Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers.

Metal-free phosphonation of benzoxazoles and benzothiazoles under oxidative conditions

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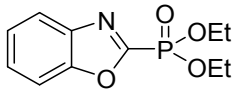
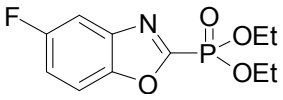
1. Diethyl benzoxazole-2-ylphosphonate (3a) The title compound was prepared according



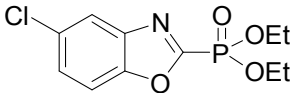
to the general procedure and purified by column chromatography to give a yellow oil, 75% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 7.6 Hz, 1H), 7.65 (d, J = 8.0 Hz, 1H), 7.47 (m, 2H), 4.47 – 4.34 (m, 4H), 1.45 (t, J = 7.2 Hz, 6H);

2. Diethyl 5-fluorobenzoxazole-2-ylphosphonate (3b) The title compound was prepared



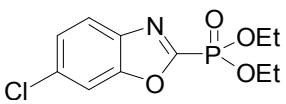
according to the general procedure and purified by column chromatography to give a white oil, 48% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (dd, J = 8.8, 4.0 Hz, 1H), 7.54 (dd, J = 8.0, 2.4 Hz, 1H), 7.27 – 7.21 (m, 1H), 4.46 – 4.34 (m, 4H), 1.45 (t, J = 7.2 Hz, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 161.30, 157.89 (J = 341), 159.69, 159.65, 157.89, 147.58, 147.54, 141.21, 141.12, 141.10, 141.01, 115.85, 115.67, 112.19, 112.12, 107.85, 107.68, 64.90, 64.86, 16.41, 16.37. ^{31}P NMR (162 MHz, $CDCl_3$) δ -2.86. ^{19}F NMR (376 MHz, $CDCl_3$) δ -122.08; HRMS (m/z): calcd for $C_{11}H_{14}NPO_4F$ $[M+H]^+$: 274.0639, found: 274.0637.

3. Diethyl 5-chlorobenzoxazole-2-ylphosphonate (3c) The title compound was prepared



according to the general procedure and purified by column chromatography to give a yellow oil, 48% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (s, 1H), 7.59 (d, J = 8.8 Hz, 1H), 7.47 (d, J = 8.8 Hz, 1H), 4.48 – 4.34 (m, 4H), 1.45 (t, J = 7.2 Hz, 6H);

4. Diethyl 6-chlorobenzoxazole-2-ylphosphonate (3d) The title compound was prepared



according to the general procedure and purified by column chromatography to give a yellow oil, 52% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (dd, J = 8.4, 4.8 Hz, 1H), 7.69 – 7.62 (m, 1H), 7.47 – 7.39 (m, 1H), 4.48 – 4.33 (m, 4H), 1.45 (dd, J = 12.0, 6.7 Hz, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 158.46, 156.70, 151.35, 151.31, 139.10, 138.99, 133.46, 126.37, 122.21, 112.18, 64.89, 64.85, 16.37, 16.33. ^{31}P NMR (162 MHz, $CDCl_3$) δ -2.86. HRMS (m/z): calcd for $C_{11}H_{14}NPO_4Cl$ $[M+H]^+$: 290.0343, found: 290.0347.

5. Diethyl 7-chlorobenzoxazole-2-ylphosphonate (3e) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 46% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, *J* = 8.0 Hz, 1H), 7.49 (d, *J* = 7.6 Hz, 1H), 7.37 (t, *J* = 8.0 Hz, 1H), 4.42 (m, 4H), 1.46 (t, *J* = 7.2 Hz, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 158.40, 156.64, 147.96, 147.92, 141.59, 141.48, 127.75, 126.21, 120.16, 117.10, 65.02, 64.98, 16.43, 16.39. ^{31}P NMR (162 MHz, $CDCl_3$) δ -3.10. HRMS (m/z): calcd for $C_{11}H_{14}NPO_4Cl$ $[M+H]^+$: 290.0343, found: 290.0344.

6. Diethyl 5-methylbenzoxazole-2-ylphosphonate (3f) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 54% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (s, 1H), 7.44 (d, *J* = 8.4 Hz, 1H), 7.22 (d, *J* = 8.4 Hz, 1H), 4.31 (m, 4H), 2.42 (s, 3H), 1.36 (t, *J* = 7.2 Hz, 6H).

7. Diethyl 6-methylbenzoxazole-2-ylphosphonate (3g) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 56% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, *J* = 8.4 Hz, 1H), 7.43 (s, 1H), 7.24 (d, *J* = 8.4 Hz, 1H), 4.43 – 4.33 (m, 4H), 2.53 (s, 3H), 1.43 (t, *J* = 7.2 Hz, 6H);

8. Diethyl 7-methylbenzoxazole-2-ylphosphonate (3h) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 60% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68 (d, *J* = 7.2 Hz, 1H), 7.31 (dd, *J* = 15.2, 7.6 Hz, 2H), 4.45 – 4.34 (m, 4H), 2.58 (s, 3H), 1.44 (t, *J* = 7.2 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 157.45, 155.68, 150.66, 150.63, 140.03, 139.93, 128.32, 125.44, 122.42, 118.98, 64.73, 64.69, 16.44, 16.40, 15.42. ^{31}P NMR (243 MHz, $CDCl_3$) δ -1.94. HRMS (m/z): calcd for $C_{12}H_{17}NPO_4$ $[M+H]^+$: 270.0890, found: 270.0887.

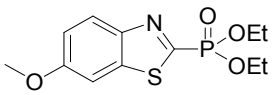
9. Diethyl 5-tert-butylbenzoxazole-2-ylphosphonate (3i) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 63% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (s, 1H), 7.56 (s, 2H), 4.46 – 4.30 (m, 4H), 1.43 (t, *J* = 7.2 Hz, 6H), 1.39 (s, 9H);

10. Diethyl benzothiazole-2-ylphosphonate (3j) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow oil, 77% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.25 (d, *J* = 8.0 Hz, 1H), 8.02 (d, *J* = 7.6 Hz, 1H), 7.56 (m, 2H), 4.43 – 4.26 (m, 4H), 1.41 (t, *J* = 7.2 Hz, 6H);

11. Diethyl 5-chlorobenzothiazole-2-ylphosphonate (3k) The title compound was prepared according to the general procedure and purified by column

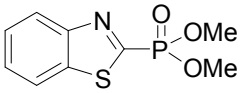
chromatography to give a yellow oil, 77% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.22 (s, 1H), 7.93 (d, *J* = 7.2 Hz, 1H), 7.51 (d, *J* = 7.6 Hz, 1H), 4.43 – 4.25 (m, 4H), 1.41 (t, *J* = 5.6 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 163.15, 161.57, 155.51, 155.32, 134.72, 134.71, 133.12, 127.72, 124.57, 122.78, 122.77, 64.36, 64.32, 16.36, 16.32. ^{31}P NMR (243 MHz, $CDCl_3$) δ 3.18. HRMS (m/z): calcd for $C_{11}H_{14}NPO_3ClS$ $[M+H]^+$: 306.0115, found: 306.0119.

12. Diethyl 6-methoxy-benzothiazole-2-ylphosphonate (3l) The title compound was



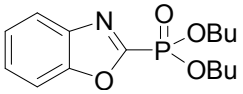
prepared according to the general procedure and purified by column chromatography to give a yellow oil, 77% yield. ^{1}H NMR (400 MHz, $cdcl_3$) δ 8.11 (d, *J* = 9.2 Hz, 1H), 7.41 (s, 1H), 7.18 (d, *J* = 9.2 Hz, 1H), 4.30 (m, 4H), 3.91 (s, 3H), 1.39 (t, *J* = 7.2 Hz, 6H).

13. Dimethyl benzothiazole -2-ylphosphonate (3m) The title compound was prepared



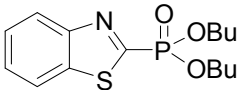
according to the general procedure and purified by column chromatography to give a yellow oil, 49% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 8.4 Hz, 1H), 8.03 (d, *J* = 7.6 Hz, 1H), 7.58 (m, 2H), 3.97 (m, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.50, 157.91, 154.69, 154.50, 136.47, 127.26, 127.06, 125.06, 122.08, 54.35, 54.31. ^{31}P NMR (162 MHz, $CDCl_3$) δ 6.71. HRMS (m/z): calcd for $C_9H_{11}NPO_3S$ $[M+H]^+$: 244.0192, found: 244.0193.

14. Dibutyl benzoxazole-2-ylphosphonate (3o) The title compound was prepared



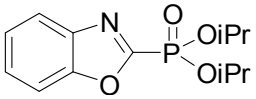
according to the general procedure and purified by column chromatography to give a yellow oil, 63% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, *J* = 7.6 Hz, 1H), 7.65 (d, *J* = 8.4 Hz, 1H), 7.46 (m, 2H), 4.39 – 4.25 (m, 4H), 1.81 – 1.72 (m, 4H), 1.50 – 1.40 (m, 4H), 0.94 (t, *J* = 7.2 Hz, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 157.75, 155.99, 151.22, 151.18, 140.41, 140.30, 127.50, 125.41, 121.75, 111.65, 68.35, 68.30, 32.44, 32.40, 18.70, 13.62. ^{31}P NMR (162 MHz, $CDCl_3$) δ -1.95. HRMS (m/z): calcd for $C_{15}H_{23}NPO_4$ $[M+H]^+$: 312.1359, found: 312.1358.

15. Dibutyl benzothiazole-2-ylphosphonate (3p) The title compound was prepared



according to the general procedure and purified by column chromatography to give a yellow solid, 69% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.25 (d, *J* = 7.6 Hz, 1H), 8.02 (d, *J* = 7.6 Hz, 1H), 7.56 (m, 2H), 4.34 – 4.19 (m, 4H), 1.77 – 1.68 (m, 4H), 1.42 (m, 4H), 0.92 (t, *J* = 7.2 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 160.92, 159.34, 154.79, 154.60, 136.52, 127.08, 126.93, 125.06, 122.06, 67.86, 67.82, 32.49, 32.44, 18.74, 13.65. ^{31}P NMR (162 MHz, $CDCl_3$) δ 4.19. HRMS (m/z): calcd for $C_{15}H_{23}NPO_3S$ $[M+H]^+$: 328.1131, found: 328.1130.

16. Diisopropyl benzoxazole-2-ylphosphonate (3q) The title compound was prepared



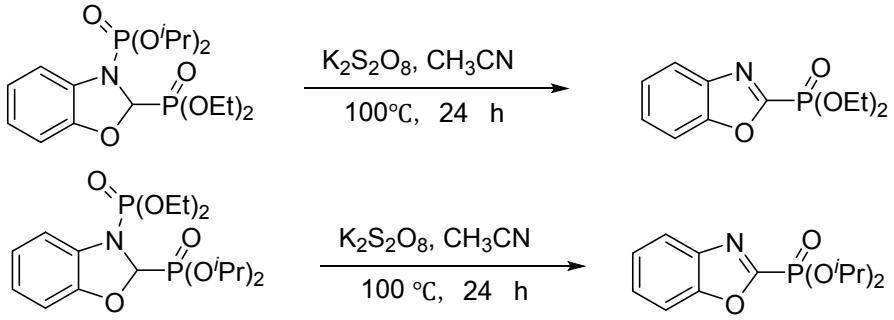
according to the general procedure and purified by column chromatography to give a yellow oil, 60% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, *J* = 7.9 Hz, 1H), 7.64 (d, *J* = 8.0 Hz, 1H), 7.45 (m, 2H), 4.97 (m, 2H), 1.43 (m, 12H);

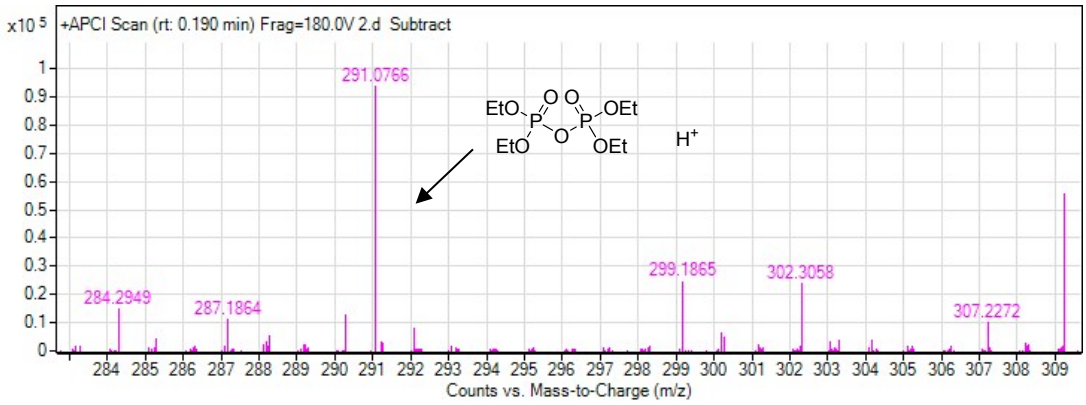
17. Diisopropyl benzothiazole-2-ylphosphonate (3r) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow solid, 78% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.25 (d, J = 8.1 Hz, 1H), 8.01 (d, J = 7.8 Hz, 1H), 7.55 (m, 2H), 4.92 (m, 2H), 1.43 (d, J = 6.2 Hz, 6H), 1.34 (d, J = 6.2 Hz, 6H);

18. (4-Methyl-thiazol-2-yl)-phosphonic acid diethyl ester (3s) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow solid, 27% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22 (d, J = 8.0 Hz, 1H), 4.34 – 4.14 (m, 4H), 2.56 (d, J = 8.0 Hz, 3H), 1.37 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.73, 119.65, 63.84, 63.79, 17.08, 16.43, 16.36. ^{31}P NMR (162 MHz, $CDCl_3$) δ 4.61. HRMS (m/z): calcd for $C_8H_{15}NPO_3S$ $[M+H]^+$: 236.0505, found: 236.0506.

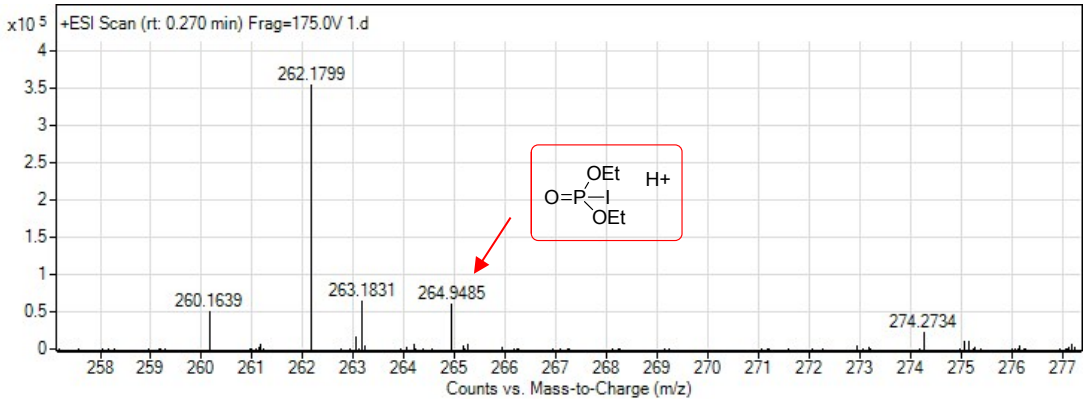
19. Thiazol-2-yl-phosphonic acid diethyl ester (3t) The title compound was prepared according to the general procedure and purified by column chromatography to give a yellow solid, 9% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.17 – 8.11 (m, 1H), 7.70 (t, J = 3.2 Hz, 1H), 4.36 – 4.18 (m, 4H), 1.38 (t, J = 7.2 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.75, 158.13, 146.27, 146.08, 124.66, 64.00, 63.96, 16.41, 16.37. ^{31}P NMR (243 MHz, $CDCl_3$) δ 4.07. HRMS (m/z): calcd for $C_7H_{13}NPO_3S$ $[M+H]^+$ 222.0348, found: 222.0350.

The studies of tracing the procedure of phosphorus

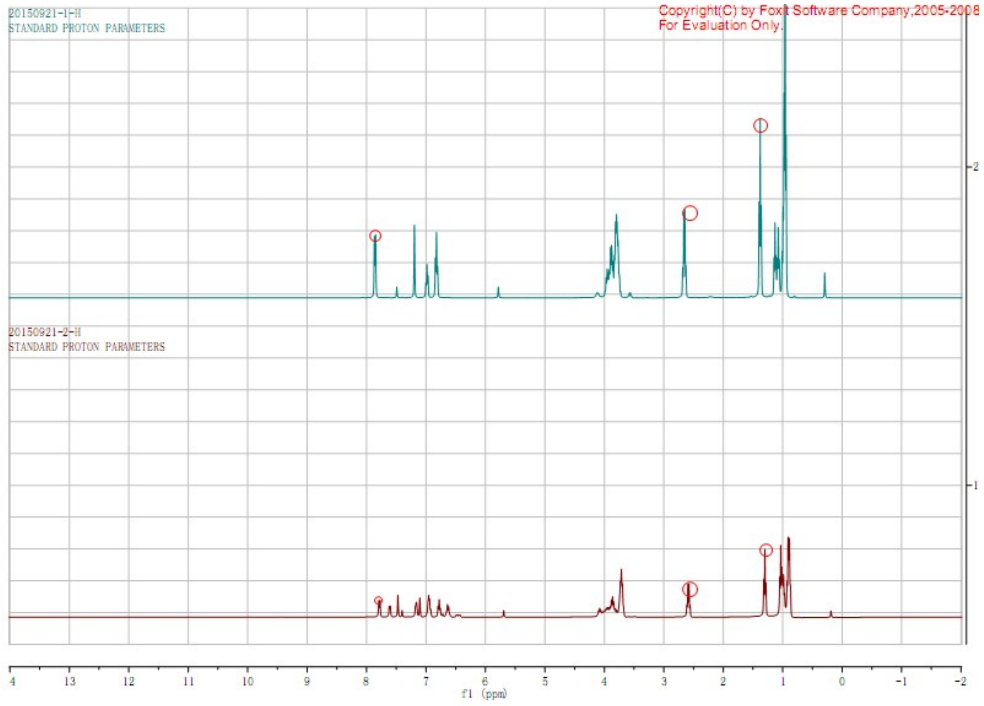




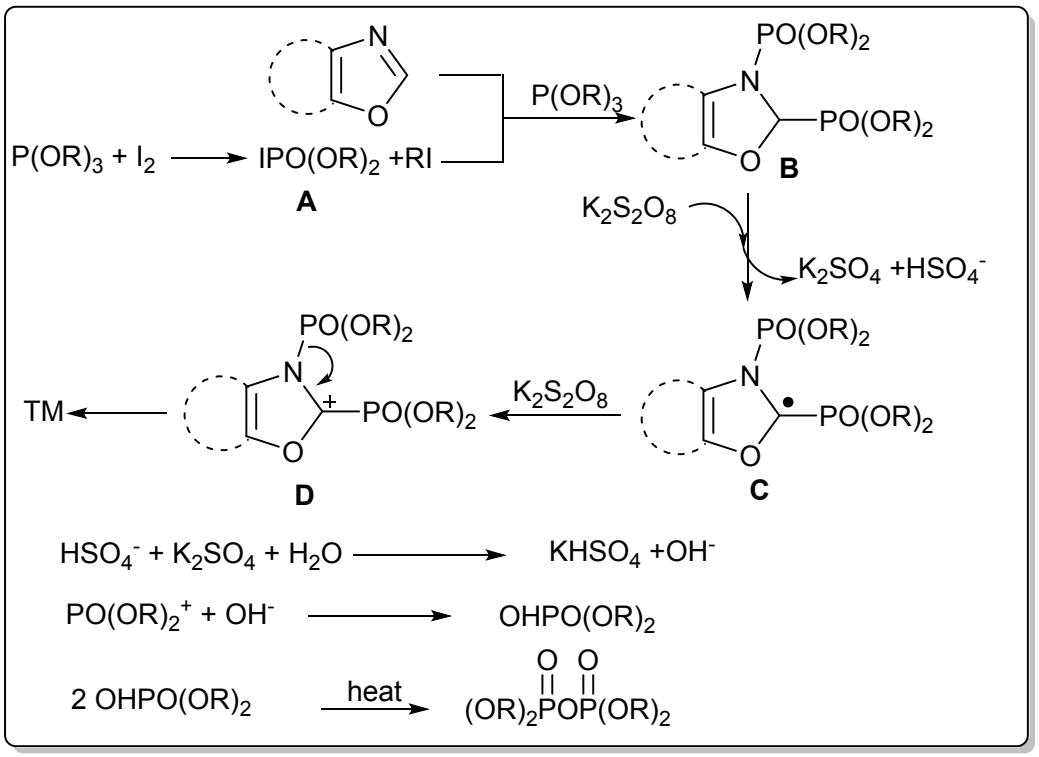
The detection of intermediate by HR-MS



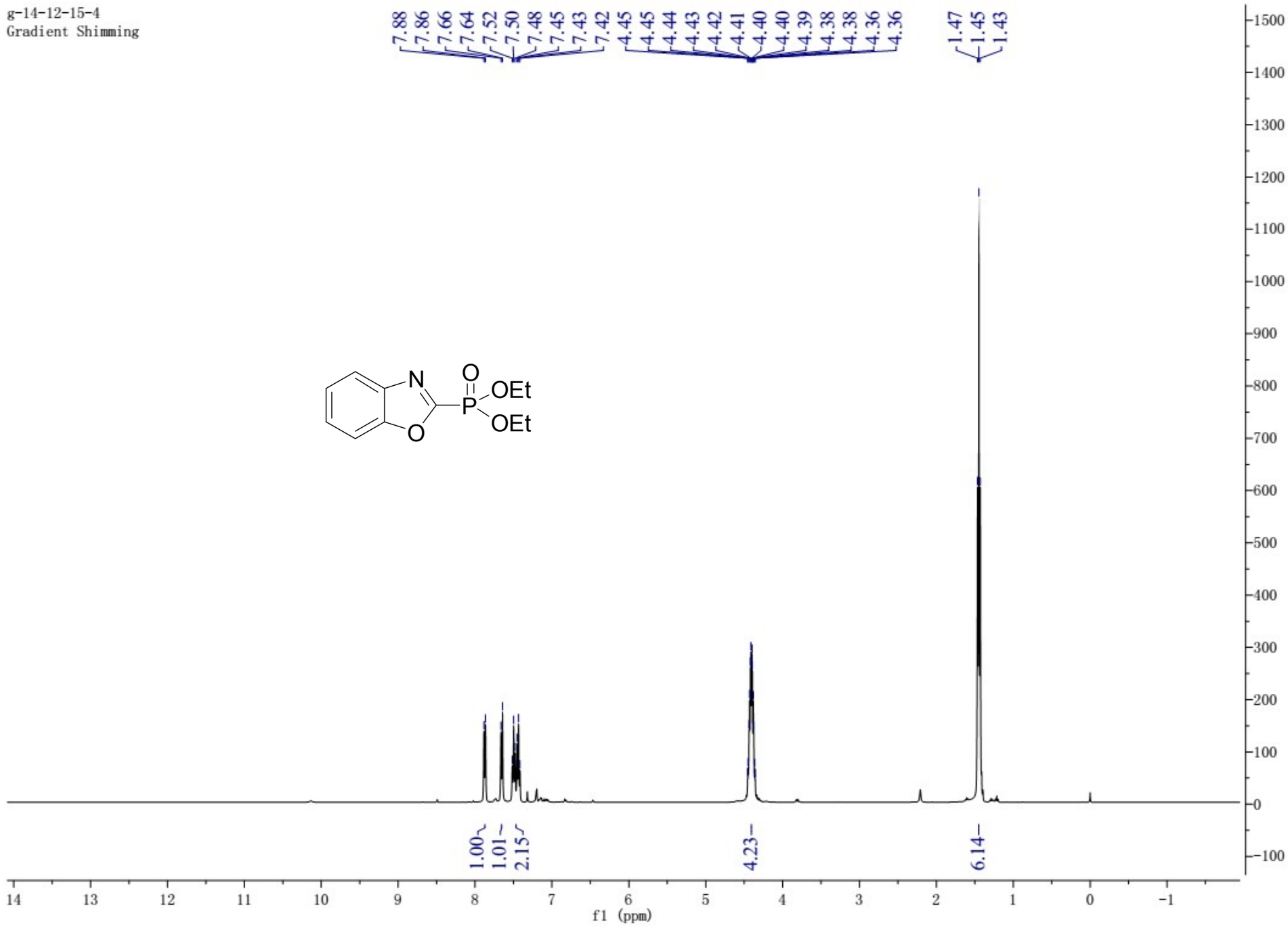
The change of the mount of ICH_2CH_3 with the procedure using the nitrobenzene as internal standard.



The probable mechanism of the reaction


P(OR)3 + I2
IPO(OR)2 +RI
A
P(OR)3
PO(OR)2
PO(OR)2
B
K2S2O8
K2SO4 +HSO4-
PO(OR)2
PO(OR)2
TM
K2S2O8
PO(OR)2
PO(OR)2
D
C
HSO4- + K2SO4 + H2O
KHSO4 +OH-
PO(OR)2+ + OH-
OHPO(OR)2
2 OHPO(OR)2
heat
(OR)2POP(OR)2

g-14-12-15-4
Gradient Shimming



20141211-3H
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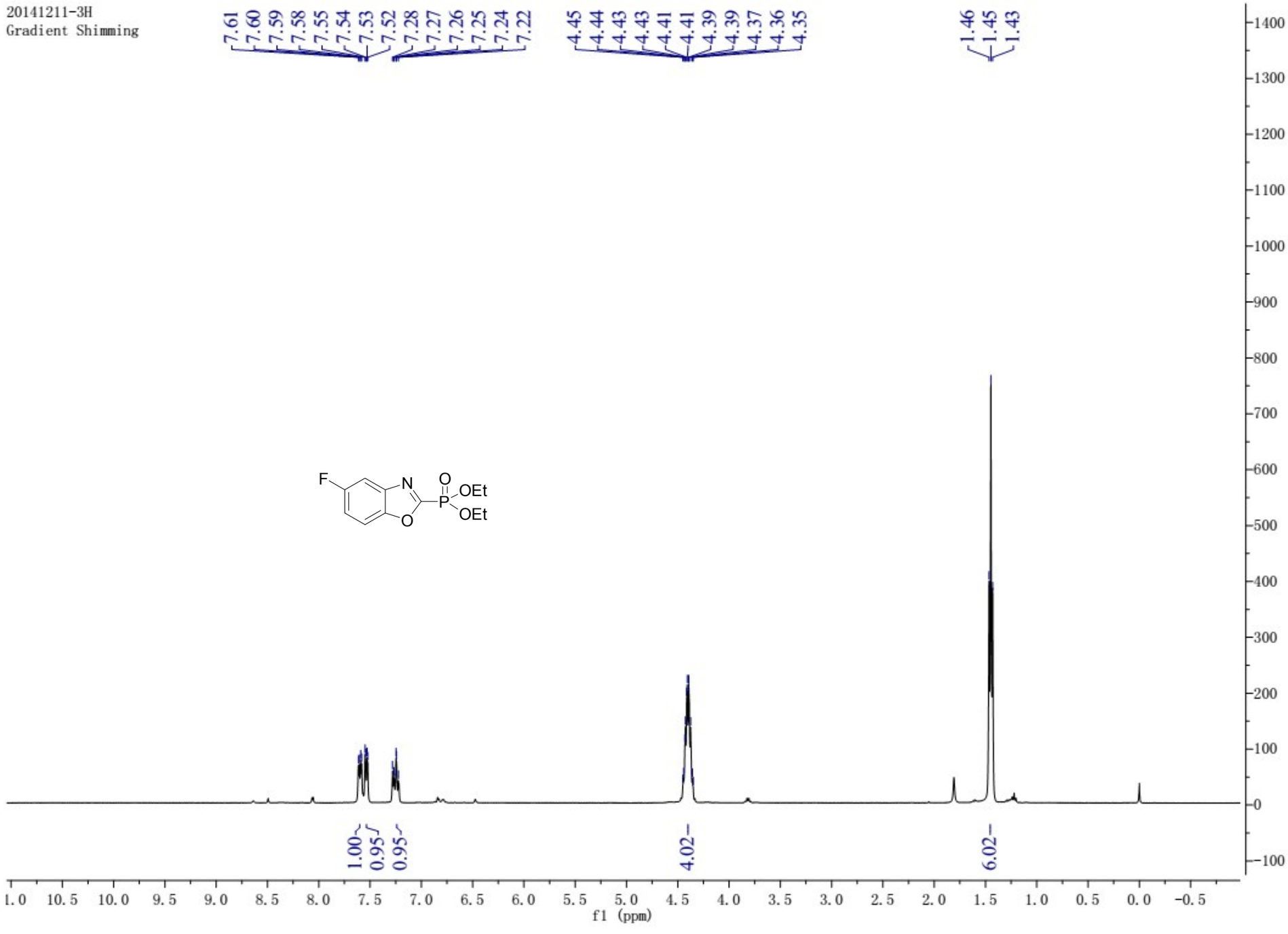
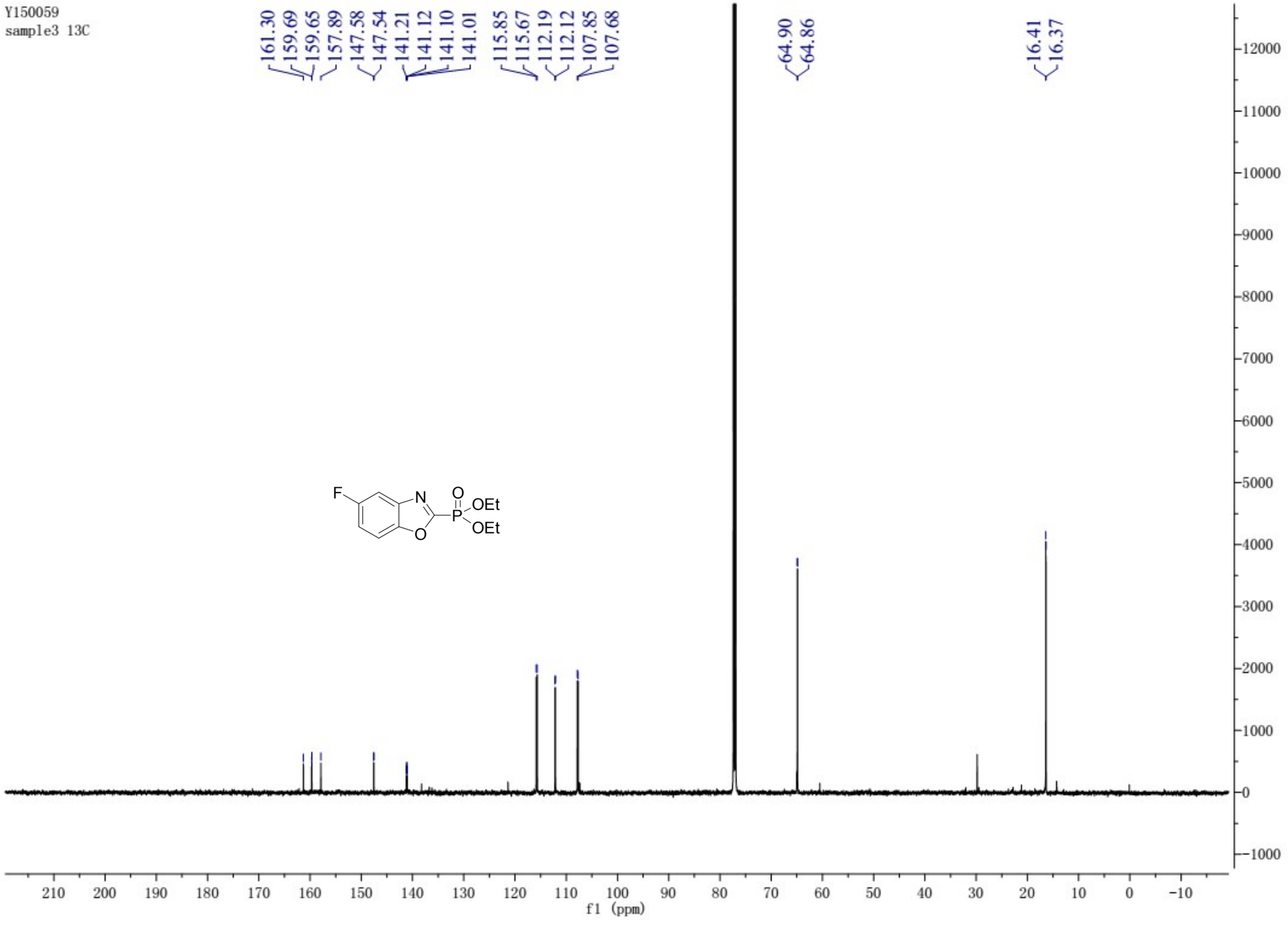
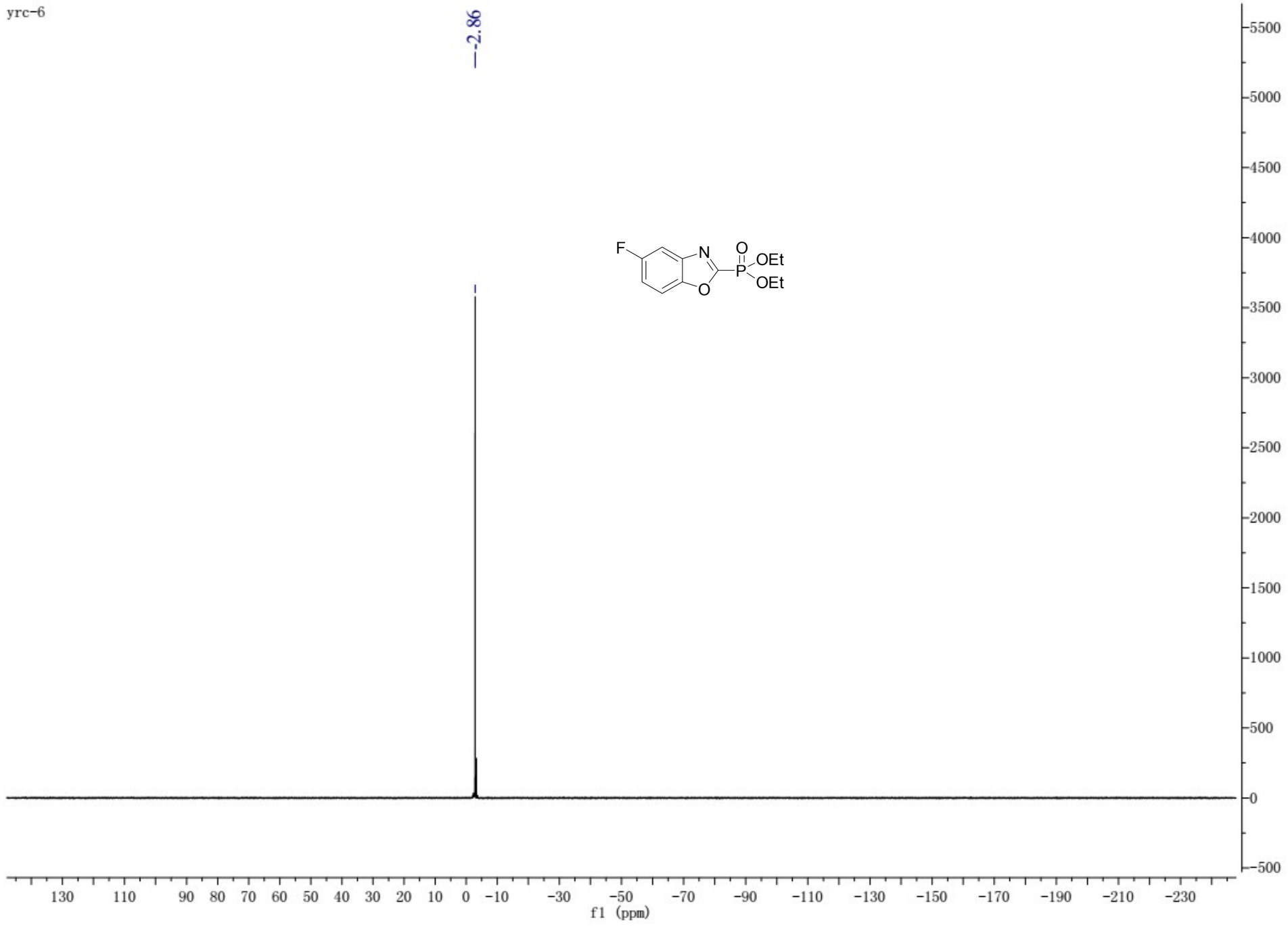
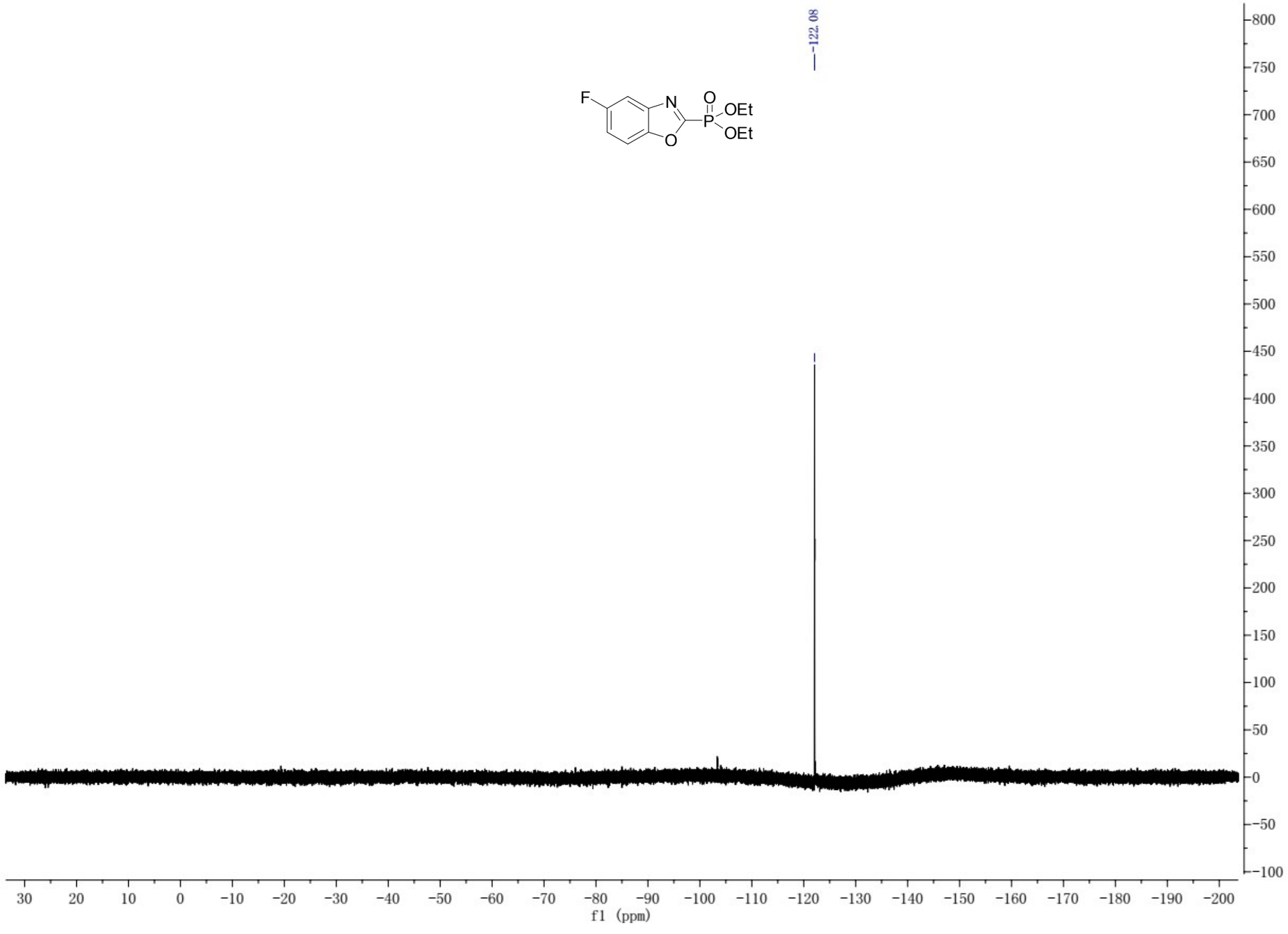


Y150059
sample3 13C



yrc-6


-2.86
F
N
O
P
O
OEt
OEt
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230
f1 (ppm)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OEt
O
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650
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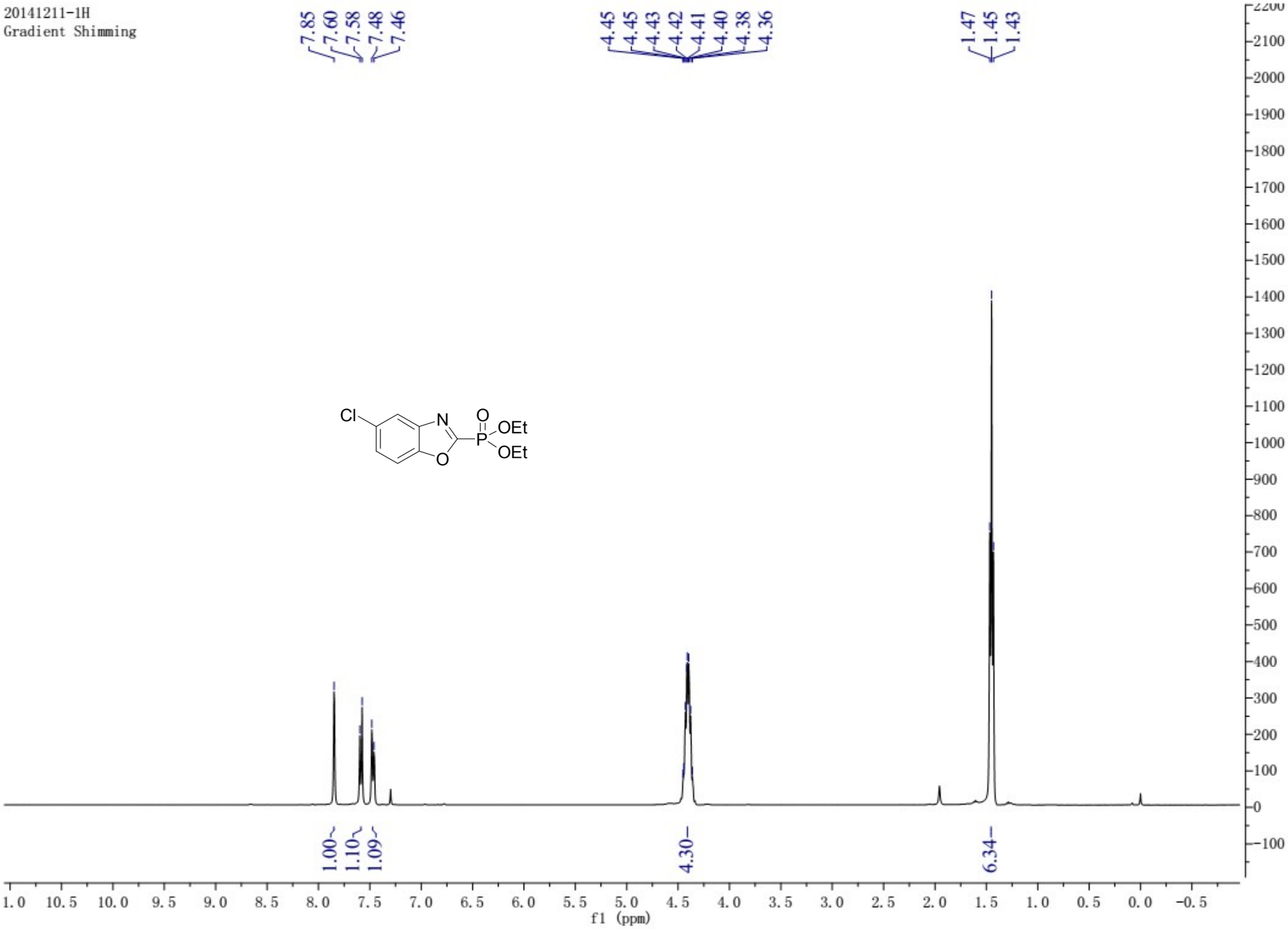
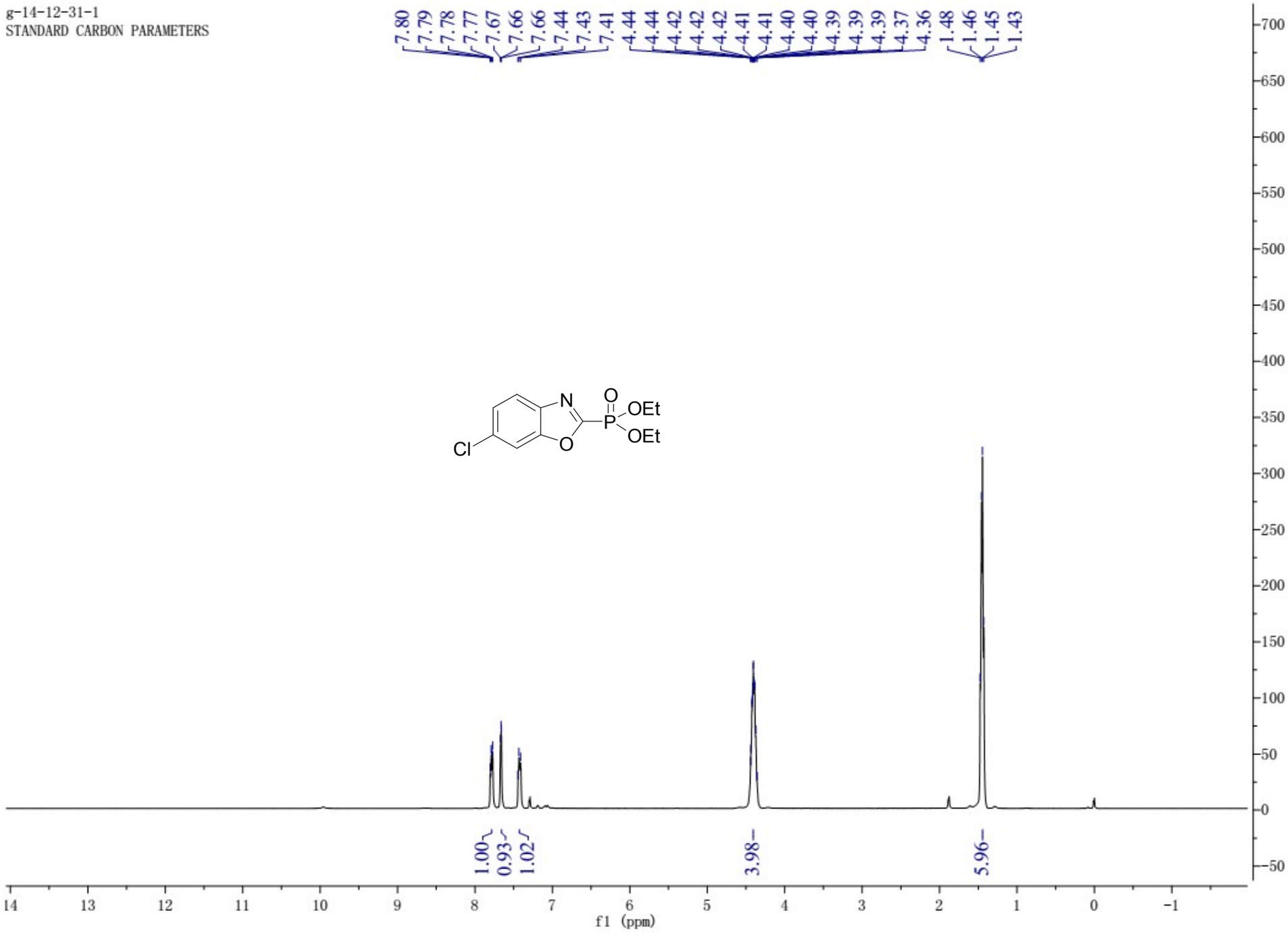
300
250
200
150
100
50
0
−50
−100
30 20 10 0 −10 −20 −30 −40 −50 −60 −70 −80 −90 −100 −110 −120 −130 −140 −150 −160 −170 −180 −190 −200
f1 (ppm)

20141211-1H
Gradient Shimming

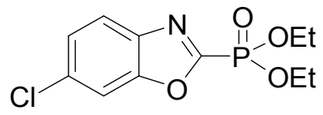


g-14-12-31-1
STANDARD CARBON PARAMETERS



Y150059
sample9 13C

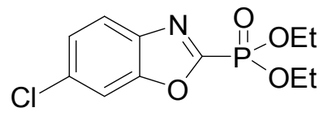
158.46
156.70
151.35
151.31
139.10
138.99
133.46
126.37
122.21
112.18
64.89
64.85
16.37
16.33



f1 (ppm)

yrc-3

-2.86

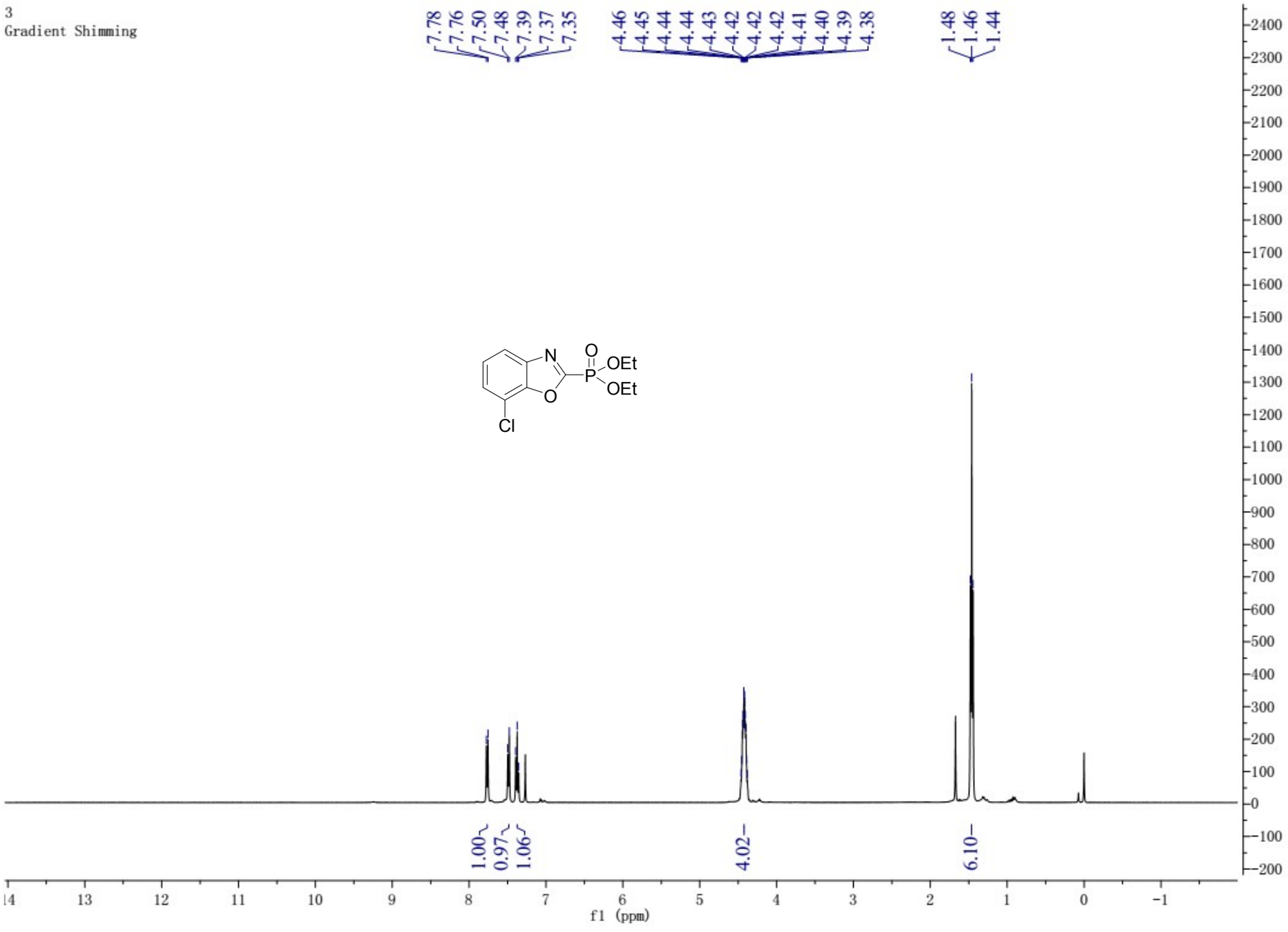


9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500

130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230

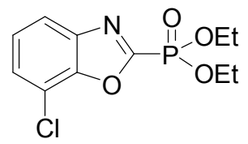
f1 (ppm)

3
Gradient Shimming



Y150059
sample14 13C

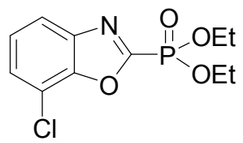
158.40
156.64
147.96
147.92
141.59
141.48
127.75
126.21
120.16
117.10
65.02
64.98
16.43
16.39



f1 (ppm)

yrc-5

3.10

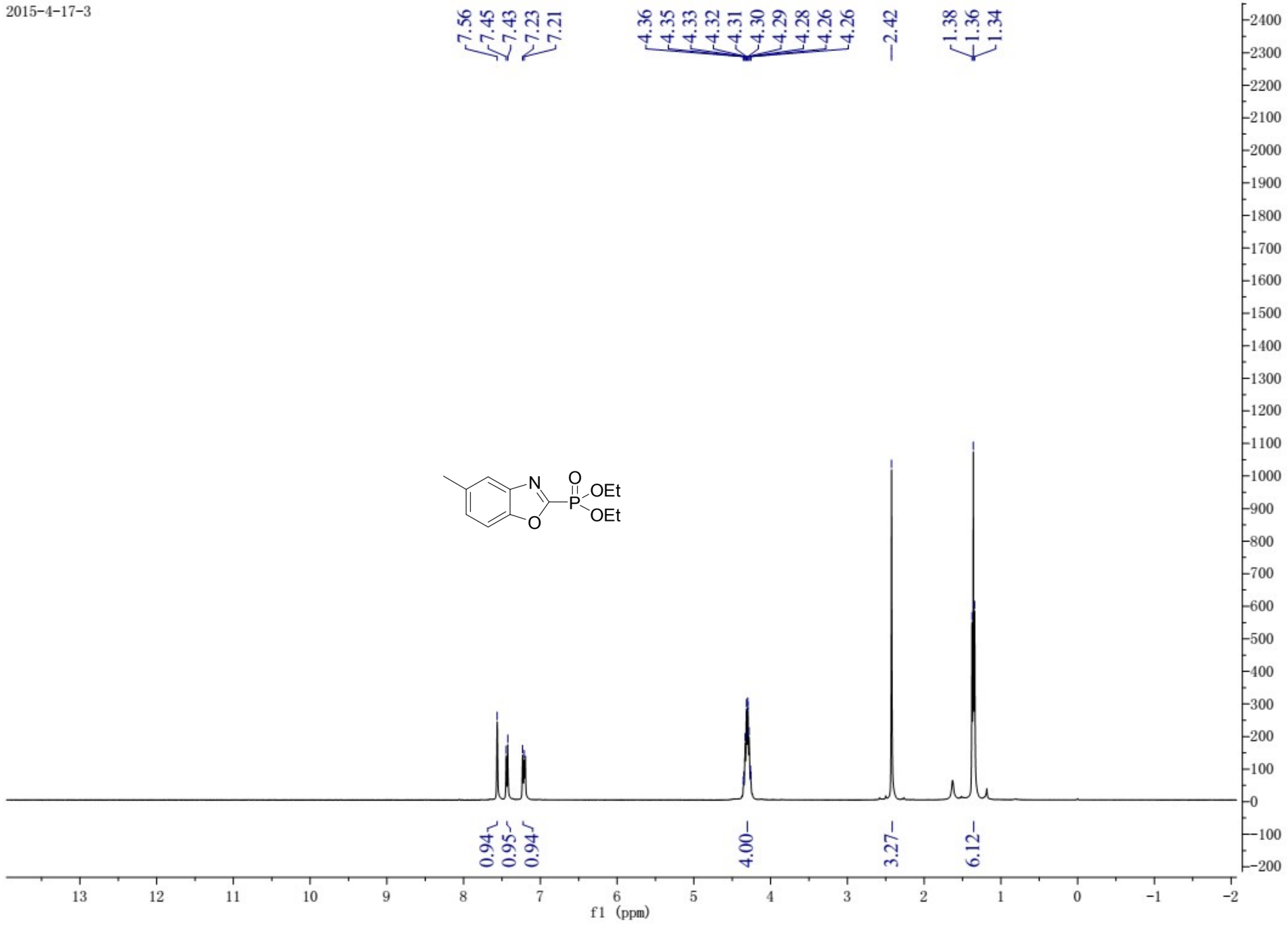


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0

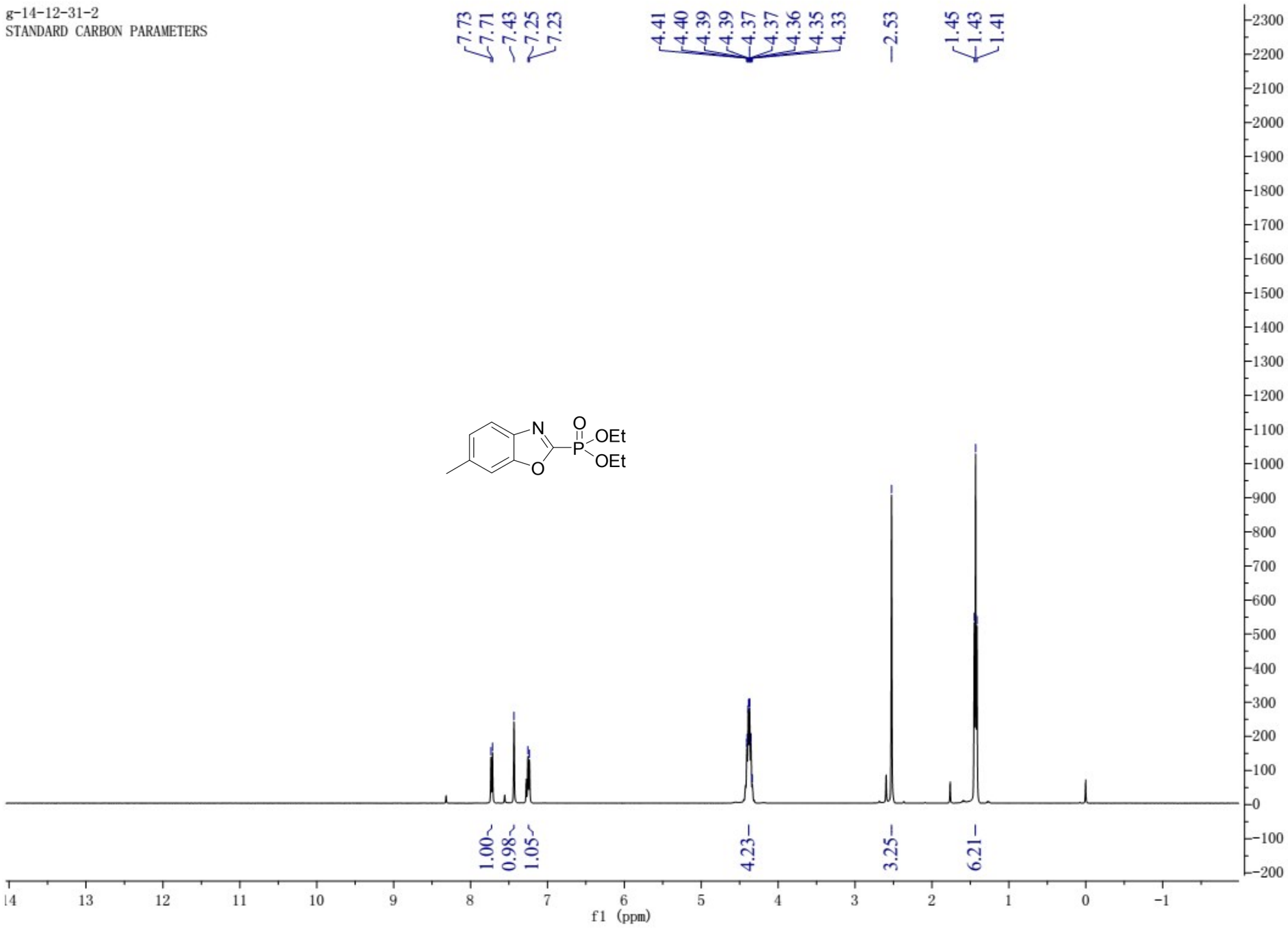
130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230

f1 (ppm)

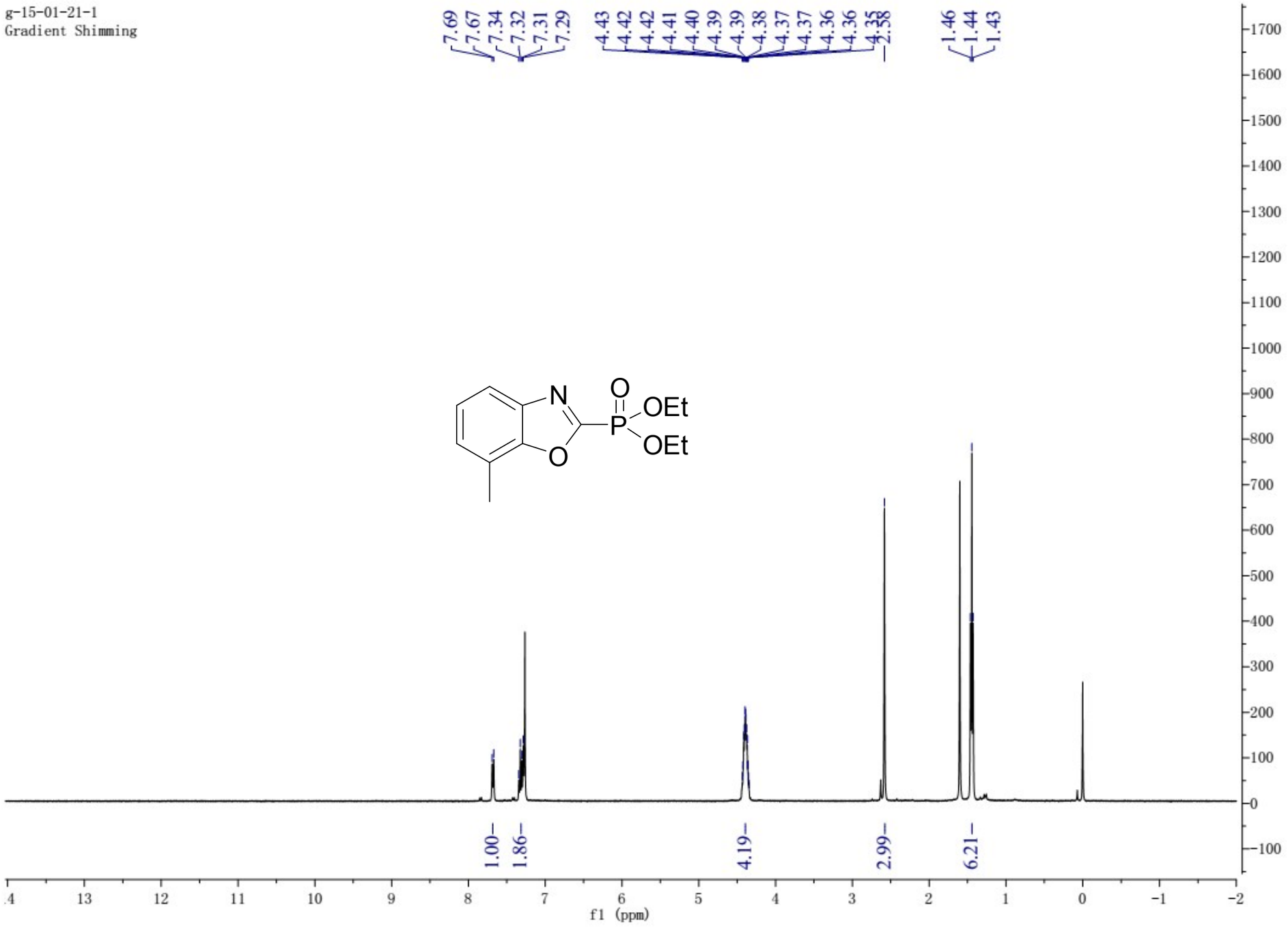
2015-4-17-3


7.56
7.45
7.43
7.23
7.21
4.36
4.35
4.33
4.32
4.31
4.30
4.29
4.28
4.26
4.26
2.42
1.38
1.36
1.34
N
O
P
OEt
OEt
O
0.94
0.95
0.94
4.00
3.27
6.12
f1 (ppm)

g-14-12-31-2
STANDARD CARBON PARAMETERS



g-15-01-21-1
Gradient Shimming

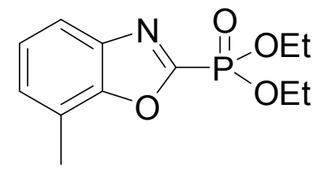


Y150445
sample7 13C

157.45
155.68
150.66
150.63
140.03
139.93
128.32
125.44
122.42
118.98

64.73
64.69

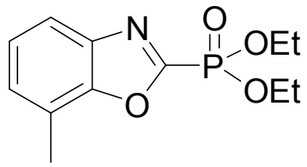
16.44
16.40
15.42



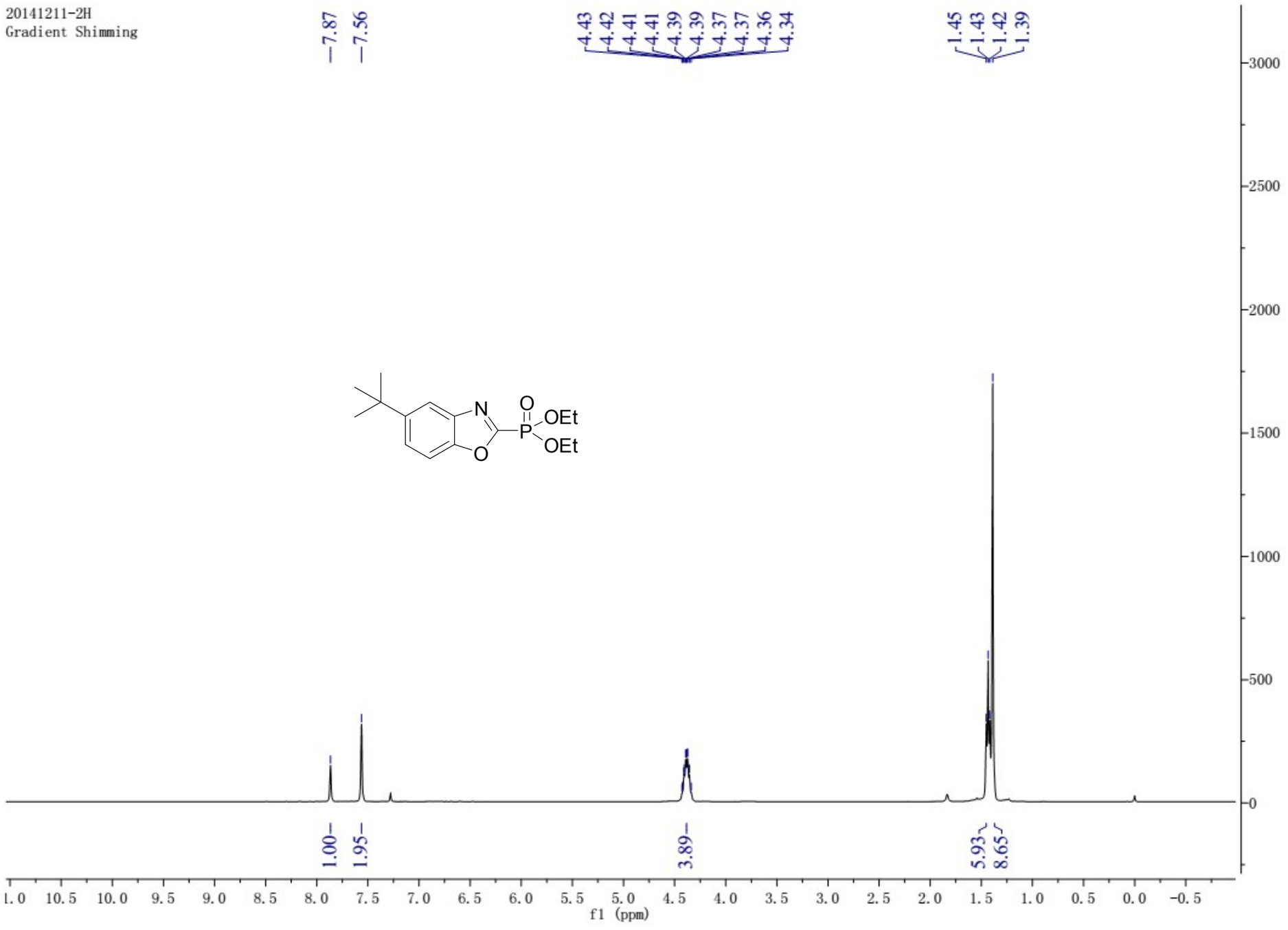
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500

220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

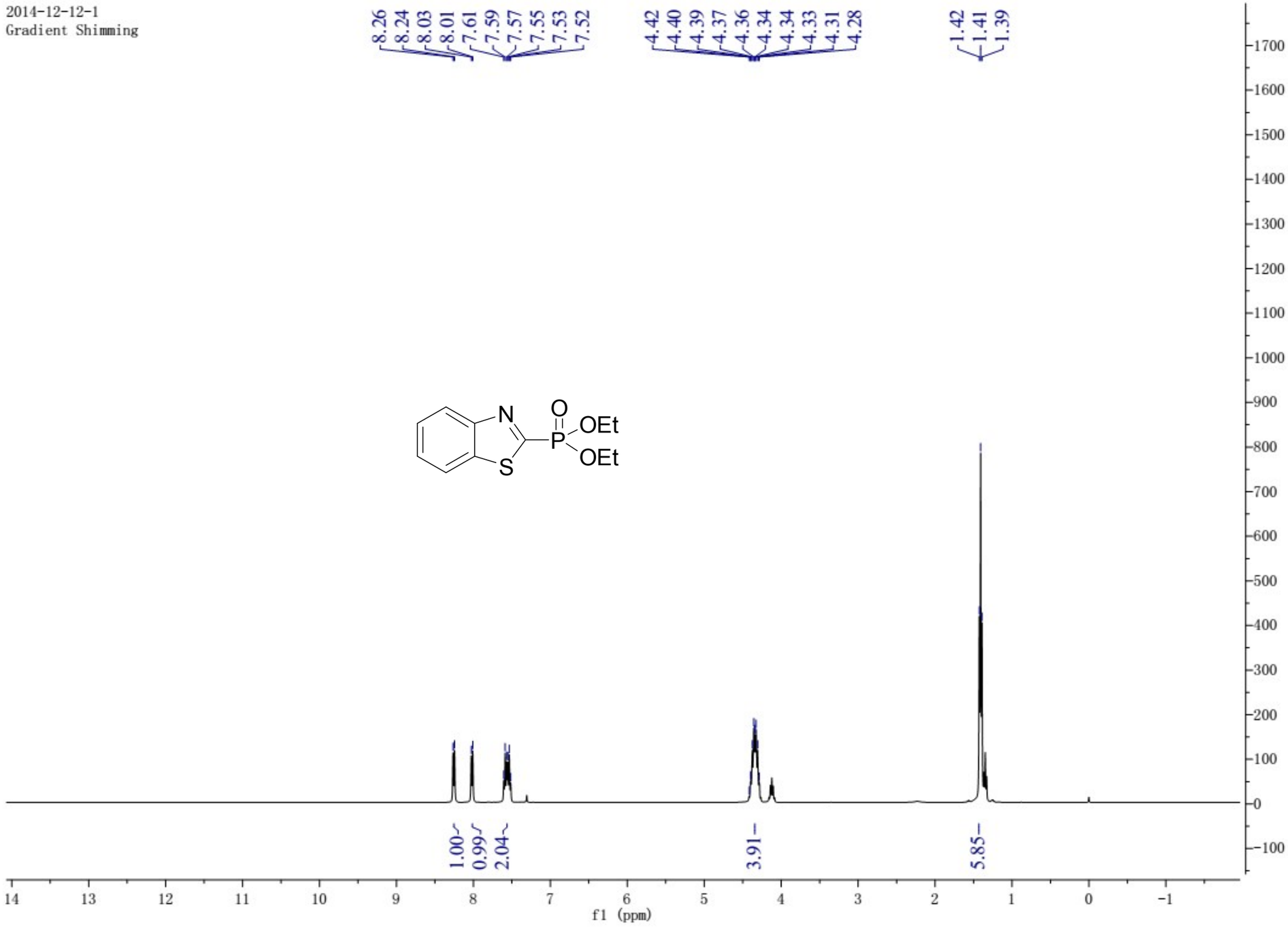
Y150445
sample7 31P



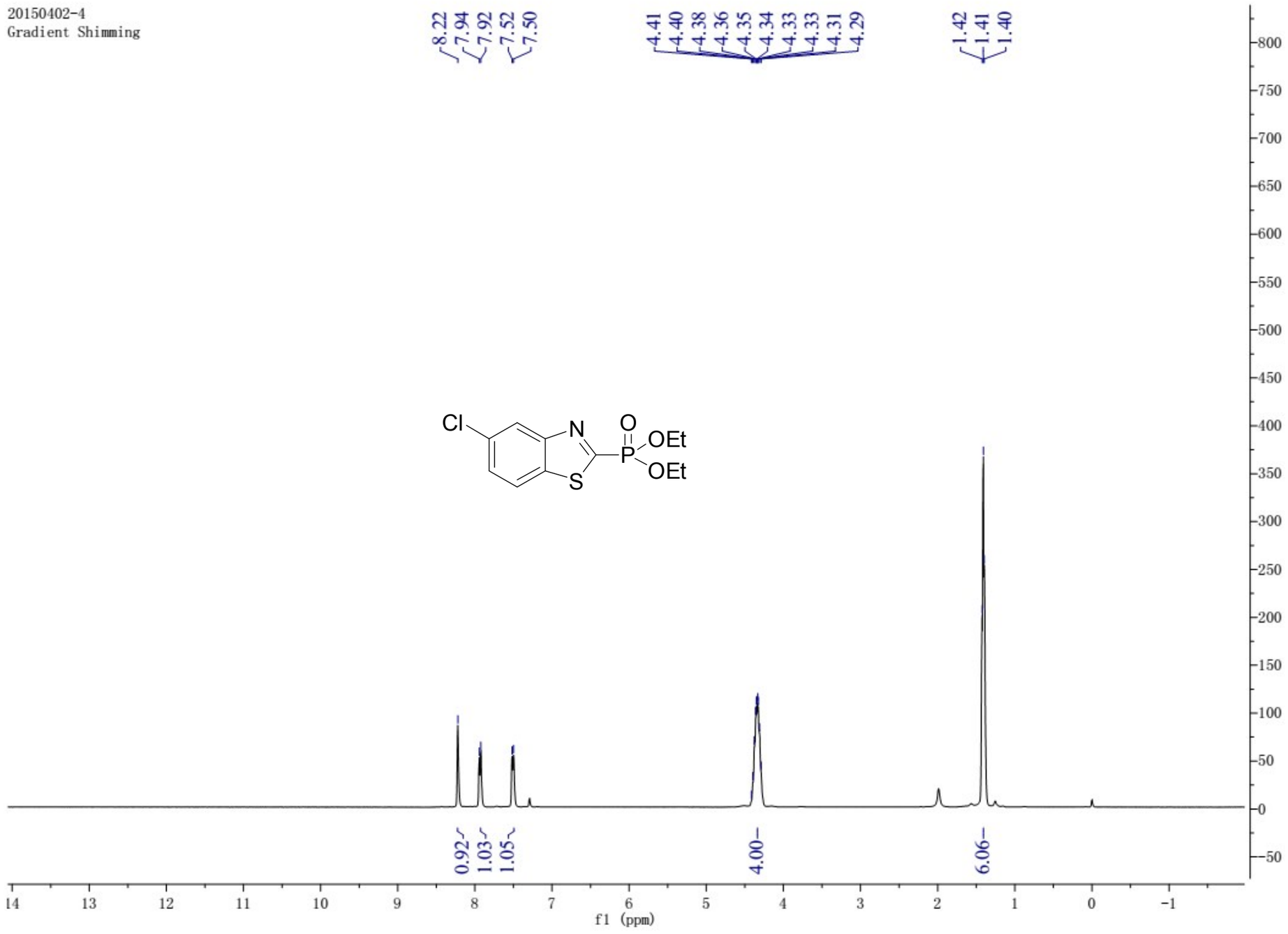
20141211-2H
Gradient Shimming



2014-12-12-1
Gradient Shimming

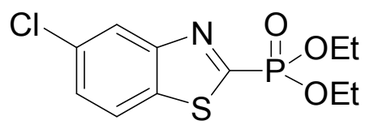


20150402-4
Gradient Shimming

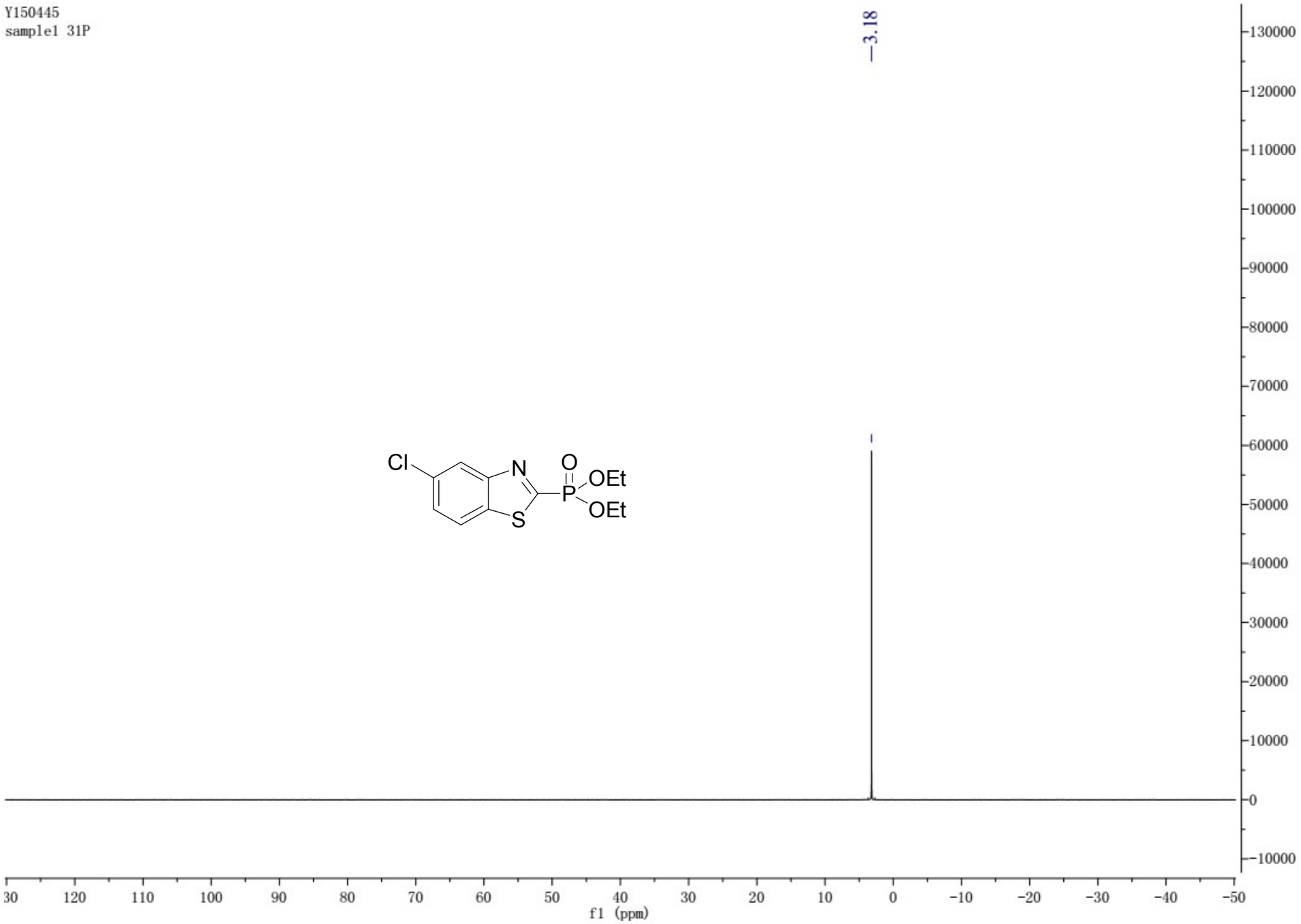


Y150445
sample1 13C

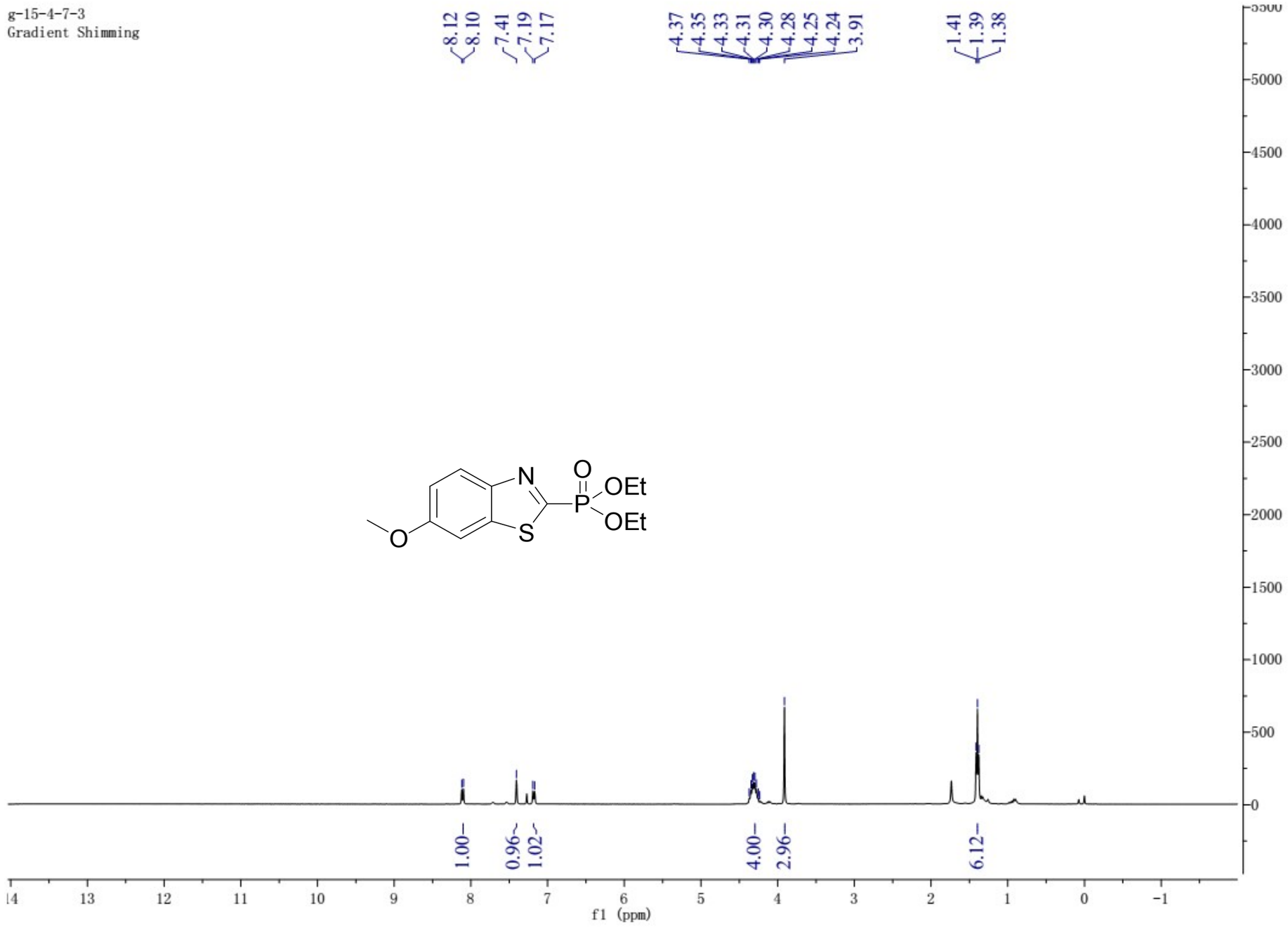
163.15
161.57
155.51
155.32
134.72
134.71
133.12
127.72
124.57
122.78
122.77
64.36
64.32
16.36
16.32



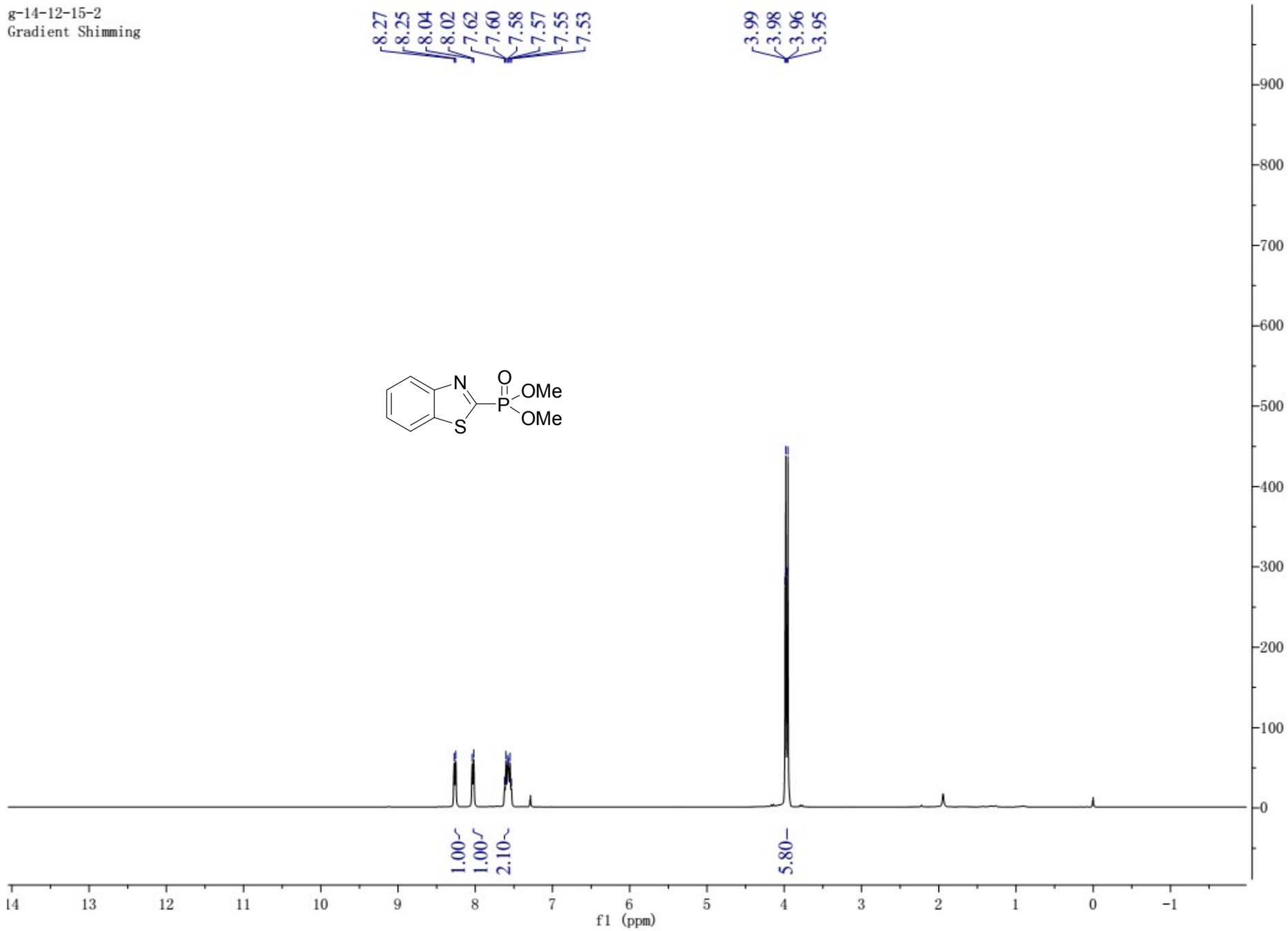
Y150445
sample1 31P



g-15-4-7-3
Gradient Shimming

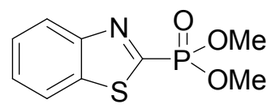


g-14-12-15-2
Gradient Shimming

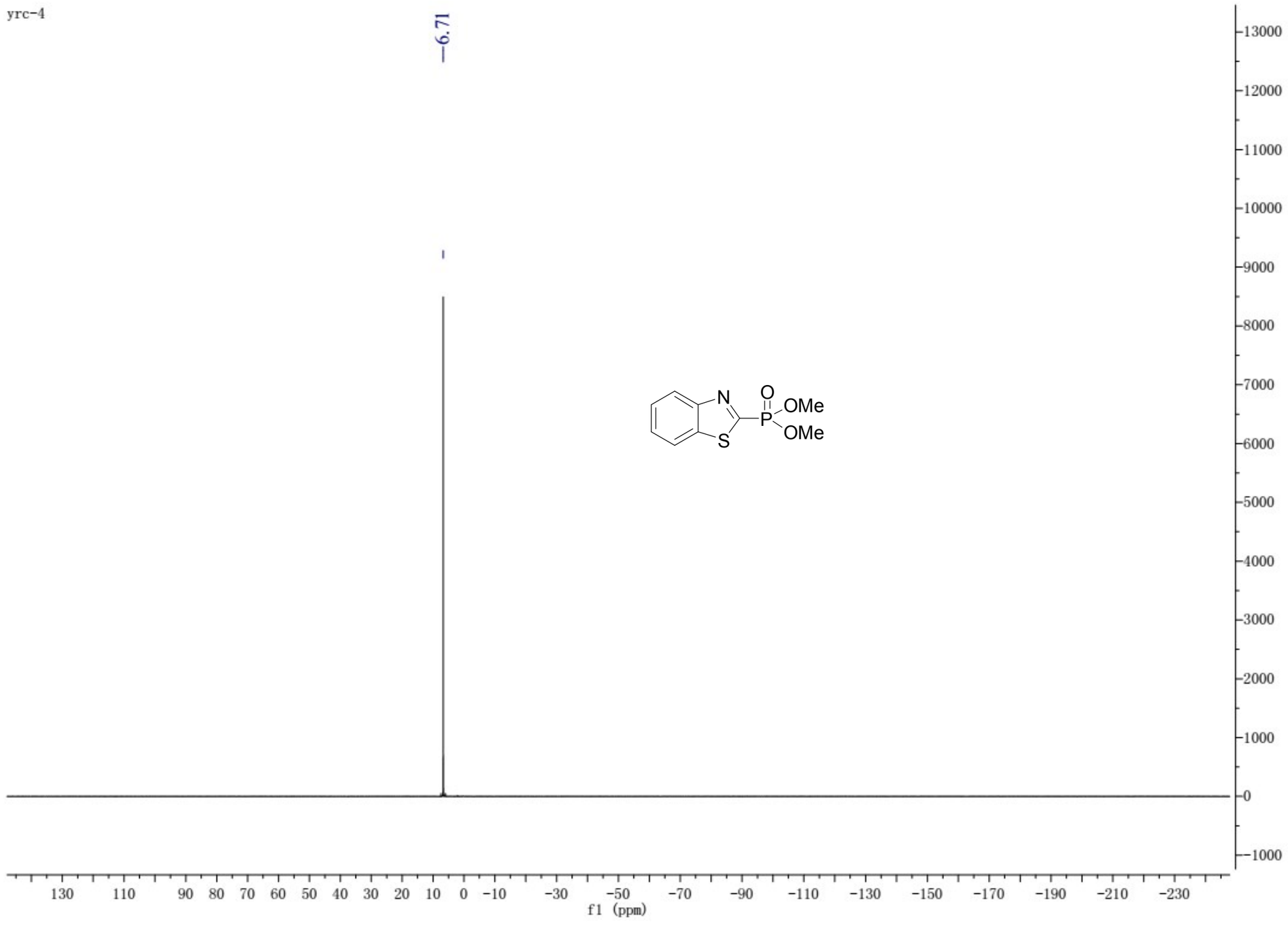


Y150059
sample6 13C

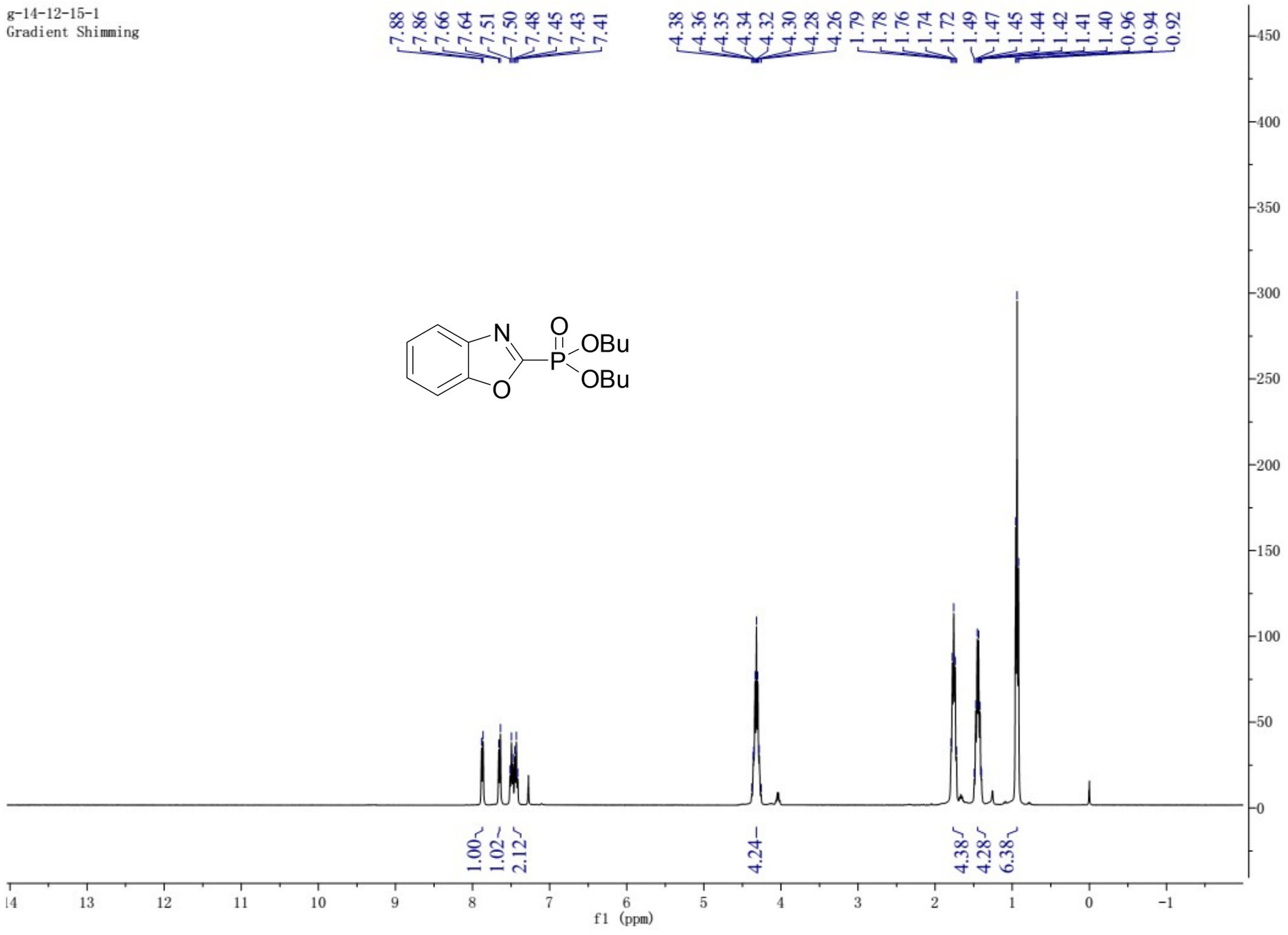
159.50
157.91
154.69
154.50
136.47
127.26
127.06
125.06
122.08
54.35
54.31



yrc-4

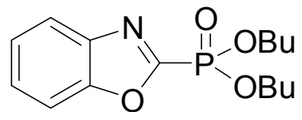

6.71
N
O
P
OMe
OMe
S
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230
f1 (ppm)

g-14-12-15-1
Gradient Shimming

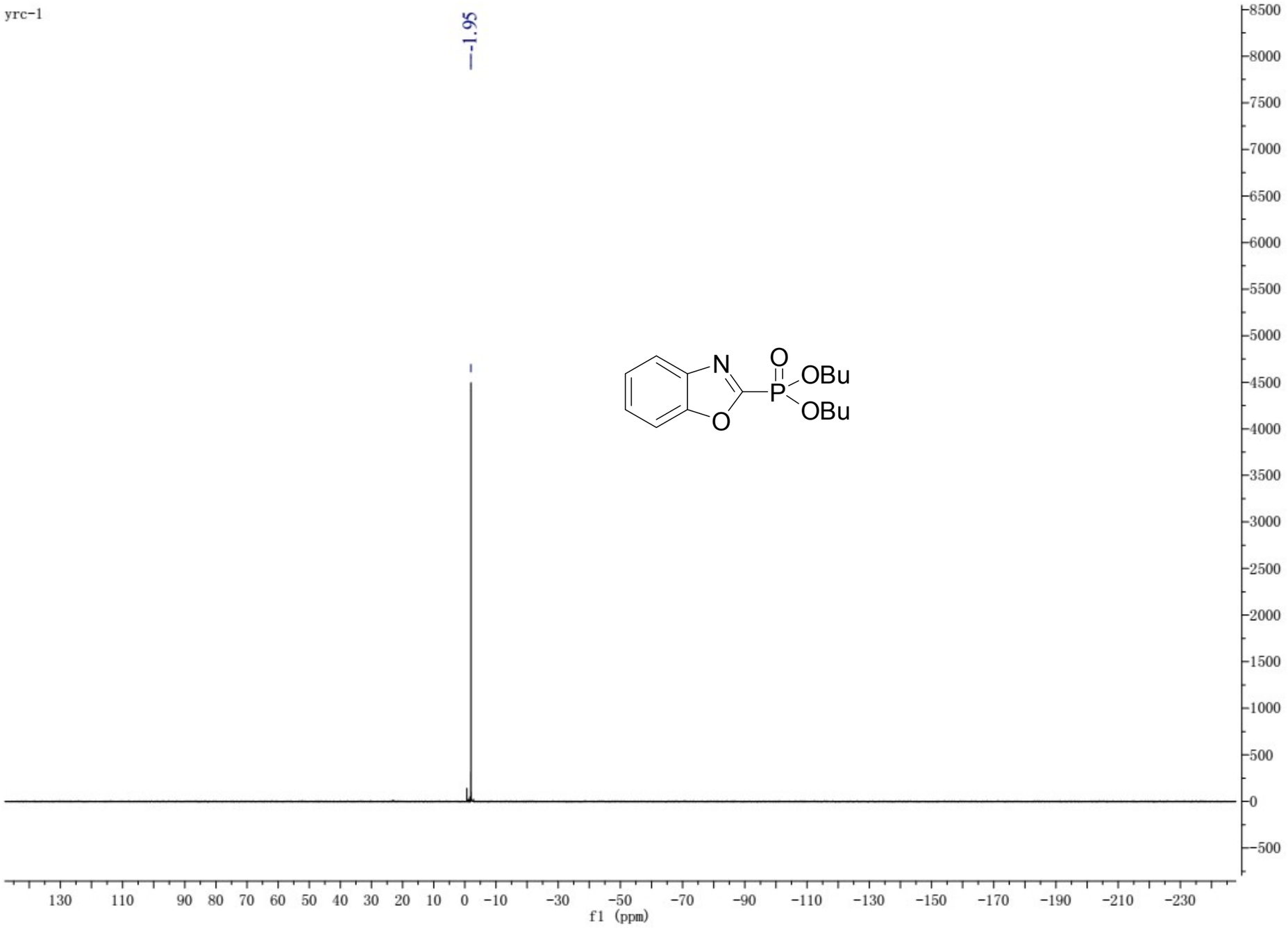


Y150059
sample5 13C

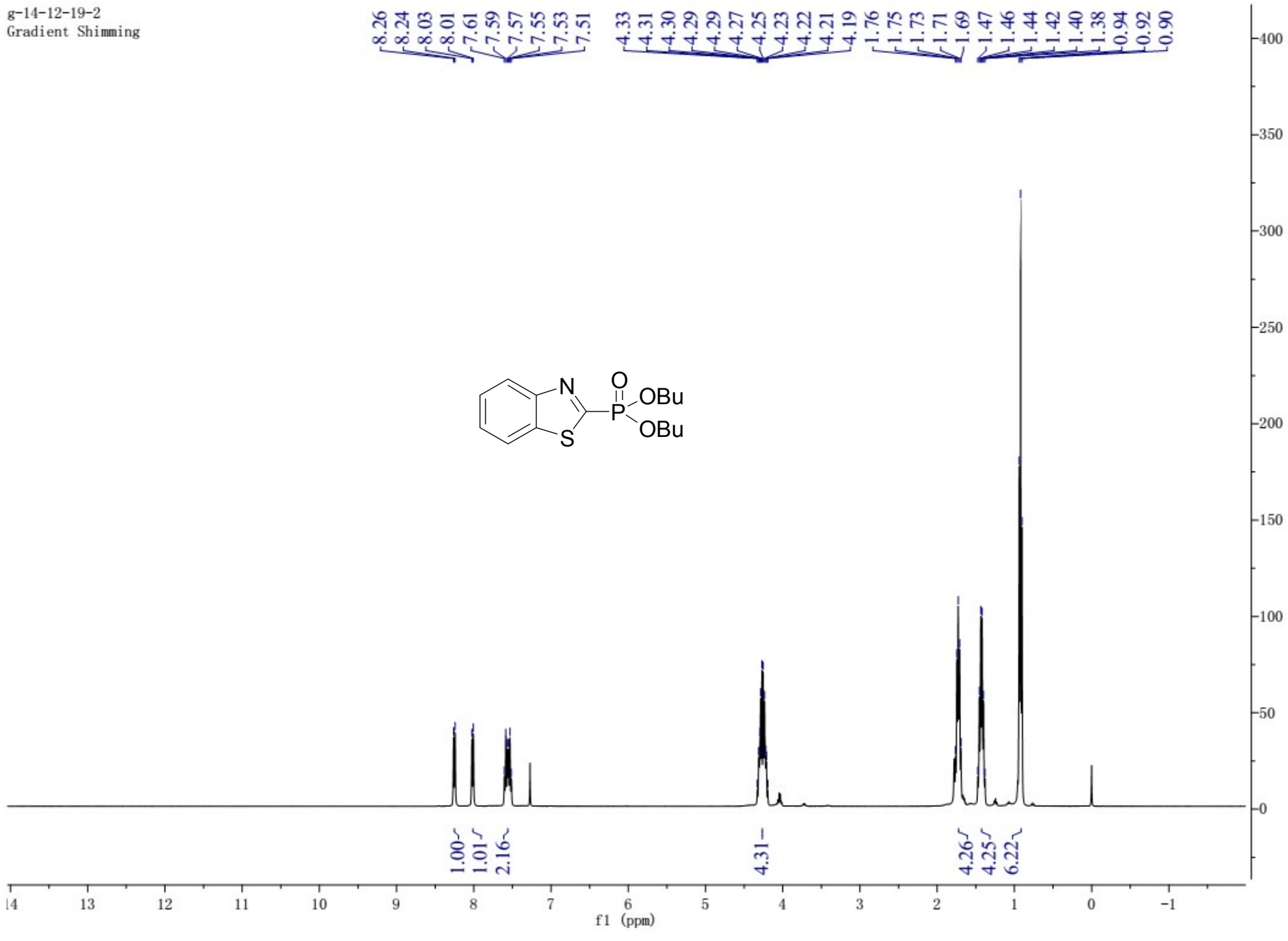
157.75
155.99
151.22
151.18
140.41
140.30
127.50
125.41
121.75
111.65
68.35
68.30
32.44
32.40
18.70
13.62



yrc-1

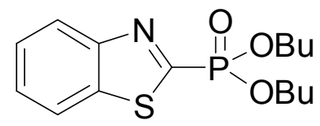

-1.95
N
O
P
O
OBu
OBu
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230
f1 (ppm)

g-14-12-19-2
Gradient Shimming



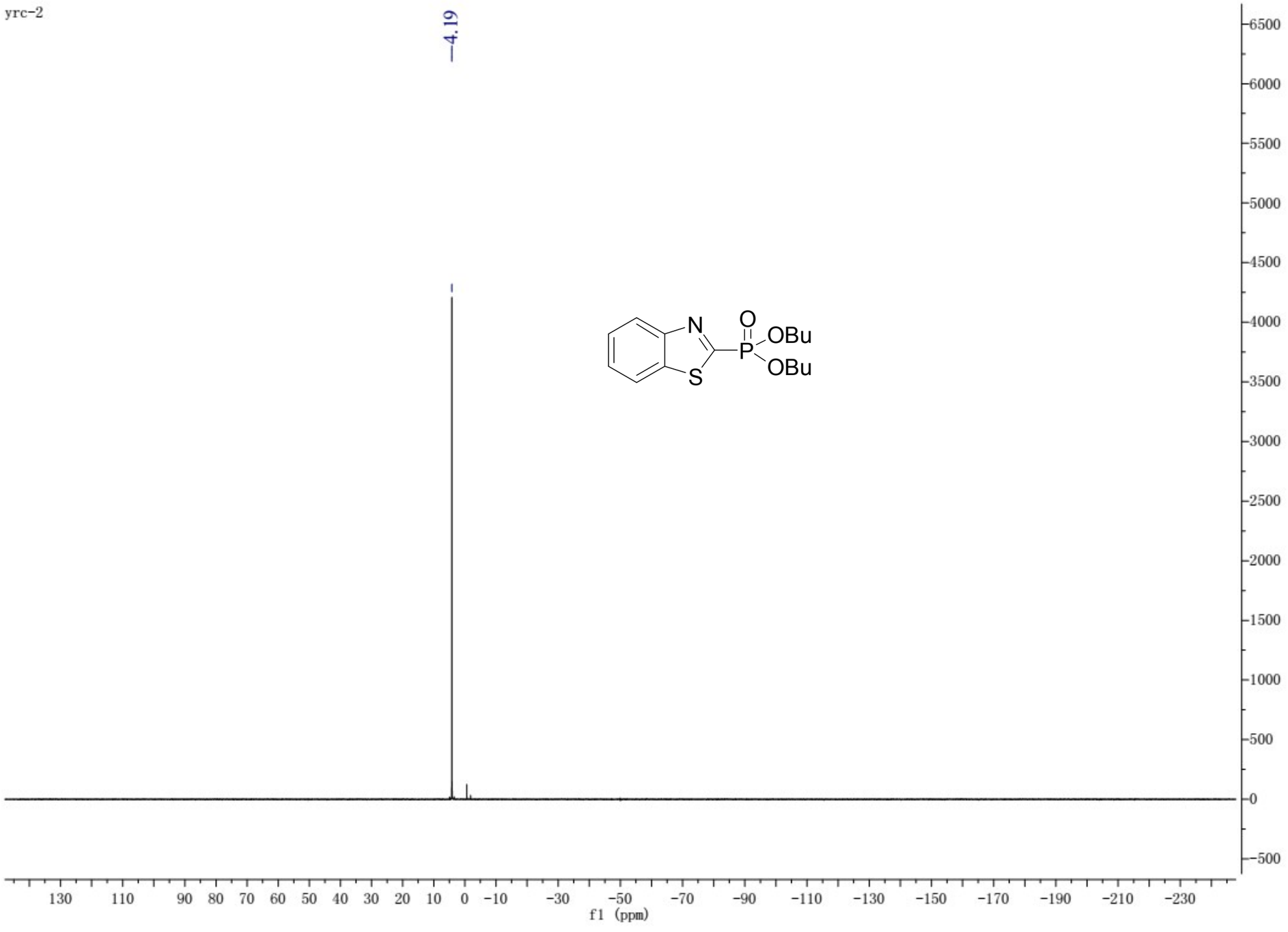
Y150059
sample8 13C

160.92
159.34
154.79
154.60
136.52
127.08
126.93
125.06
122.06
67.86
67.82
32.49
32.44
18.74
13.65

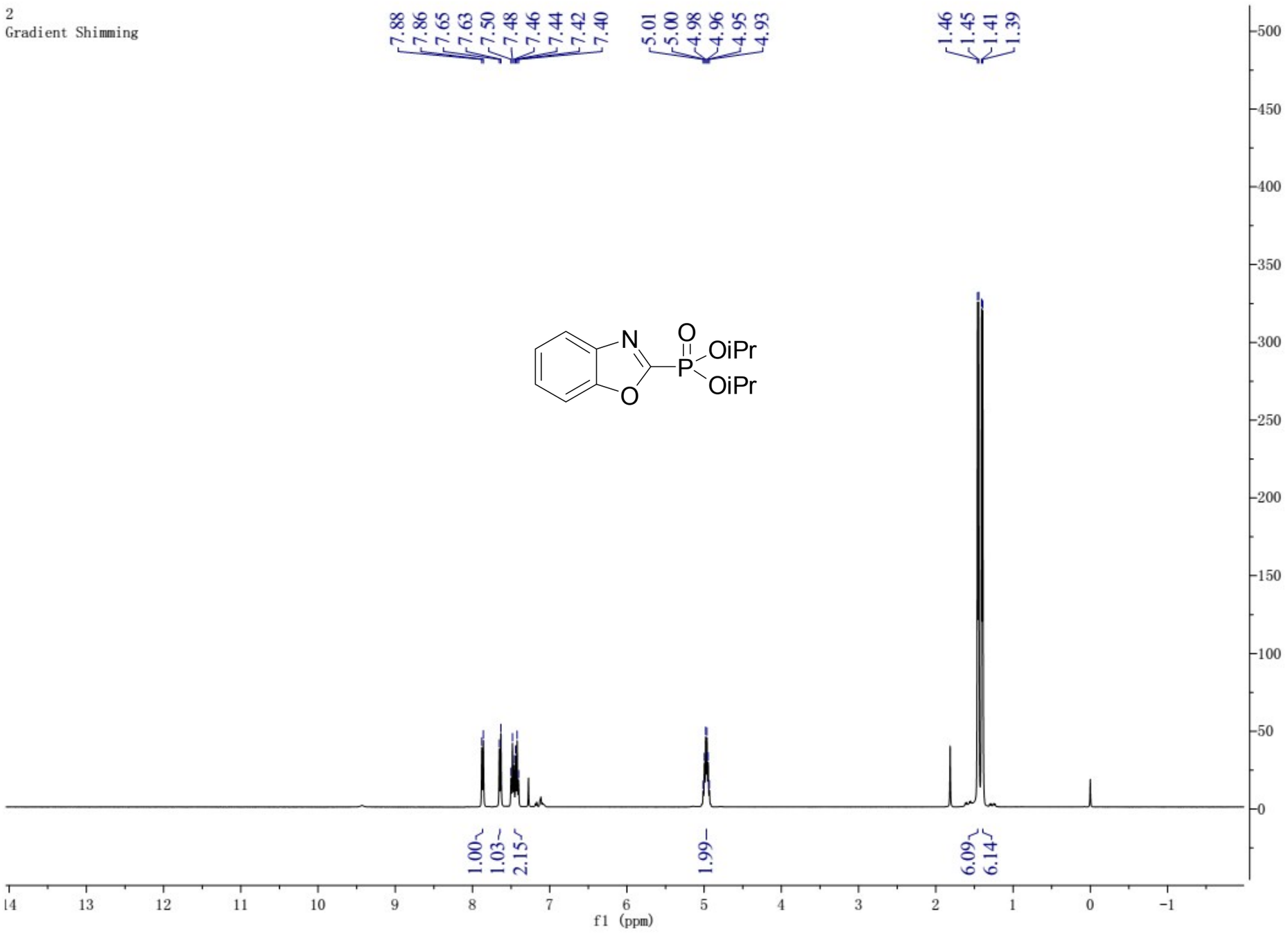


f1 (ppm)

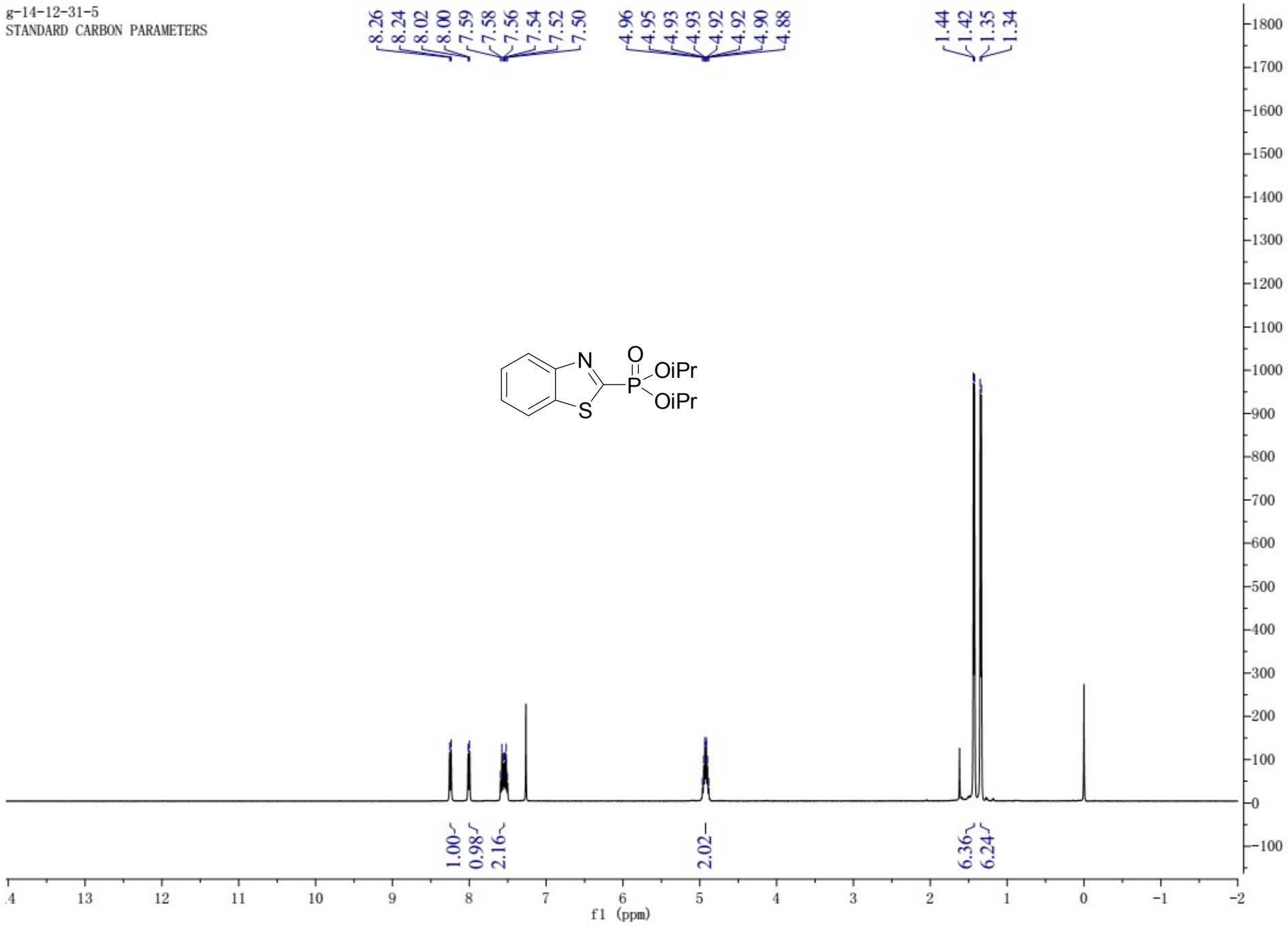
yrc-2


4.19
N
O
P
OBu
OBu
S
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
130 110 90 80 70 60 50 40 30 20 10 0 -10 -30 -50 -70 -90 -110 -130 -150 -170 -190 -210 -230
f1 (ppm)

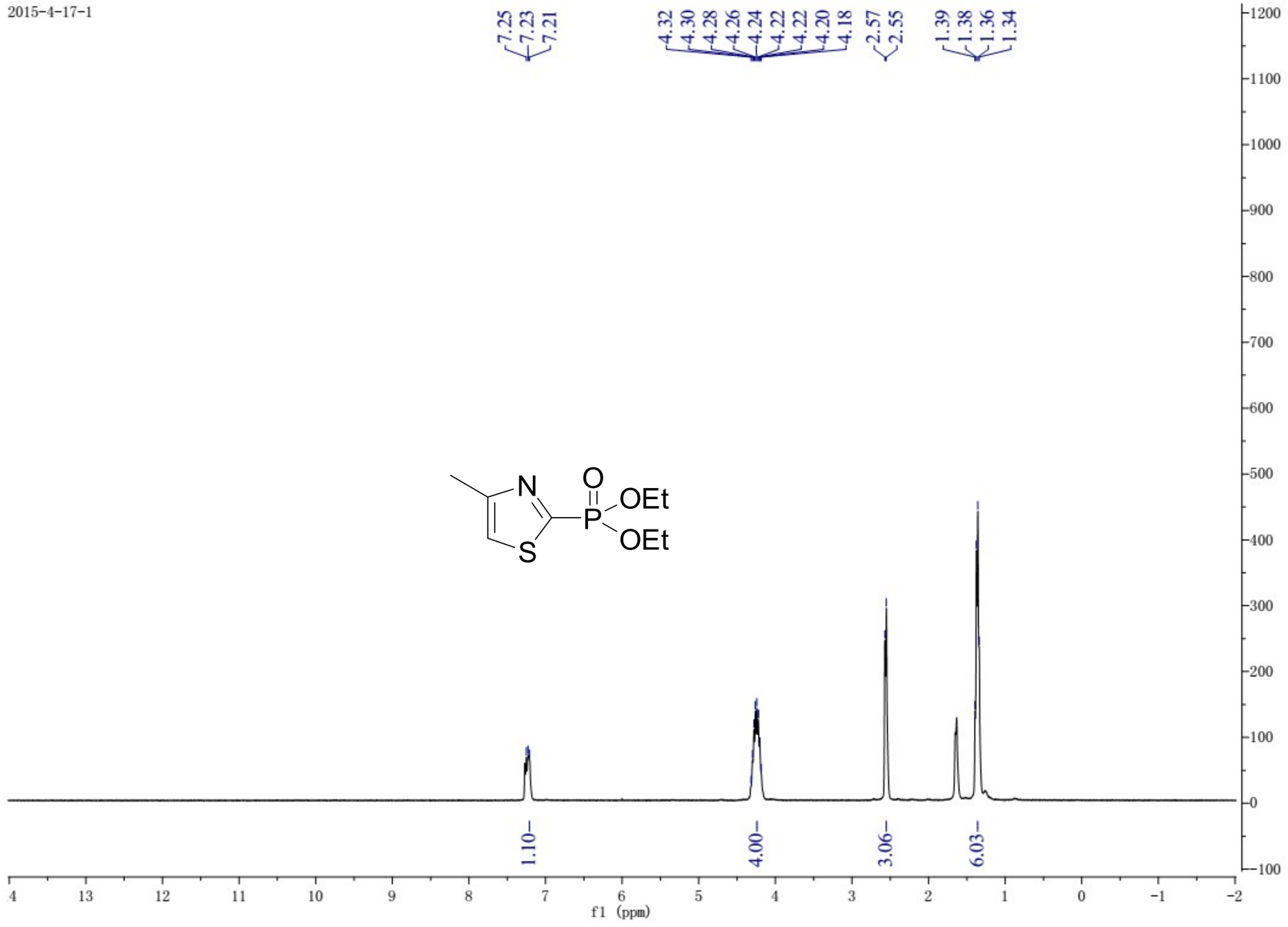
2
Gradient Shimming



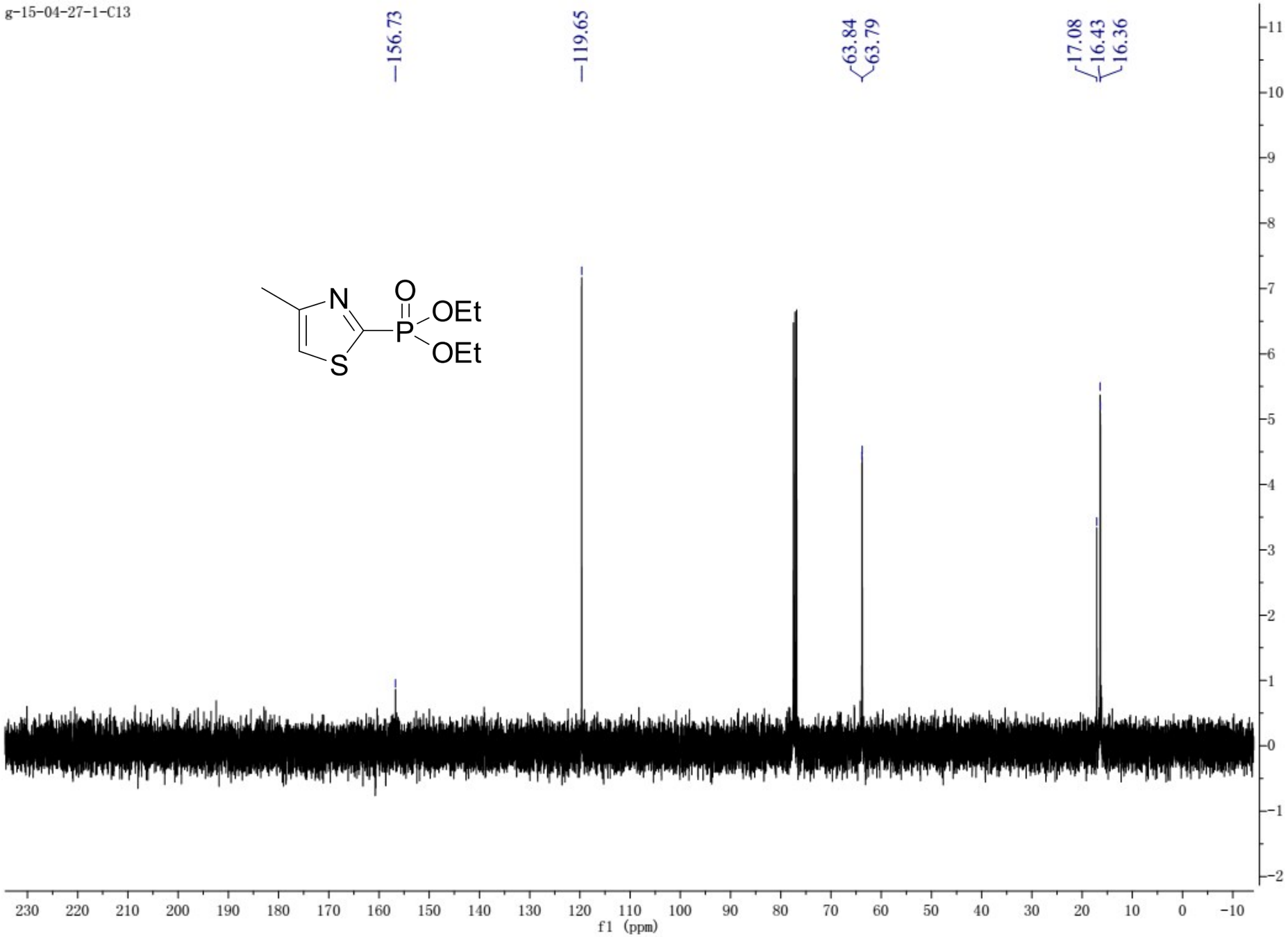
g-14-12-31-5
STANDARD CARBON PARAMETERS



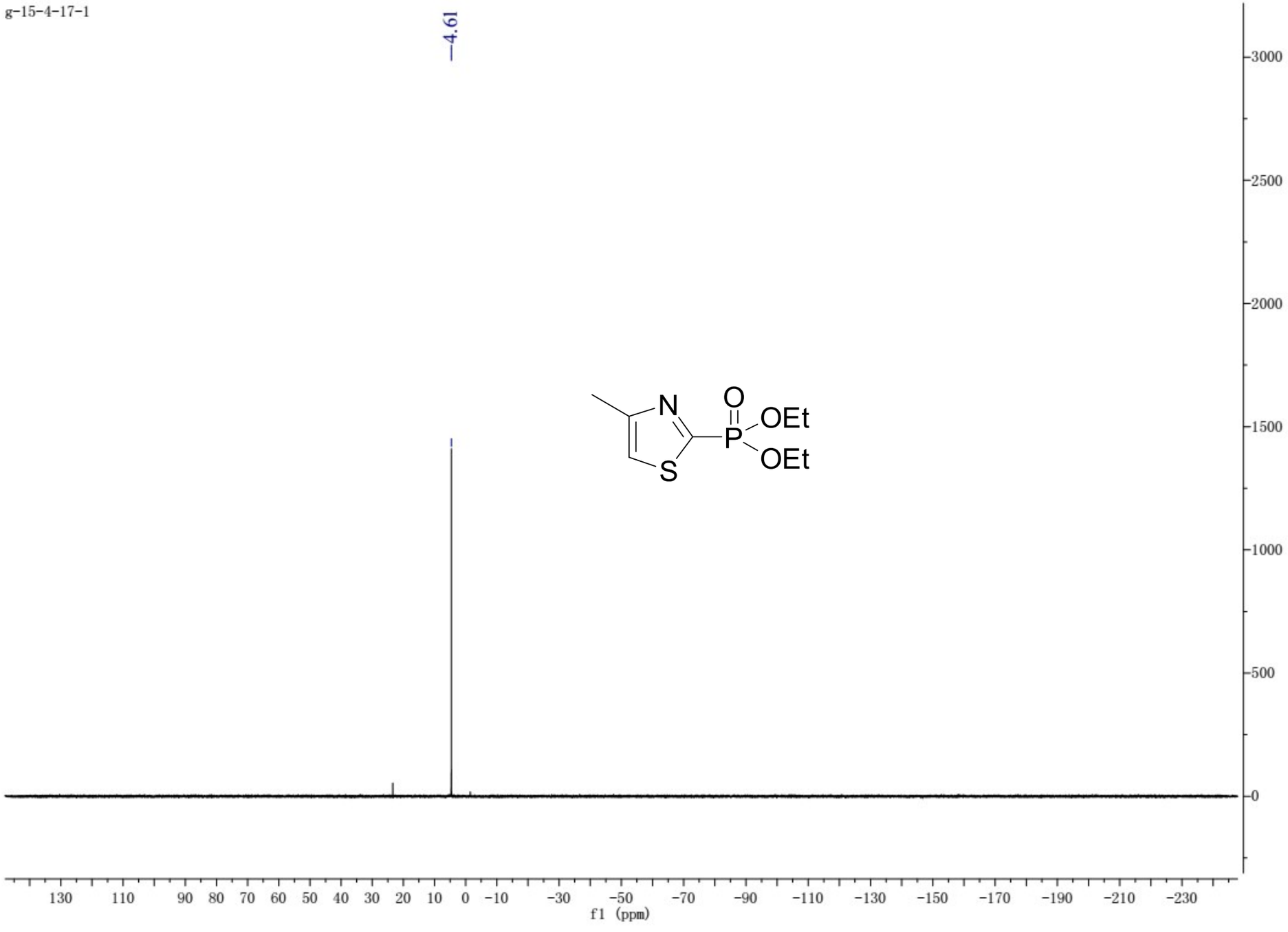
2015-4-17-1


7.25
7.23
7.21
4.32
4.30
4.28
4.26
4.24
4.22
4.22
4.20
4.18
2.57
2.55
1.39
1.38
1.36
1.34
N
O
P
OEt
OEt
S
1.10
4.00
3.06
6.03
f1 (ppm)

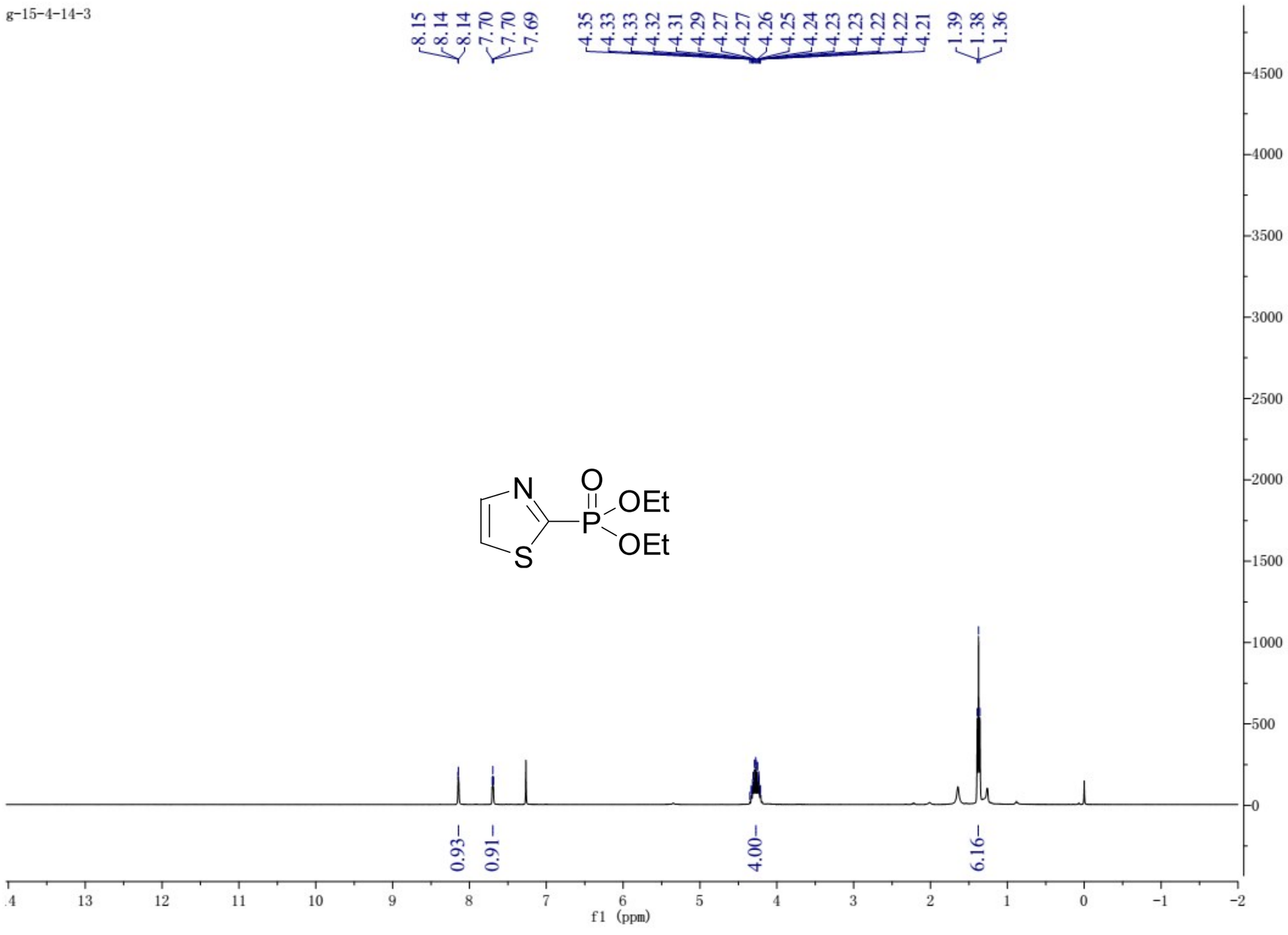
g-15-04-27-1-C13



g-15-4-17-1


4.61
N
O
P
OEt
OEt
S
3000
2500
2000
1500
1000
500
0
130
110
90
80
70
60
50
40
30
20
10
0
-10
-30
-50
-70
-90
-110
-130
-150
-170
-190
-210
-230
f1 (ppm)

g-15-4-14-3


8.15
8.14
8.14
7.70
7.70
7.69
4.35
4.33
4.33
4.32
4.31
4.29
4.27
4.27
4.26
4.25
4.24
4.23
4.23
4.22
4.22
4.21
1.39
1.38
1.36
N
O
OEt
P
OEt
S
0.93
0.91
4.00
6.16
f1 (ppm)

Y150445
sample6 13C

159.75
158.13
146.27
146.08
124.66
64.00
63.96
16.41
16.37

Y150445
sample6 31P