Supporting Information

Bisphosphine Catalyzed Sequential [3+2] Cycloaddition and Michael Addition of Ynones with Benzylidenepyrazolones *via* Dual α',α'-C(sp^3)-H Bifunctionalization to Construct Cyclopentanone-fused Spiro-Pyrazolones

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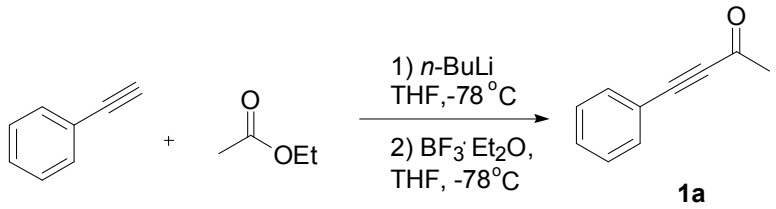
General Comments.

All reactions were performed under N_2 atmosphere in oven-dried glassware with magnetic stirring. Solvents were dried and distilled prior to use according to the standard methods. Unless otherwise indicated, all materials were obtained from commercial sources, and used as purchased without dehydration. Flash column chromatography was performed on silica gel (particle size 10-40 μm, Ocean Chemical Factory of Qingdao, China). Nitrogen gas (99.999%) was purchased from Boc Gas Inc. ^{1}H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ at Bruker 400 MHz spectrometers, TMS served as internal standard (δ = 0 ppm) for ^{1}H NMR and ^{13}C NMR. The crystal structure was determined on a Bruker SMART 1000 CCD diffractometer. Mass spectra were obtained using an electrospray ionization (ESI-TOF) mass spectrometer. Melting points were determined on a T-4 melting point apparatus.

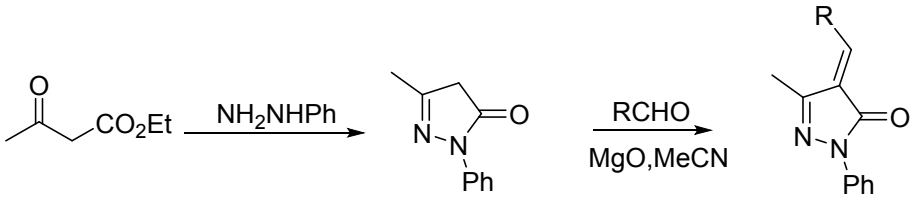
General procedure for the synthesis of ynones 1[1]



1a

To a 100 mL flame-dried Schlenk tube were added phenyl acetylene (255 mg, 2.50 mmol) and 40 mL dry THF. The mixture was cooled to -78°C and *n*-BuLi (1.1 mL, 3.0 mmol, 2.75 M in hexane solution) was added slowly and the mixture left to stir for 30 min at -78°C. Then EtOAc (265 mg, 3.0 mmol) in 20 mL dry THF was added over 10 min followed by addition of $BF_3 \cdot Et_2O$ (0.40 mL, 390 mg, 2.75 mmol). The mixture was kept at -78 °C for 30 min before being allowed to warm to room temperature. After 30 min the mixture was quenched with 10 mL saturated NH_4Cl(aq). Following extraction with EtOAc (3×20 mL). The organic phase was washed with 20 mL brine and dried over Na_2SO_4 and the solvent was removed in vacuo. The crude product was purified by column chromatography (PE/EA = 20/1) to give 4-phenylbut-3-yn-2-one **1a** as a brown oil (331.6 mg, 89% yield).

General procedure for the synthesis of benzylidenepyrazolone 2[2]

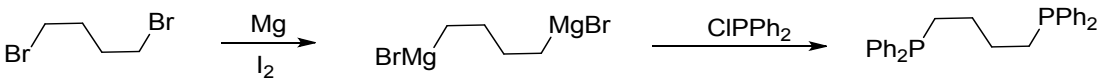


Phenyl hydrazine (10.5 mL, 0.1 mol) was taken in 40 mL of glacial acetic acid and methyl acetoacetate (12.7 mL, 0.1 mol) was added to it and stirred at reflux for 3 h. Thereafter the reaction mixture was evaporated to dryness and to the residue was extracted with water (40 mL) and EtOAc (40 mL). The organic layer was separated whereas the aqueous layer was further extracted with EtOAc (2 × 40 mL). The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated over reduced pressure to afford pure product as a white solid.

A mixture of the corresponding aldehyde (19.9 mmol), 3-methyl-1-phenyl-1H-pyrazol-5(4H)-one (19.7 mmol), MgO (0.5g) in 40 mL acetonitrile was refluxed with stirring overnight. The progress of the reaction was monitored by TLC. After completion of the reaction, MgO was separated from the reaction

mixture by filtration. The excess acetonitrile was removed by evaporation, The combined extracting was concentrated and the residue was subjected to column chromatography to provide the crude product, and recrystallized from 95% ethanol.

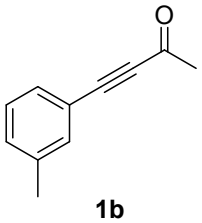
General procedure for the synthesis of bisphosphine catalysts



Synthesis of 1,4-bis(diphenylphosphino)butane (DPPB):[3]

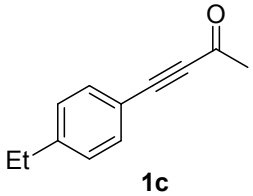
To a solution of a small crystal of iodine in THF (50 mL) was added of magnesium (69 mol, 1.67 g) under N_2. After stirred for about 5 minutes, a solution of 1,4-dibromobutane (24 mmol, 2.9 mL) in THF (50 mL) was added dropwise slowly. After stirred for 3h, a mixture of chlorodiphenylphosphine (40 mmol, 7.2 mL) in 50 mL of anhydrous THF was dropwise added over 30 minutes at 0 ºC. Then the reaction mixture was allowed to be warmed up to room temperature and stirred overnight. The resulting mixture was carefully evaporated to remove most of the solvent, then 5 mL of water was added dropwise. The mixture was filtered, and the water layer was extracted by CH_2Cl_2 (3 × 30 mL). The combined organic layer was dried over anhydrous Na_2SO_4 and the residue was subjected to column chromatography to provide the product as a white solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.34-7.44 (8 H, m), 7.30-7.33 (12 H, m), 2.04 (4 H, t, J = 7.5 Hz), 1.62-1.54 (4 H, m). ^{31}P NMR (81 MHz, $CDCl_3$): δ -16.6 ppm.

Characterization date for the ynones



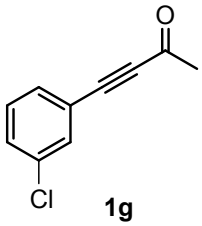
1b

4-(m-tolyl)but-3-yn-2-one (1b): Eluent: petroleum ether (PE)/EtOAc (20:1). Yield: 89% (352 mg). Brown oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (s, 2H), 7.17 (s, 2H), 2.35 (s, 3H), 2.26 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 184.6, 138.5, 133.5, 131.7, 130.2, 128.5, 119.7, 90.7, 88.1, 32.7, 21.1.



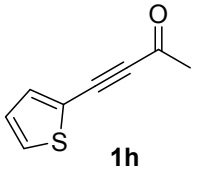
1c

4-(4-ethylphenyl)but-3-yn-2-one (1c): Eluent: petroleum ether (PE)/EtOAc (20:1). Yield: 84% (362 mg). Brown oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (d, J = 8.0 Hz, 2H), 7.22 (d, J = 7.9 Hz, 2H), 2.68 (q, J = 7.6 Hz, 2H), 2.45 (s, 3H), 1.25 (t, J = 7.6 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 184.7, 147.7, 133.2, 128.3, 116.9, 91.1, 88.2, 77.4, 77.1, 76.8, 32.7, 29.0, 15.2.



1g

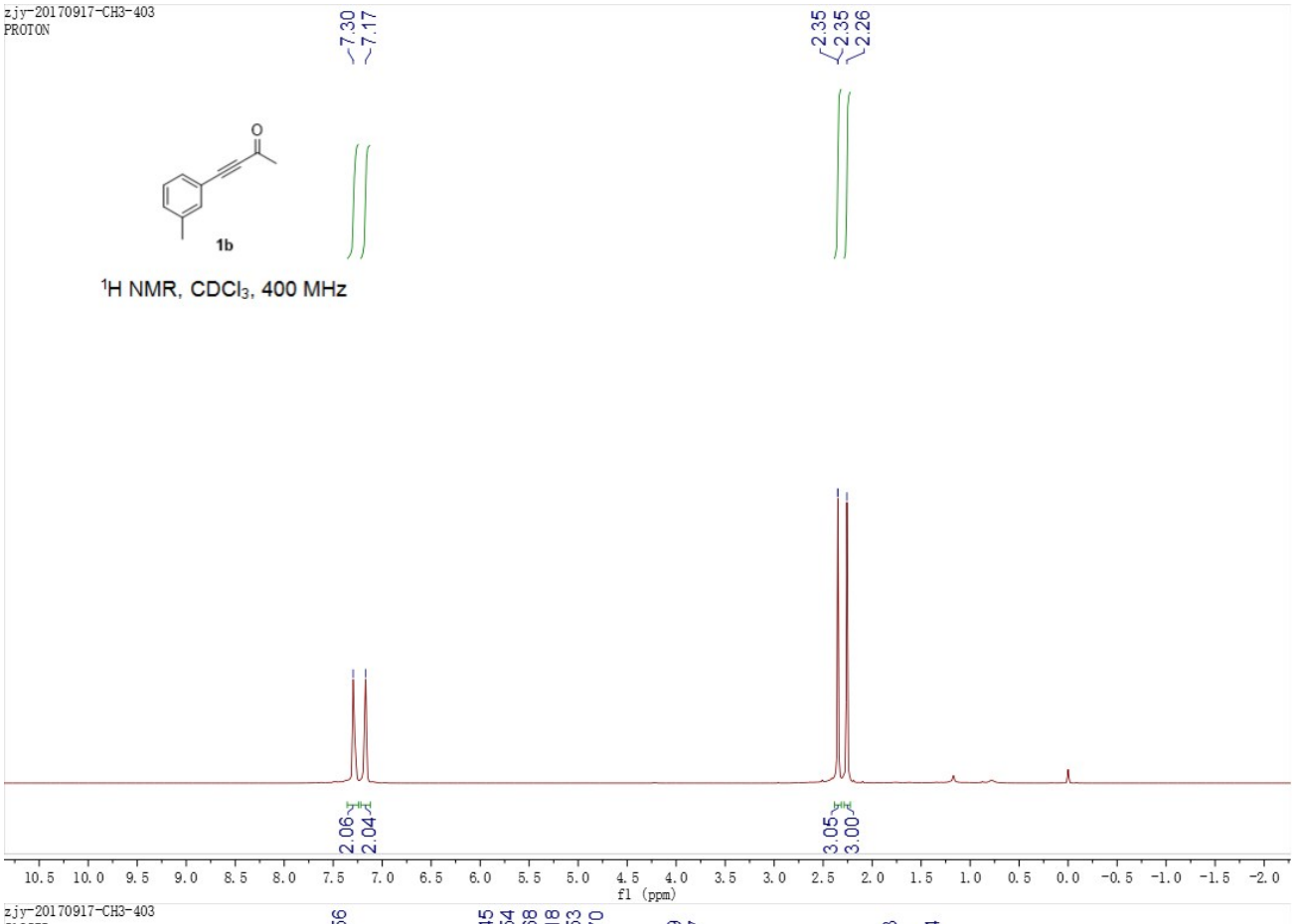
4-(3-chlorophenyl)but-3-yn-2-one (1g): Eluent: petroleum ether (PE)/EtOAc (20:1). Yield: 76% (340 mg). Brown oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (t, J = 1.7 Hz, 1H), 7.48-7.38 (m, 2H), 7.33 (t, J = 7.9 Hz, 1H), 2.46 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 183.3, 133.5, 131.6, 129.9,130.1, 128.9, 120.6, 87.7, 87.1, 31.7.

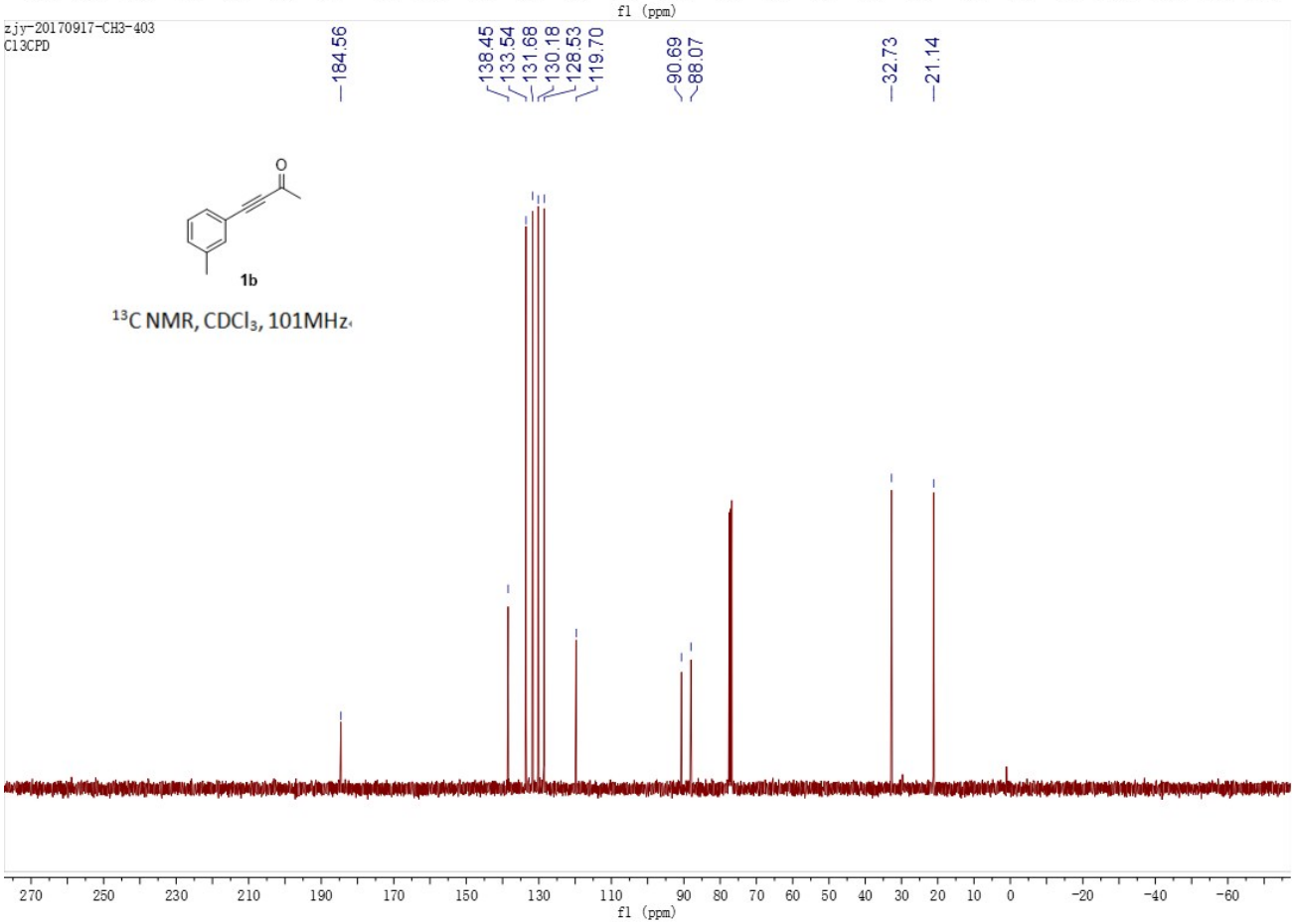


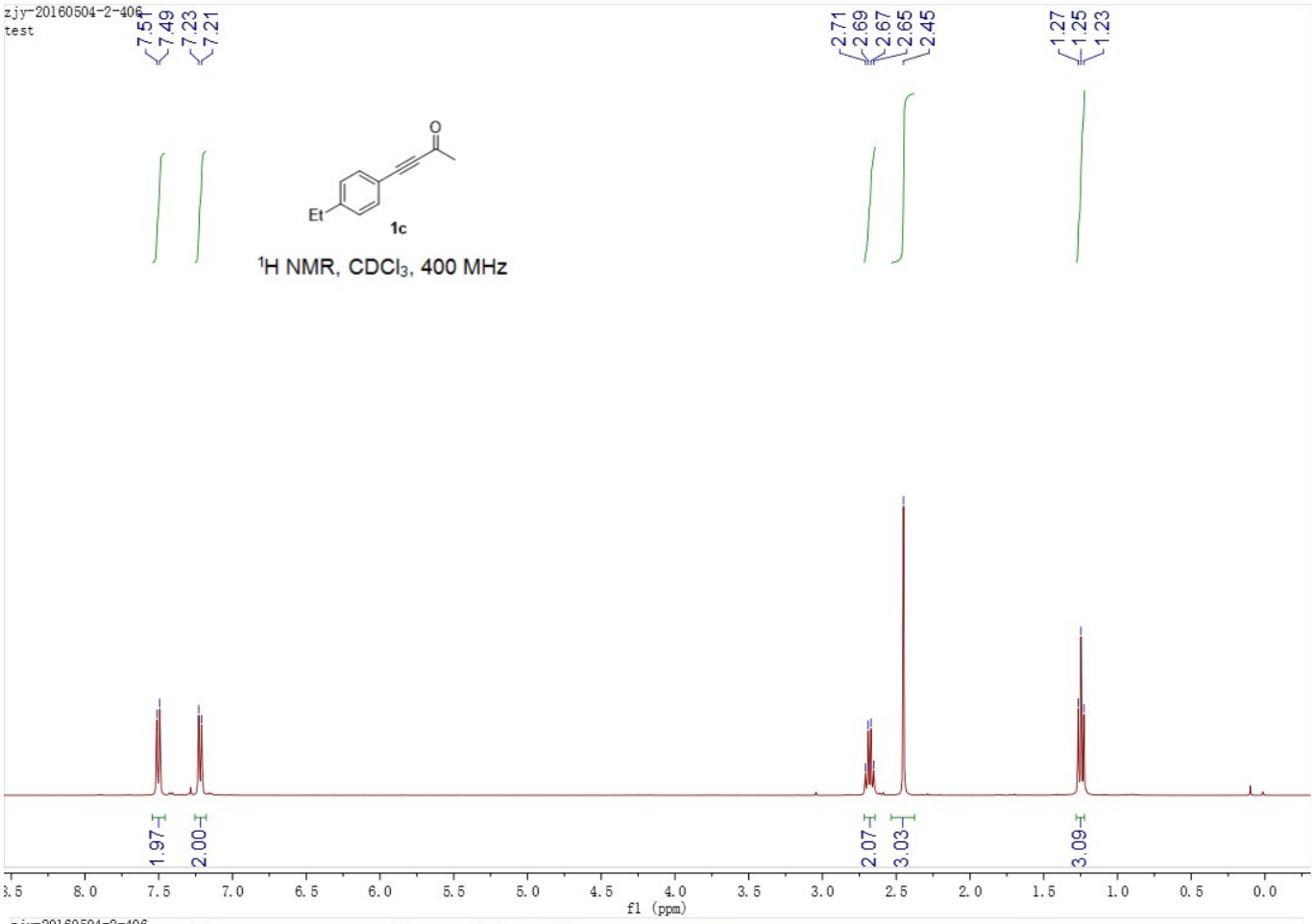
1h

4-(thiophen-2-yl)but-3-yn-2-one (1h): Eluent: petroleum ether (PE)/EtOAc (20:1). Yield: 83% (311mg). Brown oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60-7.36 (m, 2H), 6.98 (dd, J = 5.1, 3.8 Hz, 1H), 2.34 (s, 3H).^{13}C NMR (101 MHz, $CDCl_3$) δ 184.0, 136.8, 131.8, 127.8, 119.6, 92.9, 84.3, 32.4.

The ^{1}H and ^{13}C NMR spectra of compounds



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1c
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2.07
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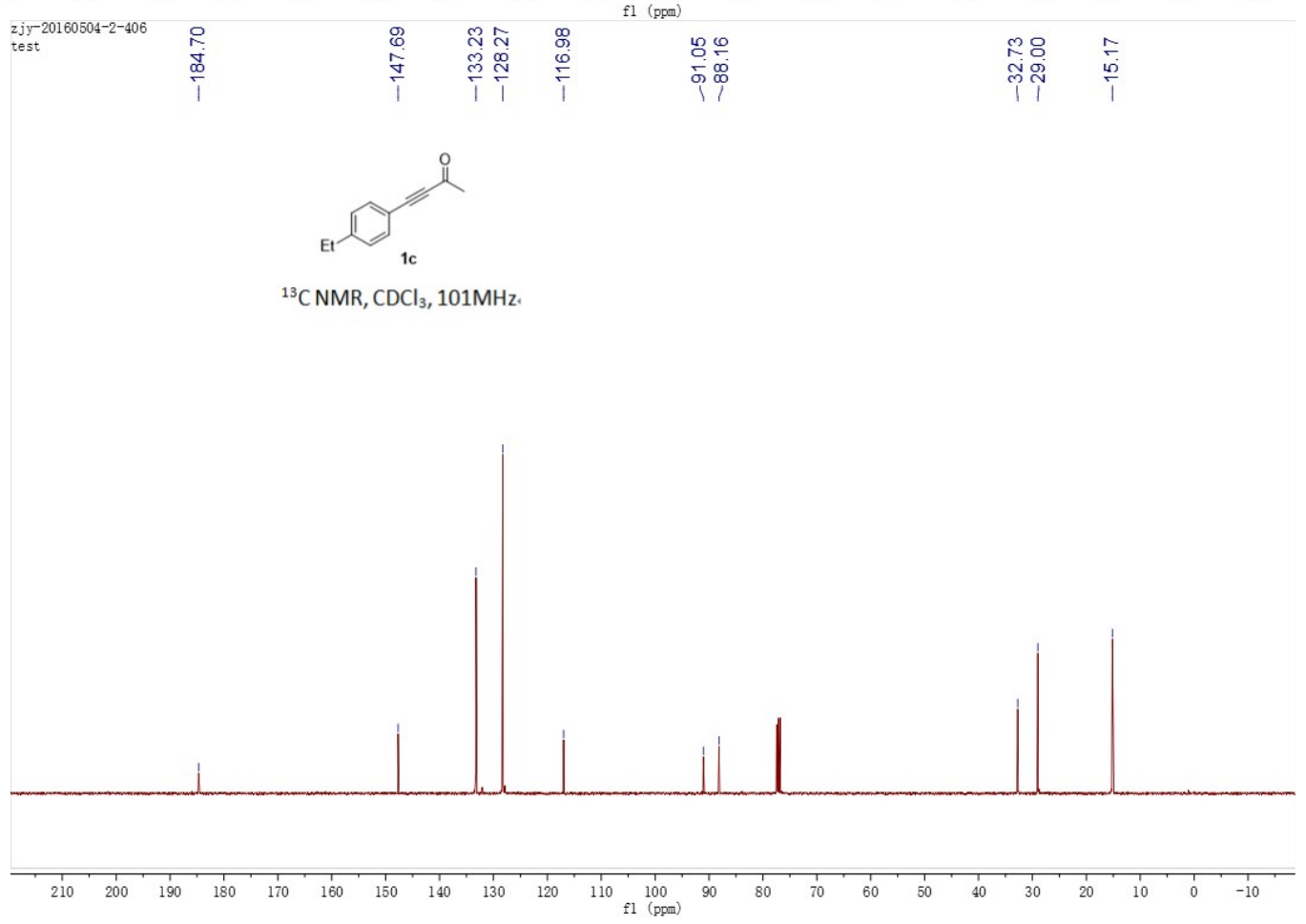
3.09
f1 (ppm)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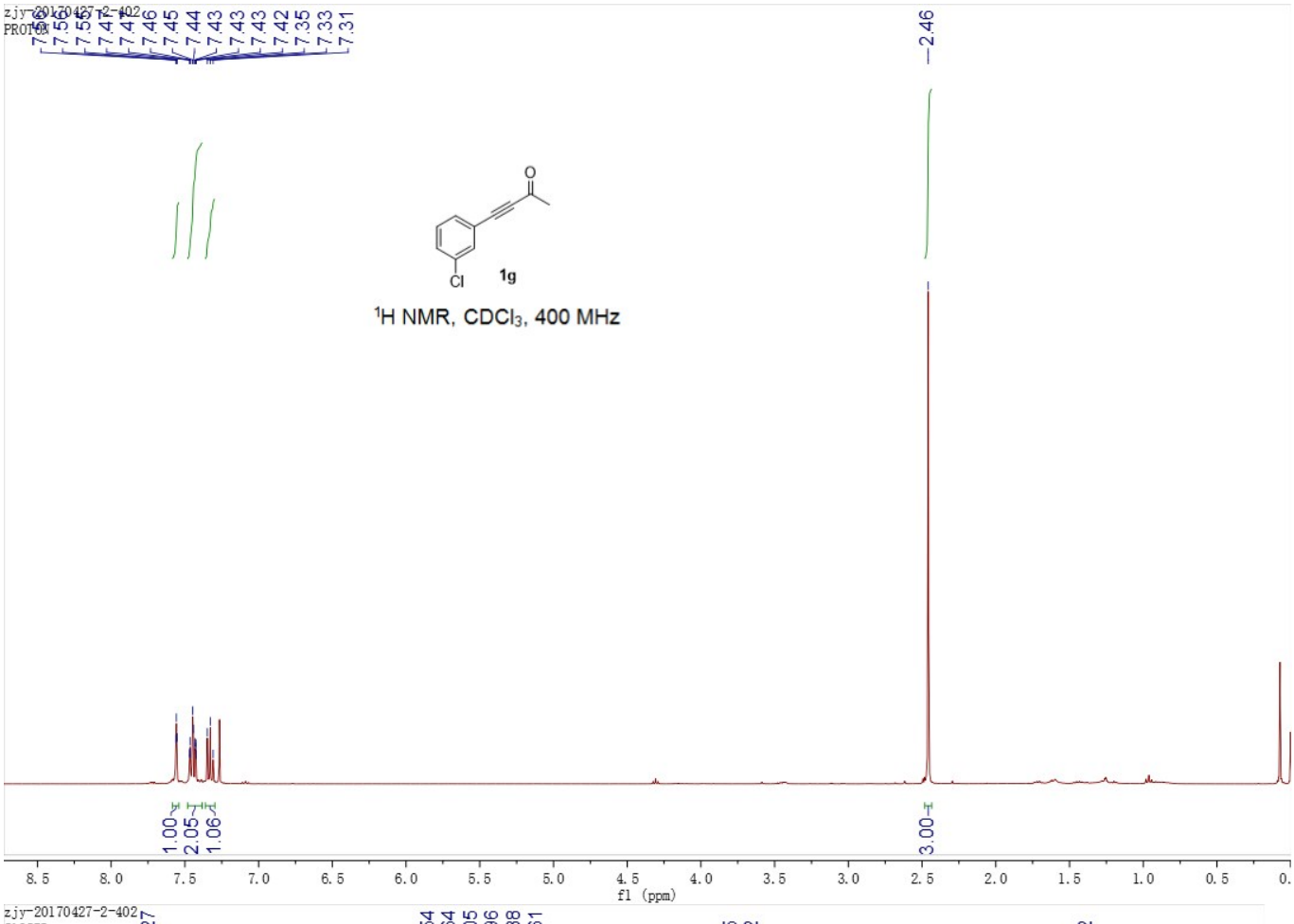
f1 (ppm)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Cl
1g
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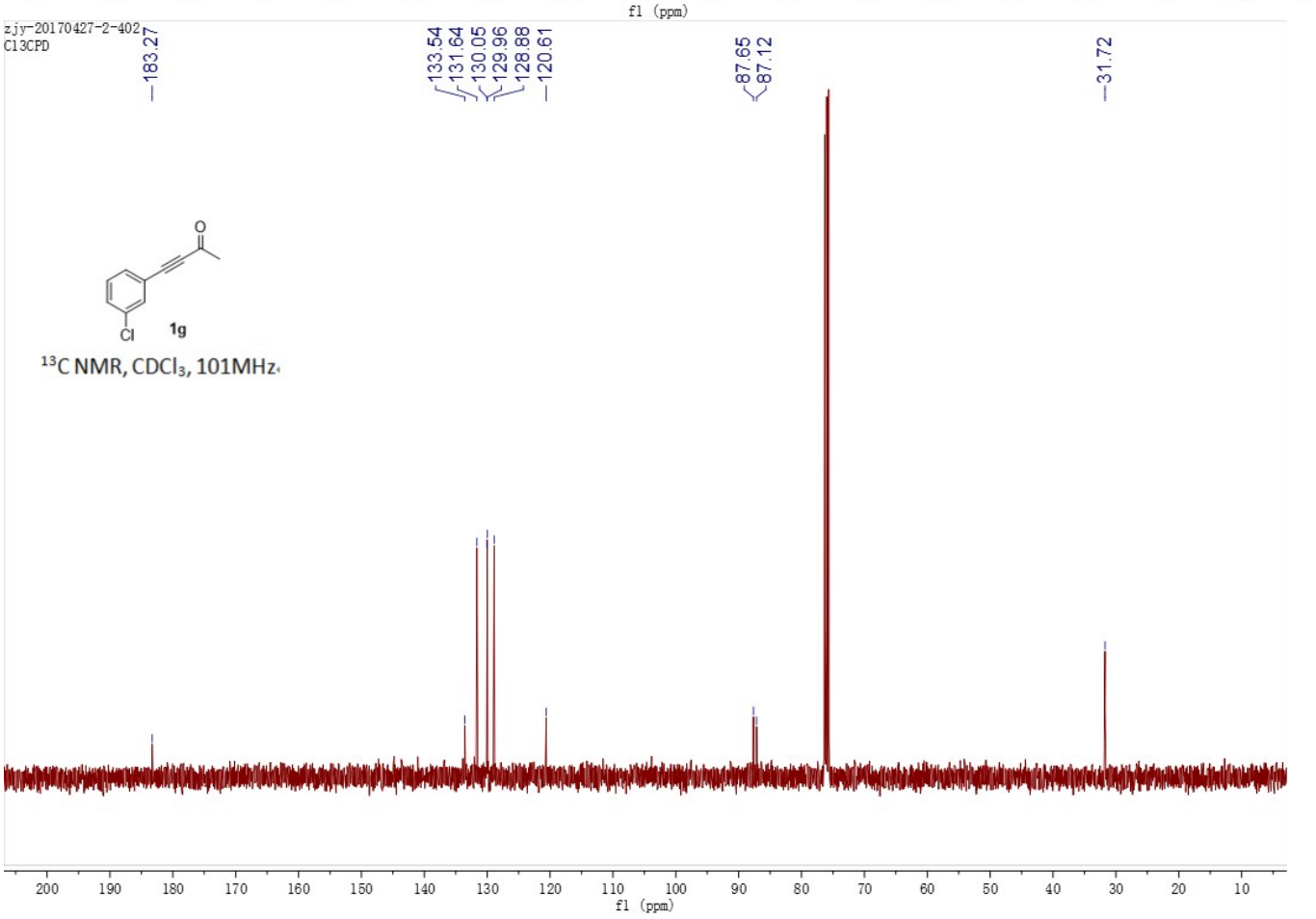
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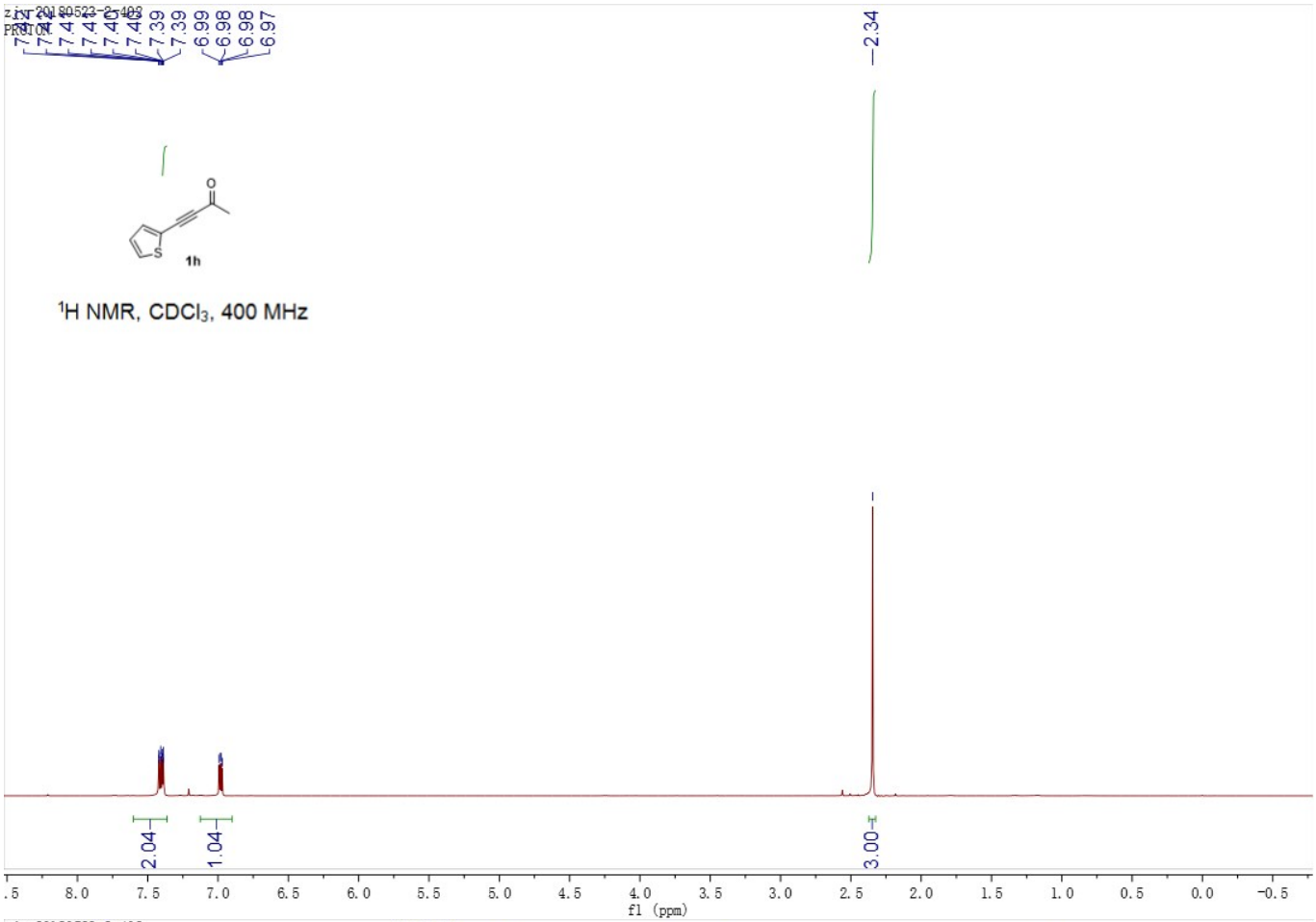
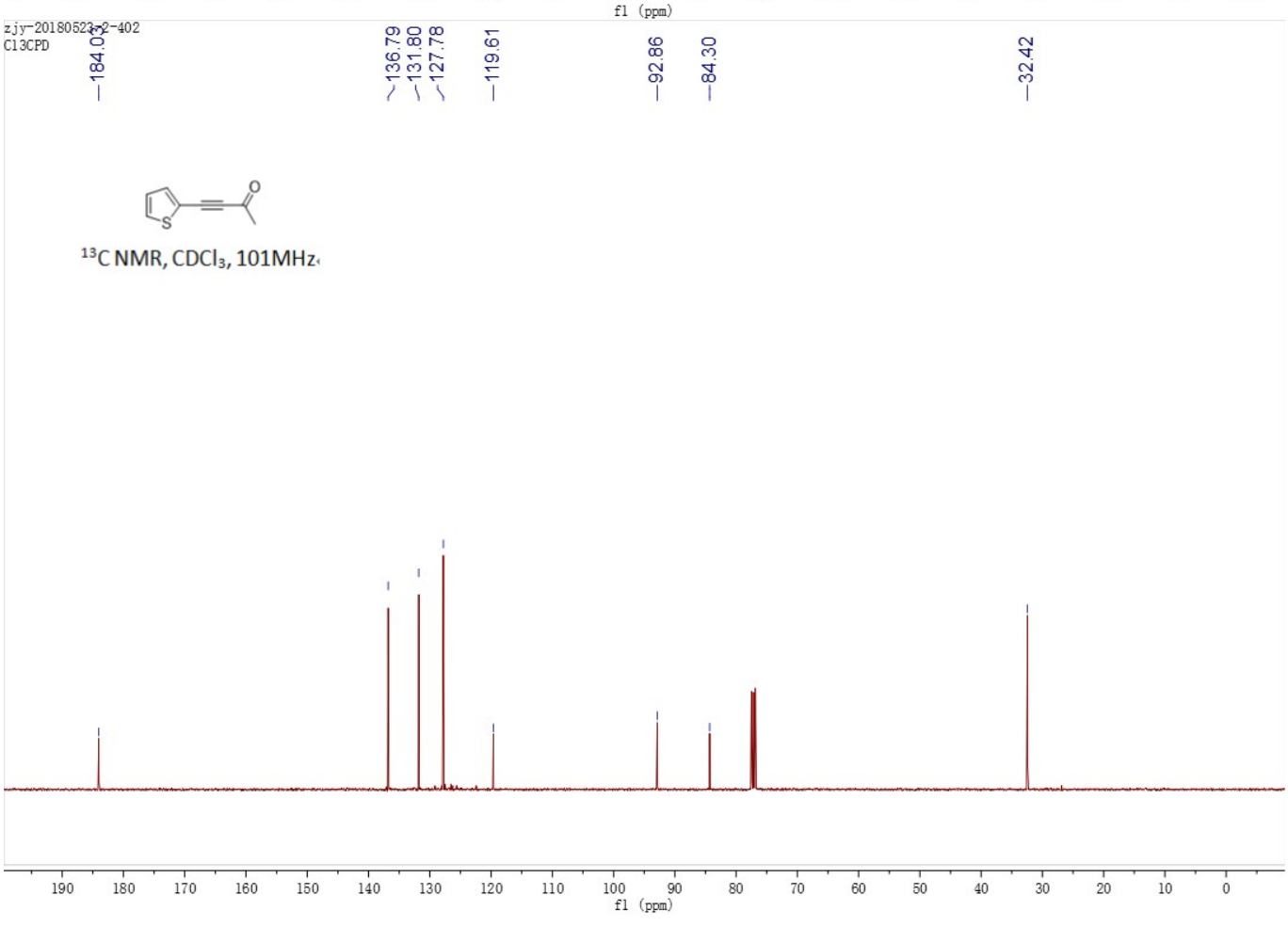
f1 (ppm)



^{1}H NMR, $CDCl_3$, 400 MHz



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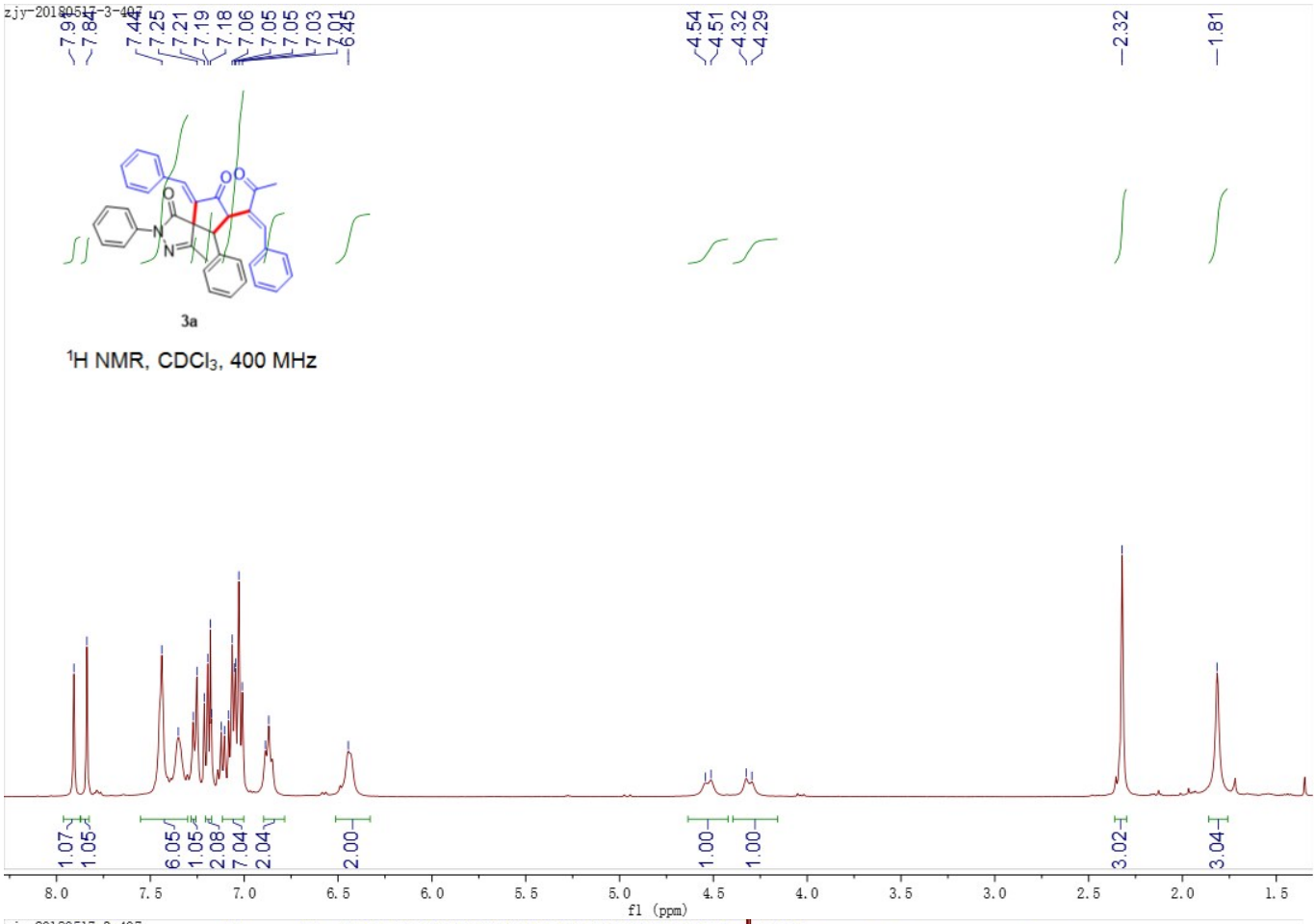

3a

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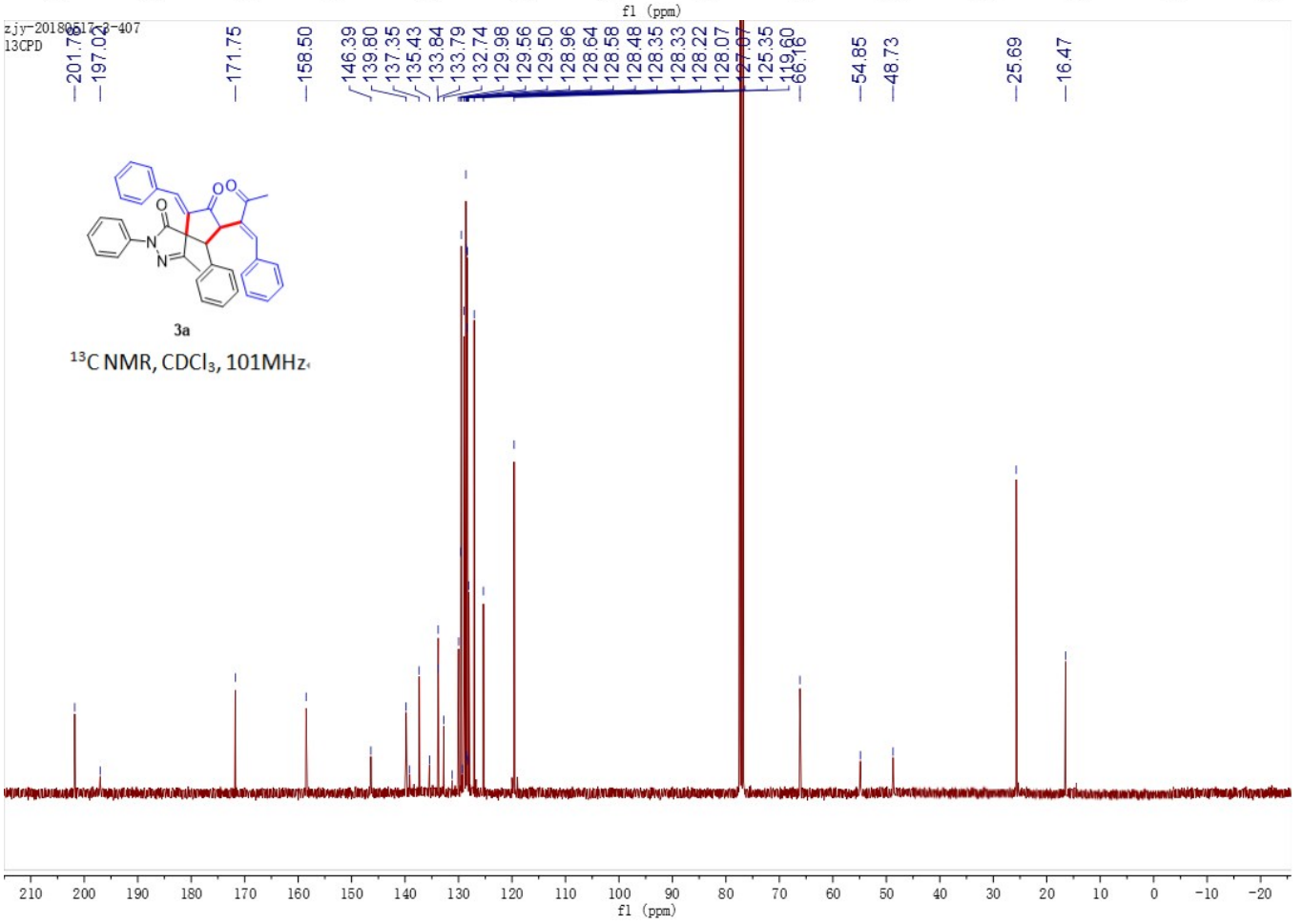

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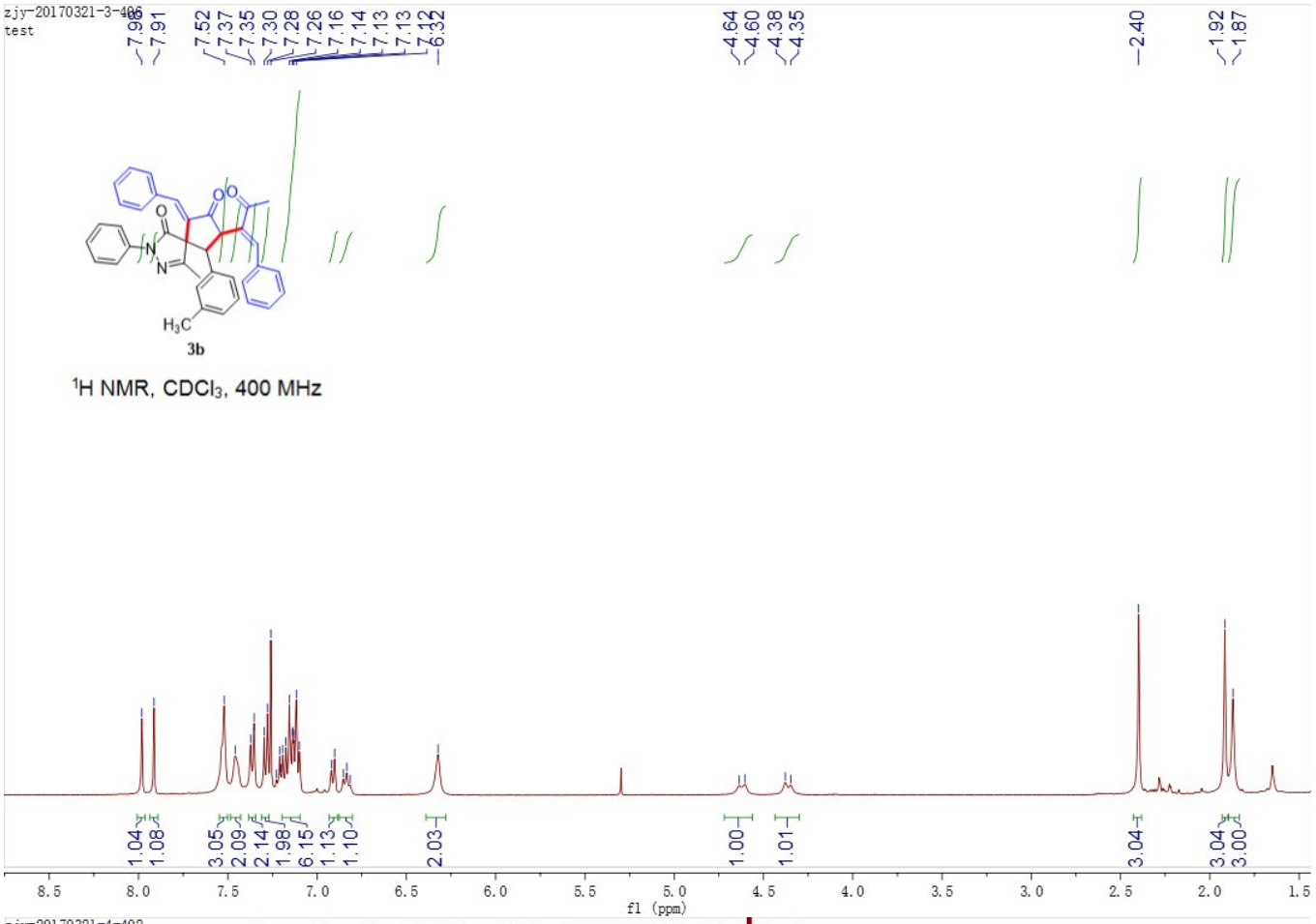

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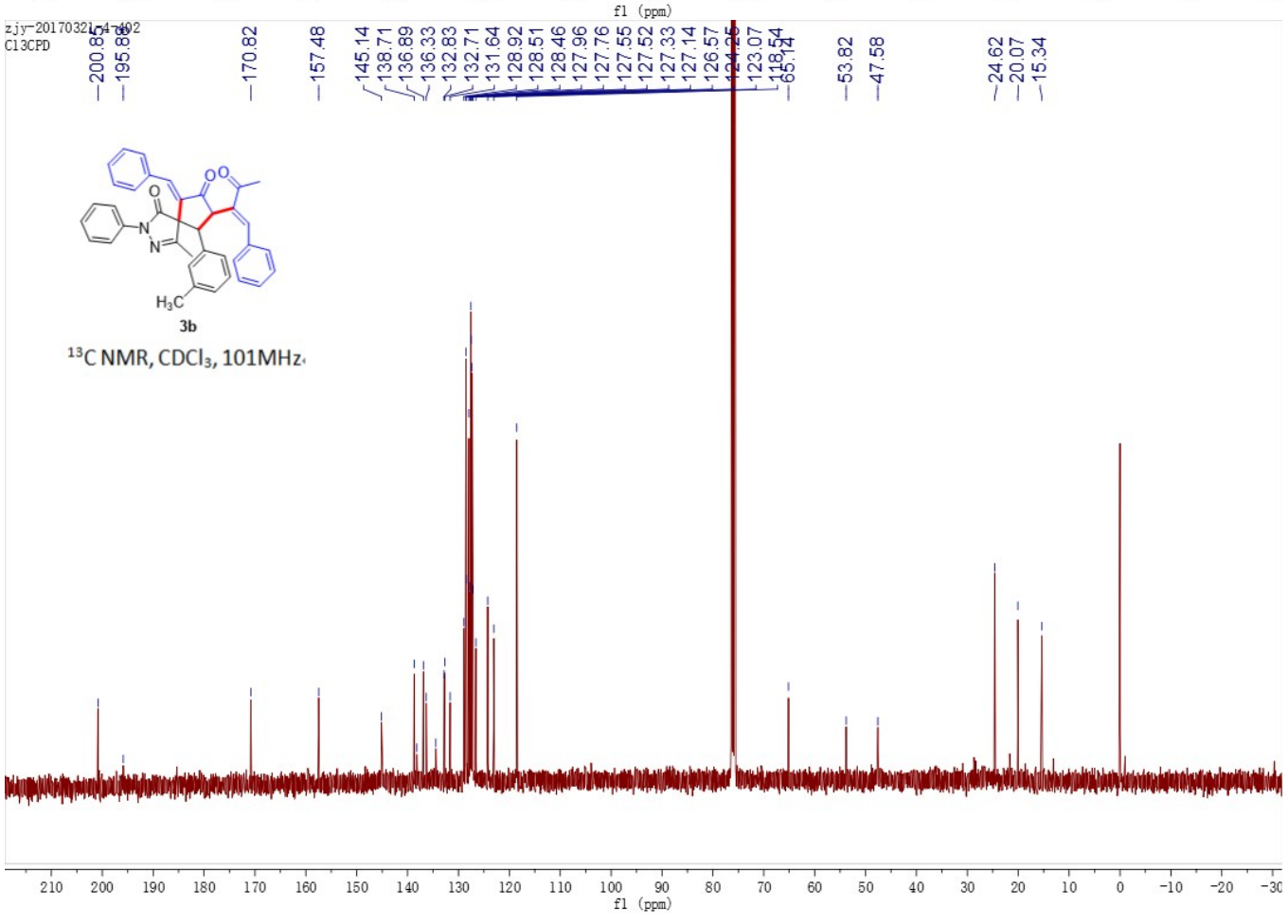

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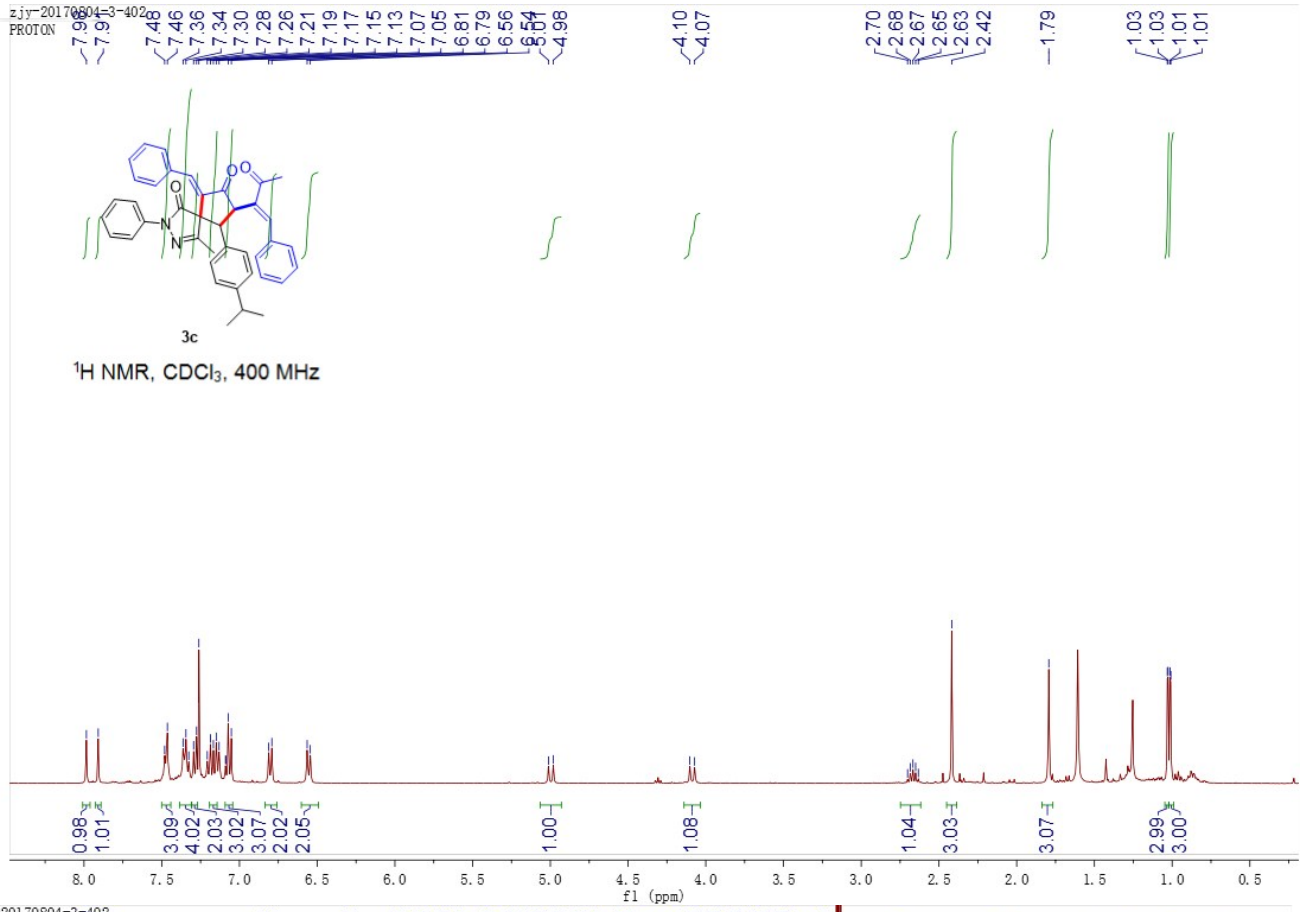

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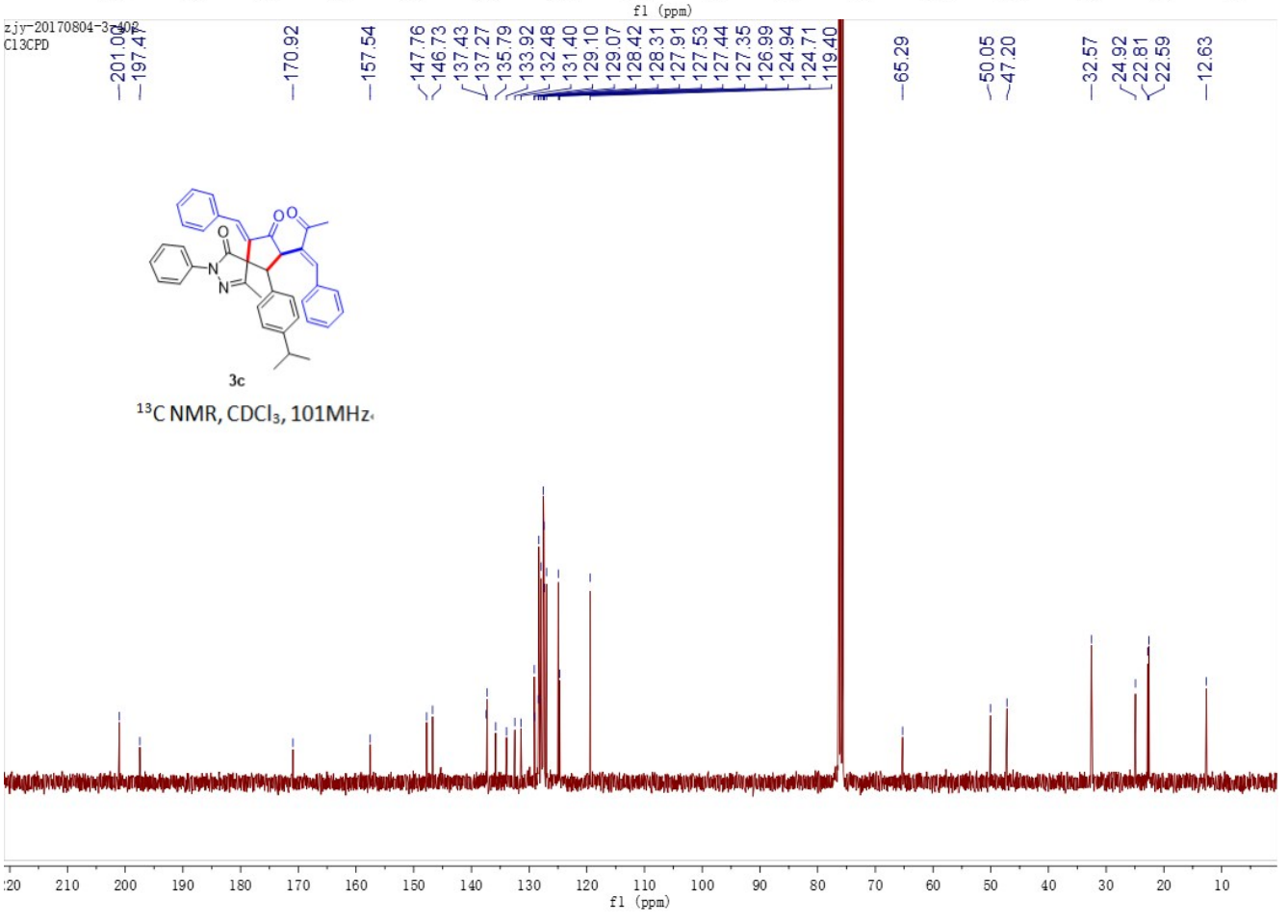

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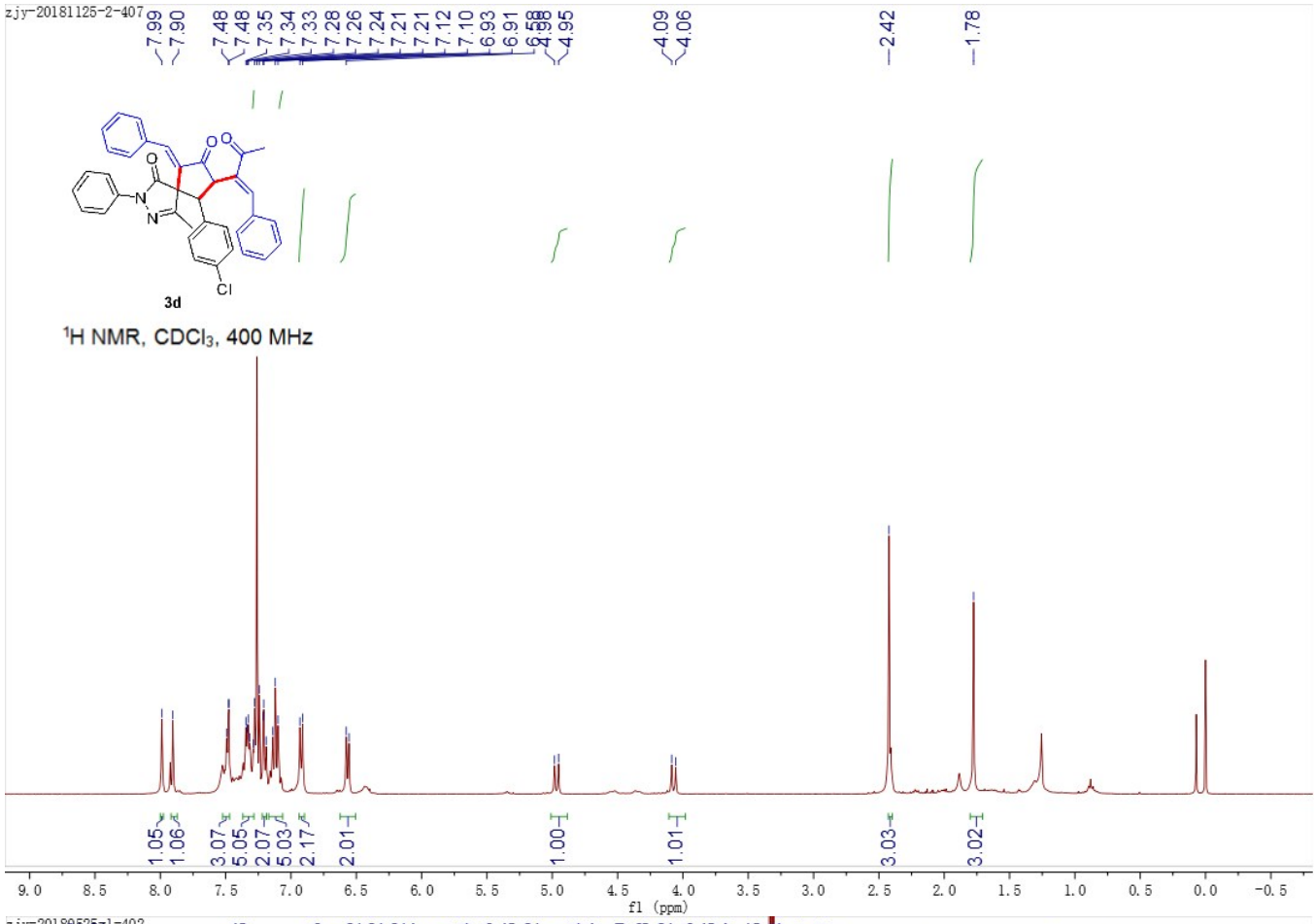
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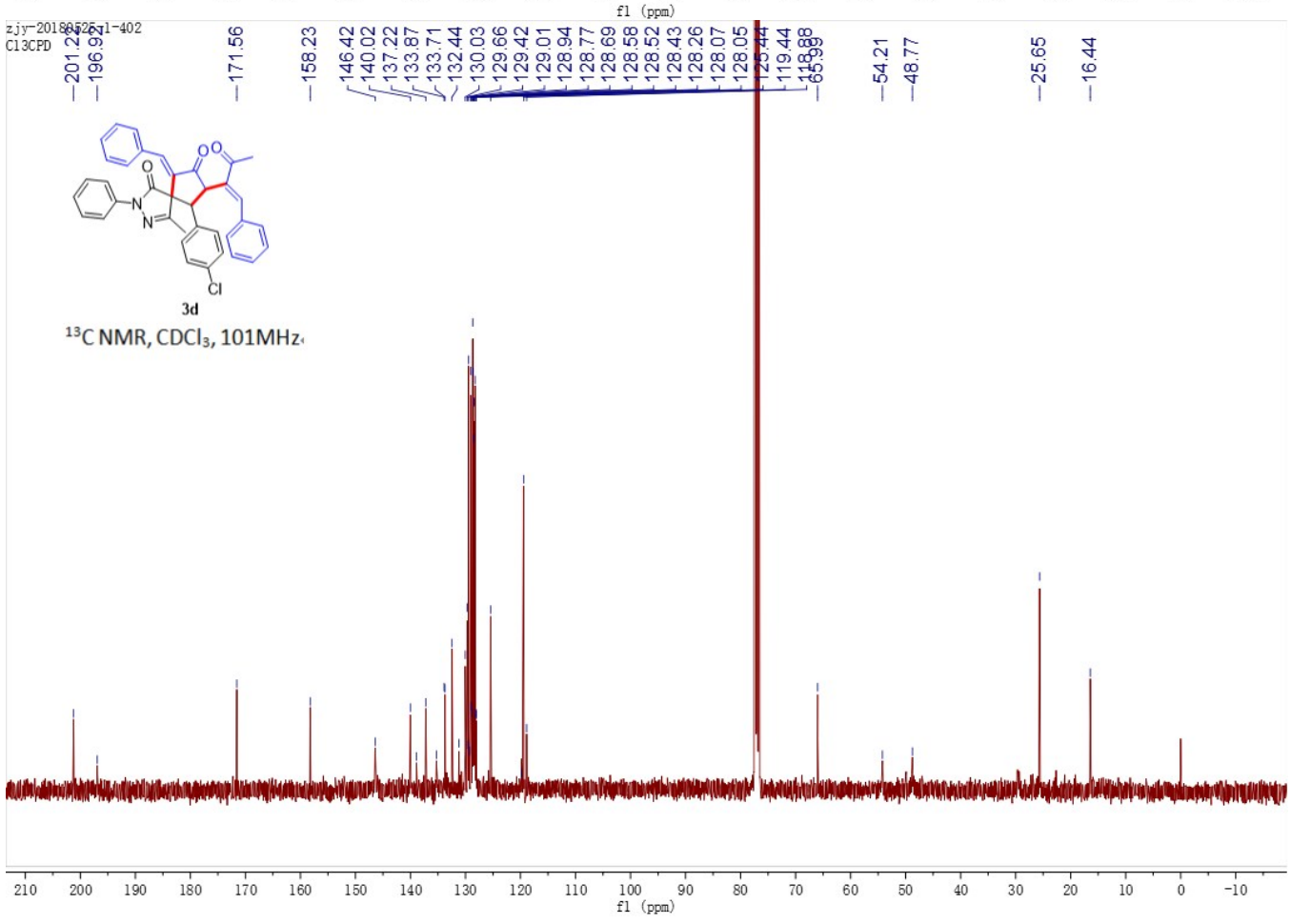
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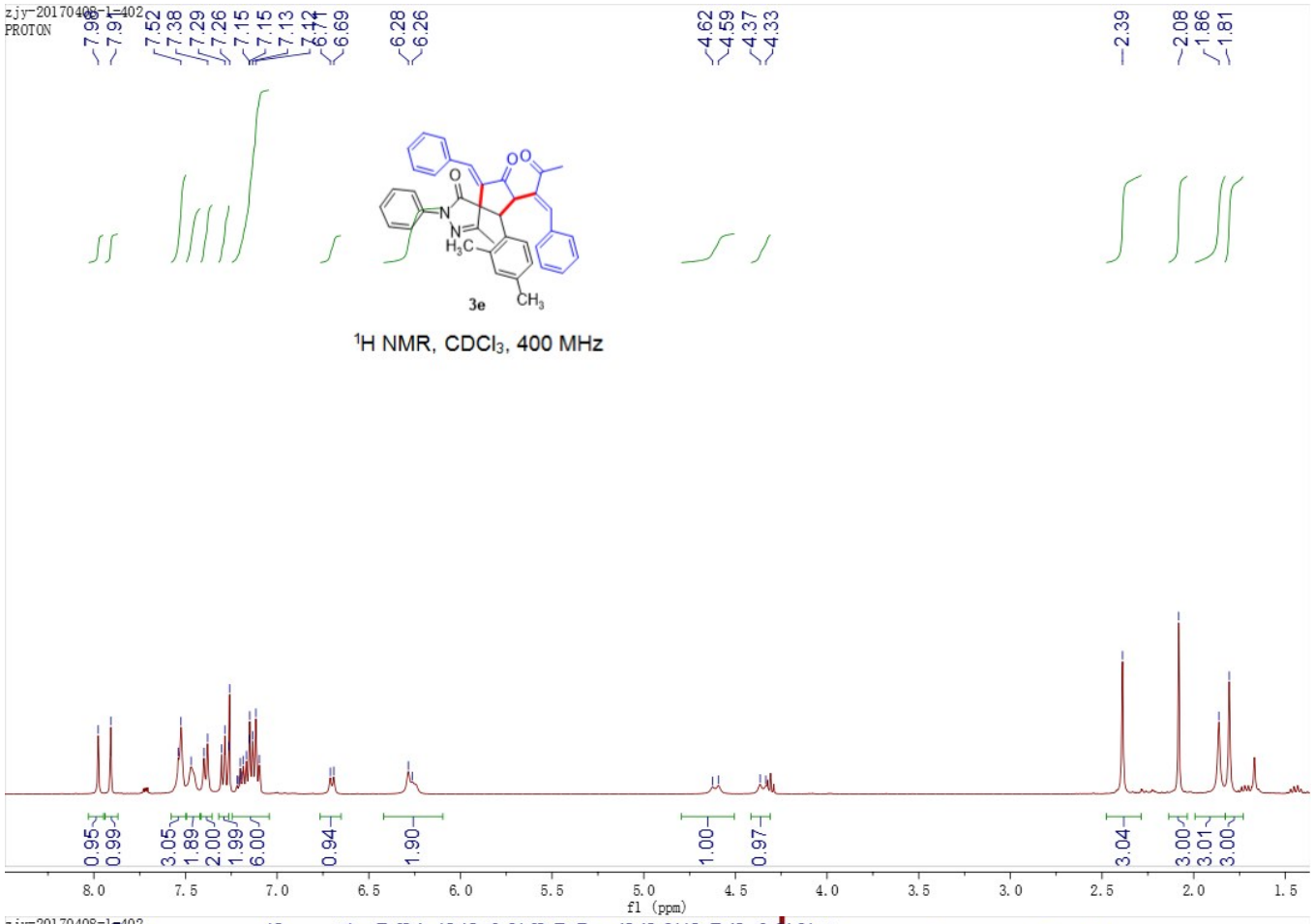
f1 (ppm)



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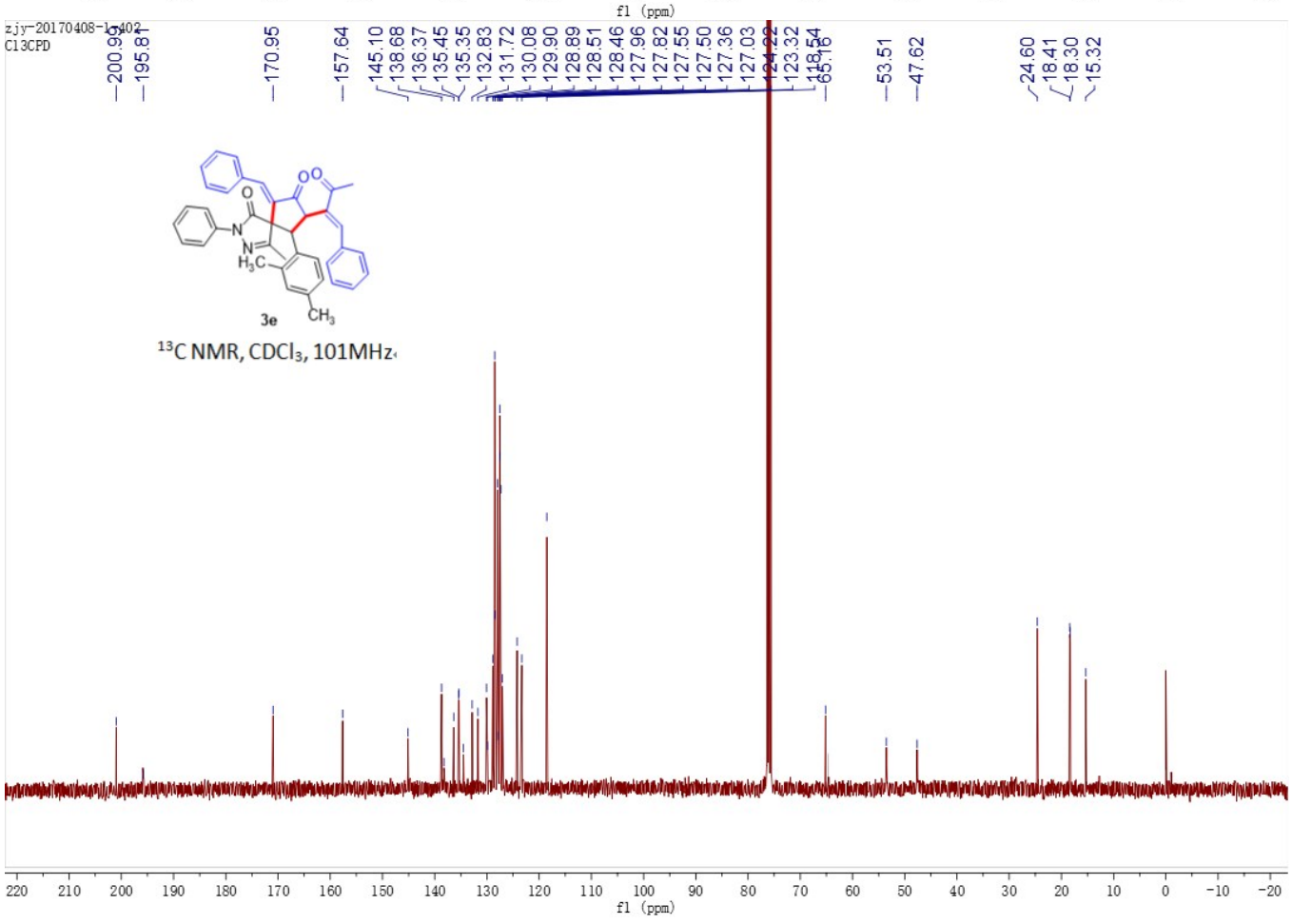

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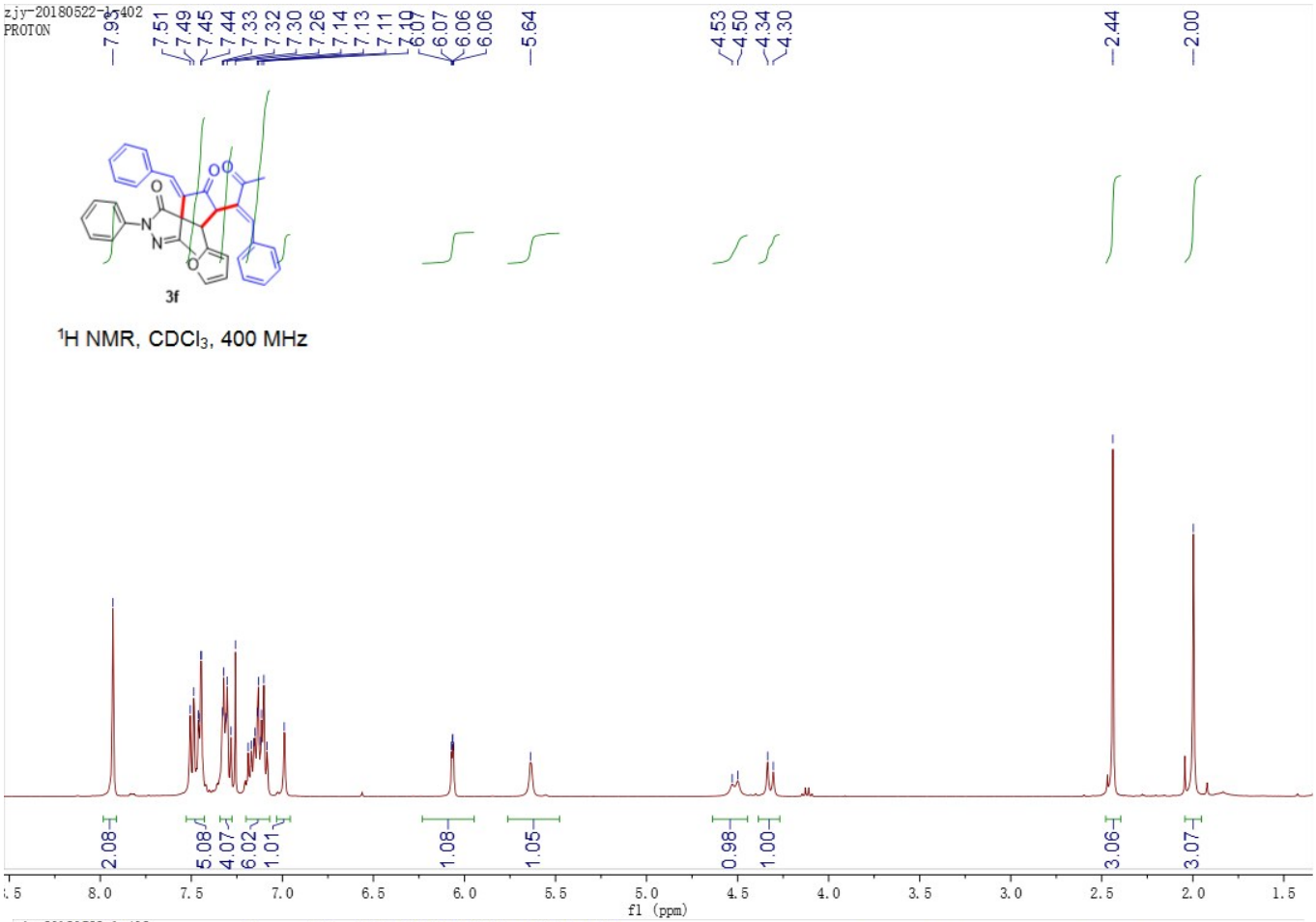

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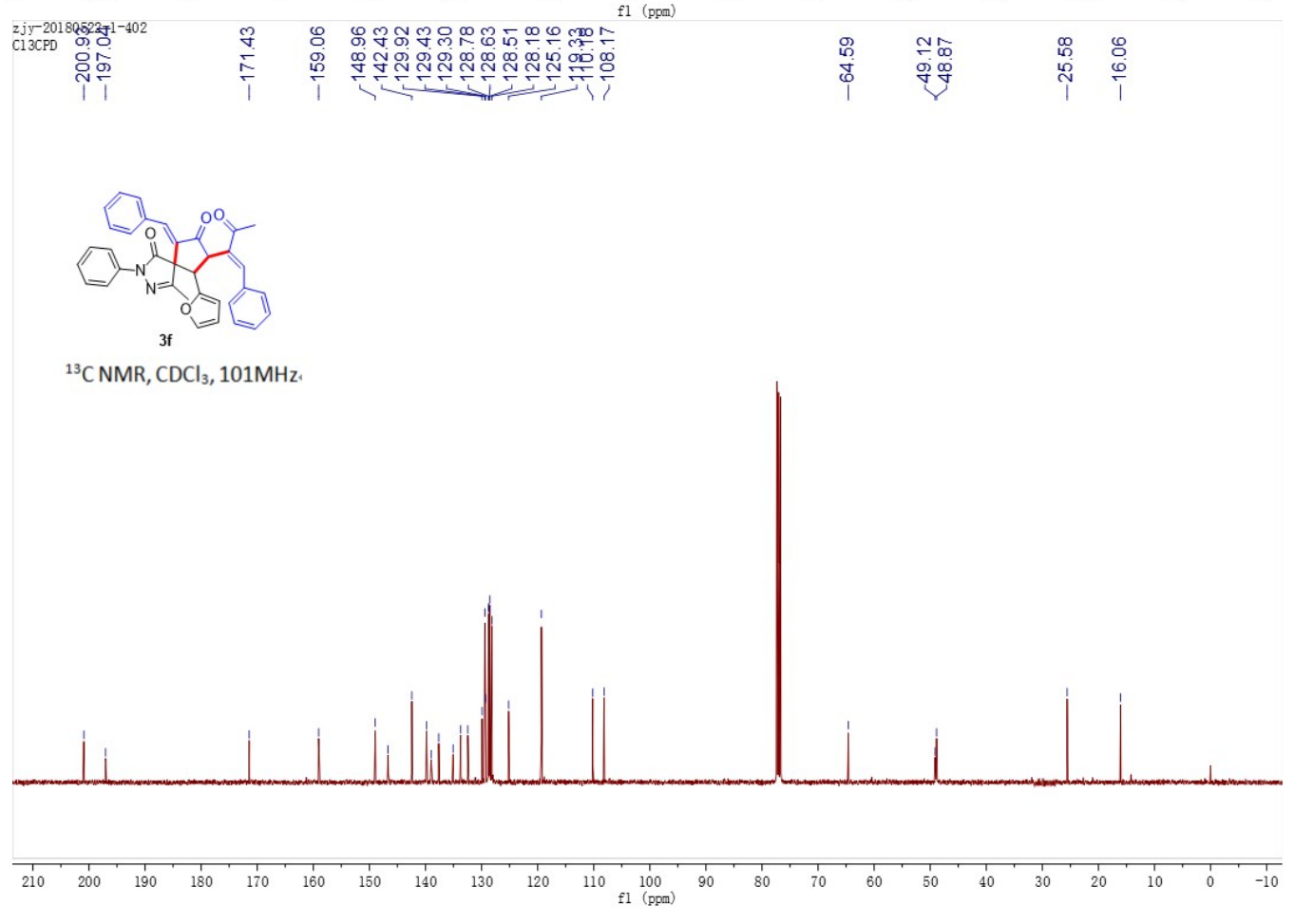

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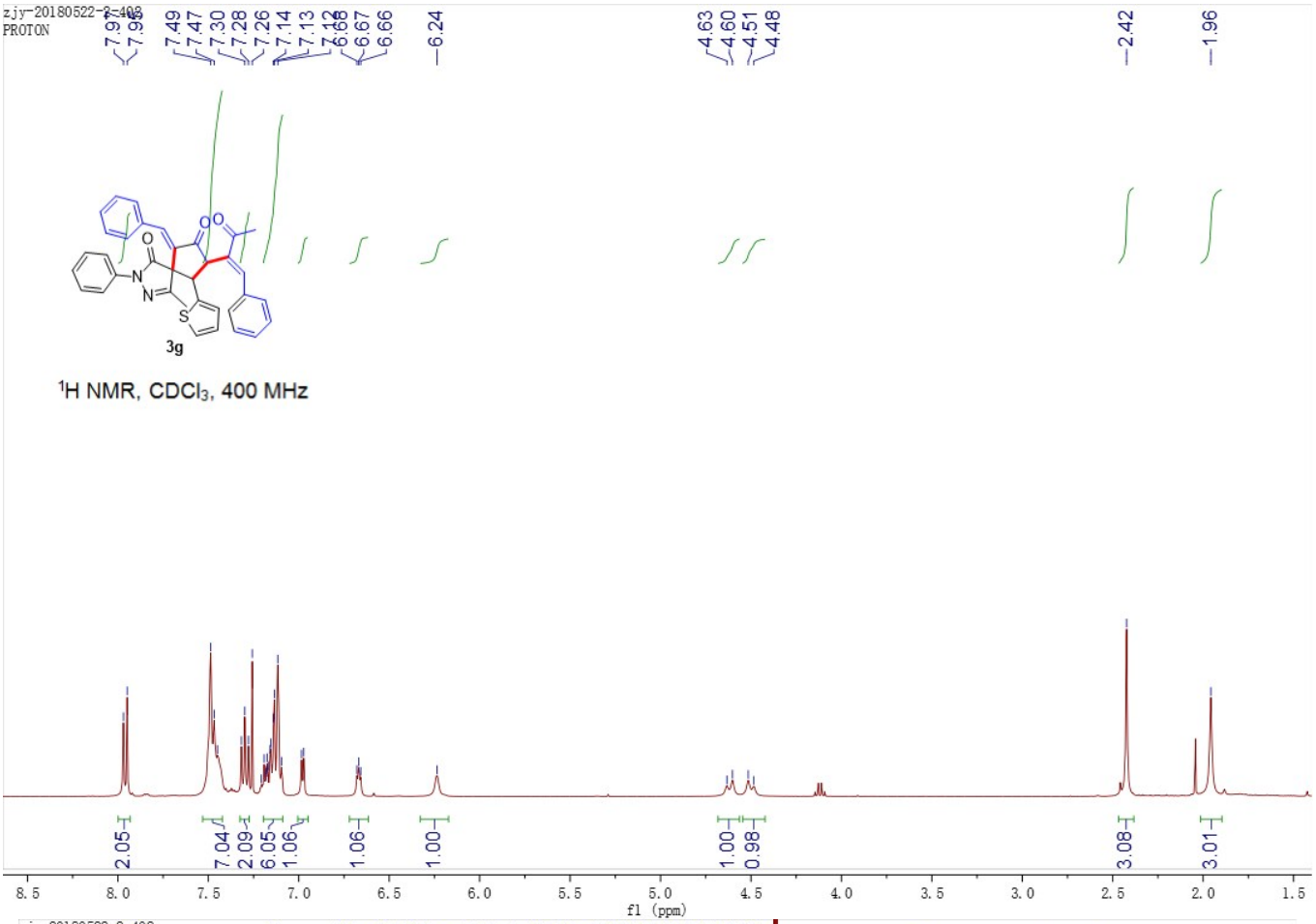

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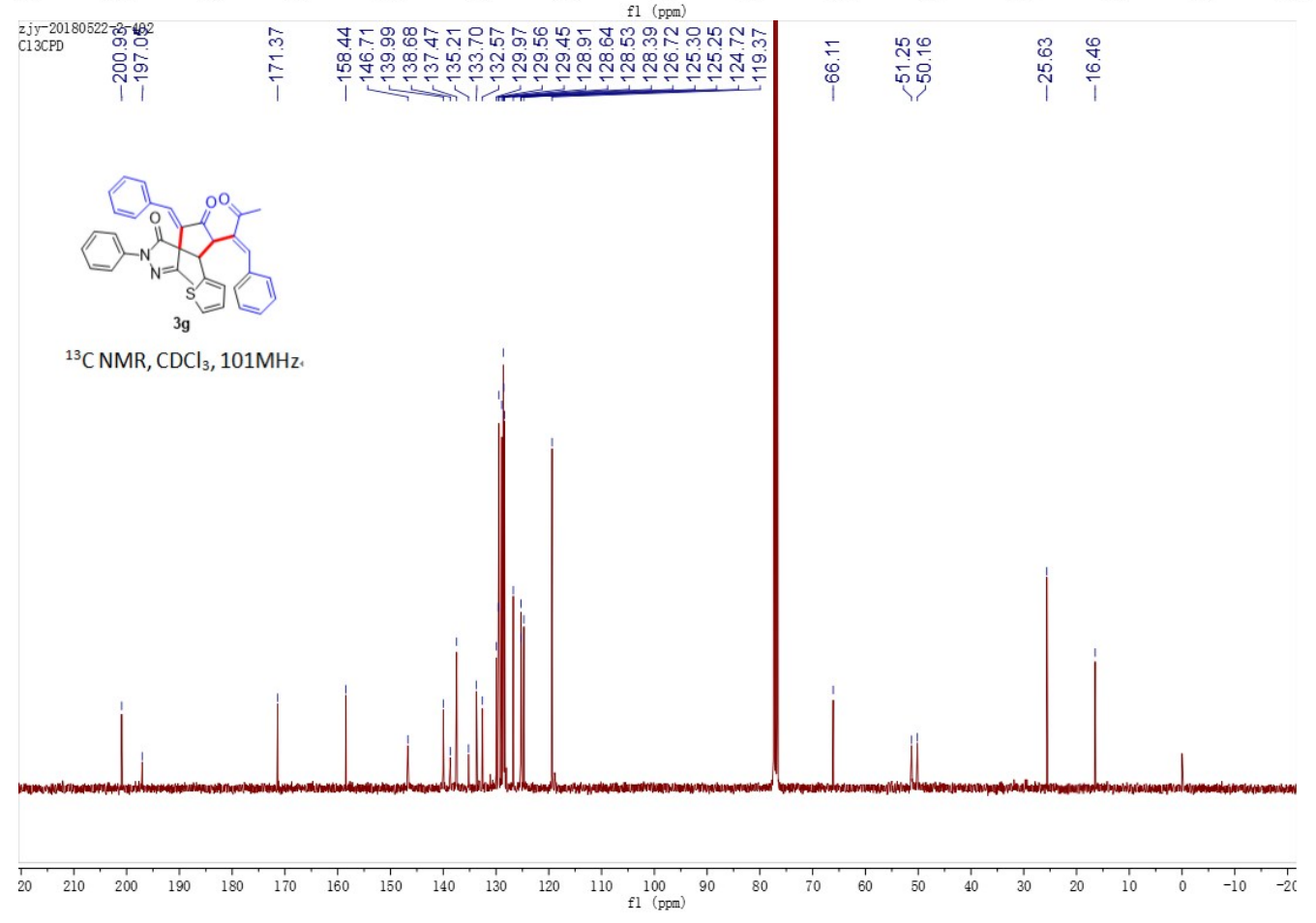

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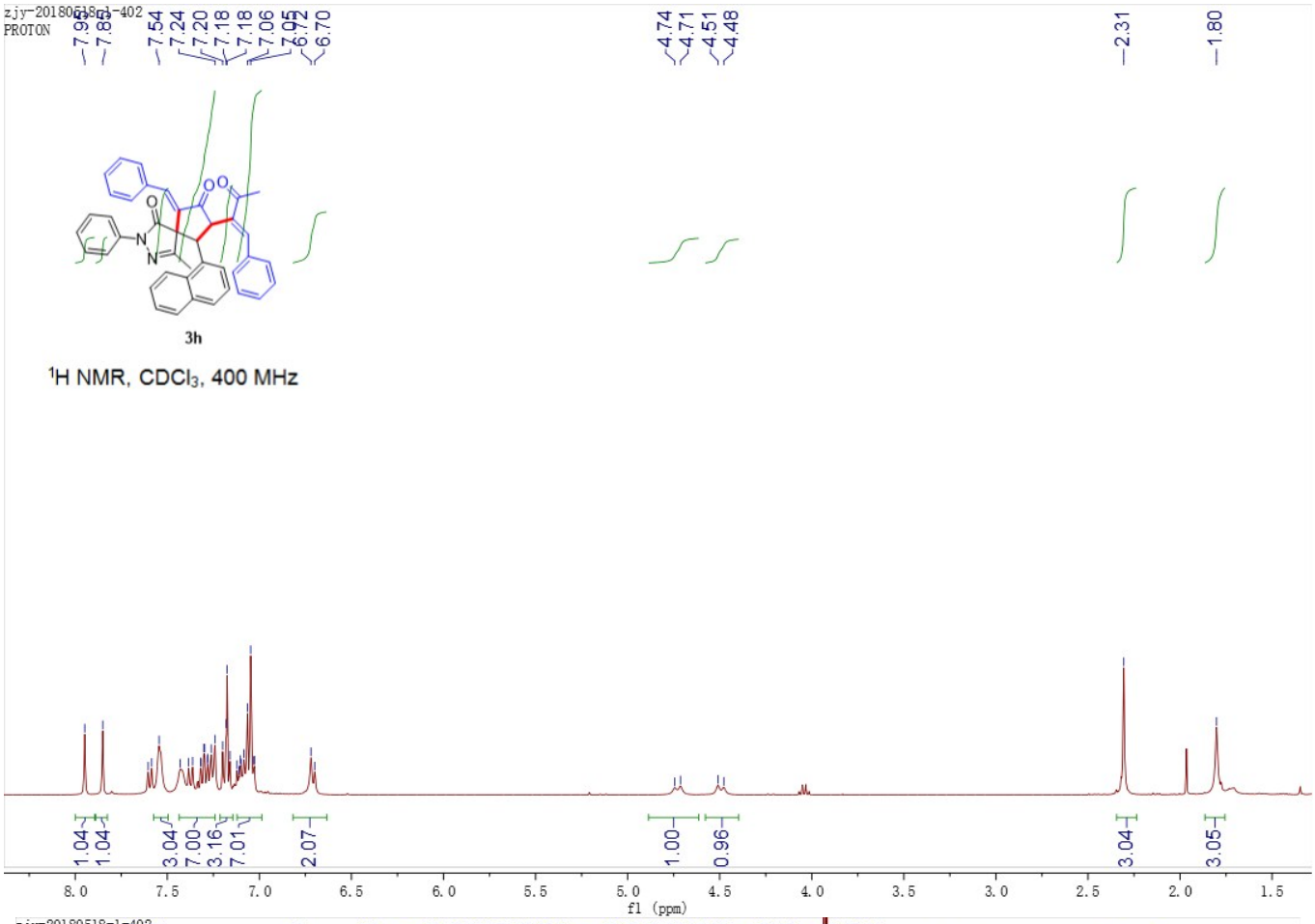

3h

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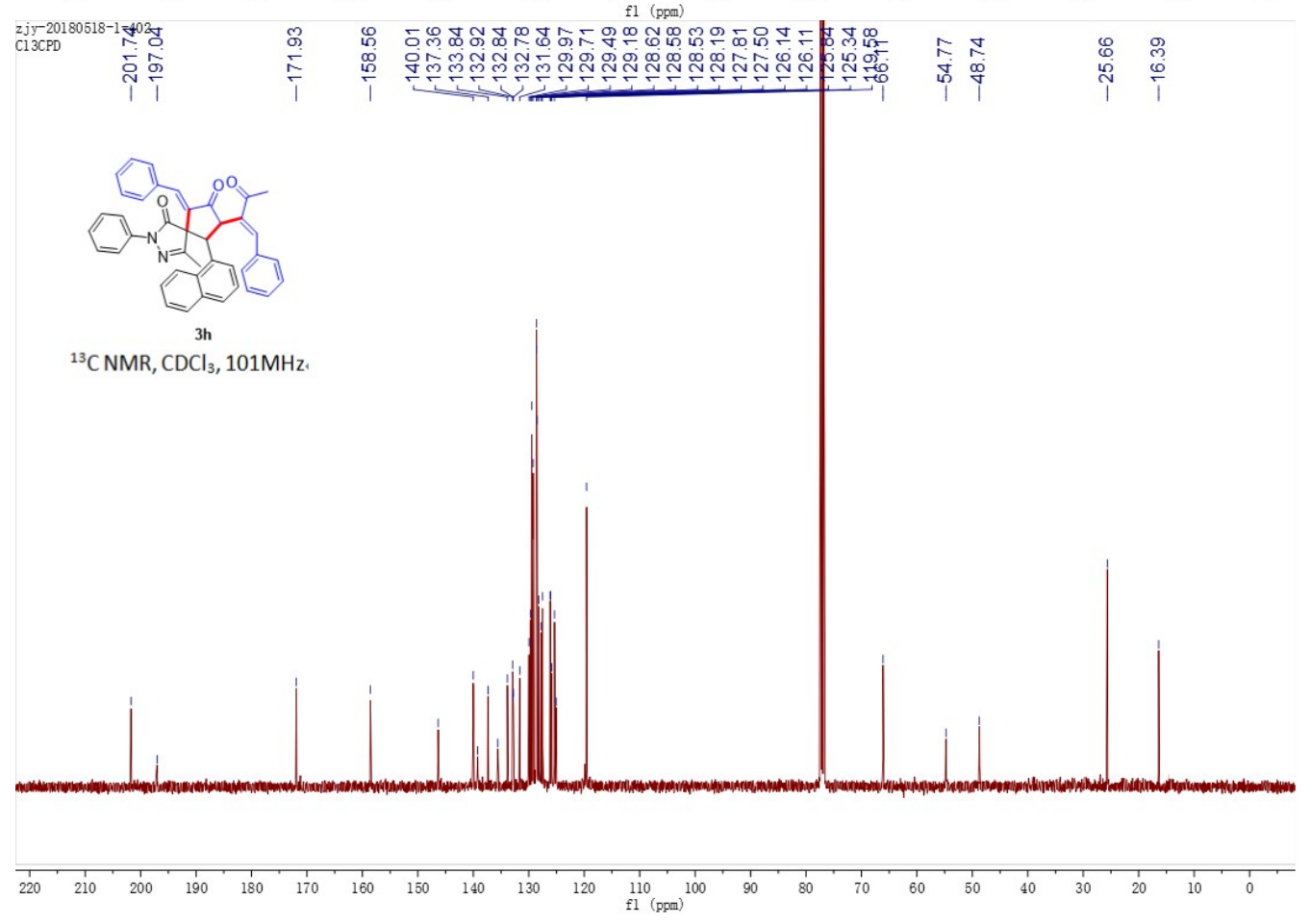

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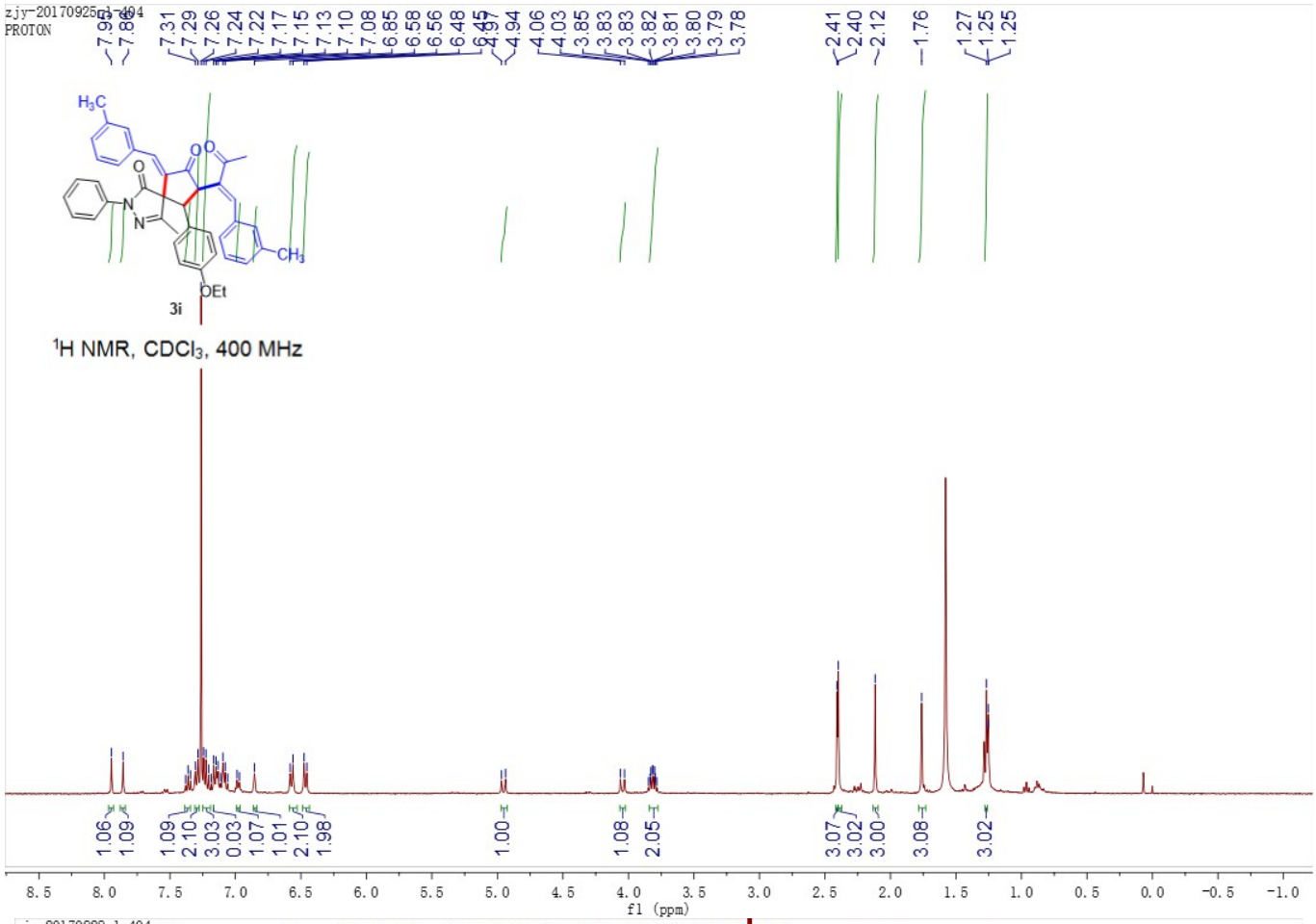
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3.82
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O
O
N
N
CH3
OEt
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3.02
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4.5
4.0
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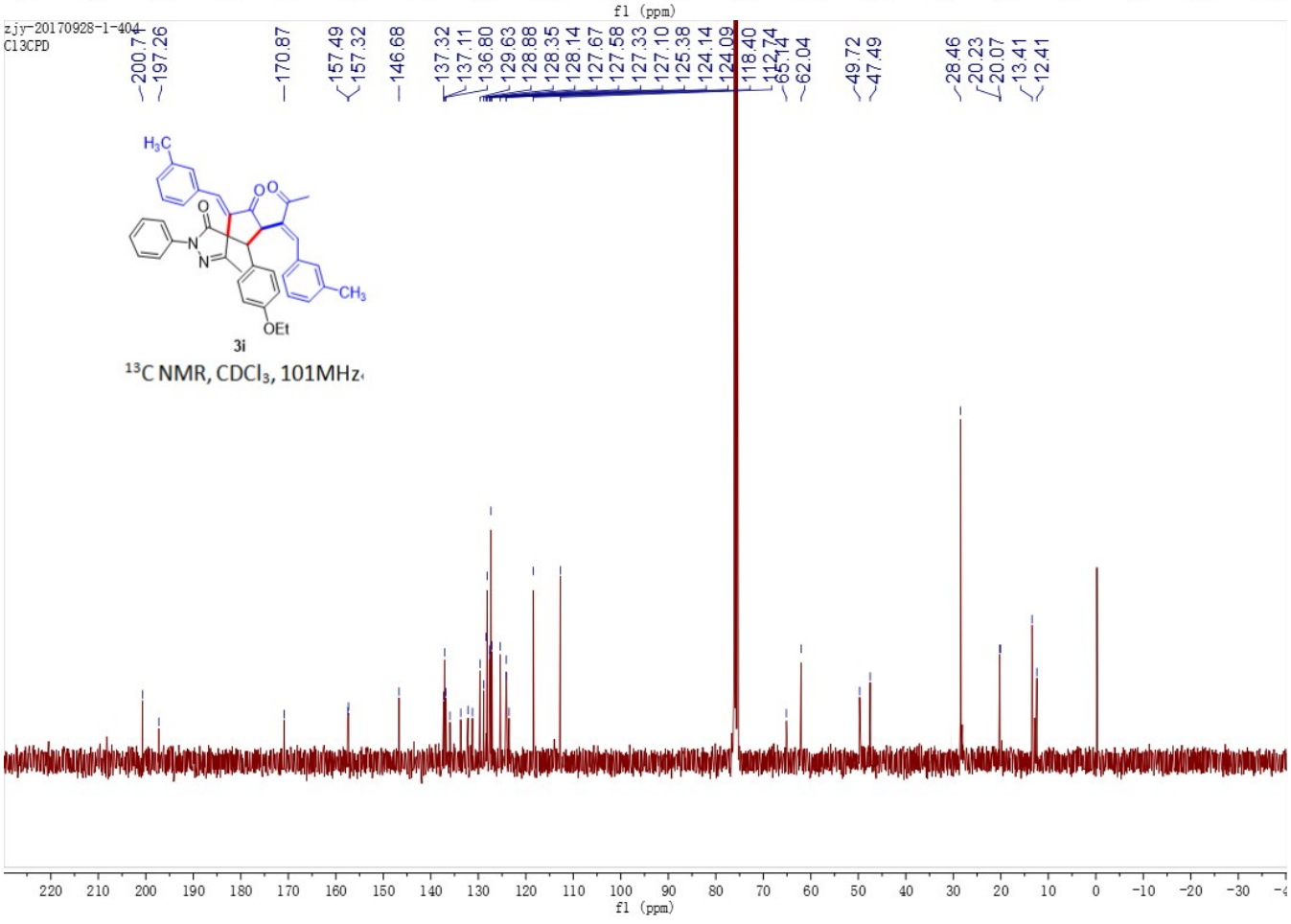
f1 (ppm)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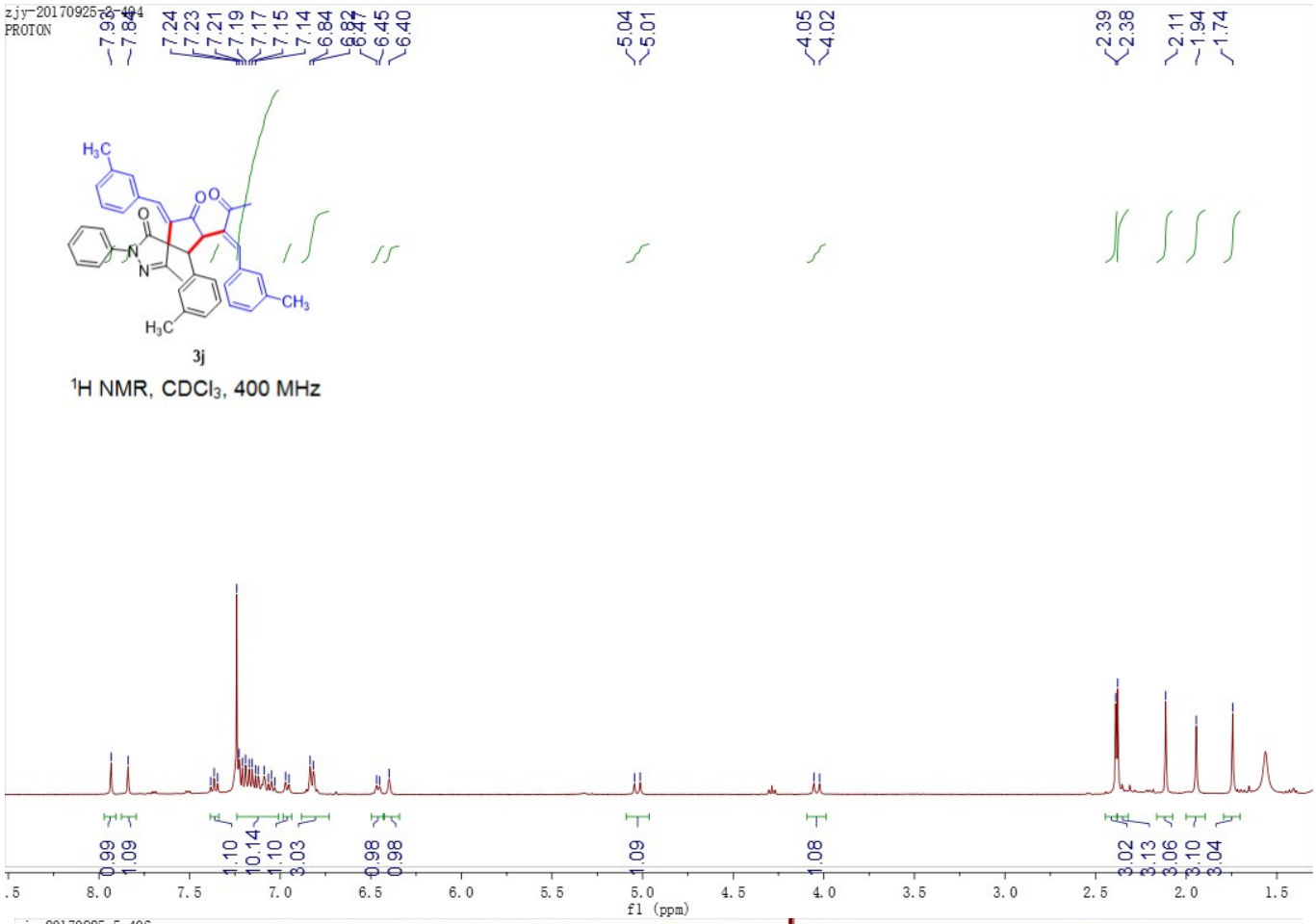
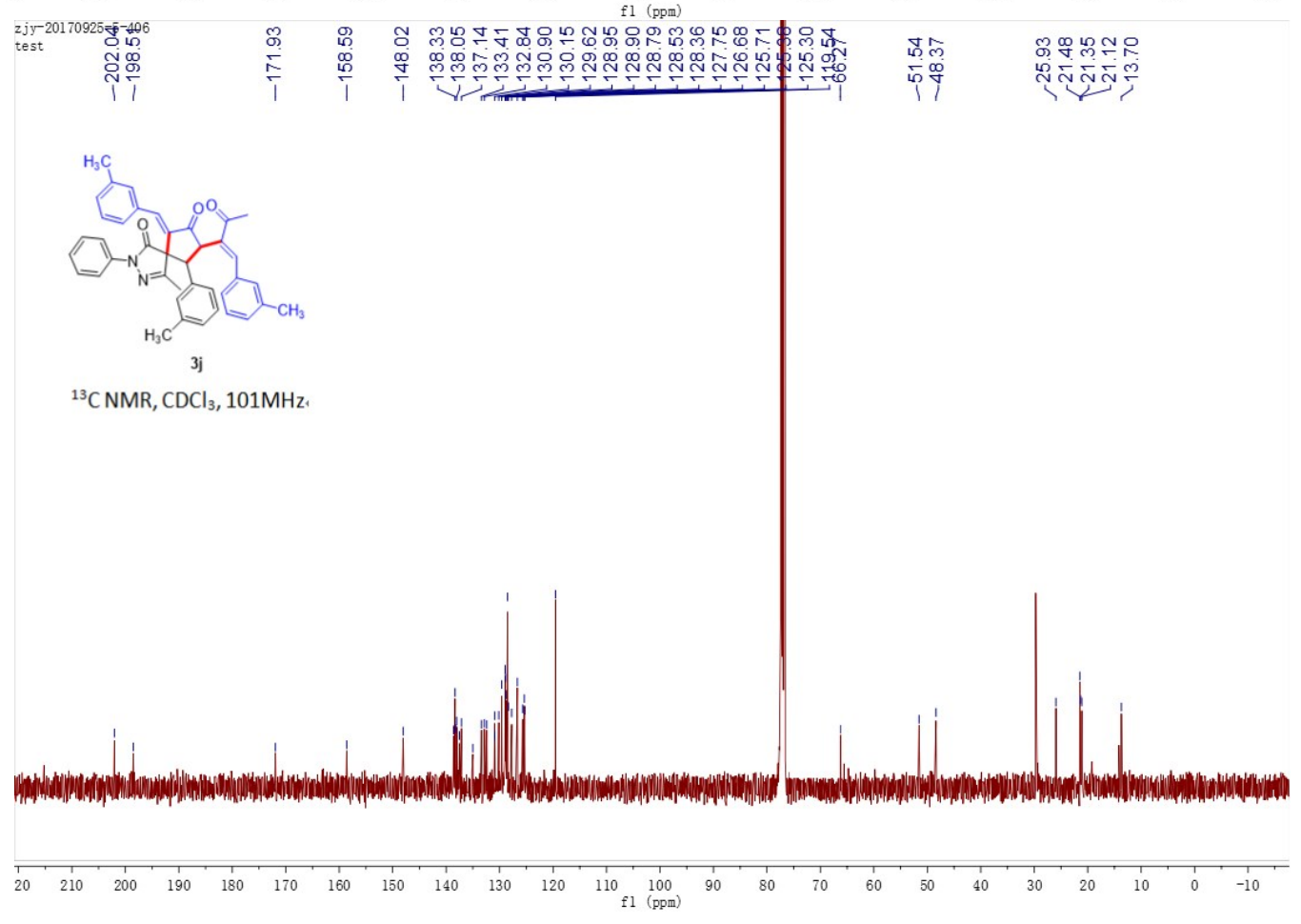
C13CPD
200.74
197.26
170.87
157.49
157.32
146.68
137.32
137.11
136.80
129.63
128.88
128.35
128.14
127.67
127.58
127.33
127.10
125.38
124.14
124.09
118.40
112.74
65.14
62.04
49.72
47.49
28.46
20.23
20.07
13.41
12.41
H3C
O
O
O
N
N
CH3
OEt
3i
13C NMR, CDCl3, 101MHz
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
f1 (ppm)



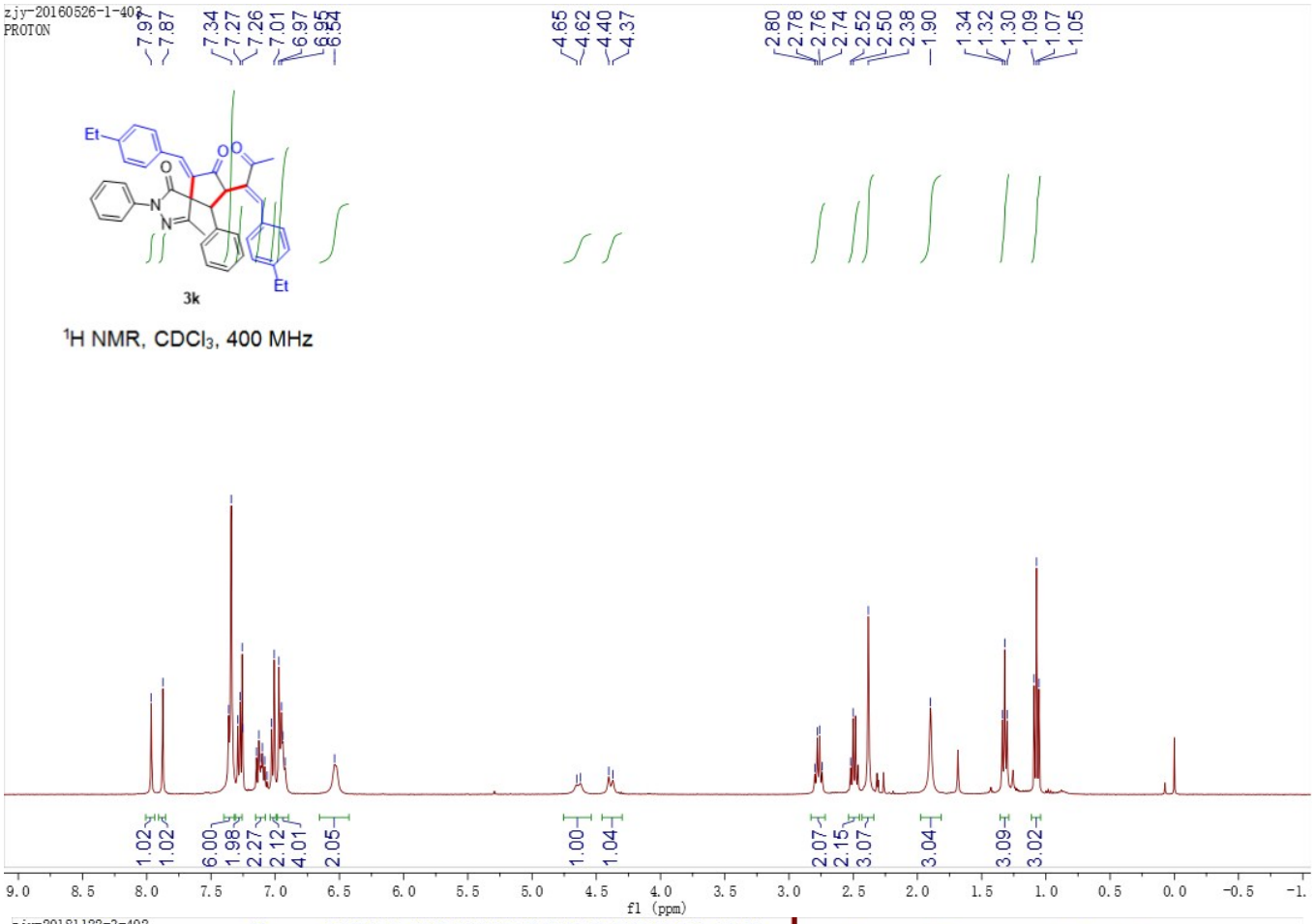
3j

^{1}H NMR, $CDCl_3$, 400 MHz



3j

^{13}C NMR, $CDCl_3$, 101MHz


zjy-20160526-1-402
PROTON
7.97
7.87
7.34
7.27
7.26
7.01
6.97
6.95
6.54
4.65
4.62
4.40
4.37
2.80
2.78
2.76
2.74
2.52
2.50
2.38
1.90
1.34
1.32
1.30
1.09
1.07
1.05
Et
O
O
N
N
Et
3k
1H NMR, CDCl3, 400 MHz
1.02
1.02
6.00
1.98
2.27
2.12
4.01
2.05
1.00
1.04
2.07
2.15
3.07
3.04
3.09
3.02
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
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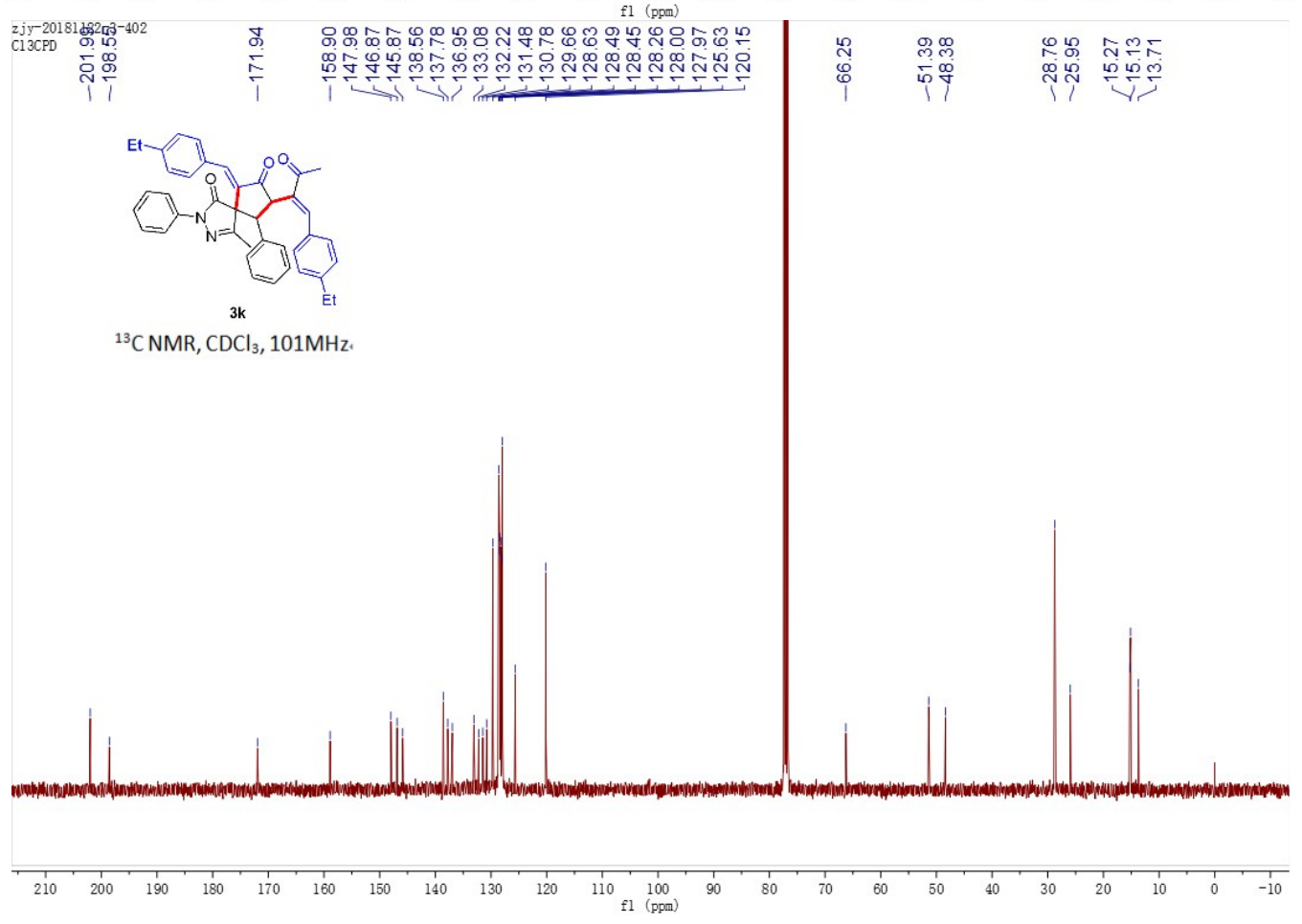
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.
f1 (ppm)


zjy-20181102-3-402
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133.08
132.22
131.48
130.78
129.66
128.63
128.49
128.45
128.26
128.00
127.97
125.63
120.15
66.25
51.39
48.38
28.76
25.95
15.27
15.13
13.71
Et
O
O
N
N
Et
3k
13C NMR, CDCl3, 101MHz
210
200
190
180
170
160
150
140
130
120
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70
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30
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10
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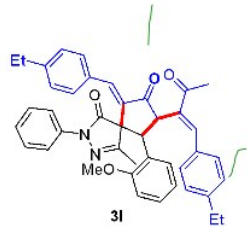
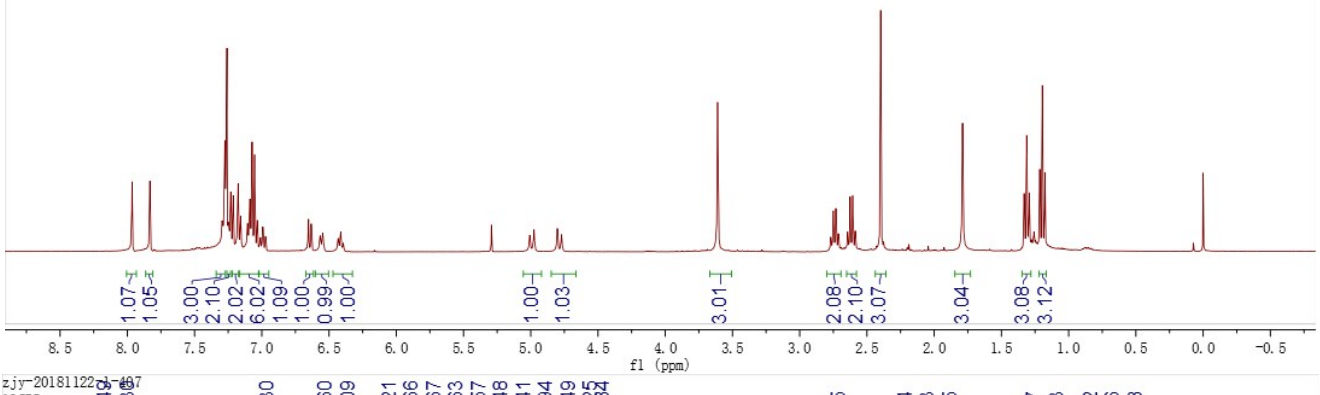
f1 (ppm)

zjy-20181122-1-407

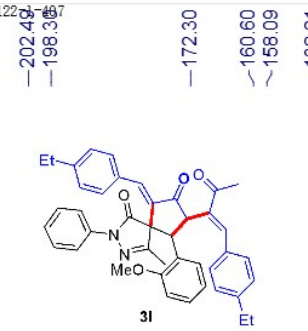


3l

^{1}H NMR, $CDCl_3$, 400 MHz

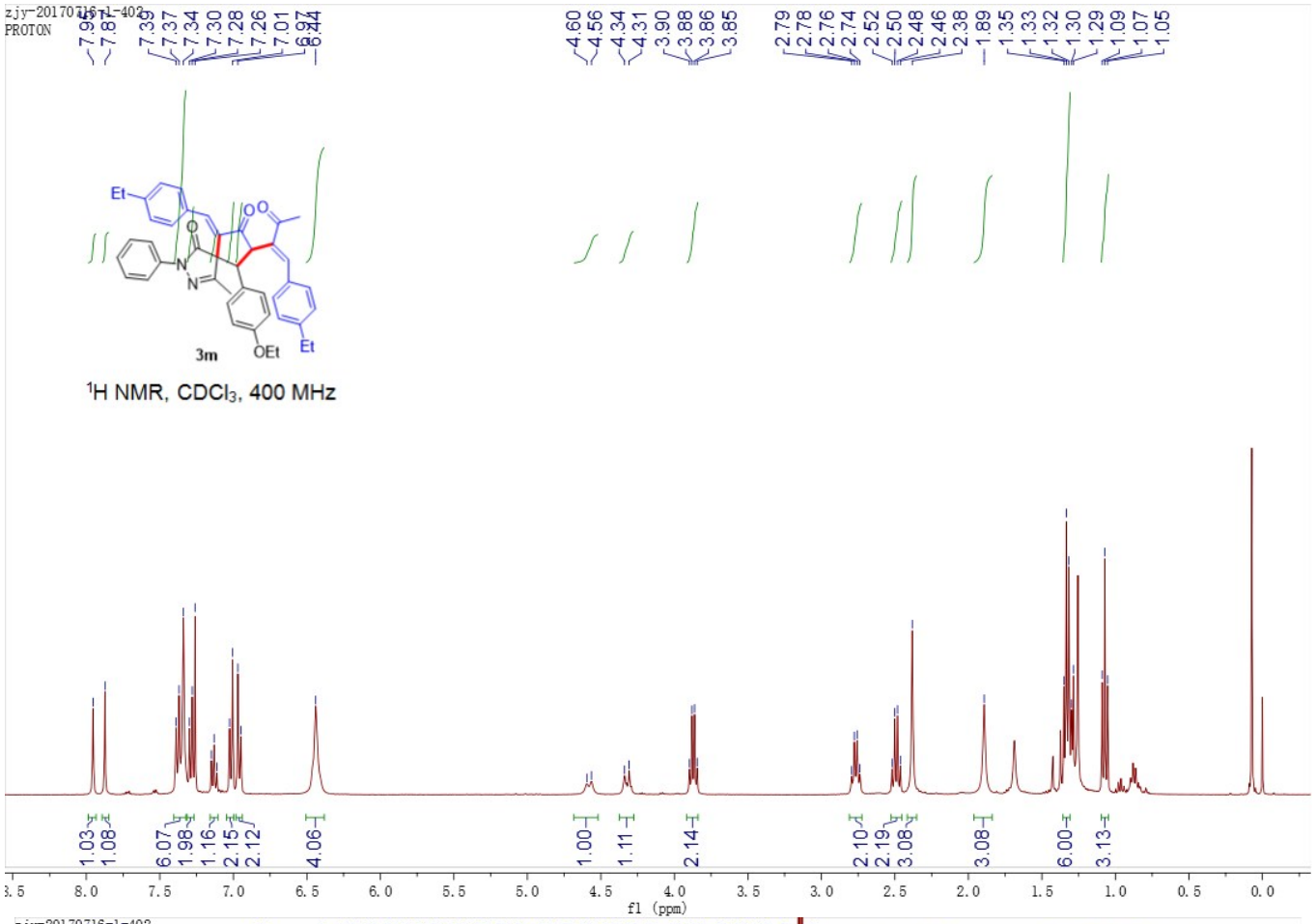


zjy-20181122-1-407
13CPD

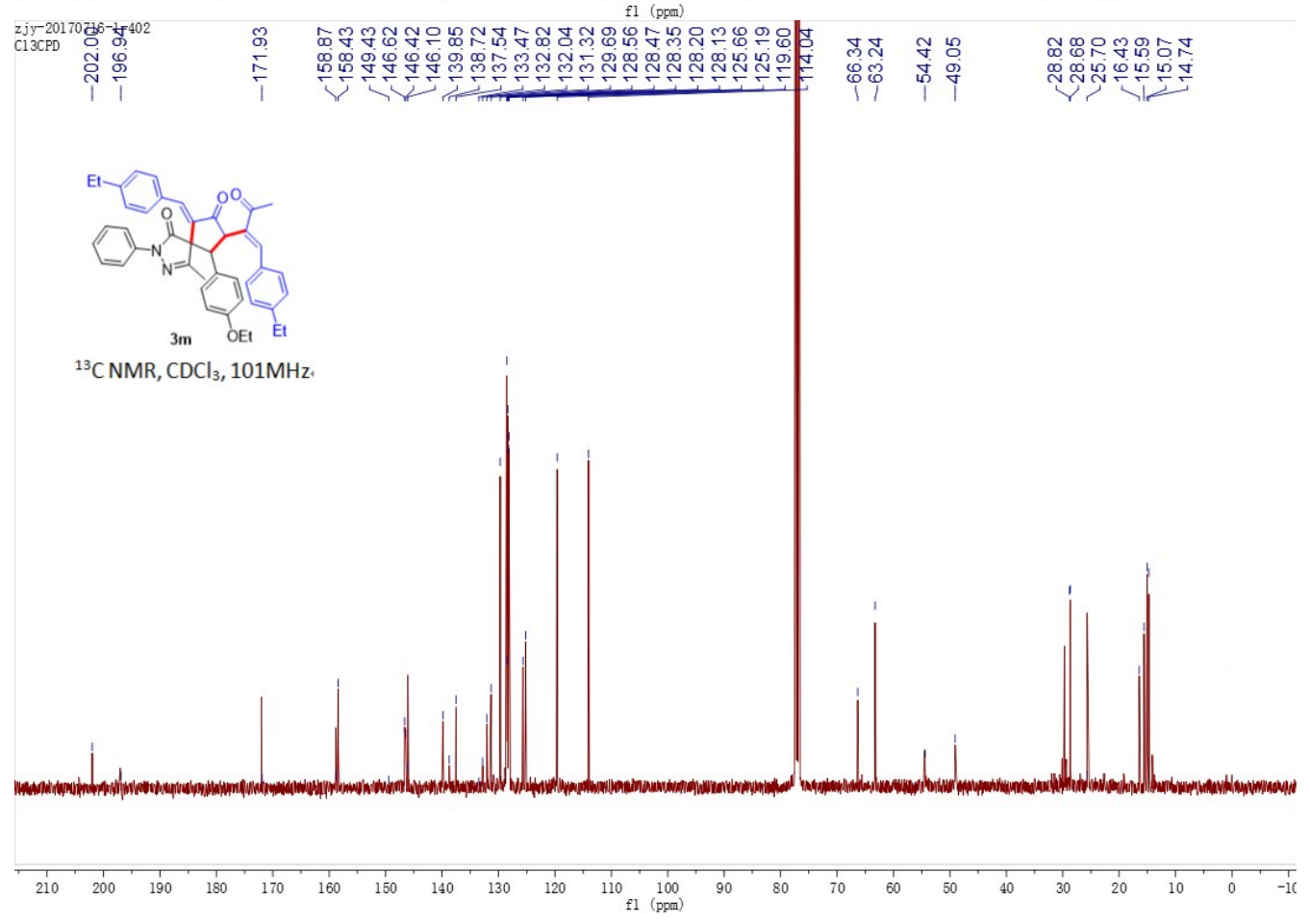


3l

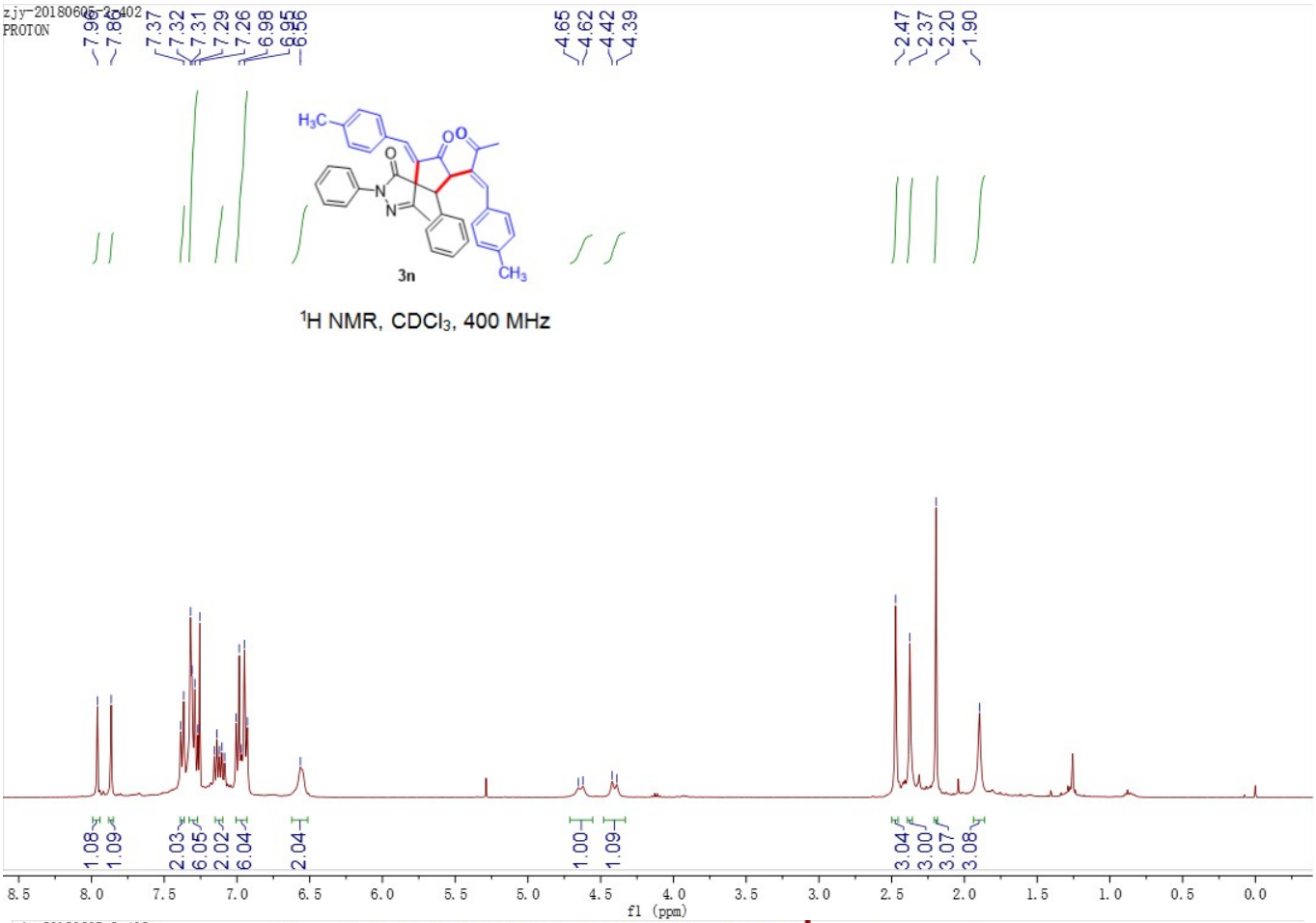
^{13}C NMR, $CDCl_3$, 101MHz



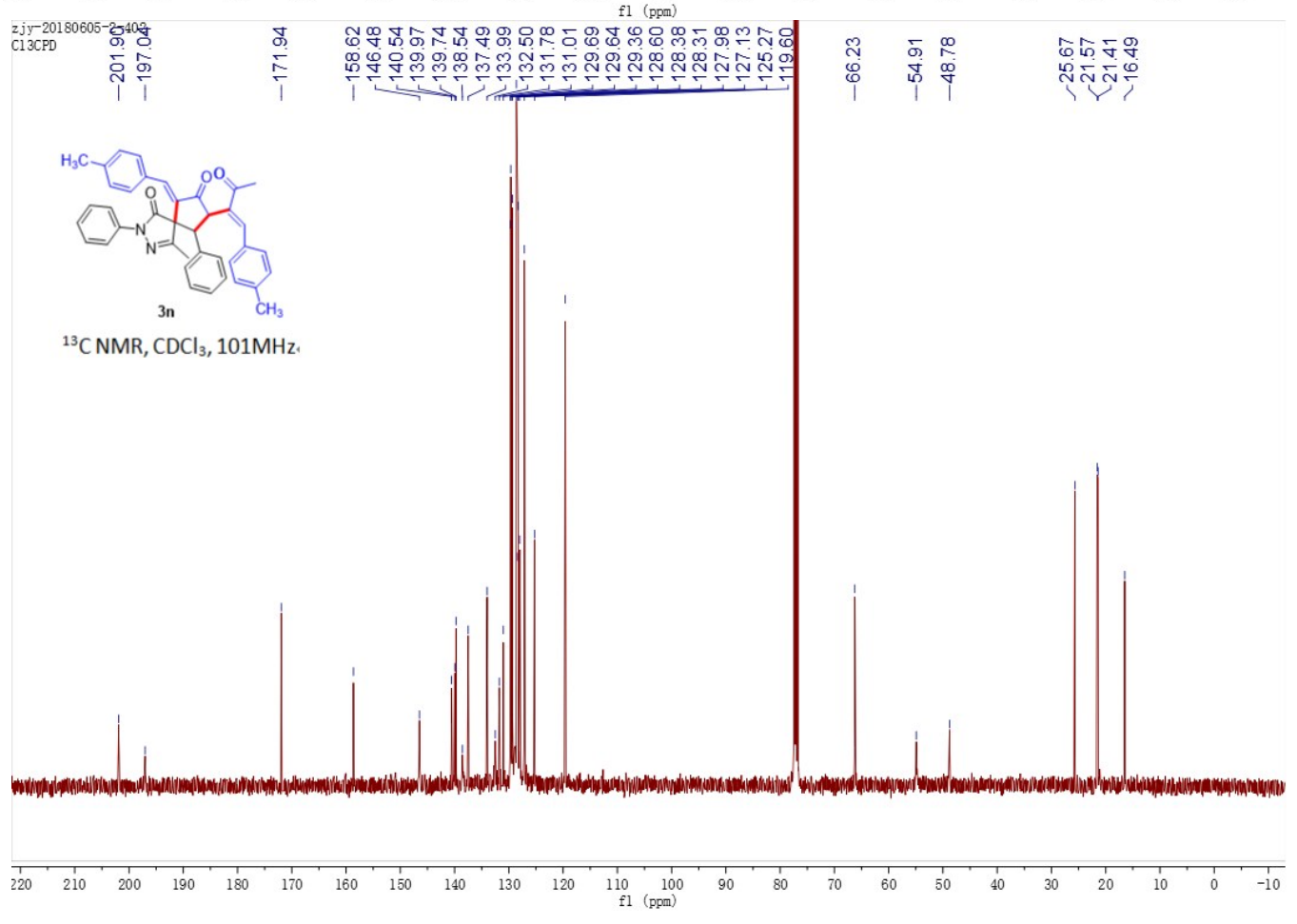
^{1}H NMR, $CDCl_3$, 400 MHz



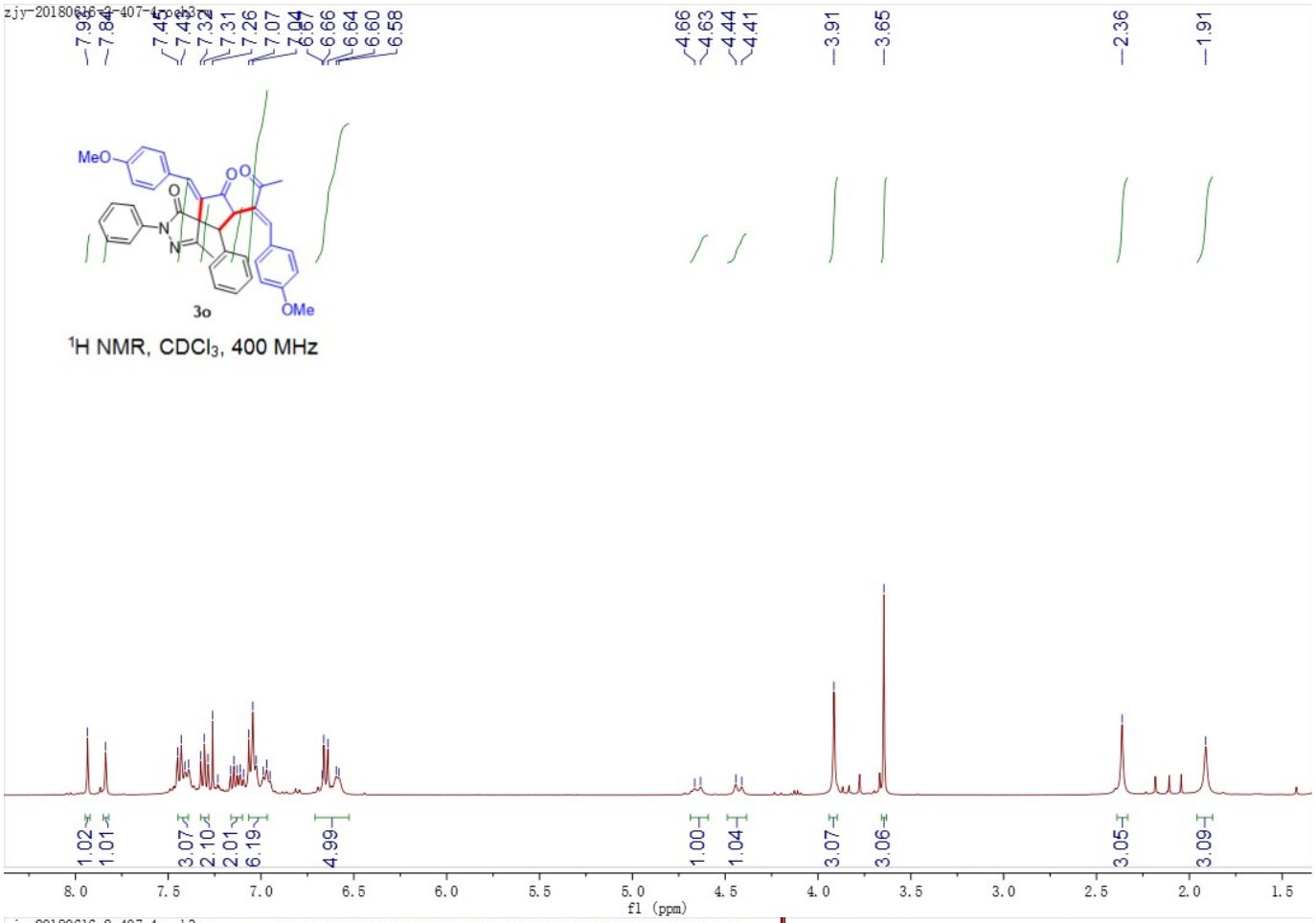
^{13}C NMR, $CDCl_3$, 101MHz



^{1}H NMR, $CDCl_3$, 400 MHz



^{13}C NMR, $CDCl_3$, 101MHz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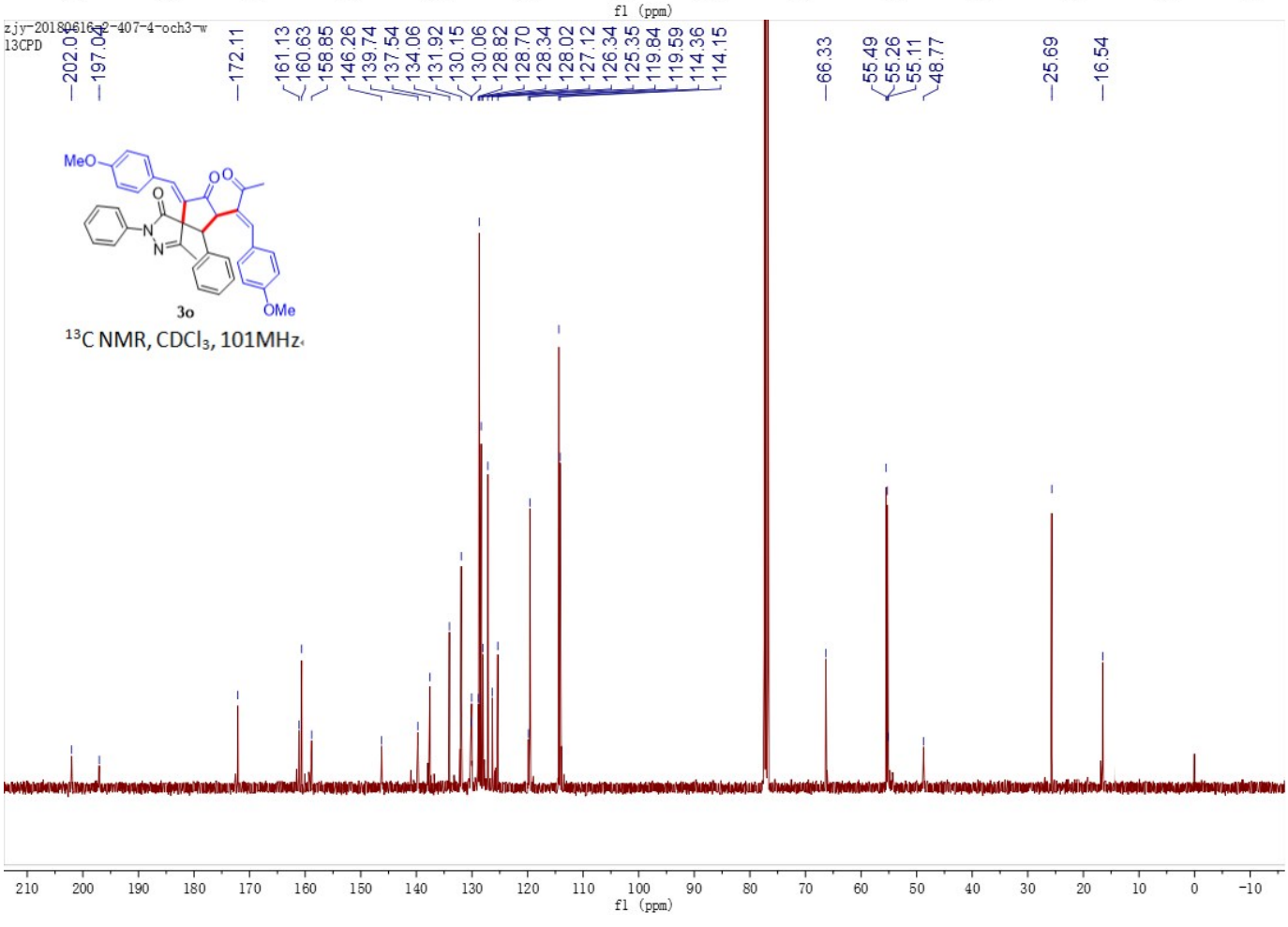
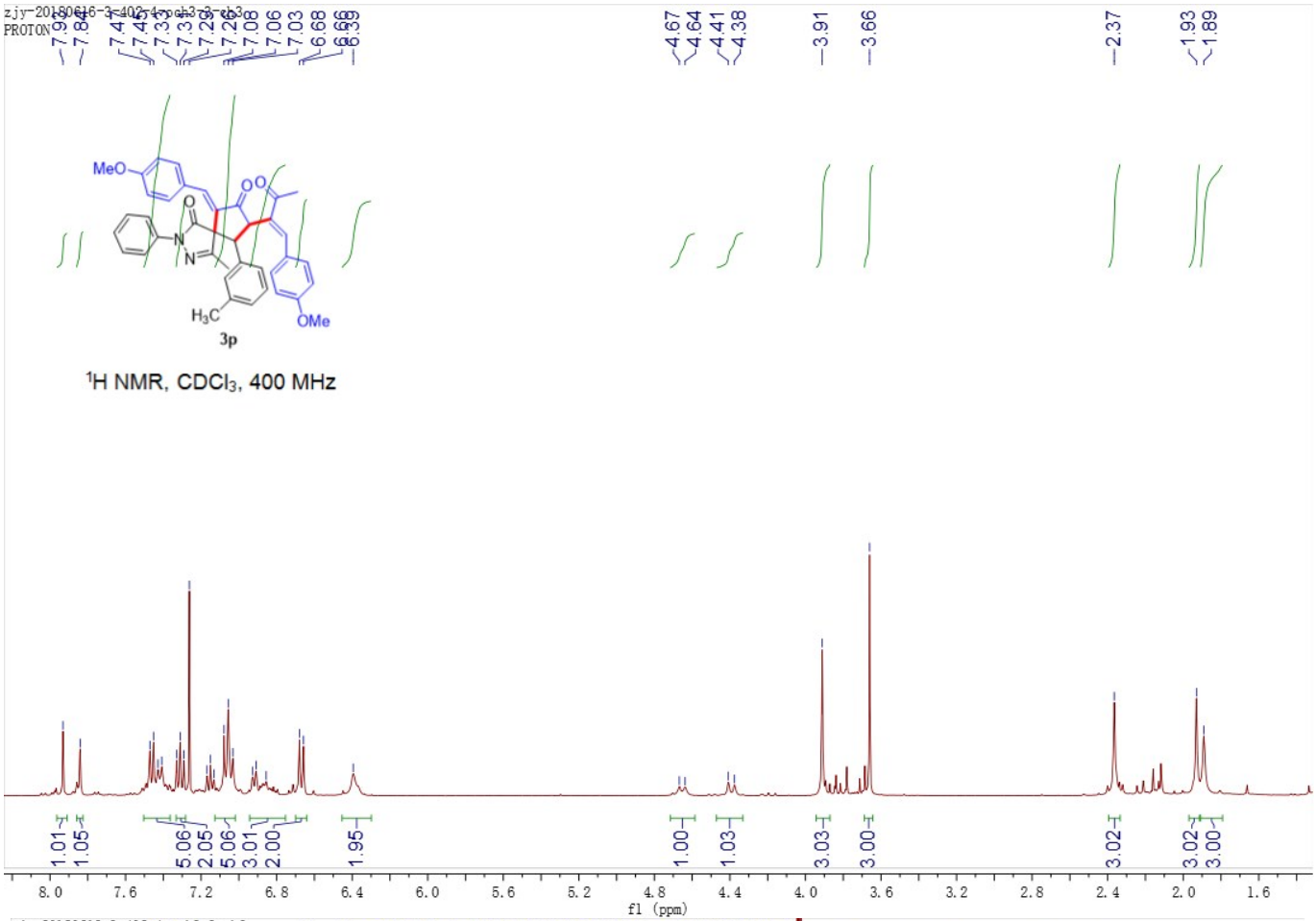
O
N
N
OMe
3o
1H NMR, CDCl3, 400 MHz
f1 (ppm)


MeO
O
O
N
N
OMe
3o
13C NMR, CDCl3, 101MHz
f1 (ppm)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7.33
7.31
7.29
7.26
7.08
7.06
7.03
6.68
6.66
6.39
4.67
4.64
4.41
4.38
3.91
3.66
2.37
1.93
1.89
MeO
O
O
N
N
H3C
OMe
3p
1H NMR, CDCl3, 400 MHz
1.01
1.05
5.06
2.05
5.06
3.01
2.00
1.95
1.00
1.03
3.03
3.00
3.02
3.02
3.00
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
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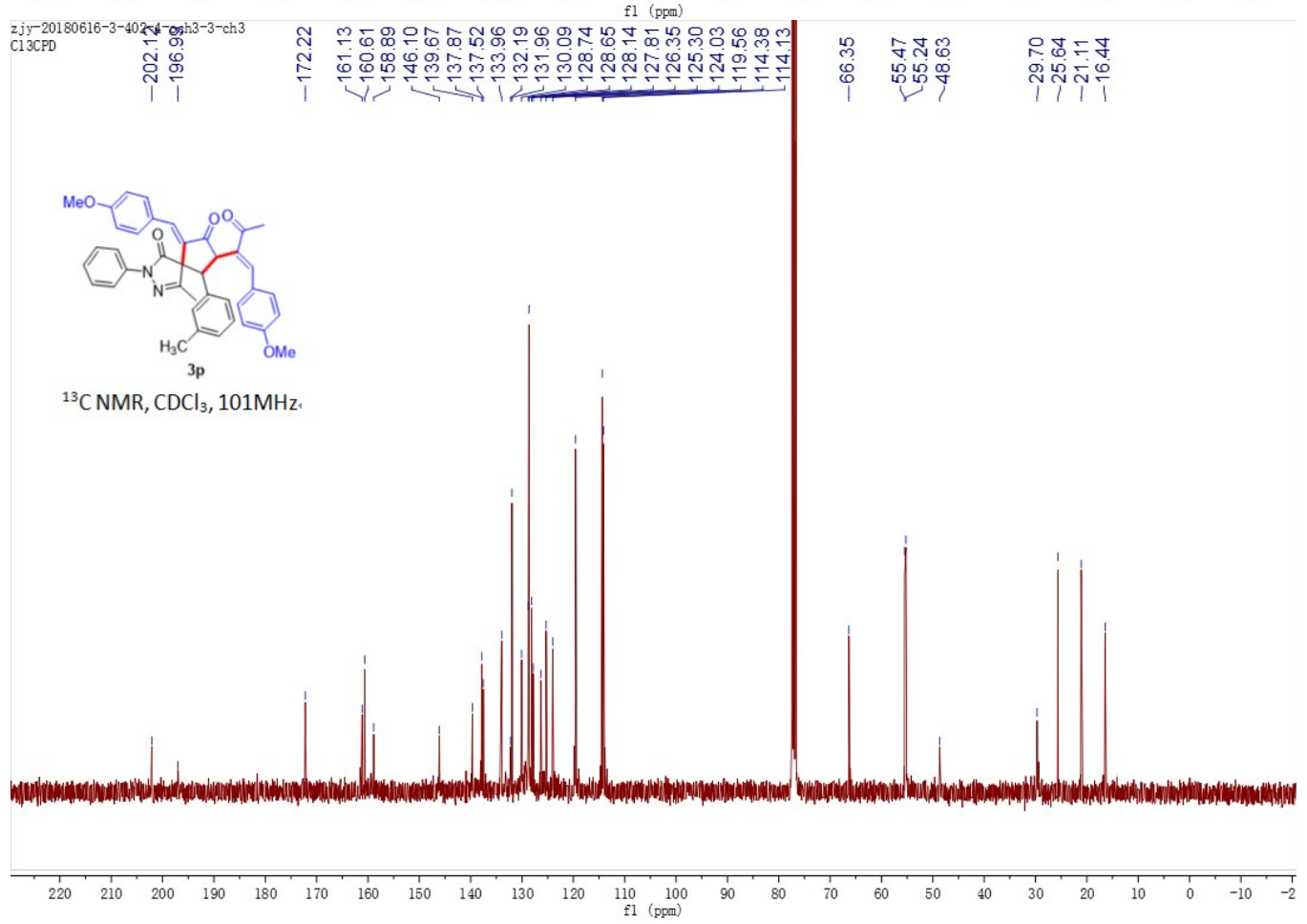
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
f1 (ppm)


zjy-20180616-3-402-4-pch3-3-ch3
C13CPD
202.14
196.99
172.22
161.13
160.61
158.89
146.10
139.67
137.87
137.52
133.96
132.19
131.96
130.09
128.74
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126.35
125.30
124.03
119.56
114.38
114.13
66.35
55.47
55.24
48.63
29.70
25.64
21.11
16.44
MeO
O
O
N
N
H3C
OMe
3p
13C NMR, CDCl3, 101MHz
220
210
200
190
180
170
160
150
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120
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100
90
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70
60
50
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30
20
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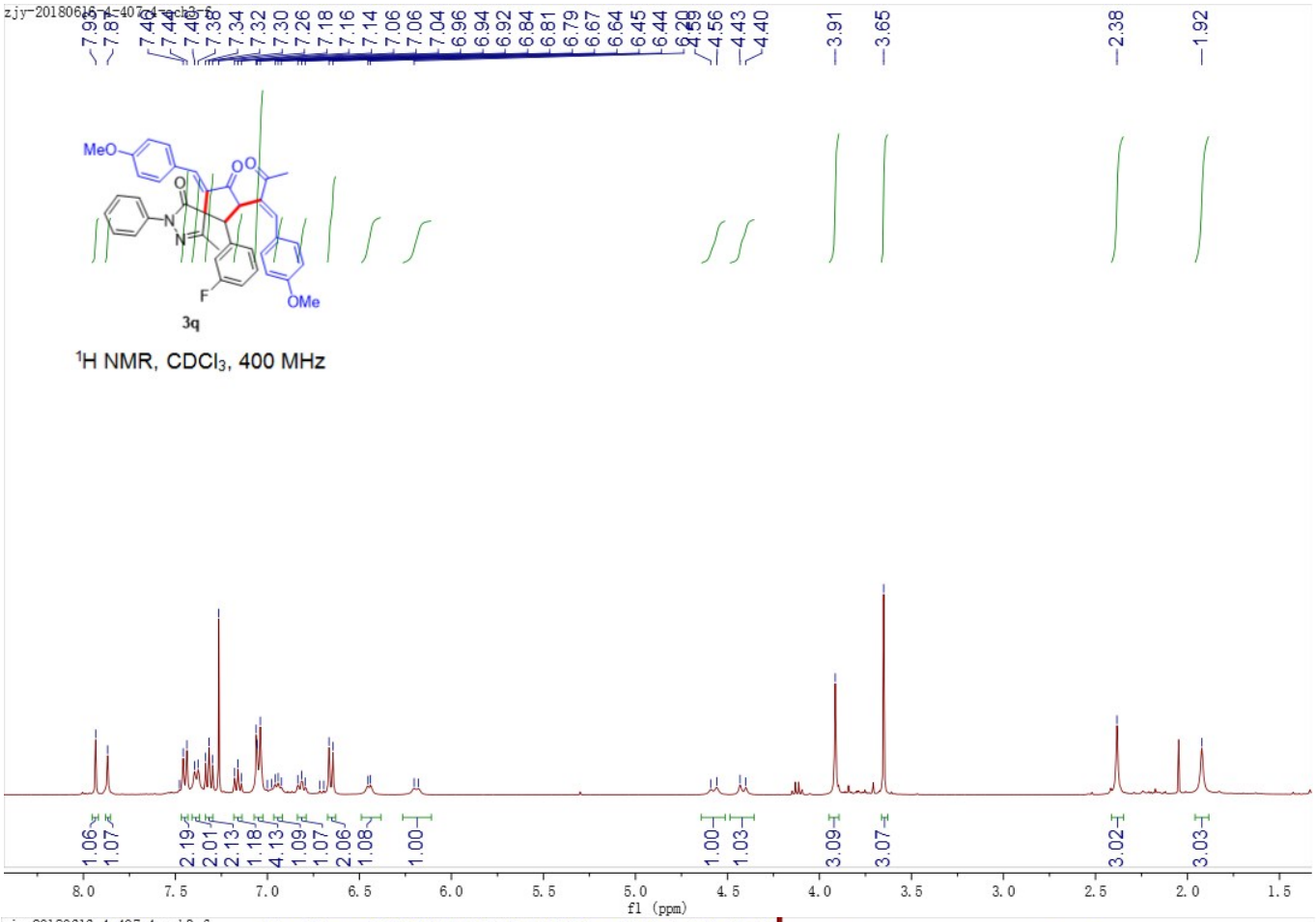
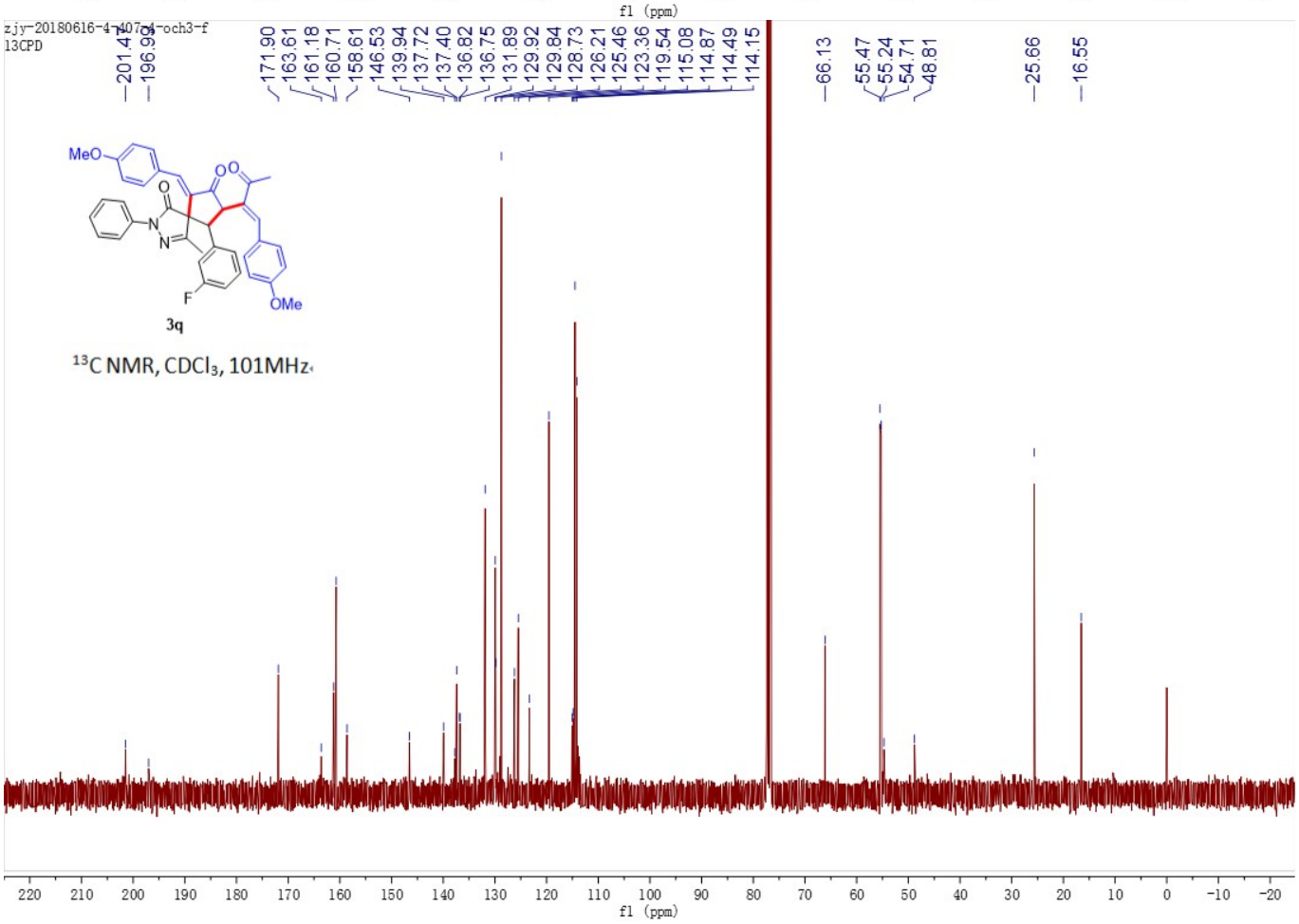
0
-10
-2
f1 (ppm)


MeO
OMe
F
3q
1H NMR, CDCl3, 400 MHz
f1 (ppm)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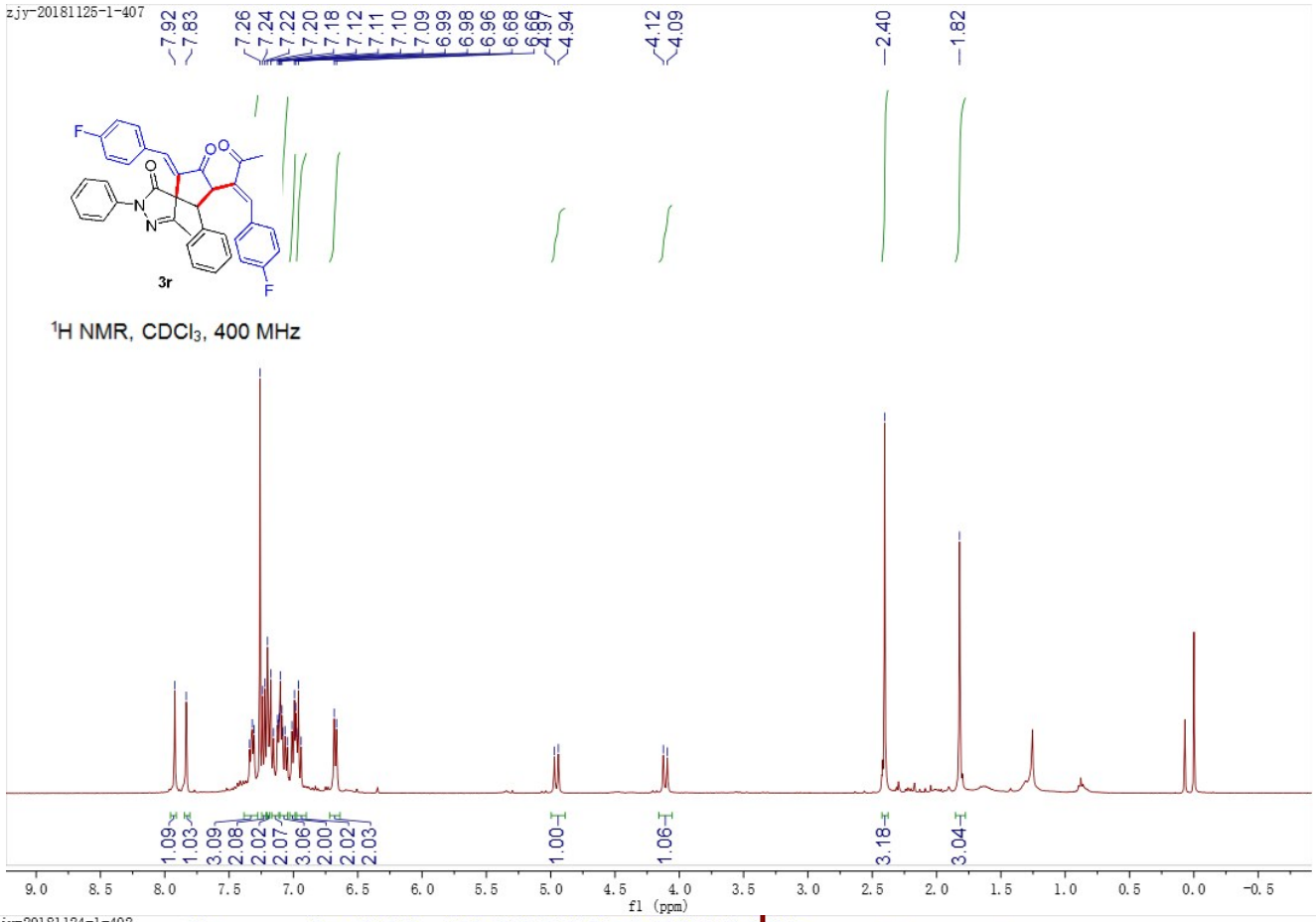
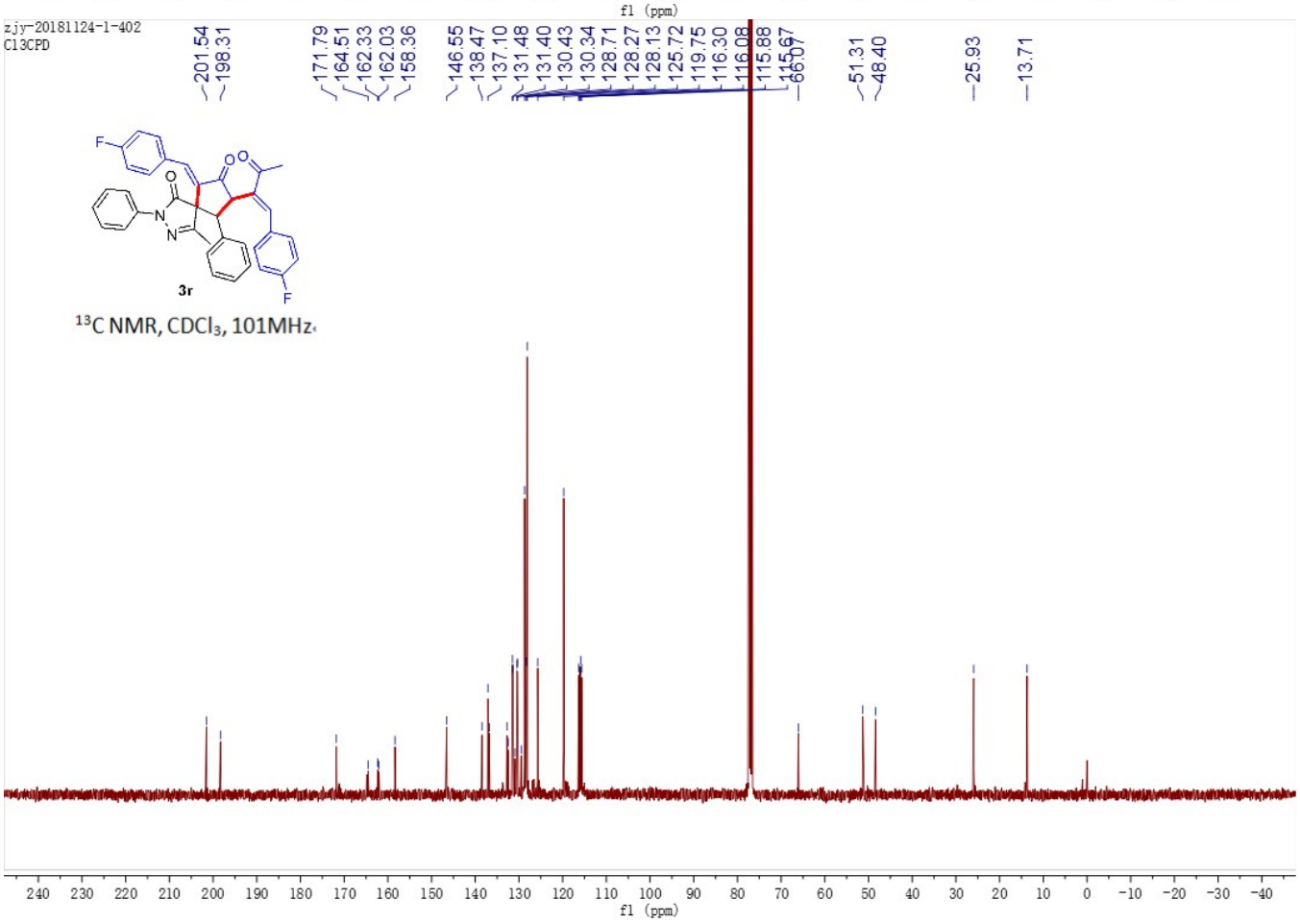
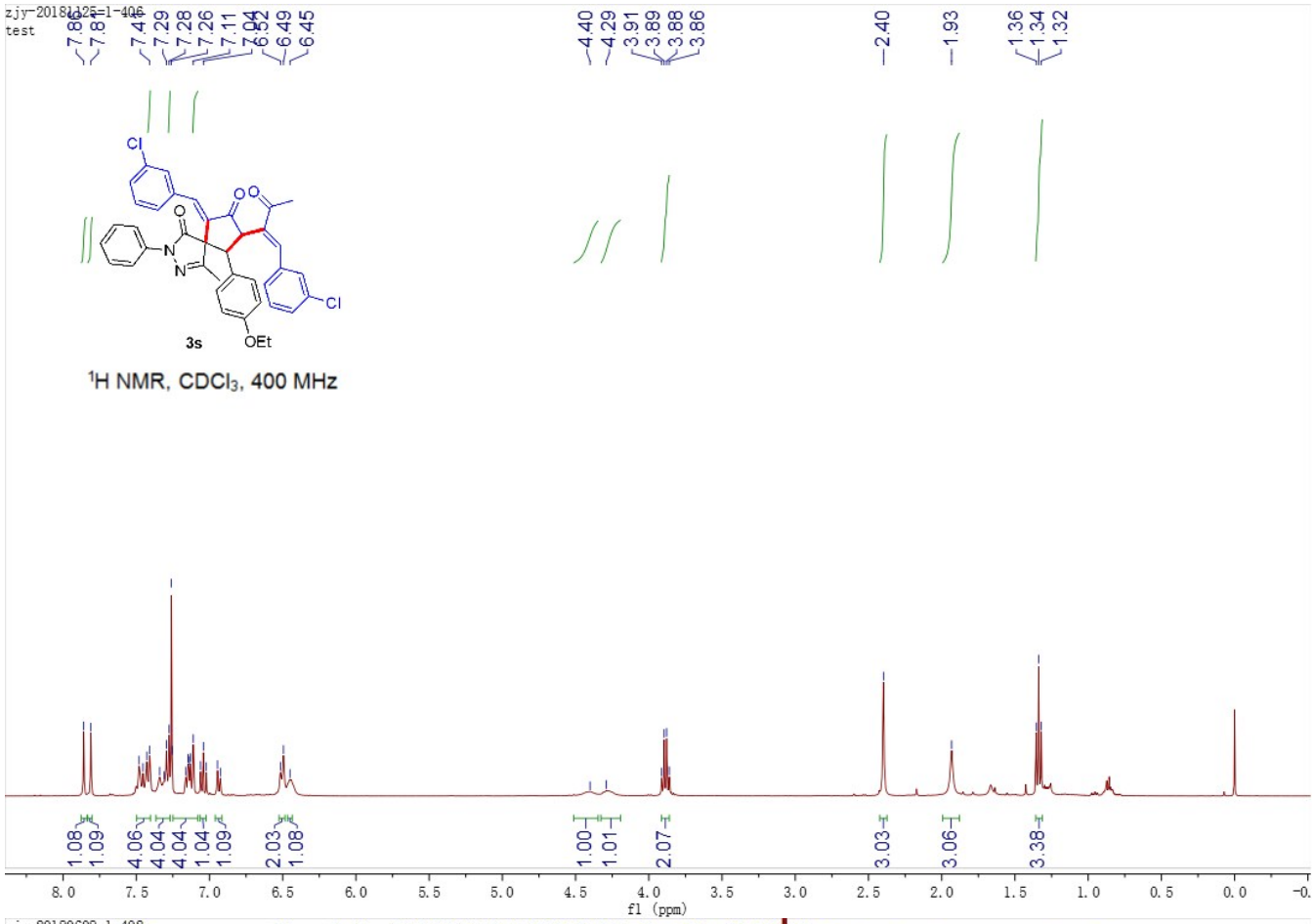
OMe
F
3q
13C NMR, CDCl3, 101MHz
f1 (ppm)



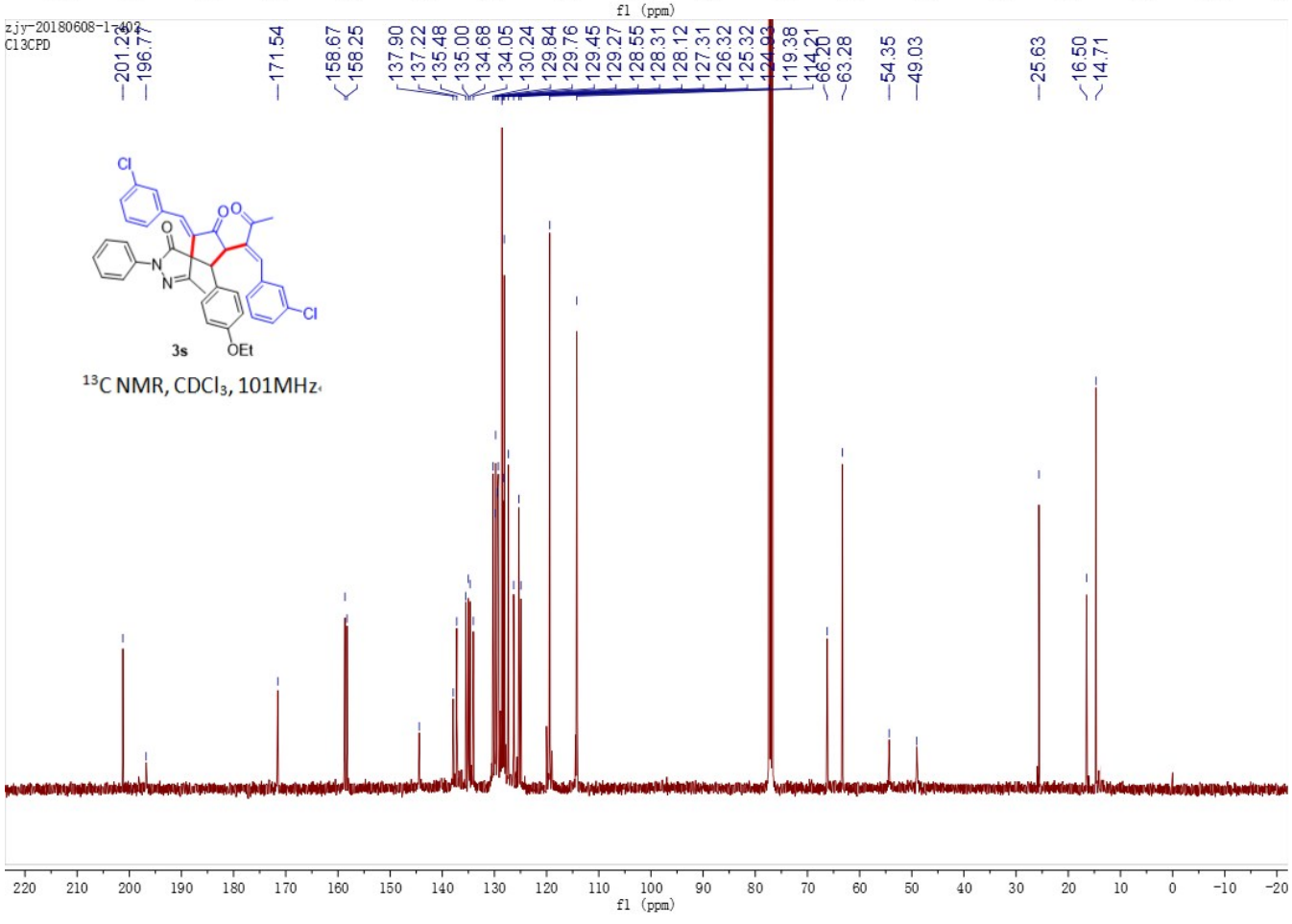
^{1}H NMR, $CDCl_3$, 400 MHz



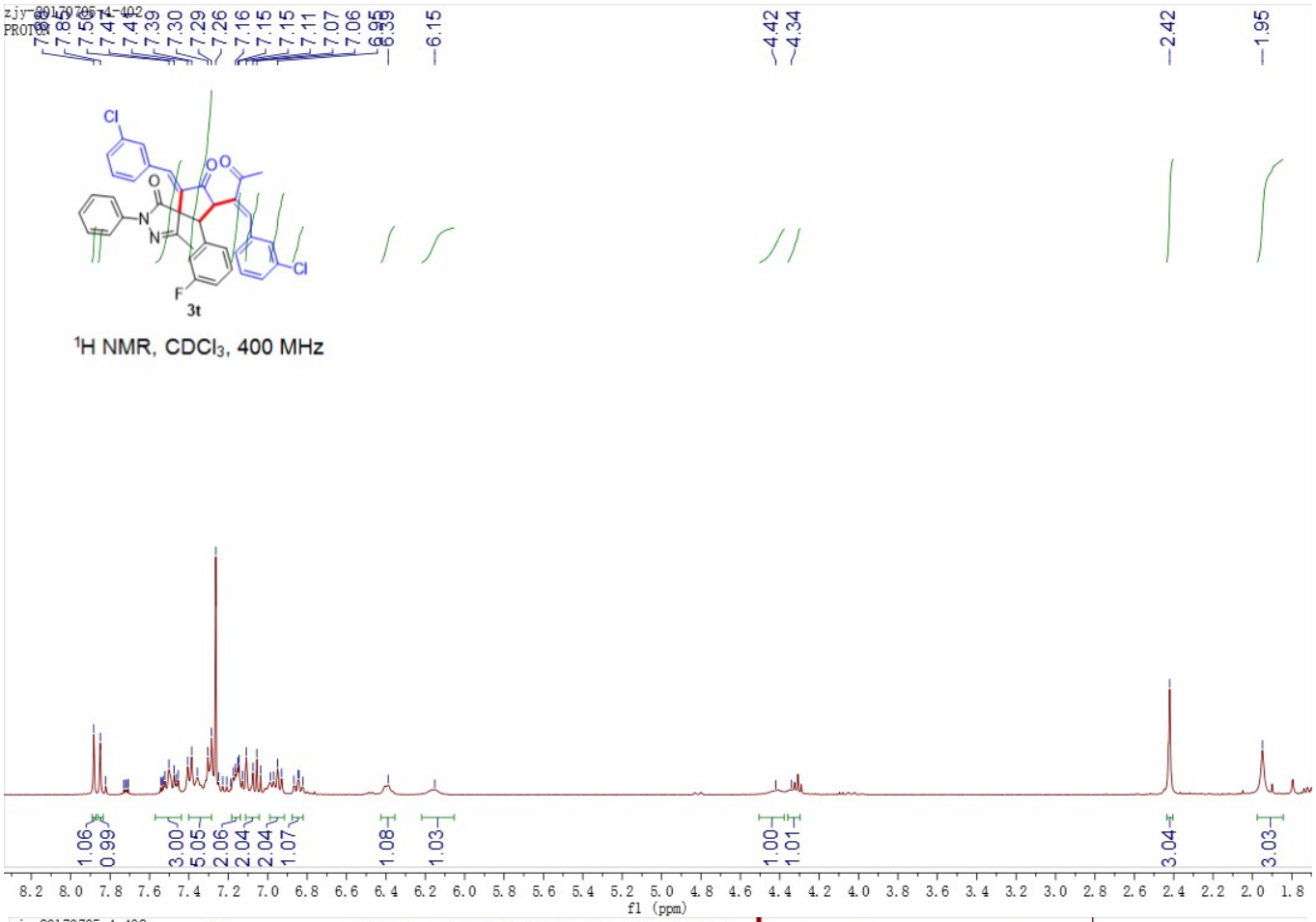
^{13}C NMR, $CDCl_3$, 101MHz



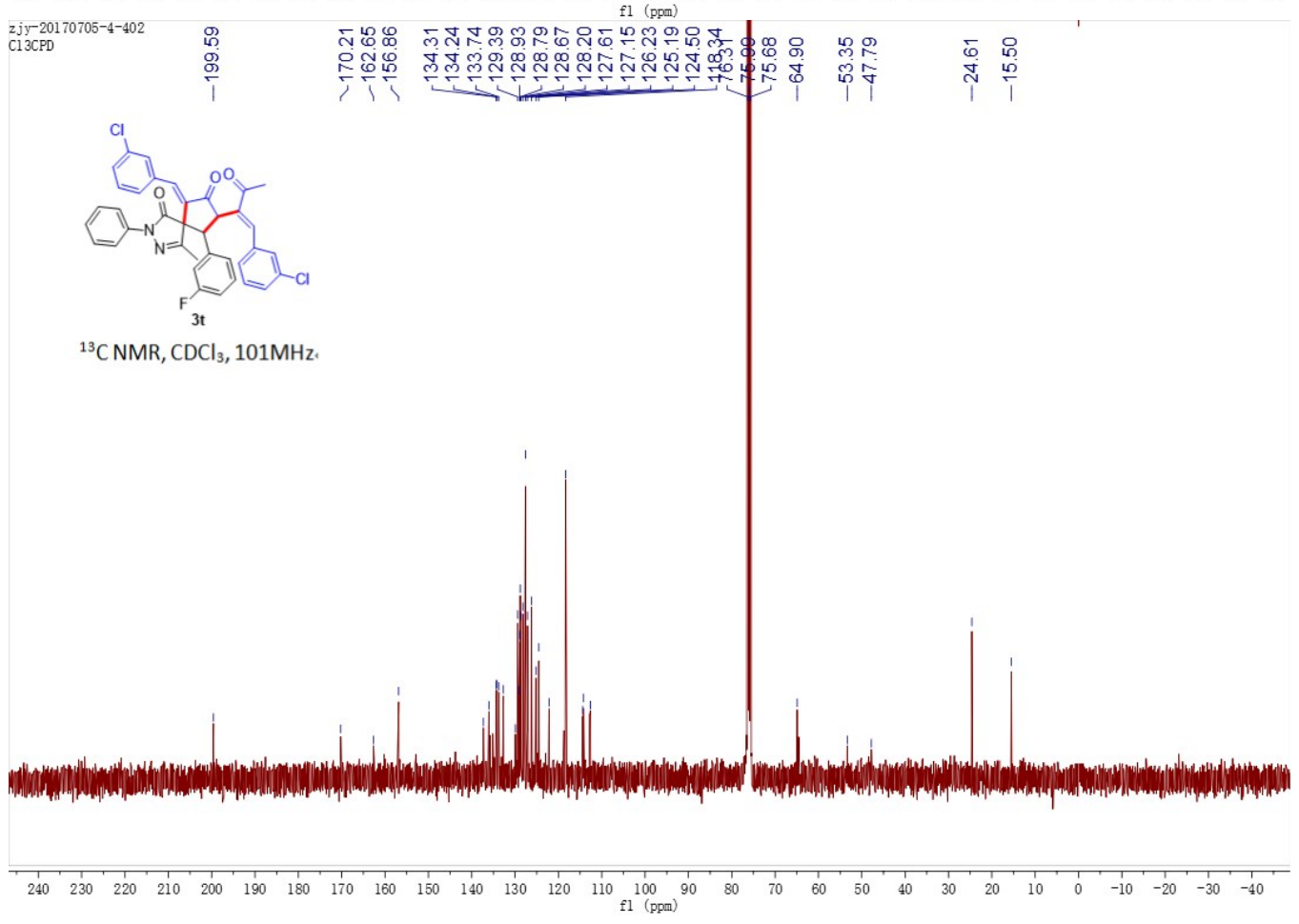
^{1}H NMR, $CDCl_3$, 400 MHz



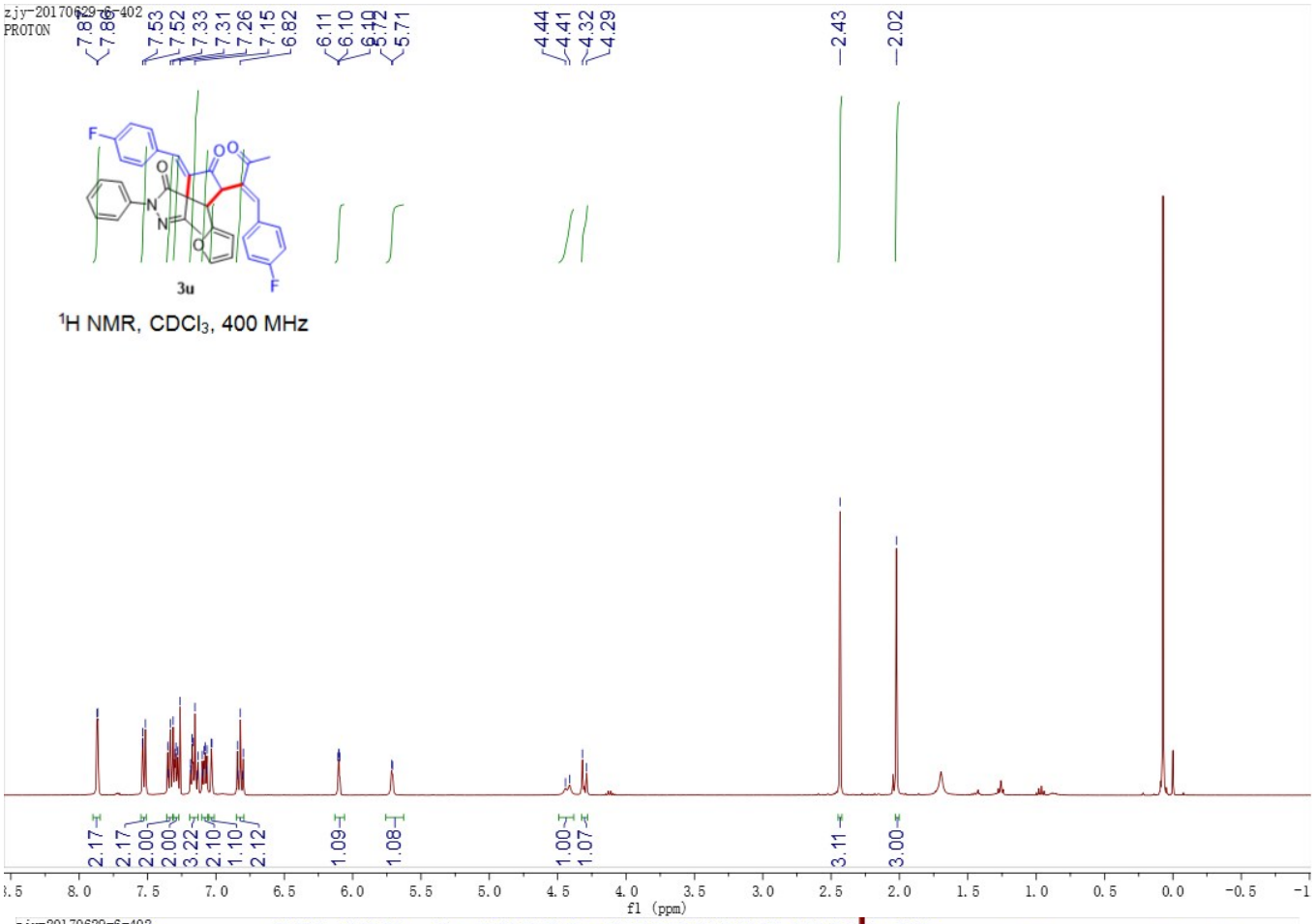
^{13}C NMR, $CDCl_3$, 101MHz



^{1}H NMR, $CDCl_3$, 400 MHz

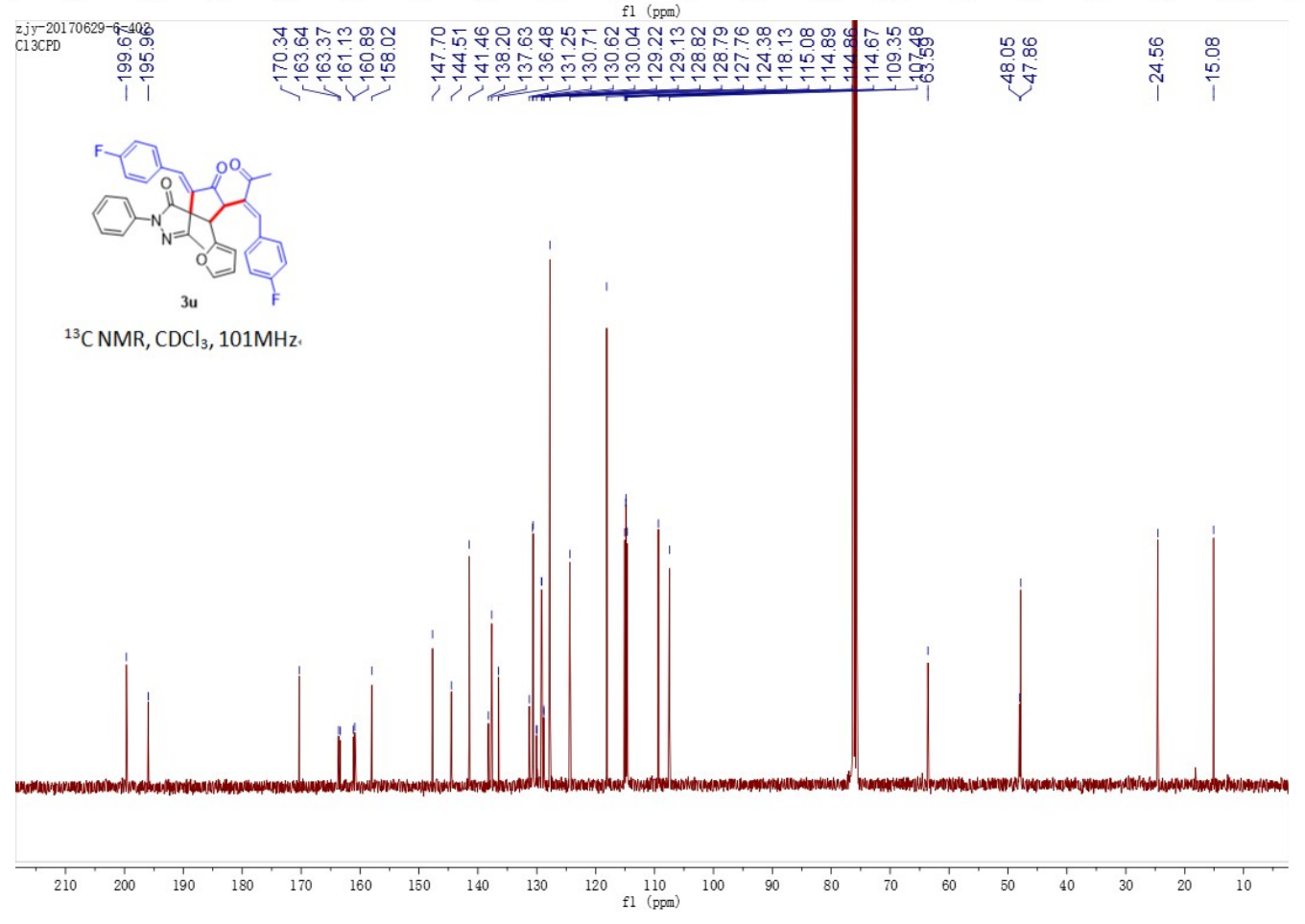


^{13}C NMR, $CDCl_3$, 101MHz



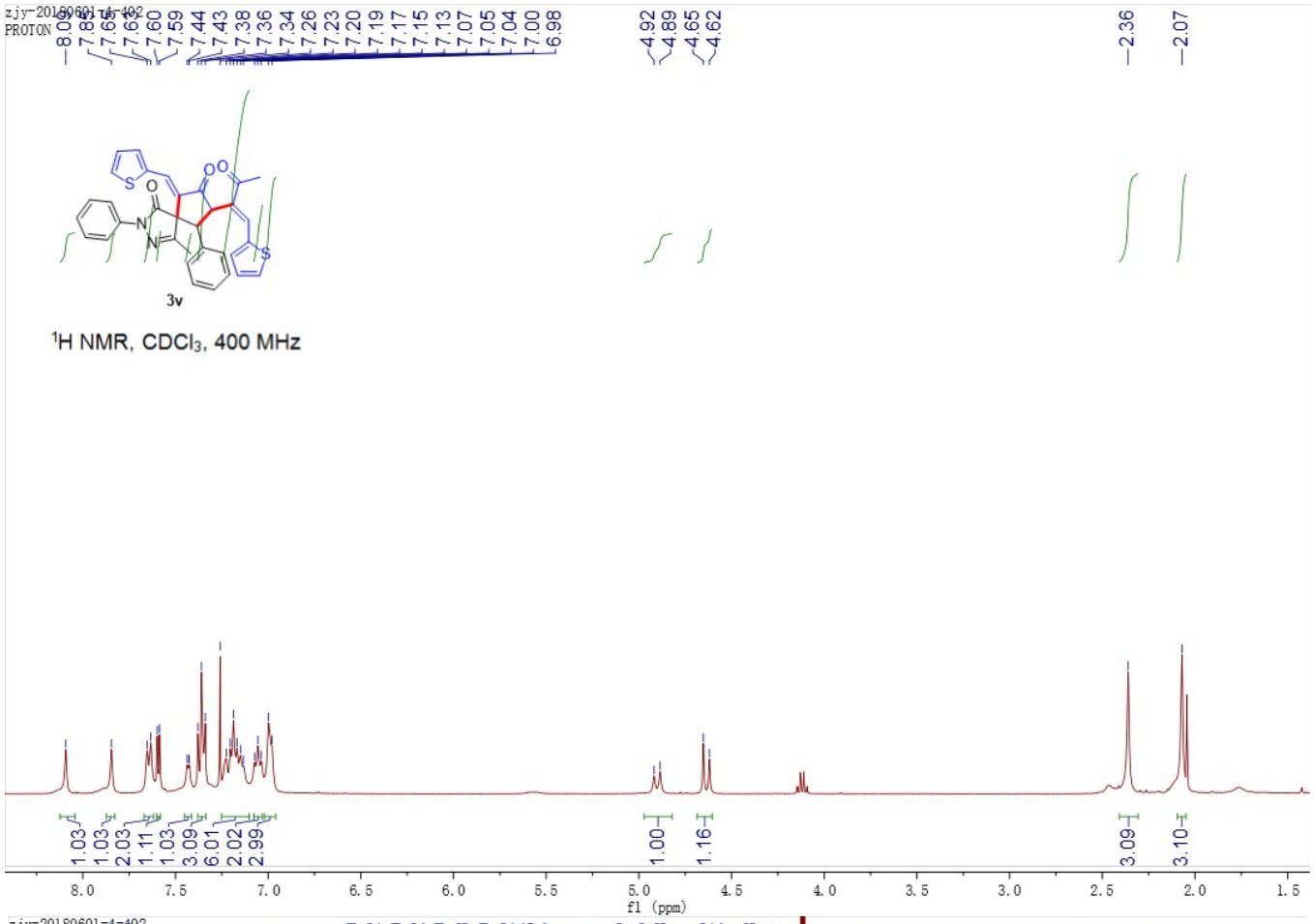
3u

^{1}H NMR, $CDCl_3$, 400 MHz



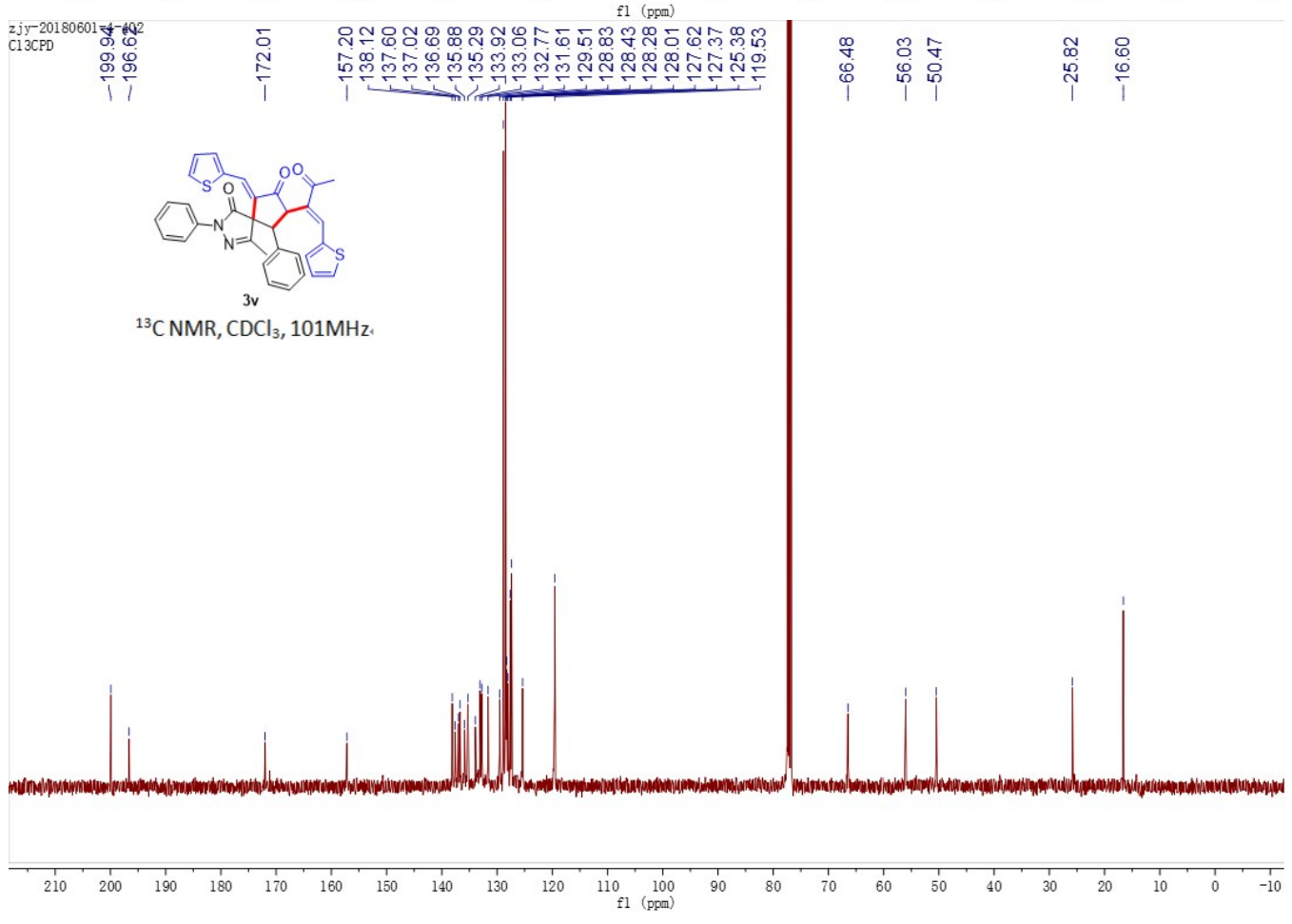
3u

^{13}C NMR, $CDCl_3$, 101MHz



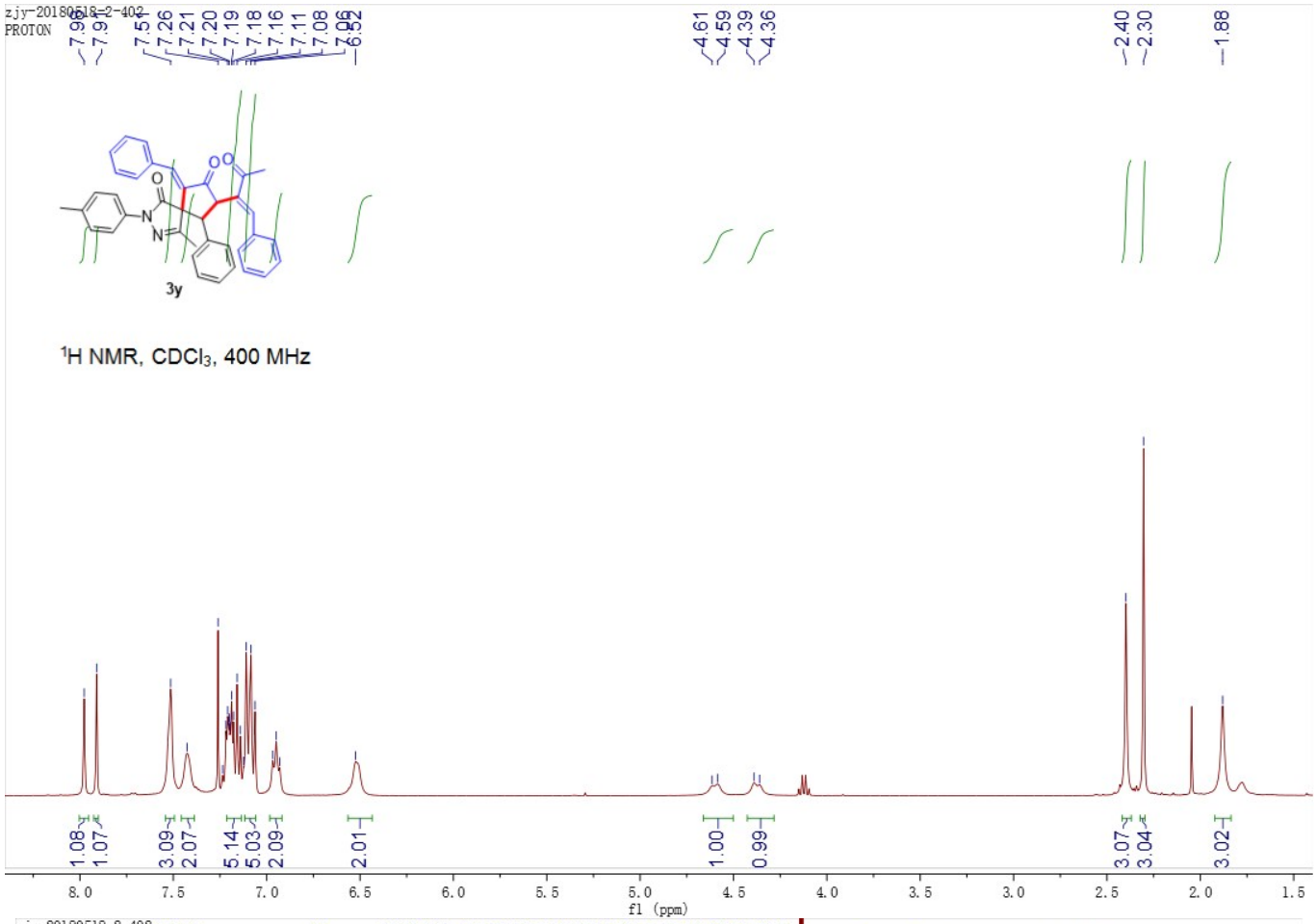
3v

^{1}H NMR, $CDCl_3$, 400 MHz

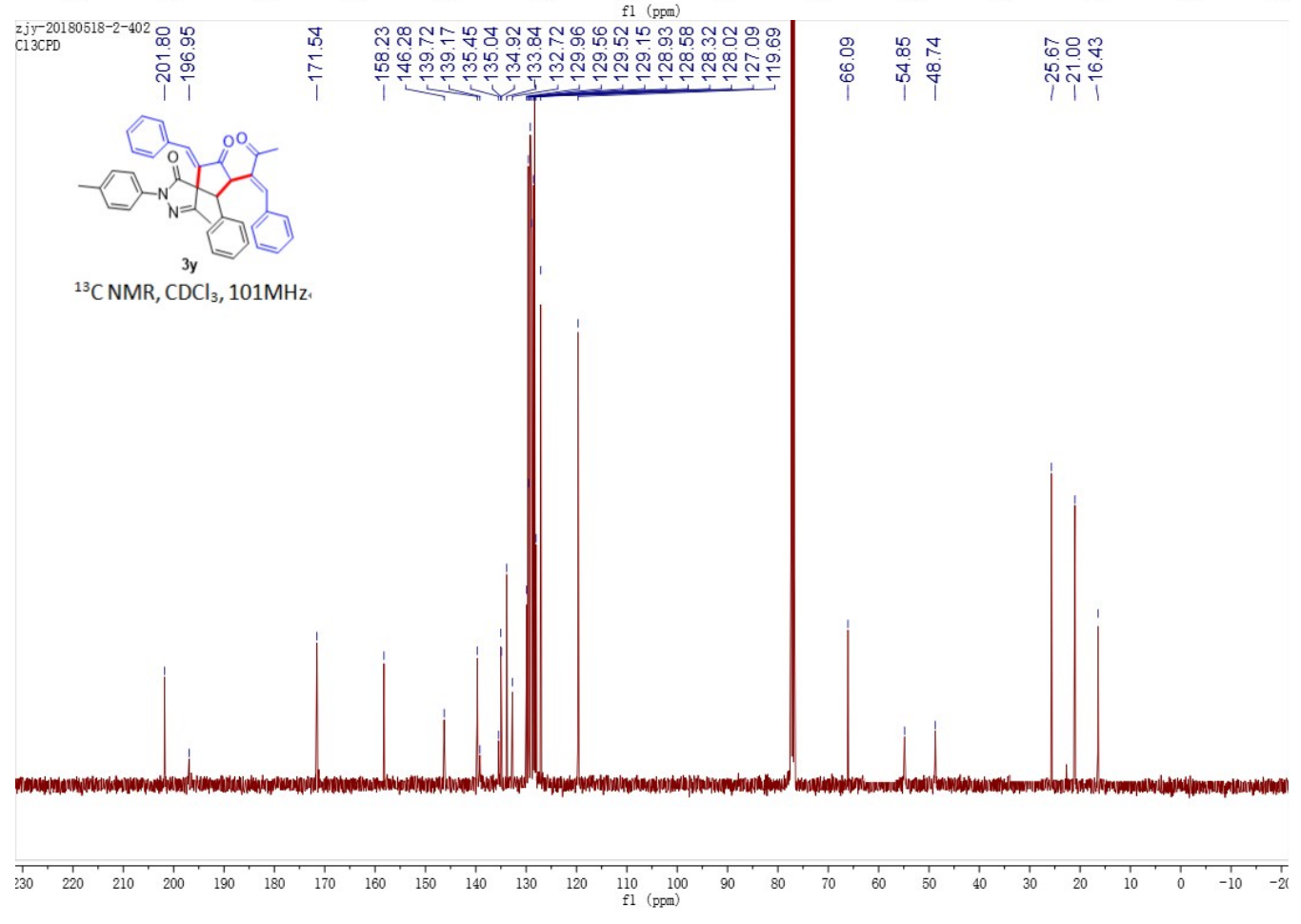


3v

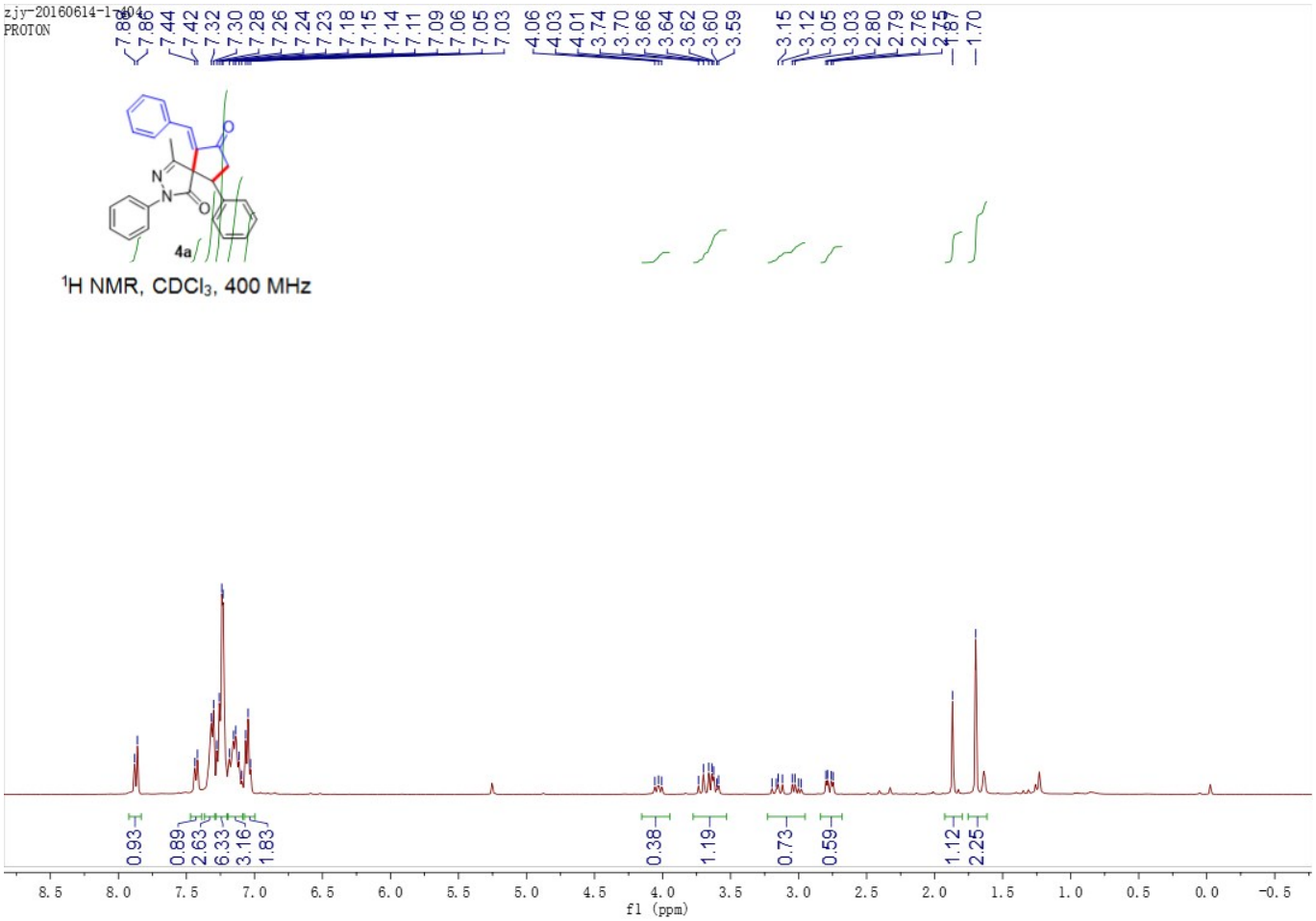
^{13}C NMR, $CDCl_3$, 101MHz

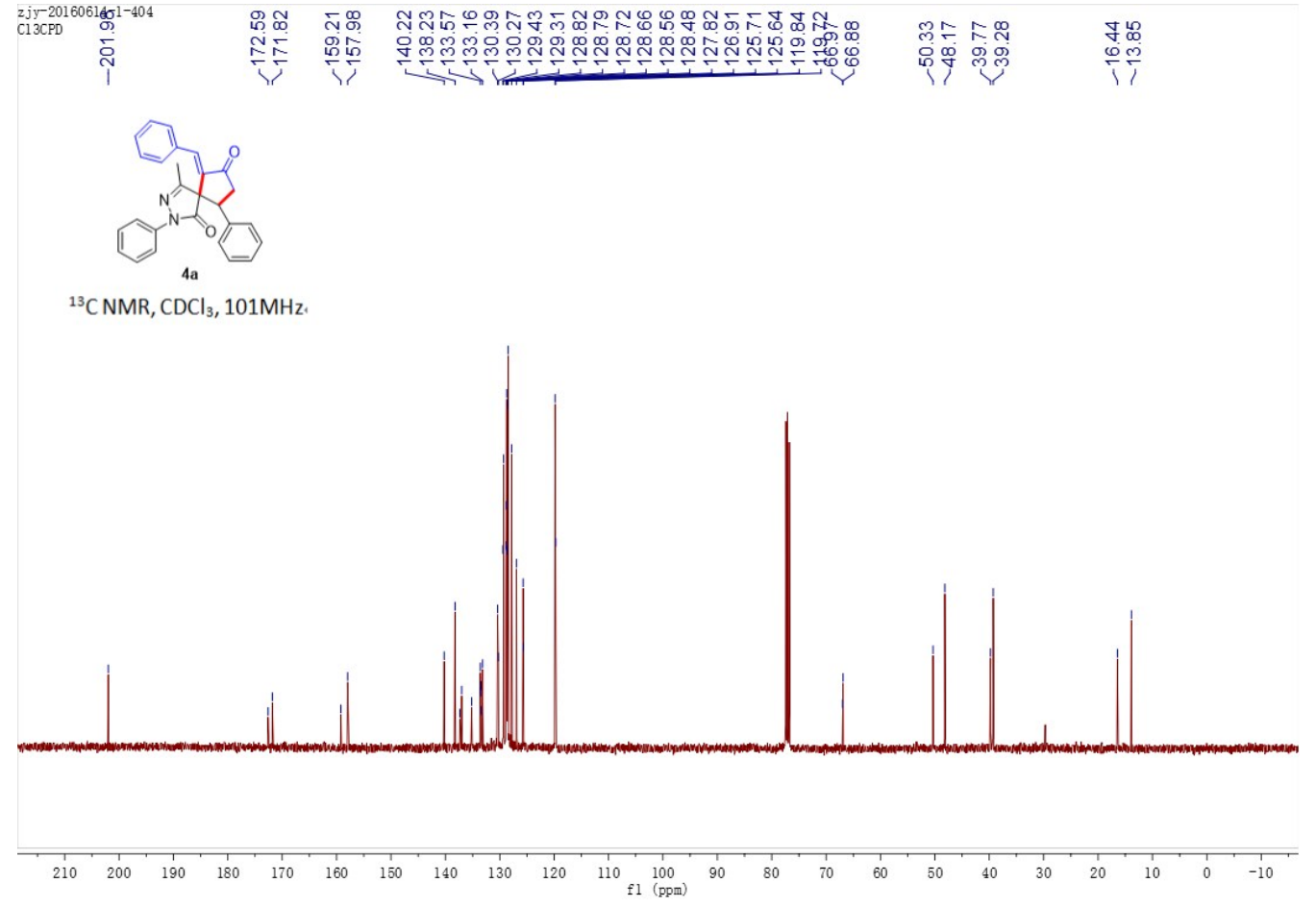


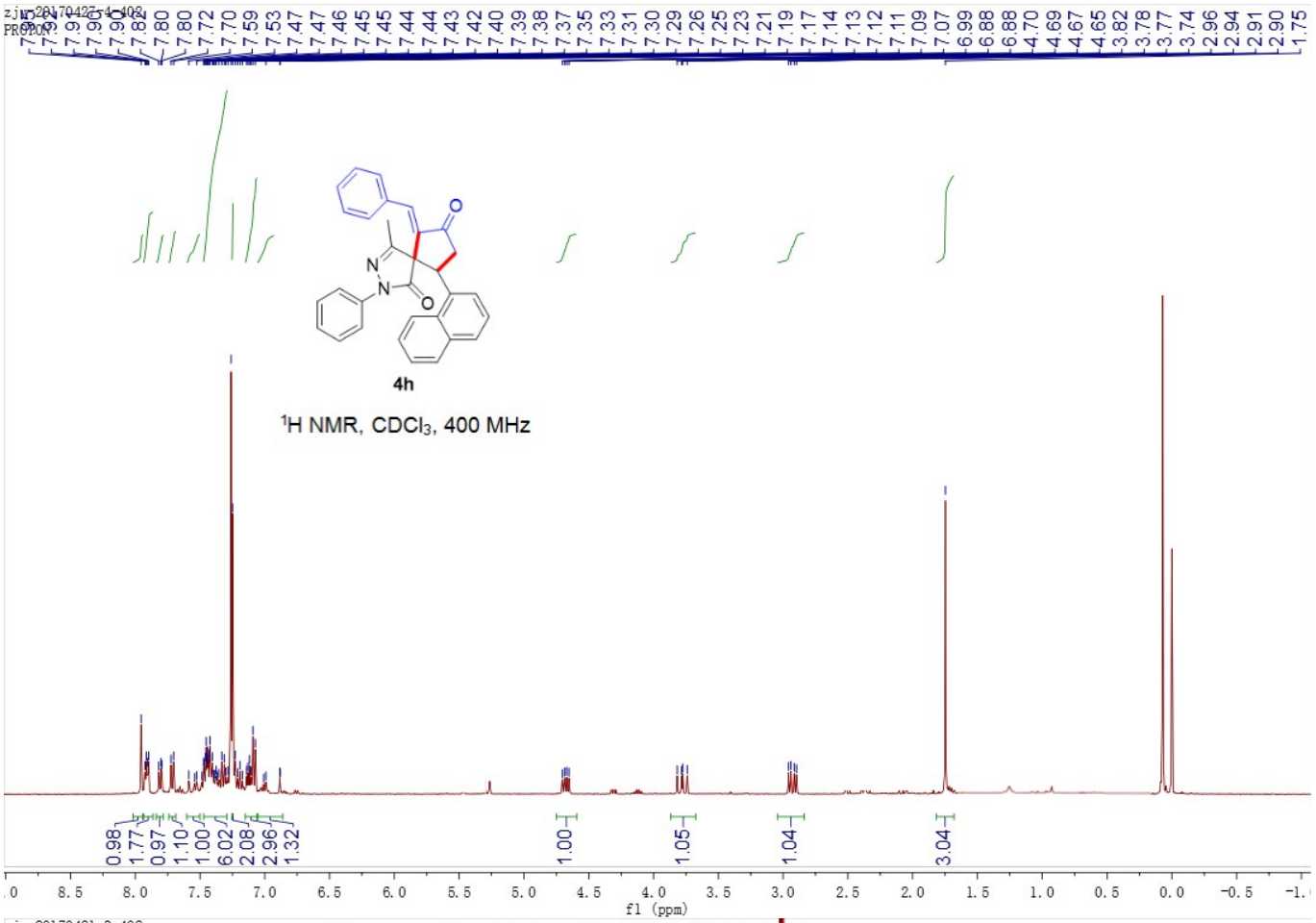
^{1}H NMR, $CDCl_3$, 400 MHz

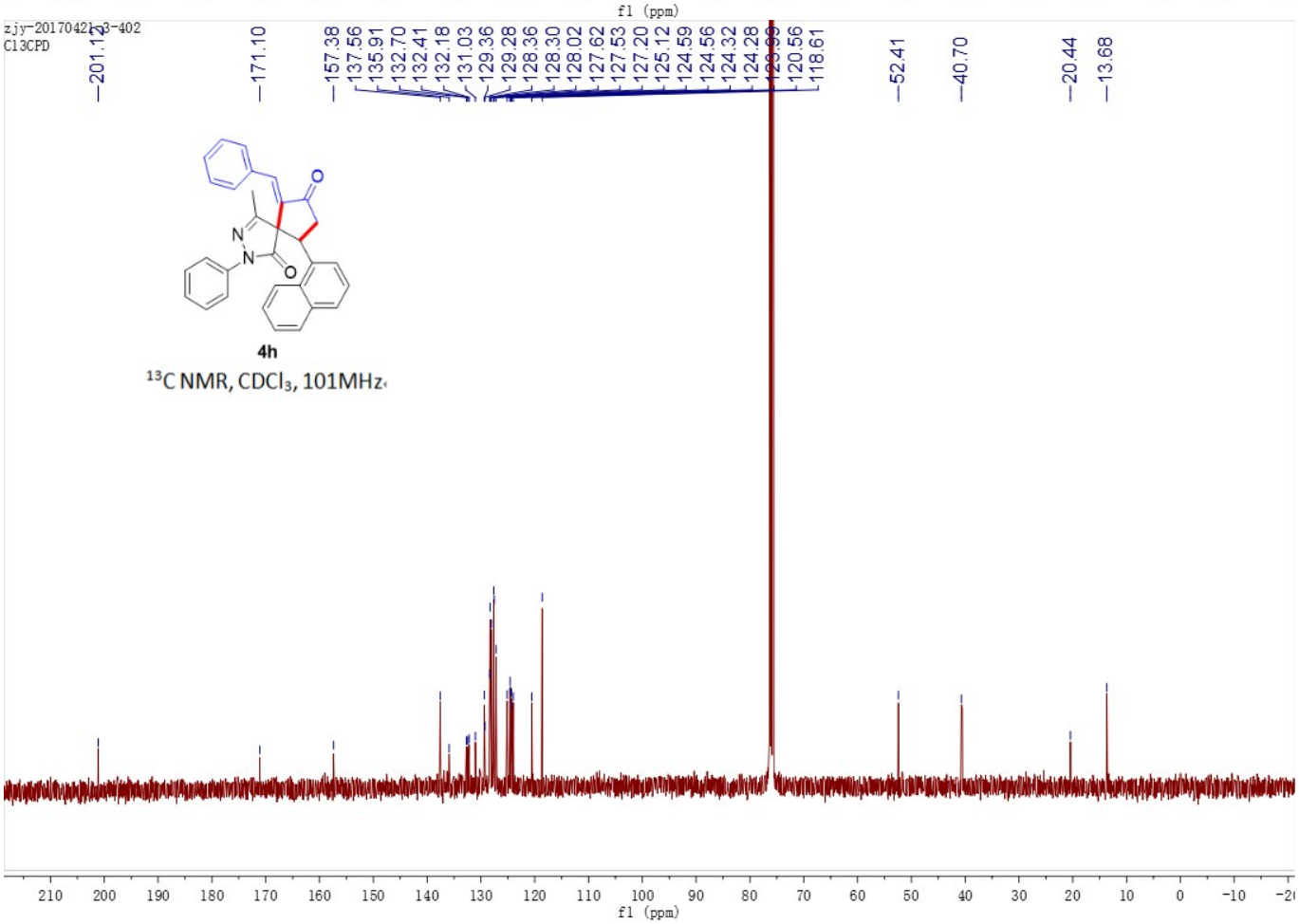


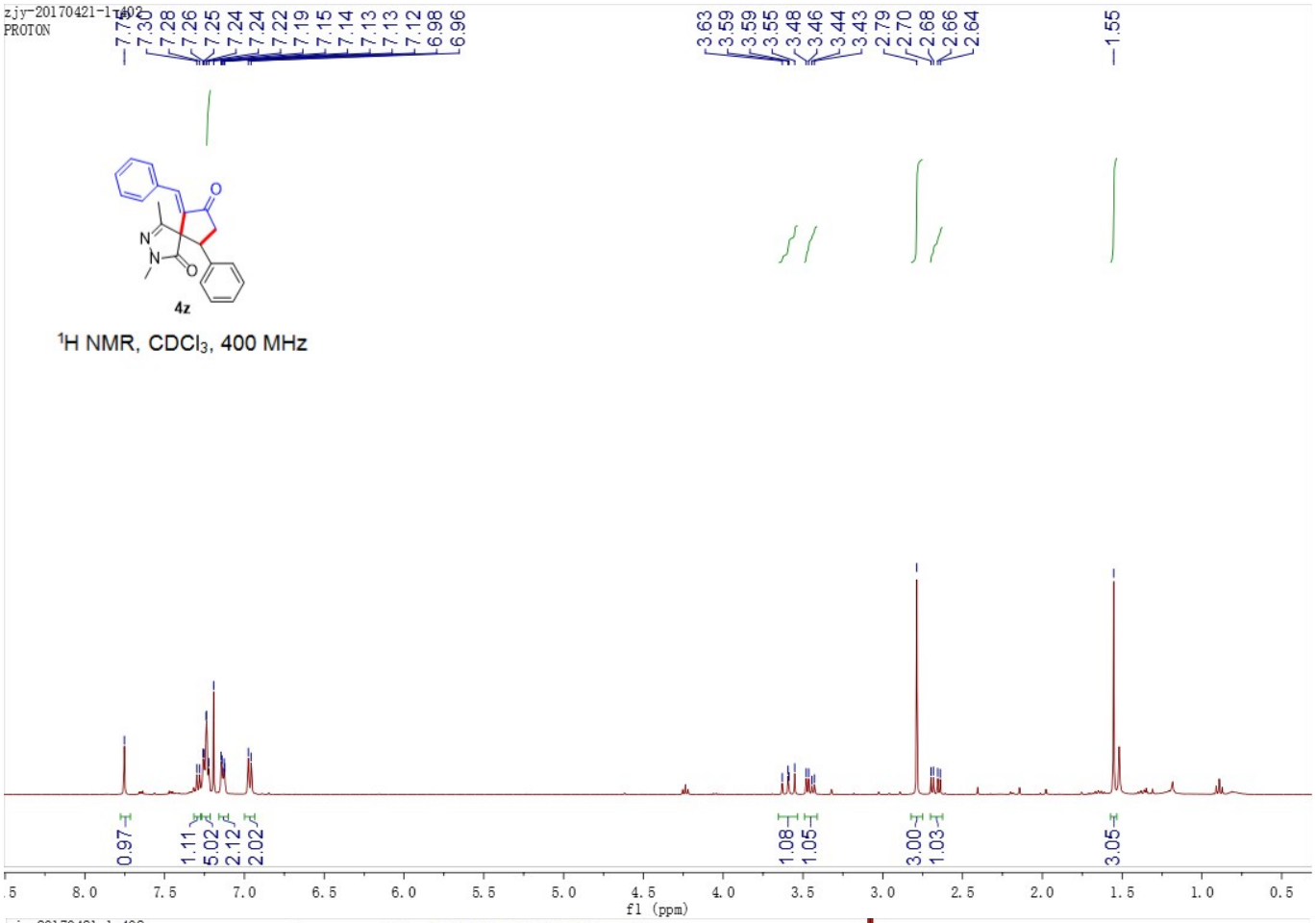
^{13}C NMR, $CDCl_3$, 101MHz


zjy-20160614-1-404
PROTON
4a
^{1}H NMR, $CDCl_3$, 400 MHz
f1 (ppm)


zjy-20160614-1-404
C13CPD
4a
^{13}C NMR, $CDCl_3$, 101MHz
f1 (ppm)

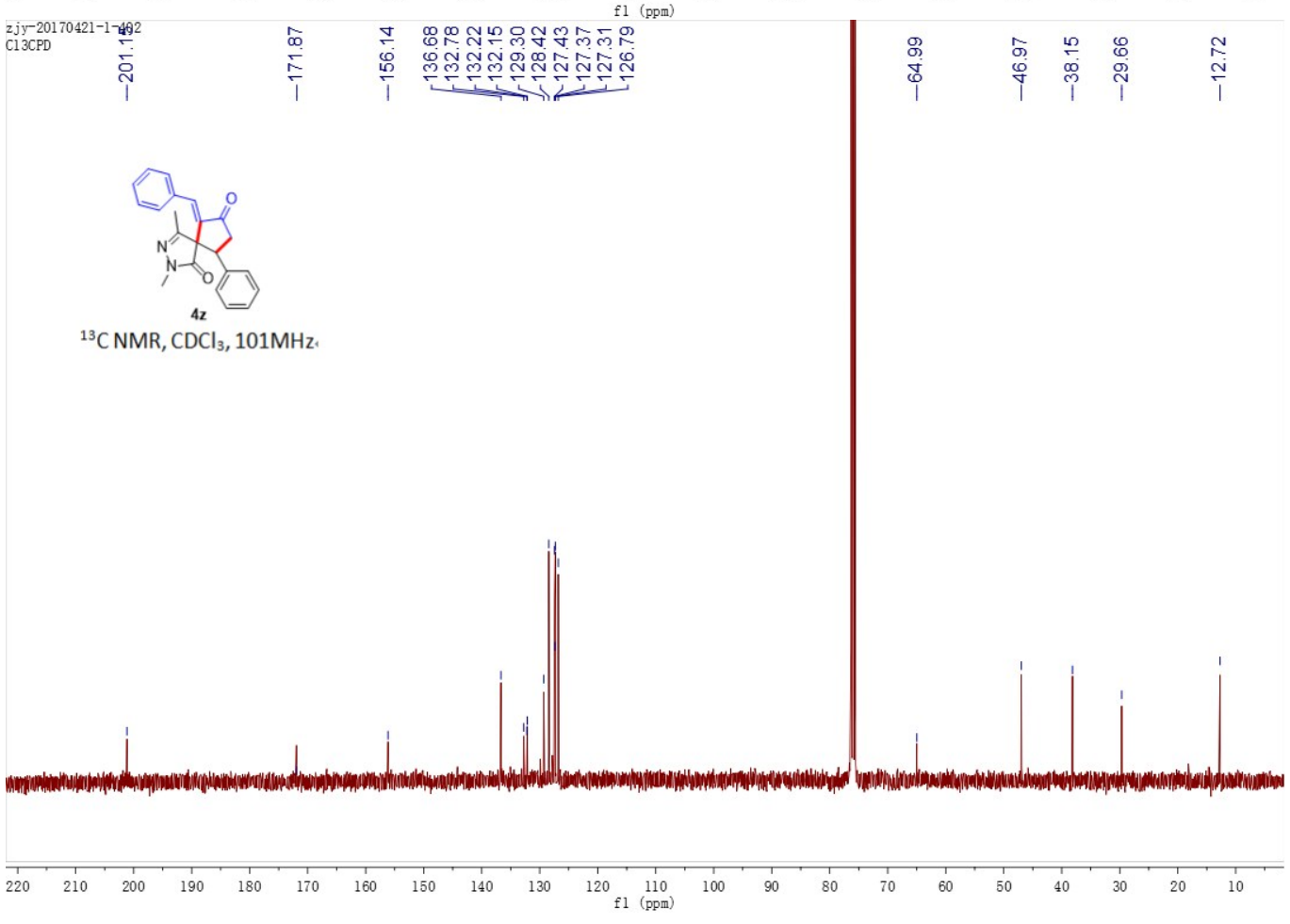

4h
^{1}H NMR, $CDCl_3$, 400 MHz
f1 (ppm)


4h
^{13}C NMR, $CDCl_3$, 101MHz
f1 (ppm)



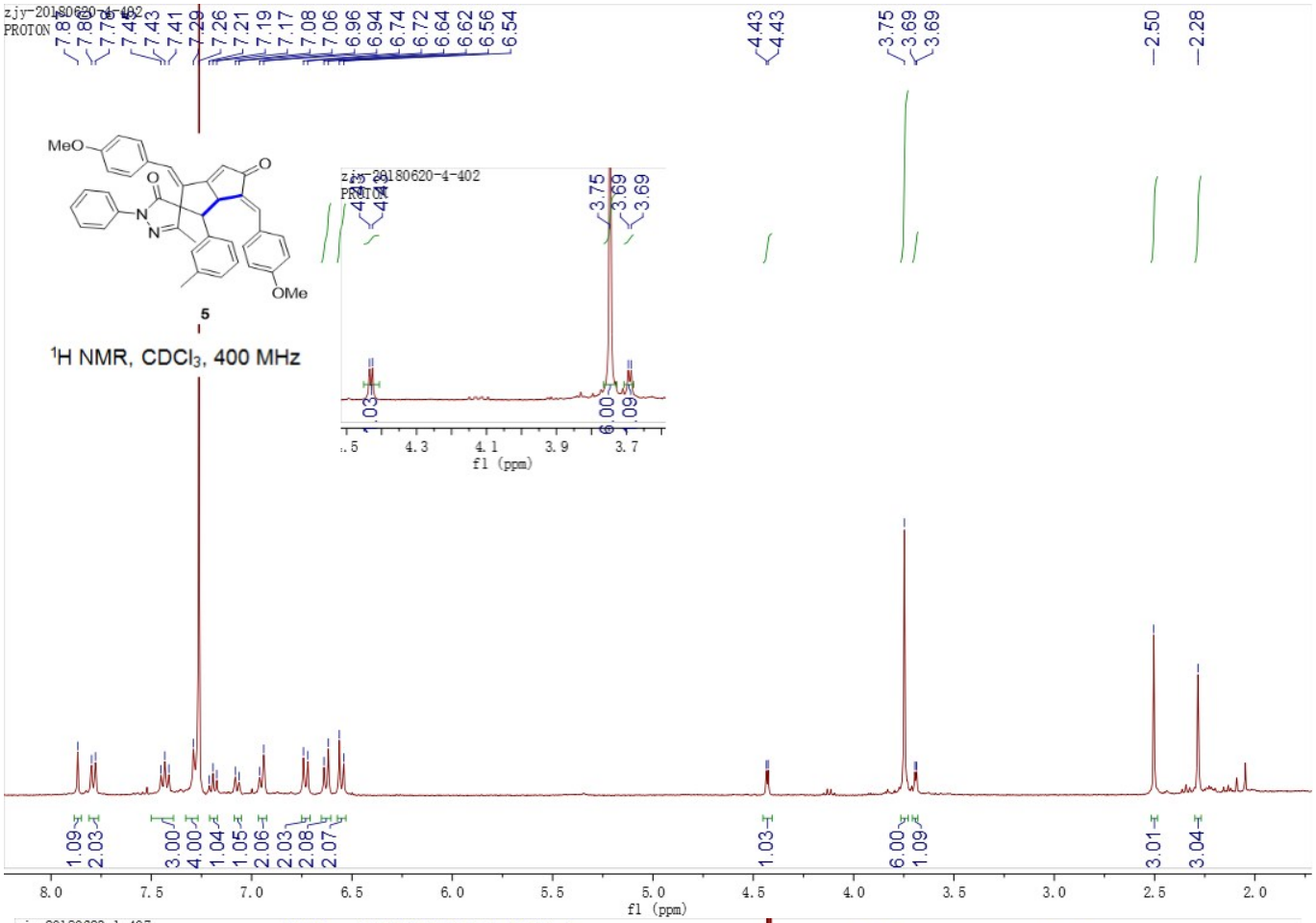
4z

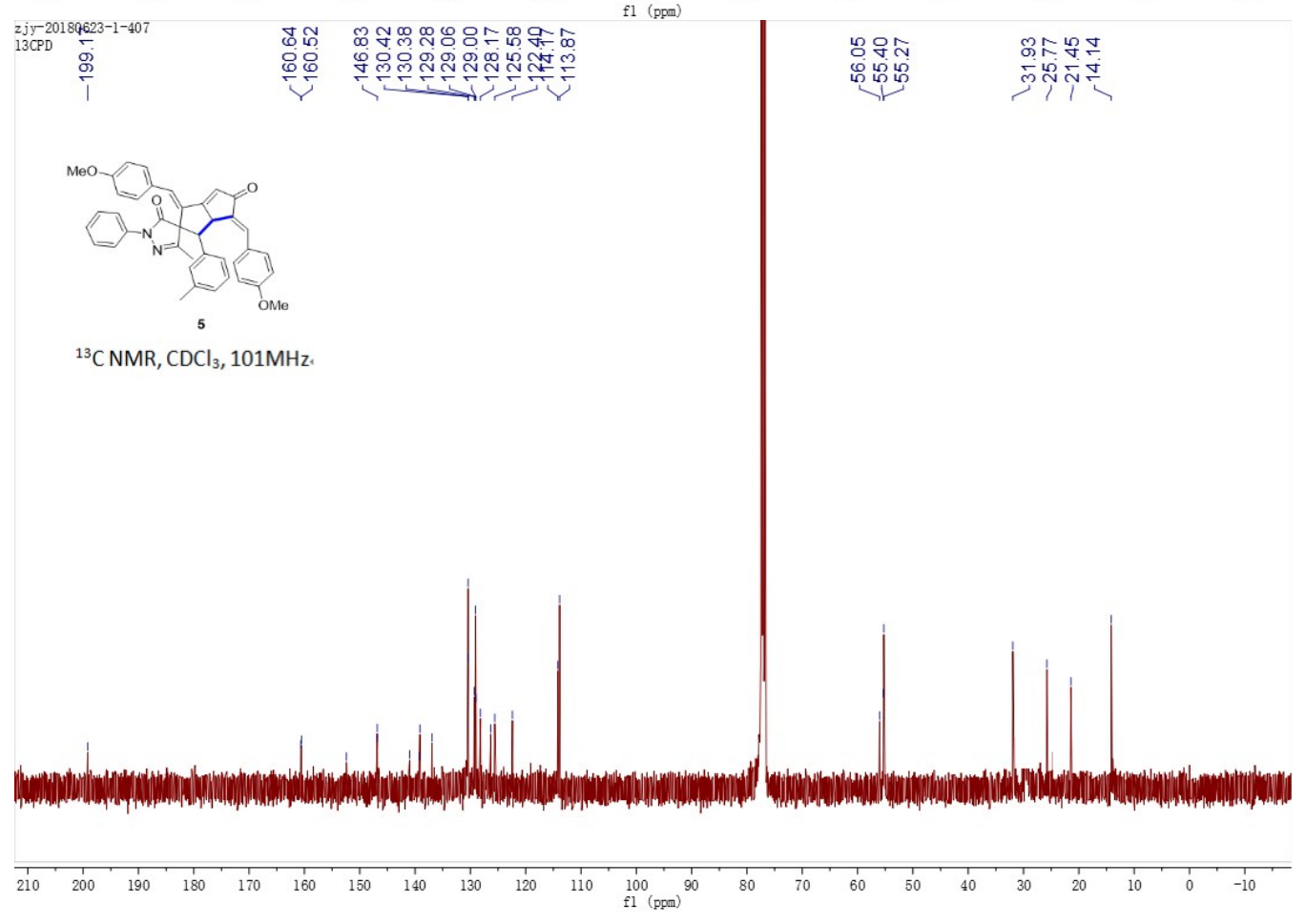
^{1}H NMR, $CDCl_3$, 400 MHz

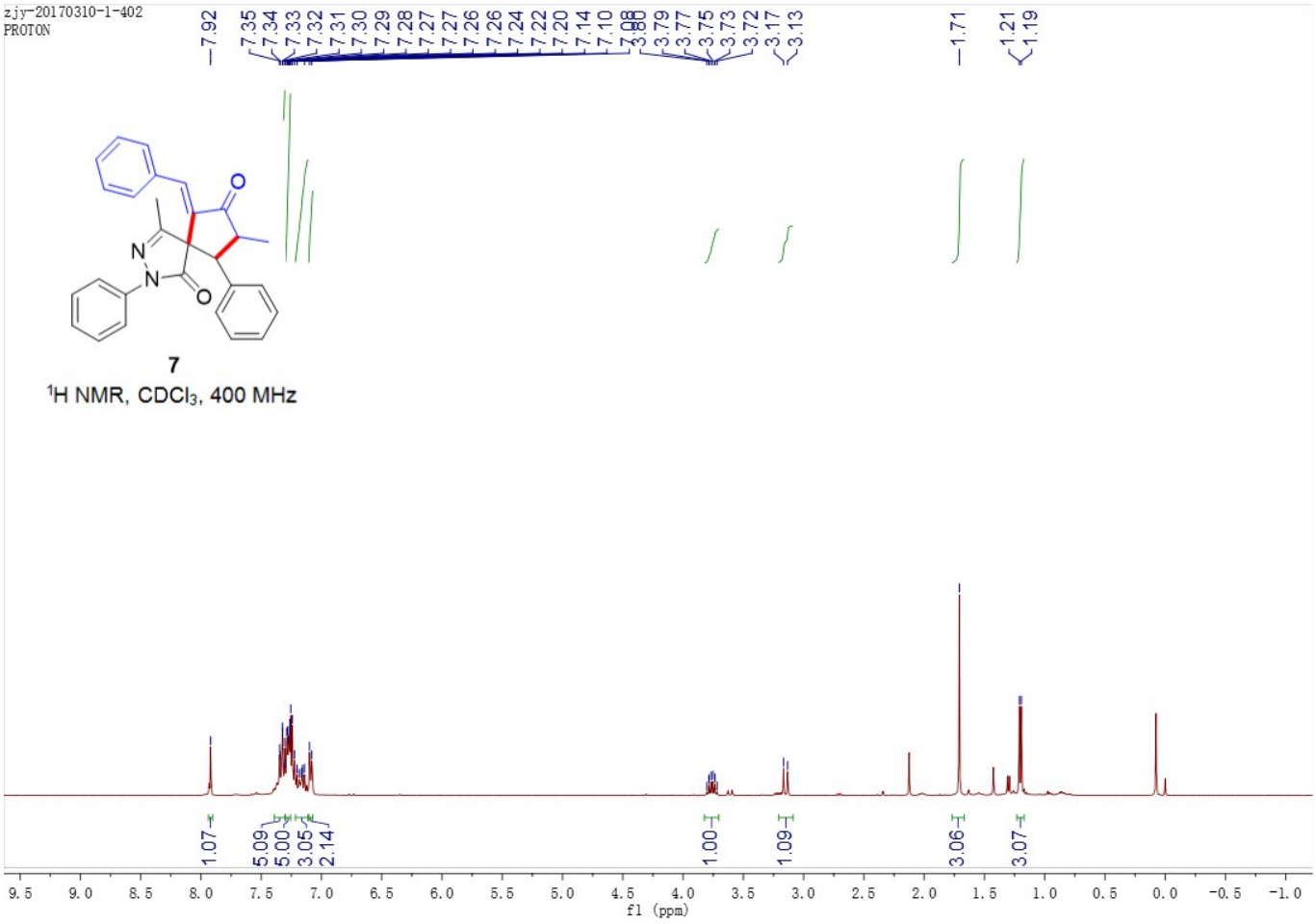


4z

^{13}C NMR, $CDCl_3$, 101MHz

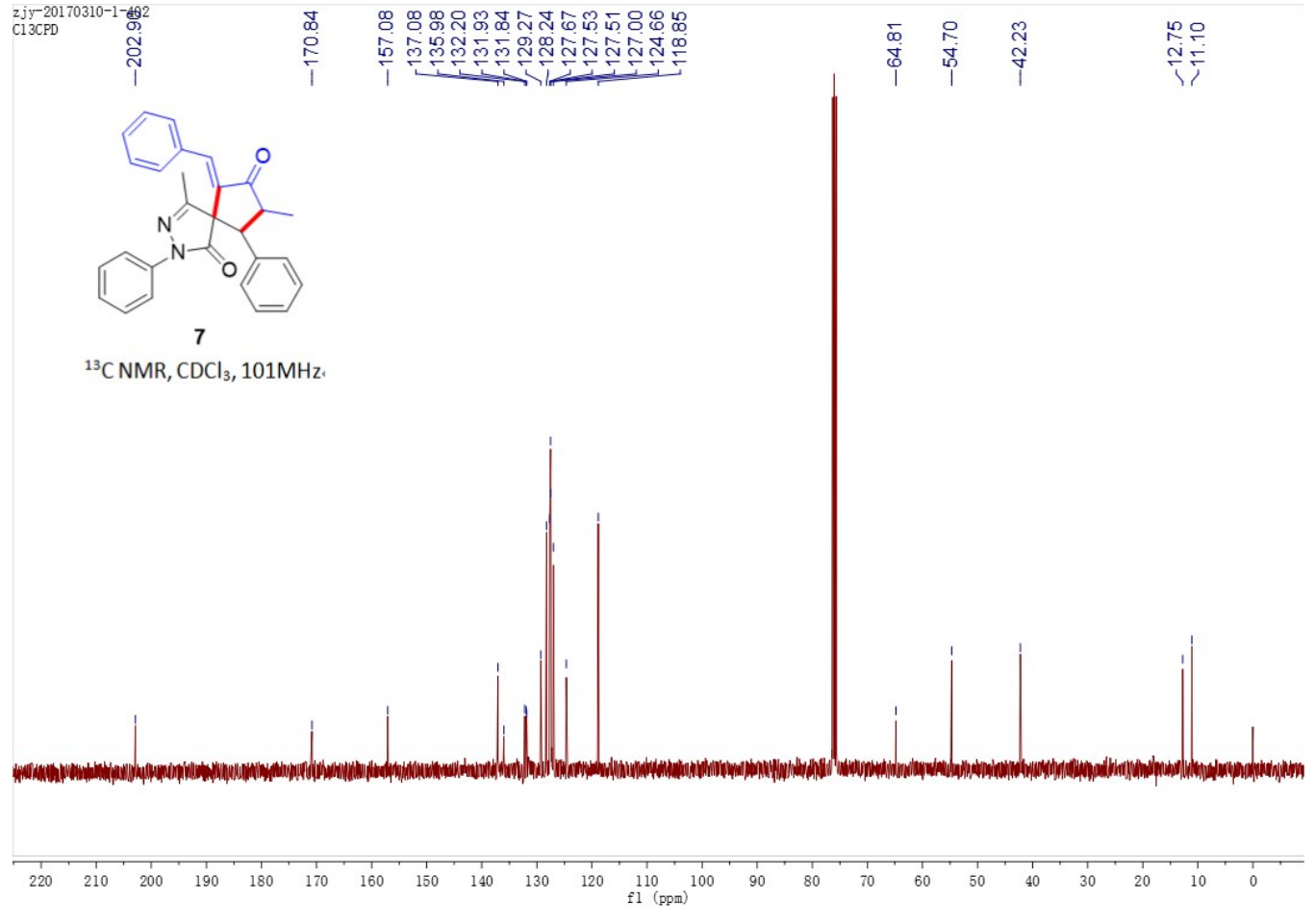

zjy-20180620-4-402
PROTON
MeO
OMe
5
^{1}H NMR, CDCl$_3$, 400 MHz
f1 (ppm)


zjy-20180623-1-407
13CPD
MeO
OMe
5
^{13}C NMR, CDCl$_3$, 101MHz
f1 (ppm)



7

^{1}H NMR, $CDCl_3$, 400 MHz

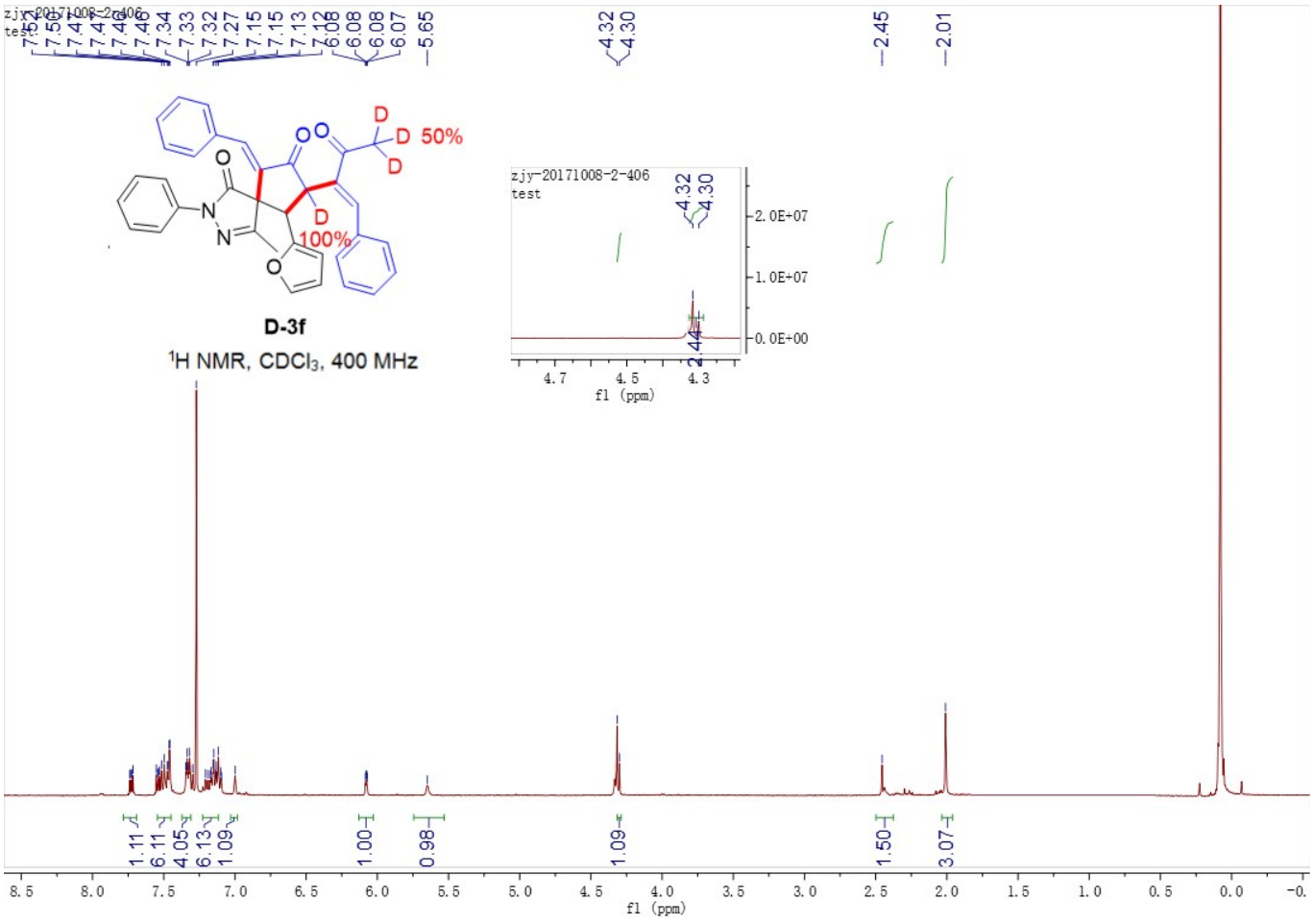


7

^{13}C NMR, $CDCl_3$, 101MHz

General procedure for deuteration experiment

Under a nitrogen atmosphere, to a mixture of benzylidenepyrazolone **2f** (0.1 mmol, 1.0 equiv.), D_2O (40.0 mg, 2.0 mmol, 20 equiv.) and DPPB (8.5 mg, 0.02 mmol, 20 mmol%) was added toluene (1 mL) *via* a syringe and allowed to stir for 5 min at 60°C. Ynones **1a** (31.7 mg, 0.22 mmol, 2.2 equiv.) was added and the reaction was allowed to stir for 36 h at 60°C. The reaction was monitored by TLC. After the reaction was completed, the reaction mixture was directly purified by flash column chromatograph (eluted with 5:1 petroleum ether/EtOAc) to afford the corresponding cycloaddition product **D-3f**.



X-ray crystallographic data of compound 3a

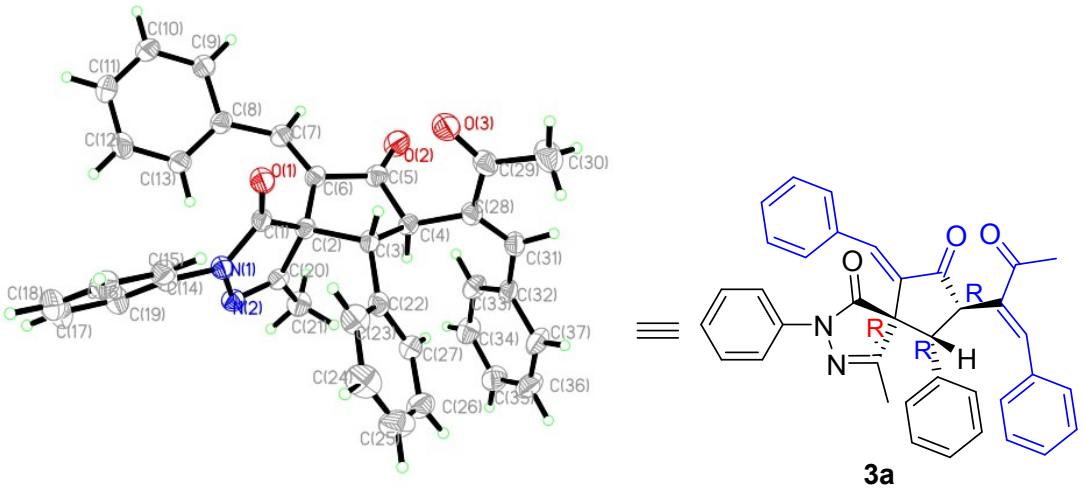


Table S1. Crystal data and structure refinement for compound **3a**

Name	Compound **3a**
Empirical formula	C37 H30N2O3
Formula weight	550.63
Temperature	113(2) K
Wavelength	0.71073Å
Crystal system, space group	Monoclinic, P2(1)/n
Unit cell dimensions	a = 9.4914(7)Å alpha = 90 deg.
	b = 13.1578(9) Å beta = 90.676(2) deg.
	c = 24.0997(19) Å gamma = 90 deg.
Volume	3009.5(4)Å^3
Z, Calculated density	4, 1.215 Mg/m^3
Absorption coefficient	0.077 mm^{-1}
F(000)	1160
Crystal size	0.20 x 0.18 x 0.12 mm
Theta range for data collection	3.10 to 27.49º

Limiting indices	-12<=h<=12, -17<=k<=17, -31<=l<=31
Reflections collected / unique	37829 / 6865 [R(int) = 0.0365]
Completeness to theta = 27.92	99.5 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9908 and 0.9847
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6865 / 0 / 381
Goodness-of-fit on F^2	1.008
Final R indices [I>2sigma(I)]	R1 = 0.0418, wR2 = 0.1195
R indices (all data)	R1 = 0.0632, wR2 = 0.1302
Largest diff. peak and hole	0.219 d -0.162 e.$Å^{-3}$

X-ray crystallographic data of compound 4h

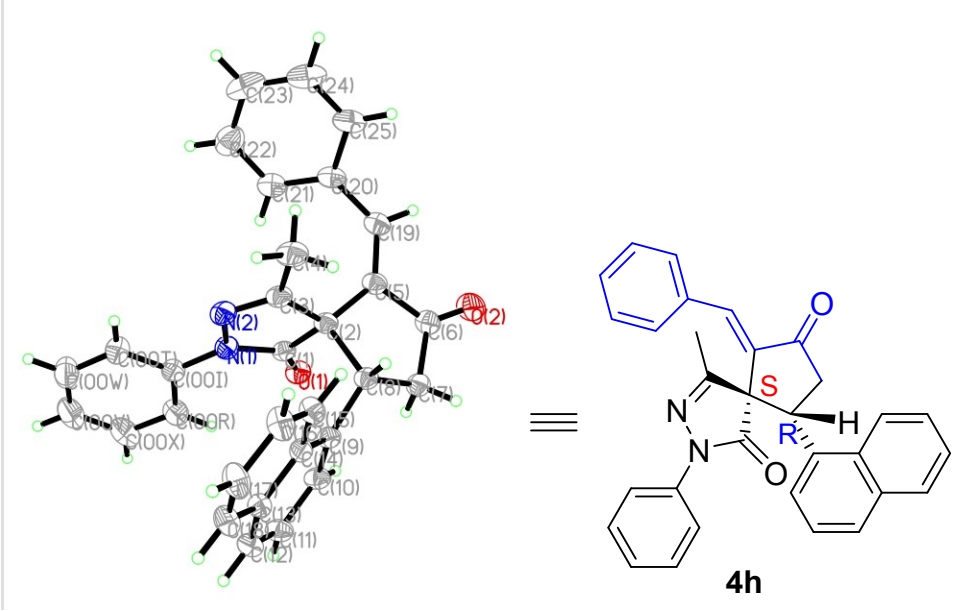


Table S2 Crystal data and structure refinement for compound **4h**

Name	Compound **4h**
Empirical formula	C31H24N2O2
Formula weight	456.52
Temperature/K	294.15
Crystal system	monoclinic
Space group	I2/a
a/Å	14.50950(10)
b/Å	15.42510(10)
c/Å	22.00390(10)
α/°	90
β/°	107.7770(10)
γ/°	90
Volume/Å^3	4689.56(6)
Z	8
ρcalcg/cm^3	1.293

μ/mm-1	0.641
F(000)	1920.0
Crystal size/mm^3	0.28 × 0.26 × 0.24
Index ranges	-17 ≤ h ≤ 18, -16 ≤ k ≤ 19, -28 ≤ l ≤ 26
Reflections collected	39753
Independent reflections	5030 [Rint = 0.0153, Rsigma = 0.0079]
Data/restraints/parameters	5030/0/318
Goodness-of-fit on F^2	1.035
Final R indexes [I>=2σ (I)]	R1 = 0.0363, wR2 = 0.1001
Final R indexes [all data]	R1 = 0.0375, wR2 = 0.1010
Largest diff. peak/hole / e Å^{-3}	0.19/-0.14

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[3] P. J. Murphy and H. Boeckemeier, *Science of Synthesis* 2007, **31b**, 2057.