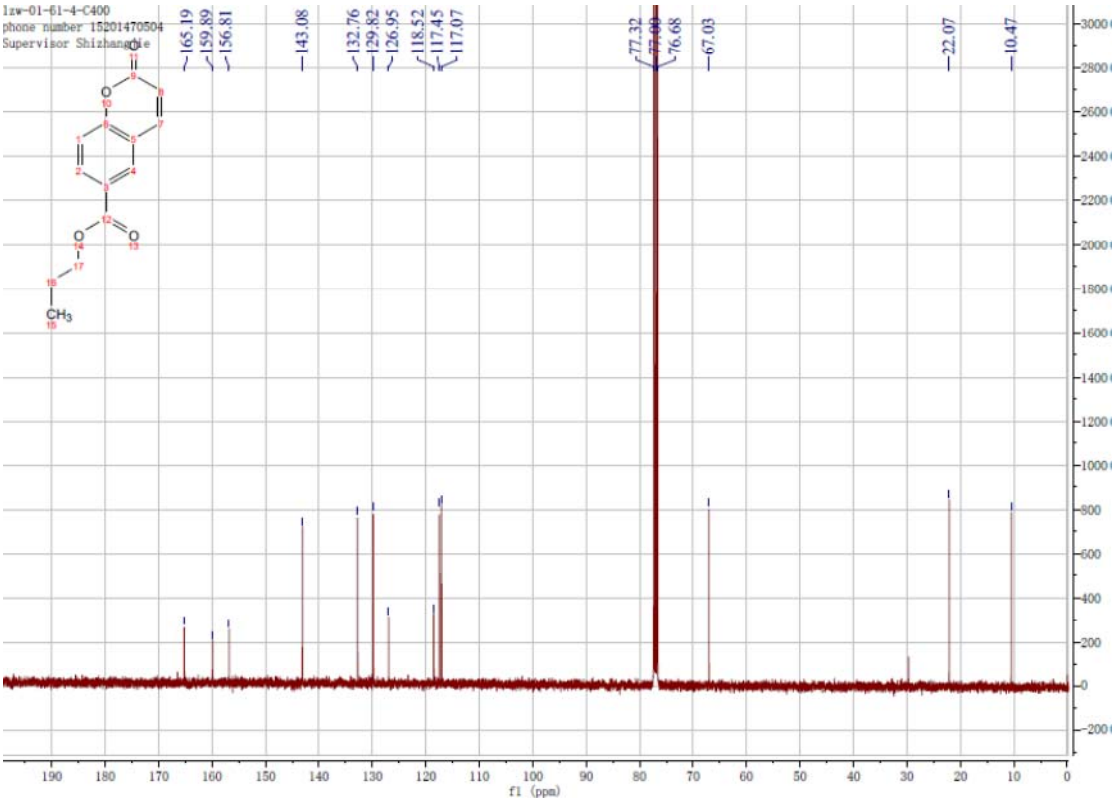

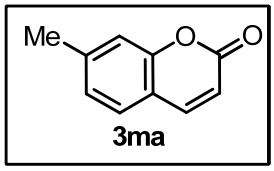

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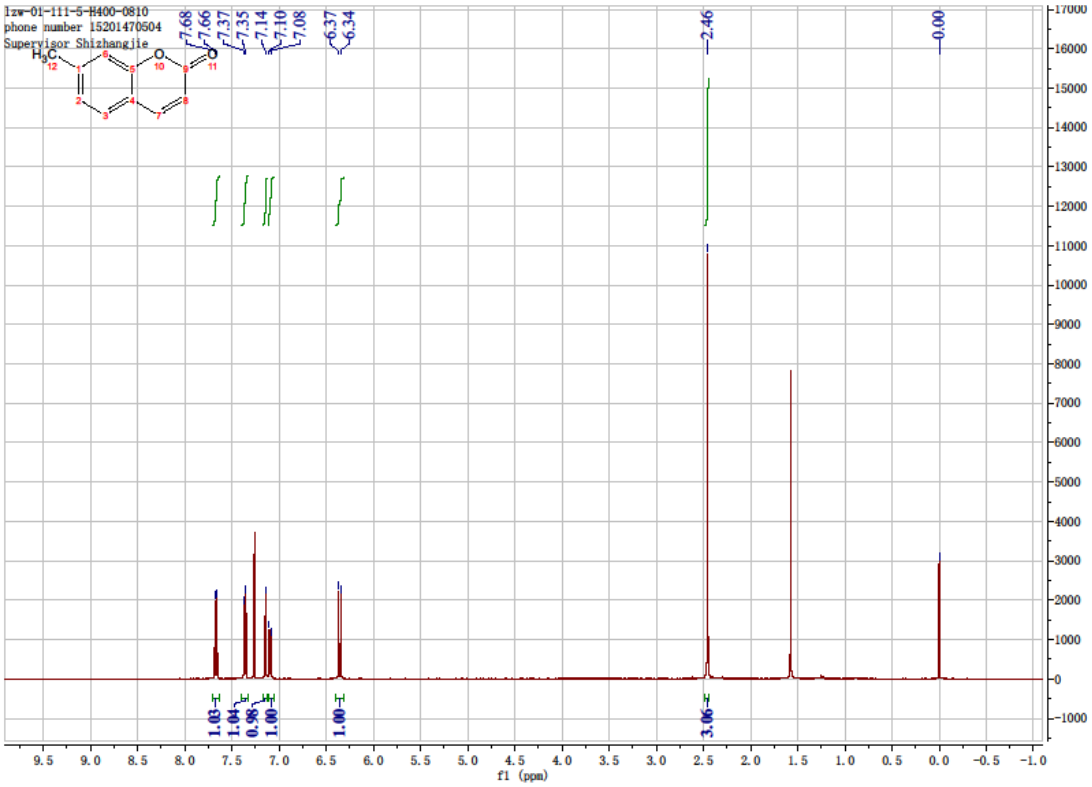

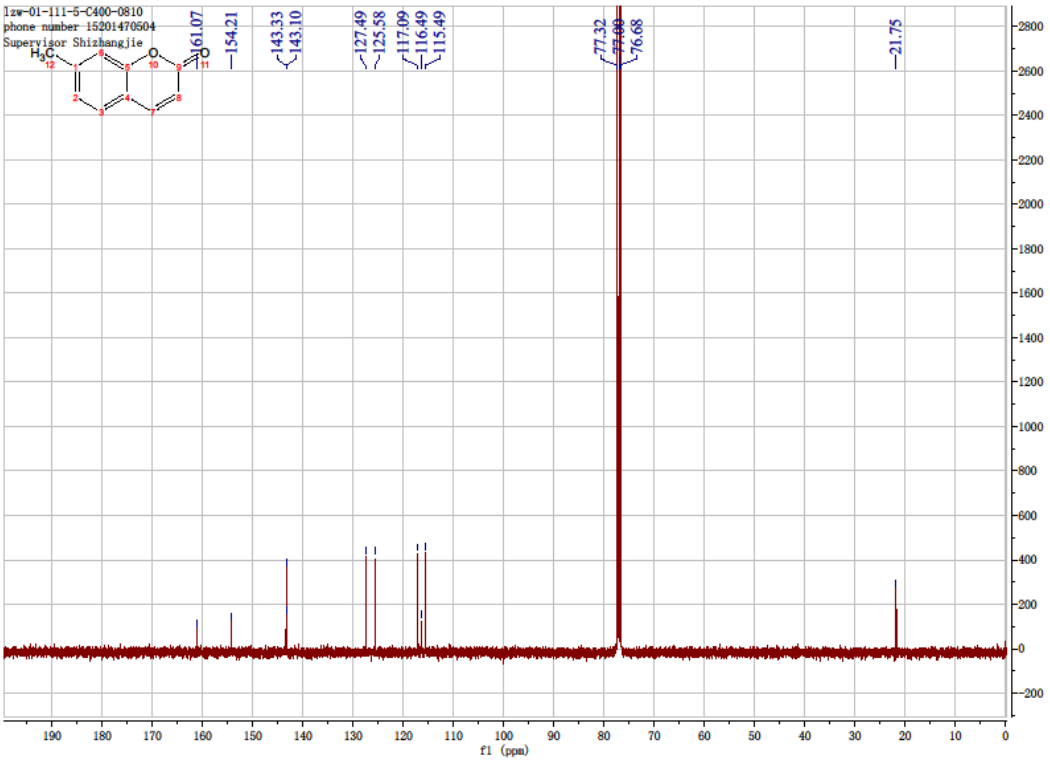

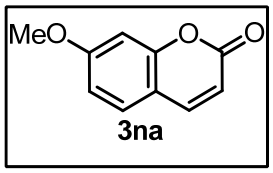

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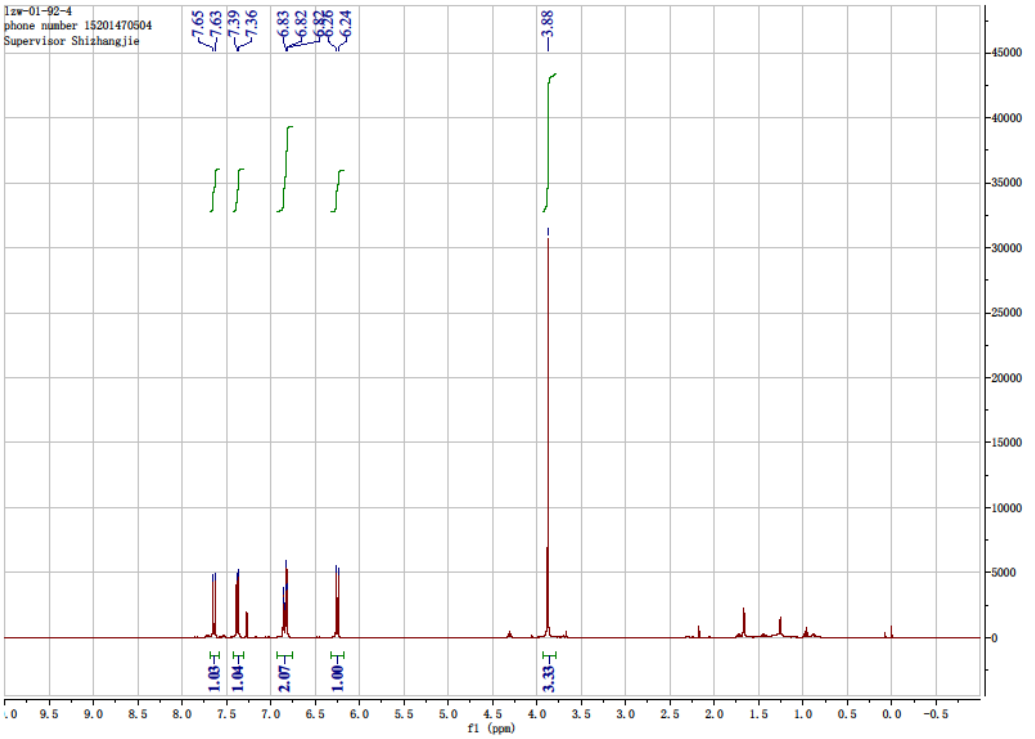

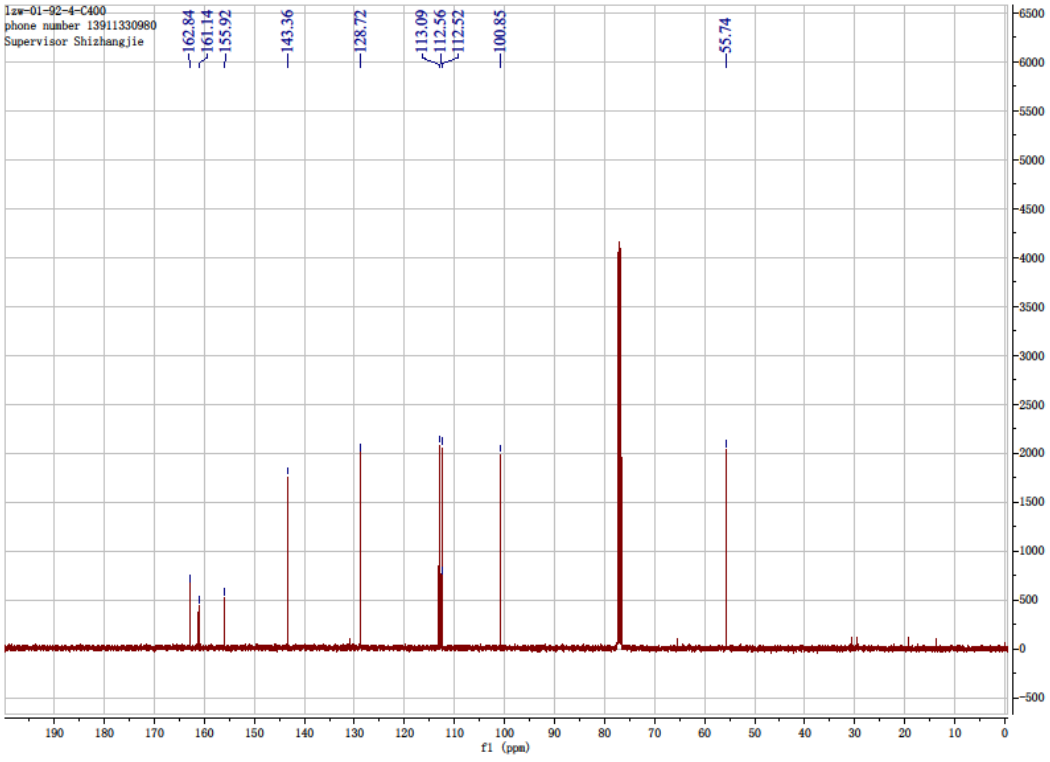

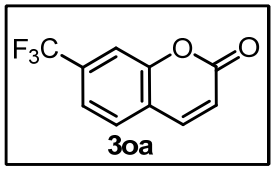

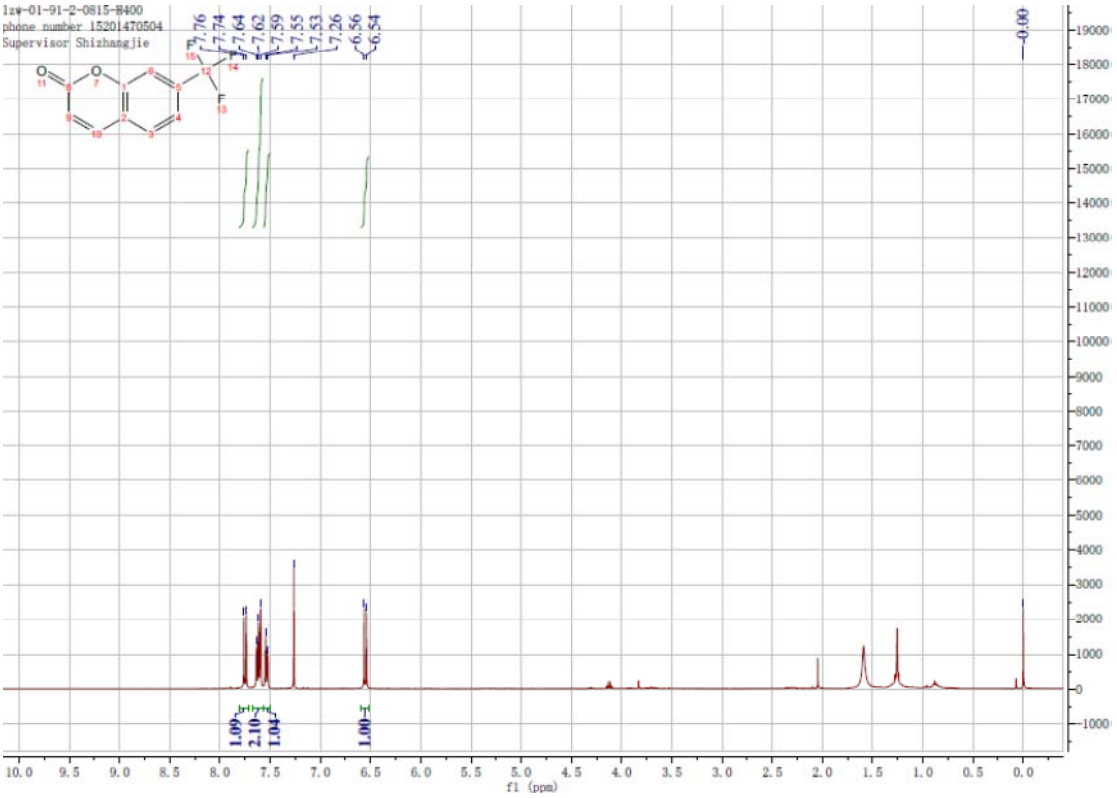

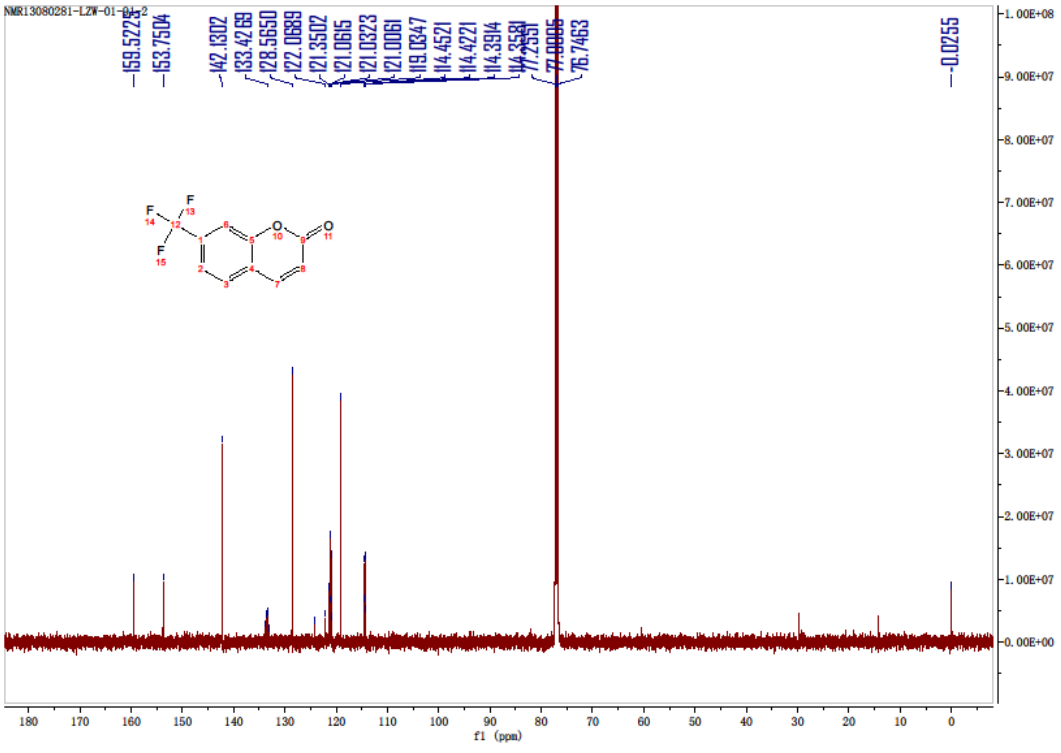

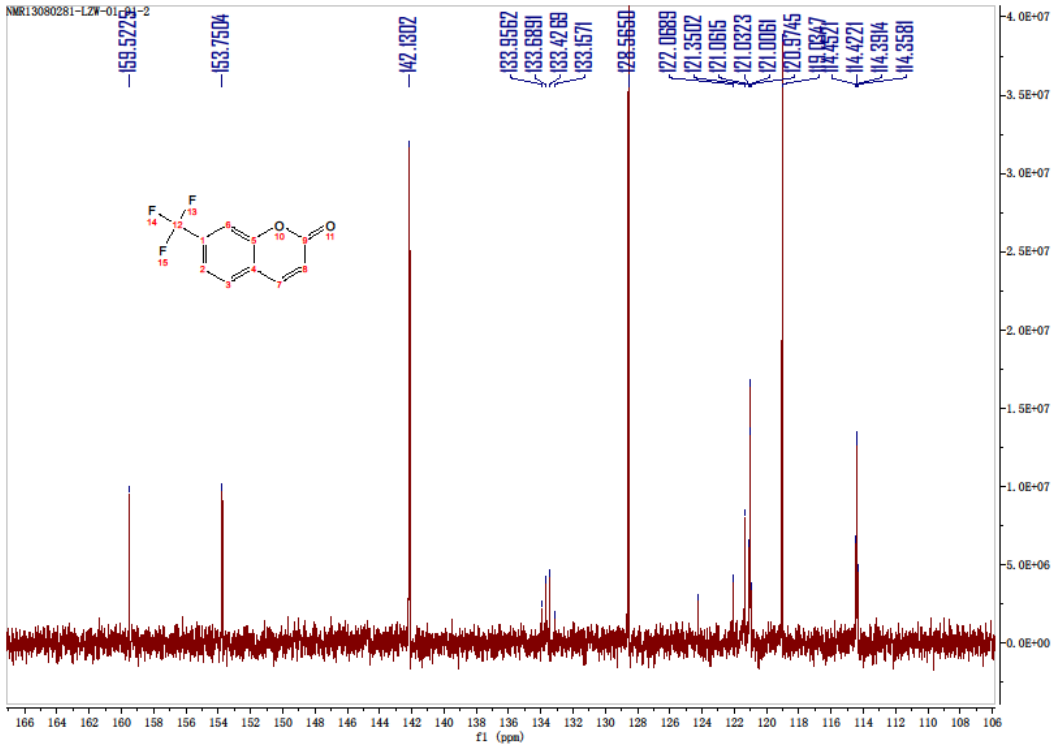

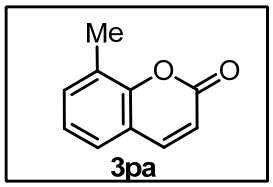

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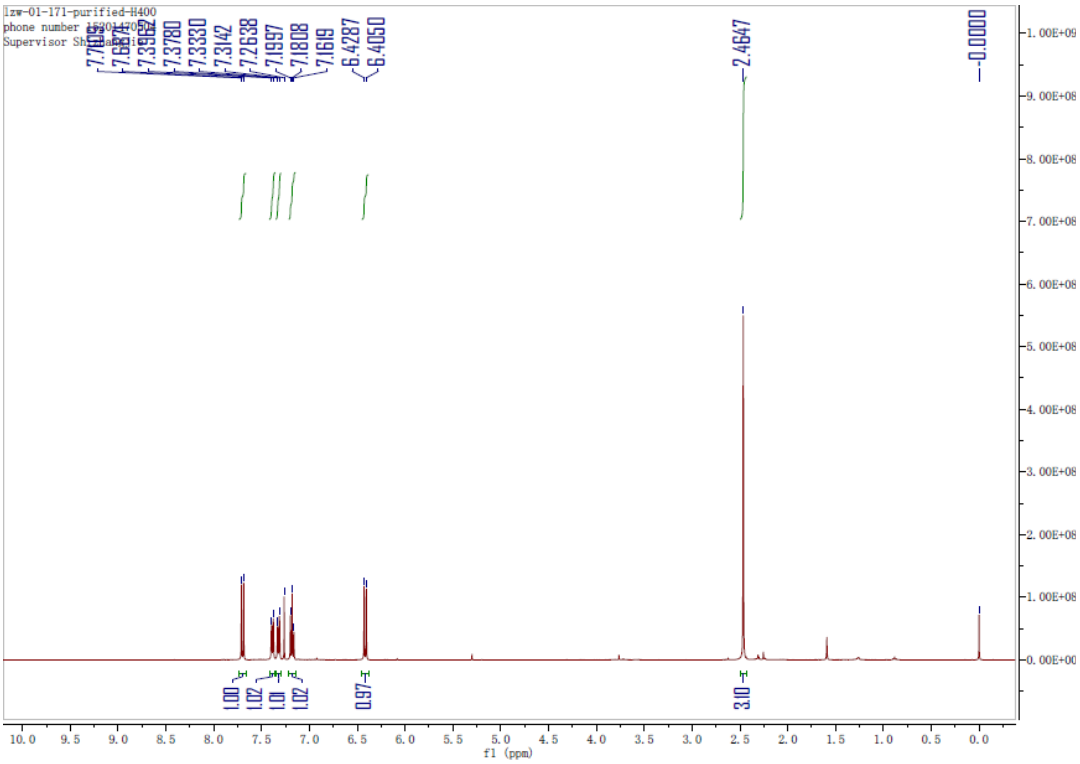

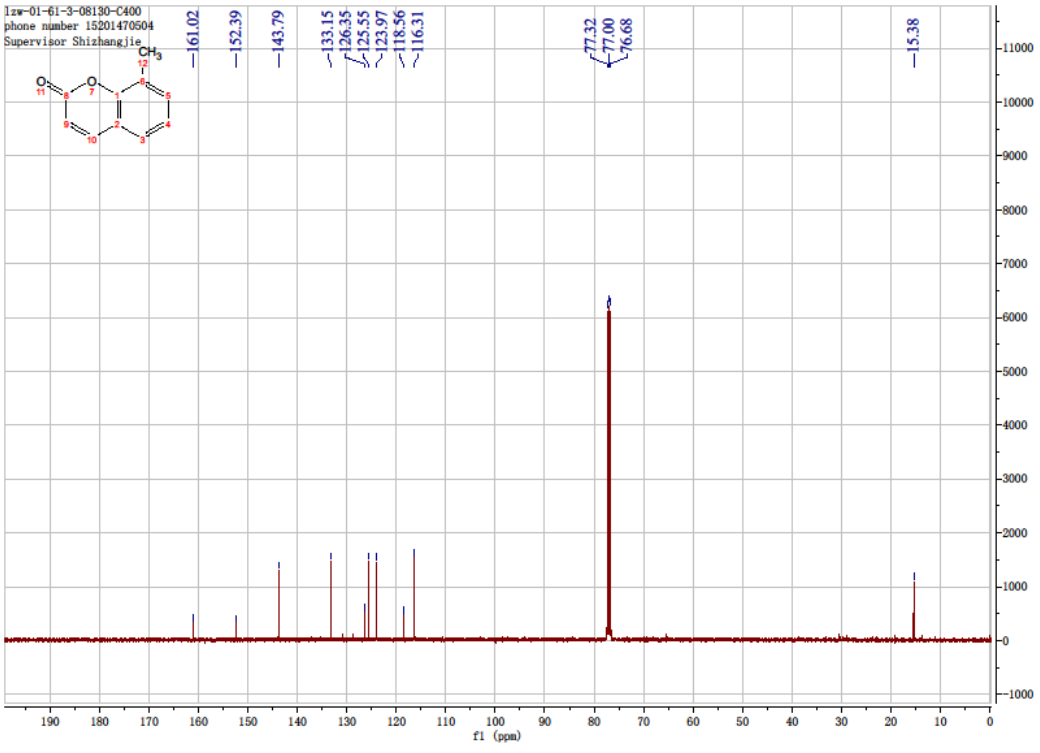

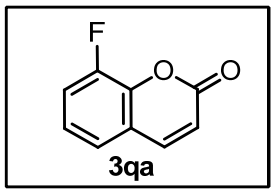

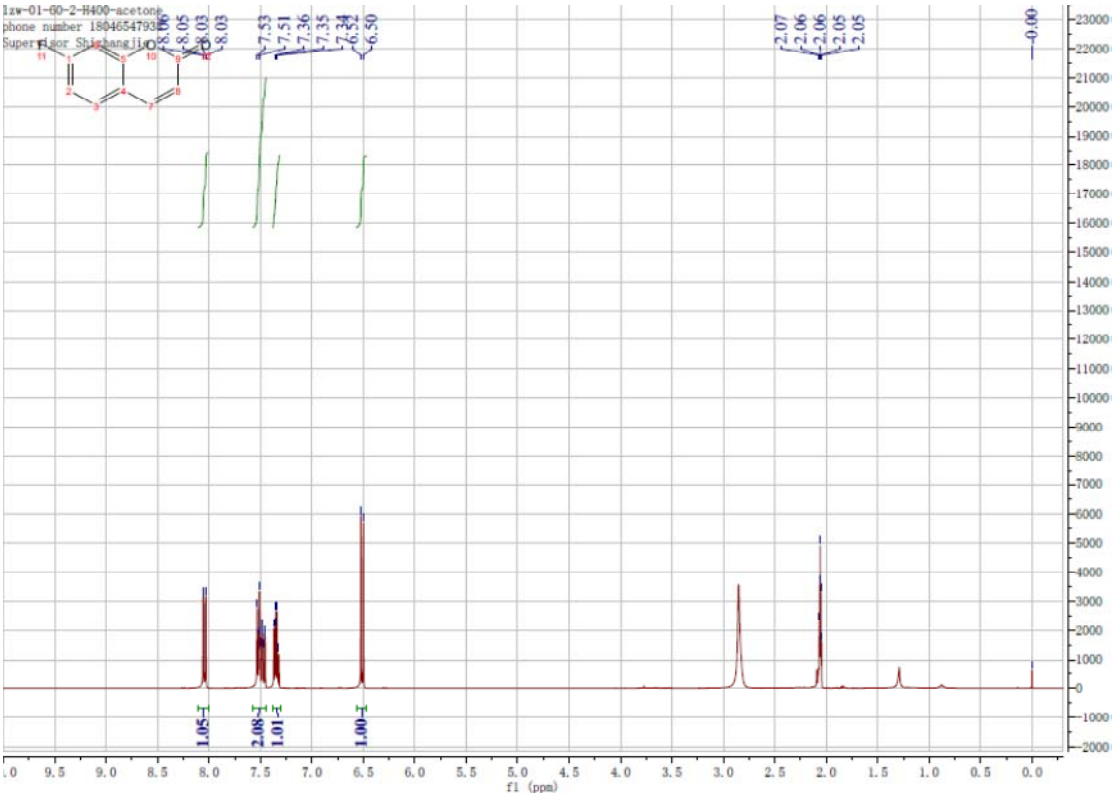

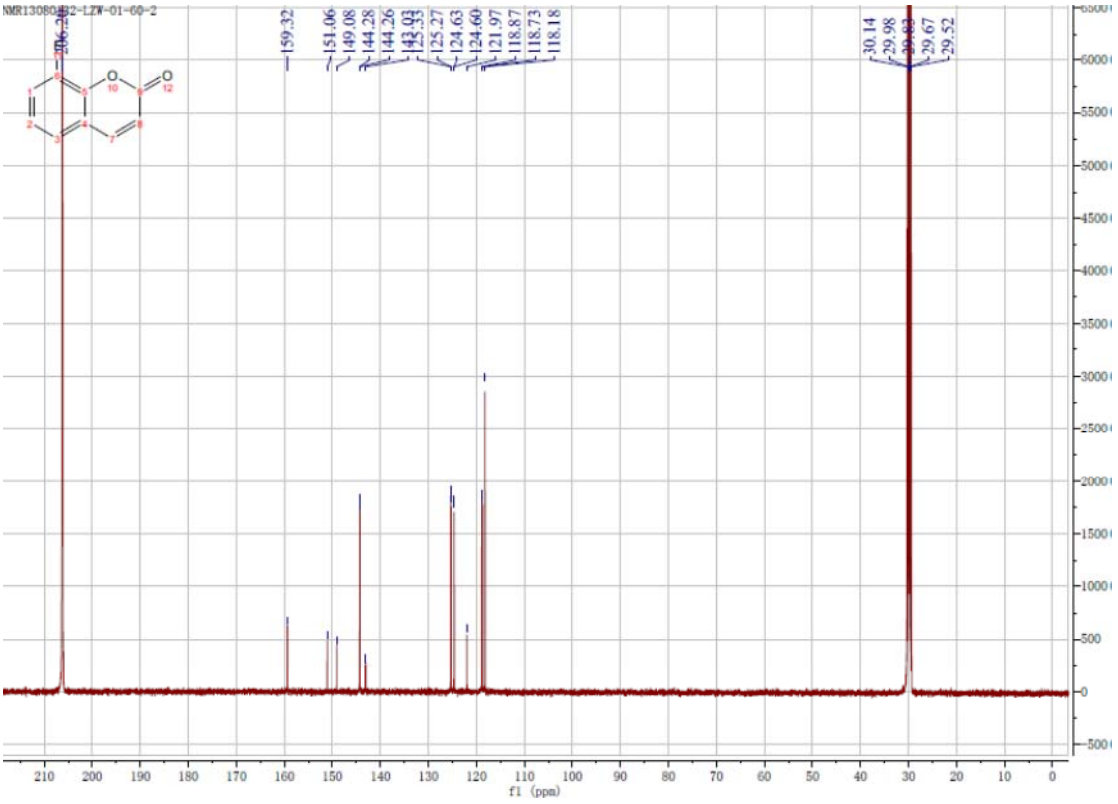

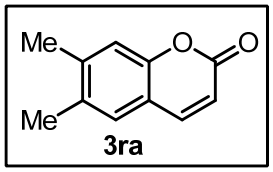

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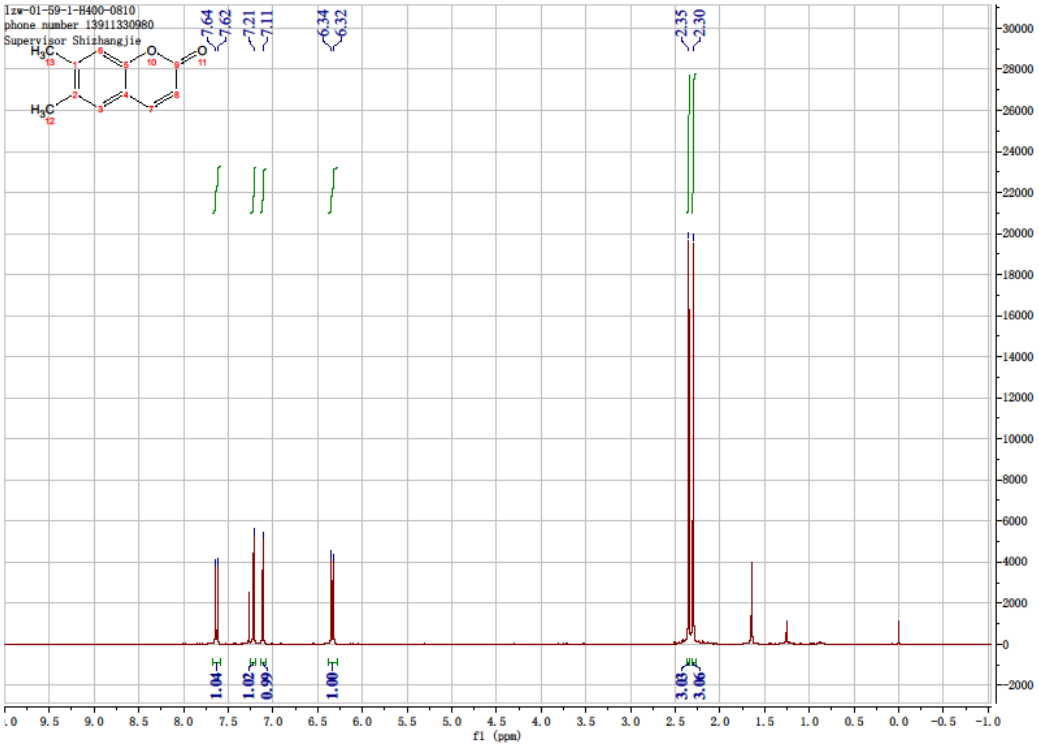
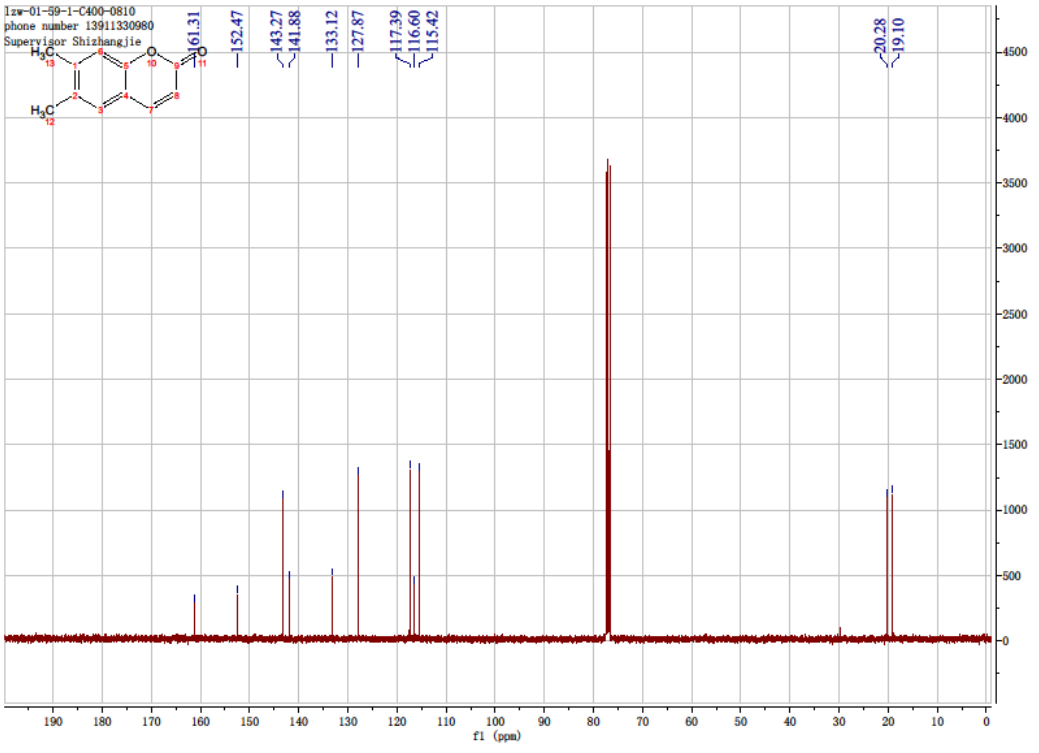
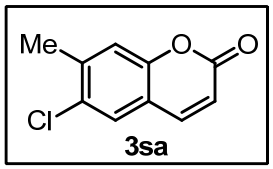
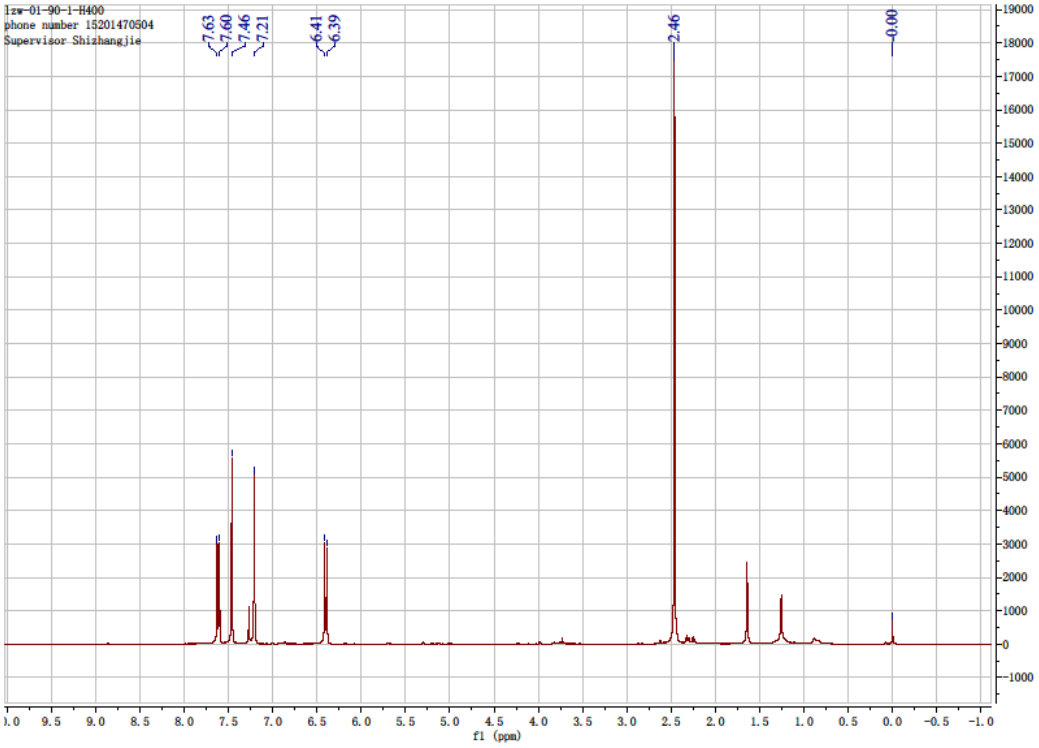
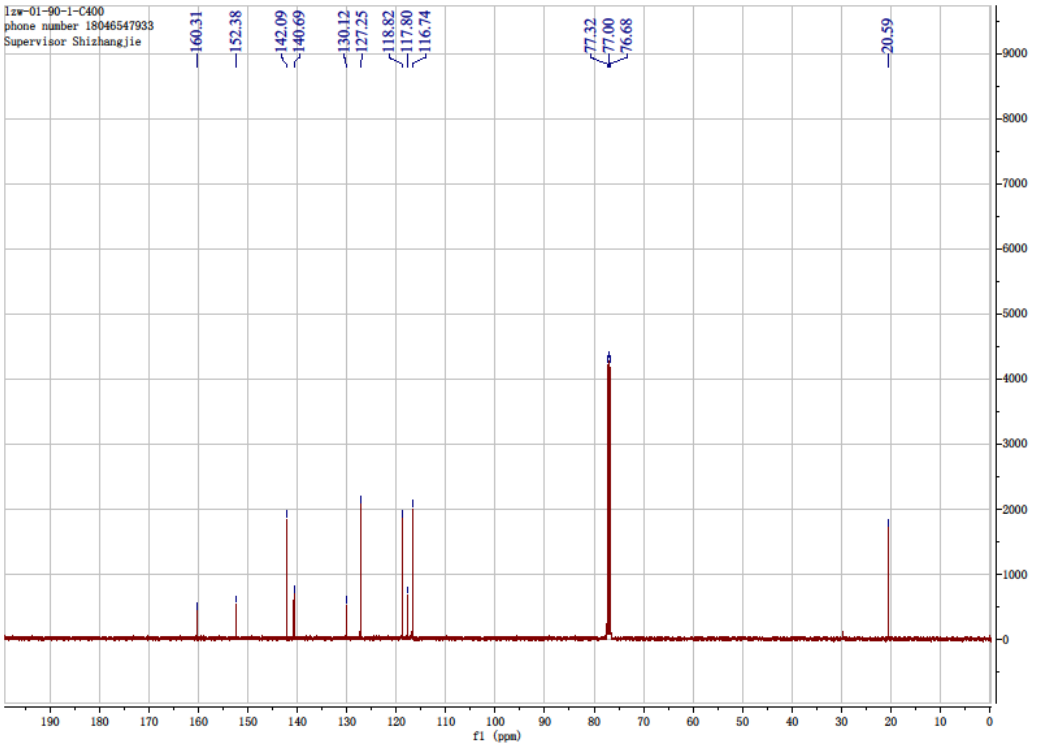


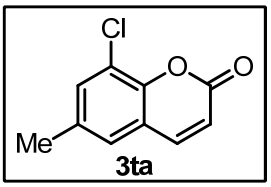




3sa







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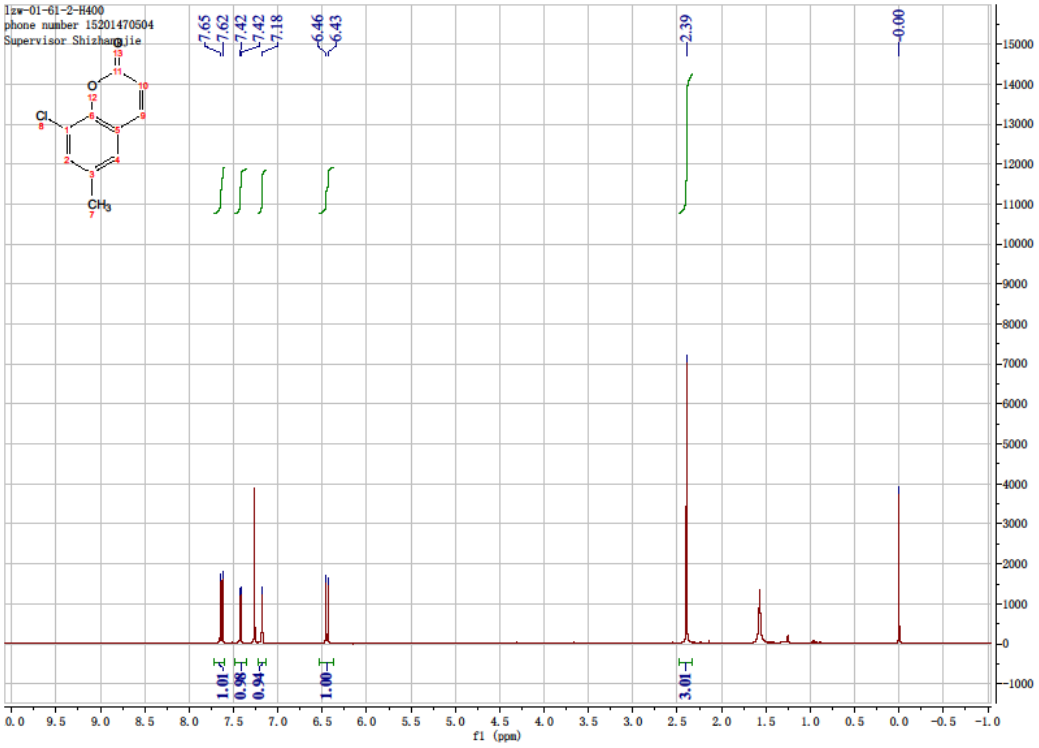

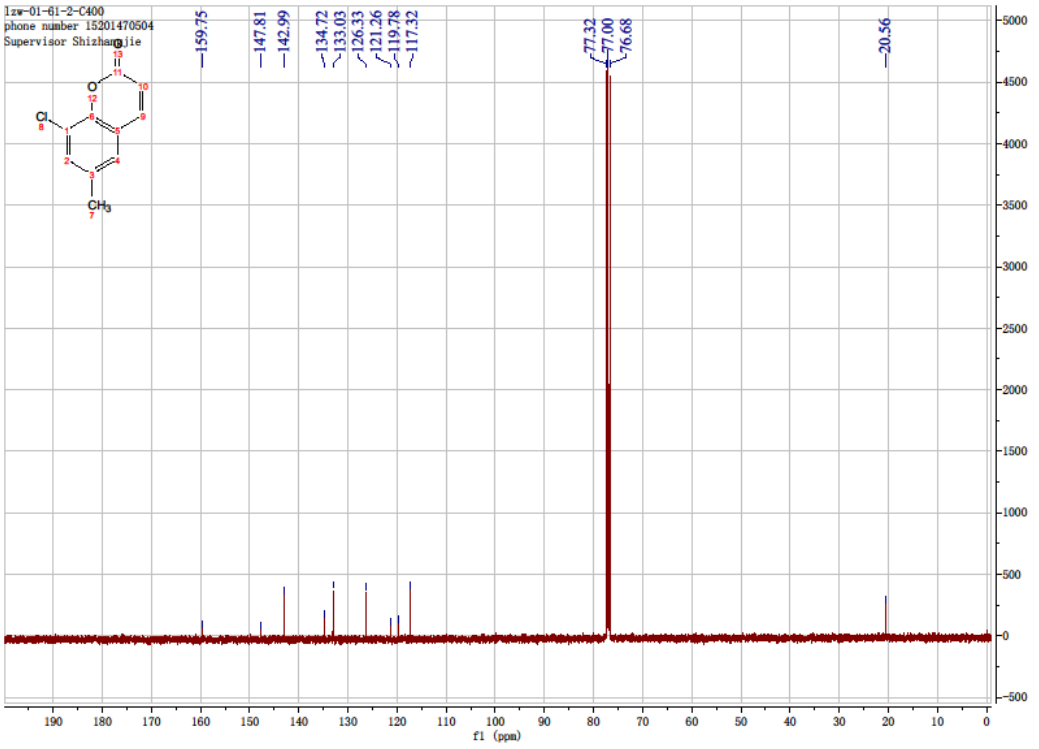

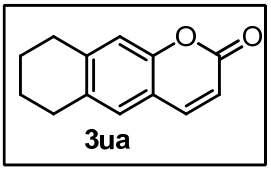

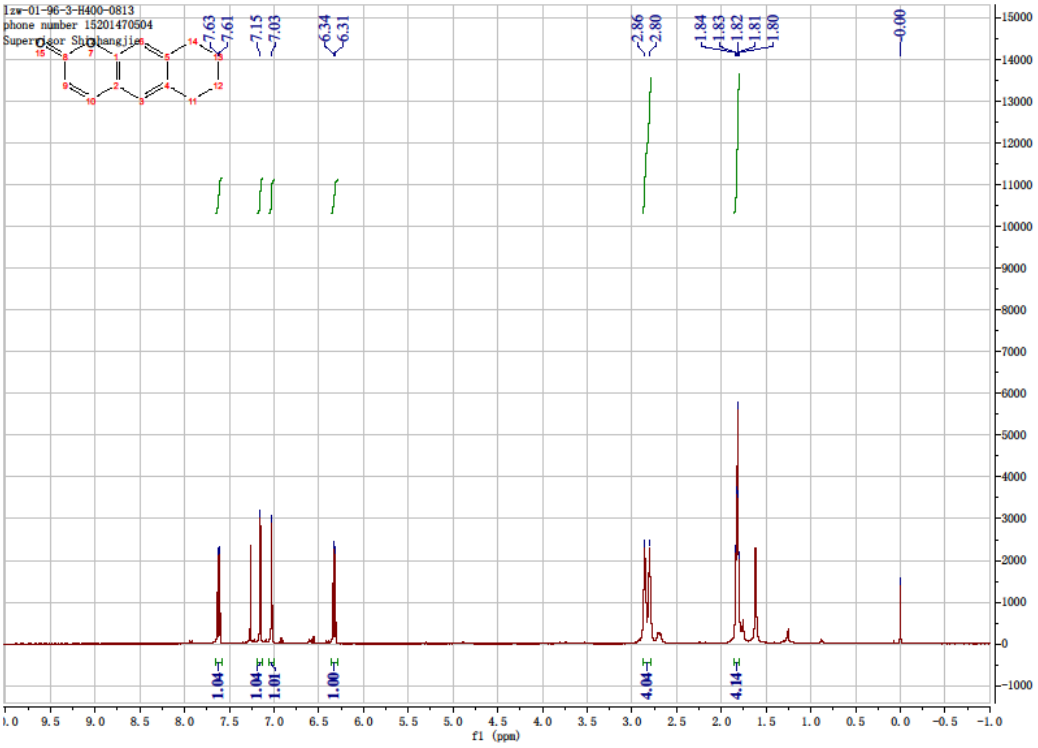

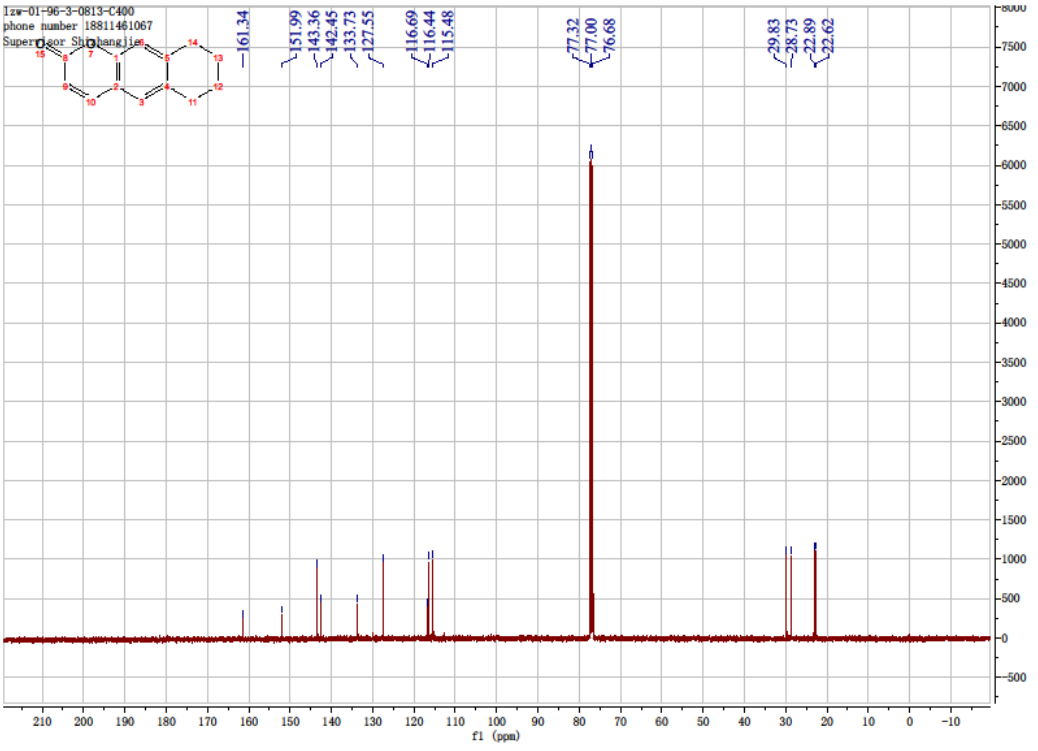

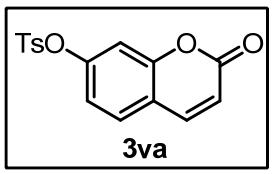

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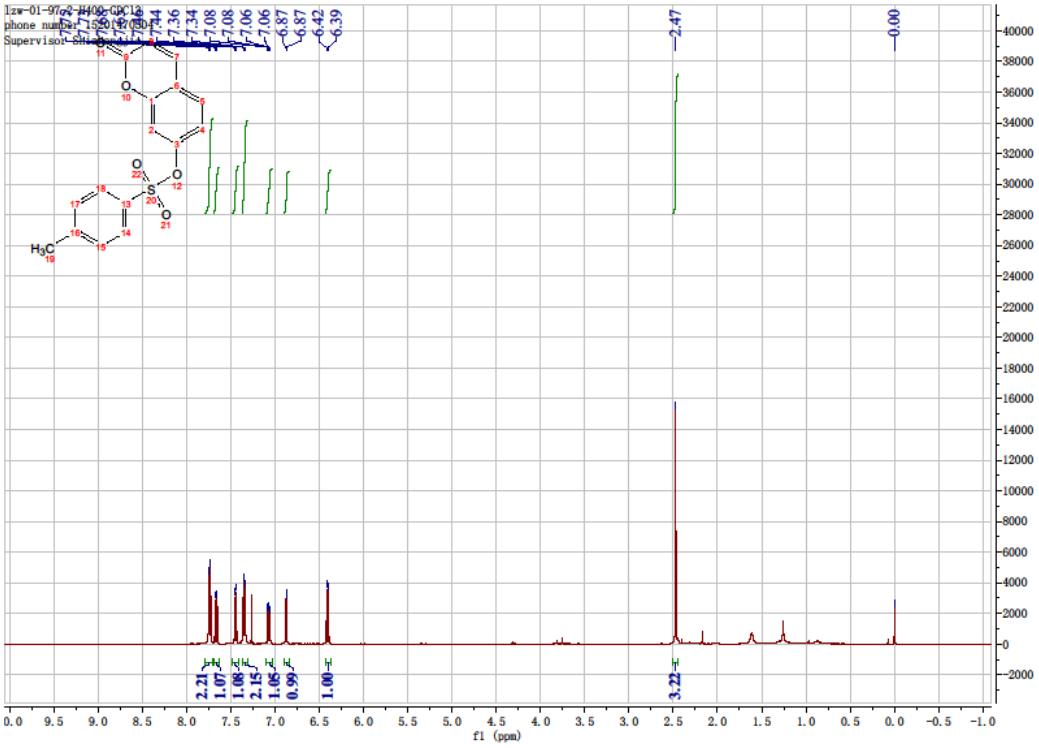
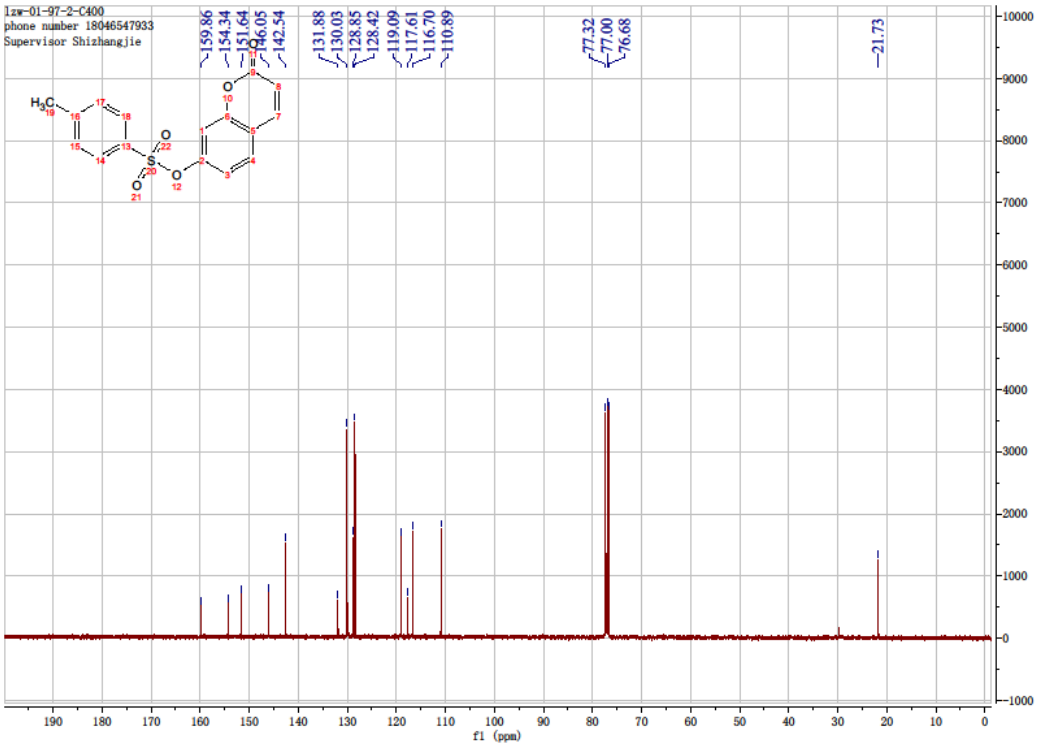
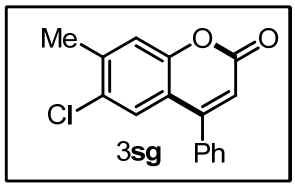
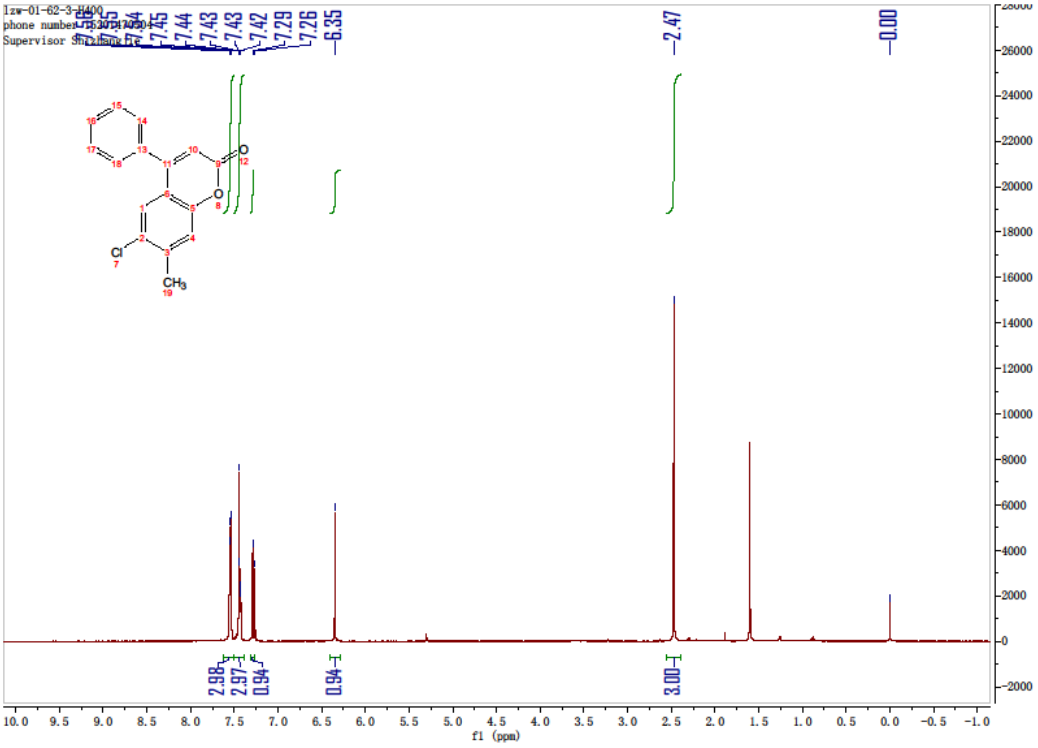
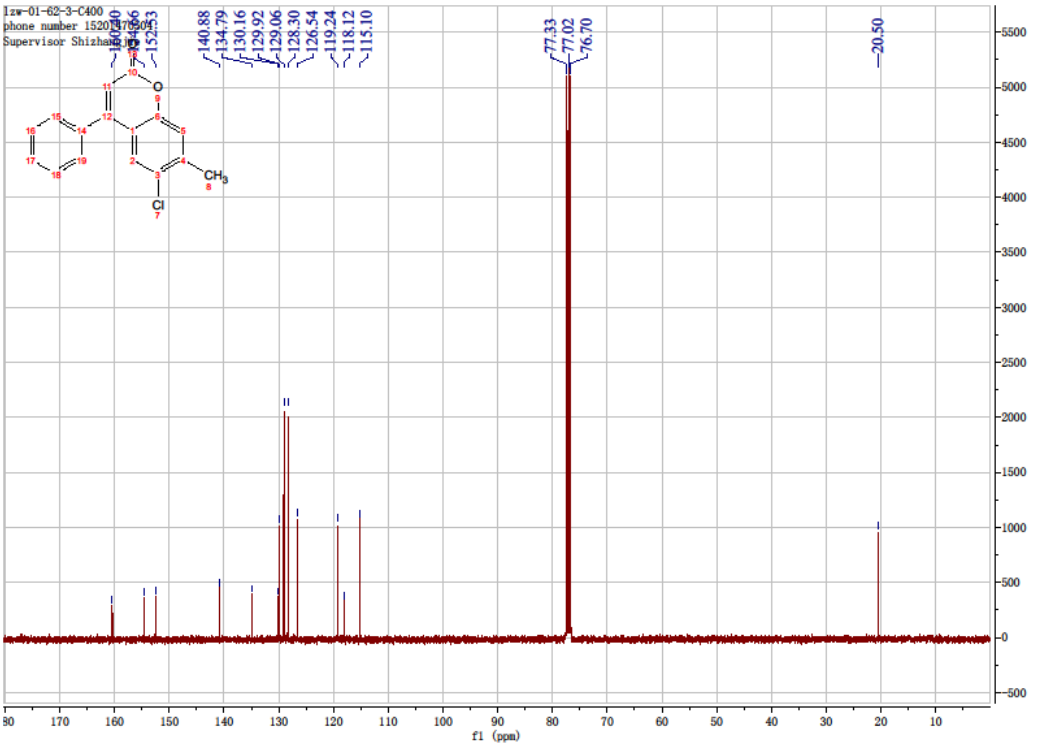
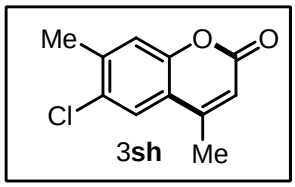


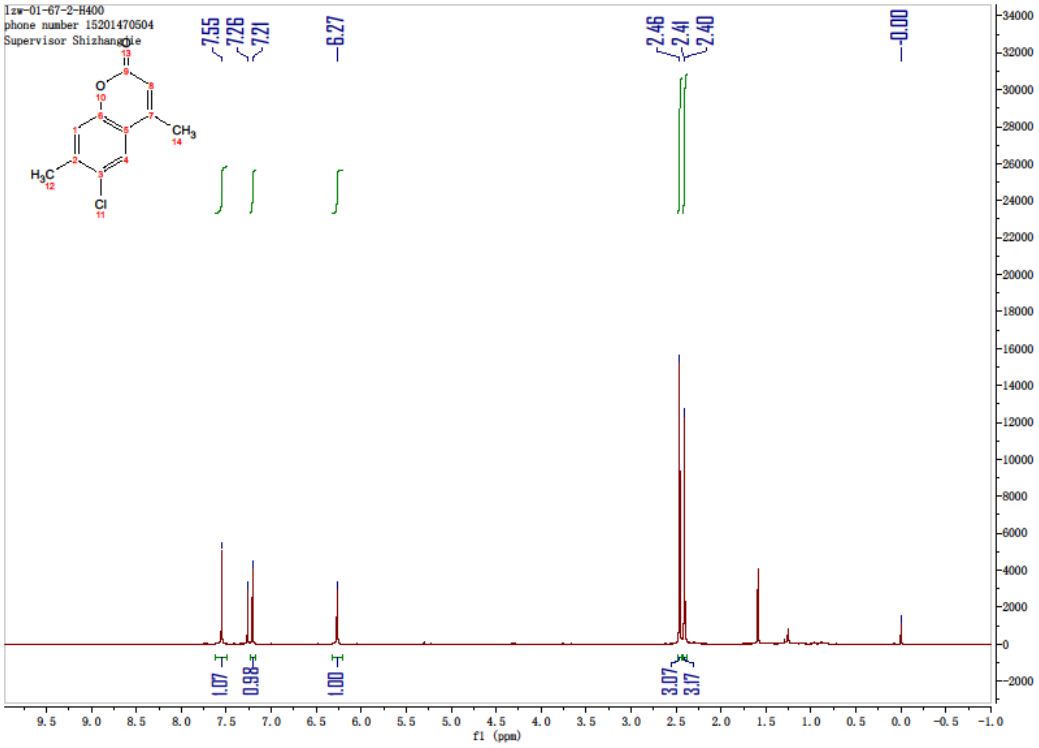


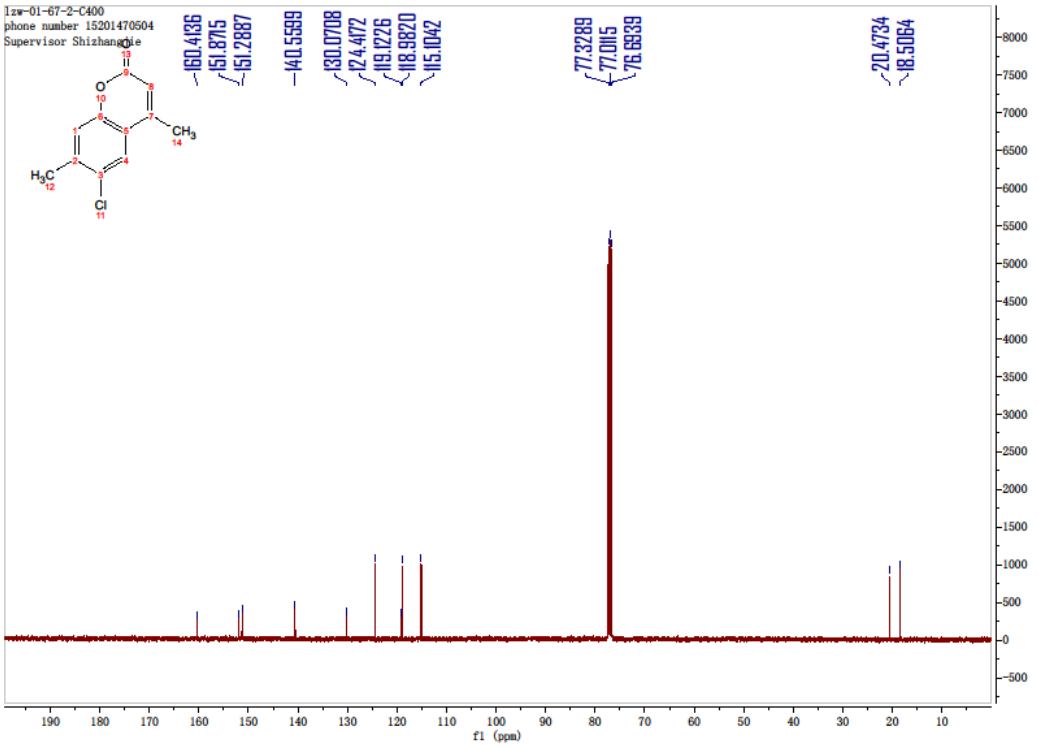


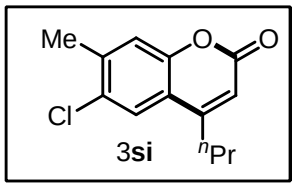


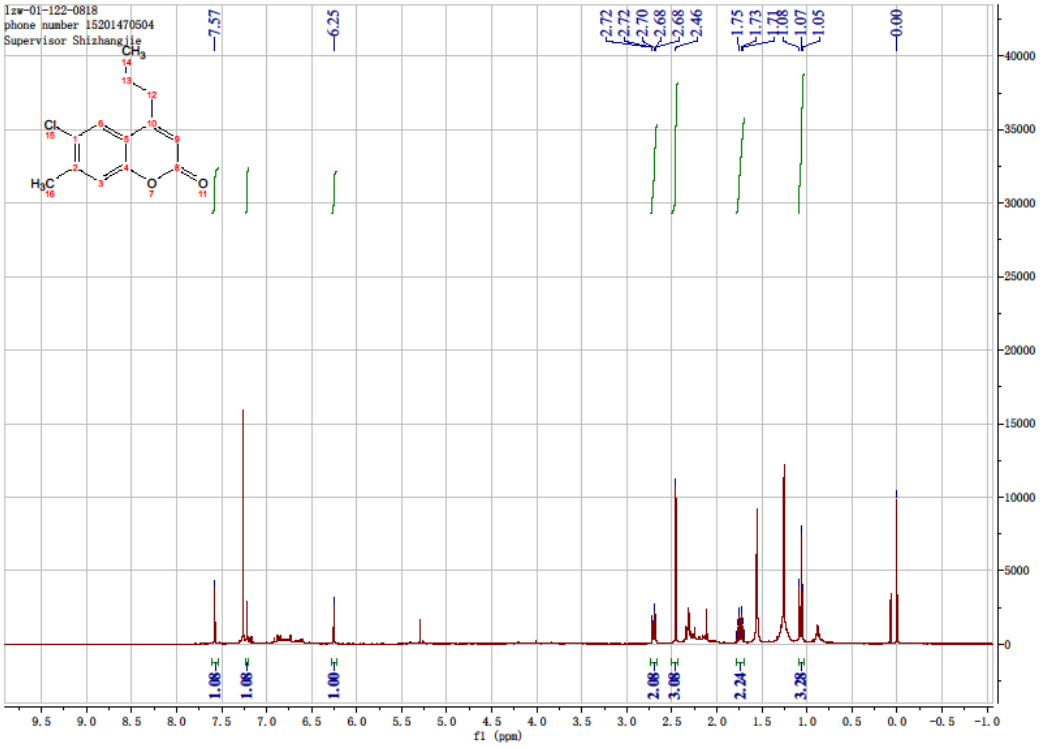


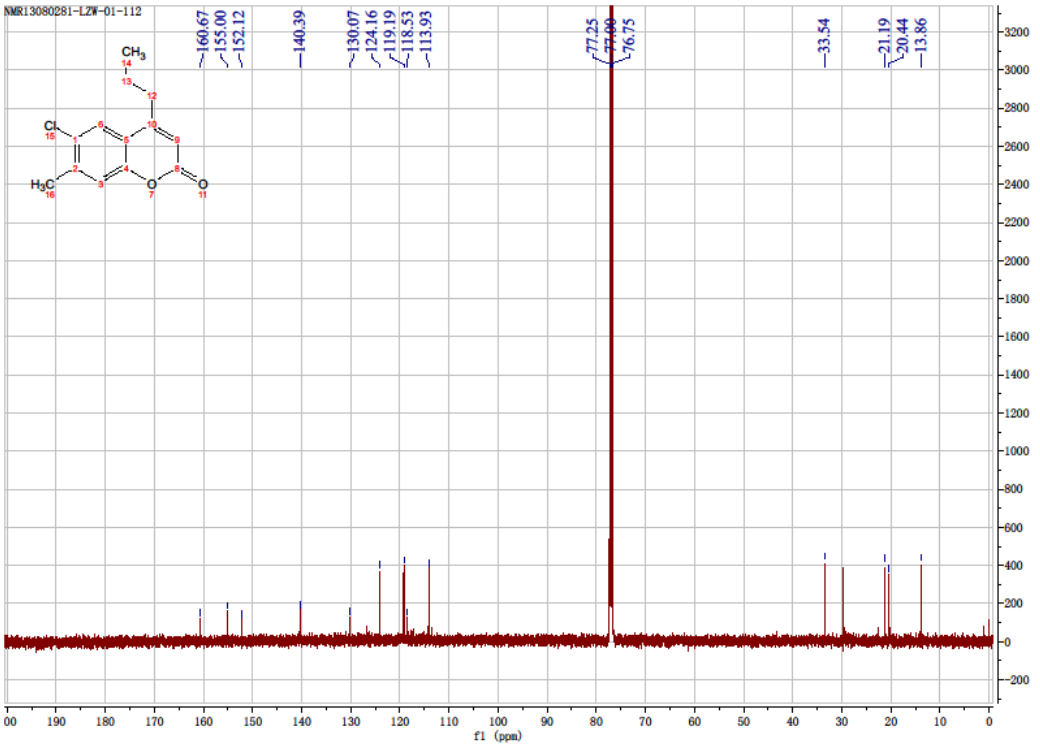




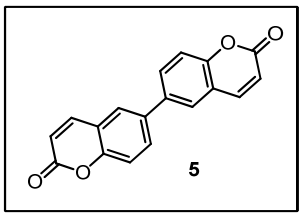


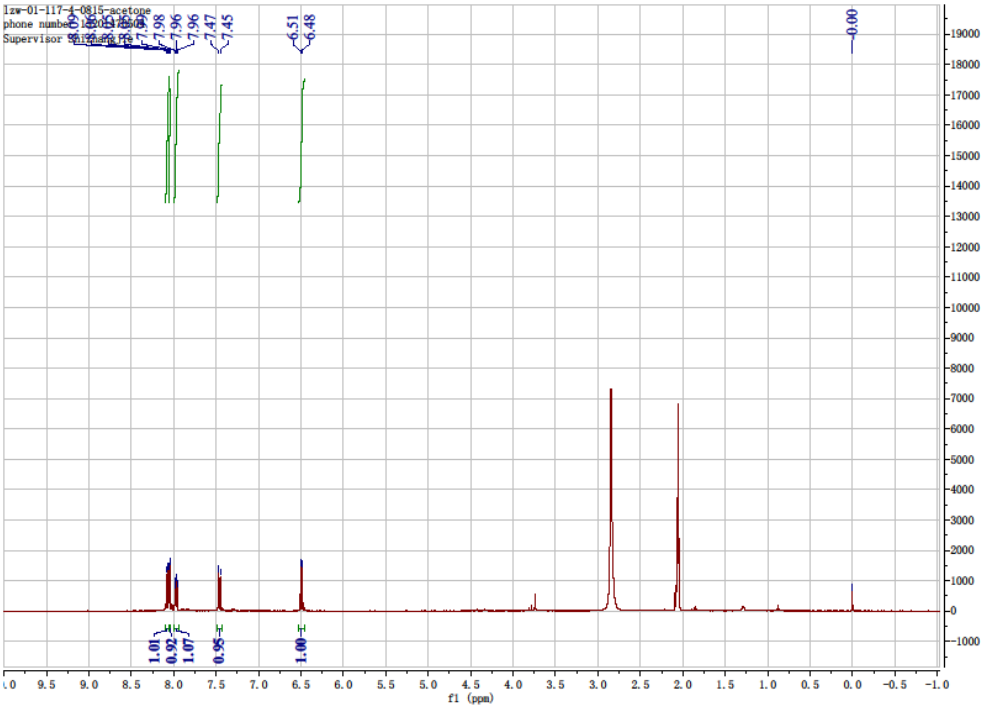


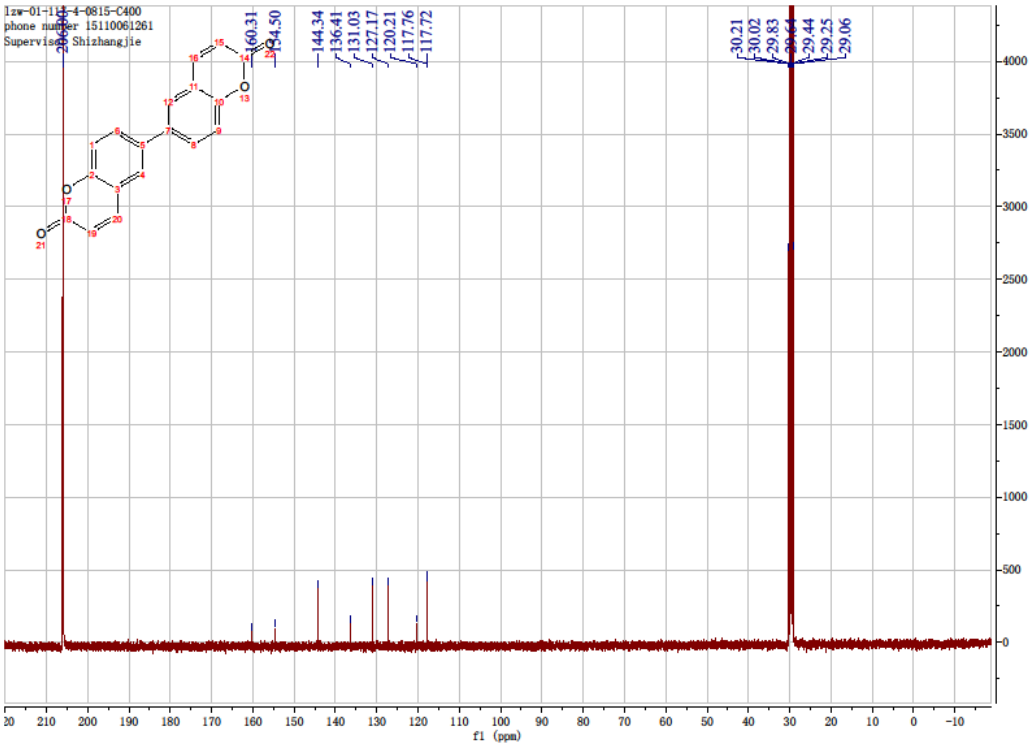


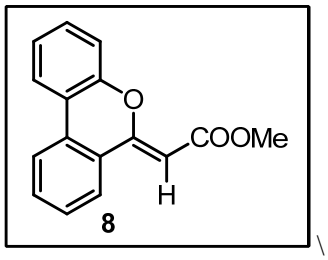


4 NMR specta of other transformations

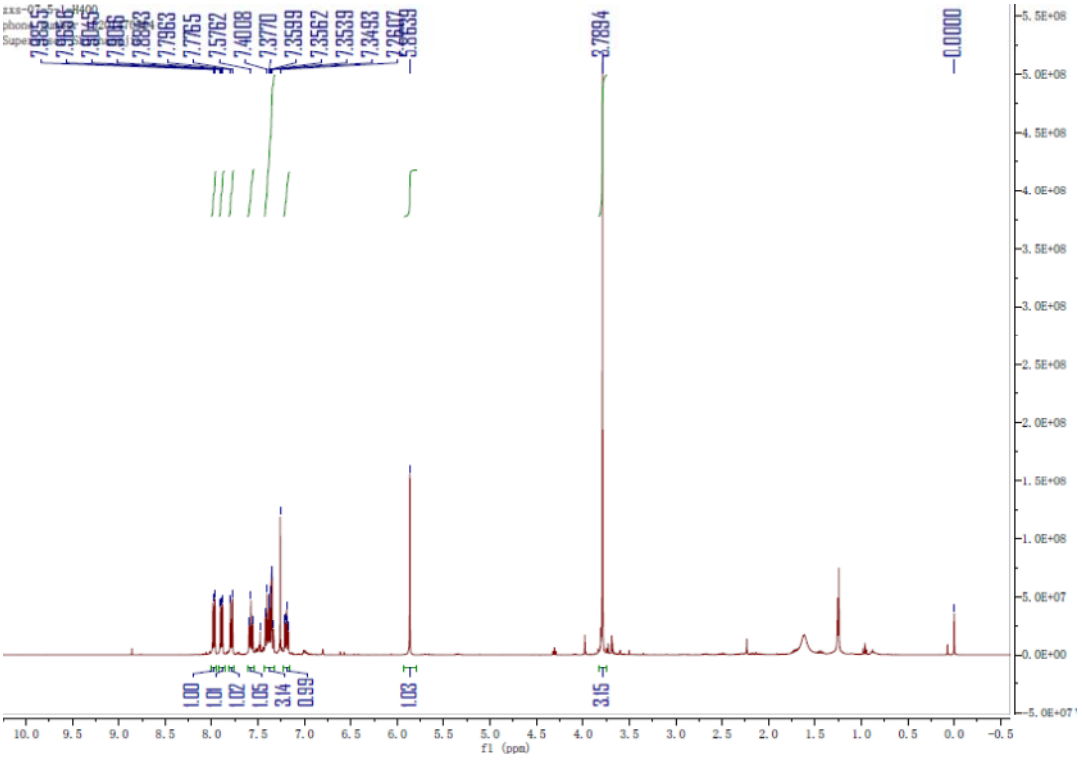


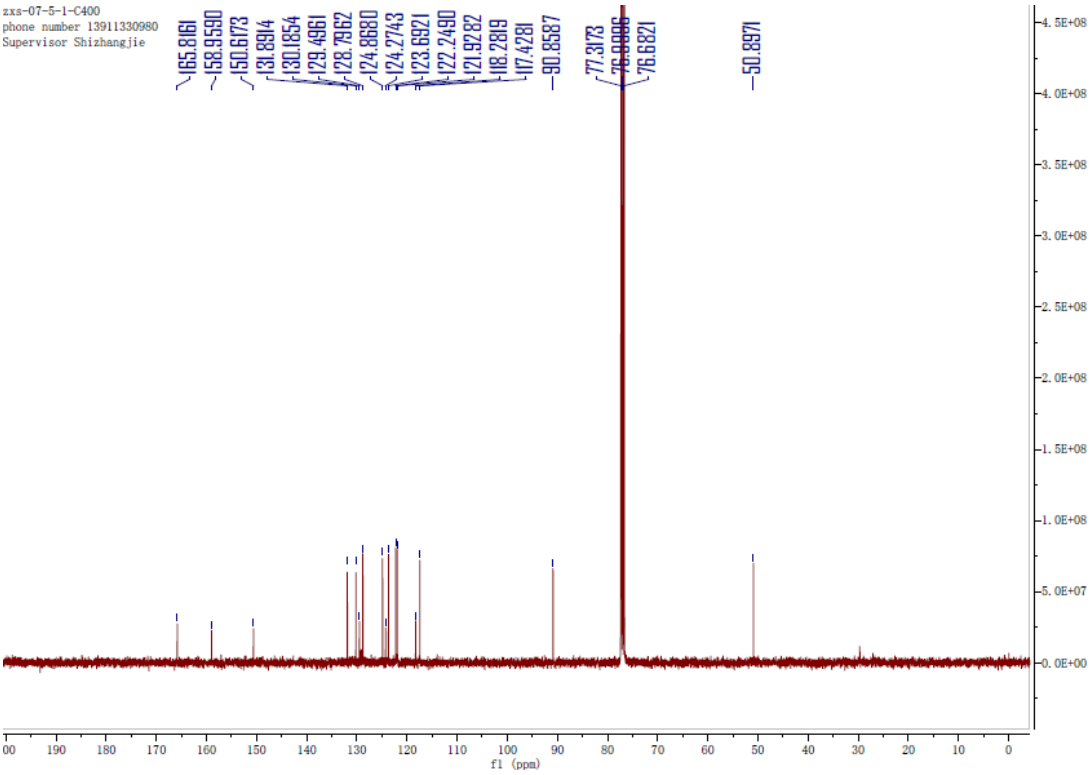






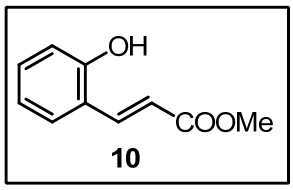
8



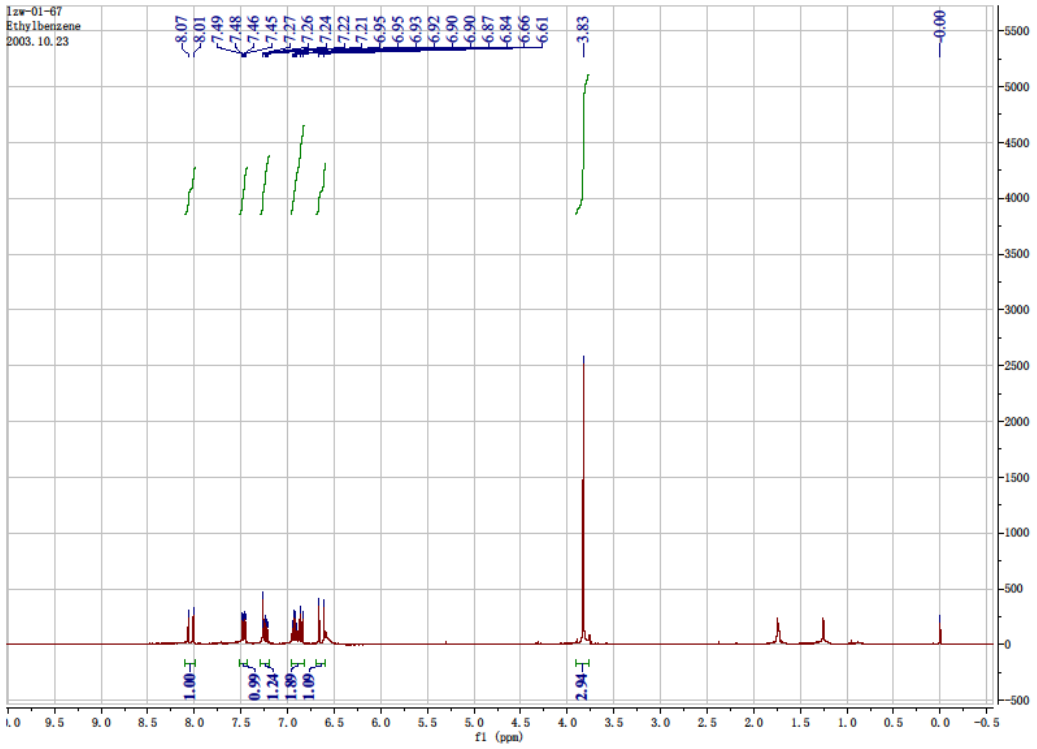


5 NMR spectra of mechanistic studies

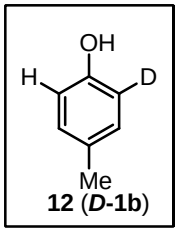
a) NMR spectra of reaction pathway study (Scheme 4)



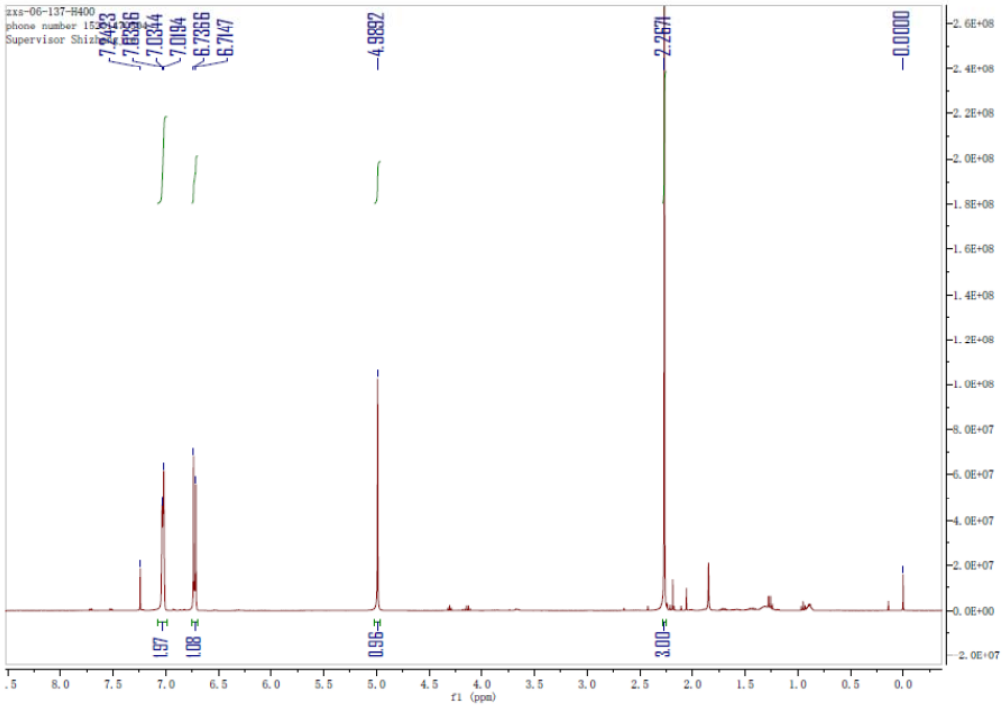
10

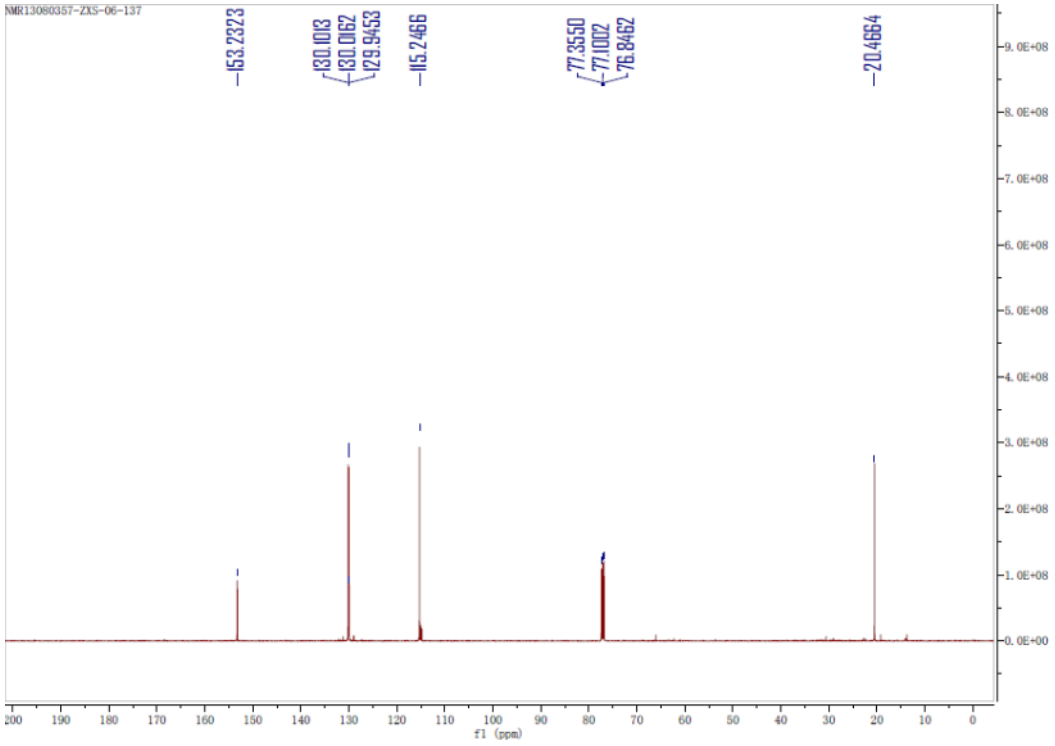


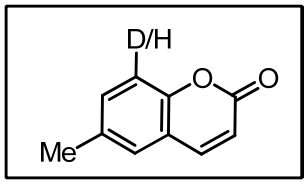
b) NMR spectra of deuterium labeling experiments (Scheme 5)

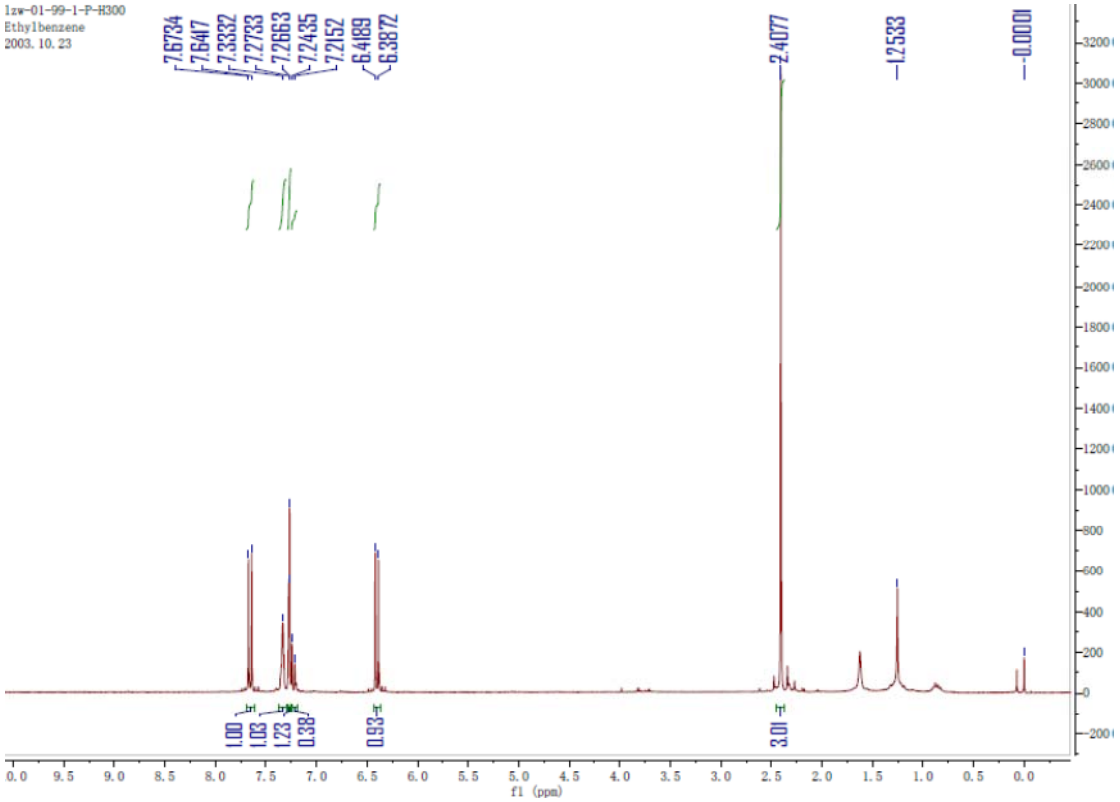


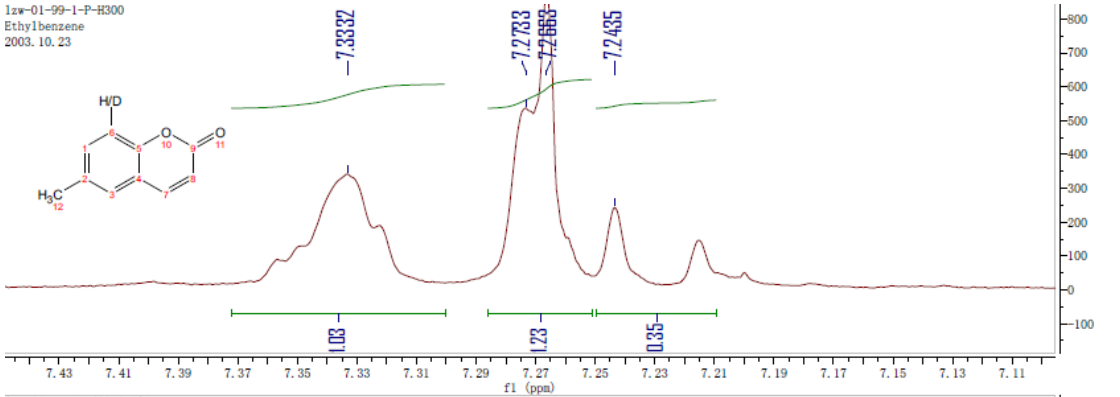
12 (*D*-1b)

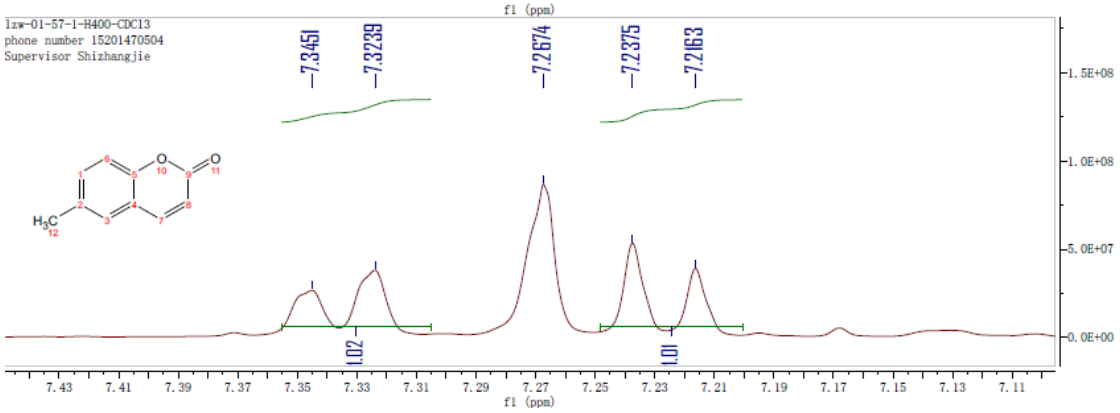






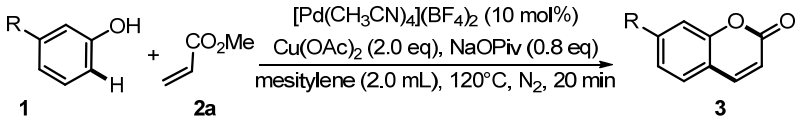






c) NMR spectra of competing experiments (Scheme 6)

Scheme 6. Competing reaction



1

R = Me, **1m**
R = OMe, **1n**

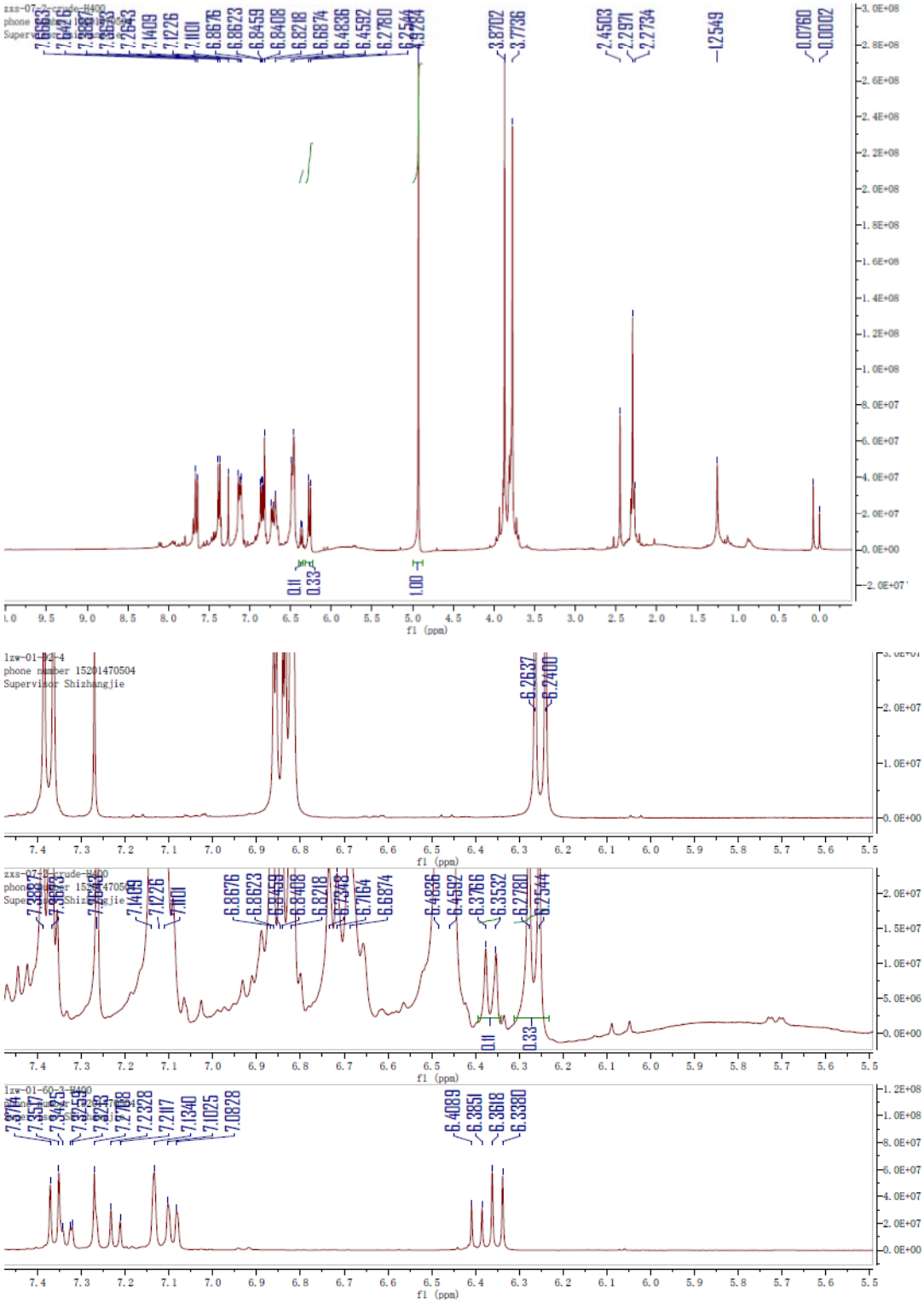
2a

2.0 eq
0.4 mmol

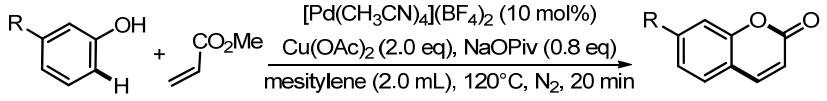
n(1m)=n(1n)=0.1 mmol

3

3ma:**3na** = 1:3



Scheme 6. Competing reaction

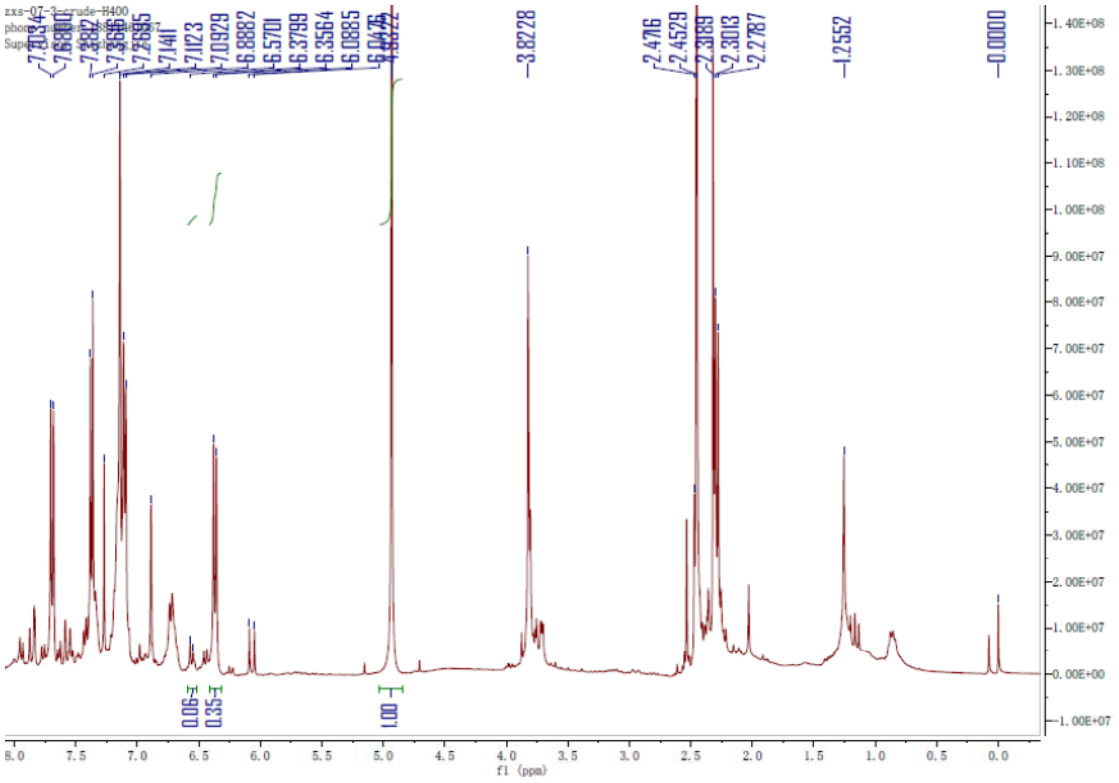


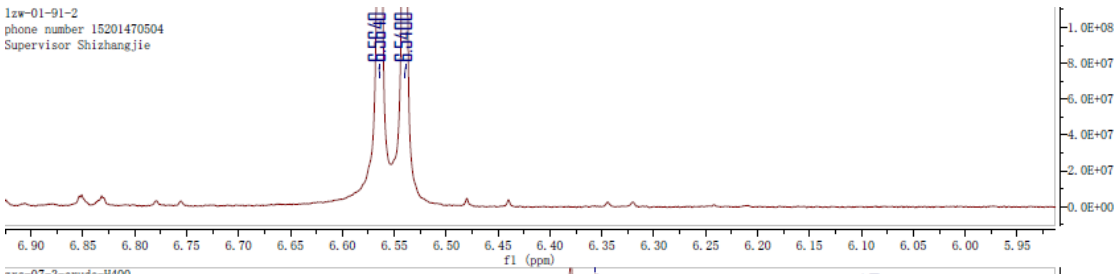
1 R = Me, **1m**; R = CF_3, **1o**

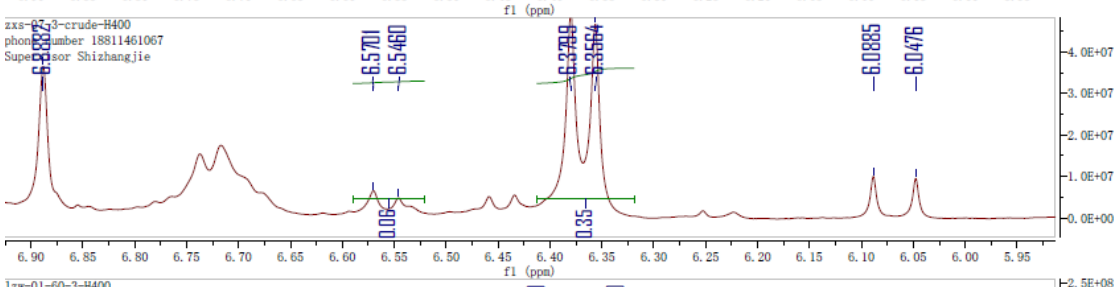
2a 2.0 eq, 0.4 mmol

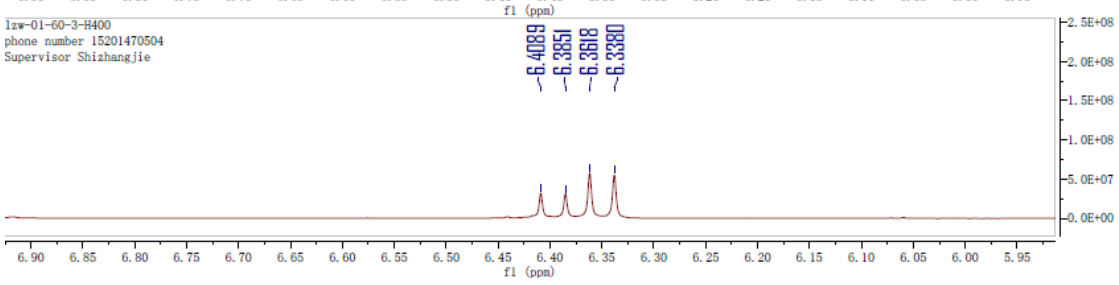
n(1m)=n(1o=0.1 mmol

3 **3ma**:**3oa** = 6:1









6 NMR spectra of synthesis of bioactive molecules (Scheme 8 and 9)