Supporting Information

Copper-catalyzed bi-cyclization of α,β-unsaturated arylketones for accessing cyclopenta[*b*]tetralines

Xia-Run Yao,[a,1] Hao-Nan Shi,[a,1] Rong Fu,[a] Ke Chen,*[,a] Wen-Huan Hao,[a] Bo Jiang*[,a]

[a]C. W. Chu College and School of Chemistry & Materials Science, Jiangsu Normal University, Xuzhou 221116, P. R. China. E-mail: chenke@jsnu.edu.cn(KC); jiangchem@jsnu.edu.cn(BJ); Tel./fax: +86 51683500065

[1]These authors contributed equally.

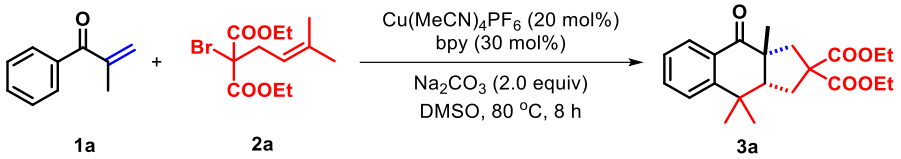
Table of contents

1. General Information

Unless otherwise stated, all other starting materials and solvents were commercially available and used without further purification. H NMR (^{13}C NMR) spectra were measured on a Bruker DPX 400 MHz spectrometer in $CDCl_3$ (DMSO-d_6) with chemical shift (δ) given in ppm relative to TMS as internal standard [(s = singlet, d = doublet, t = triplet, brs = broad singlet, m = multiplet), coupling constant (Hz)]. HRMS (ESI) was determined by using microTOF-QII HRMS/MS instrument (BRUKER).

2. General Procedure for the Synthesis of Compounds 3 and 5

Example for the synthesis of **3a**

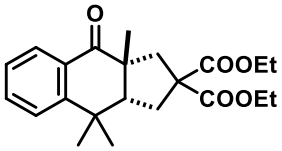


1a **2a** **3a**

In a nitrogen-filled glove box, to an oven-dried 10 mL reaction tube equipped with a magnetic stir bar was added 2-methyl-1-phenylprop-2-en-1-one (**1a**, 0.2 mmol, 29.2 mg, 1.0 equiv.) **2a** (0.4 mmol, 122.4 mg, 2.0 equiv.), $Cu(CH_3CN)_4PF_6$ (0.04 mmol, 14.9 mg, 20 mol%), bpy (0.06 mmol, 9.3 mg, 30 mol%), Na_2CO_3 (0.4 mmol, 42.4 mg, 2.0 equiv.) and DMSO (2.0 mL). Then the tube was sealed, moved out of the glovebox and stirred at 80 °C for 8 h. After the reaction was completed, the reaction mixture was concentrated by vacuum and the residue was purified by flash column chromatography to afford the desired product **3a** as light-yellow oil.

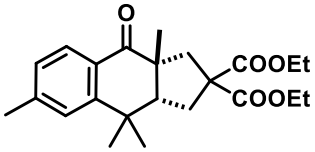
3. Product Characterization

Diethyl 3a,9,9-trimethyl-4-oxo-3a,4,9,9a-tetrahydro-1H-cyclopenta[b]naphthalene-2,2(3H)-dicarboxylate (3a)



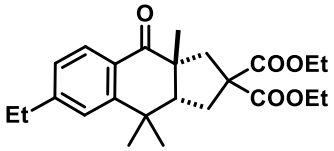
Light yellow oil, 49.1 mg, 66% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) δ 7.90 (dd, J = 7.6, 1.2 Hz, 1H), 7.53 (td, J = 7.6, 1.2 Hz, 1H), 7.37 – 7.31 (m, 2H), 4.27 – 4.21 (m, 2H), 4.11 – 4.01 (m, 2H), 2.68 – 2.65 (m, 1H), 2.57 – 2.51 (m, 1H), 2.40 (dd, J = 14.4, 1.4 Hz, 1H), 2.34 – 2.29 (m, 1H), 1.74 (t, J = 12.8 Hz, 1H), 1.44 (s, 3H), 1.43 (s, 3H), 1.41 (s, 1H), 1.37 (s, 1H), 1.31 – 1.28 (m, 6H), 1.16 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.7, 172.2, 171.1, 149.4, 133.7, 130.7, 128.3, 126.8, 125.6, 61.7, 61.6, 57.9, 55.9, 51.6, 46.6, 39.2, 36.2, 34.5, 27.3, 26.9, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3516, 1725, 1442, 1364, 1259, 1211, 1188, 1062, 1023, 775; $C_{22}H_{28}NaO_5$ $[M + Na]^+$ 395.1829; Found 395.1842.

Diethyl 3a,7,9,9-tetramethyl-4-oxo-3a,4,9,9a-tetrahydro-1H-cyclopenta[b]naphthalene-2,2(3H)-dicarboxylate (3b)



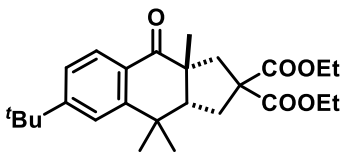
Light yellow oil, 48.0 mg, 62% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.80 (d, J = 7.6 Hz, 1H), 7.13 – 7.11 (m, 2H), 4.25 – 4.19 (m, 2H), 4.10 – 4.01 (m, 2H), 2.69 – 2.65 (m, 1H), 2.53 – 2.48 (m, 1H), 2.41 – 2.39 (m, 4H), 2.27 (dd, J = 12.4, 6.8 Hz, 1H), 1.76 (t, J = 12.8 Hz, 1H), 1.42 (s, 3H), 1.40 (s, 3H), 1.29 (s, 3H), 1.27 – 1.24 (m, 3H), 1.15 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.3, 172.3, 171.2, 149.4, 144.4, 128.5, 128.1, 127.6, 126.2, 61.6, 61.5, 57.9, 55.9, 51.6, 46.7, 39.2, 36.1, 34.6, 27.4, 26.9, 22.1, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3515, 1724, 1612, 1585, 1508, 1487, 1368, 1160, 1080, 1021; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{30}NaO_5$ 409.1985; Found 409.1993.

Diethyl 7-ethyl-3a,9,9-trimethyl-4-oxo-3a,4,9,9a-tetrahydro-1H-cyclopenta[b]naphthalene-2,2(3H)-dicarboxylate (3c)



Light yellow oil, 53.7 mg, 67% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.83 (d, J = 8.4 Hz, 1H), 7.16 – 7.13 (m, 2H), 4.25 – 4.19 (m, 2H), 4.10 – 4.01 (m, 2H), 2.70 – 2.67 (m, 2H), 2.66 – 2.60 (m, 1H), 2.53 – 2.47 (m, 1H), 2.39 (dd, J = 14.4, 1.6 Hz, 1H), 2.31 – 2.23 (m, 1H), 1.77 (t, J = 12.8 Hz, 1H), 1.42 (s, 3H), 1.40 (s, 3H), 1.30 (s, 3H), 1.28 – 1.26 (m, 3H), 1.26 – 1.25 (m, 3H), 1.15 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.4, 172.3, 171.2, 150.5, 149.5, 128.6, 128.3, 126.4, 125.0, 61.7, 61.6, 61.5, 57.8, 55.9, 51.6, 46.7, 39.2, 36.2, 34.6, 29.3, 27.5, 26.9, 15.2, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3532, 1731, 1682, 1630, 1446, 1366, 1296, 1257, 1235, 1188; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{24}H_{32}NaO_5$ 423.2142; Found 423.2149.

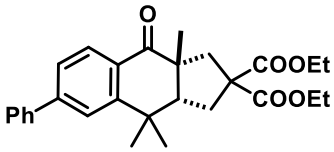
Diethyl 7-(tert-butyl)-3a,9,9-trimethyl-4-oxo-3a,4,9,9a-tetrahydro-1H-cyclopenta[b]naphthalene-2,2(3H)-dicarboxylate (3d)



Light yellow oil, 60.8 mg, 71% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.83 (d, J = 8.4 Hz, 1H), 7.34 – 7.30 (m,

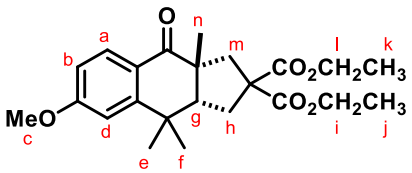
2H), 4.23 – 4.17 (m, 2H), 4.10 – 4.00 (m, 2H), 2.70 (d, J = 14.4 Hz, 1H), 2.51 – 2.46 (m, 1H), 2.40 – 2.36 (m, 1H), 2.28 – 2.23 (m, 1H), 1.78 (t, J = 12.9 Hz, 1H), 1.41 (s, 6H), 1.32 (s, 9H), 1.30 (s, 3H), 1.28 – 1.25 (m, 3H), 1.14 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.2, 172.3, 171.2, 157.3, 149.1, 128.2, 127.9, 123.9, 122.2, 61.6, 61.5, 57.7, 56.0, 51.6, 46.5, 39.1, 36.3, 35.3, 34.7, 31.2, 27.6, 26.9, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3519, 1731, 1678, 1464, 1389, 1365, 1255, 1188, 1159, 1067; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{26}H_{36}NaO_5$ 451.2455; Found 451.2460.

Diethyl 3a,9,9-trimethyl-4-oxo-7-phenyl-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3e)



Light yellow oil, 61.8 mg, 69% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 8.00 – 7.97 (m, 1H), 7.65 – 7.60 (m, 2H), 7.55 – 7.52 (m, 2H), 7.48 – 7.44 (m, 2H), 7.41 – 7.39 (m, 1H), 4.27 – 4.21 (m, 2H), 4.11 – 4.02 (m, 2H), 2.73 (d, J = 13.2 Hz, 1H), 2.58 – 2.53 (m, 1H), 2.43 (dd, J = 14.4, 1.2 Hz, 1H), 2.36 – 2.31 (m, 1H), 1.82 (t, J = 12.8 Hz, 1H), 1.48 (s, 3H), 1.46 (s, 3H), 1.36 (s, 3H), 1.30 – 1.26 (m, 3H), 1.15 (d, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.9, 172.2, 171.1, 148.9, 146.5, 136.3, 136.2, 134.6, 130.6, 130.4, 128.6, 127.9, 126.9, 125.6, 61.6, 61.5, 57.9, 55.9, 51.7, 46.5, 39.2, 35.9, 34.6, 27.3, 26.9, 20.9, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3334, 1730, 1678, 1602, 1389, 1366, 1274, 1260, 1188, 1029; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{28}H_{32}NaO_5$ 471.2142; Found 471.2148.

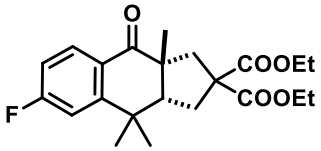
Diethyl 7-methoxy-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3f)



Light yellow oil, 60.3 mg, 75% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) major diastereomer: 7.92 – 7.90 (H_d, m, 1H), 6.83 – 6.80 (H_a and H_b, m, 2H), 4.25 – 4.17 (H_i, m, 2H), 4.09 – 4.00 (H_l, m, 2H), 3.86 (H_c, s, 3H), 2.69 (H_m, d, J = 14.4 Hz, 1H), 2.51 – 2.46 (H_h, m, 1H), 2.42 – 2.38 (H_m, m, 1H), 2.25 (H_h, dd, J = 12.8, 6.8 Hz, 1H), 1.79 (H_g, t, J = 12.8 Hz, 1H), 1.42 (H_e, s, 3H), 1.38 (H_f, s, 3H), 1.30 (H_n, s, 3H), 1.28 – 1.24 (H_i, m, 3H), 1.15 (H_j, t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.3, 172.3, 171.2, 164.1, 151.9, 130.9, 123.9, 111.7, 111.3, 61.6, 61.5,

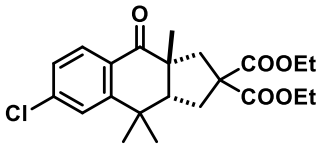
57.7, 55.9, 55.4, 51.4, 46.9, 39.2, 36.3, 34.5, 27.5, 27.0, 14.1, 13.9. IR (KBr, *v*, cm^{-1}) 3446, 1730, 1671, 1628, 1598, 1488, 1389, 1366, 1297, 1186; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{30}NaO_6$ 425.1935; Found 425.1943.

Diethyl 7-fluoro-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3g)



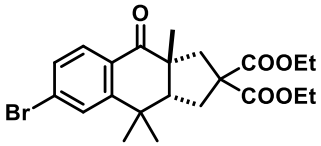
Light yellow oil, 45.2 mg, 58% yield; ^1H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.93 (dd, J = 8.4, 6.0 Hz, 1H), 7.03 – 6.96 (m, 2H), 4.25 – 4.19 (m, 2H), 4.10 – 4.01 (m, 2H), 2.67 (d, J = 14.4 Hz, 1H), 2.54 – 2.49 (m, 1H), 2.40 (d, J = 14.0 Hz, 1H), 2.34 – 2.25 (m, 1H), 1.74 (d, J = 12.8 Hz, 1H), 1.42 (s, 3H), 1.39 (s, 3H), 1.30 (s, 3H), 1.28 – 1.26 (m, 3H), 1.15 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.1, 172.1, 171.1, 167.7 ($^1J_{CF}$ = 252.8 Hz), 152.9 ($^5J_{CF}$ = 8 Hz), 131.4 ($^4J_{CF}$ = 9.6 Hz), 127.1 ($^6J_{CF}$ = 2.7 Hz), 114.3 ($^3J_{CF}$ = 21.8 Hz), 112.7 ($^2J_{CF}$ = 22.1 Hz), 61.7, 57.8, 55.8, 51.6, 46.7, 39.2, 36.4, 34.3, 27.3, 26.9, 14.0. IR (KBr, *v*, cm^{-1}) 3446, 1731, 1682, 1606, 1583, 1481, 1367, 1297, 1256, 1158; $C_{22}H_{27}FNaO_5$ $[M + Na]^+$ 413.1735; Found 413.1740.

Diethyl 7-chloro-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3h)



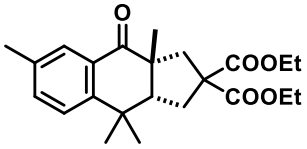
Light yellow oil, 48.0 mg, 59% yield; ^1H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.83 (d, J = 8.4 Hz, 1H), 7.31 (d, J = 2.0 Hz, 1H), 7.29 – 7.26 (m, 1H), 4.24 – 4.18 (m, 2H), 4.10 – 4.00 (m, 2H), 2.64 (d, J = 14.0 Hz, 1H), 2.54 – 2.49 (m, 1H), 2.38 (d, J = 14.4 Hz, 1H), 2.33 – 2.26 (m, 1H), 1.73 (d, J = 13.2 Hz, 1H), 1.41 (s, 3H), 1.39 (s, 3H), 1.28 (s, 3H), 1.25 – 1.24 (m, 3H), 1.15 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.5, 172.0, 171.0, 151.2, 140.1, 130.0, 129.1, 127.2, 126.0, 61.74, 61.70, 61.6, 57.8, 55.9, 51.6, 46.6, 39.2, 36.4, 34.3, 27.2, 26.8, 24.9, 14.1, 14.0, 13.9. IR (KBr, *v*, cm^{-1}) 3447, 1731, 1684, 1629, 1465, 1367, 1345, 1256, 1188, 1030; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{22}H_{27}{}^{35}ClNaO_5$ 429.1439, Found 429.1446; Calcd for $C_{22}H_{27}{}^{37}ClNaO_5$ 431.1410, Found 431.1415.

Diethyl 7-bromo-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3i)



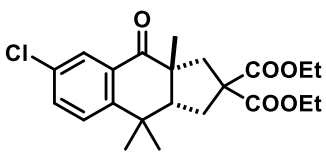
Light yellow oil, 56.7 mg, 63% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.75 (d, J = 8.0 Hz, 1H), 7.48 (d, J = 2.0 Hz, 1H), 7.47 – 7.44 (m, 1H), 4.24 – 4.20 (m, 2H), 4.10 – 4.01 (m, 2H), 2.65 – 2.61 (m, 1H), 2.55 – 2.50 (m, 1H), 2.38 (dd, J = 14.4, 1.6 Hz, 1H), 2.33 – 2.26 (m, 1H), 1.74 – 1.68 (m, 1H), 1.41 (s, 3H), 1.40 (s, 3H), 1.29 (s, 3H), 1.26 (s, 3H), 1.15 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.9, 172.2, 171.1, 148.9, 146.5, 136.3, 136.2, 134.6, 130.6, 130.4, 128.6, 127.9, 126.9, 125.6, 61.6, 61.5, 57.9, 55.9, 51.7, 46.5, 39.2, 35.9, 34.6, 27.3, 26.9, 20.9, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3446, 1731, 1683, 1585, 1367, 1256, 1232, 1182, 1158, 1069; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{22}H_{27}{}^{79}BrNaO_5$ 473.0934, Found 473.0941; Calcd for $C_{22}H_{27}{}^{81}BrNaO_5$ 475.0914, Found 475.0920.

Diethyl 3a,6,9,9-tetramethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3j)



Light yellow oil, 51.0 mg, 66% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.69 (d, J = 1.2 Hz, 1H), 7.35 – 7.31 (m, 1H), 7.23 (d, J = 8.0 Hz, 1H), 4.23 – 4.19 (m, 2H), 4.12 – 3.99 (m, 2H), 2.65 (d, J = 14.3 Hz, 1H), 2.53 – 2.48 (m, 1H), 2.40 – 2.36 (m, 1H), 2.35 (s, 3H), 2.30 – 2.24 (m, 1H), 1.73 (t, J = 12.8 Hz, 1H),, 1.41 (s, 3H), 1.38 (s, 3H), 1.28 – 1.26 (m, 6H), 1.15 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.4, 172.3, 171.2, 149.9, 146.5, 128.9, 127.4, 125.7, 124.5, 61.7, 61.6, 57.9, 56.1, 51.7, 46.7, 39.3, 37.1, 36.4, 34.6, 27.5, 27.0, 14.1, 14.0. IR (KBr, v, cm^{-1}) 3446, 1731, 1682, 1493, 1446, 1388, 1274, 1187, 1165, 1069; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{30}NaO_5$ 409.1985; Found 409.1992.

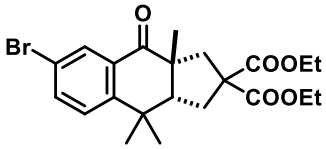
Diethyl 6-chloro-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3k)



Light yellow oil, 51.2 mg, 63% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.86 (d, J = 2.4 Hz, 1H), 7.49 – 7.46 (m, 1H), 7.40 (d, J = 8.4 Hz, 1H), 4.25 – 4.21 (m, 2H), 4.12 – 4.02 (m, 2H), 2.67 – 2.64 (m, 1H), 2.55 – 2.49 (m, 1H),

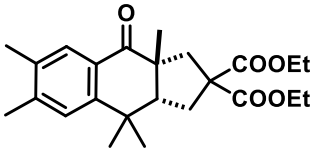
2.39 (dd, J = 14.4, 1.6 Hz, 1H), 2.31 – 2.27 (m, 1H), 1.74 (d, J = 12.8 Hz, 1H), 1.42 (s, 3H), 1.40 (s, 3H), 1.28 (s, 3H), 1.27 – 1.26 (m, 3H), 1.16 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.8, 172.1, 171.1, 153.8, 151.4, 130.3, 130.1, 129.5, 129.1, 61.82, 61.78, 61.7, 57.9, 55.9, 51.7, 46.7, 39.2, 36.5, 34.4, 27.2, 26.9, 14.1, 14.0. IR (KBr, ν, cm^{-1}) 3441, 1652, 1585, 1475, 1386, 1261, 1187, 1160, 1080, 957; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{22}H_{27}{}^{35}ClNaO_5$ 429.1439, Found 429.1445; Calcd for $C_{22}H_{27}{}^{37}ClNaO_5$ 431.1410; Found 431.1418.

Diethyl 6-bromo-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3l)



Light yellow oil, 54.0 mg, 60% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.99 (d, J = 2.2 Hz, 1H), 7.63 – 7.60 (m, 1H), 7.23 (d, J = 8.0 Hz, 1H), 7.23 (d, J = 8.0 Hz, 1H), 4.23 – 4.19 (m, 2H), 4.11 – 4.02 (m, 2H), 2.66 – 2.63 (m, 1H), 2.54 – 2.48 (m, 1H), 2.38 (dd, J = 14.4, 1.6 Hz, 1H), 2.32 – 2.26 (m, 1H), 1.92 (dd, J = 5.9, 1.3 Hz, 1H), 1.71 (t, J = 12.8 Hz, 1H), 1.41 (s, 3H), 1.39 (s, 3H), 1.28 – 1.27 (m, 3H), 1.26 – 1.25 (m, 3H), 1.16 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.3, 172.0, 171.0, 148.2, 136.4, 132.2, 131.0, 129.0, 127.8, 120.9, 61.7, 57.8, 55.8, 51.8, 46.4, 41.8, 39.1, 36.1, 34.3, 27.2, 26.7, 24.9, 14.1. IR (KBr, ν, cm^{-1}) 3334, 1731, 1684, 1590, 1465, 1367, 1256, 1158, 1030, 981; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{22}H_{27}{}^{79}BrNaO_5$ 473.0934, Found 473.0941; Calcd for $C_{22}H_{27}{}^{81}BrNaO_5$ 475.0914, Found 475.0919.

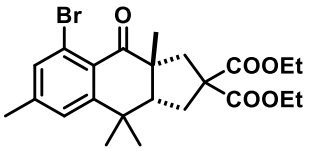
Diethyl 3a,6,7,9,9-pentamethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3m)



Light yellow oil, 56.8 mg, 71% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.64 (s, 1H), 7.07 (s, 1H), 4.21 – 4.18 (m, 2H), 4.10 – 3.97 (m, 2H), 2.67 (d, J = 14.4 Hz, 1H), 2.49 – 2.44 (m, 1H), 2.38 – 2.34 (m, 1H), 2.28 (s, 3H), 2.23 (s, 3H), 1.75 (t, J = 12.8 Hz, 1H), 1.65 – 1.60 (m, 1H), 1.39 (s, 3H), 1.36 (s, 3H), 1.26 (s, 3H), 1.24 – 1.22 (m, 3H), 1.13 (t, J = 7.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.5, 172.3, 171.2, 147.0, 143.3, 135.1, 129.2, 128.3, 126.9, 117.0, 63.0, 61.5, 57.8, 56.0, 51.6, 46.6, 39.2, 35.7, 34.6, 27.5, 26.9, 20.4, 19.2, 14.1. IR (KBr, ν, cm^{-1}) 3415, 1640, 1512, 1462, 1365, 1258, 1188, 1094, 1060, 950; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{24}H_{32}NaO_5$

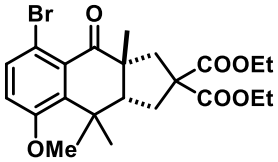
423.2142; Found 423.2148.

Diethyl 7-methoxy-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3n)



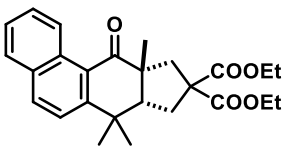
Light yellow oil, 62.2 mg, 67% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.41 (s, 1H), 7.07 (s, 1H), 4.30 – 4.24 (m, 2H), 4.16 – 4.05 (m, 2H), 2.71 – 2.66 (m, 1H), 2.62 – 2.44 (m, 1H), 2.40 (s, 3H), 2.35 – 2.32 (m, 3H), 1.41 (s, 3H), 1.37 (s, 3H), 1.35 – 1.31 (m, 3H), 1.22 – 1.18 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.0, 171.6, 170.6, 150.9, 143.3, 133.3, 129.8, 125.2, 121.7, 61.7, 61.6, 59.9, 57.3, 52.4, 45.2, 39.4, 37.3, 32.5, 26.2, 25.8, 21.5, 14.0, 13.9. IR (KBr, ν, cm^{-1}) 3414, 1749, 1645, 1590, 1472, 1365, 1302, 1272, 1190, 1025; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{29}{}^{79}BrNaO_5$ 487.1091, Found 487.1097; Calcd for $C_{23}H_{29}{}^{81}BrNaO_5$ 489.1071, Found 489.1079.

Diethyl 5-bromo-8-methoxy-3a,9,9-trimethyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3o)



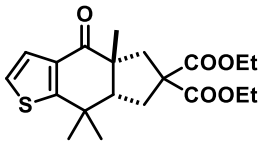
Light yellow oil, 64.3 mg, 67% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.42 (d, J = 8.8 Hz, 1H), 6.81 (d, J = 8.8 Hz, 1H), 4.25 – 4.20 (m, 2H), 4.12 – 4.02 (m, 2H), 3.84 (s, 1H), 3.75 (s, 3H), 2.68 – 2.61 (m, 1H), 2.50 (d, J = 14.4 Hz, 1H), 2.27 (dd, J = 14.0, 2.0 Hz, 1H), 2.21 – 2.15 (m, 1H), 1.62 – 1.56 (m, 1H), 1.49 (s, 3H), 1.33 (s, 3H), 1.27 – 1.25 (m, 3H), 1.23 – 1.21 (m, 3H), 1.15 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 202.0, 171.7, 170.7, 157.6, 137.7, 135.1, 132.9, 116.2, 112.2, 61.7, 60.2, 59.5, 55.8, 51.6, 44.7, 40.0, 38.0, 31.1, 28.6, 25.6, 13.9. IR (KBr, ν, cm^{-1}) 3446, 1730, 1671, 1598, 1488, 1346, 1297, 1186, 1076, 982; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{29}{}^{79}BrNaO_6$ 503.1040, Found 503.1047; Calcd for $C_{23}H_{29}{}^{81}BrNaO_6$ 505.1020, Found 505.1026.

Diethyl 7,7,10a-trimethyl-11-oxo-7,7a,8,10,10a,11-hexahydro-9H-cyclopenta[b]phenanthrene-9,9-dicarboxylate (3p)



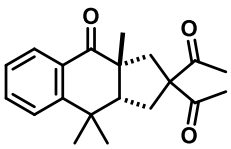
Light yellow oil, 48.1 mg, 57% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 8.59 – 8.55 (m, 2H), 8.11 (dd, J = 8.4, 5.2 Hz, 2H), 7.90 – 7.83 (m, 2H), 7.79 – 7.74 (m, 2H), 7.57 – 7.48 (m, 4H), 4.28 – 4.15 (m, 8H), 3.22 (d, J = 14.4 Hz, 1H), 2.78 – 2.73 (m, 2H), 2.56 – 2.51 (m, 2H), 2.49 – 2.42 (m, 3H), 2.36 – 2.27 (m, 2H), 2.15 (t, J = 13.2 Hz, 1H), 1.91 (s, 3H), 1.85 (s, 3H), 1.79 (s, 3H), 1.72 (s, 3H), 1.40 (s, 3H), 1.31 – 1.29 (m, 3H), 1.28 – 1.25 (m, 6H), 1.21 (t, J = 7.2 Hz, 3H), 1.17 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 201.4, 201.1, 172.4, 172.4, 172.1, 171.0, 150.1, 147.7, 133.6, 133.5, 133.0, 132.8, 132.3, 131.9, 129.8, 128.7, 128.1, 127.5, 127.5, 61.8, 61.7, 61.7, 57.8, 56.2, 55.8, 51.8, 51.6, 51.6, 46.5, 41.8, 39.1, 36.7, 36.1, 34.4, 33.3, 32.3, 27.3, 26.7, 24.9, 19.9, 14.1, 13.9. IR (KBr, v, cm^{-1}) 3316, 1730, 1682, 1585, 1446, 1366, 1296, 1235, 1158, 1067; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{26}H_{30}NaO_5$ 445.1985; Found 445.1992.

Diethyl 4a,8,8-trimethyl-4-oxo-4,4a,5,7,7a,8-hexahydro-6H-indeno[5,6-b]thiophene-6,6-dicarboxylate (3q)



Light yellow oil, 32.5 mg, 43% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.64 (d, J = 5.2 Hz, 1H), 7.00 (d, J = 5.2 Hz, 1H), 4.20 – 4.17 (m, 2H), 4.12 – 4.06 (m, 2H), 3.14 (d, J = 14.4 Hz, 1H), 2.52-2.50 (m, 1H), 2.39-2.32 (m, 2H), 2.17 (s, 1H), 1.41 (s, 3H), 1.40 (s, 3H), 1.36 (s, 3H), 1.25 – 1.21 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 196.7, 195.0, 172.7, 172.4, 172.4, 171.6, 160.0, 157.2, 135.6, 134.7, 134.4, 133.2, 126.7, 126.3, 61.7, 61.7, 61.6, 56.9, 56.6, 56.2, 53.9, 53.9, 53.1, 44.7, 41.7, 38.4, 36.5, 36.1, 32.6, 31.9, 31.6, 28.7, 26.7, 23.6, 20.9, 14.1, 14.0, 13.9. IR (KBr, v, cm^{-1}) 3441, 1725, 1650, 1475, 1387, 1259, 1188, 1107, 1023, 912; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{26}NaO_5S$ 401.1393; Found 401.1400.

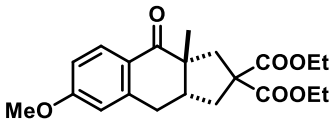
1,1'-(3a,9,9-Trimethyl-4-oxo-2,3,3a,4,9,9a-hexahydro-1H-cyclopenta[b]naphthalene-2,2-diyl)diethanone (3s)



Light yellow oil, 37.4 mg, 60% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.91 (d, J = 8.0 Hz, 1H), 7.54 – 7.52 (m, 1H), 7.38 – 7.32 (m, 2H), 2.74 (d, J = 14.4 Hz, 1H), 2.47 – 2.41 (m, 1H), 2.34 (d, J = 14.4 Hz, 1H), 2.13 (s, 3H), 2.08 – 2.04 (m, 1H), 2.00 (s, 3H), 1.74 (t, J = 13.2 Hz, 1H), 1.44 (s, 3H), 1.40 (s, 3H), 1.34 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 204.9, 204.7, 202.4, 149.3, 133.9, 130.1, 128.3, 126.8, 125.9, 72.5, 55.4, 52.0, 43.3, 36.0, 34.2, 28.1, 26.6, 26.2. IR (KBr, v, cm^{-1}) 3445, 1698, 1628, 1448, 1358, 1275, 1260, 1145, 1050, 983; HRMS (ESI-TOF) m/z:

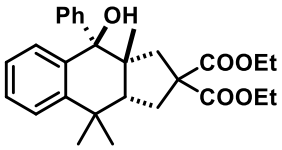
[M + Na]$^+$ Calcd for $C_{20}H_{24}NaO_3$ 335.1618; Found 335.1630.

Diethyl 7-methoxy-3a-methyl-4-oxo-1,3,3a,4,9,9a-hexahydro-2H-cyclopenta[b]naphthalene-2,2-dicarboxylate (3t)



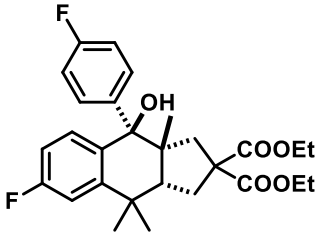
Light yellow oil, 47.2 mg, 63% yield; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 8.01 – 7.97 (m, 1H), 6.85 – 6.81 (m, 1H), 6.67 (d, J = 17.4 Hz, 1H), 4.27 – 4.12 (m, 4H), 3.85 (s, 3H), 3.21 – 3.16 (m, 1H), 2.99 – 2.80 (m, 2H), 2.63 – 2.56 (m, 1H), 2.43 – 2.35 (m, 1H), 2.32 – 2.27 (m, 1H), 2.22-2.14 (m, 1H), 1.28 – 1.15 (m, 9H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm) 200.7, 199.6, 172.8, 172.5, 172.4, 171.7, 163.9, 163.3, 145.1, 142.9, 130.5, 130.4, 125.2, 124.0, 113.4, 113.2, 113.1, 61.7, 61.6, 61.5, 57.4, 57.3, 55.4, 52.3, 51.5, 44.3, 44.1, 43.9, 40.8, 38.3, 36.6, 30.9, 27.9, 22.6, 16.2, 14.03, 13.99, 13.8. IR (KBr, v, cm^{-1}) 3448, 1734, 1662, 1624, 1596, 1485, 1382, 1369, 1294, 1185; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{21}H_{26}NaO_6$ 397.1622; Found 397.1629.

Diethyl 9-hydroxy-3a,4,4-trimethyl-9-phenyl-3a,4,9,9a-tetrahydro-1H-cyclopenta[b]naphthalene-2,2(3H)-dicarboxylate (5a)



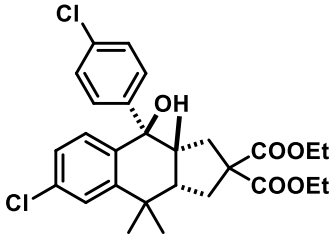
White solid, 64.1 mg, 71% yield; mp 171-172 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 8.01 (d, J = 7.6 Hz, 1H), 7.54 (d, J = 7.6 Hz, 1H), 7.47 (td, J = 7.6, 1.3 Hz, 1H), 7.41 – 7.32 (m, 2H), 7.27 – 7.14 (m, 3H), 6.95 (d, J = 8.0 Hz, 1H), 4.32 – 4.24 (m, 2H), 4.18 – 4.14 (m, 2H), 3.04 (d, J = 13.6 Hz, 1H), 2.80 (dd, J = 13.6, 6.8 Hz, 1H), 2.63 (dd, J = 13.2, 6.8 Hz, 1H), 2.42 (t, J = 13.2 Hz, 1H), 2.01 (s, 1H), 1.70 (d, J = 13.6 Hz, 1H), 1.43 (s, 3H), 1.41 (s, 3H), 1.32 (t, J = 7.2 Hz, 3H), 1.26 (t, J = 7.2 Hz, 3H), 0.74 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 173.3, 172.9, 147.0, 143.7, 140.1, 130.4, 129.9, 128.3, 127.9, 127.6, 126.7, 125.8, 79.5, 61.5, 56.3, 48.6, 46.9, 40.9, 36.4, 34.6, 33.4, 25.9, 21.2, 14.1. IR (KBr, v, cm^{-1}) 3341, 1756, 1665, 1609, 1567, 1493, 1366, 1275, 1165, 938; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{28}H_{34}NaO_5$ 473.2298; Found 473.2306.

Diethyl 6-fluoro-9-(4-fluorophenyl)-9-hydroxy-3a,4,4-trimethyl-3a,4,9,9a-tetrahydro-1H-cyclopenta[b] naphthalene-2,2(3H)-dicarboxylate (5b)



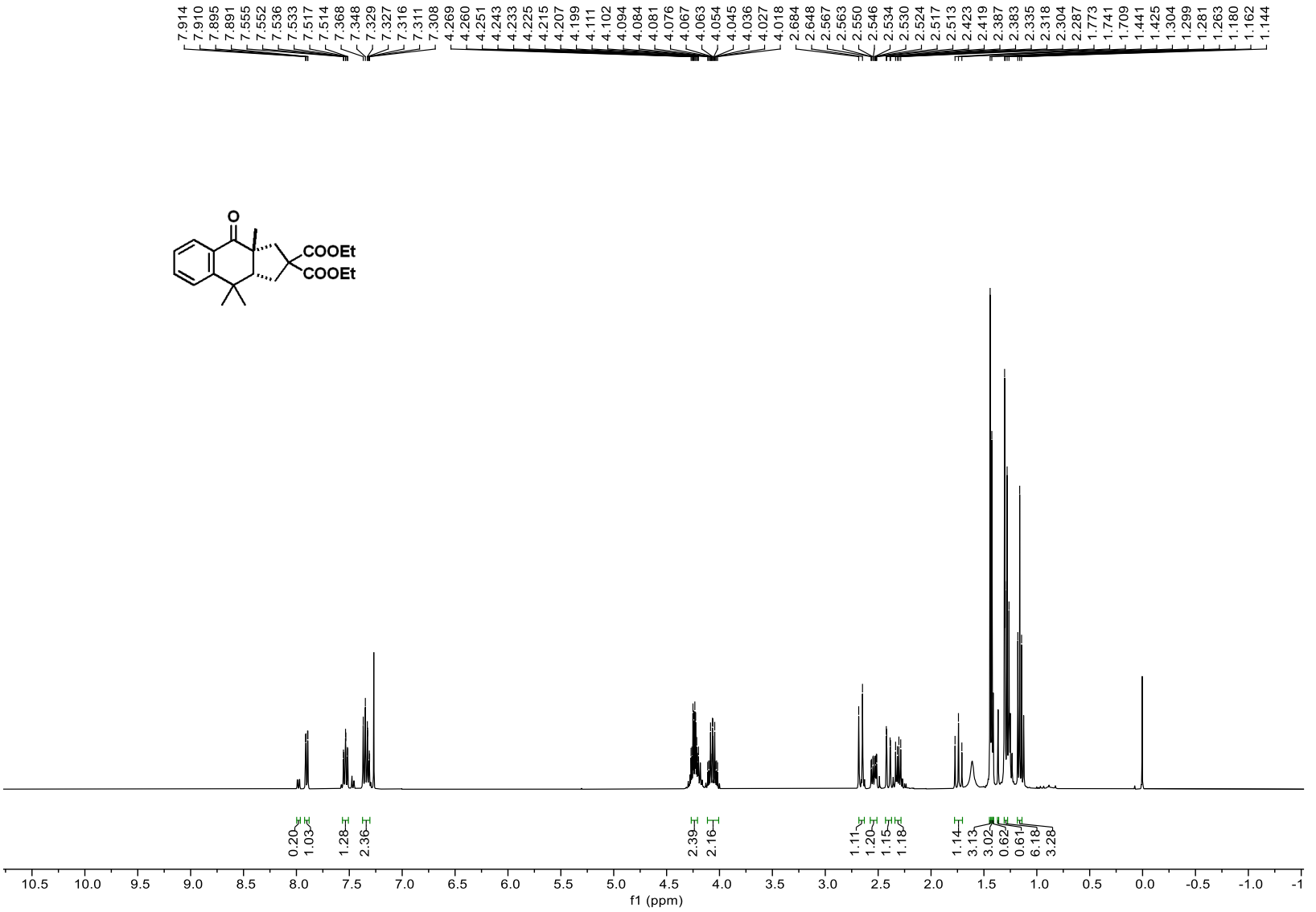
White solid, 54.2 mg, 56% yield; mp 164-165 °C; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.95 – 7.88 (m, 1H), 7.15 – 7.07 (m, 3H), 6.89 – 6.78 (m, 3H), 4.26 – 4.19 (m, 2H), 4.14 (q, J = 7.2 Hz, 2H), 2.93 (d, J = 13.6 Hz, 1H), 2.70 (dd, J = 13.6, 6.8 Hz, 1H), 2.56 (dd, J = 13.2, 6.8 Hz, 1H), 2.35 (t, J = 13.2 Hz, 1H), 1.93 (s, 1H), 1.61 (d, J = 13.6 Hz, 1H), 1.35 (s, 3H), 1.34 (s, 3H), 1.27 (t, J = 7.2 Hz, 3H), 1.21 (t, J = 7.2 Hz, 3H), 0.66 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 173.1 (J = 35.7 Hz), 163.93, 163.09, 161.48, 160.65, 150.03, 149.97, 139.22, 135.93, 131.65, 131.57, 129.48, 129.40, 114.59, 114.38, 114.18, 113.97, 113.44, 113.23, 113.05, 112.84, 78.80, 61.65, 61.54, 56.33, 48.68, 46.71, 40.76, 36.75, 34.53, 33.36, 25.81, 21.17, 14.10, 14.05. IR (KBr, v, cm^{-1}) 3331, 1731, 1683, 1559, 1478, 1381, 1279, 1167, 1080, 913; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{28}H_{32}F_2NaO_5$ 509.2110; Found 509.2118.

Diethyl 7-chloro-4-(4-chlorophenyl)-4-hydroxy-3a,9,9-trimethyl-3a,4,9,9a-tetrahydro-1H-cyclopenta[b] naphthalene-2,2(3H)-dicarboxylate (5c)

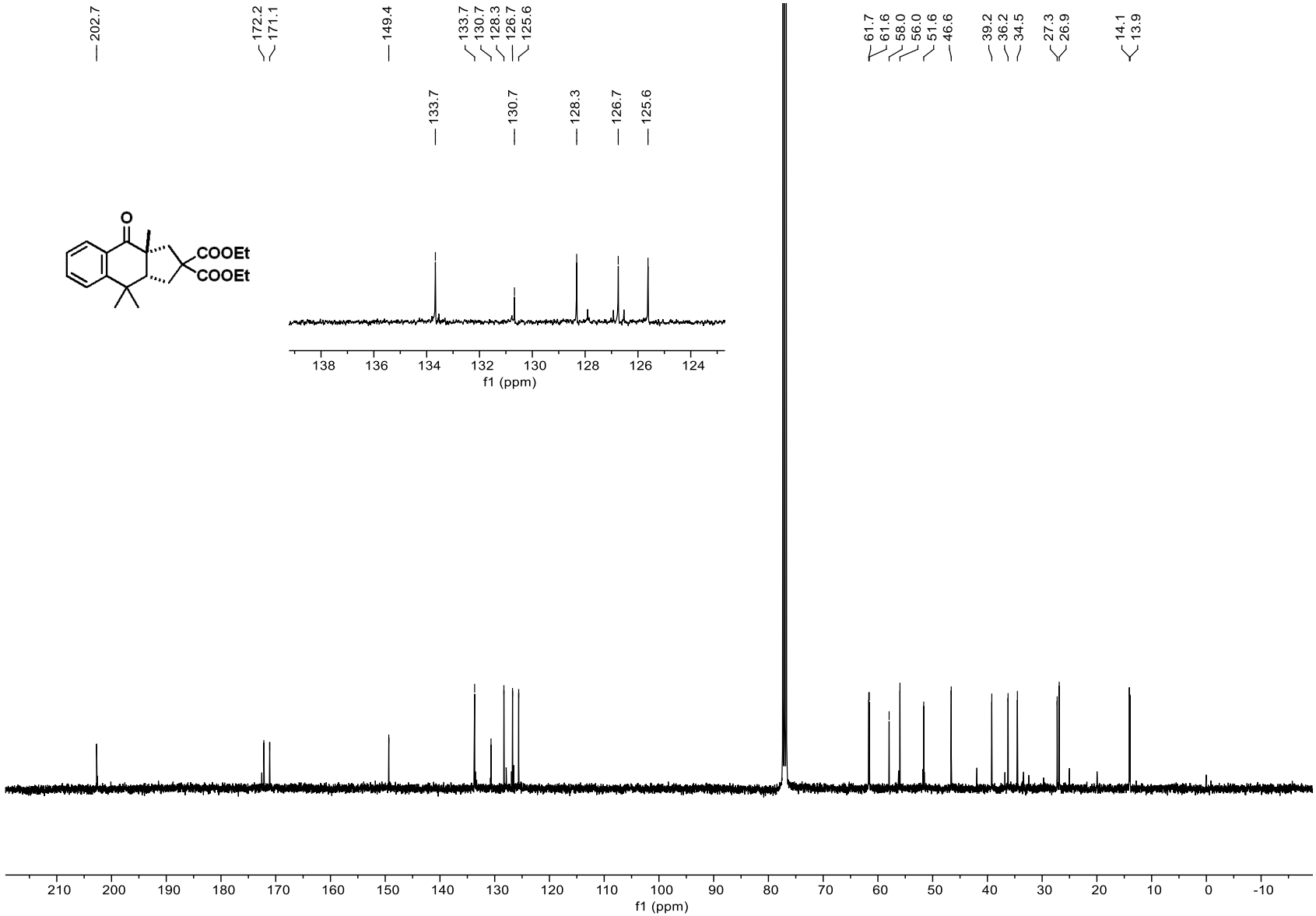


White solid, 66.4 mg, 64% yield; mp 167-168 °C; ^{1}H NMR (400 MHz, $CDCl_3$; δ, ppm) 7.88 (dd, J = 8.4, 2.4 Hz, 1H), 7.43 (d, J = 2.0 Hz, 1H), 7.39 (dd, J = 8.4, 2.4 Hz, 1H), 7.18 (dd, J = 8.4, 2.4 Hz, 1H), 7.10 (dd, J = 8.4, 2.4 Hz, 1H), 7.04 (d, J = 8.4 Hz, 1H), 6.80 (dd, J = 8.4, 2.4 Hz, 1H), 4.26 – 4.18 (m, 2H), 4.14 – 4.13 (m, 2H), 2.92 (d, J = 13.6 Hz, 1H), 2.69 (dd, J = 13.6, 6.8 Hz, 1H), 2.55 (dd, J = 13.2, 6.8 Hz, 1H), 2.36 (t, J = 13.2 Hz, 1H), 2.00 (s, 1H), 1.60 (d, J = 13.6 Hz, 1H), 1.35 (d, J = 7.6 Hz, 6H), 1.27 (t, J = 7.2 Hz, 3H), 1.21 (t, J = 7.2 Hz, 3H), 0.66 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$; δ, ppm): 173.1, 172.7, 149.3, 141.8, 138.3, 134.4, 132.9, 131.4, 131.2, 129.2, 128.1, 127.9, 126.4, 126.2, 78.9, 61.7, 61.6, 56.3, 48.5, 46.7, 40.7, 36.7, 34.5, 33.3, 25.8, 21.1, 14.1, 14.0. IR (KBr, v, cm^{-1}) 3414, 1713, 1680, 1656, 1418, 1367, 1289, 1170, 1167, 981, 851; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{28}H_{32}{}^{35}Cl_2NaO_5$ 541.1519, Found 541.1524; Calcd for $C_{28}H_{32}{}^{35}Cl^{37}ClNaO_5$ 543.1490; Found 543.1497.

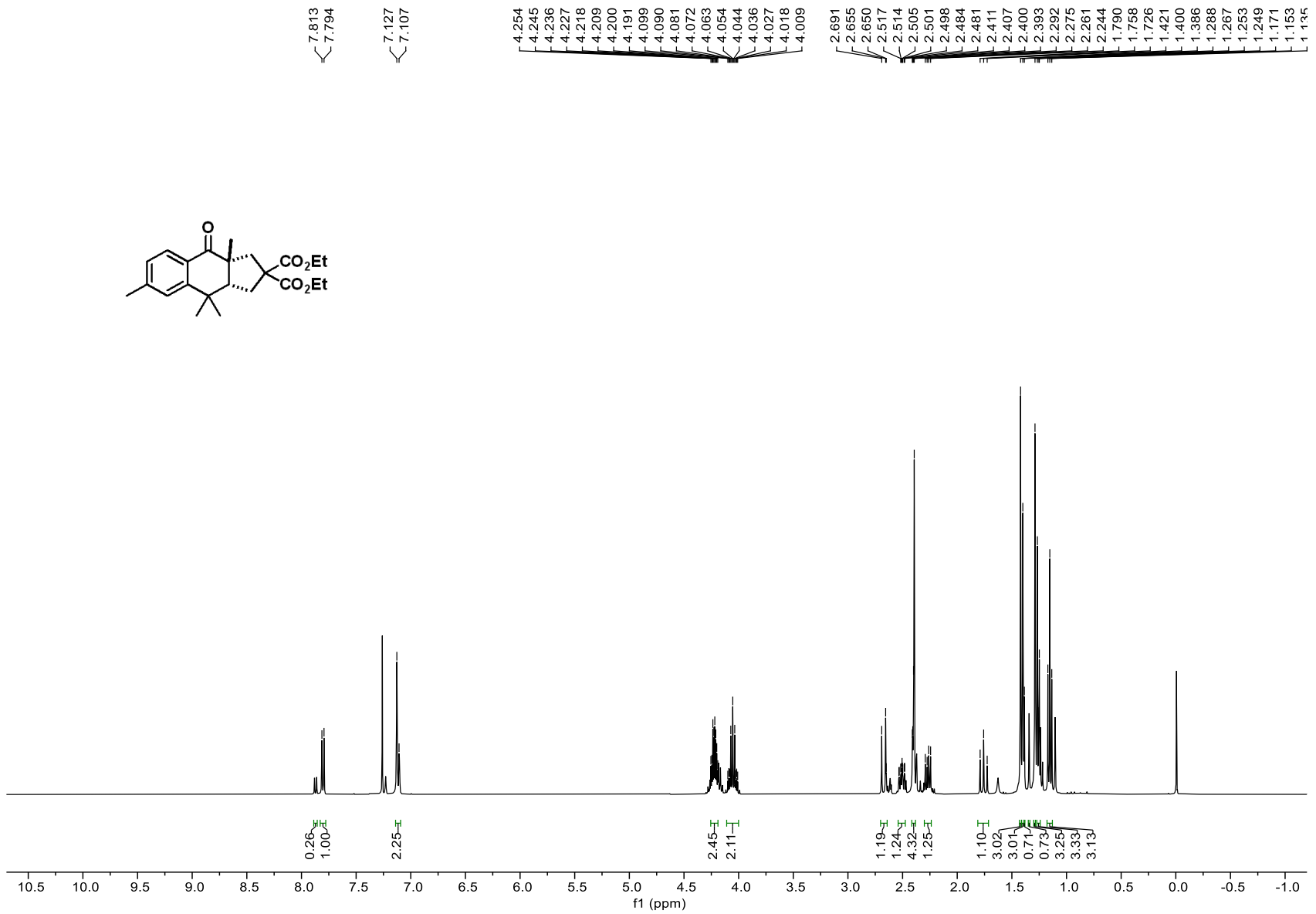
4. NMR Spectra



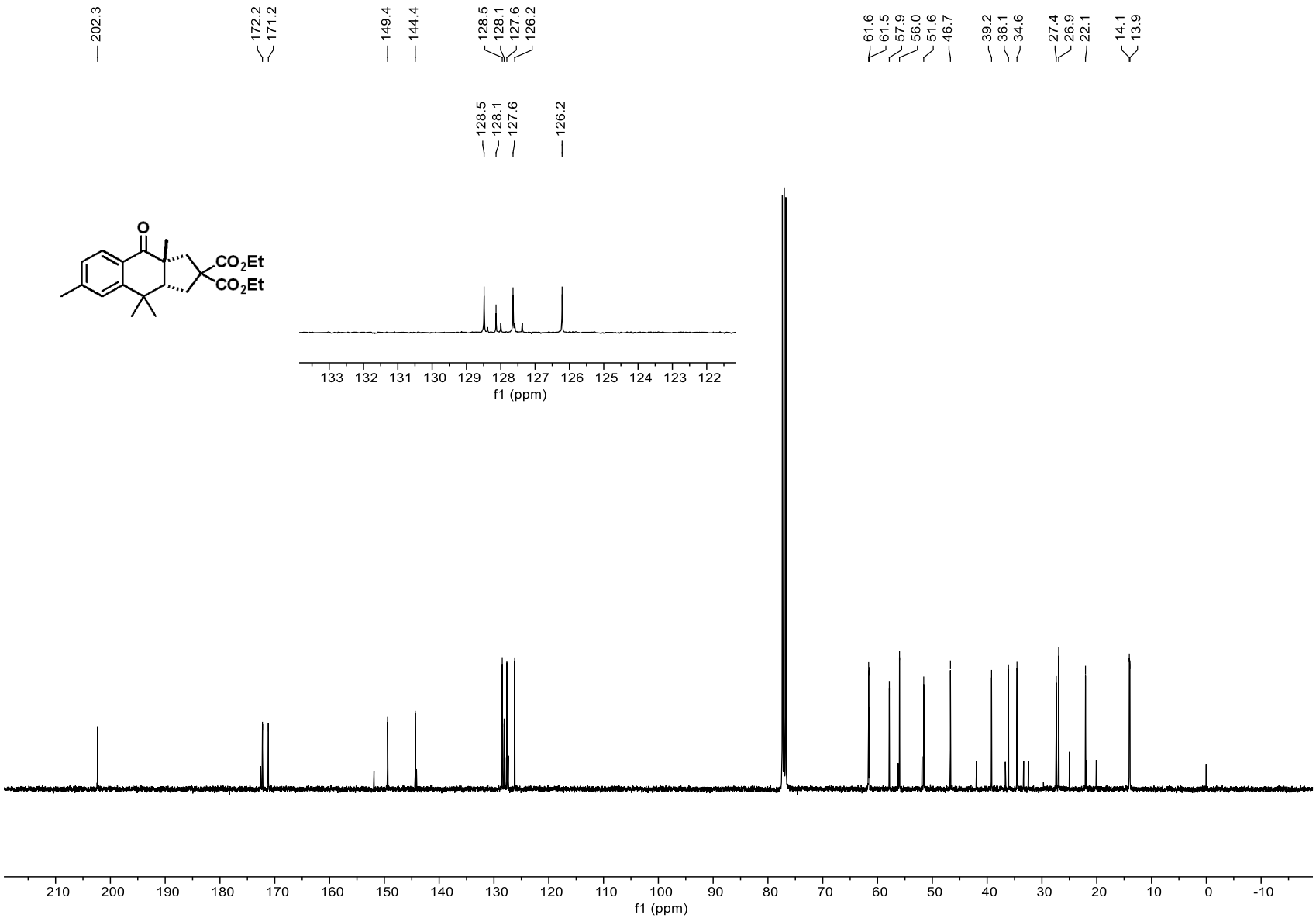
^{1}H NMR Spectrum of Compound 3a



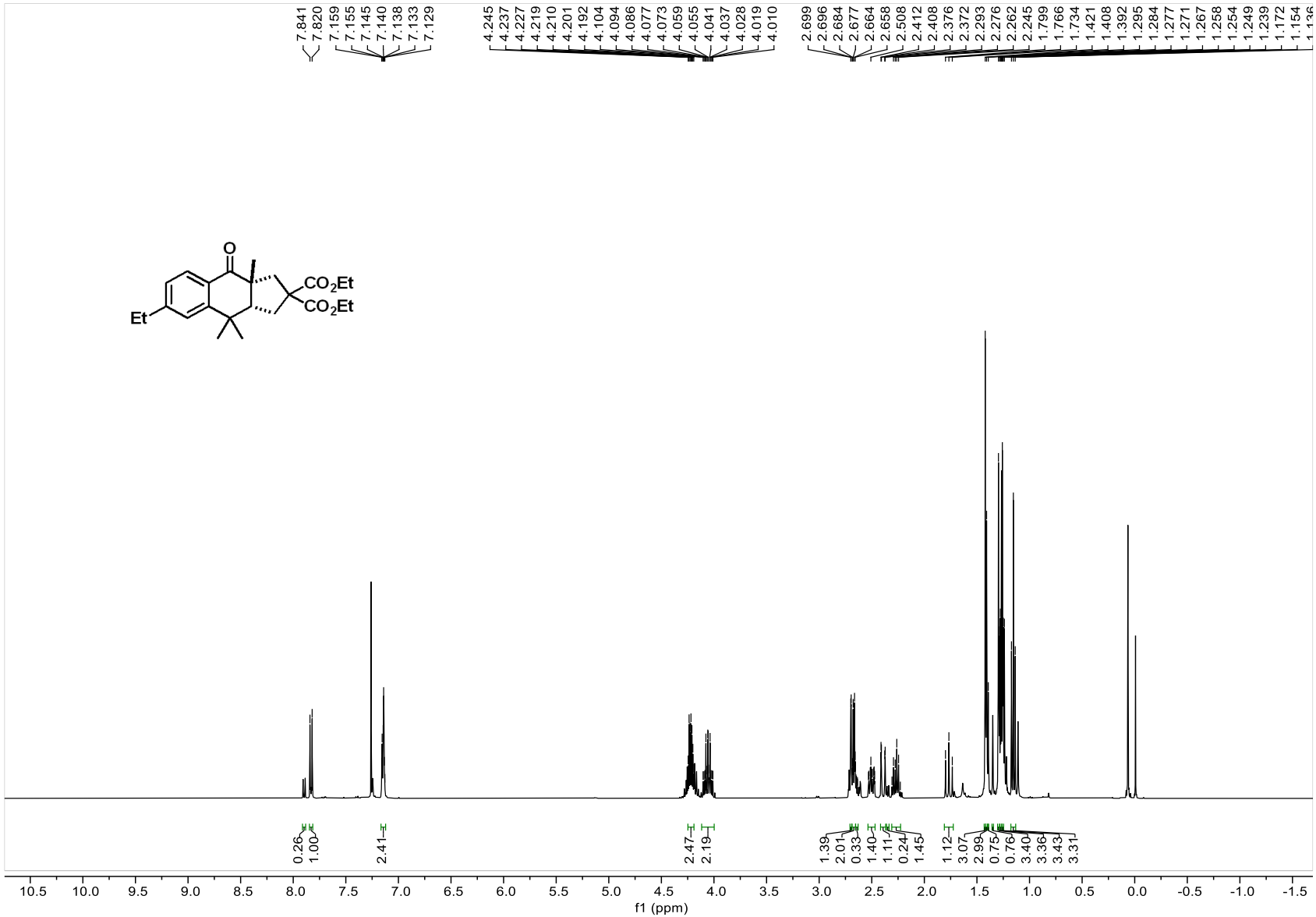
^{13}C NMR Spectrum of Compound 3a



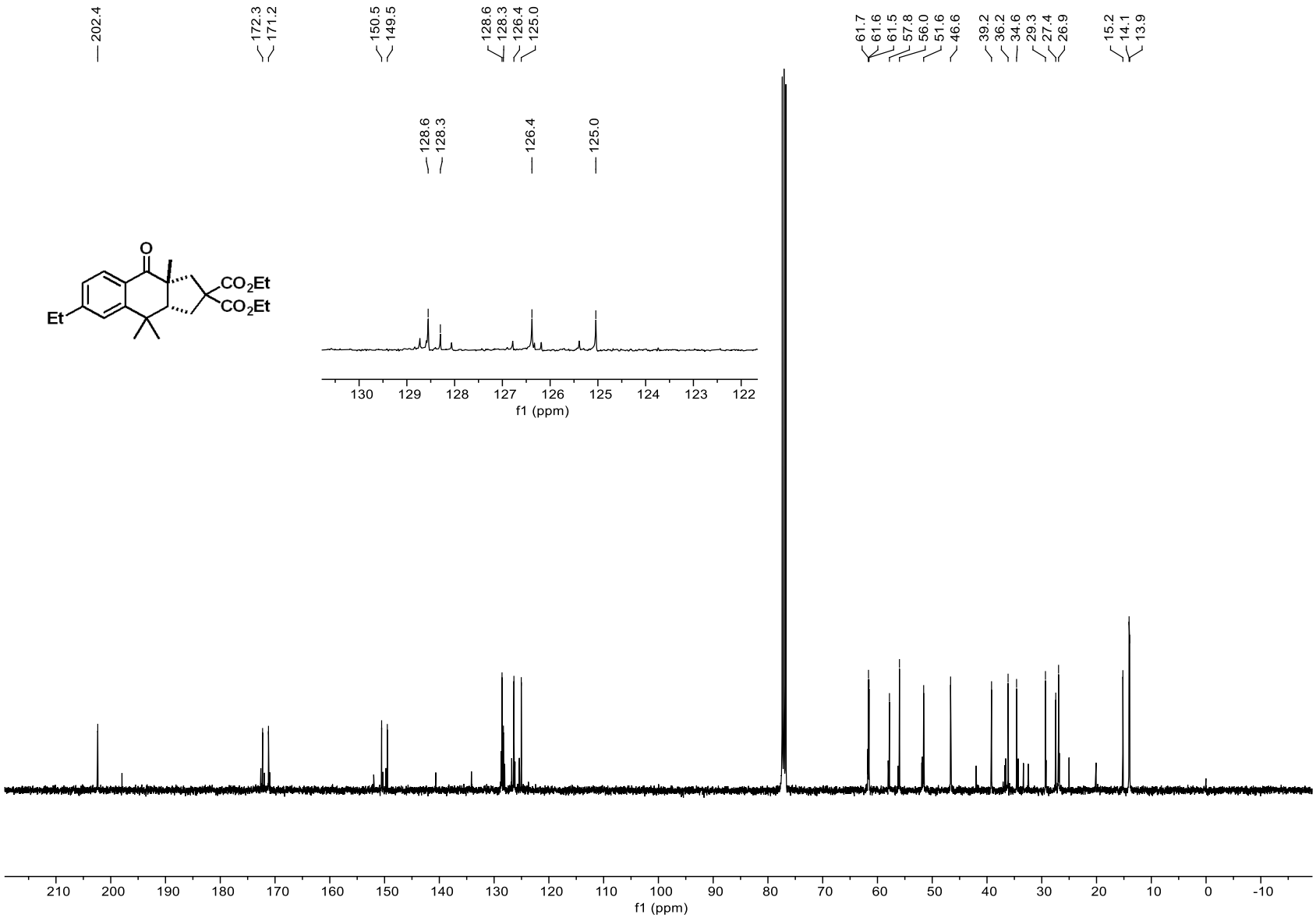
^{1}H NMR Spectrum of Compound 3b



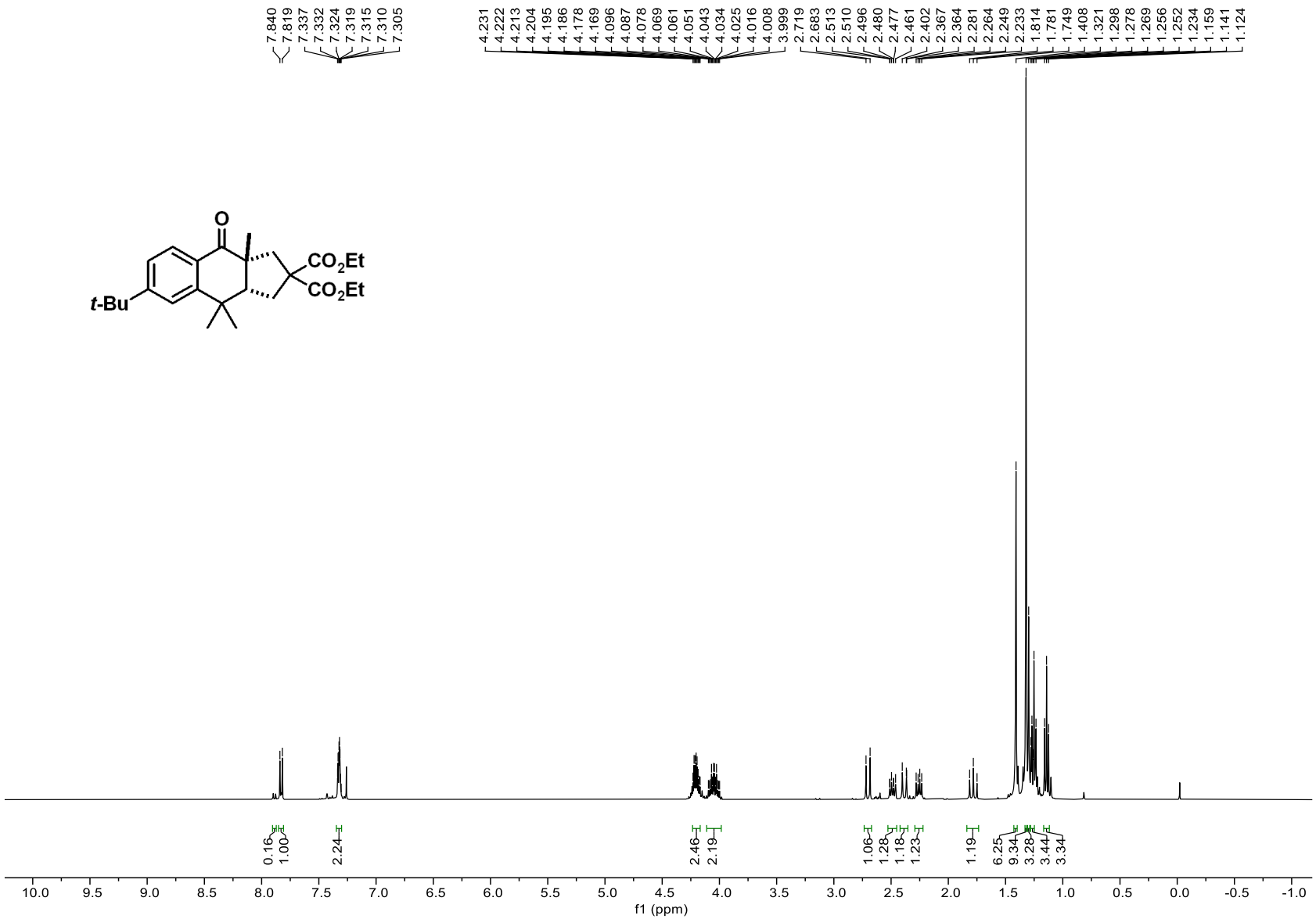
^{13}C NMR Spectrum of Compound 3b



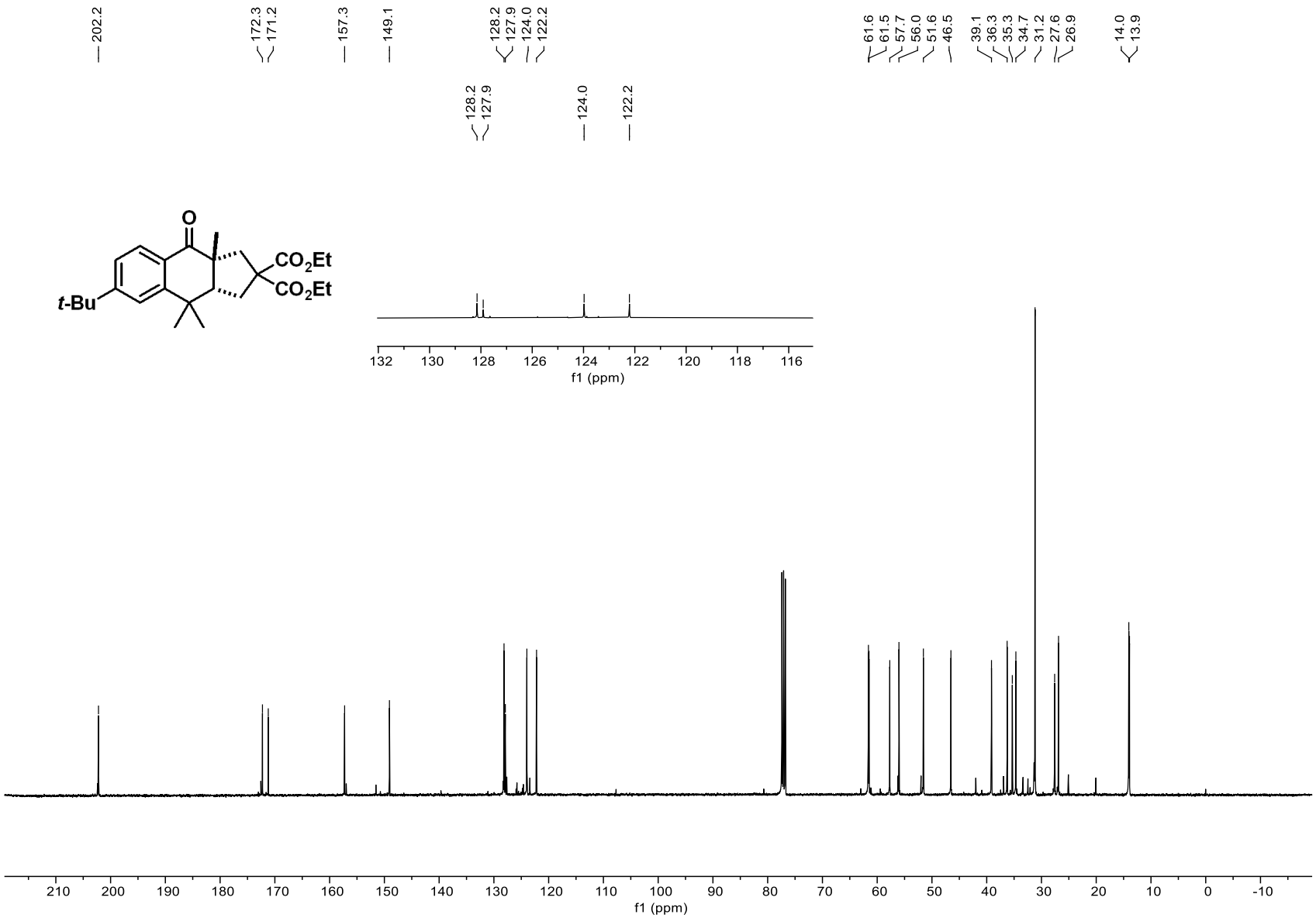
^{1}H NMR Spectrum of Compound 3c



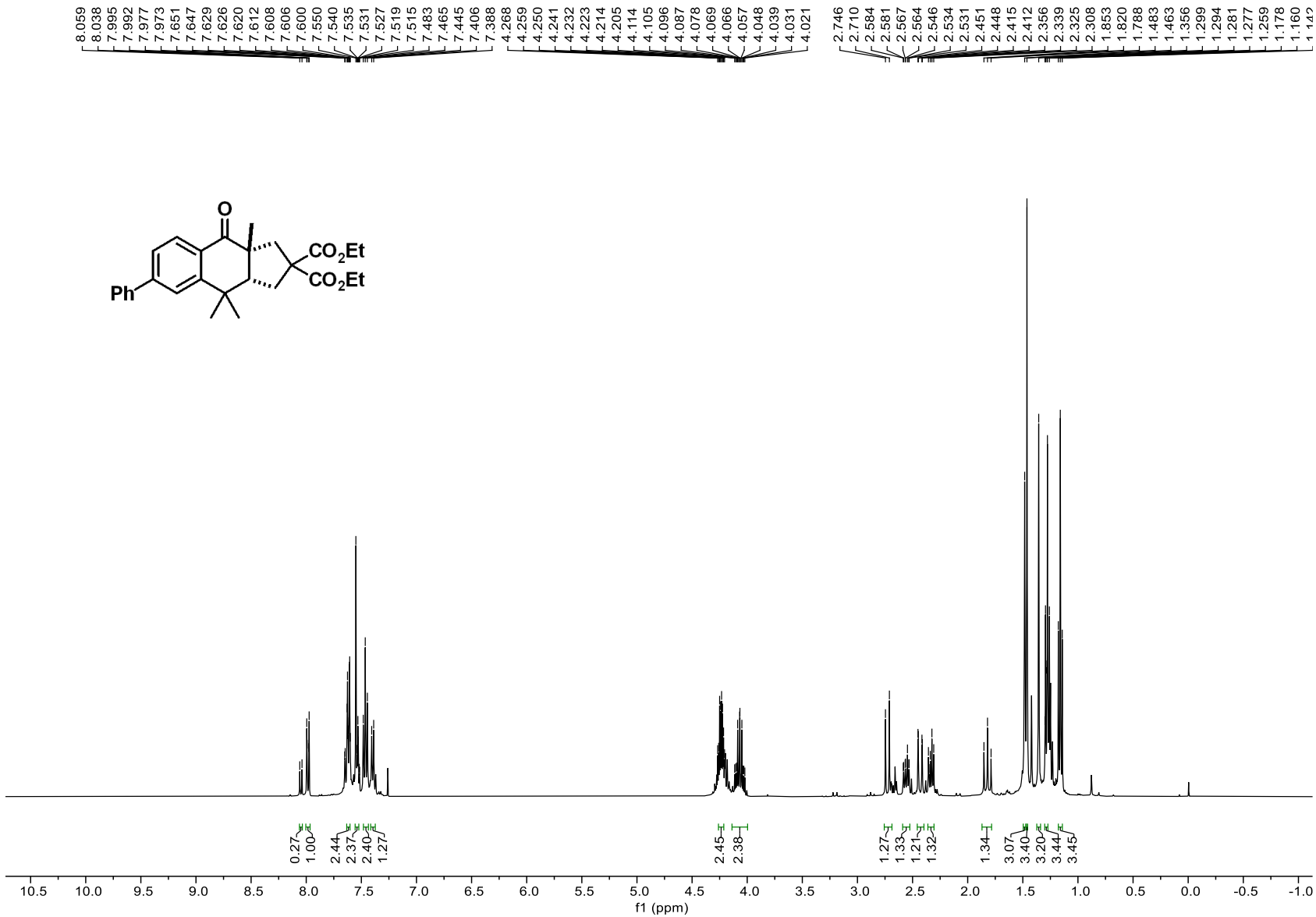
^{13}C NMR Spectrum of Compound 3c



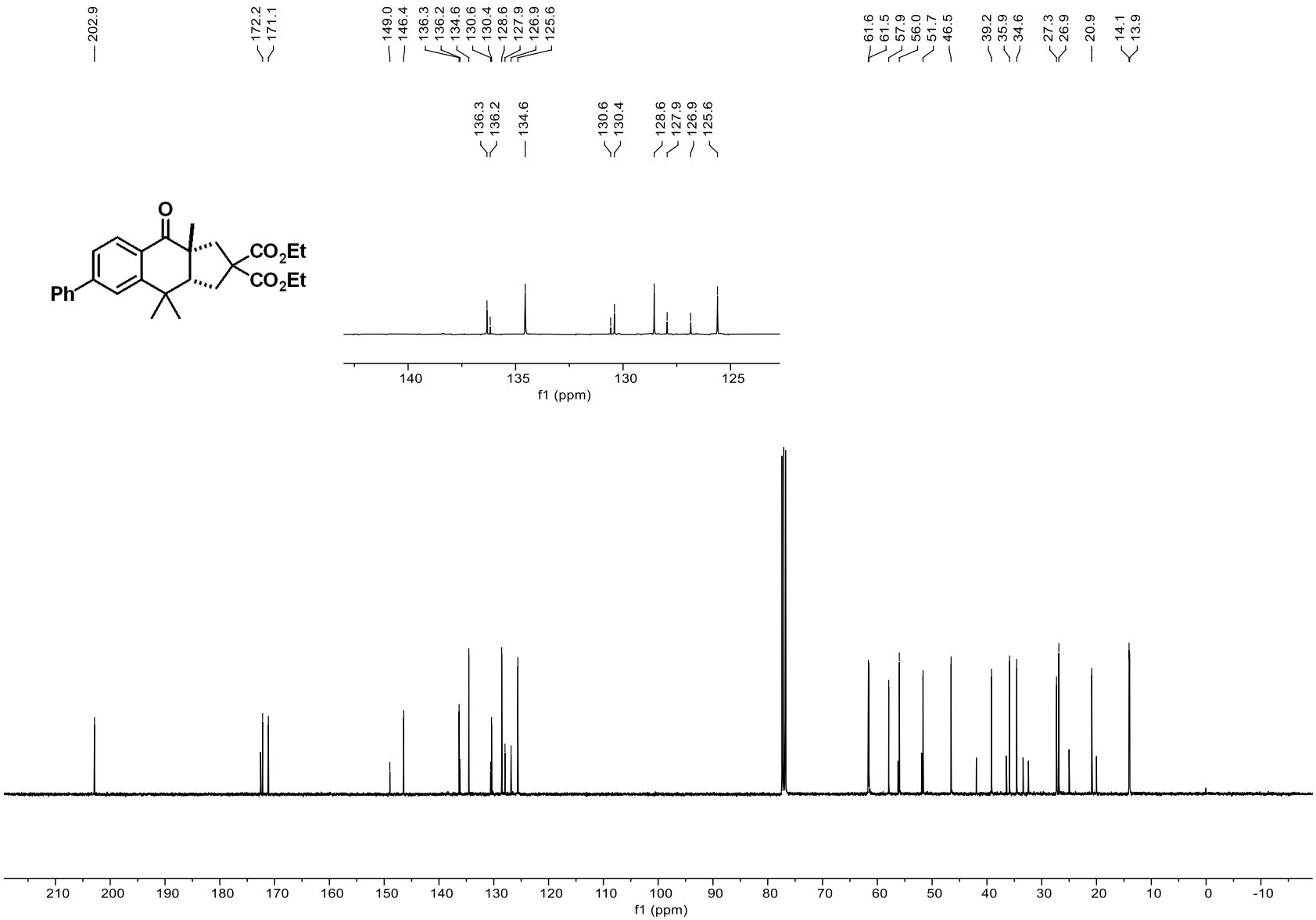
^{1}H NMR Spectrum of Compound 3d



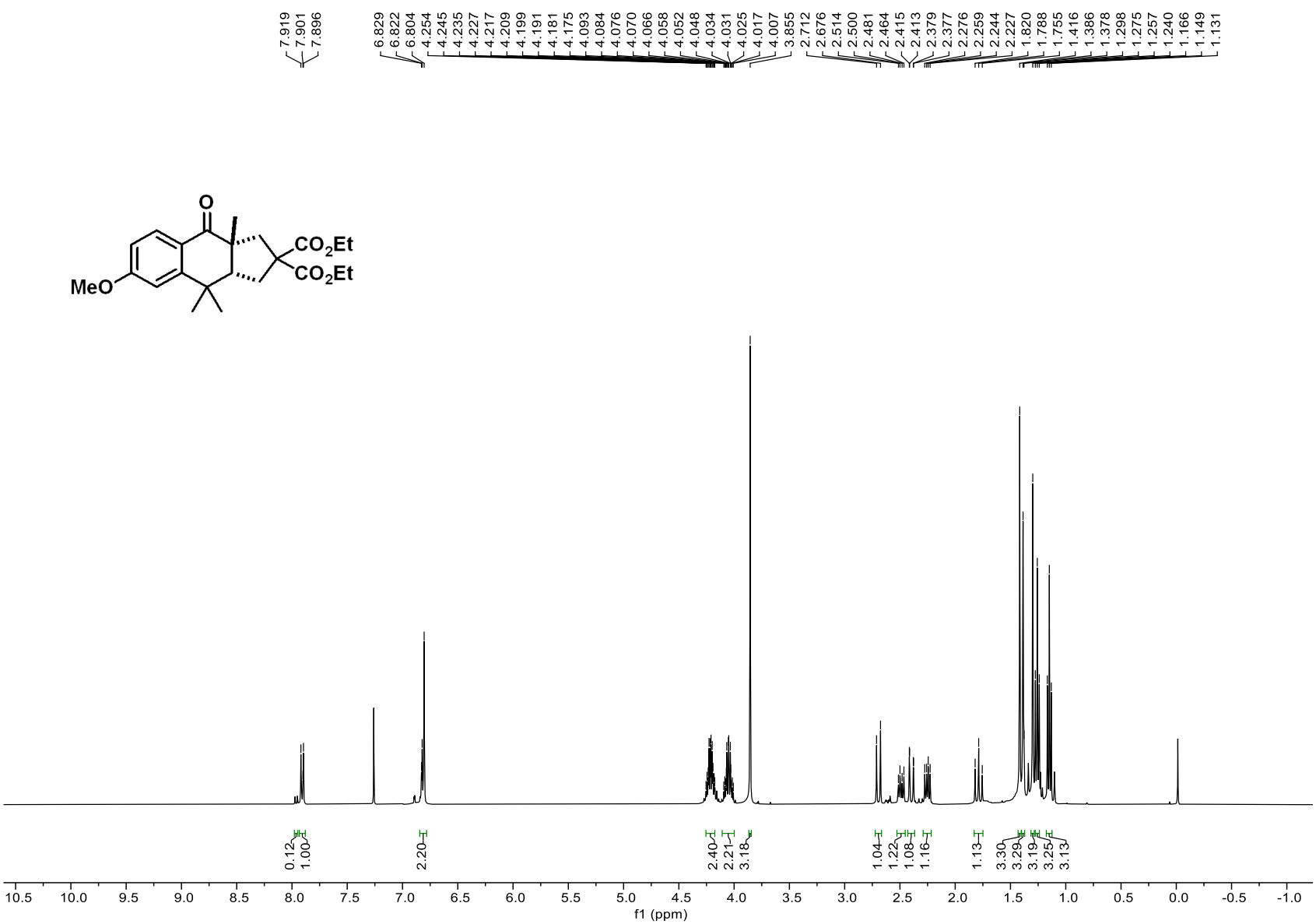
^{13}C NMR Spectrum of Compound 3d



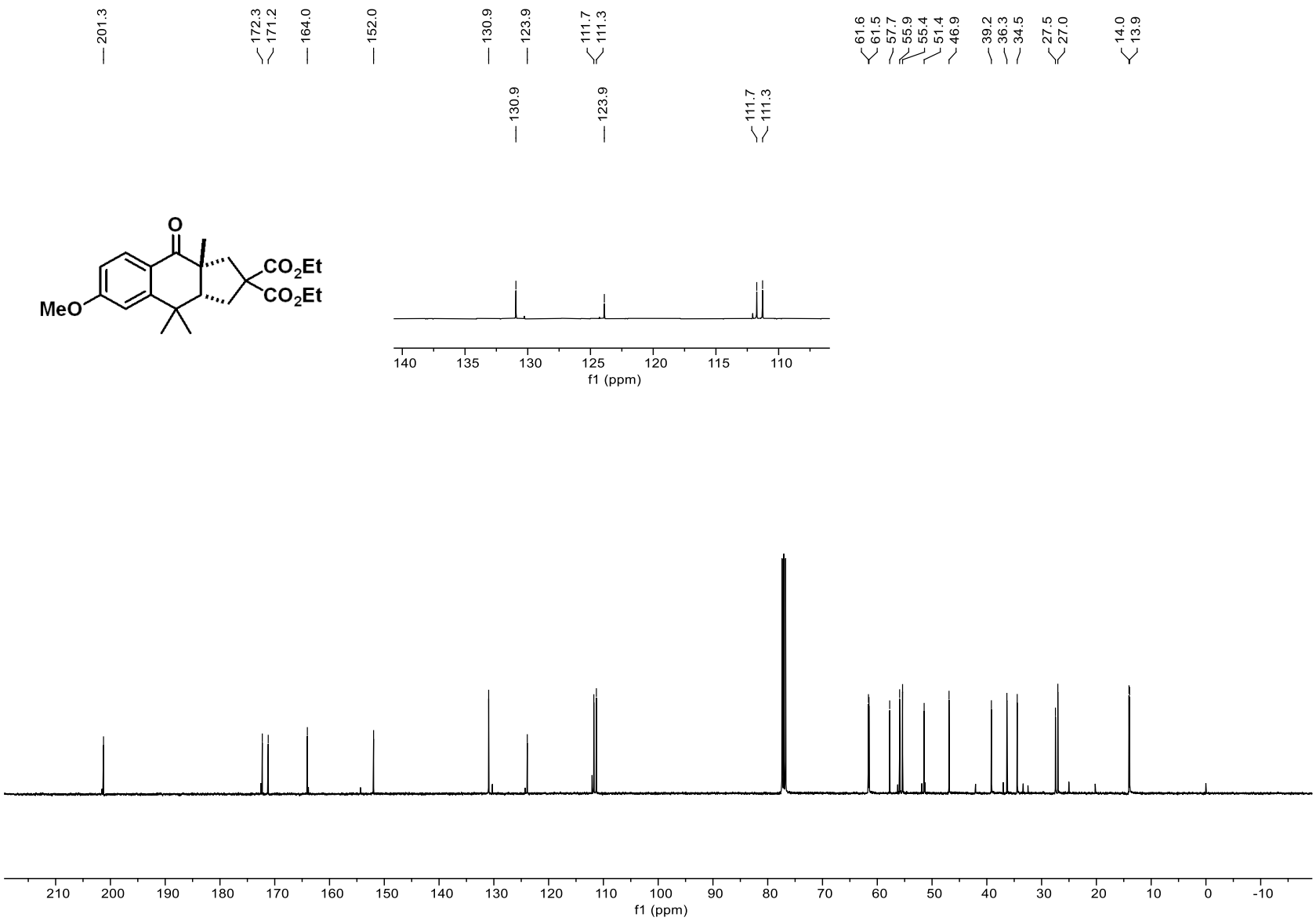
^{1}H NMR Spectrum of Compound 3e



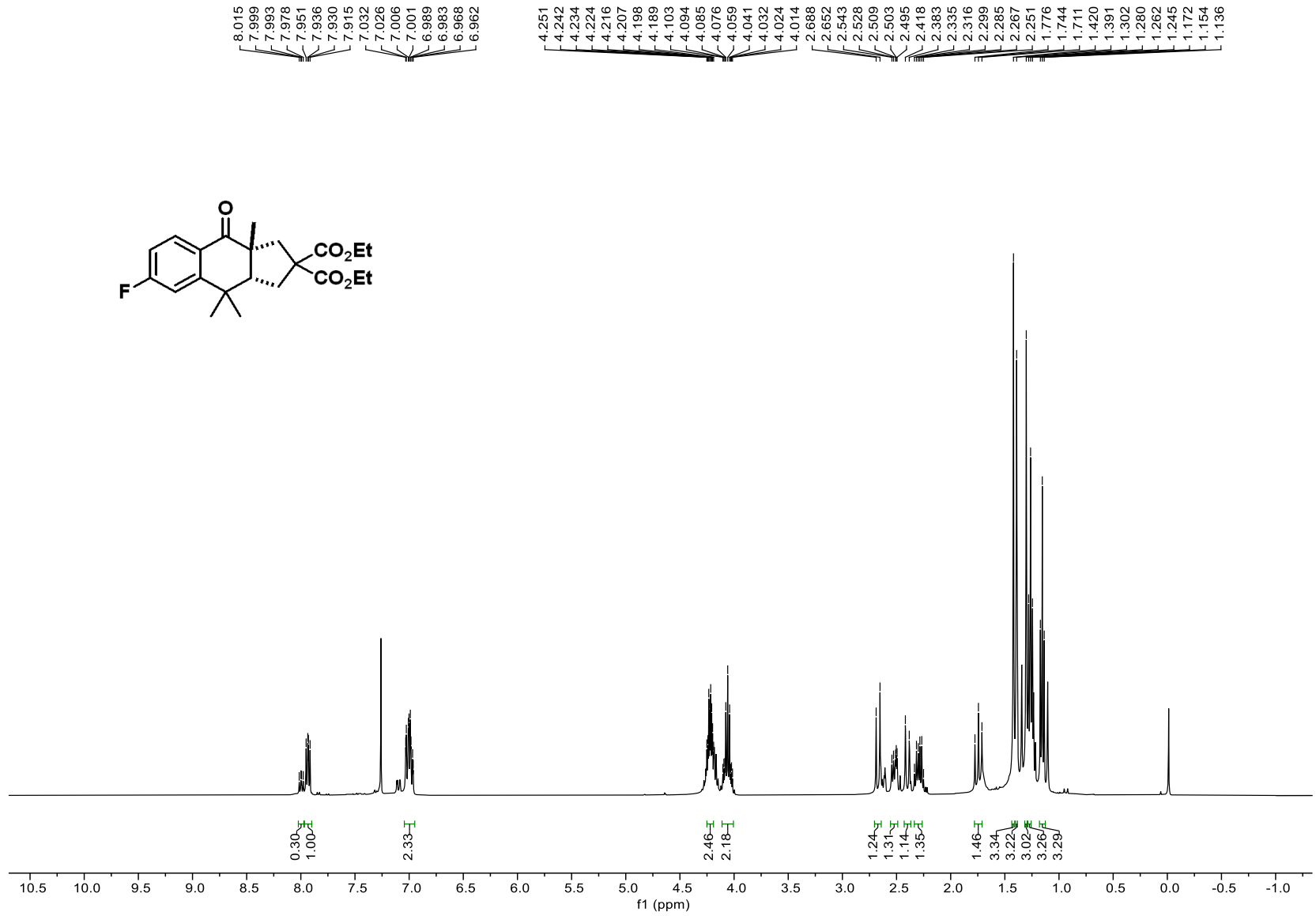
^{13}C NMR Spectrum of Compound 3e



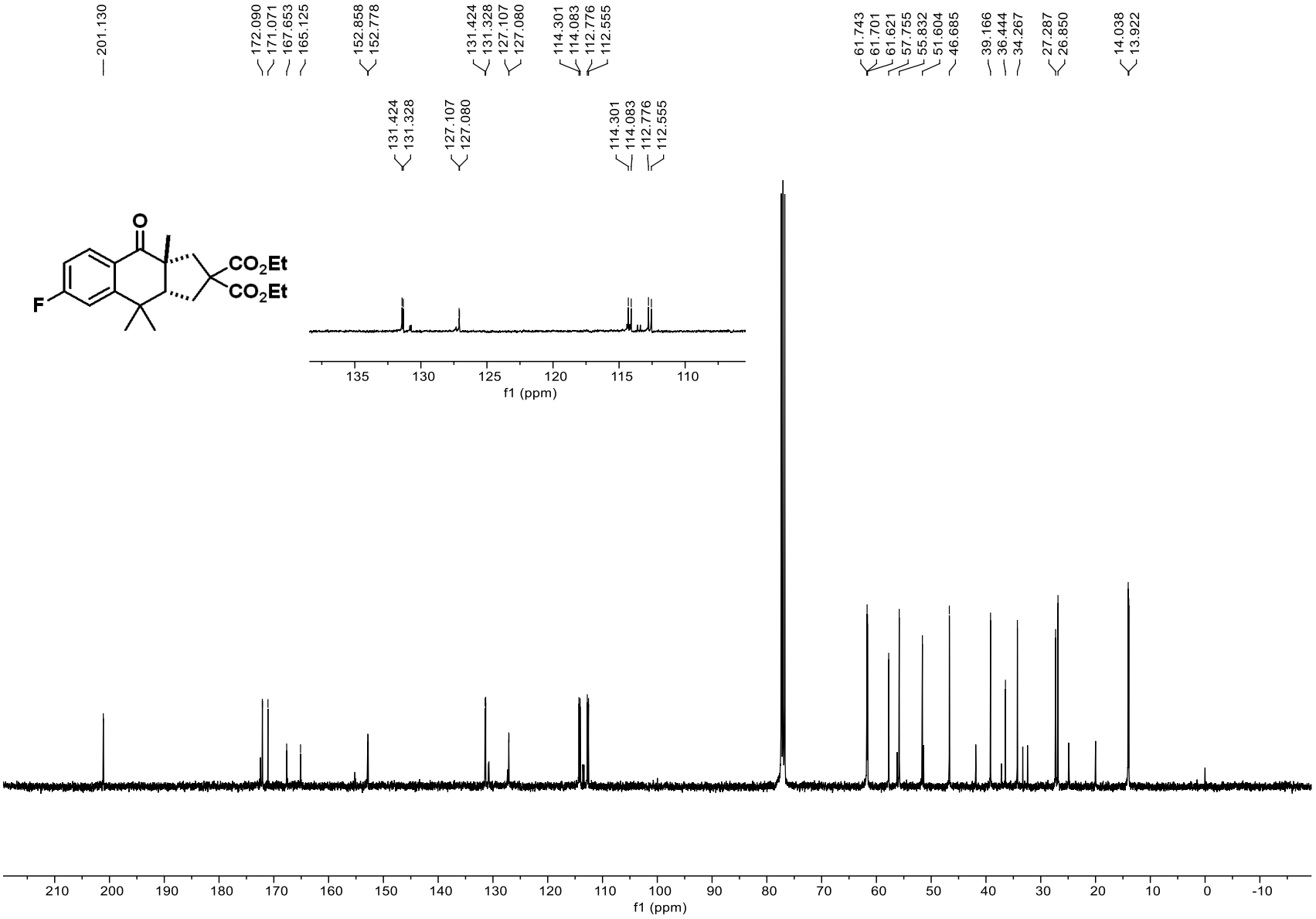
^{1}H NMR Spectrum of Compound 3f



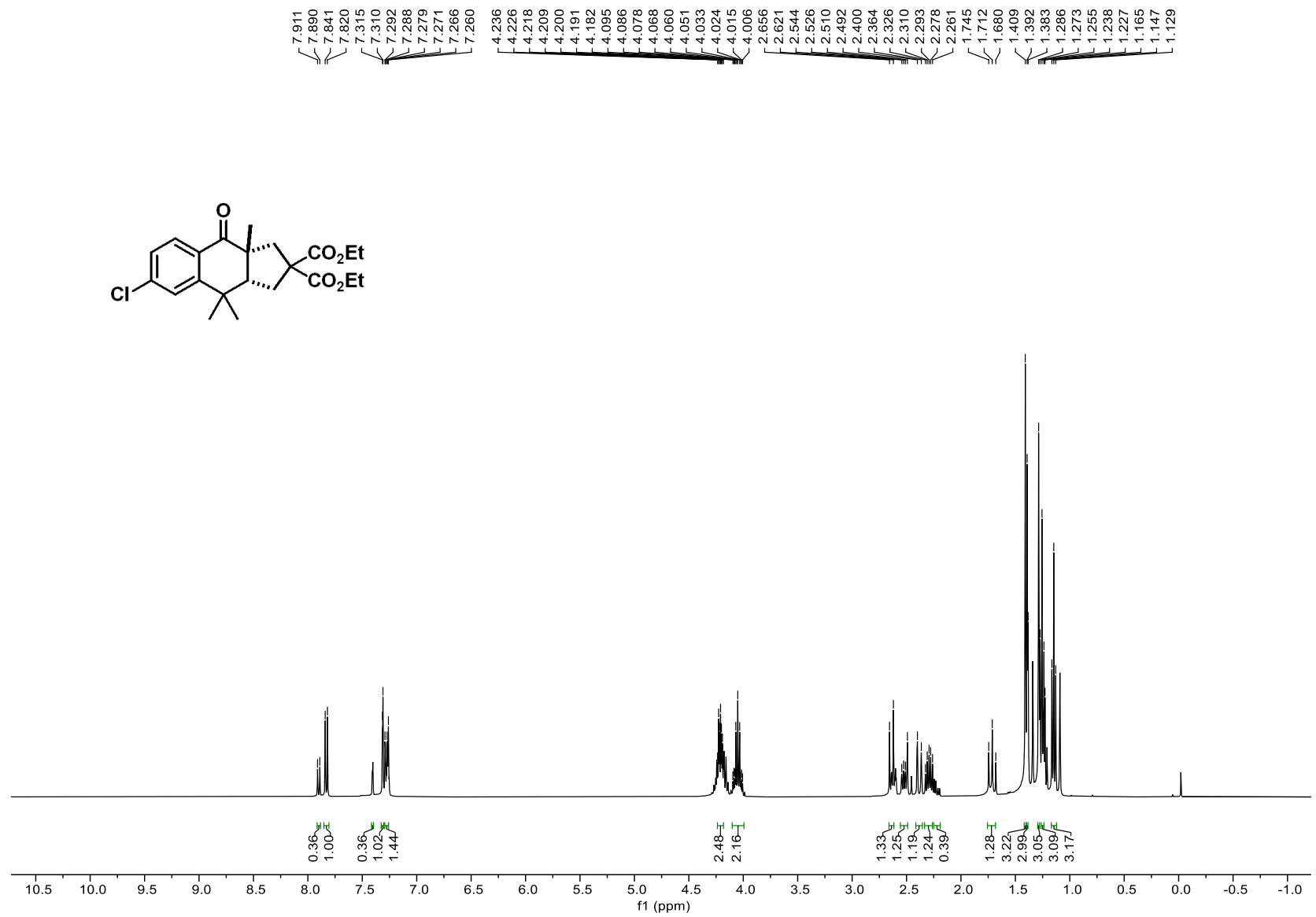
^{13}C NMR Spectrum of Compound 3f



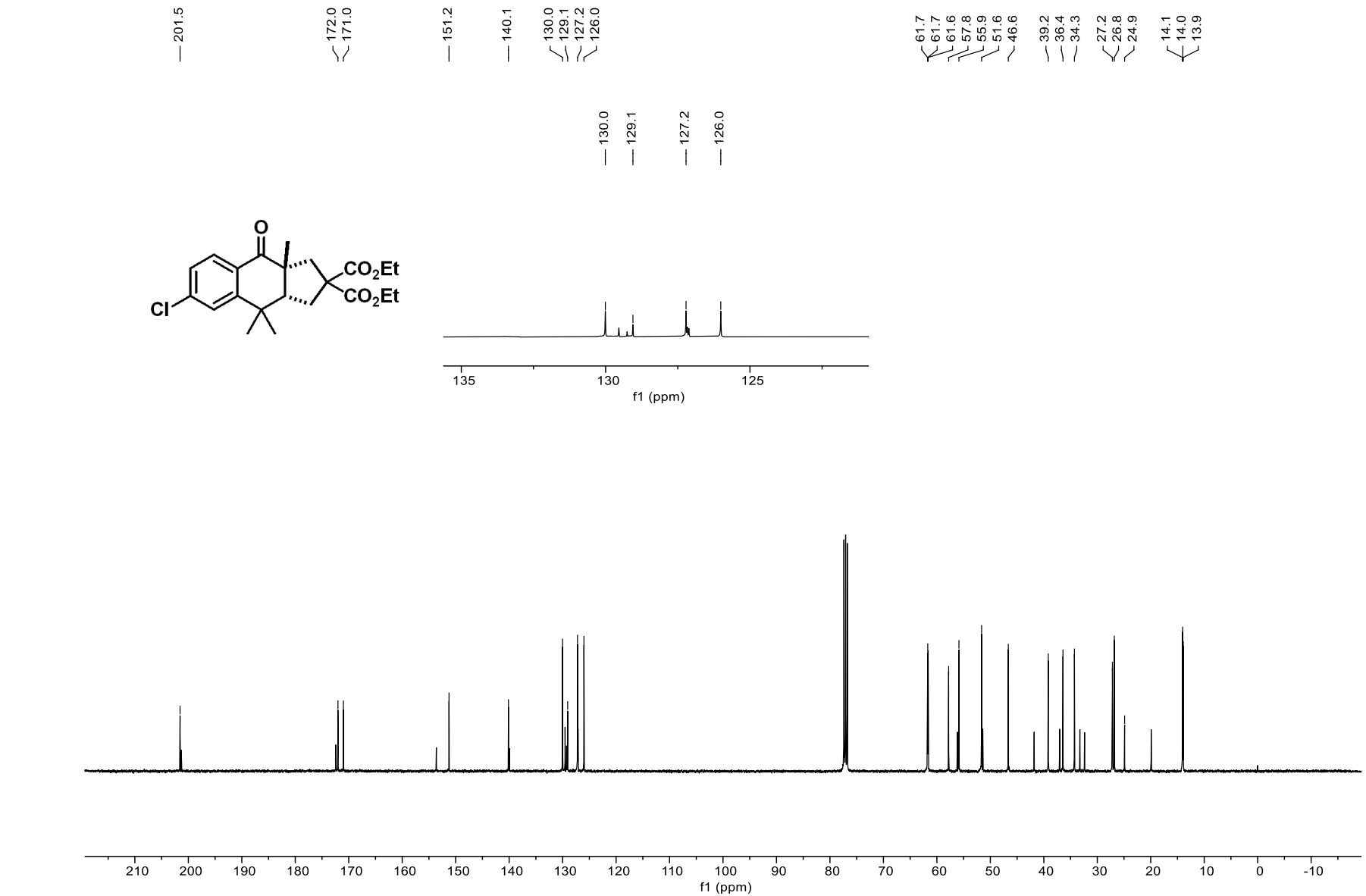
^{1}H NMR Spectrum of Compound 3g



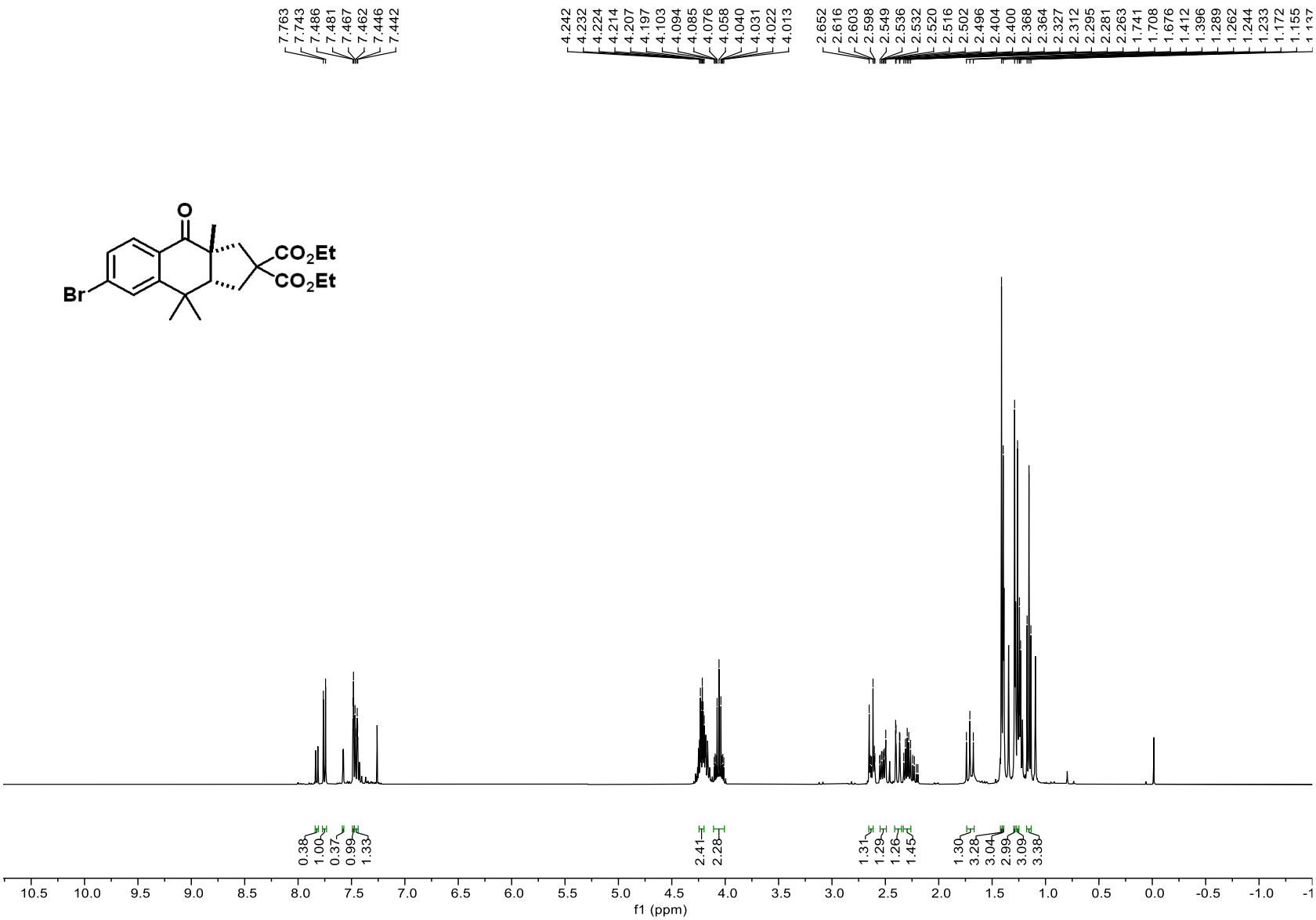
^{13}C NMR Spectrum of Compound 3g



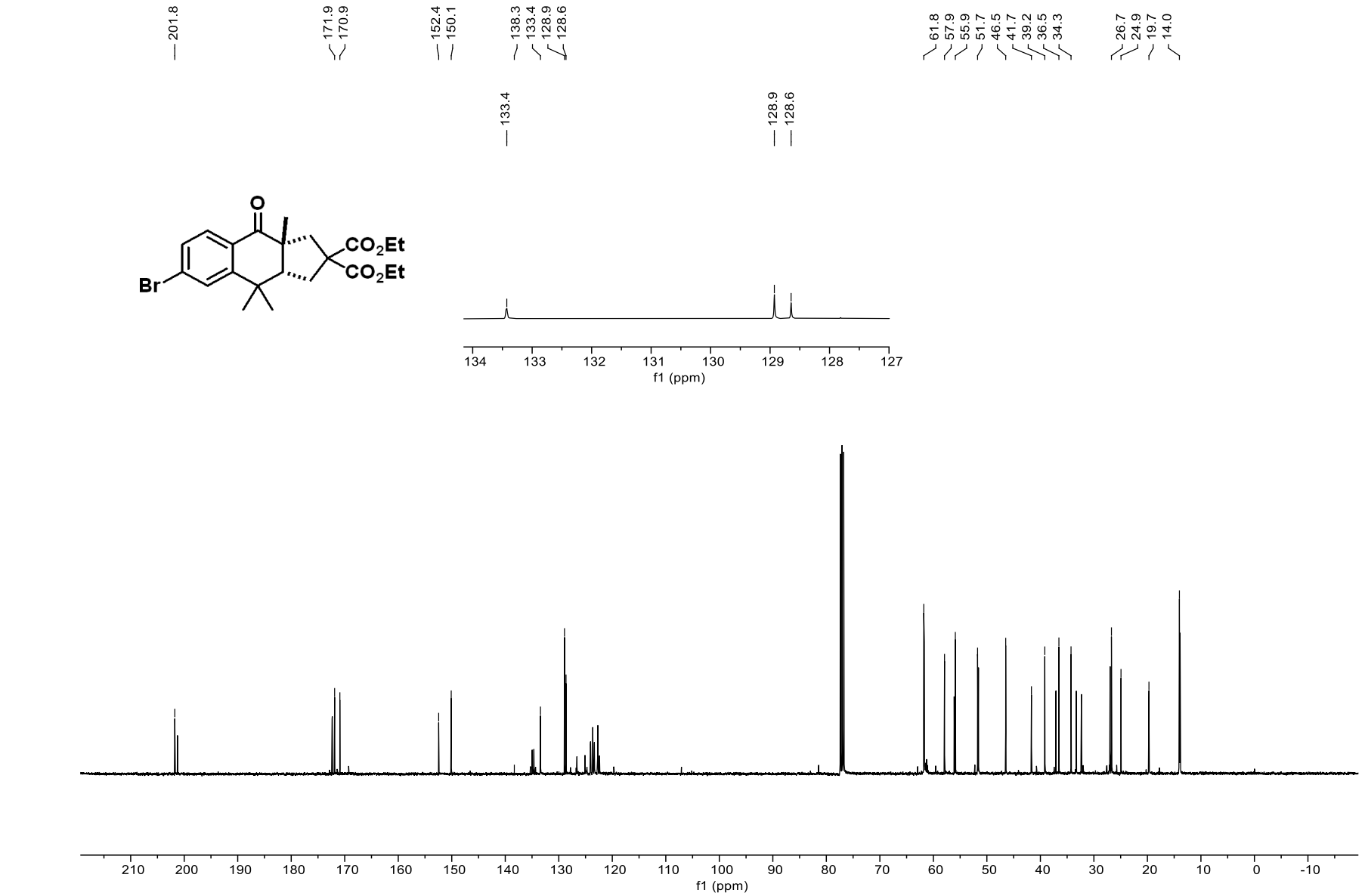
^{1}H NMR Spectrum of Compound 3h



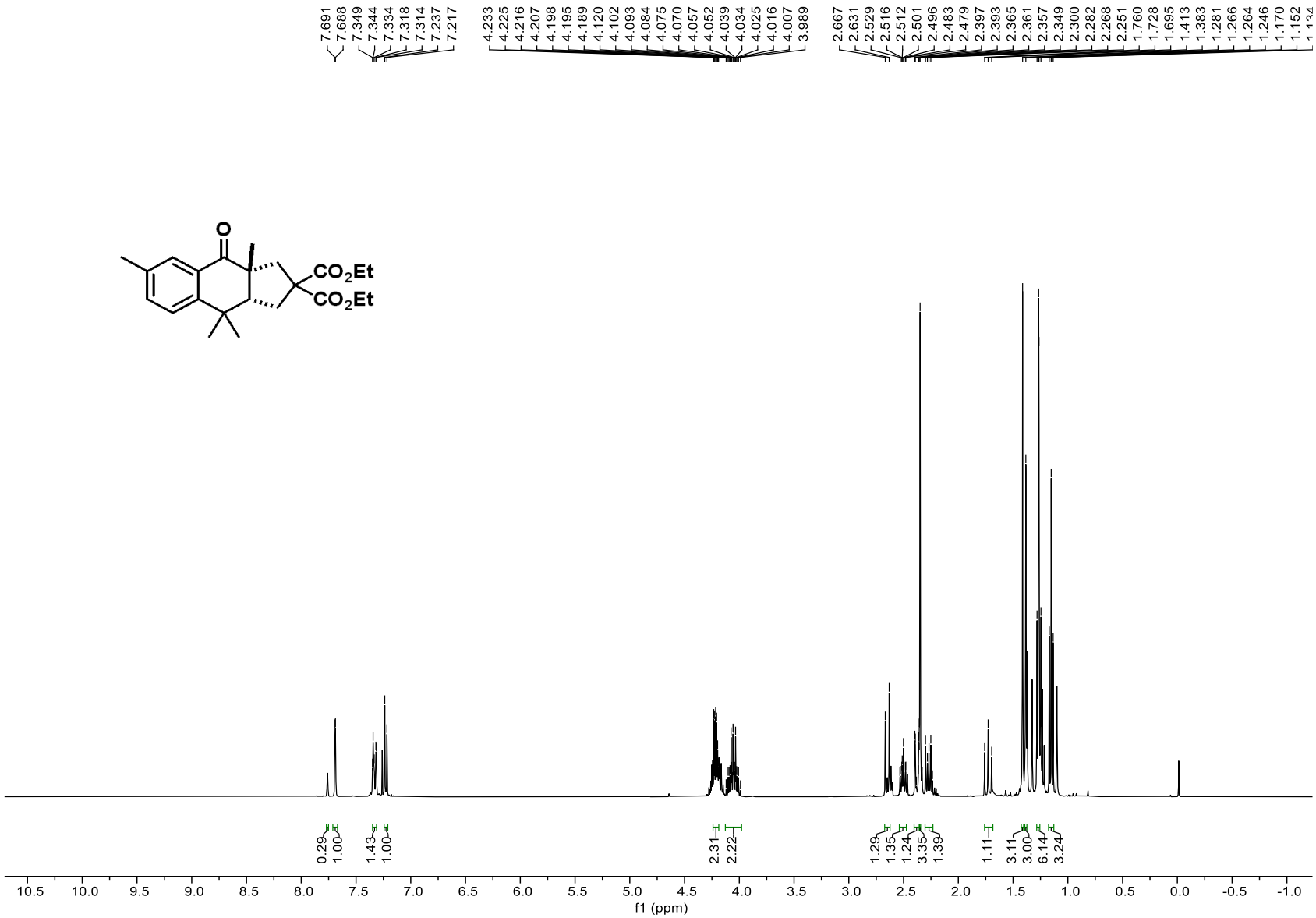
^{13}C NMR Spectrum of Compound 3h



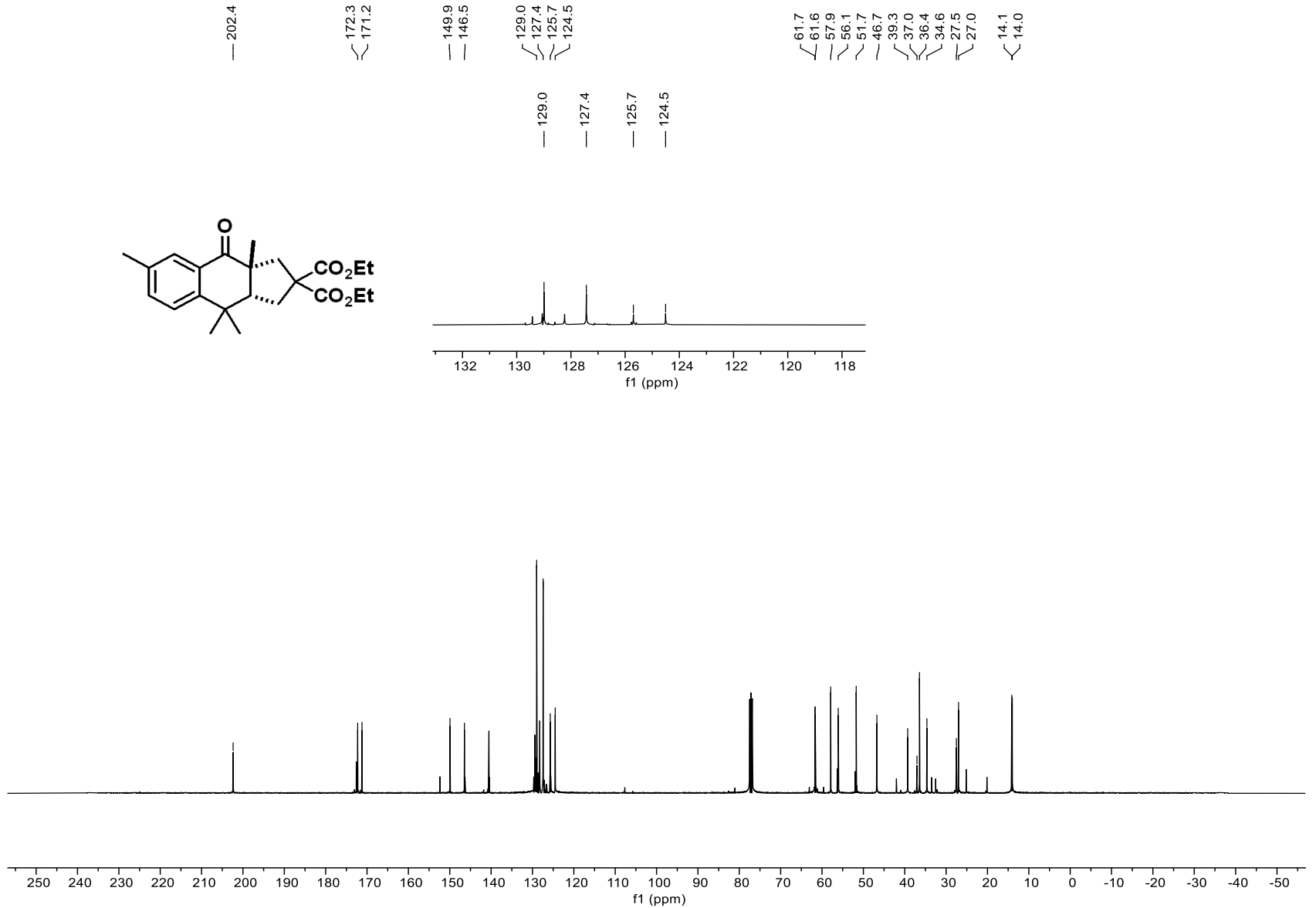
^{1}H NMR Spectrum of Compound 3i



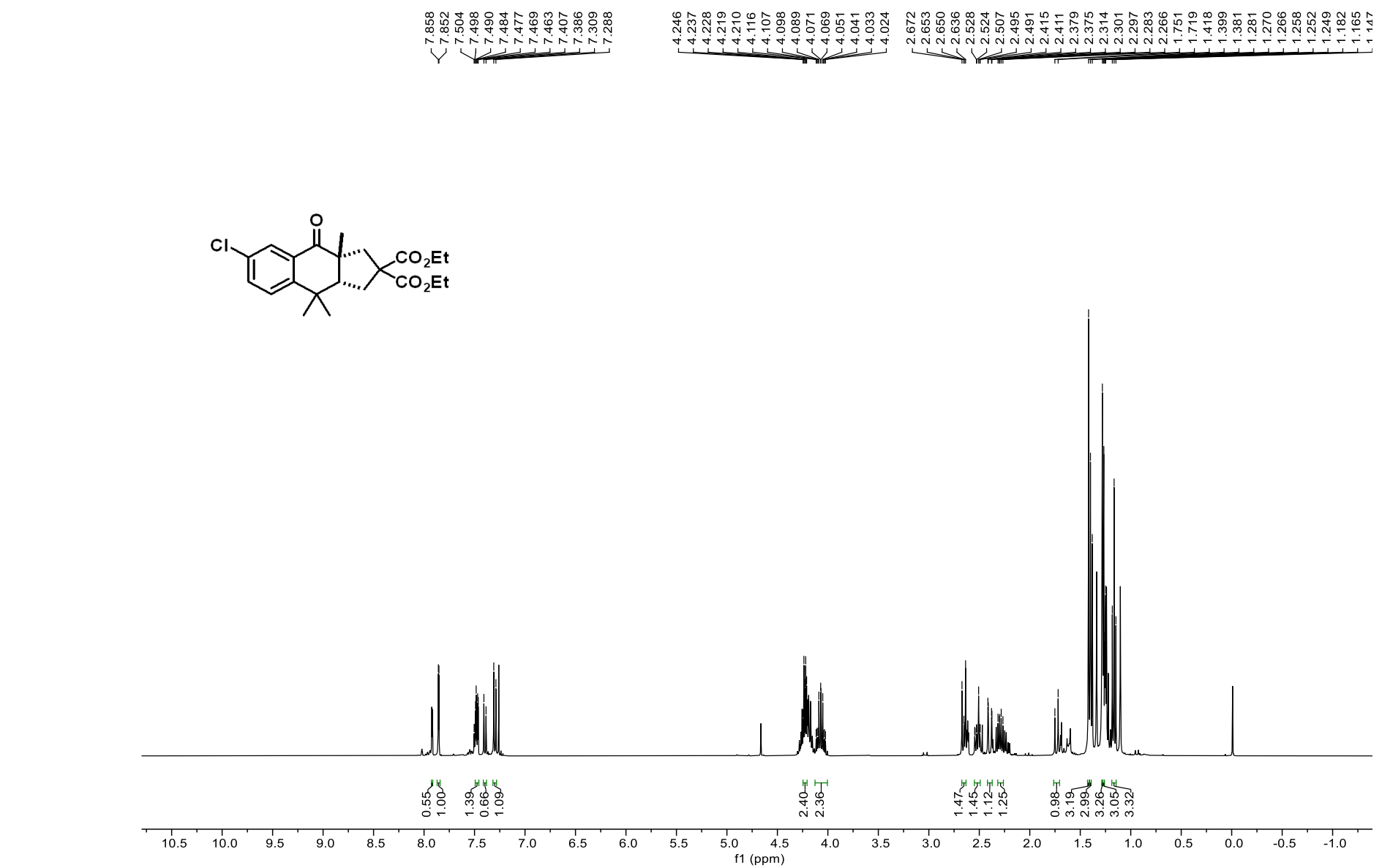
^{13}C NMR Spectrum of Compound 3i



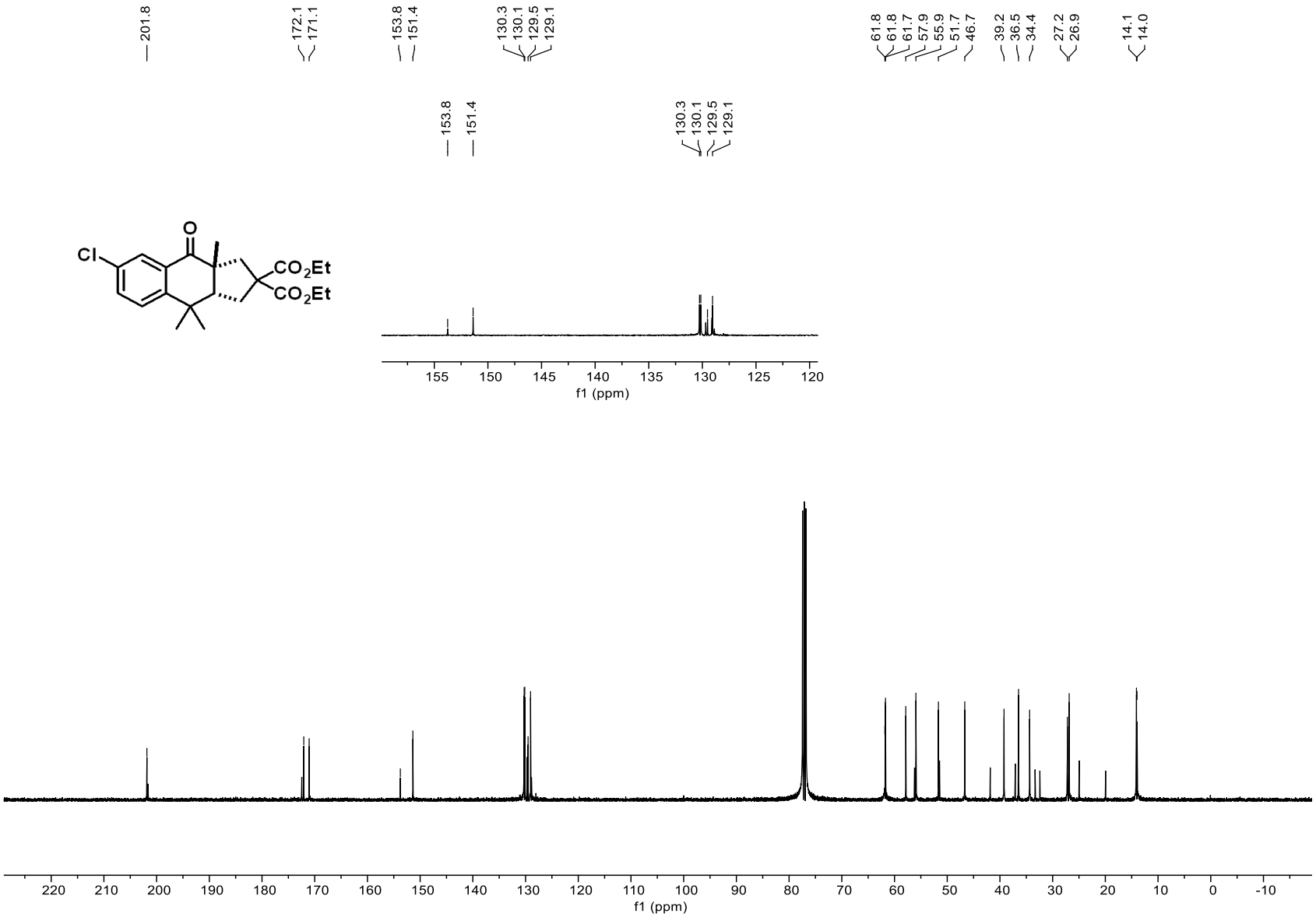
^{1}H NMR Spectrum of Compound 3j



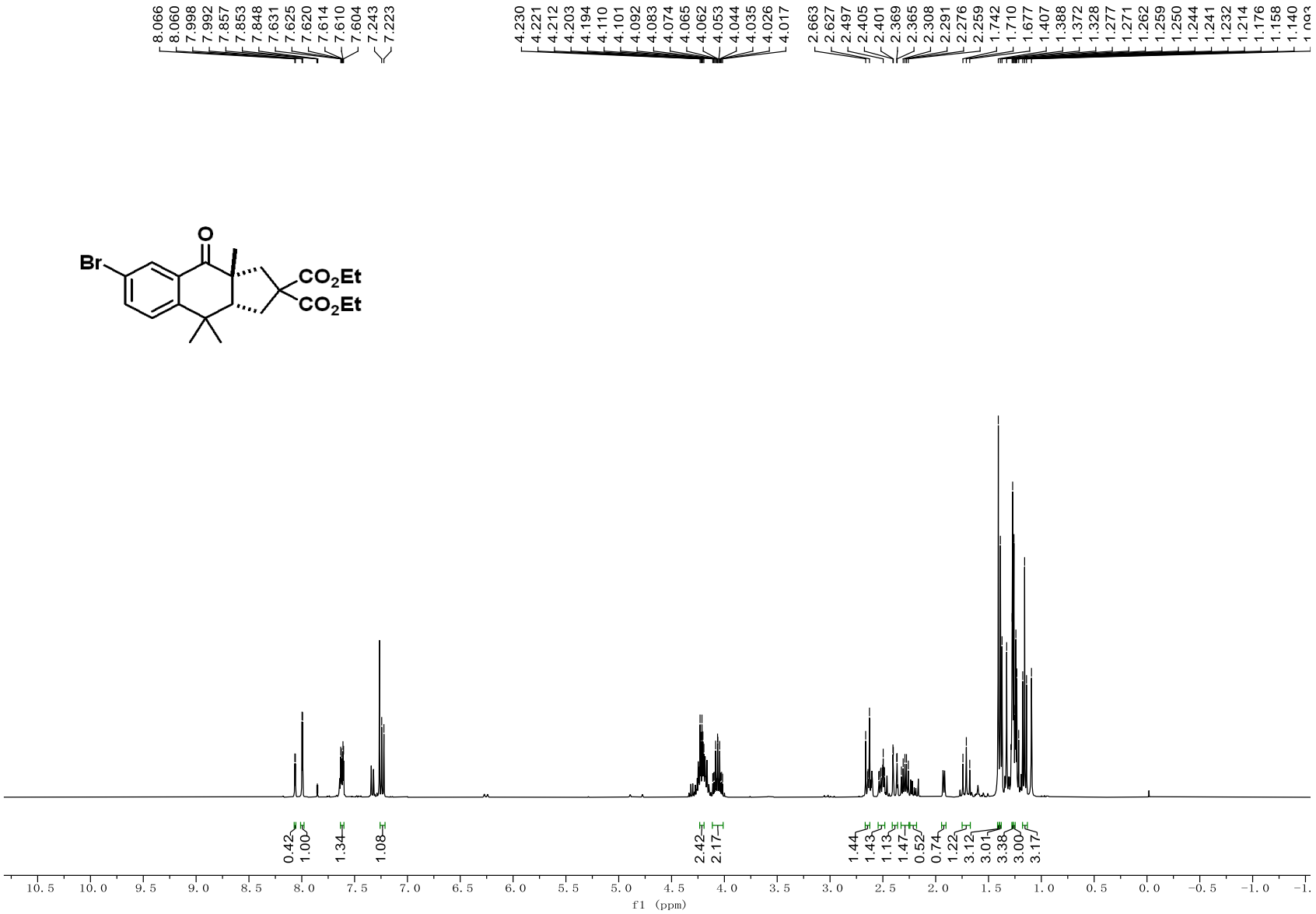
^{13}C NMR Spectrum of Compound 3j



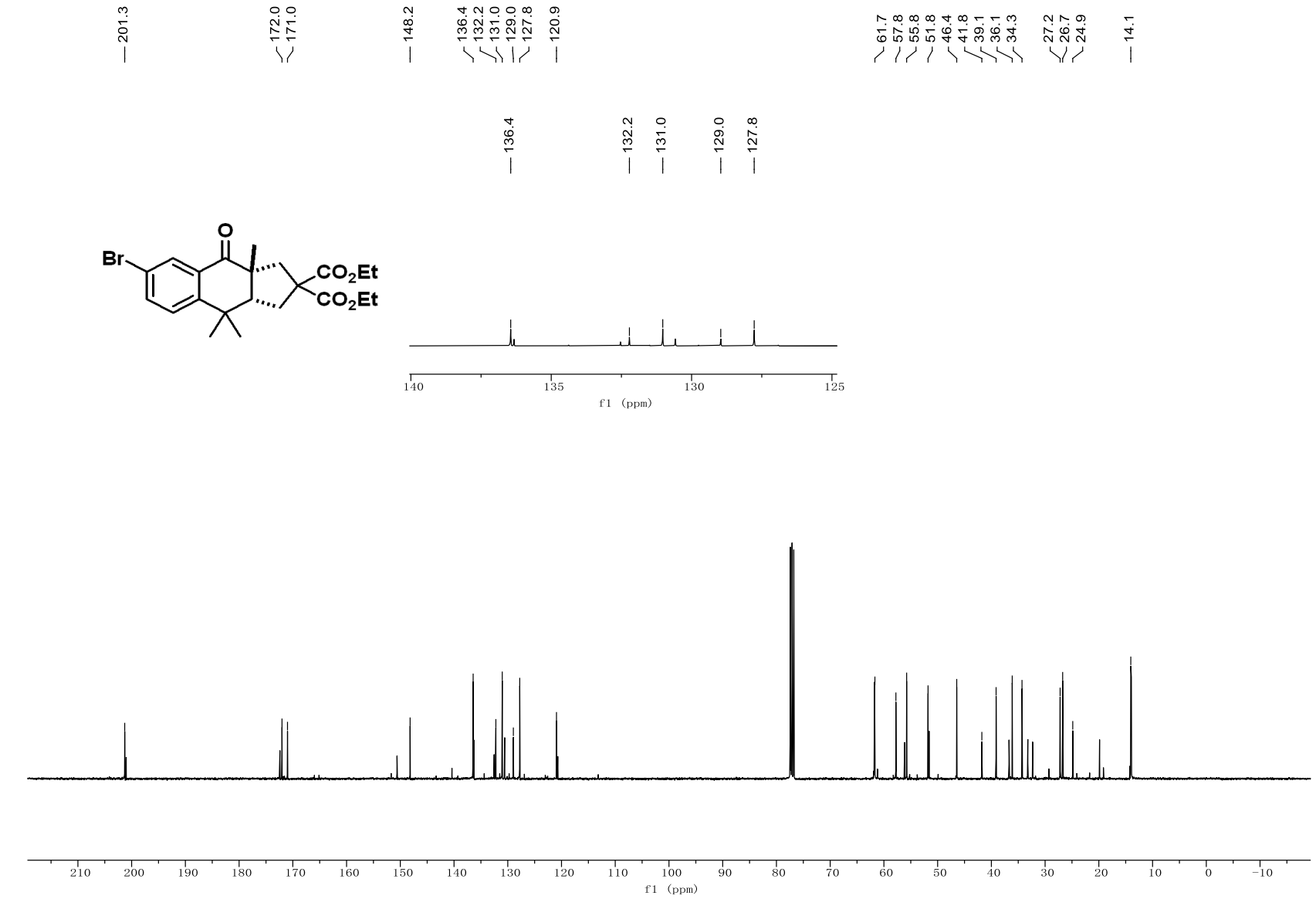
^{1}H NMR Spectrum of Compound 3k



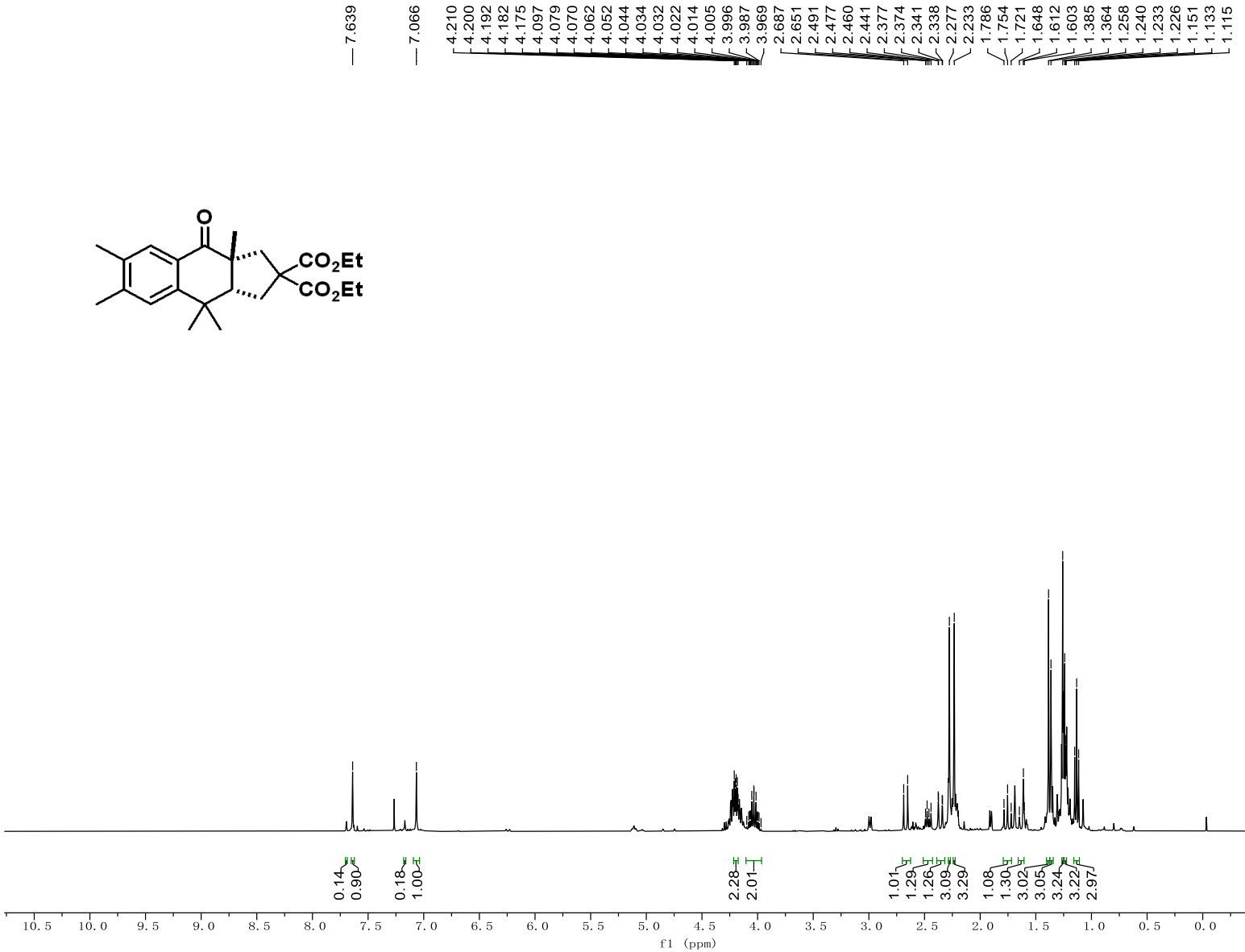
^{13}C NMR Spectrum of Compound 3k



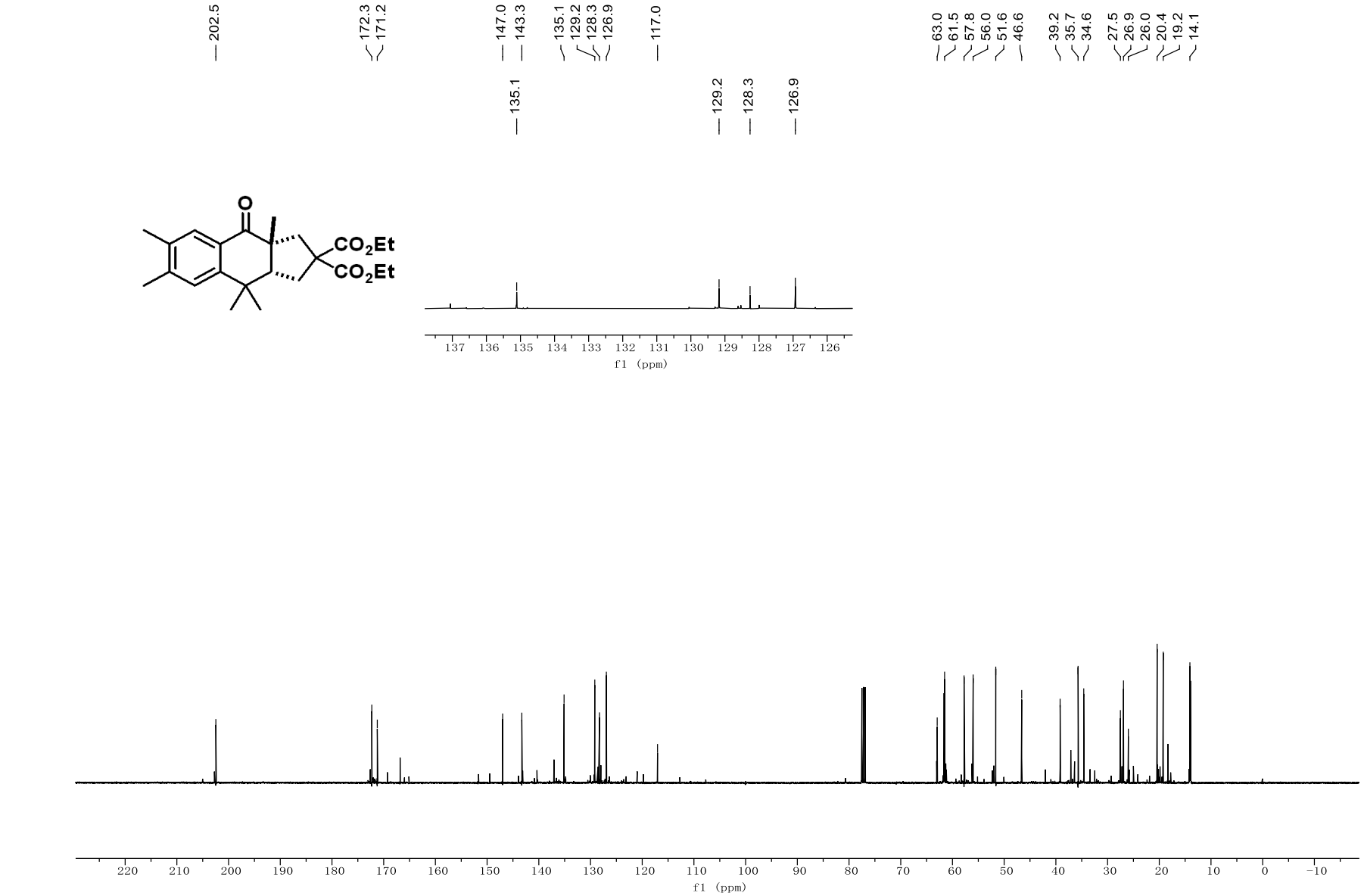
^{1}H NMR Spectrum of Compound 3l



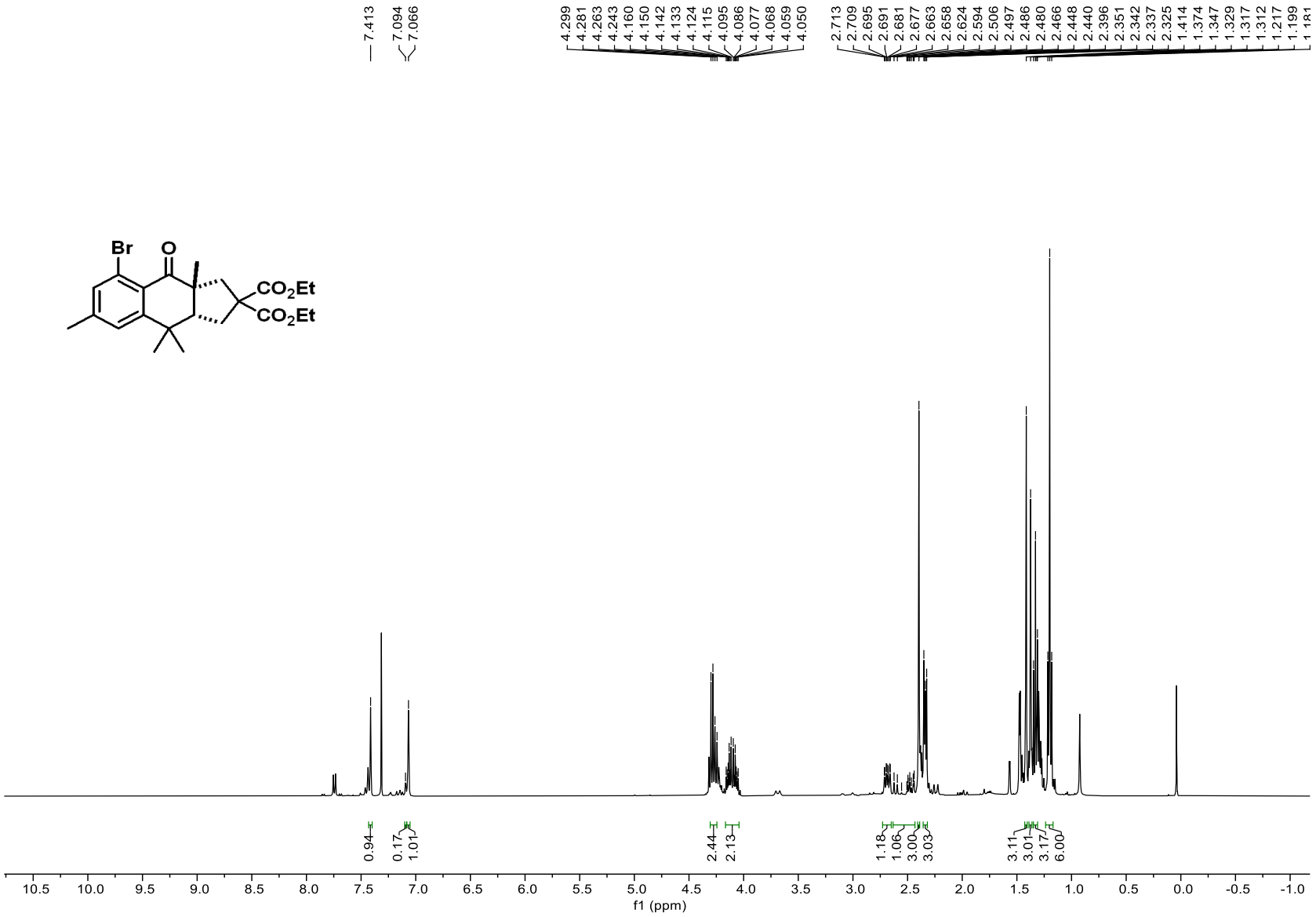
^{13}C NMR Spectrum of Compound 3l



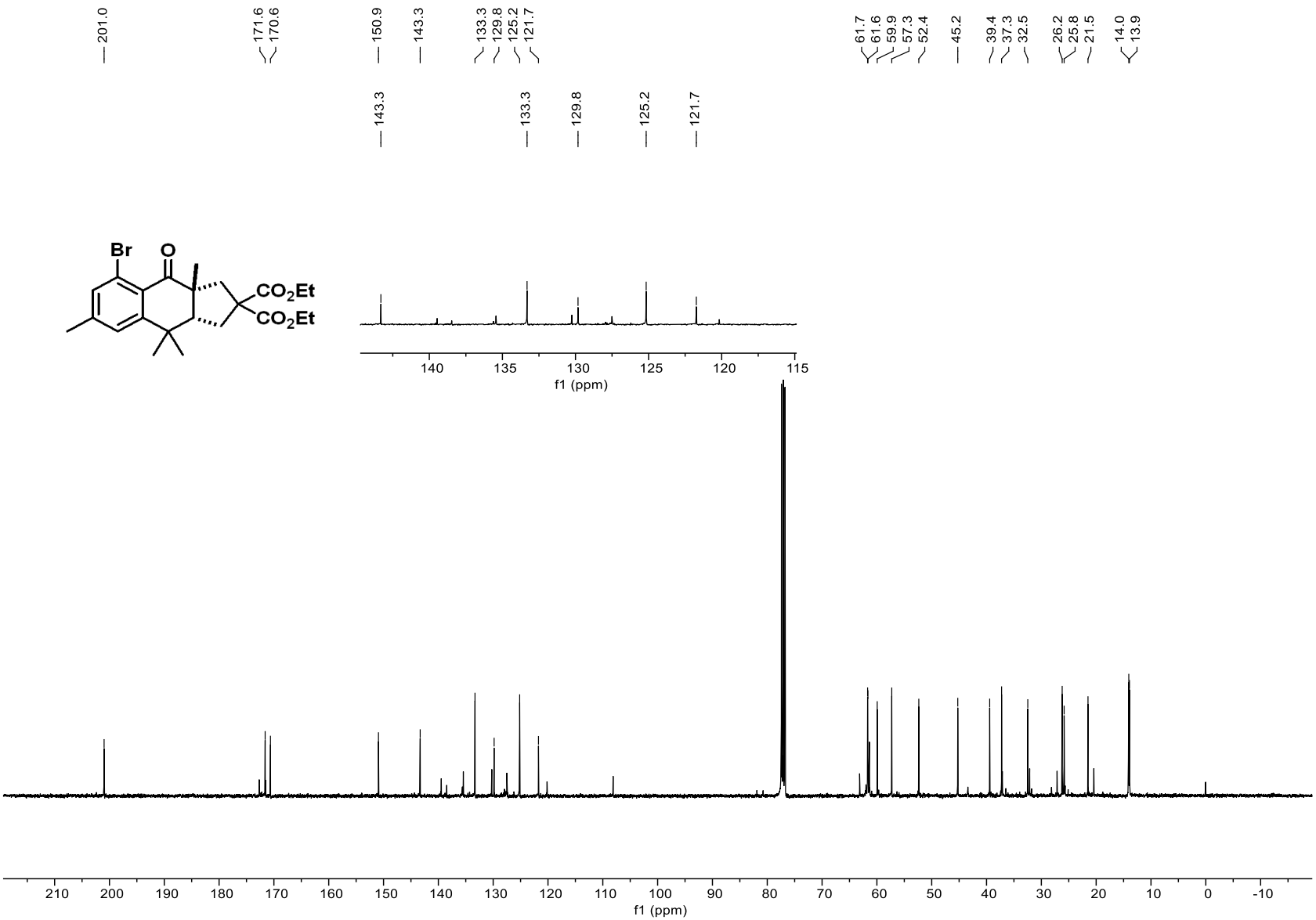
^{1}H NMR Spectrum of Compound 3m



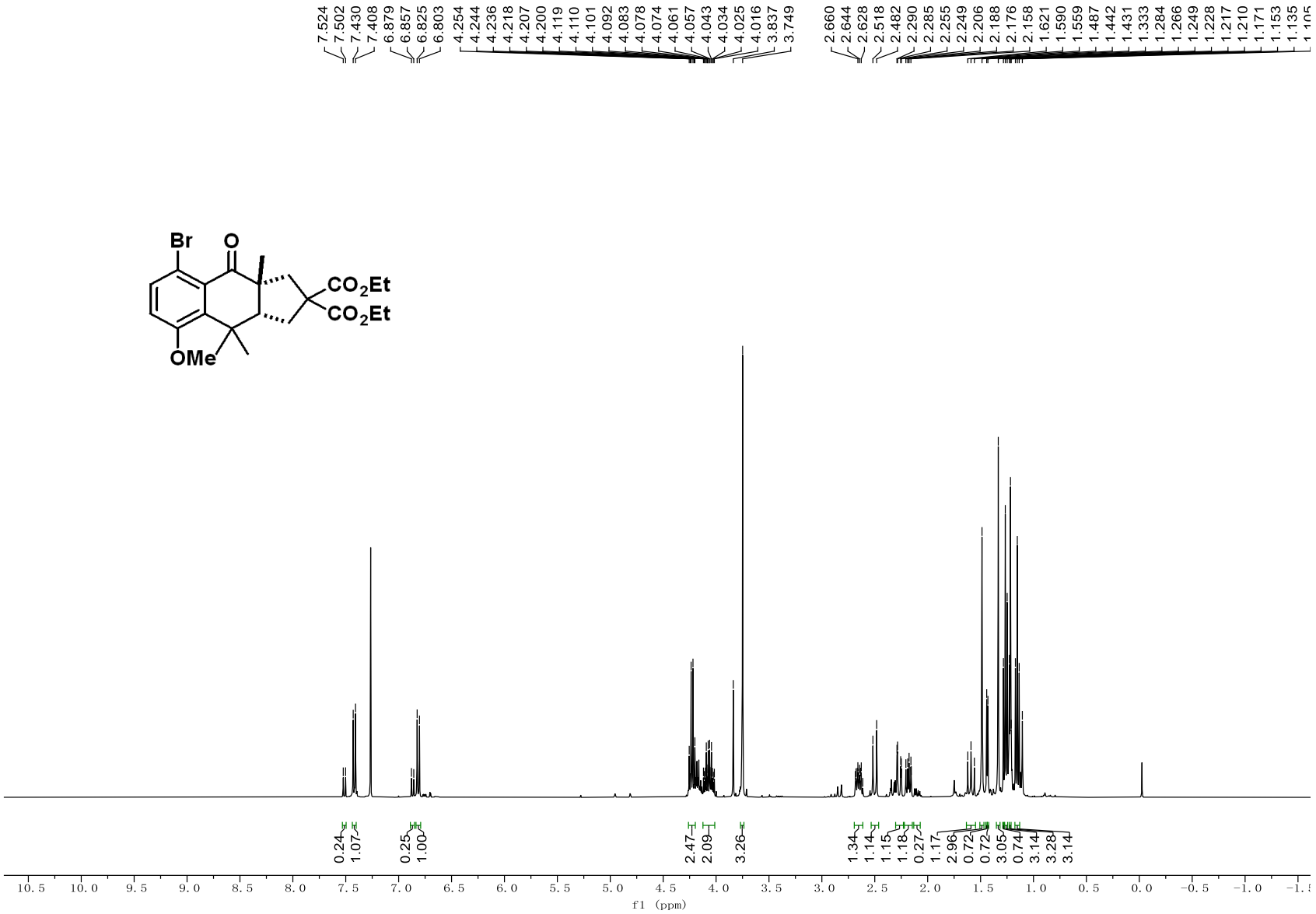
^{13}C NMR Spectrum of Compound 3m



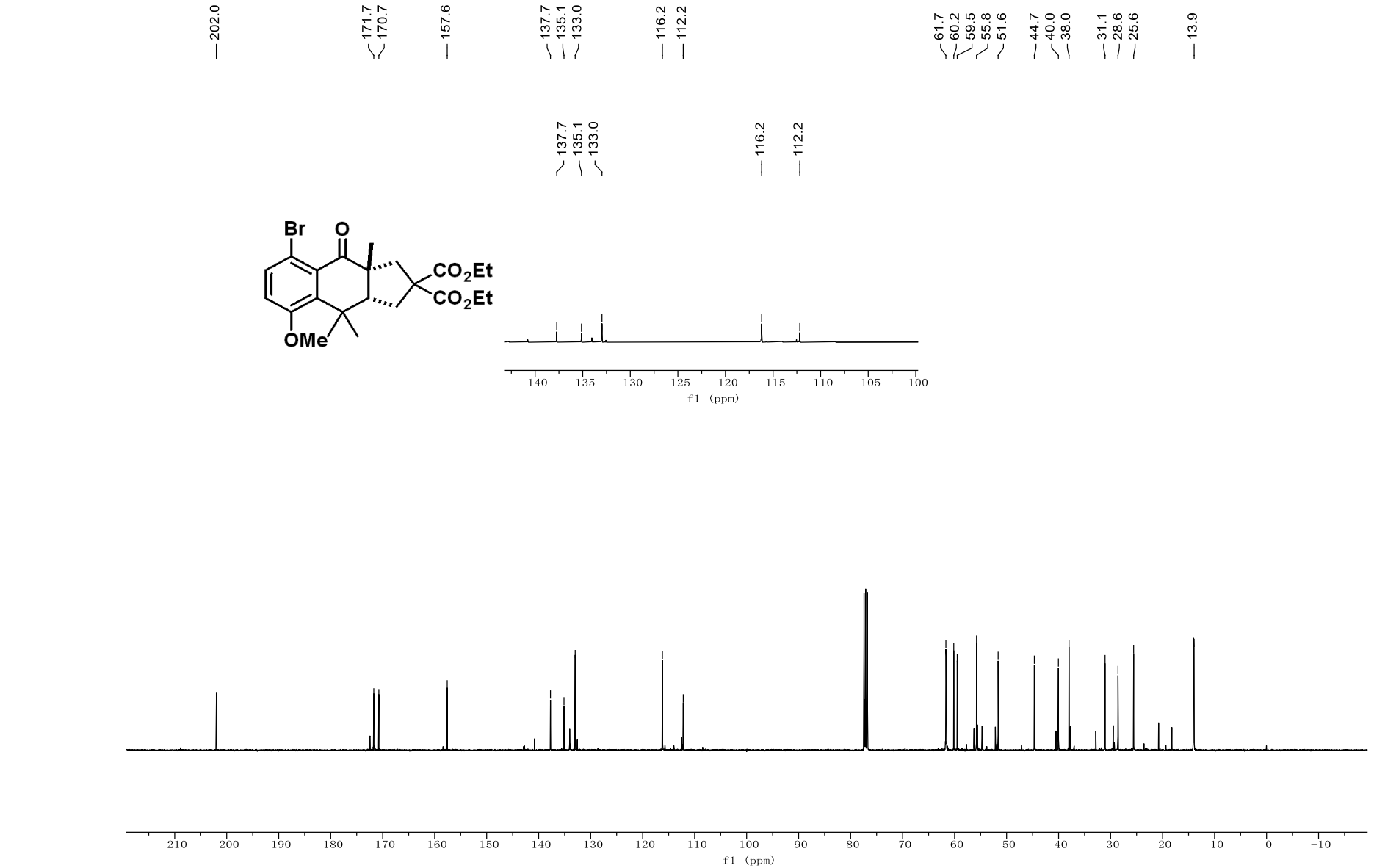
^{1}H NMR Spectrum of Compound 3n



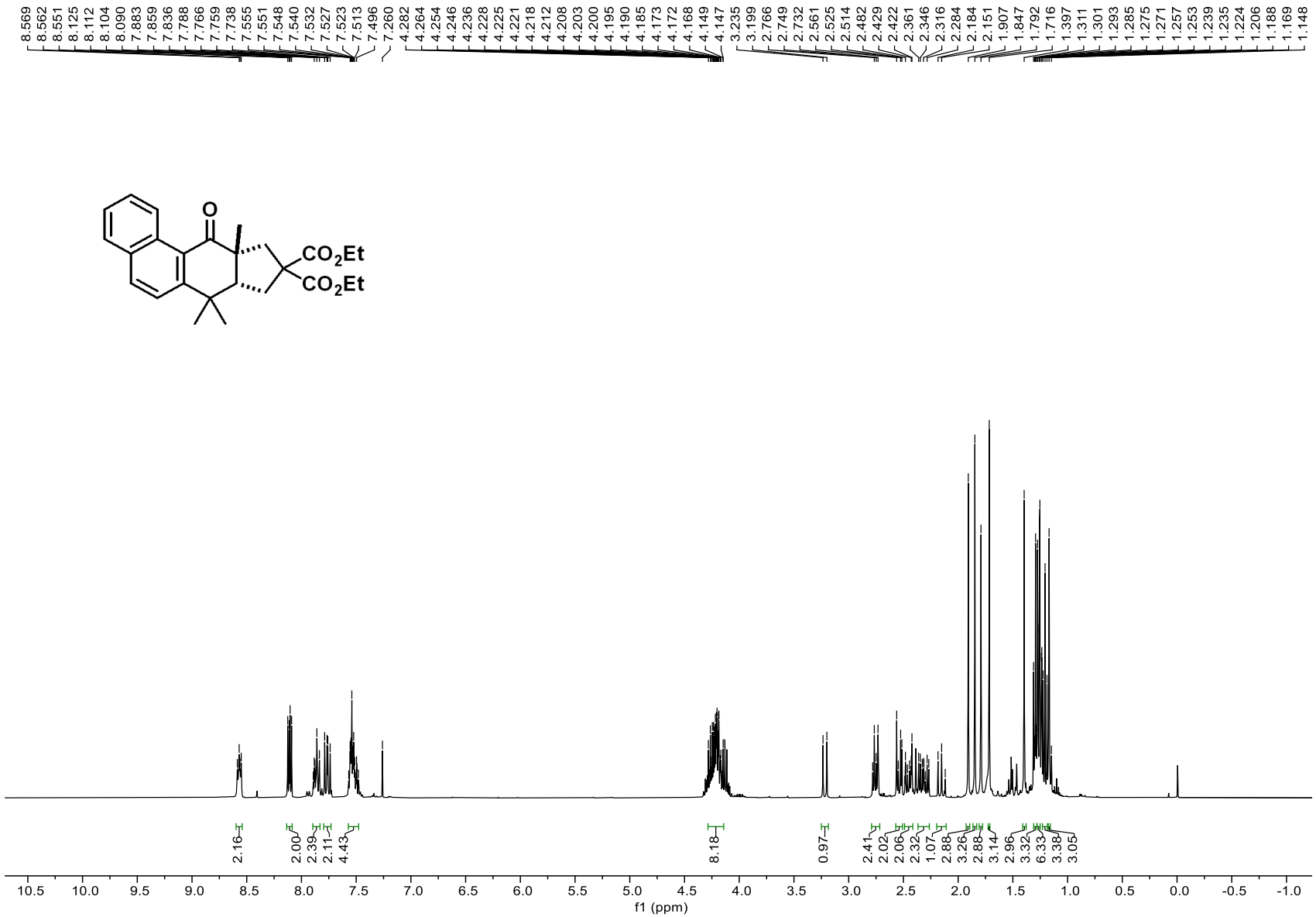
^{13}C NMR Spectrum of Compound 3n



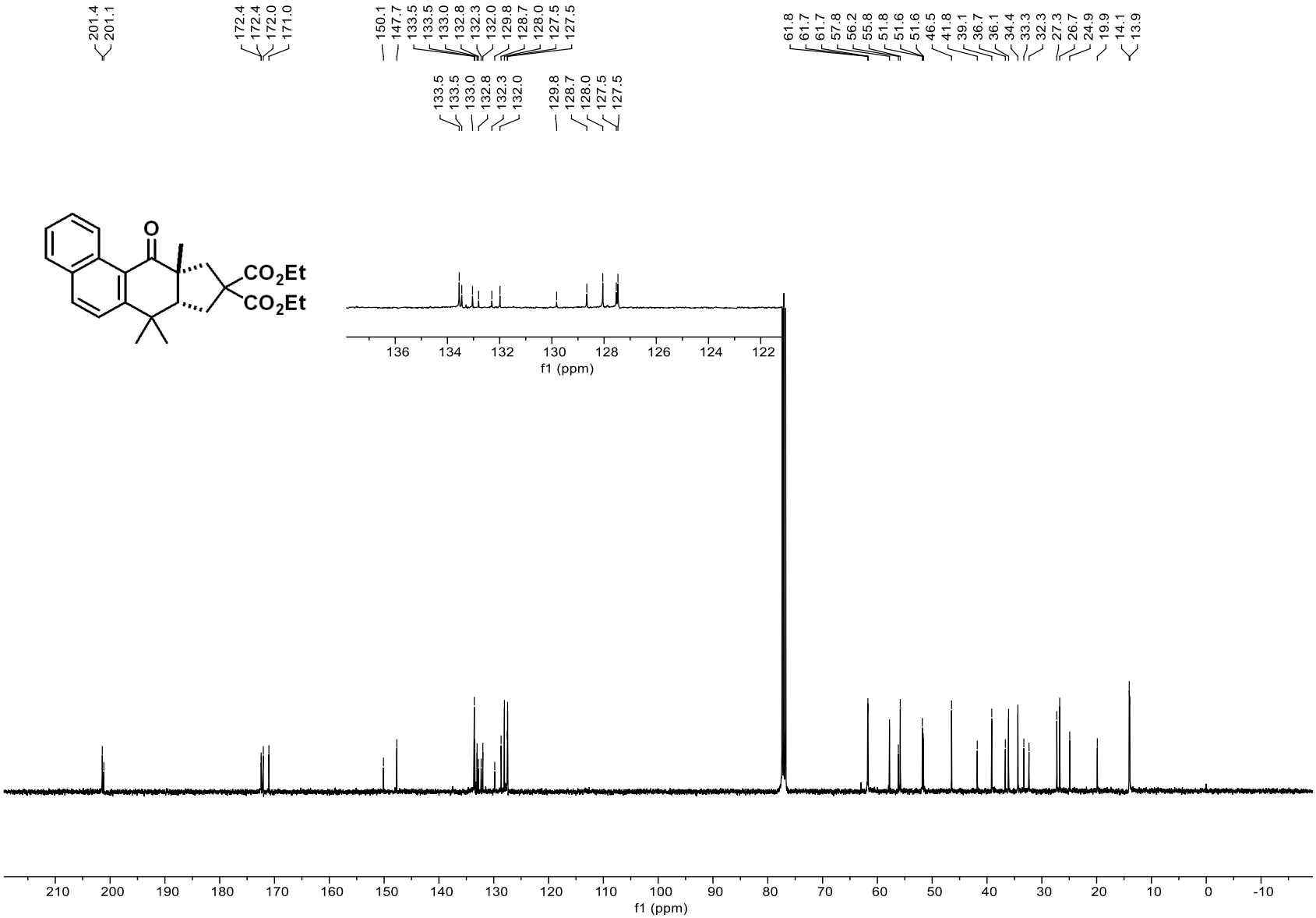
^{1}H NMR Spectrum of Compound 3o



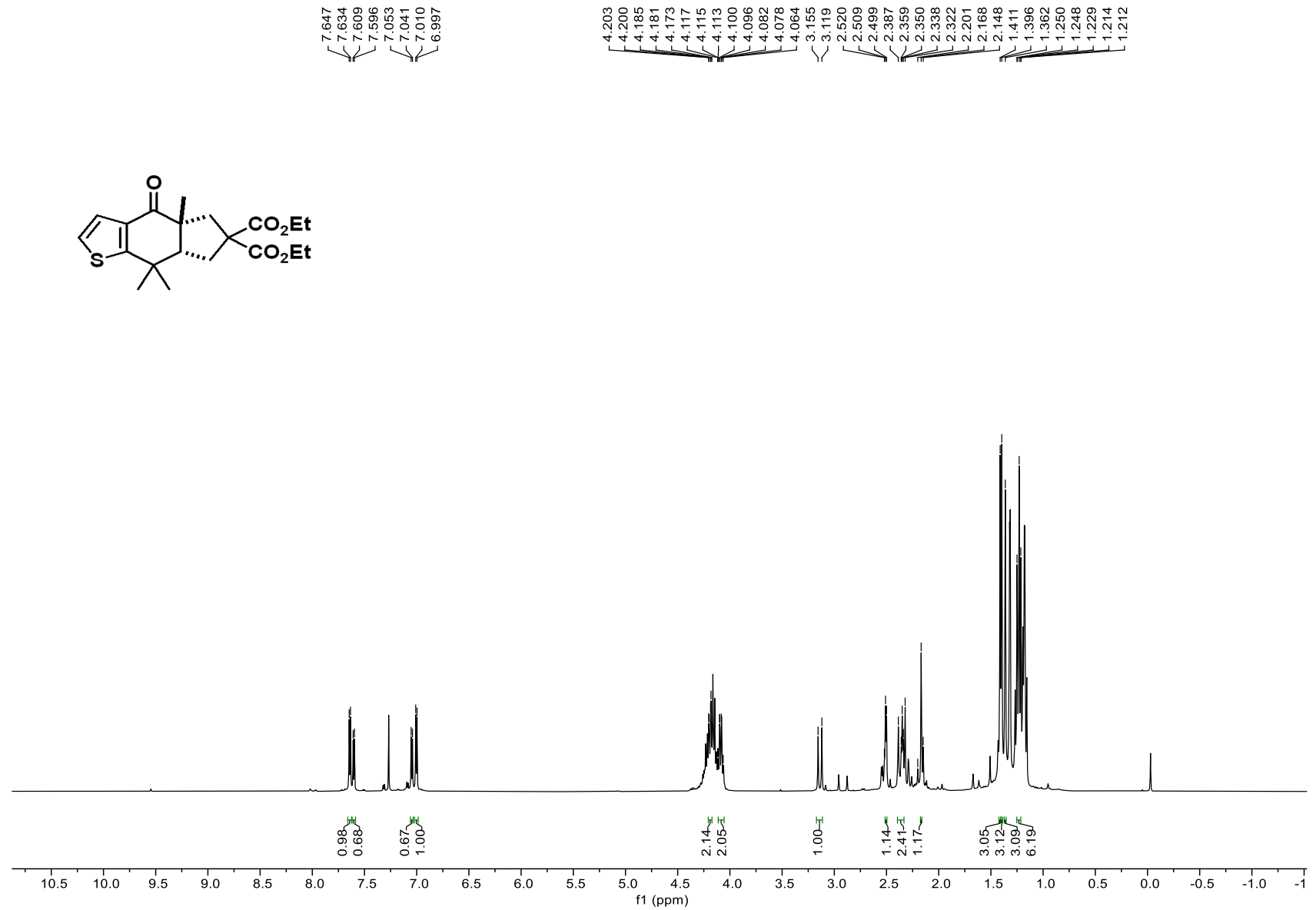
^{13}C NMR Spectrum of Compound 3o



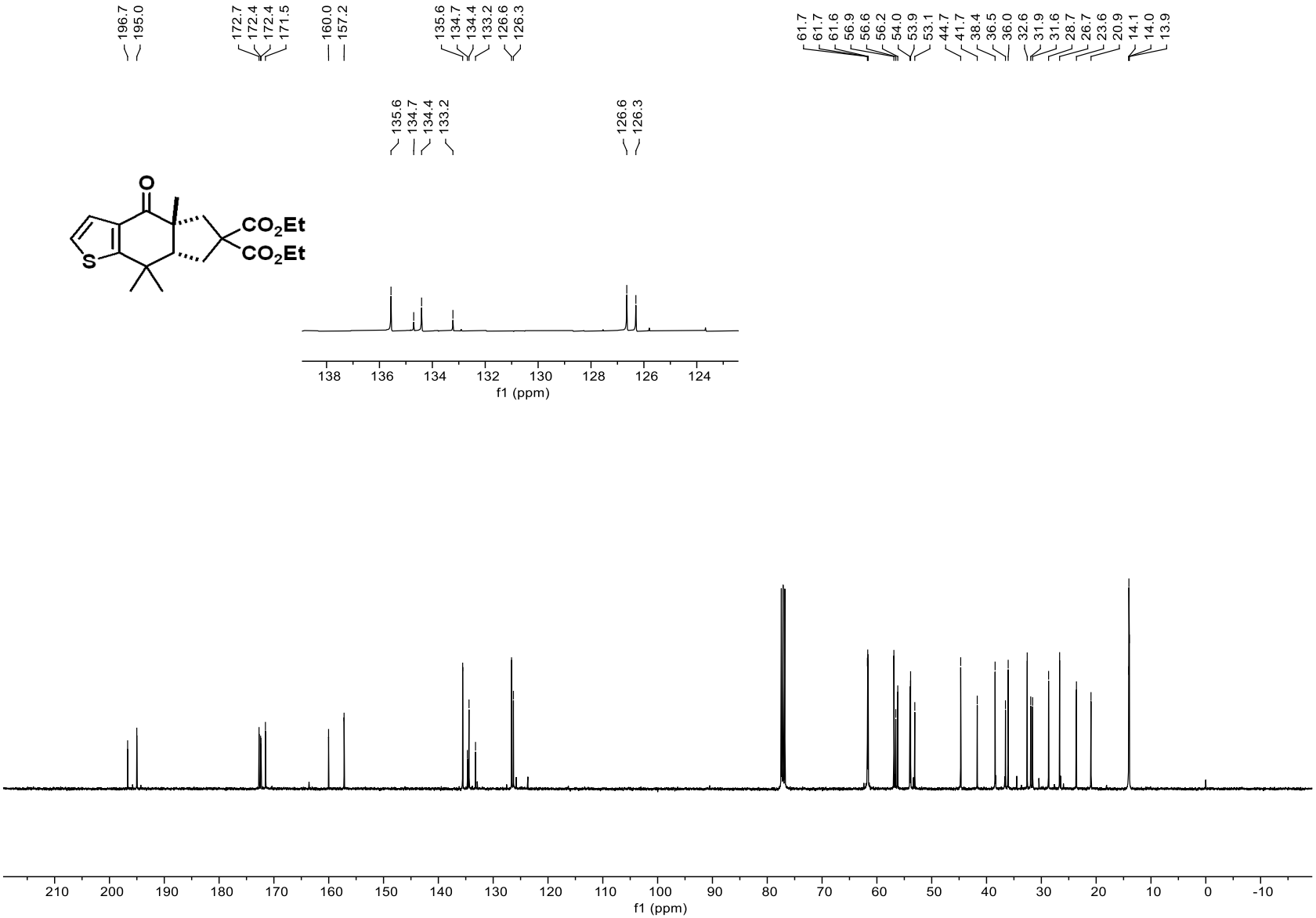
^{1}H NMR Spectrum of Compound 3p



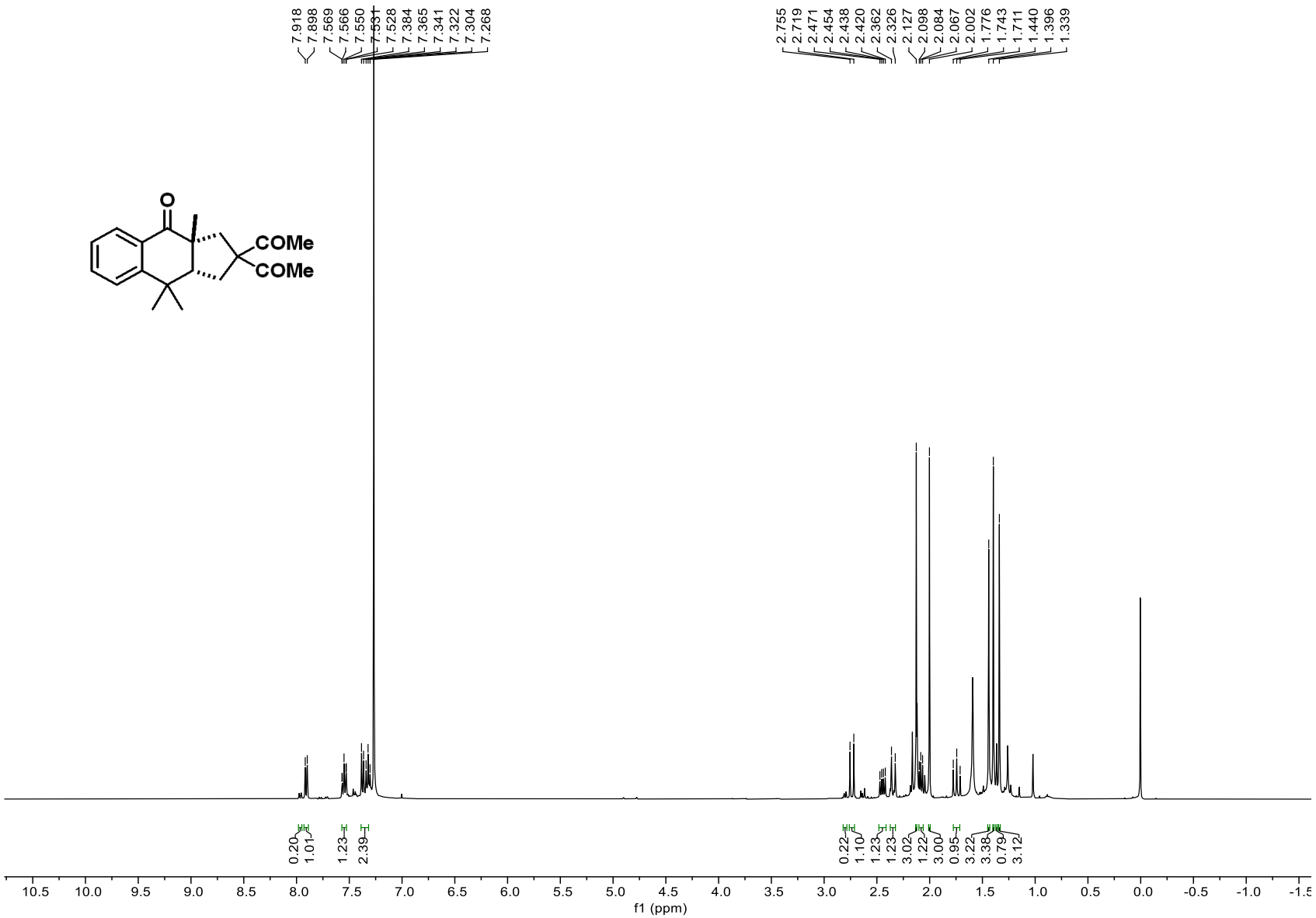
^{13}C NMR Spectrum of Compound 3p



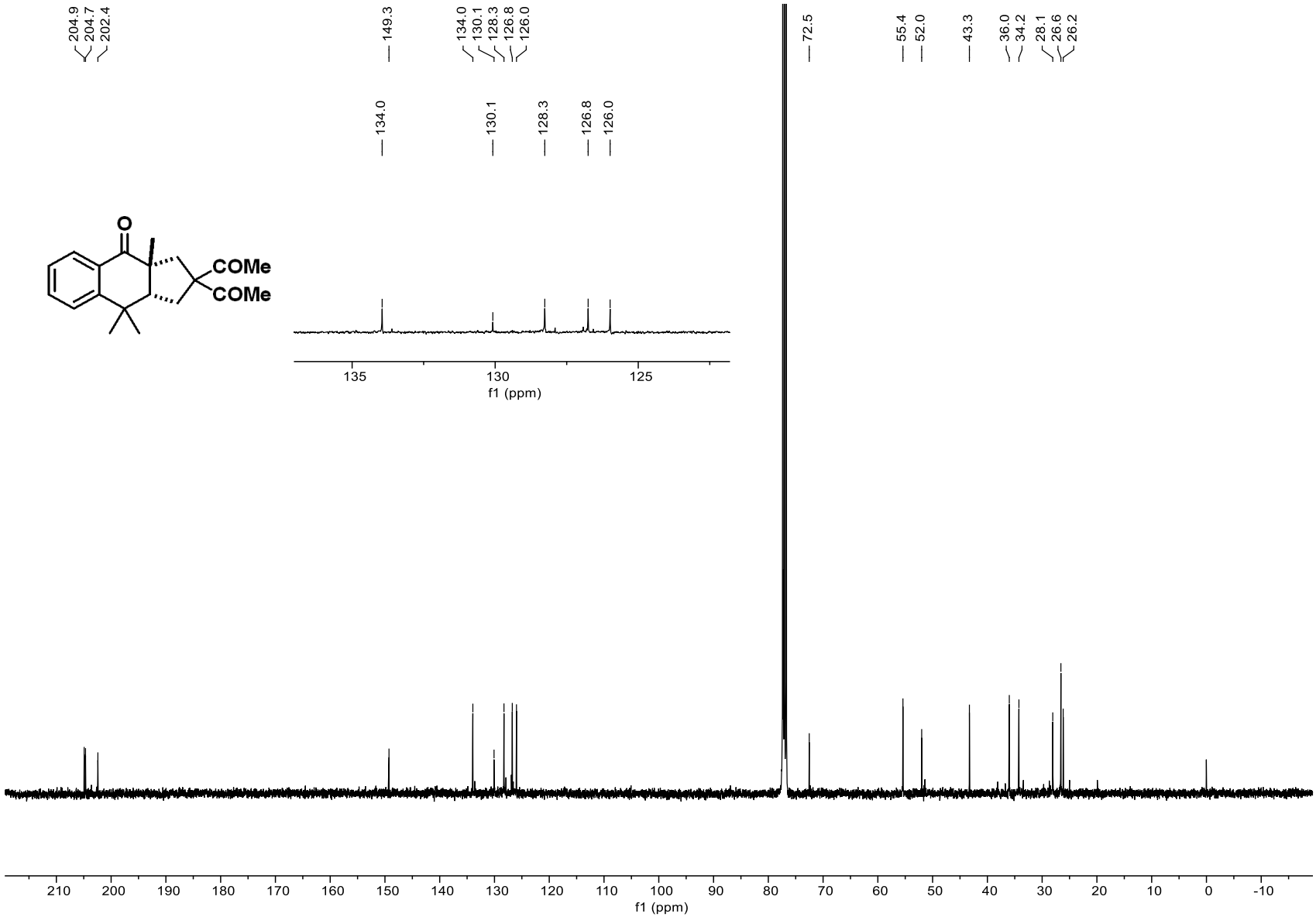
^{1}H NMR Spectrum of Compound 3q



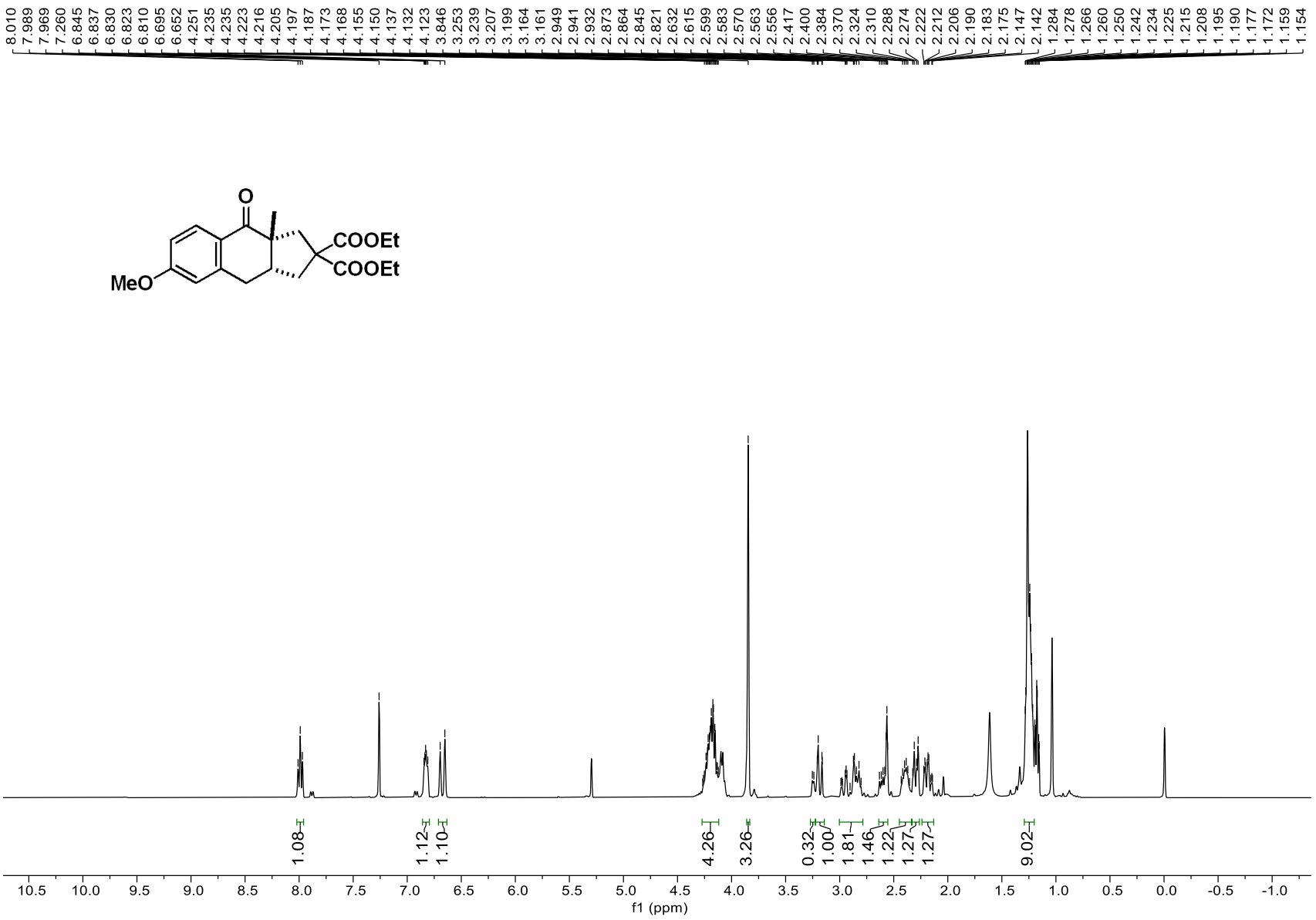
^{13}C NMR Spectrum of Compound 3q



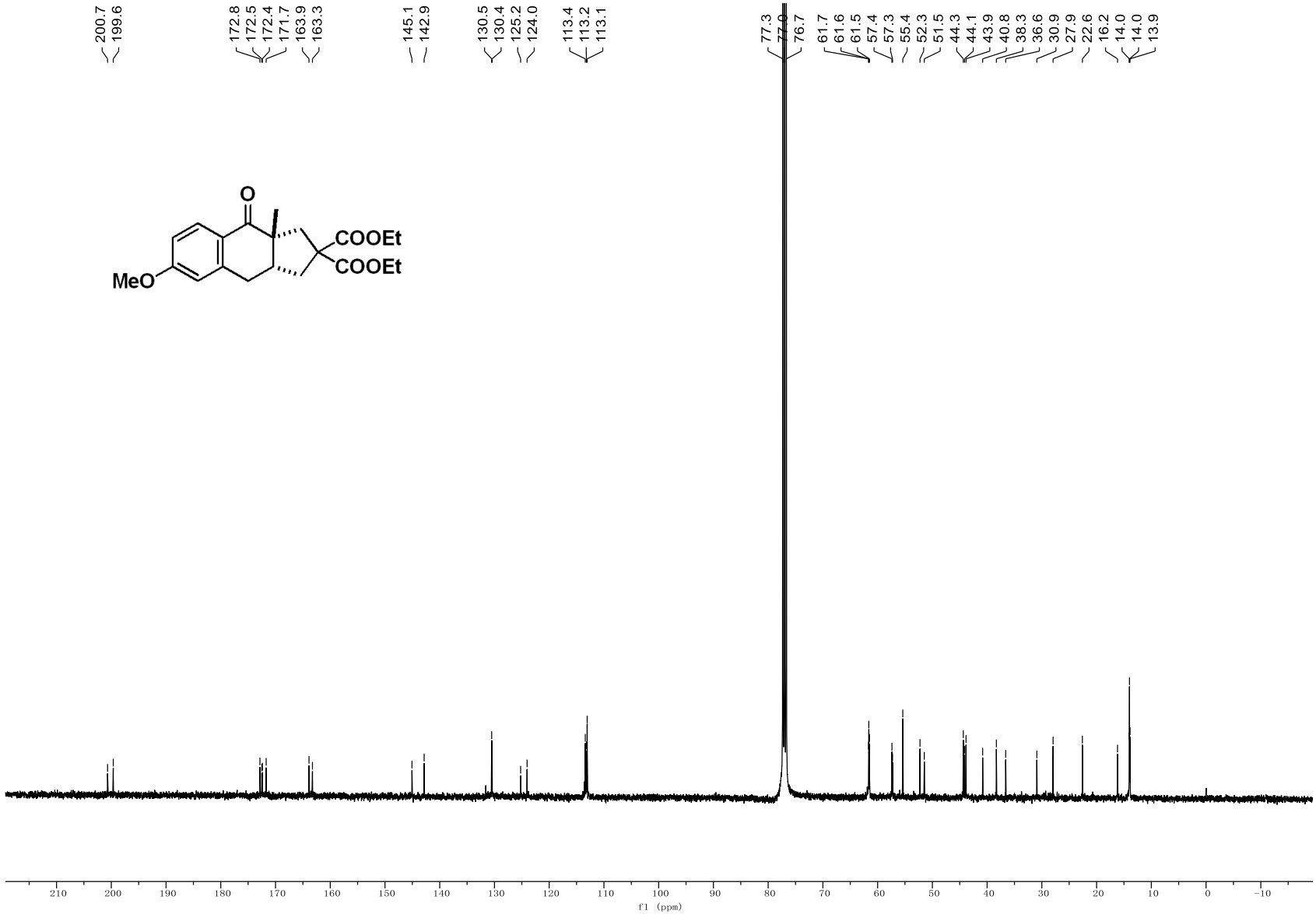
^{1}H NMR Spectrum of Compound 3s



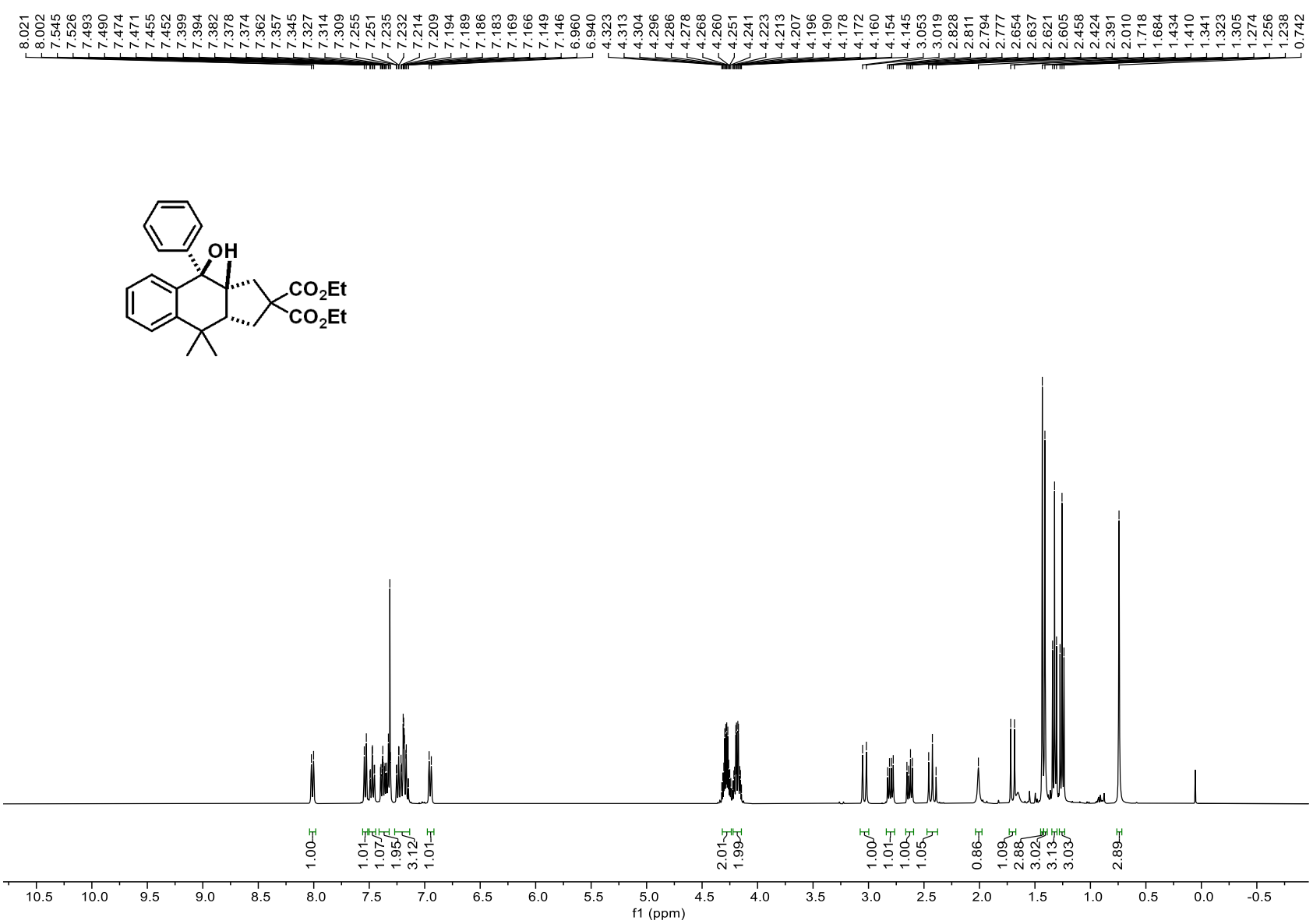
^{13}C NMR Spectrum of Compound 3s



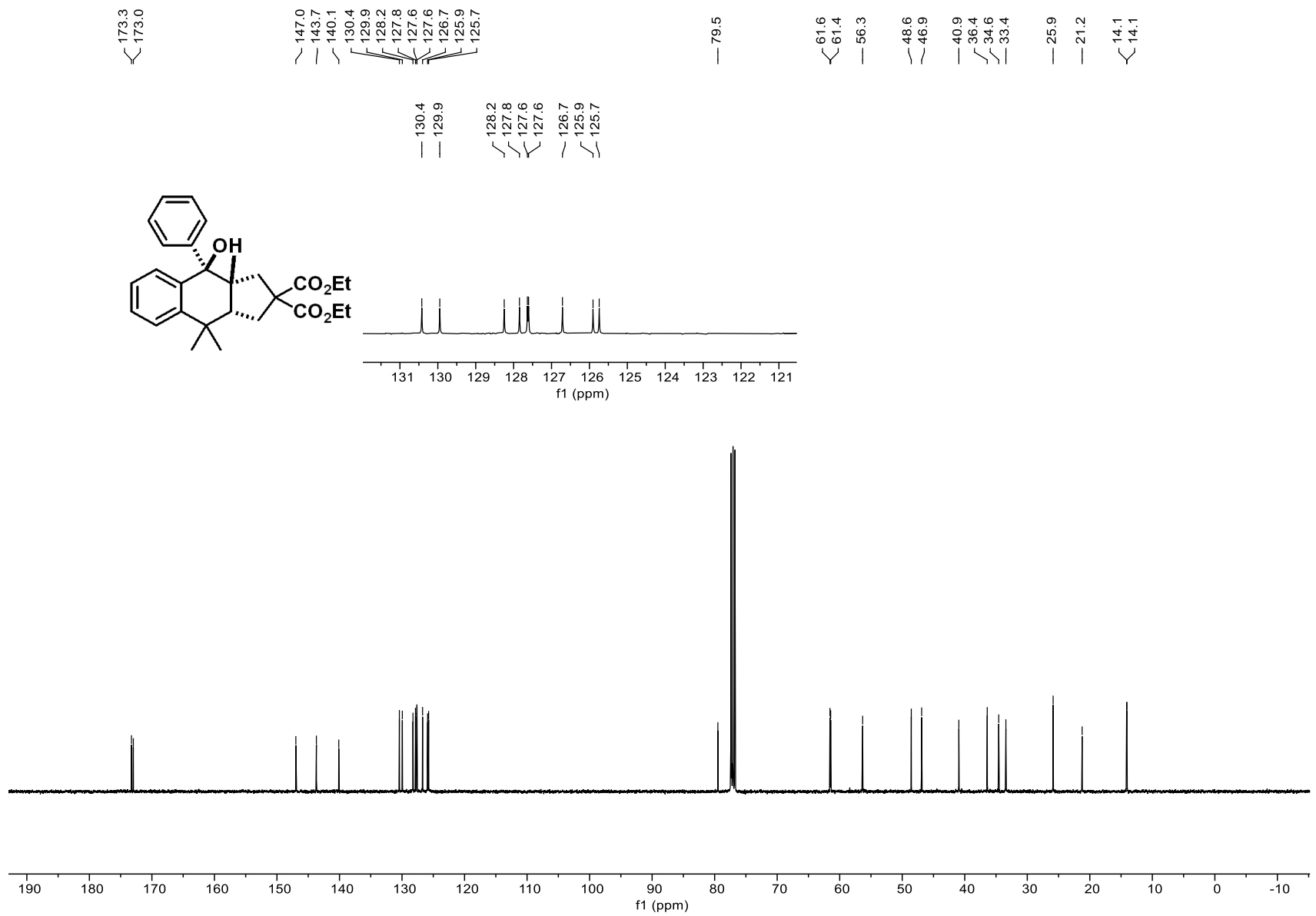
^{1}H NMR Spectrum of Compound 3t



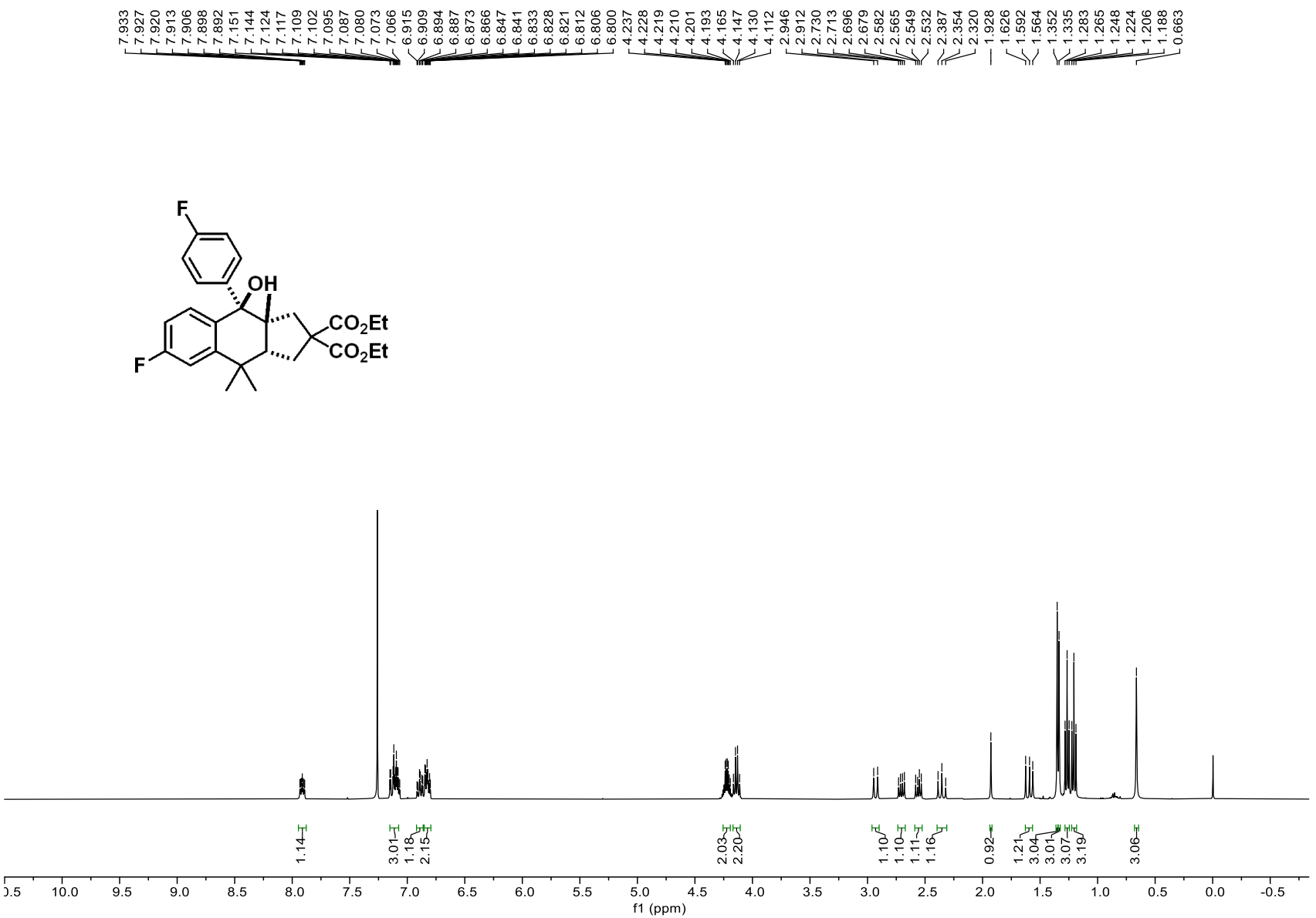
^{13}C NMR Spectrum of Compound 3t



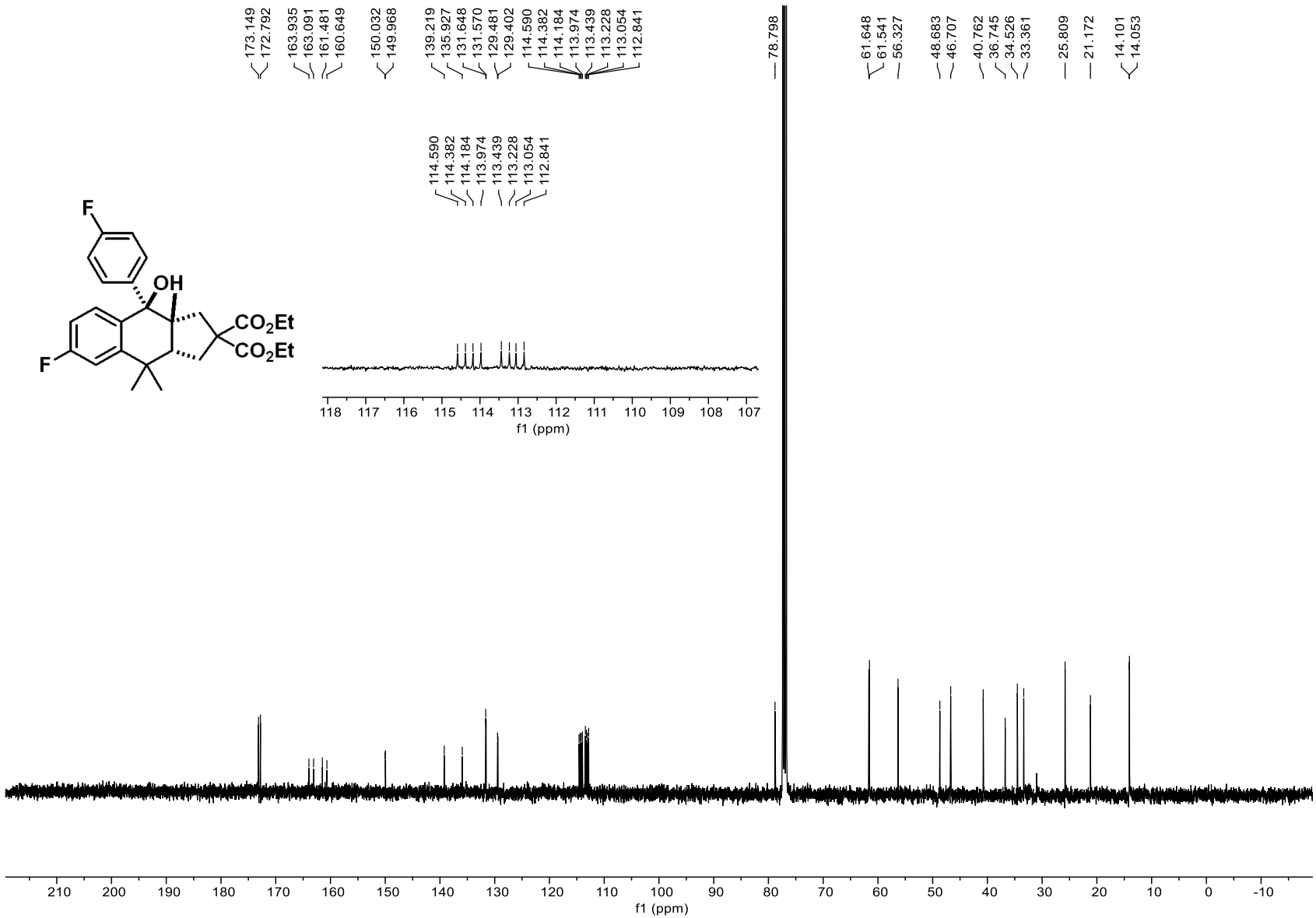
^{1}H NMR Spectrum of Compound 5a



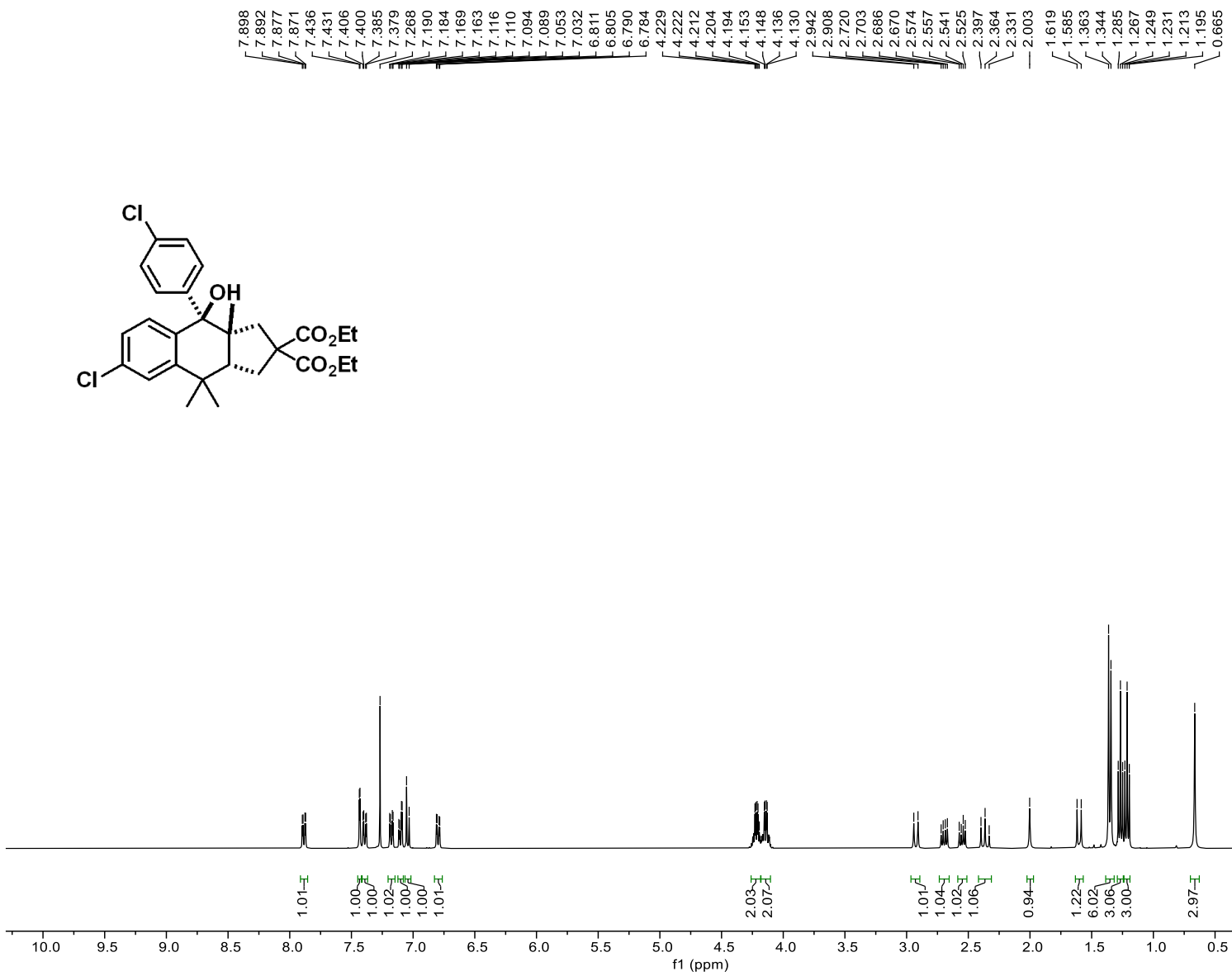
^{13}C NMR Spectrum of Compound 5a



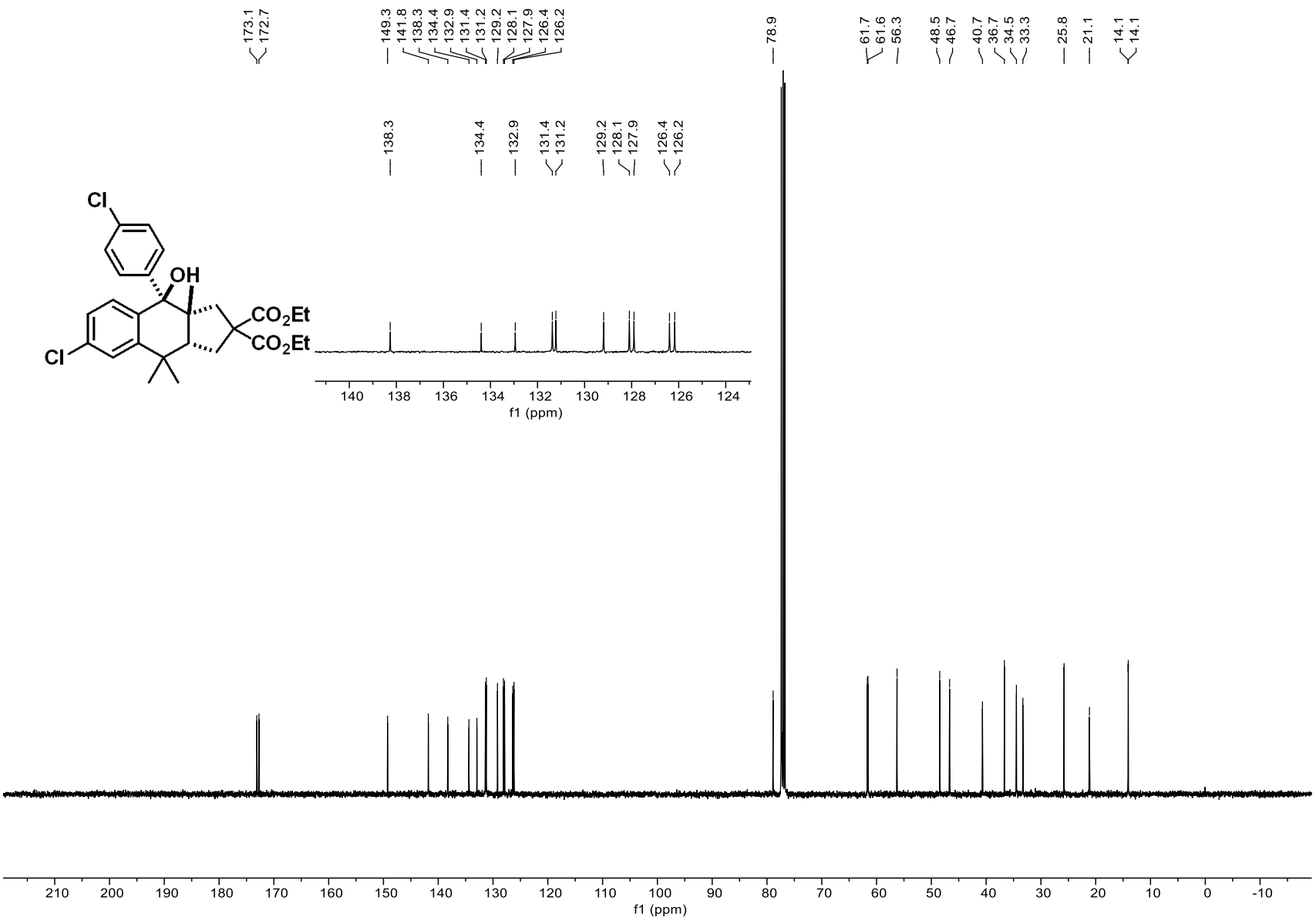
^{1}H NMR Spectrum of Compound 5b



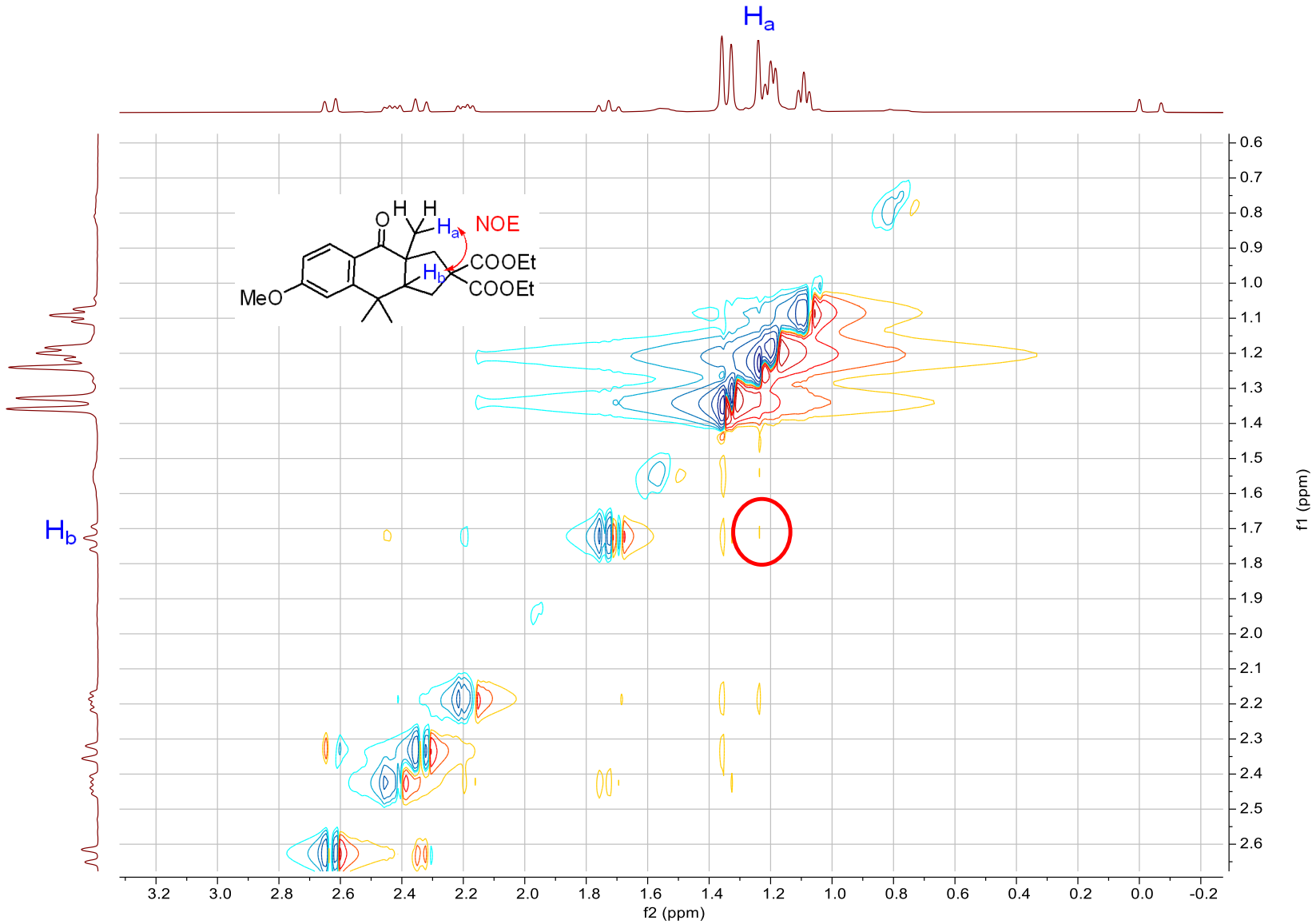
^{13}C NMR Spectrum of Compound 5b



^{1}H NMR Spectrum of Compound 5c



^{13}C NMR Spectrum of Compound 5c



NOESY spectrum of product 3f