Enantioselective Synthesis of Acyclic α-Quaternary Carboxylic Acid Derivatives via Iridium-Catalyzed Allylic Alkylation

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Materials and Methods

Unless otherwise stated, reactions were performed in flame-dried glassware under an argon or nitrogen atmosphere using dry, deoxygenated solvents. Solvents were dried by passage through an activated alumina column under argon. Commercially obtained reagents were used as received. Chemicals were purchased from Sigma Aldrich/Strem/Alfa Aesar/Oakwood Chemicals and used as received. Reaction temperatures were controlled by an IKAmag temperature modulator. Glove box manipulations were performed under a nitrogen atmosphere. Thin-layer chromatography (TLC) and preparatory TLC was

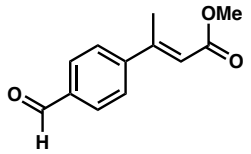
performed using E. Merck silica gel 60 F254 precoated plates (0.25 mm) and visualized by UV fluorescence quenching, $KMnO_4$, or *p*-anisaldehyde staining. Silia*Flash* P60 Academic Silica gel (particle size 0.040–0.063 mm) was used for flash chromatography. Analytical chiral HPLC was performed with an Agilent 1100 Series HPLC utilizing a Chiralpak IC column (4.6 mm x 25 cm) or a Chiralpak AD-H column (4.6 mm x 25 cm), both obtained from Daicel Chemical Industries, Ltd. with visualization at 210 nm. Analytical SFC was performed with a Mettler SFC supercritical CO_2 analytical chromatography system utilizing a Chiralpak AD-H column (4.6 mm x 25 cm) obtained from Daicel Chemical Industries, Ltd. with visualization at 210 nm. Preparatory HPLC was performed with an Agilent 1200 Series HPLC equipped with a Viridis SFC 2-Ethylpyridine 5 μm column (4.6 x 250 mm). ^{1}H NMR spectra were recorded on a Bruker Avance HD 400 MHz spectrometer and are reported relative to residual $CHCl_3$ (δ 7.26 ppm). ^{13}C NMR spectra were recorded on a Bruker Avance HD 400 MHz spectrometer and are reported relative to residual $CDCl_3$ (δ 77.16 ppm). Data for ^{1}H NMR are reported as follows: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, sept = septuplet, m = multiplet, br s = broad singlet. Data for ^{13}C NMR are reported in terms of chemical shifts (δ ppm). Some reported spectra include minor solvent impurities of benzene (δ 7.36 ppm), water (δ 1.56 ppm), ethyl acetate (δ 4.12, 2.05, 1.26 ppm), methylene chloride (δ 5.30 ppm), grease (δ 1.26, 0.86 ppm), and/or silicon grease (δ 0.07 ppm), which do not impact product assignments. IR spectra were obtained using a Perkin Elmer Paragon 1000 spectrometer using thin films deposited on NaCl plates and reported in frequency of absorption (cm^{-1}). High resolution mass spectra (HRMS) were obtained from the Caltech Mass Spectral Facility using a JEOL JMS-600H High Resolution Mass Spectrometer in fast atom bombardment (FAB+) or electron ionization (EI+) mode, or an Agilent 6200 Series TOF with an Agilent G1978A Multimode source in electrospray ionization (ESI+), atmospheric pressure chemical ionization (APCI+), or mixed ionization mode (MM: ESI-APCI+). Optical rotations were measured with a Jasco P-2000 polarimeter operating on the sodium D-line (589 nm), using a 100 mm pathlength cell and are reported as: $[\alpha]_D^T$ (concentration in g/100 mL, solvent).

List of Abbreviations: ee – enantiomeric excess, HPLC – high-performance liquid chromatography, TLC – thin-layer chromatography, EtOAc – ethyl acetate, THF – tetrahydrofuran, MeOH – methanol, Et_2O – diethyl ether, IPA – isopropanol, AcOH – acetic acid, DME – dimethoxyethane, TBD – 1,5,7-triazabicyclo[4.4.0]dec-5-ene, cod – *cis,cis*-1,5-cyclooctadiene, DIBAL – diisobutylaluminium hydride, dppp – 1,3-bis(diphenylphosphino)propane, MAC – masked acyl cyanide, CSA – camphorsulfonic acid

Preparation of Known Compounds: Previously reported methods were used to prepare ligands (S,S_a)-**L1**[1] and (S_a)-**L3**[2] as well as starting materials **1**[3], **2**[5], **5**[4], **6a**[5], **6b**[6], **6d**[6], **6e**[6], **6j**[6], **6l**[6], **8a**[6], **8d**[6], and **8f**[6].

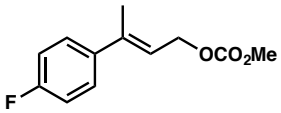
Representative Procedures for the Synthesis of Electrophiles

Representative Procedure #1: Oxidative Heck Reaction[7]



Methyl (*E*)-3-(4-formylphenyl)but-2-enoate (SI-1). To a solution of (4-formylphenyl)boronic acid (0.75 g, 5.0 mmol, 1 equiv), $Pd(OAc)_2$ (23 mg, 0.10 mmol, 0.02 equiv), dppp (62 mg, 0.15 mmol, 0.03 equiv) in acetone (8 mL) was added methyl crotonate (1.1 mL, 10.0 mmol, 2 equiv) followed by trifluoroacetic acid (0.12 mL, 1.5 mmol, 0.3 equiv). The resulting slurry was heated under reflux for 48 h, whereupon the reaction was cooled to ambient temperature and concentrated under reduced pressure. The crude product was purified by silica gel flash column chromatography (5% EtOAc/hexanes) to give carbonate **SI-1** as a colorless oil (0.17 g, 17% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.06 (s, 1H), 7.97 – 7.78 (m, 2H), 7.74 – 7.58 (m, 2H), 6.22 (q, J = 1.3 Hz, 1H), 3.80 (s, 3H), 2.62 (d, J = 1.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.8, 167.0, 154.4, 148.2, 136.5, 130.1, 127.1, 119.0, 51.5, 18.1; IR (Neat Film, NaCl) 2950, 2839, 1704, 1631, 1605, 1434, 1349, 1273, 1214, 1171, 1036, 828 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{13}O_3$ $[M+H]^+$: 205.0865, found 205.0860.

Representative Procedure #2: Reduction & Acylation

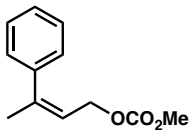


(*E*)-3-(4-Fluorophenyl)but-2-en-1-yl methyl carbonate (6c). To a solution of methyl (*E*)-3-(4-fluorophenyl)but-2-enoate[8] (0.30 g, 1.6 mmol, 1 equiv) in THF (3.1 mL) at –78 °C was added DIBAL (0.85 mL, 4.8 mmol, 3 equiv) dropwise. The resulting reaction mixture was stirred at –78 °C for 2.5 h, whereupon the reaction was quenched with a saturated aqueous Rochelle's salt solution (5 mL). The cooling bath was then removed and the reaction was stirred for 18 h at ambient temperature. The aqueous layer was extracted with CH_2Cl_2 (3 x 20 mL) and the combined organic layers were washed with brine (20 mL), dried over Na_2SO_4, and concentrated under reduced pressure.

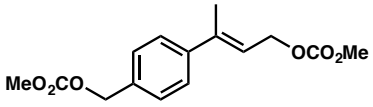
The crude material was then dissolved in CH_2Cl_2 (6.4 mL) and cooled to 0 °C. Pyridine (1.1 mL, 13 mmol, 8.3 equiv) was added followed by methyl chloroformate (0.28 mL, 3.7 mmol, 2.3 equiv) dropwise. The resulting solution was allowed to warm to ambient temperature and stirred for 18 h. The reaction was quenched with the addition of 1 M HCl (5 mL) and the aqueous layer was extracted with CH_2Cl_2 (3 x 20 mL). The combined organic layers were washed with brine (20 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified by silica gel flash column chromatography (5% EtOAc/hexanes) to give carbonate **6c** as a colorless solid (0.14 g,

38% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.33 (m, 2H), 7.05 – 6.96 (m, 2H), 5.87 (tq, *J* = 7.0, 1.4 Hz, 1H), 4.84 (dd, *J* = 7.1, 0.8 Hz, 2H), 3.80 (s, 3H), 2.11 (dd, *J* = 1.4, 0.7 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 163.7, 161.3, 156.0, 140.2, 138.6 (d, *J* = 3.3 Hz), 127.6 (d, *J* = 8.0 Hz), 120.7 (d, *J* = 1.3 Hz), 115.4, 115.1, 65.0, 55.0, 16.5; IR (Neat Film, NaCl) 2961, 1896, 1742, 1649, 1589, 1468, 1442, 1379, 1334, 1252, 1110, 994, 960, 945, 825, 794 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{13}FO_3$ $[M]^+$: 224.0849, found 224.0850.

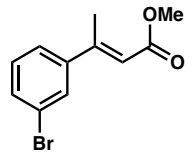
Spectroscopic Data for the Synthesis of Electrophiles



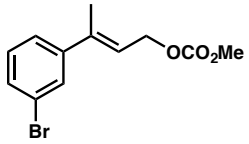
(*Z*)-methyl (3-phenylbut-2-en-1-yl) carbonate (4). Carbonate **4** was prepared from ethyl (*Z*)-3-phenylbut-2-enoate[9] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.18 g, 49% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.18 (m, 5H), 5.76 – 5.68 (m, 1H), 4.58 (dd, *J* = 7.2, 1.1 Hz, 2H), 3.79 (s, 3H), 2.13 (q, *J* = 1.2 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.8, 143.8, 140.3, 128.4, 127.8, 127.6, 120.5, 65.8, 54.8, 25.6; IR (Neat Film, NaCl) 3023, 2956, 1748, 1494, 1441, 1382, 1350, 1263, 1024, 944, 792, 765, 702 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{15}O_3$ $[M+H]^+$: 207.1021, found 207.1011.



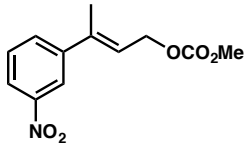
(*E*)-3-(4-(((Methoxycarbonyl)oxy)methyl)phenyl)but-2-en-1-yl methyl carbonate (6f). Carbonate **6f** was prepared from **SI-1** according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless solid (0.11 g, 46% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 – 7.31 (m, 4H), 5.98 – 5.88 (m, 1H), 5.15 (s, 2H), 4.85 (dd, *J* = 7.0, 0.9 Hz, 2H), 3.802 (s, 3H), 3.795 (s, 3H), 2.13 – 2.10 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.0, 155.9, 142.8, 140.6, 134.7, 128.5, 126.3, 121.2, 69.4, 65.0, 55.1, 55.0, 16.4; IR (Neat Film, NaCl) 2959, 1754, 1443, 1385, 1333, 1288, 958, 909, 794, 731 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{15}H_{18}O_6$ $[M]^+$: 294.1103, found 294.1098.



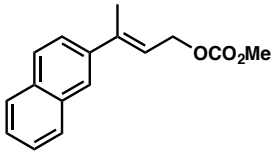
Methyl (*E*)-3-(3-bromophenyl)but-2-enoate (SI-2). Ester **SI-2** was prepared from (3-bromophenyl)boronic acid according to Representative Procedure #1 and isolated by silica gel flash column chromatography (3% EtOAc/hexanes) as a colorless oil (0.54 g, 42% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65 – 7.59 (m, 1H), 7.51 (ddd, *J* = 7.9, 2.0, 1.0 Hz, 1H), 7.45 – 7.37 (m, 1H), 7.31 – 7.26 (m, 1H), 6.14 (q, *J* = 1.3 Hz, 1H), 3.78 (d, *J* = 1.2 Hz, 3H), 2.57 (d, *J* = 1.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.1, 154.3, 144.4, 132.1, 130.2, 129.6, 125.1, 122.8, 117.9, 51.4, 18.1; IR (Neat Film, NaCl) 3062, 2948, 1719, 1631, 1558, 1435, 1346, 1274, 1191, 1168, 1037, 869, 785, 688 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}O_2Br$ $[M+H]^+$: 255.0021, found 255.0020.



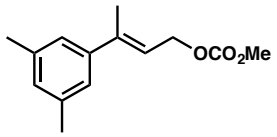
(*E*)-3-(3-Bromophenyl)but-2-en-1-yl methyl carbonate (6g). Carbonate **6g** was prepared from **SI-2** according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.47 g, 78% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (t, *J* = 1.8 Hz, 1H), 7.40 (ddd, *J* = 7.9, 1.9, 1.0 Hz, 1H), 7.32 (ddd, *J* = 7.8, 1.8, 1.0 Hz, 1H), 7.22 – 7.14 (m, 1H), 5.96 – 5.88 (m, 1H), 4.88 – 4.76 (m, 2H), 3.81 (s, 3H), 2.12 – 2.08 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.93, 144.65, 139.74, 130.68, 129.96, 129.18, 124.64, 122.65, 122.08, 64.84, 55.02, 16.38; IR (Neat Film, NaCl) 2955, 1748, 1590, 1558, 1442, 1376, 1332, 1263, 946, 789, 690 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{13}O_3Br$ $[M]^+$: 284.0048, found 284.0073.



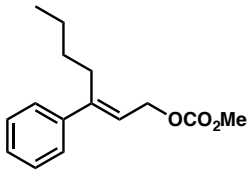
(*E*)-Methyl (3-(3-nitrophenyl)but-2-en-1-yl) carbonate (6h). Carbonate **6h** was prepared from methyl (*E*)-3-(3-nitrophenyl)but-2-enoate[8] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (10% EtOAc/hexanes) as a colorless oil (0.47 g, 78% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (t, *J* = 2.0 Hz, 1H), 8.14 (ddd, *J* = 8.2, 2.3, 1.0 Hz, 1H), 7.73 (ddd, *J* = 7.8, 1.8, 1.1 Hz, 1H), 7.51 (t, *J* = 8.0 Hz, 1H), 6.10 – 5.91 (m, 1H), 4.88 (dt, *J* = 6.9, 0.8 Hz, 2H), 3.82 (s, 3H), 2.18 (dd, *J* = 1.4, 0.7 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.9, 148.5, 144.1, 138.7, 131.9, 129.4, 123.6, 122.5, 121.0, 64.7, 55.1, 16.4; IR (Neat Film, NaCl) 3108, 3026, 2969, 2868, 1750, 1530, 1443, 1384, 1353, 1279, 1096, 994, 949, 930, 876, 788, 736, 682 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{14}O_5N$ $[M+H]^+$: 252.0872, found 252.0884.



(*E*)-methyl (3-(Naphthalen-2-yl)but-2-en-1-yl) carbonate (6i). Carbonate **6i** was prepared from methyl (*E*)-3-(naphthalen-2-yl)but-2-enoate[10] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.26 g, 51% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 – 7.77 (m, 4H), 7.58 (dd, *J* = 8.6, 1.9 Hz, 1H), 7.52 – 7.42 (m, 2H), 6.12 – 6.05 (m, 1H), 4.92 (dq, *J* = 7.0, 0.7 Hz, 2H), 3.82 (s, 3H), 2.29 – 2.22 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.0, 140.9, 139.7, 133.4, 133.0, 128.3, 128.0, 127.7, 126.4, 126.1, 124.9, 124.3, 121.3, 65.2, 55.0, 16.5; IR (Neat Film, NaCl) 3057, 2952, 1752, 1740, 1596, 1467, 1442, 1382, 1248, 997, 941, 818, 794, 740 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{16}H_{16}O_3$ $[M]^+$: 256.1100, found 256.1095.

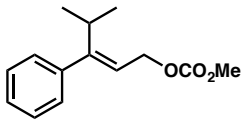


(*E*)-3-(3,5-Dimethylphenyl)but-2-en-1-yl methyl carbonate (6k). Carbonate **6k** was prepared from methyl (*E*)-3-(3,5-dimethylphenyl)but-2-enoate[11] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.32 g, 86% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.02 (dt, *J* = 1.6, 0.8 Hz, 2H), 6.93 (td, *J* = 1.6, 0.8 Hz, 1H), 5.96 – 5.82 (m, 1H), 4.84 (dd, *J* = 7.0, 0.8 Hz, 2H), 3.80 (s, 3H), 2.31 (d, *J* = 0.7 Hz, 6H), 2.15 – 2.06 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.0, 142.6, 141.5, 137.9, 129.4, 123.9, 120.4, 65.1, 54.9, 21.5, 16.5; IR (Neat Film, NaCl) 2956, 2918, 2862, 1748, 1601, 1443, 1376, 1335, 1262, 944, 905, 849, 792, 699 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{14}H_{18}O_3$ $[M]^+$: 234.1256, found 234.1252.

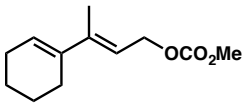


(*E*)-Methyl (3-phenylhept-2-en-1-yl) carbonate (8b). Carbonate **8b** was prepared from ethyl (*E*)-3-phenylhept-2-enoate[12] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.31 g, 58% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 – 7.27 (m, 5H), 5.89 – 5.71 (m, 1H), 4.84 (d, *J* = 7.0 Hz, 2H), 3.80 (s, 3H), 2.73 – 2.46 (m, 2H), 1.41 – 1.24 (m, 4H), 1.06 – 0.73 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.0, 146.6, 142.0, 128.4, 127.6, 126.6, 121.1, 65.0, 55.0, 31.2, 30.2, 22.7, 14.0; IR (Neat Film, NaCl) 3034, 2957, 2872, 1748, 1644, 1599,

1493, 1444, 1378, 1344, 1262, 1129, 941, 792, 766, 698 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{15}H_{20}O_3$ $[M]^+$: 248.1412, found 248.1424.

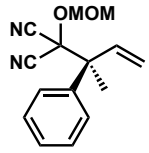


(*E*)-Methyl (4-methyl-3-phenylpent-2-en-1-yl) carbonate (8c). Carbonate **8c** was prepared from ethyl (*E*)-4-methyl-3-phenylpent-2-enoate[13] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.17 g, 17% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.27 (m, 3H), 7.11 – 7.02 (m, 2H), 5.61 (td, *J* = 7.0, 1.3 Hz, 1H), 4.46 (dd, *J* = 7.0, 0.8 Hz, 2H), 3.75 (s, 3H), 2.66 – 2.54 (m, 1H), 1.03 (d, *J* = 6.8 Hz, 6H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.8, 154.0, 139.7, 128.5, 128.2, 127.3, 117.8, 66.1, 54.8, 36.0, 21.5; IR (Neat Film, NaCl) 2961, 2872, 1749, 1492, 1442, 1263, 942, 792, 771, 703 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{14}H_{19}O_3$ $[M+H]^+$: 235.1334, found 235.1344.



(*E*)-3-(Cyclohex-1-en-1-yl)but-2-en-1-yl methyl carbonate (8e). Carbonate **8e** was prepared from ethyl (*E*)-3-(cyclohex-1-en-1-yl)but-2-enoate[14] according to Representative Procedure #2 and isolated by silica gel flash column chromatography (5% EtOAc/hexanes) as a colorless oil (0.25 g, 73% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.00 – 5.92 (m, 1H), 5.68 – 5.55 (m, 1H), 4.79 (d, *J* = 7.0 Hz, 2H), 3.78 (s, 3H), 2.16 (ddd, *J* = 12.0, 5.9, 3.7 Hz, 4H), 1.85 (d, *J* = 1.1 Hz, 3H), 1.73 – 1.49 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.0, 141.2, 137.0, 126.0, 116.8, 65.5, 54.9, 26.1, 25.8, 23.0, 22.3, 14.1; IR (Neat Film, NaCl) 2929, 2859, 1749, 1638, 1443, 1263, 1119, 940, 792 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{18}O_3$ $[M]^+$: 210.1256, found 210.1252.

General Procedure for Optimization of the Ir-Catalyzed Allylic Alkylation (Table 1)

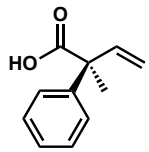


(*S*)-2-(Methoxymethoxy)-2-(2-phenylbut-3-en-2-yl)malononitrile (3). In a nitrogen-filled glove box, to a 1 dram vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (1.3 mg, 0.0020 mmol, 2 mol %), ligand (S_a)-**L3** (2.5 mg, 0.0042 mmol, 4.2 mol %), TBD (1.4 mg, 0.010 mmol, 10 mol %), and THF (0.5 mL). Vial A was stirred at 25 °C (ca. 10 min) while another 1 dram vial (vial B) was charged with MAC nucleophile **1** (0.10 mmol or 0.20 mmol, as specified), THF (0.5 mL), and the Lewis acid additive (200 mol %). The

pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **2** (0.20 mmol, 0.10 mmol, or 0.12 mmol, as specified). The vial was sealed and stirred at 60 °C. After 18 h, the vial was removed from the glove box and filtered through a pad of silica, rinsing with EtOAc. The crude mixture was concentrated and 1,2,4,5-tetrachloro-3-nitrobenzene (0.10 mmol in 0.5 mL $CDCl_3$) was added. The NMR yield (measured in reference to 1,2,4,5-tetrachloro-3-nitrobenzene δ 7.74 ppm (s, 1H)) was determined by ^{1}H NMR analysis of the crude mixture. The residue was purified by preparatory TLC (15% EtOAc/hexanes) to afford MAC adduct product **3** as a colorless oil. For the purposes of characterization, product **3** was further purified by preparatory HPLC (20% EtOAc/hexanes, Viridis SFC 2-Ethylpyridine 5 μm column, flow rate = 1.5 mL/min; λ = 230 nm): 94% ee (entry 9); $[\alpha]_D^{25}$ +11.7 (*c* 0.07, $CHCl_3$) (entry 9); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 – 7.54 (m, 2H), 7.42 – 7.32 (m, 3H), 6.51 (dd, *J* = 17.4, 11.0 Hz, 1H), 5.59 – 5.34 (m, 2H), 5.02 (s, 2H), 3.42 (s, 3H), 1.84 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.3, 137.6, 129.0, 128.57, 238.55, 128.3, 125.2, 119.2, 112.8, 112.7, 96.7, 73.9, 57.5, 52.8, 20.9; IR (Neat Film, NaCl) 3062, 2957, 2896, 2242, 2189, 1750, 1492, 1445, 1358, 1268, 1161, 1108, 1030, 930, 751, 698 cm^{-1}; HRMS (ESI+) *m/z* calc'd for $C_{15}H_{17}N_2O_2$ $[M+H]^+$: 257.1290, found 257.1313; HPLC conditions: 1% IPA, 1.0 mL/min, Chiralpak IC column, λ = 210 nm, t_R (min): major = 13.303, minor = 17.243.

General Procedure for the Enantioenriched Carboxylic Acid Synthesis

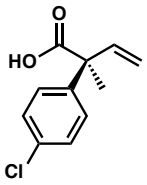
Please note that the absolute configuration was determined only for compound **7h** via x-ray crystallographic analysis. The absolute configuration for all other products has been inferred by analogy. For respective HPLC and SFC conditions, please refer to Table S1.



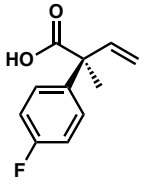
(*S*)-2-Methyl-2-phenylbut-3-enoic acid (7a). In a nitrogen-filled glove box, to a 1 dram vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (2.7 mg, 0.0040 mmol, 2 mol %), ligand (S_a)-**L3** (4.9 mg, 0.0084 mmol, 4.2 mol %), TBD (2.8 mg, 0.020 mmol, 10 mol %), and THF (1 mL). Vial A was stirred at 25 °C (ca. 10 min) while another 1 dram vial (vial B) was charged with MAC nucleophile **1** (25 mg, 0.20 mmol, 100 mol %), THF (1 mL), and BEt_3 (400 μL, 1M in hexanes). The pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **2** (83 mg, 0.40 mmol, 200 mol %). The vial was sealed and stirred at 60 °C. After 18 h or 48 h, the vial was removed from the glove box, transferred to a 20 mL vial with CH_2Cl_2, and concentrated. The crude material was heated at 80 °C in 6M HCl (4 mL) for 18 h. Whereupon, the reaction mixture was cooled to 0 °C and basified with 6M NaOH (4.5 mL). The aqueous layer was extracted with CH_2Cl_2 (4 x 8 mL). The combined organic layers were washed with 2M NaOH (8 mL). The combined aqueous layers were acidified with concentrated HCl, extracted with CH_2Cl_2 (4 x 8 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C to give the product **7a** as a colorless solid (27 mg, 77% yield): 95% ee; $[\alpha]_D^{25}$ +13.5 (*c* 1.3,

$CHCl_3$); HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 12.198, minor = 11.426. Characterization data match those reported in the literature.[15] *Please note* Compounds **7i**, **7j**, **7k**, and **9a**–**9g** were prepared at the same concentration with double catalyst loadings.

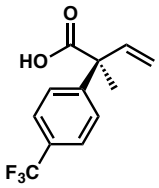
Spectroscopic Data for the Enantioenriched Carboxylic Acids



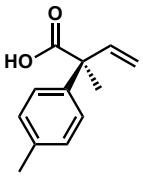
(*S*)-2-(4-Chlorophenyl)-2-methylbut-3-enoic acid (7b). Product **7b** was prepared according to the general procedure to give a pale yellow oil (33 mg, 80% yield): 93% ee; $[\alpha]_D^{25}$ +8.1 (*c* 1.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 – 7.24 (m, 4H), 6.38 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.44 – 5.16 (m, 2H), 1.66 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.4, 141.1, 140.1, 133.3, 128.7, 128.3, 116.1, 53.3, 23.3; IR (Neat Film, NaCl) 3089, 2987, 2645, 2539, 1705, 1493, 1400, 1282, 1097, 1014, 928, 826, 755 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}O_2Cl$ $[M+H]^+$: 211.0526, found 211.0528; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 15.642, minor = 14.104.



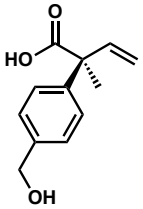
(*S*)-2-(4-Fluorophenyl)-2-methylbut-3-enoic acid (7c). Product **7c** was prepared according to the general procedure to give a pale yellow oil (35 mg, 90% yield): 90% ee; $[\alpha]_D^{25}$ +3.4 (*c* 1.5, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 – 7.19 (m, 2H), 7.05 (t, *J* = 8.7 Hz, 2H), 6.39 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.42 – 5.14 (m, 2H), 1.67 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.6, 163.2, 160.7, 140.4, 138.3 (d, *J* = 3.4 Hz), 128.5 (d, *J* = 8.1 Hz), 115.9, 115.5, 115.3, 53.2, 23.5; IR (Neat Film, NaCl) 3088, 2987, 2924, 2642, 1704, 1603, 1510, 1462, 1412, 1277, 1234, 1165, 928, 833, 816, 735 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}FO_2$ $[M+H]^+$: 195.0833, found 195.0841; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 15.499, minor = 13.811.



(*S*)-2-Methyl-2-(4-(trifluoromethyl)phenyl)but-3-enoic acid (7d). Product **7d** was prepared according to the general procedure to give a pale yellow oil (41 mg, 83% yield): 92% ee; $[\alpha]_D^{25}$ –2.2 (*c* 2.3, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (dt, *J* = 8.1, 0.8 Hz, 2H), 7.45 (dt, *J* = 8.3, 0.8 Hz, 2H), 6.38 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.48 – 5.09 (m, 2H), 1.68 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.0, 146.6, 139.7, 129.6, 130.0, 129.5, 127.2, 125.6 (q, *J* = 3.7 Hz), 122.8, 116.6, 53.7, 29.9, 23.4; IR (Neat Film, NaCl) 2926, 2649, 1707, 1618, 1413, 1328, 1277, 1167, 1126, 1081, 1016, 930, 940 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{12}O_2F_3$ $[M+H]^+$: 245.0789, found 245.0794; SFC conditions: 2% IPA, 2.5 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 13.592, minor = 15.745.

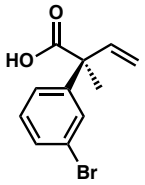


(*S*)-2-Methyl-2-(*p*-tolyl)but-3-enoic acid (7e). Product **7e** was prepared according to the general procedure to give a pale yellow oil (24 mg, 63% yield): 94% ee; $[\alpha]_D^{25}$ +4.6 (*c* 0.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 – 7.01 (m, 4H), 6.40 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.59 – 5.08 (m, 2H), 2.34 (s, 3H), 1.64 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 181.0, 140.7, 139.8, 137.0, 129.3, 126.6, 115.4, 53.3, 23.3, 21.1; IR (Neat Film, NaCl) 2986, 1702, 1636, 1512, 1457, 1412, 1276, 1191, 1132, 1077, 1020, 925, 815, 730 cm^{-1}; HRMS (ESI-) *m/z* calc'd for $C_{12}H_{13}O_2$ $[M-H]^-$: 189.0916, found 189.0903; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 15.393, minor = 14.288.

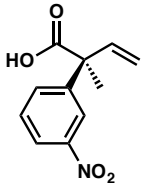


(*S*)-2-(4-(Hydroxymethyl)phenyl)-2-methylbut-3-enoic acid (7f). Product **7f** was prepared according to the general procedure and isolated by preparatory TLC (30% acetone/hexanes) to give a colorless soild (21 mg, 51% yield): 95% ee; $[\alpha]_D^{25}$ +3.4 (*c* 0.5, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (q, *J* = 8.2 Hz, 4H), 6.37 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.39 – 5.10 (m, 2H), 4.57 (s, 2H), 1.63 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ

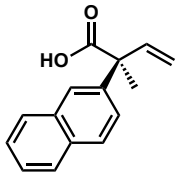
180.1, 143.2, 140.4, 136.4, 128.8, 127.2, 115.8, 53.6, 45.9, 23.4; IR (Neat Film, NaCl) 2985, 2927, 2642, 1703, 1636, 1512, 1460, 1268, 1182, 1076, 926, 836, 731, 683 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{15}O_3$ $[M+H]^+$: 207.1021, found 207.1025; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 15.258, minor = 14.667.



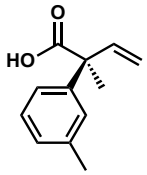
(*S*)-2-(3-Bromophenyl)-2-methylbut-3-enoic acid (7g). Product **7g** was prepared according to the general procedure to give a pale yellow oil (35 mg, 69% yield): 92% ee; $[\alpha]_D^{25}$ –2.6 (*c* 1.8, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 7.47 (t, *J* = 1.9 Hz, 1H), 7.41 (ddd, *J* = 7.6, 1.9, 1.2 Hz, 1H), 7.29 – 7.18 (m, 2H), 6.35 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.42 – 5.09 (m, 2H), 1.65 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.7, 145.0, 139.8, 130.5, 130.2, 129.9, 125.5, 122.8, 116.4, 53.5, 23.3; IR (Neat Film, NaCl) 2987, 2644, 1705, 1593, 1566, 1475, 1413, 1280, 1129, 1070, 997, 928, 785, 760, 700 cm^{-1}; HRMS (ESI-) *m/z* calc'd for $C_{11}H_{10}O_2Br$ $[M-H]^-$: 252.9864, found 252.9864; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 15.217, minor = 14.439.



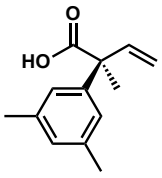
(*S*)-2-Methyl-2-(3-nitrophenyl)but-3-enoic acid (7h). Product **7h** was prepared according to the general procedure to give a colorless solid (41 mg, 93% yield): 87% ee; $[\alpha]_D^{25}$ +94.5 (*c* 3.4, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 8.22 (t, *J* = 2.0 Hz, 1H), 8.15 (ddd, *J* = 8.2, 2.2, 1.0 Hz, 1H), 7.69 (ddd, *J* = 7.9, 1.9, 1.1 Hz, 1H), 7.53 (t, *J* = 8.0 Hz, 1H), 6.38 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.59 – 5.11 (m, 2H), 1.72 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.6, 148.5, 144.7, 139.2, 133.3, 129.6, 122.5, 122.1, 117.2, 53.7, 23.4; IR (Neat Film, NaCl) 3089, 2988, 2924, 2641, 1707, 1530, 1351, 1276, 1106, 929, 808, 738, 688 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}O_4N$ $[M+H]^+$: 222.0766, found 222.0769; HPLC conditions: 3% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 24.060, minor = 20.907.



(*S*)-2-Methyl-2-(naphthalen-2-yl)but-3-enoic acid (7i). Product **7i** was prepared according to the general procedure to give a pale yellow oil (30 mg, 66% yield): 92% ee; $[\alpha]_D^{25}$ +7.8 (*c* 0.6, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.72 (m, 4H), 7.55 – 7.39 (m, 3H), 6.52 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.57 – 5.11 (m, 2H), 1.77 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.9, 140.5, 140.0, 133.3, 132.5, 128.3, 128.2, 127.6, 126.3, 126.2, 125.3, 125.2, 116.0, 53.9, 23.4; IR (Neat Film, NaCl) 3057, 2984, 1701, 1506, 1458, 1411, 1274, 1182, 1128, 1102, 925, 856, 816, 747 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{15}H_{14}O_2$ $[M]^+$: 226.0994, found 226.0992; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 28.272, minor = 24.870.

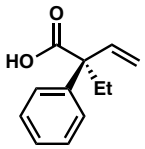


(*S*)-2-Methyl-2-(*m*-tolyl)but-3-enoic acid (7j). Product **7j** was prepared according to the general procedure to give a pale yellow oil (26 mg, 68% yield): 93% ee; $[\alpha]_D^{25}$ +5.2 (*c* 1.6, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25 – 7.04 (m, 4H), 6.40 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.45 – 5.08 (m, 2H), 2.44 – 2.20 (m, 3H), 1.65 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.2, 142.7, 140.6, 138.3, 128.5, 128.1, 127.3, 123.7, 115.6, 53.6, 23.3, 21.7; IR (Neat Film, NaCl) 2984, 2923, 2648, 1703, 1606, 1459, 1411, 1275, 1178, 1127, 1002, 926, 785, 703 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{15}O_2$ $[M+H]^+$: 191.1072, found 191.1074; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 13.800, minor = 12.388.

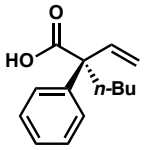


(*S*)-2-(3,5-Dimethylphenyl)-2-methylbut-3-enoic acid (7k). Product **7k** was prepared according to the general procedure and isolated by preparatory TLC (30% acetone/hexanes) to give a colorless oil (13 mg, 32% yield): 85% ee; $[\alpha]_D^{25}$ –40.6 (*c* 0.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.94 (d, *J* = 8.5 Hz, 3H), 6.42 (dd, *J* = 17.4, 10.6 Hz, 1H), 5.45 – 5.08 (m, 2H), 2.33 (s, 6H), 1.65 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.5, 142.8, 140.8, 138.1, 129.0, 124.4, 115.3, 53.6, 23.3, 21.6; IR (Neat Film, NaCl) 2983, 2919, 2639, 1700, 1602, 1411, 1279, 1125, 923, 848, 708 cm^{-1}; HRMS (FAB+) *m/z*

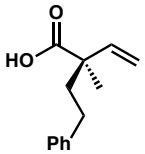
calc'd for $C_{13}H_{17}O_2$ $[M+H]^+$: 205.1229, found 205.1233; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 11.107, minor = 10.064. *Please note* an HMBC has been included due to the low intensity of the carbonyl ^{13}C shift at δ 180.5.



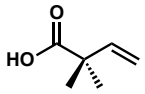
(*S*)-2-Ethyl-2-phenylbut-3-enoic acid (9a). Product **9a** was prepared according to the general procedure and isolated by preparatory TLC (30% acetone/hexanes) to give a a colorless oil (23 mg, 61% yield): 92% ee; $[\alpha]_D^{25}$ +17.4 (*c* 0.4, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 7.38 – 7.22 (m, 5H), 6.36 (dd, *J* = 17.7, 10.9 Hz, 1H), 5.35 (d, *J* = 10.7 Hz, 1H), 5.09 (d, *J* = 17.6 Hz, 1H), 2.36 – 2.00 (m, 2H), 0.87 (t, *J* = 7.2 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.1, 141.3, 139.1, 128.4, 127.6, 127.2, 116.9, 58.0, 29.4, 9.4; IR (Neat Film, NaCl) 3060, 2970, 2928, 2636, 1702, 1495, 1448, 1407, 1381, 1261, 1083, 924, 761, 700 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{15}O_2$ $[M+H]^+$: 191.1072, found 191.1071; HPLC conditions: 1.5% IPA, 1.0 mL/min, two Chiralpak AD–H columns in series, λ = 210 nm, t_R (min): major = 46.253, minor = 47.271.



(*S*)-2-Phenyl-2-vinylhexanoic acid (9b). Product **9b** was prepared according to the general procedure and isolated by preparatory TLC (30% acetone/hexanes) to give a colorless oil (6 mg, 14% yield): 95% ee; $[\alpha]_D^{25}$ –106.0 (*c* 0.07, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.29 (m, 5H), 6.38 (dd, *J* = 17.6, 10.9 Hz, 1H), 5.32 (dd, *J* = 10.9, 0.9 Hz, 1H), 5.06 (dd, *J* = 17.6, 0.9 Hz, 1H), 2.28 – 1.98 (m, 2H), 1.44 – 1.14 (m, 4H), 0.87 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.4, 141.6, 139.7, 128.4, 127.5, 127.1, 116.6, 57.5, 36.5, 27.0, 23.4, 14.1; IR (Neat Film, NaCl) 2956, 2920, 2851, 1734, 1706, 1466, 1378, 1260, 1098, 925, 800, 722, 700 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{14}H_{19}O_2$ $[M+H]^+$: 219.1385, found 219.1291; SFC conditions: 5% IPA, 2.5 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 10.646, minor = 11.952.



(*R*)-2-Methyl-2-phenethylbut-3-enoic acid (9f). Product **9f** was prepared according to the general procedure and isolated by preparatory TLC (33% acetone/hexanes) to give a colorless oil (13 mg, 32% yield): 3% ee; $[\alpha]_D^{25}$ –12.1 (*c* 0.7, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 – 7.04 (m, 5H), 6.10 (dd, *J* = 17.6, 10.7 Hz, 1H), 5.21 (dd, *J* = 14.0, 3.3 Hz, 2H), 2.60 (dt, *J* = 11.0, 4.9 Hz, 2H), 2.33 – 1.79 (m, 2H), 1.40 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 182.0, 142.0, 140.9, 128.54, 128.49, 126.1, 114.7, 48.7, 41.1, 31.2, 20.7; IR (Neat Film, NaCl) 3026, 2927, 1702, 1496, 1454, 1380, 1264, 1097, 925, 748, 700 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{13}H_{17}O_2$ $[M+H]^+$: 267.1385, found 267.1376; HPLC conditions: 2% IPA, 1.0 mL/min, Chiralpak AD–H column, λ = 210 nm, t_R (min): major = 18.485, minor = 14.652. *Please note* an HMBC has been included due to the low intensity of the carbonyl ^{13}C shift at δ 182.0.

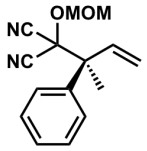
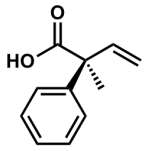
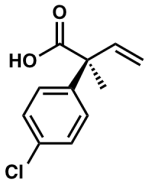
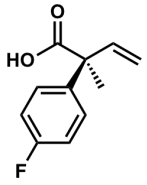
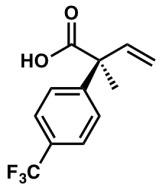
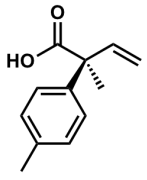


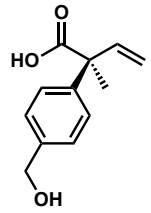
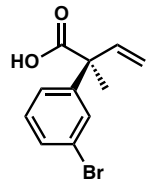
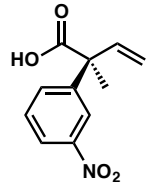
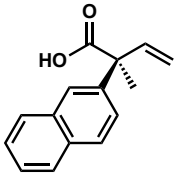
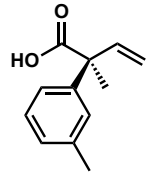
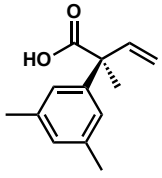
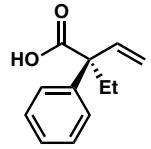
2,2-Dimethylbut-3-enoic acid (9g). Product **9g** was prepared according to the general procedure to give a colorless oil (15 mg, 63% yield). Characterization data match those reported in the literature.[16]

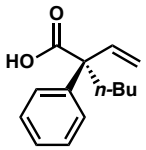
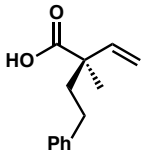
Determination of Enantiomeric Excess

Please note racemic products were synthesized using racemic **L3**.

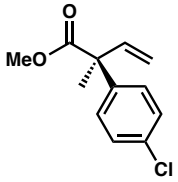
Table S1: Determination of Enantiomeric Excess

Entry	Product	Assay Conditions	Retention time of major isomer (min)	Retention time of minor isomer (min)	%ee
1		HPLC Chiralpak IC 1% IPA isocratic, 1 mL/min	13.303	17.243	94%
2		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	12.198	11.426	95%
3		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	15.642	14.104	93%
4		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	15.499	13.811	90%
5		SFC Chiralpak AD–H 2% IPA isocratic, 2.5 mL/min	13.592	15.745	92%
6		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	15.393	14.288	94%

Entry	Product	Assay Conditions	Retention time of major isomer (min)	Retention time of minor isomer (min)	%ee
7		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	15.258	14.667	95%
8		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	15.217	14.439	92%
9		HPLC Chiralpak AD–H 3% IPA isocratic, 1 mL/min	24.060	20.907	87%
10		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	28.272	24.870	92%
11		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	13.800	12.388	93%
12		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	11.107	10.064	85%
13		HPLC two Chiralpak AD–H in series 1.5% IPA isocratic, 1 mL/min	46.253	47.271	92%

Entry	Product	Assay Conditions	Retention time of major isomer (min)	Retention time of minor isomer (min)	%ee
14		SFC Chiralpak AD–H 5% IPA isocratic, 2.5 mL/min	10.646	11.952	95%
15		HPLC Chiralpak AD–H 2% IPA isocratic, 1 mL/min	18.485	14.652	3%

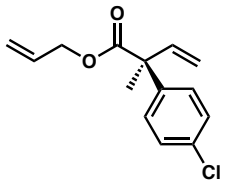
Experimental Procedures and Spectroscopic Data for the One-pot Syntheses of Carboxylic Acid Derivatives



Methyl (*S*)-2-(4-chlorophenyl)-2-methylbut-3-enoate (10). In a nitrogen-filled glove box, to a scintillation vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (13 mg, 0.02 mmol, 2 mol %), ligand (S_a)-**L3** (25 mg, 0.042 mmol, 4.2 mol %), TBD (14 mg, 0.10 mmol, 10 mol %), and THF (5 mL). Vial A was stirred at 25 °C (ca. 10 min) while another scintillation vial (vial B) was charged with MAC nucleophile **1** (126 mg, 1.0 mmol, 100 mol %), THF (5 mL), and BEt_3 (2.0 mL, 1M in hexanes). The pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **6b** (480 mg, 2.0 mmol, 200 mol %). The vial was sealed and stirred at 60 °C. After 18 h, the vial was removed from the glove box and the reaction mixture was concentrated under reduced pressure.

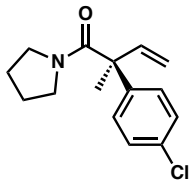
To the vial of crude MAC adduct equipped with a stir bar and septum cap was added 1:1 AcOH/DME (2 mL, 0.5 M) and CSA (0.26 g, 1.1 mmol, 1.1 equiv) under a nitrogen atmosphere. The reaction was heated to 60 °C for 6 h, whereupon the reaction mixture was cooled to ambient temperature, diluted with anhydrous MeOH (2.8 mL), and cooled to –40 °C. A solution of 1:1 MeOH/Et_3N (5.6 mL, 20.1 equiv of Et_3N) was added dropwise over 10 min. The reaction mixture was allowed to warm to ambient temperature over 18 h, whereupon the reaction was slowly quenched with saturated NH_4Cl aqueous solution (5 mL). The aqueous layer was then extracted with CH_2Cl_2 (3 x 10 mL) and the combined

organic layers were washed with brine (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by silica gel flash column chromatography (10% EtOAc/hexanes) to give methyl ester **10** as a colorless oil (0.20 g, 88% yield): $[\alpha]_D^{25}$ +1.5 (*c* 0.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 6.99 (m, 4H), 6.35 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.48 – 5.00 (m, 2H), 3.70 (s, 3H), 1.62 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.0, 142.0, 140.6, 132.9, 128.7, 128.1, 115.6, 53.5, 52.7, 23.7; IR (Neat Film, NaCl) 2986, 2952, 1734, 1637, 1493, 1459, 1246, 1181, 1123, 1098, 1014, 926, 828, 757 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{13}ClO_2$ $[M+]^+$: 224.0604, found 224.0621.



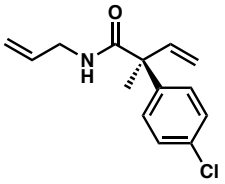
Allyl (*S*)-2-(4-chlorophenyl)-2-methylbut-3-enoate (11). In a nitrogen-filled glove box, to a 1 dram vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (2.7 mg, 0.0040 mmol, 2 mol %), ligand (S_a)-**L3** (4.9 mg, 0.0084 mmol, 4.2 mol %), TBD (2.8 mg, 0.020 mmol, 10 mol %), and THF (1 mL). Vial A was stirred at 25 °C (ca. 10 min) while another 1 dram vial (vial B) was charged with MAC nucleophile **1** (25 mg, 0.20 mmol, 100 mol %), THF (1 mL), and BEt_3 (400 μL, 1M in hexanes). The pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **6b** (96 mg, 0.40 mmol, 200 mol %). The vial was sealed and stirred at 60 °C. After 18 h, the vial was removed from the glove box, transferred to a 20 mL vial with CH_2Cl_2, and concentrated.

To the vial of crude MAC adduct equipped with a stir bar and septum cap was added 1:1 AcOH/DME (0.4 mL, 0.5 M) and CSA (51 mg, 0.22 mmol, 1.1 equiv) under a nitrogen atmosphere. The reaction was heated to 60 °C for 6 h, whereupon the reaction mixture was cooled to ambient temperature, diluted with allyl alcohol (0.4 mL), and cooled to 0 °C. A solution of 1:1 Et_3N/allyl alcohol (1.1 mL, 20.4 equiv of Et_3N) was added dropwise over 10 min. The reaction mixture was allowed to warm to ambient temperature over 18 h, whereupon the reaction was slowly quenched with saturated NH_4Cl aqueous solution (5 mL). The aqueous layer was then extracted with CH_2Cl_2 (3 x 10 mL) and the combined organic layers were washed with brine (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by preparatory TLC (8% EtOAc/hexanes) to give allyl ester **11** as a colorless oil (37 mg, 74% yield): $[\alpha]_D^{25}$ +0.4 (*c* 2.3, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.12 (m, 4H), 6.36 (dd, *J* = 17.5, 10.7 Hz, 1H), 5.85 (ddt, *J* = 17.2, 10.5, 5.6 Hz, 1H), 5.38 – 5.02 (m, 4H), 4.61 (dt, *J* = 5.6, 1.4 Hz, 2H), 1.63 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 174.1, 142.0, 140.6, 132.9, 131.9, 128.6, 128.1, 118.5, 115.6, 65.9, 53.5, 23.6; IR (Neat Film, NaCl) 3089, 2985, 2930, 2857, 1900, 1734, 1638, 1493, 1236, 1177, 1122, 1097, 1014, 926, 828, 756 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{14}H_{16}O_2Cl$ $[M+H]^+$: 251.0839, found 251.0842.



(*S*)-2-(4-Chlorophenyl)-2-methyl-1-(pyrrolidin-1-yl)but-3-en-1-one (12). In a nitrogen-filled glove box, to a 1 dram vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (2.7 mg, 0.0040 mmol, 2 mol %), ligand (S_a)-**L3** (4.9 mg, 0.0084 mmol, 4.2 mol %), TBD (2.8 mg, 0.020 mmol, 10 mol %), and THF (1 mL). Vial A was stirred at 25 °C (ca. 10 min) while another 1 dram vial (vial B) was charged with MAC nucleophile **1** (25 mg, 0.20 mmol, 100 mol %), THF (1 mL), and BEt_3 (400 μL, 1M in hexanes). The pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **6b** (96 mg, 0.40 mmol, 200 mol %). The vial was sealed and stirred at 60 °C. After 18 h, the vial was removed from the glove box, transferred to a 20 mL vial with CH_2Cl_2, and concentrated.

To the vial of crude MAC adduct equipped with a stir bar and septum cap was added 1:1 AcOH/DME (0.4 mL, 0.5 M) and CSA (51 mg, 0.22 mmol, 1.1 equiv) under a nitrogen atmosphere. The reaction was heated to 60 °C for 6 h, whereupon the reaction mixture was cooled to ambient temperature, diluted with CH_2Cl_2 (0.4 mL), and cooled to –40 °C. A solution of 1:1 pyrrolidine/CH_2Cl_2 (0.67 mL, 20.4 equiv of pyrrolidine) was added dropwise over 10 min then Et_3N (0.57 mL, 4.1 mmol, 20.4 equiv). The reaction mixture was allowed to warm to ambient temperature over 18 h, whereupon the reaction was slowly quenched with saturated NH_4Cl aqueous solution (5 mL). The aqueous layer was then extracted with CH_2Cl_2 (3 x 10 mL) and the combined organic layers were washed with brine (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by preparatory TLC (30% acetone/hexanes) to give amide **12** as a colorless oil (32 mg, 61% yield): $[\alpha]_D^{25}$ –49.5 (*c* 1.7, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 – 7.28 (m, 2H), 7.21 – 7.14 (m, 2H), 6.45 (dd, *J* = 17.4, 10.7 Hz, 1H), 5.27 (dd, *J* = 10.7, 0.8 Hz, 1H), 5.10 (dd, *J* = 17.4, 0.8 Hz, 1H), 3.63 – 3.47 (m, 2H), 2.98 (dt, *J* = 10.6, 6.3 Hz, 1H), 2.52 (dt, *J* = 10.6, 6.7 Hz, 1H), 1.78 – 1.62 (m, 2H), 1.64 – 1.55 (m, 5H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 172.1, 143.2, 139.7, 132.5, 129.0, 127.6, 115.5, 54.3, 47.52, 47.44, 28.4, 26.5, 23.5; IR (Neat Film, NaCl) 2928, 2873, 1742, 1627, 1491, 1396, 1228, 1185, 1096, 1012, 921, 829, 723 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{15}H_{19}ClNO$ $[M+H]^+$: 264.1155, found 264.1154.

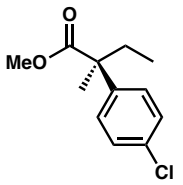


(*S*)-*N*-allyl-2-(4-chlorophenyl)-2-methylbut-3-enamide (13). In a nitrogen-filled glove box, to a 1 dram vial (vial A) equipped with a stir bar was added $[Ir(cod)Cl]_2$ (2.7 mg, 0.0040 mmol, 2 mol %), ligand (S_a)-**L3** (4.9 mg, 0.0084 mmol, 4.2 mol %), TBD (2.8 mg,

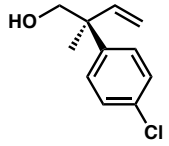
0.020 mmol, 10 mol %), and THF (1 mL). Vial A was stirred at 25 °C (ca. 10 min) while another 1 dram vial (vial B) was charged with MAC nucleophile **1** (25 mg, 0.20 mmol, 100 mol %), THF (1 mL), and BEt_3 (400 μL, 1M in hexanes). The pre-formed catalyst solution (vial A) was then transferred to vial B followed immediately by carbonate **6b** (96 mg, 0.40 mmol, 200 mol %). The vial was sealed and stirred at 60 °C. After 18 h, the vial was removed from the glove box, transferred to a 20 mL vial with CH_2Cl_2, and concentrated.

To the vial of crude MAC adduct equipped with a stir bar and septum cap was added 1:1 AcOH/DME (0.4 mL, 0.5 M) and CSA (51 mg, 0.22 mmol, 1.1 equiv) under a nitrogen atmosphere. The reaction was heated to 60 °C for 6 h, whereupon the reaction mixture was cooled to ambient temperature, diluted with allyl amine (0.4 mL), and cooled to 0 °C. A solution of 1:1 Et_3N/allyl amine (1.1 mL, 20.4 equiv of Et_3N) was added dropwise over 10 min. The reaction mixture was allowed to warm to ambient temperature over 18 h, whereupon the reaction was slowly quenched with saturated NH_4Cl aqueous solution (5 mL). The aqueous layer was then extracted with CH_2Cl_2 (3 x 10 mL) and the combined organic layers were washed with brine (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by preparatory TLC (30% EtOAc/hexanes) to give allyl amide **13** as a colorless oil (31 mg, 63% yield): $[\alpha]_D^{25}$ +10.2 (*c* 1.6, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 – 7.17 (m, 4H), 6.29 (dd, *J* = 17.4, 10.6 Hz, 1H), 5.90 – 5.75 (m, 1H), 5.64 (s, 1H), 5.33 (dd, *J* = 10.6, 0.8 Hz, 1H), 5.20 – 5.03 (m, 3H), 3.96 – 3.82 (m, 2H), 1.67 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 174.1, 142.0, 141.8, 134.1, 133.1, 128.9, 128.8, 116.6, 116.5, 54.3, 42.3, 24.6; IR (Neat Film, NaCl) 3341, 3085, 2983, 2931, 1739, 1658, 1520, 1493, 1414, 1270, 1096, 1014, 922, 827, 725, 657 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{14}H_{17}NOCl$ $[M+H]^+$: 250.0999, found 250.0991.

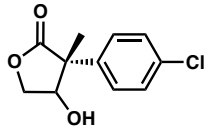
Experimental Procedures and Spectroscopic Data for the Product Transformations



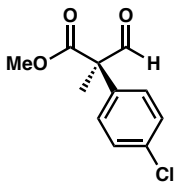
Methyl (*S*)-2-(4-chlorophenyl)-2-methylbutanoate (14). To a solution of olefin **10** (13 mg, 0.056 mmol, 1 equiv) in EtOAc (1 mL) was added Pd/C (2.5 mg, 20% w/w). The reaction mixture was sparged with a hydrogen gas (balloon) for 5 minutes and then stirred under a hydrogen atmosphere for 18 h, whereupon the reaction was filtered through celite with EtOAc (5 mL) and concentrated under reduced pressure at 0 °C to give alkyl **14** as a colorless oil (12 mg, 97% yield): $[\alpha]_D^{25}$ +3.6 (*c* 1.2, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.15 (m, 4H), 3.67 (s, 3H), 2.31 – 1.80 (m, 2H), 1.53 (s, 3H), 0.83 (t, *J* = 7.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.5, 142.4, 132.6, 128.6, 127.7, 52.3, 50.4, 32.0, 22.2, 9.2; IR (Neat Film, NaCl) 2970, 2880, 1731, 1493, 1457, 1383, 1307, 1238, 1147, 1096, 1012, 824, 756, 720 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{12}H_{16}O_2Cl$ $[M+H]^+$: 227.0839, found 227.0840.



(*S*)-2-(4-Chlorophenyl)-2-methylbut-3-en-1-ol (15). DIBAL (0.029 mL, 0.16 mmol, 3 equiv) was added dropwise to a solution of methyl ester **10** (13 mg, 0.056 mmol, 1 equiv) in Et_2O (1.0 mL) at 0 °C. The mixture was stirred at 0 °C for 2 h, whereupon the reaction was quenched with a saturated Rochelle's salt aqueous solution (1 mL) and stirred for 18 h at ambient temperature. The aqueous layer was then extracted with CH_2Cl_2 (3 x 5 mL) and the combined organic layers were washed with brine (5 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by preparatory TLC (25% acetone/hexanes) to give alcohol **15** as a colorless oil (8 mg, 73% yield): $[\alpha]_D^{25}$ +11.0 (*c* 0.4, $CHCl_3$). Characterization data match those reported in the literature.[17]



(3*S*)-3-(4-Chlorophenyl)-4-hydroxy-3-methyldihydrofuran-2(3*H*)-one (16). To a solution of olefin **10** (24 mg, 0.10 mmol, 1 equiv) in THF/H_2O (4:1, 1 mL) was added K_2OsO_4 (4.0 mg, 0.010 mmol, 0.1 equiv) and *N*-methylmorpholine *N*-oxide (19 mg, 0.16 mmol, 1.6 equiv). The reaction mixture was stirred for 18 h, whereupon the reaction was quenched with sodium sulfite (10 mg, 0.079 mmol, 0.79 equiv) and diluted with water (0.5 mL). The aqueous layer was then extracted with EtOAc (3 x 5 mL) and the combined organic layers were washed with brine (5 mL), dried over Na_2SO_4, and concentrated under reduced pressure at 0 °C. The crude residue was purified by preparatory TLC (30% acetone/hexanes) to give lactone **16** as a colorless oil (19 mg, 82% yield, 1:1 dr): $[\alpha]_D^{25}$ – 115.6 (*c* 0.5, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 – 7.26 (m, 4H), 4.58 (dd, *J* = 4.4, 2.8 Hz, 0.5H), 4.54 (dd, *J* = 10.2, 4.5 Hz, 0.5H), 4.35 – 4.31 (m, 0.5H), 4.28 – 4.20 (m, 1H), 4.16 (dd, *J* = 10.1, 2.8 Hz, 0.5H), 1.66 (s, 1.5H), 1.57 (s, 1.5H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.4, 178.1, 138.4, 134.4, 134.0, 133.9, 129.6, 129.4, 129.3, 127.8, 76.5, 76.2, 71.8, 71.6, 53.2, 52.8, 22.3, 18.5; IR (Neat Film, NaCl) 3448, 2976, 2929, 1761, 1496, 1384, 1218, 1178, 1096, 1072, 1014, 982, 927, 737, 688 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}O_3Cl$ $[M+H]^+$: 227.0475, found 227.0481.



Methyl (*R*)-2-(4-chlorophenyl)-2-methyl-3-oxopropanoate (17). A solution of olefin **10** (10 mg, 0.045 mmol, 1 equiv) and $NaHCO_3$ (1.0 mg, 0.011 mmol, 0.25 equiv) in MeOH/

CH_2Cl_2 (1:5, 2.6 mL) was cooled to –78 °C. Ozone was bubbled through the reaction mixture for 0.5 h, whereupon the reaction mixture was sparged with N_2 and dimethyl sulfide (0.10 mL, 0.14 mmol, 3 equiv) was added. The cooling bath was then removed and the reaction was stirred for 18 h at ambient temperature. The reaction mixture was concentrated under reduced pressure at 0 °C and the crude residue was purified by preparatory TLC (17% Et_2O/hexanes) to afford aldehyde **17** as a colorless oil (5.0 mg, 50% yield): $[\alpha]_D^{25}$ +9.1 (*c* 0.07, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.83 (s, 1H), 7.41 – 7.33 (m, 2H), 7.22 – 7.13 (m, 2H), 3.81 (s, 3H), 1.69 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 196.2, 171.8, 134.8, 134.5, 129.5, 128.5, 61.7, 53.1, 18.0; IR (Neat Film, NaCl) 2992, 2954, 2845, 2726, 1721, 1596, 1494, 1455, 1252, 1122, 1096, 1013, 911, 823, 758, 718 cm^{-1}; HRMS (FAB+) *m/z* calc'd for $C_{11}H_{12}ClO_3$ $[M+H]^+$: 227.0475, found 227.0479.

Crystal Structure Data for Carboxylic Acid 7h

Carboxylic acid **7h** was recrystallized by slow evaporation of CH_2Cl_2 to provide crystals suitable for X-ray analysis.

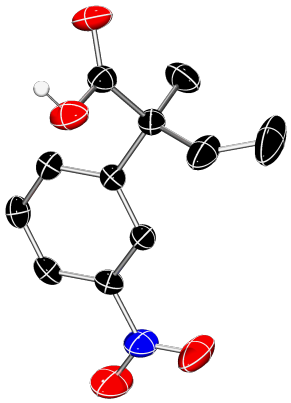


*Table S2. Crystal data and structure refinement for **7h**.*

Empirical formula	C11 H11 N O4	
Formula weight	221.21	
Temperature	200(2) K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	$P2_1$	
Unit cell dimensions	a = 7.3561(3) Å	a= 90°.
	b = 6.7600(3) Å	b= 94.5940(10)°.
	c = 10.9461(5) Å	g = 90°.
Volume	542.57(4) $Å^3$	
Z	2	
Density (calculated)	1.354 Mg/m^3	

Absorption coefficient	0.879 mm^{-1}
F(000)	232
Theta range for data collection	4.051 to 72.406°.
Index ranges	-9<=h<=9, -8<=k<=8, -13<=l<=13
Reflections collected	24109
Independent reflections	2132 [R(int) = 0.0427]
Completeness to theta = 67.679°	100.0 %
Absorption correction	Semi-empirical from equivalents
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2132 / 1 / 146
Goodness-of-fit on F^2	1.315
Final R indices [I>2sigma(I)]	R1 = 0.0495, wR2 = 0.1336
R indices (all data)	R1 = 0.0497, wR2 = 0.1346
Absolute structure parameter	0.08(5)
Extinction coefficient	n/a
Largest diff. peak and hole	0.312 and -0.539 $e.Å^{-3}$

Table S3. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for ***7h****. U(eq) is defined as one third of the trace of the orthogonalized* U^{ij} *tensor.*

	x	y	z	U(eq)
C(1)	6927(3)	5263(3)	4602(2)	32(1)
C(2)	7734(2)	5232(3)	5795(2)	30(1)
C(3)	6640(2)	5267(3)	6762(2)	27(1)
C(4)	4752(2)	5328(3)	6510(2)	33(1)
C(5)	3969(2)	5364(3)	5309(2)	35(1)
C(6)	5062(3)	5332(3)	4329(2)	34(1)
C(7)	7495(2)	5394(3)	8089(2)	33(1)
C(8)	7573(4)	7595(4)	8448(2)	52(1)
C(9)	9331(3)	4360(5)	8210(2)	51(1)
C(10)	10884(3)	5180(9)	8624(2)	86(2)
C(11)	6291(2)	4290(3)	8935(2)	33(1)
O(1)	6125(2)	2390(3)	8666(1)	46(1)
O(2)	5572(2)	5042(3)	9776(1)	49(1)
N(1)	8117(3)	5216(4)	3590(2)	47(1)
O(3)	9753(2)	5210(6)	3825(2)	84(1)
O(4)	7426(3)	5157(6)	2546(2)	81(1)

*Table S4. Bond lengths [Å] and angles [°] for **7h**.*

C(1)-C(6)	1.381(3)
C(1)-C(2)	1.390(2)
C(1)-N(1)	1.466(3)
C(2)-C(3)	1.380(2)
C(3)-C(4)	1.395(2)
C(3)-C(7)	1.538(2)
C(4)-C(5)	1.392(3)
C(5)-C(6)	1.391(3)
C(7)-C(9)	1.517(3)
C(7)-C(11)	1.527(2)
C(7)-C(8)	1.539(3)
C(9)-C(10)	1.318(4)
C(11)-O(2)	1.210(2)
C(11)-O(1)	1.321(3)
N(1)-O(3)	1.210(3)
N(1)-O(4)	1.214(3)
C(6)-C(1)-C(2)	123.08(18)
C(6)-C(1)-N(1)	118.68(17)
C(2)-C(1)-N(1)	118.25(17)
C(3)-C(2)-C(1)	119.26(16)
C(2)-C(3)-C(4)	118.74(16)
C(2)-C(3)-C(7)	120.38(14)
C(4)-C(3)-C(7)	120.72(15)
C(5)-C(4)-C(3)	121.17(17)
C(6)-C(5)-C(4)	120.45(17)
C(1)-C(6)-C(5)	117.31(17)
C(9)-C(7)-C(11)	106.08(18)
C(9)-C(7)-C(3)	110.51(16)
C(11)-C(7)-C(3)	109.42(14)
C(9)-C(7)-C(8)	114.1(2)
C(11)-C(7)-C(8)	109.22(15)
C(3)-C(7)-C(8)	107.45(17)
C(10)-C(9)-C(7)	125.3(4)

O(2)-C(11)-O(1)	122.7(2)
O(2)-C(11)-C(7)	124.49(19)
O(1)-C(11)-C(7)	112.85(17)
O(3)-N(1)-O(4)	122.26(19)
O(3)-N(1)-C(1)	118.91(17)
O(4)-N(1)-C(1)	118.82(19)

Table S5. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for ***7h****. The anisotropic displacement factor exponent takes the form: $-2p^2[\ h^2\ a^{*2}U^{11} + \ldots + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$*

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
C(1)	38(1)	32(1)	26(1)	-1(1)	2(1)	1(1)
C(2)	29(1)	34(1)	28(1)	0(1)	1(1)	0(1)
C(3)	30(1)	25(1)	27(1)	1(1)	1(1)	-1(1)
C(4)	30(1)	34(1)	35(1)	1(1)	4(1)	1(1)
C(5)	29(1)	34(1)	41(1)	3(1)	-5(1)	-1(1)
C(6)	40(1)	28(1)	32(1)	-2(1)	-8(1)	1(1)
C(7)	31(1)	42(1)	26(1)	0(1)	3(1)	-4(1)
C(8)	72(2)	48(1)	36(1)	-7(1)	6(1)	-24(1)
C(9)	33(1)	91(2)	30(1)	16(1)	4(1)	5(1)
C(10)	32(1)	176(5)	49(1)	35(2)	-6(1)	-14(2)
C(11)	33(1)	39(1)	26(1)	2(1)	1(1)	2(1)
O(1)	62(1)	37(1)	42(1)	0(1)	22(1)	-4(1)
O(2)	60(1)	51(1)	38(1)	-7(1)	22(1)	5(1)
N(1)	50(1)	67(1)	26(1)	2(1)	4(1)	5(1)
O(3)	40(1)	176(3)	36(1)	0(1)	9(1)	5(1)
O(4)	66(1)	151(3)	25(1)	-7(1)	-1(1)	12(1)

*Table S6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **7h**.*

	x	y	z	U(eq)
H(2)	9023	5188	5942	36
H(4)	3987	5347	7168	40
H(5)	2680	5410	5158	42
H(6)	4546	5355	3505	40
H(8A)	8291	8322	7880	78
H(8B)	8145	7730	9284	78
H(8C)	6333	8135	8410	78
H(9)	9363	3012	7967	62
H(10A)	10911	6525	8877	103
H(10B)	11978	4427	8671	103
H(1)	5466	1842	9160	69

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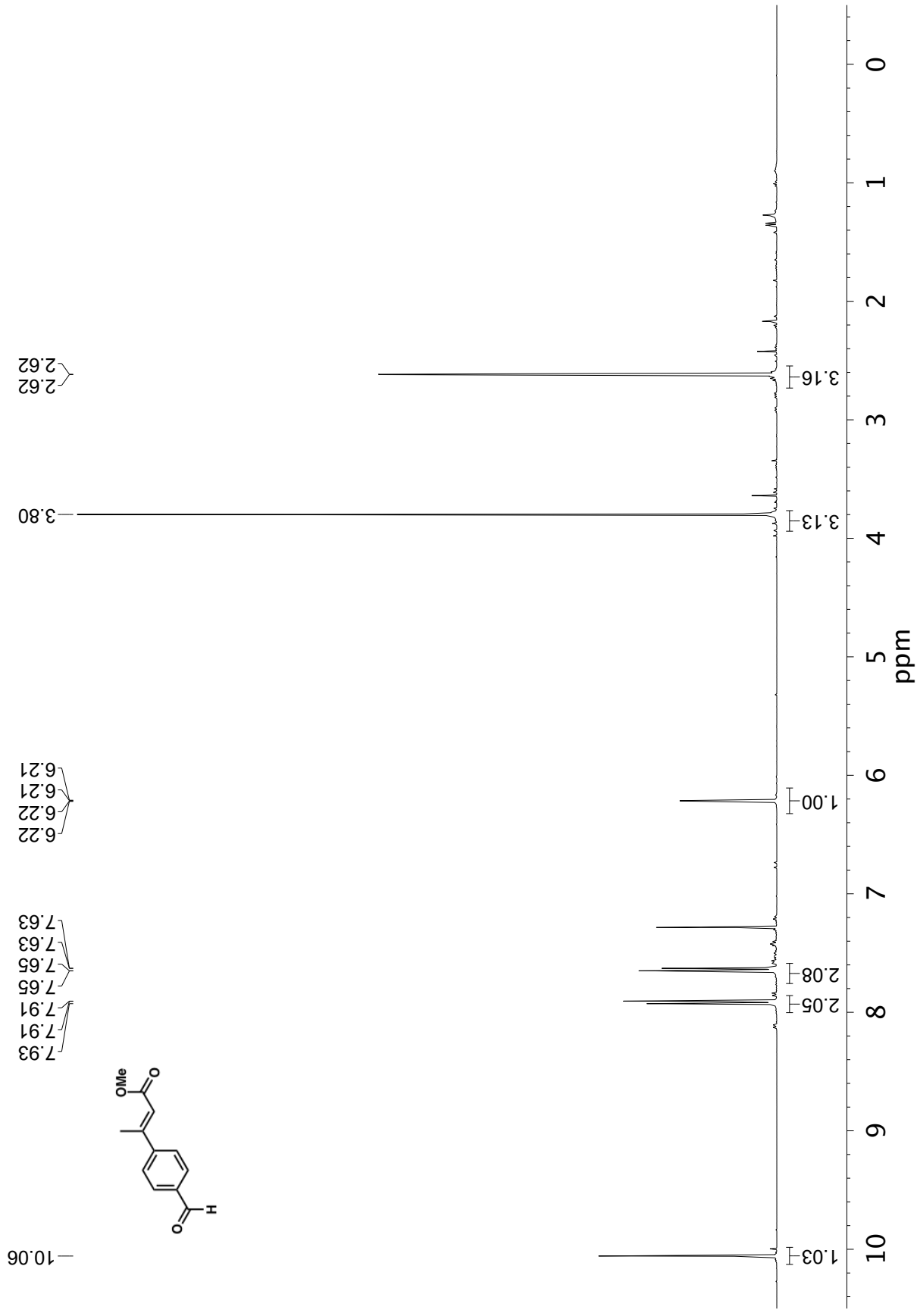
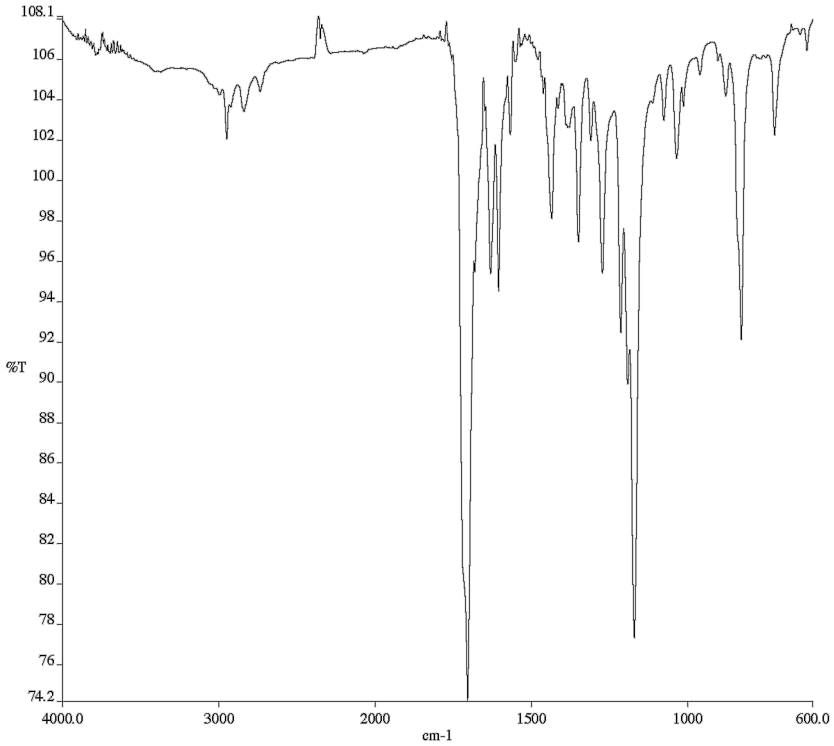
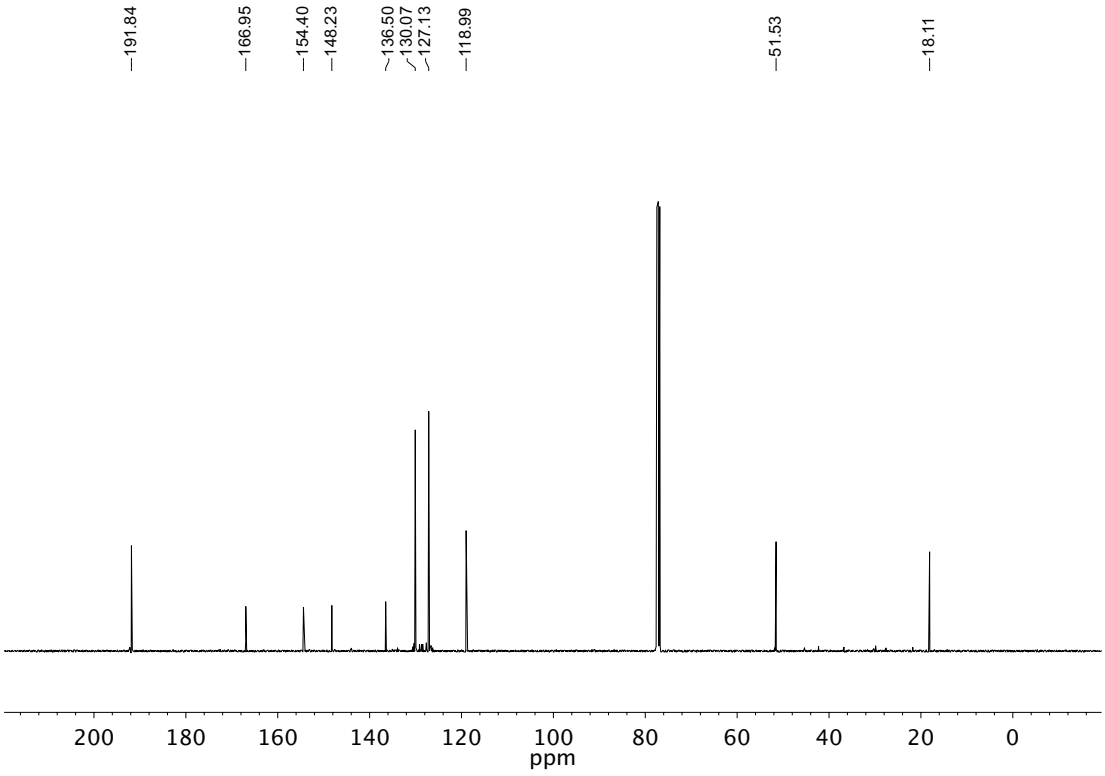


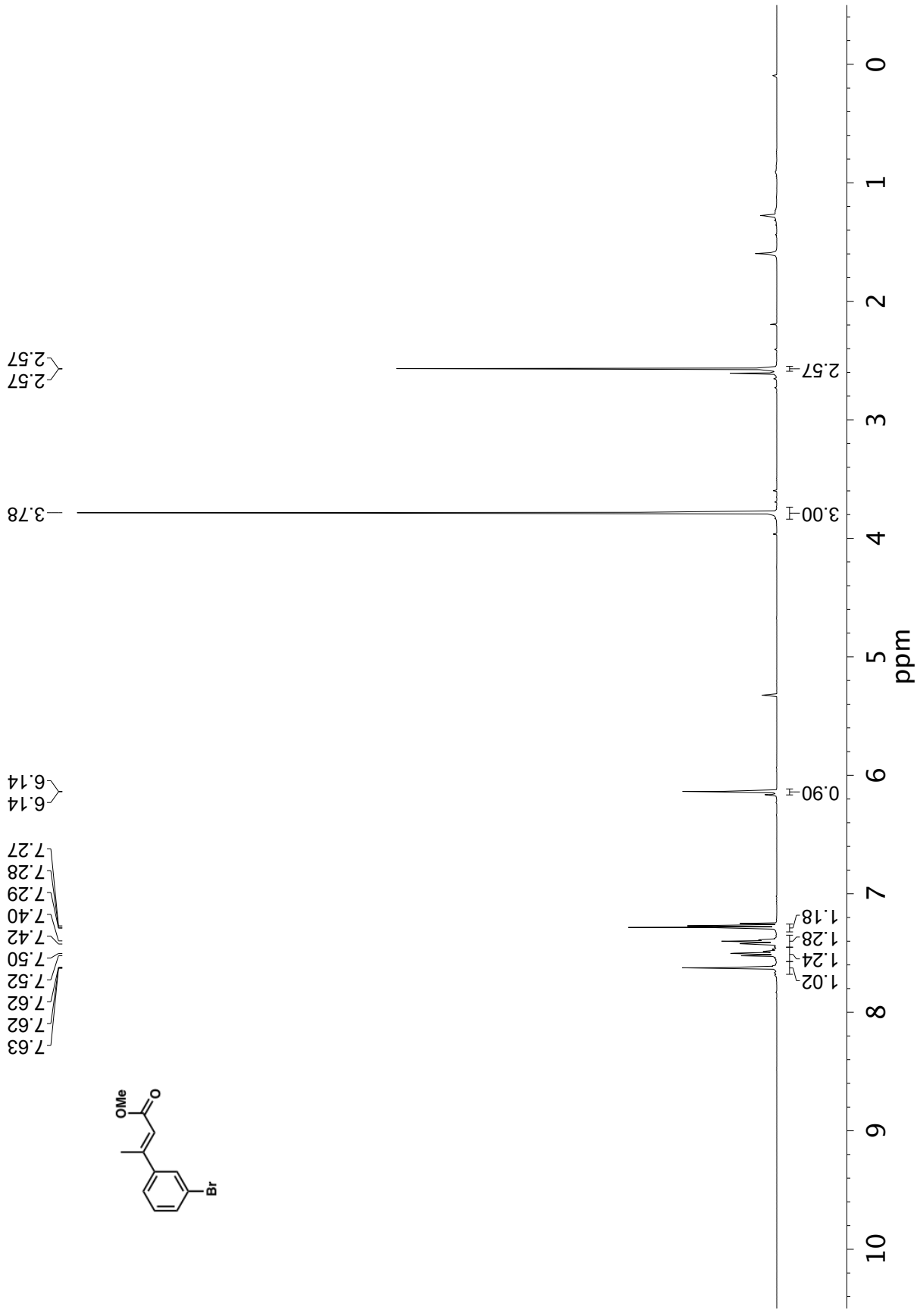
^{1}H NMR (400 MHz, $CDCl_3$) of compound **SI-1**.



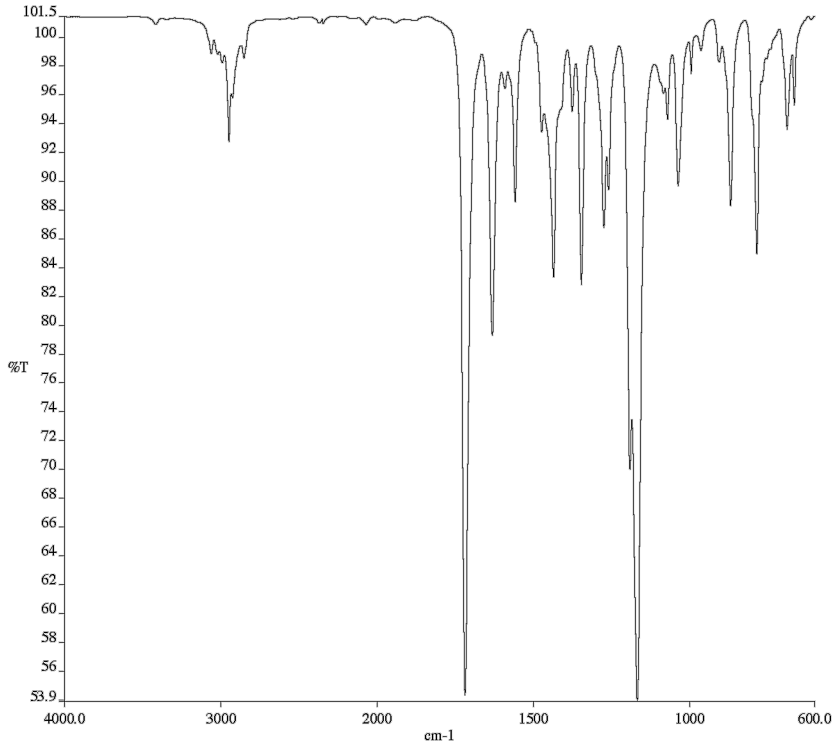
Infrared spectrum (Thin Film, NaCl) of compound **SI-1**.



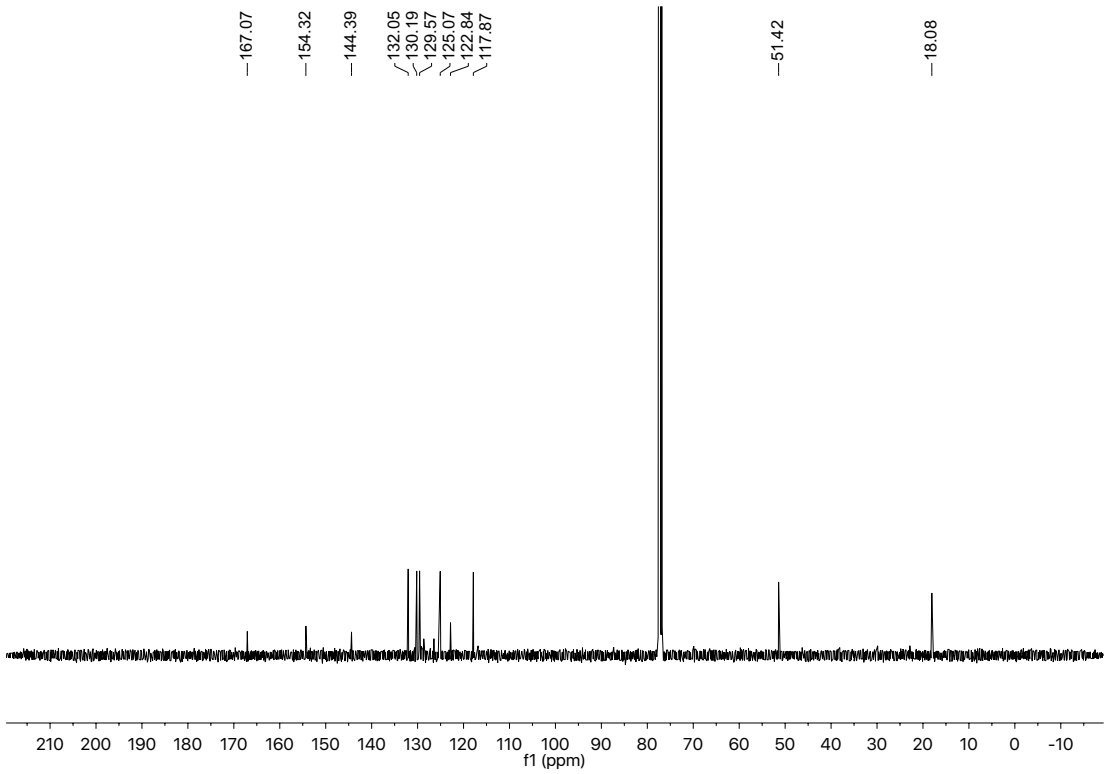
^{13}C NMR (101 MHz, $CDCl_3$) of compound **S1-1**.



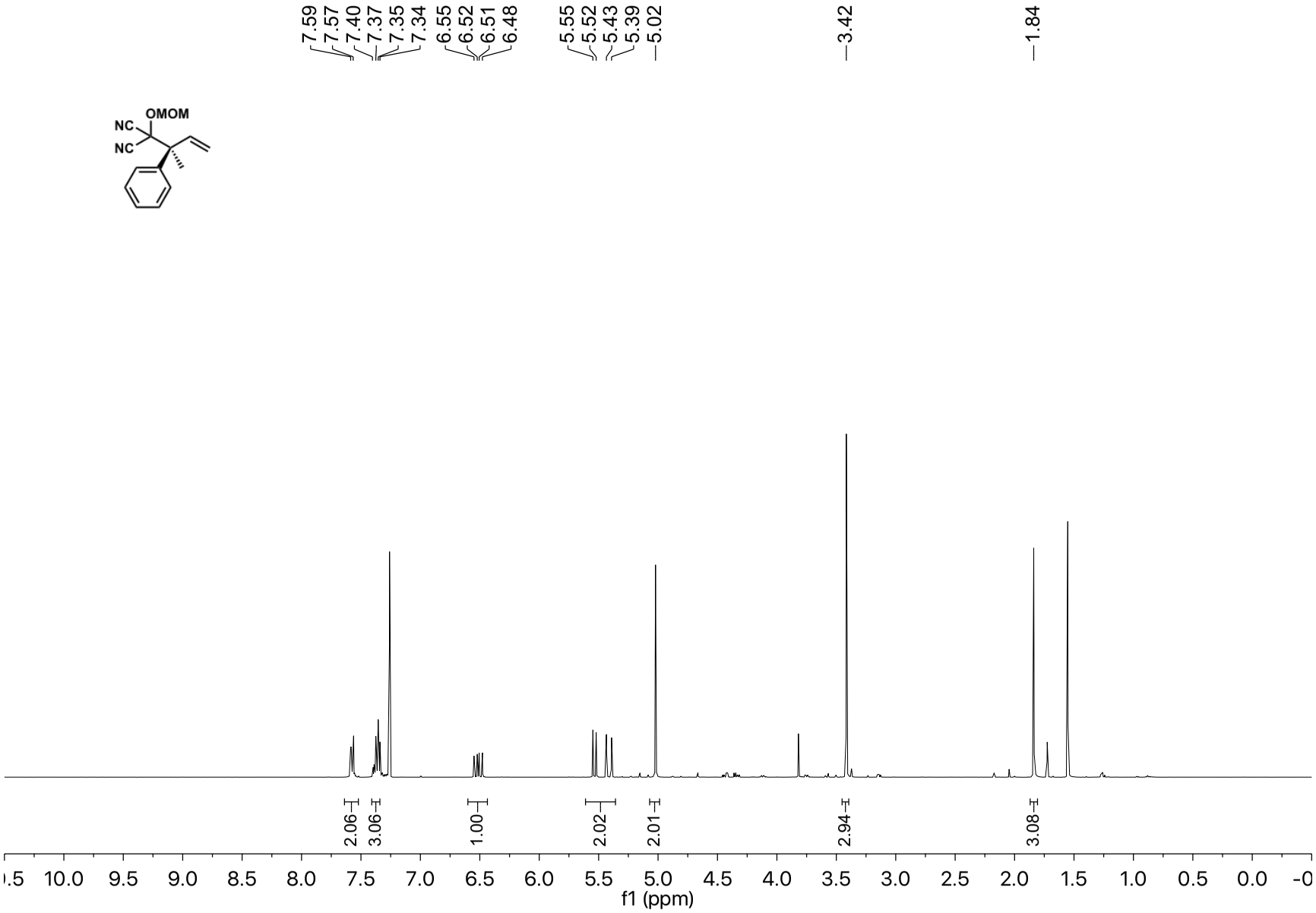
^{1}H NMR (400 MHz, $CDCl_3$) of compound **SI-2**.



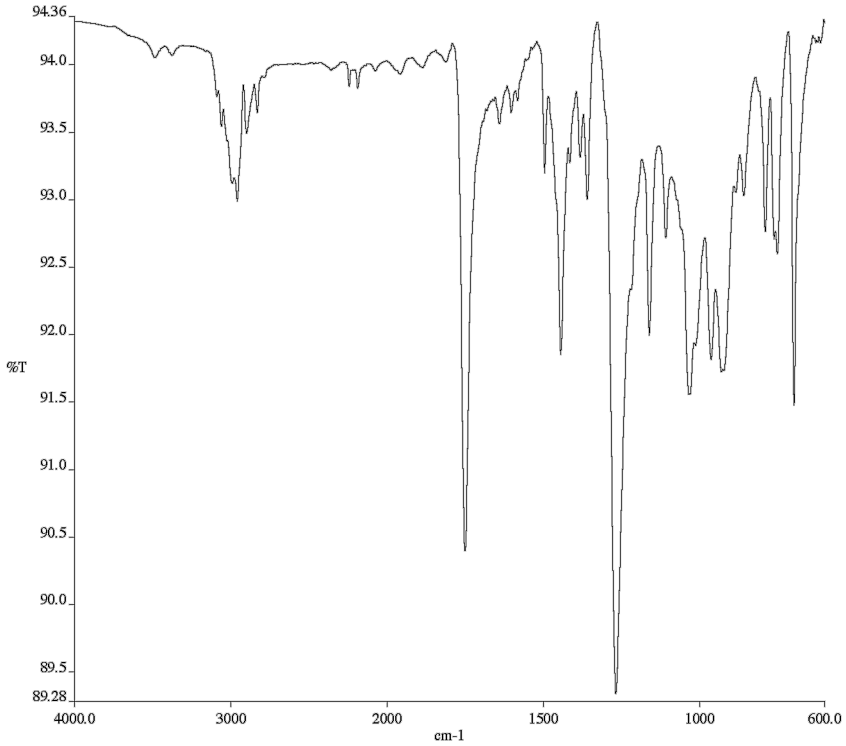
Infrared spectrum (Thin Film, NaCl) of compound **SI-2**.



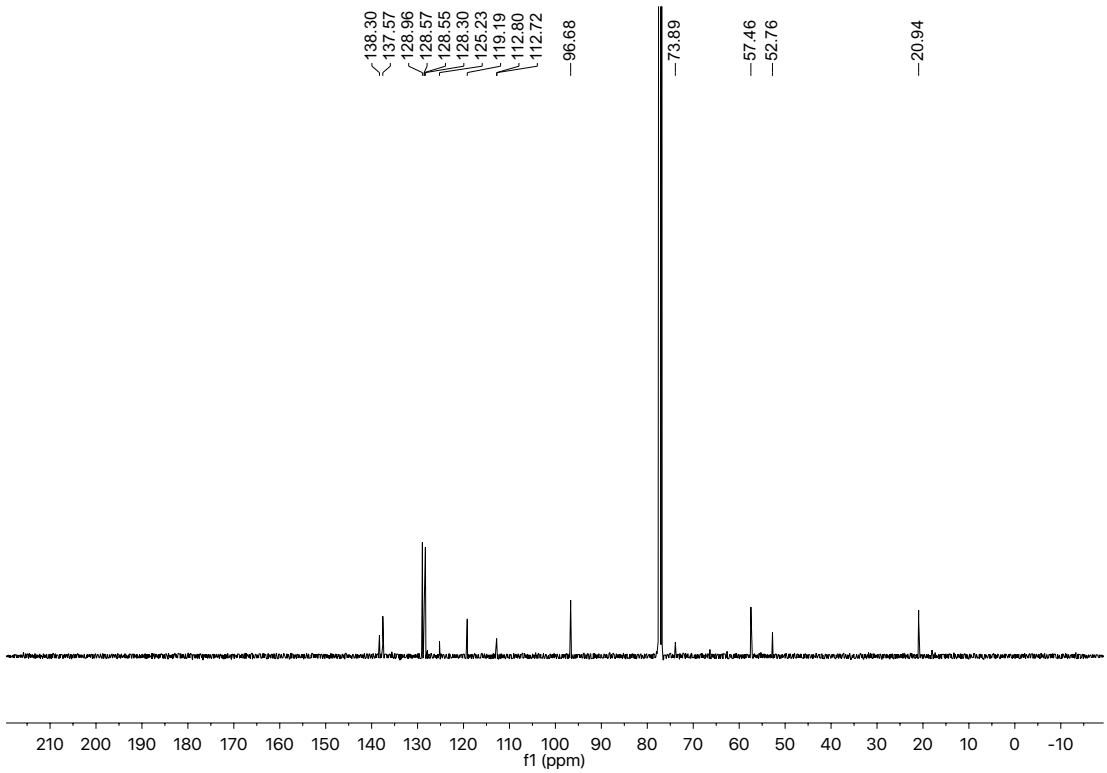
^{13}C NMR (101 MHz, $CDCl_3$) of compound **S1-2**.



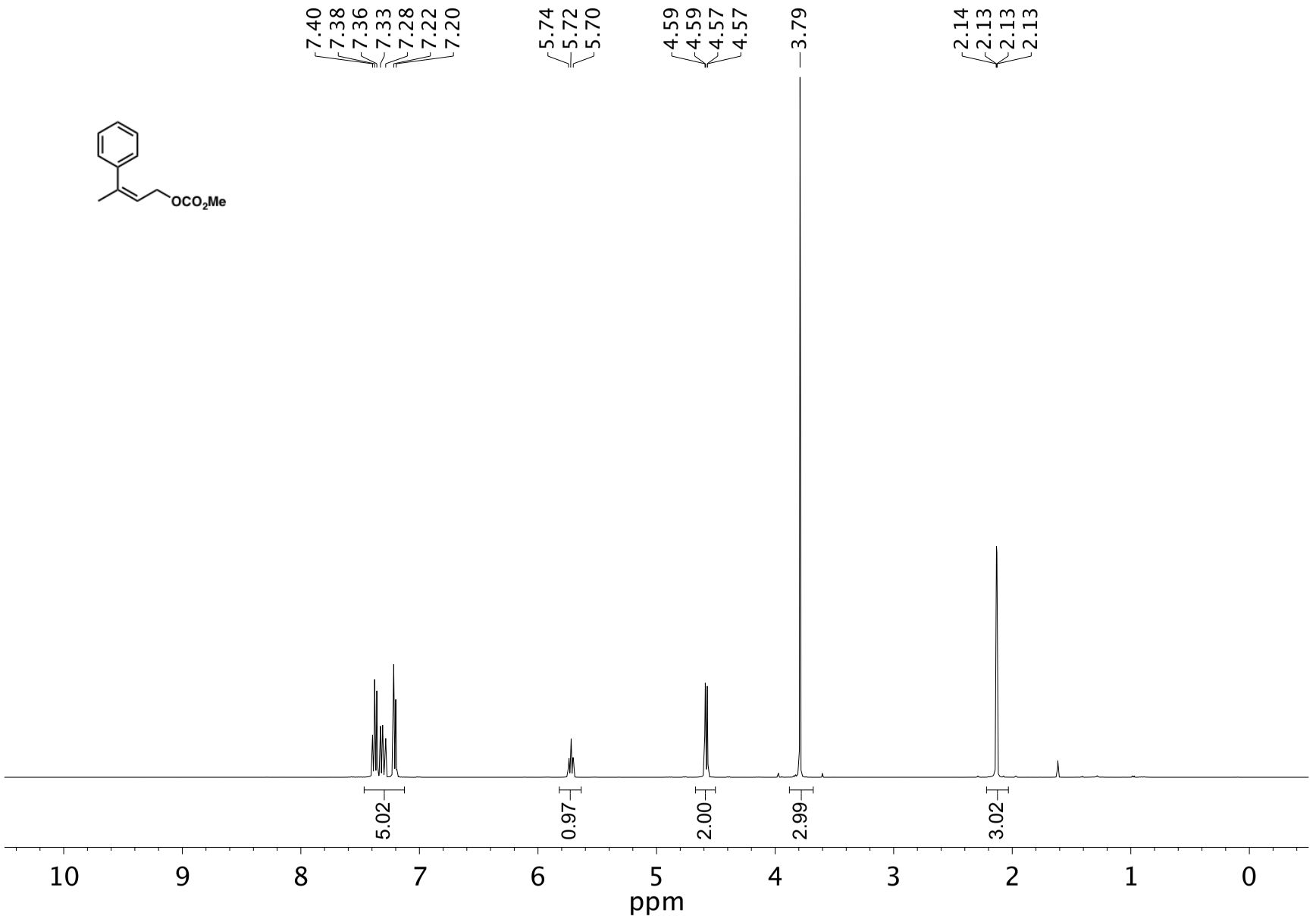
^{1}H NMR (400 MHz, $CDCl_3$) of compound **3**.



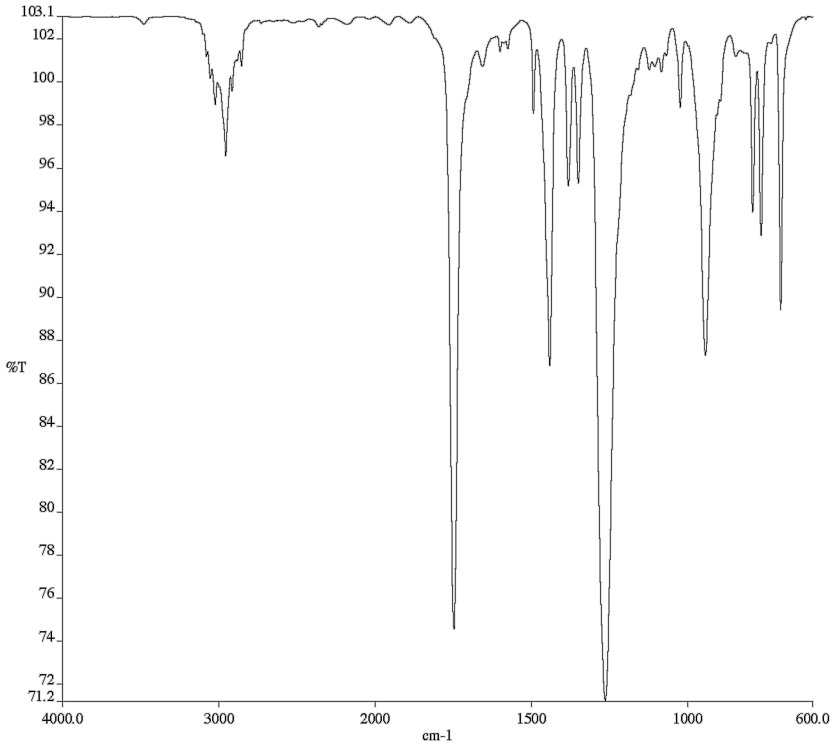
Infrared spectrum (Thin Film, NaCl) of compound **3**.



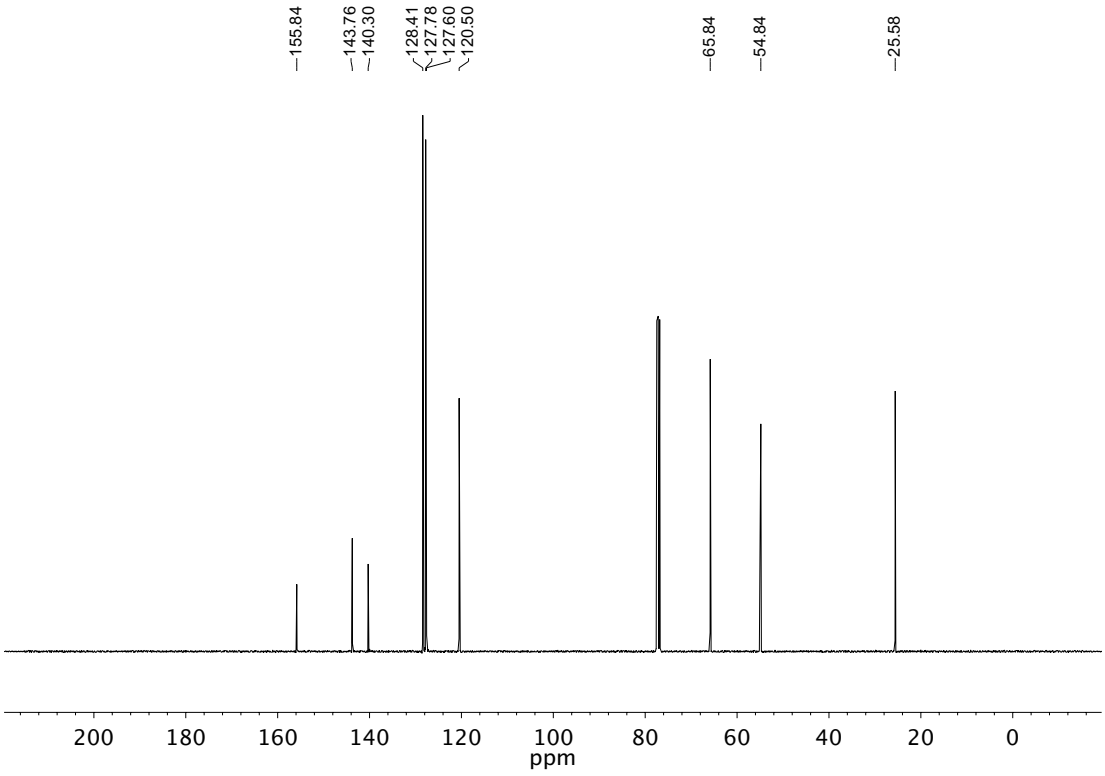
^{13}C NMR (101 MHz, $CDCl_3$) of compound **3**.



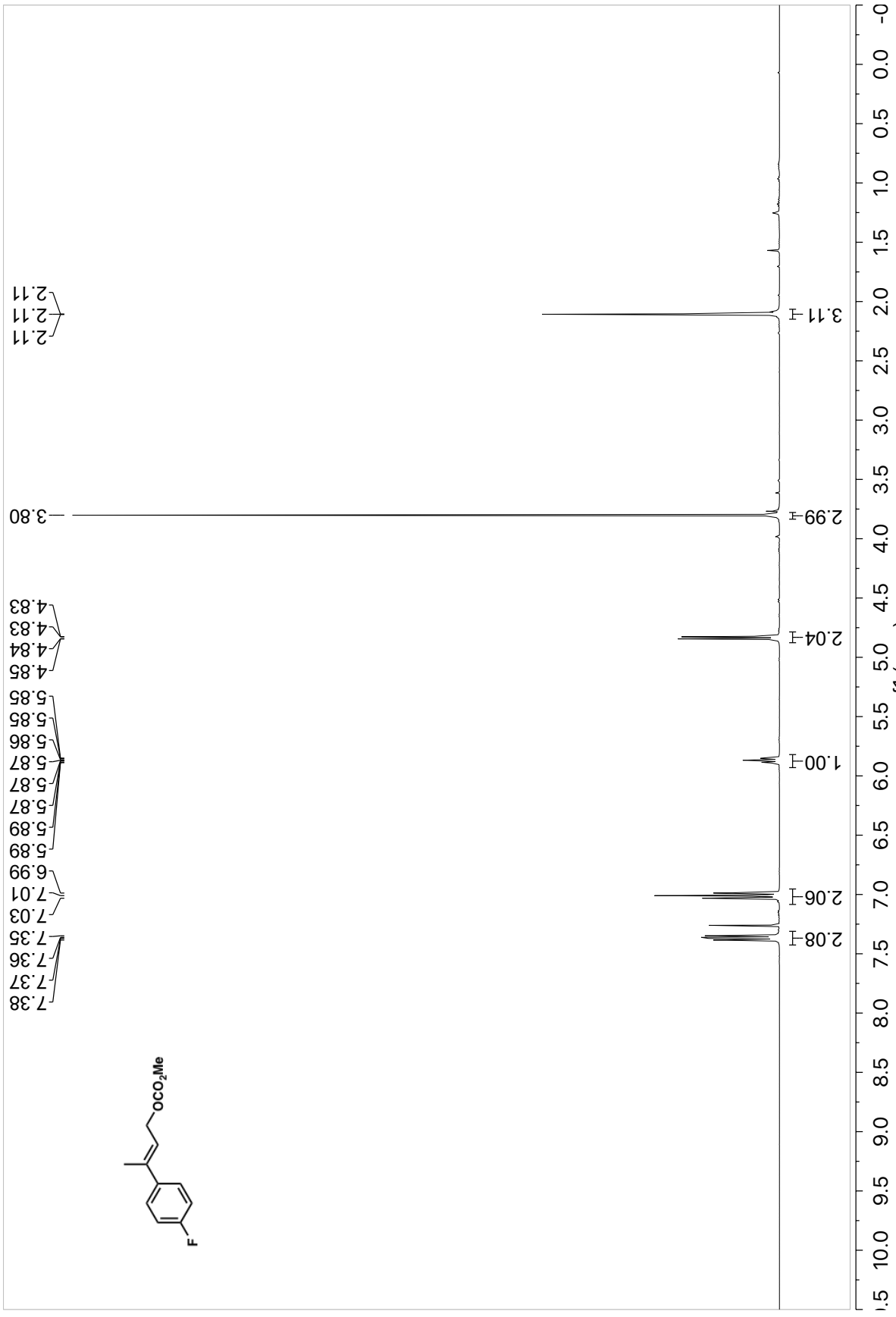
^{1}H NMR (400 MHz, $CDCl_3$) of compound **4**.



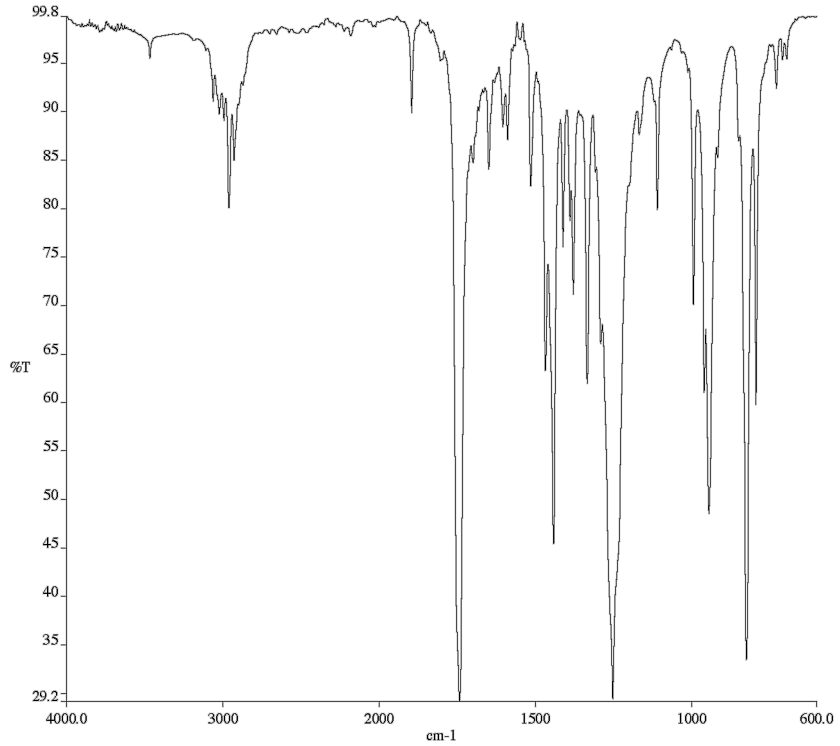
Infrared spectrum (Thin Film, NaCl) of compound **4**.



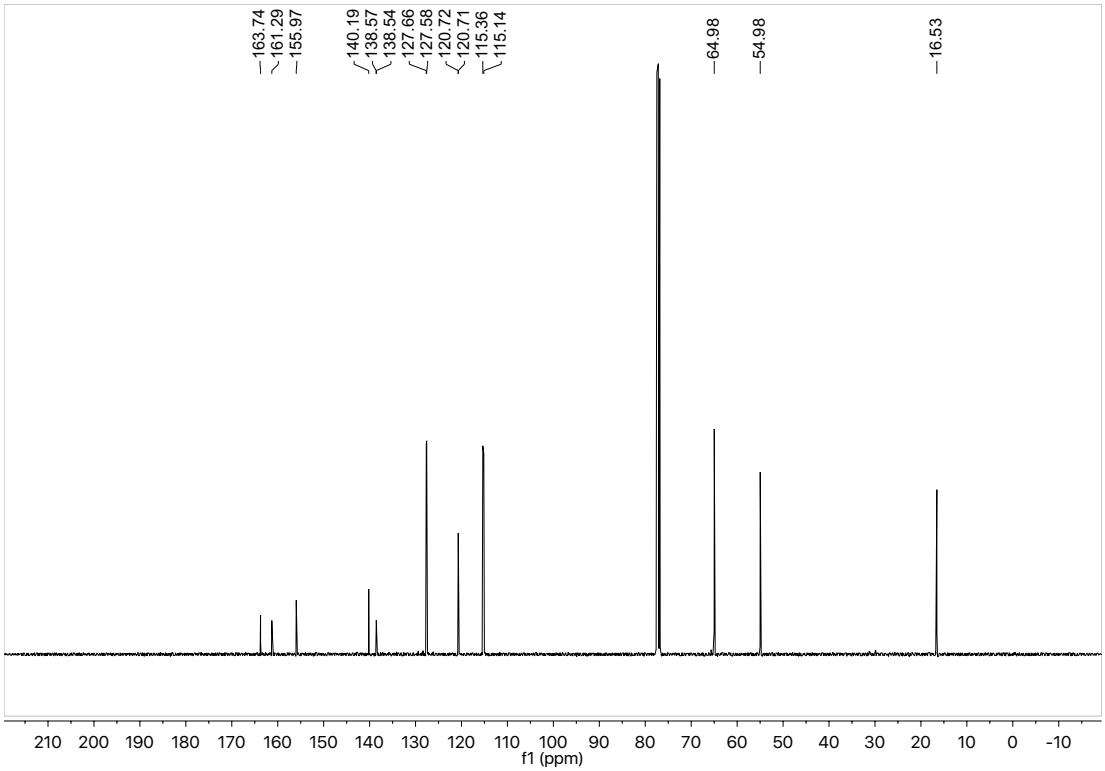
^{13}C NMR (101 MHz, $CDCl_3$) of compound **4**.



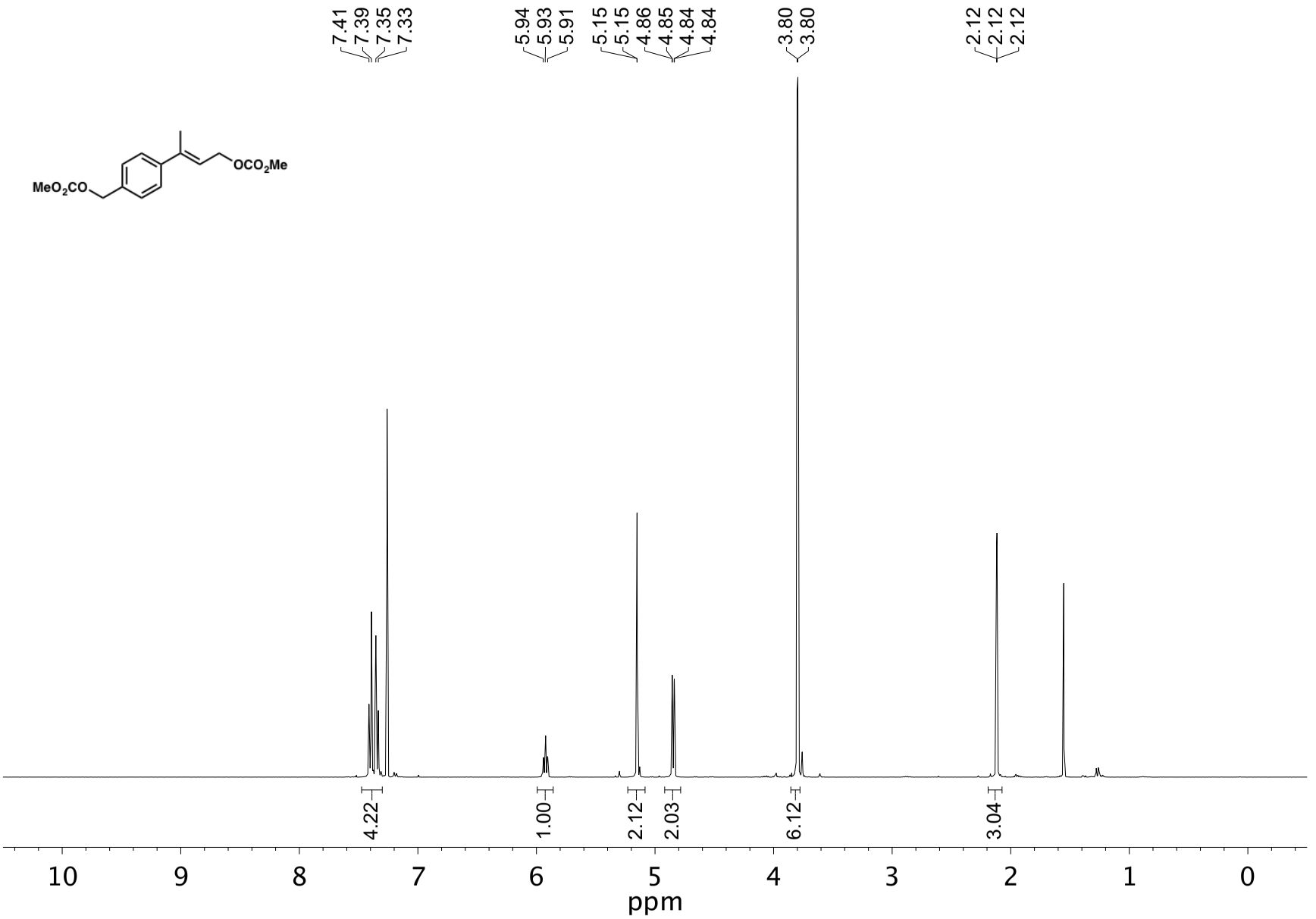
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6c**.



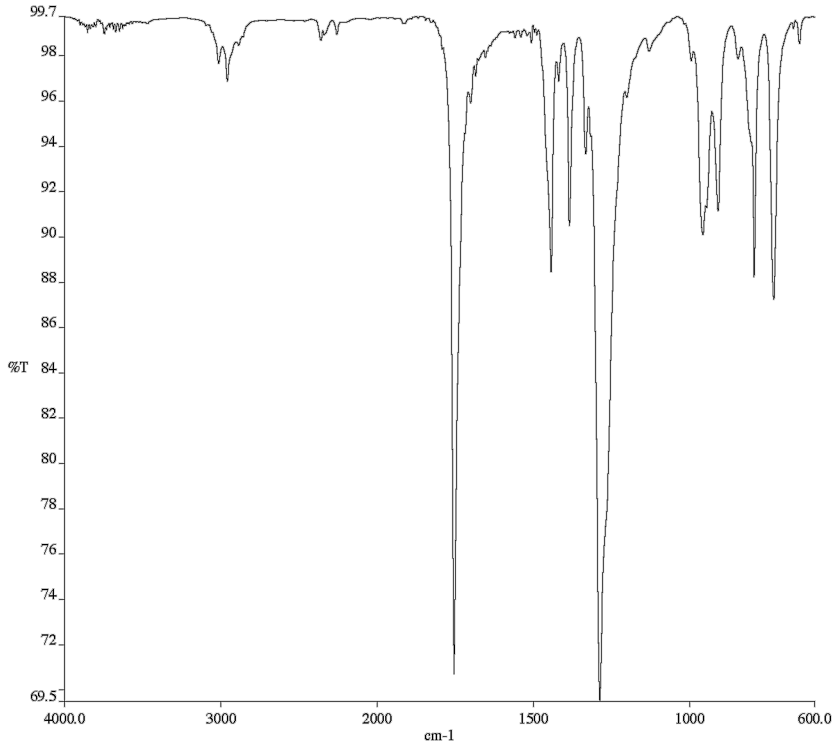
Infrared spectrum (Thin Film, NaCl) of compound **6c**.



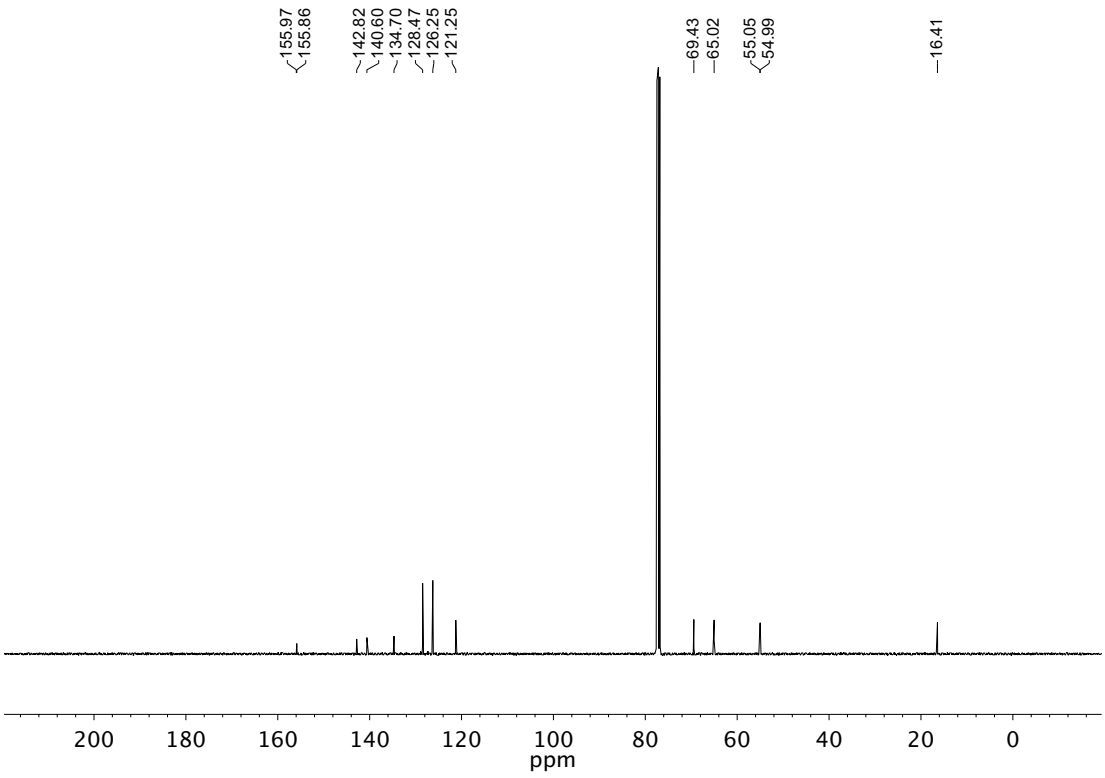
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6c**.



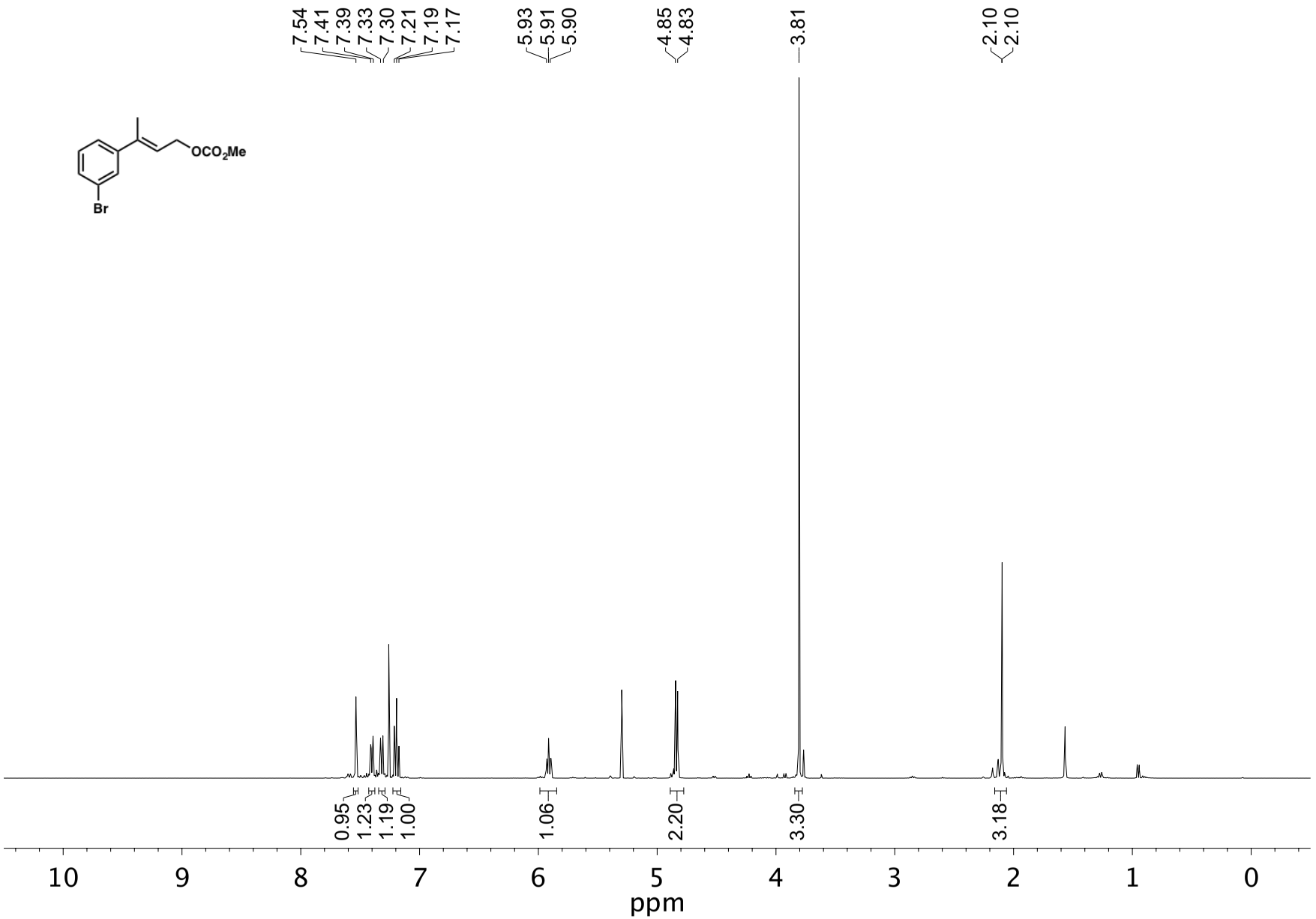
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6f**.



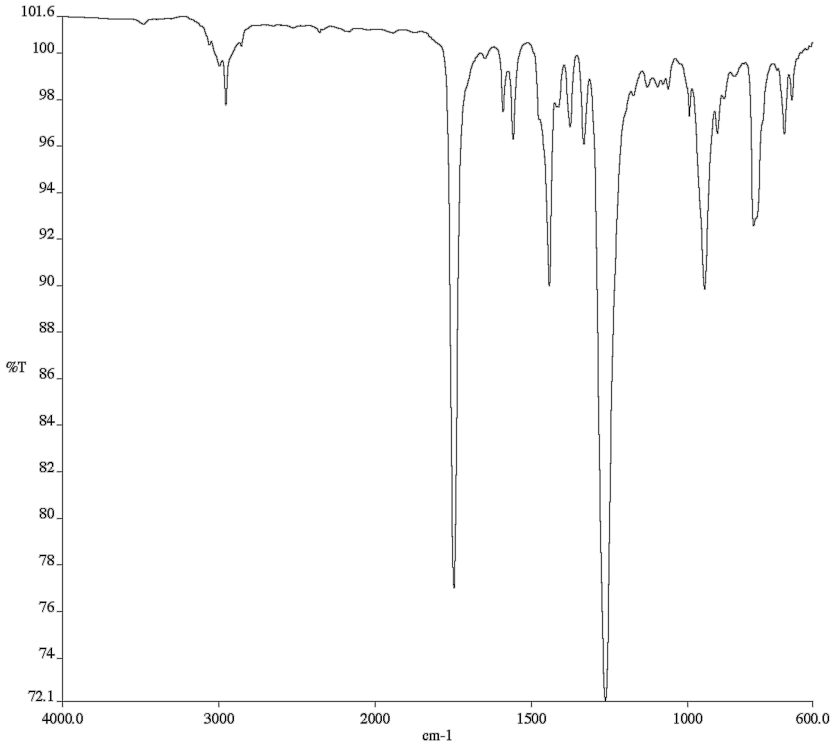
Infrared spectrum (Thin Film, NaCl) of compound **6f**.



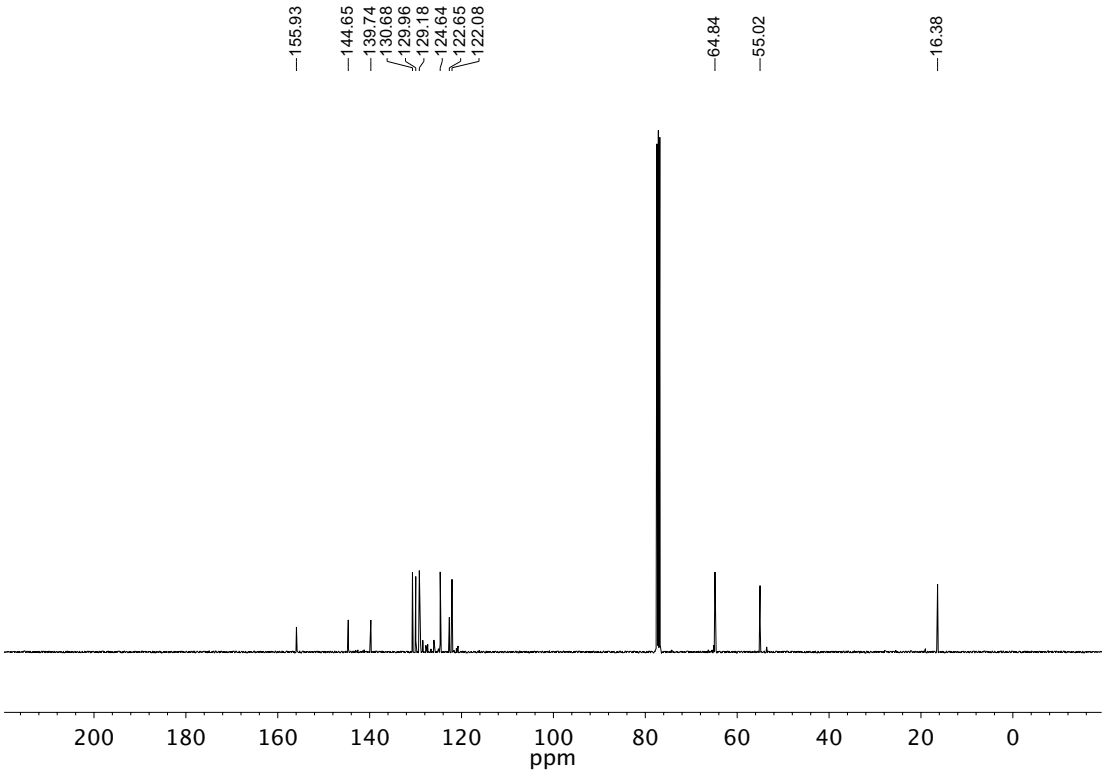
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6f**.



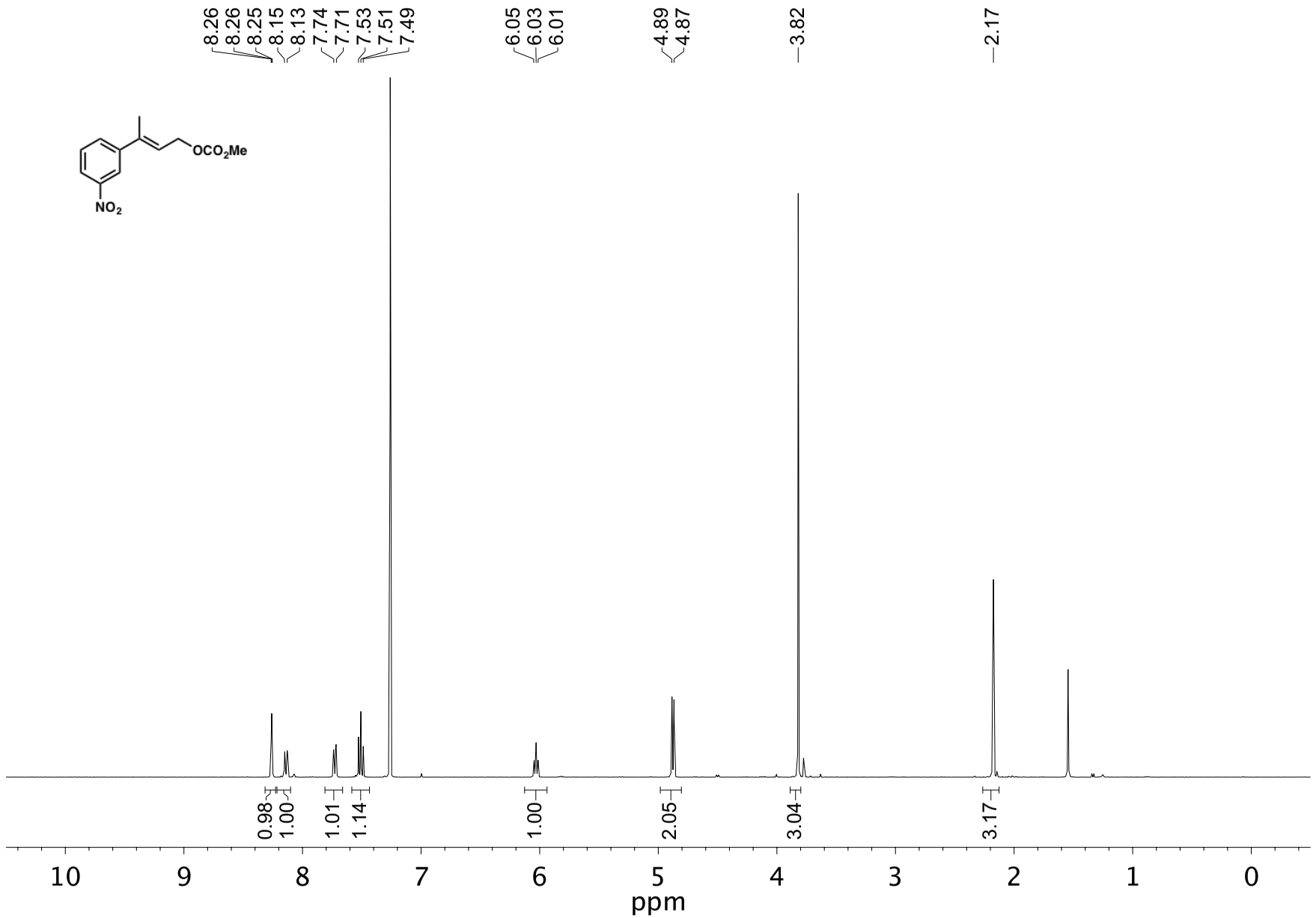
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6g**.



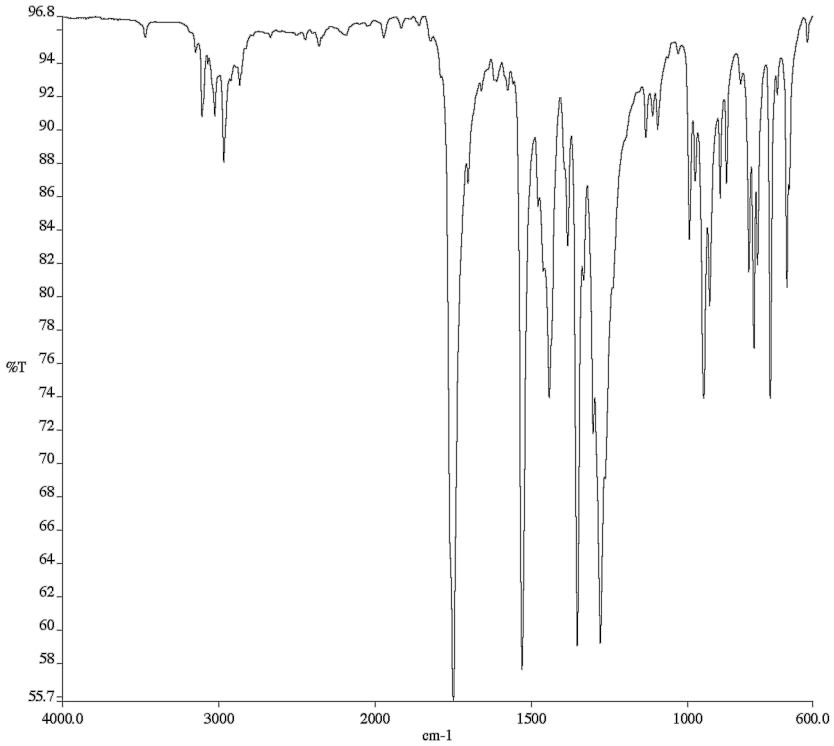
Infrared spectrum (Thin Film, NaCl) of compound **6g**.



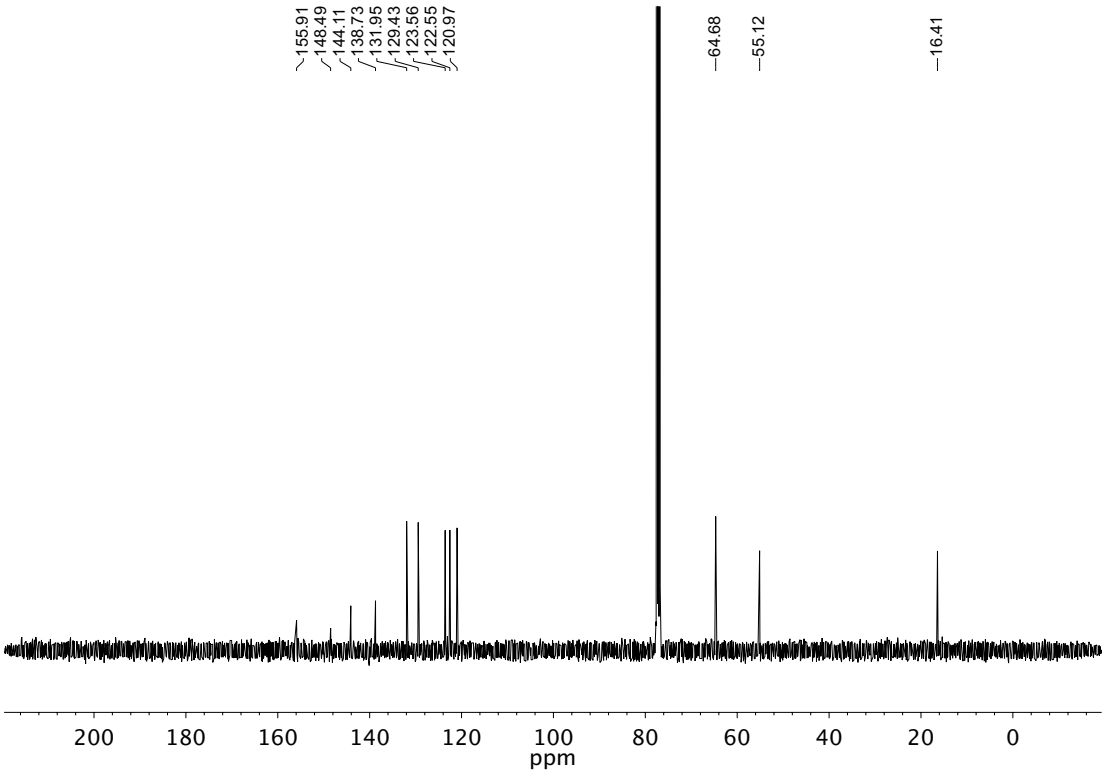
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6g**.



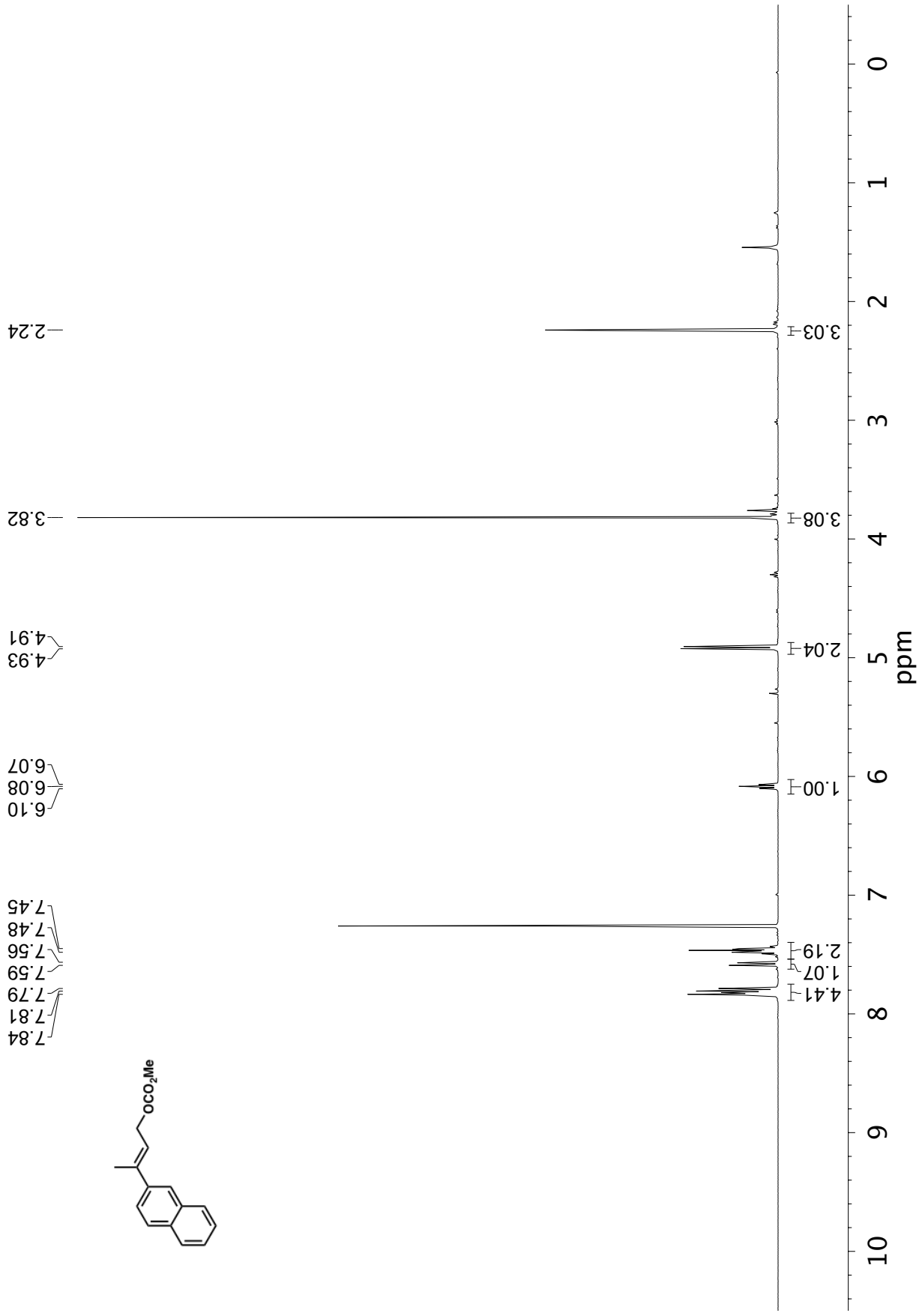
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6h**.



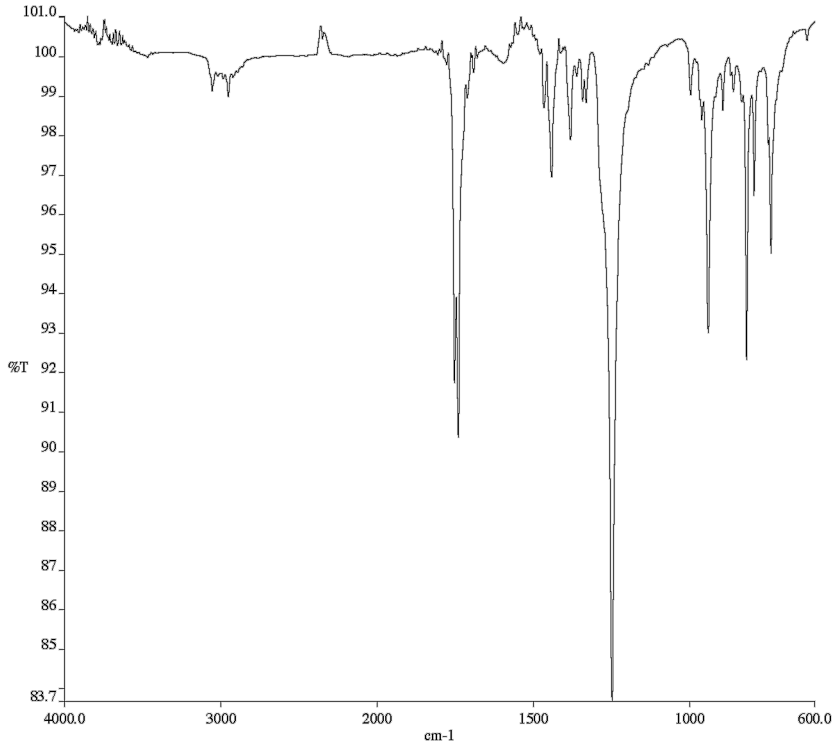
Infrared spectrum (Thin Film, NaCl) of compound **6h**.



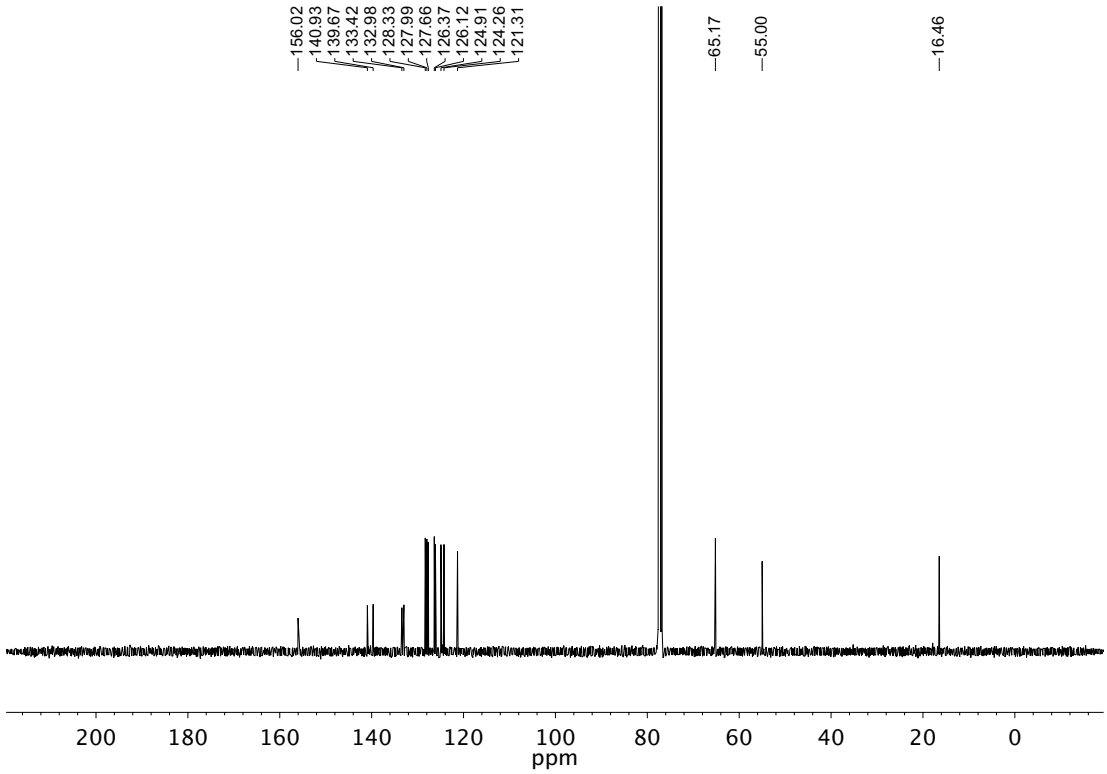
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6h**.



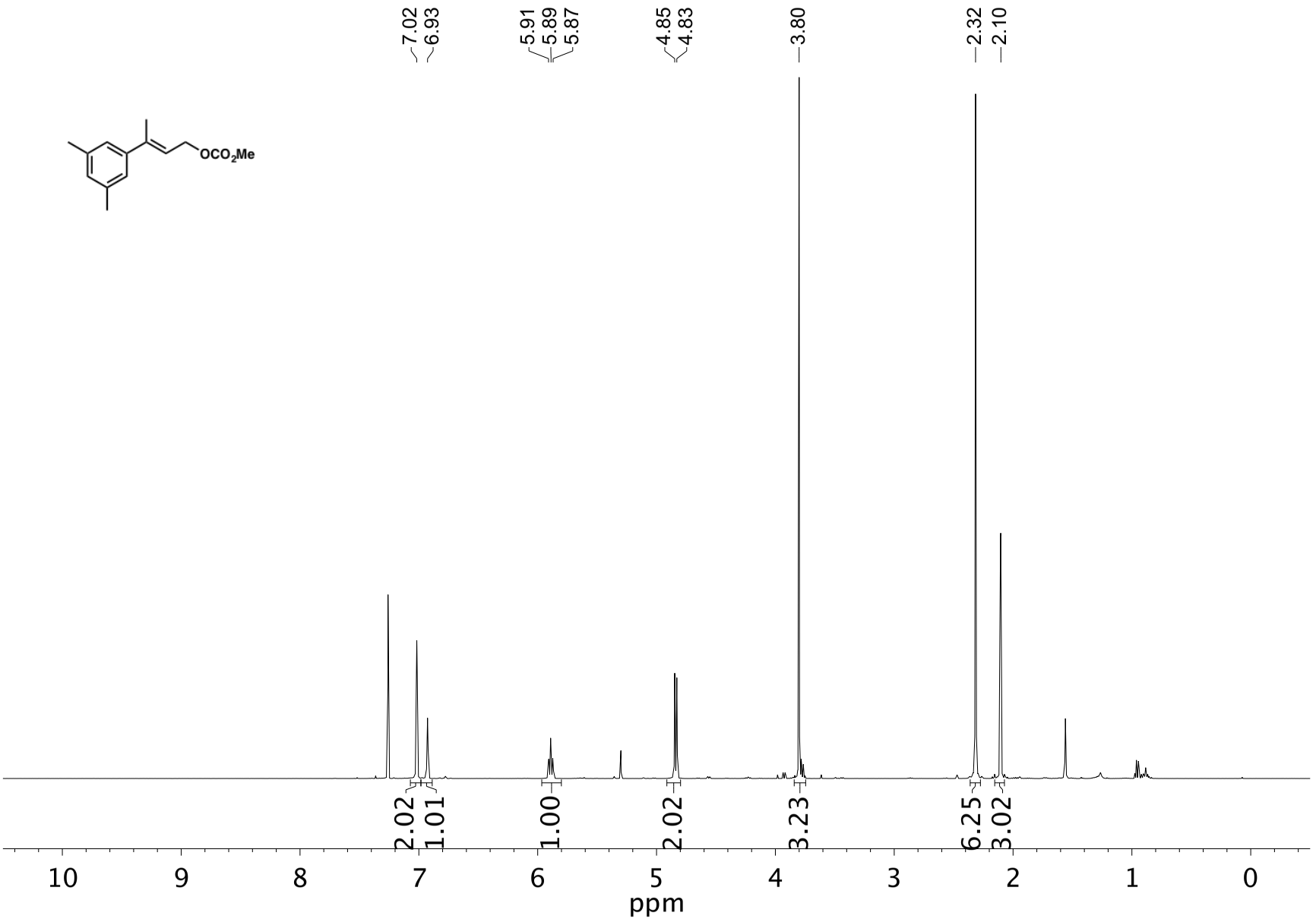
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6i**.



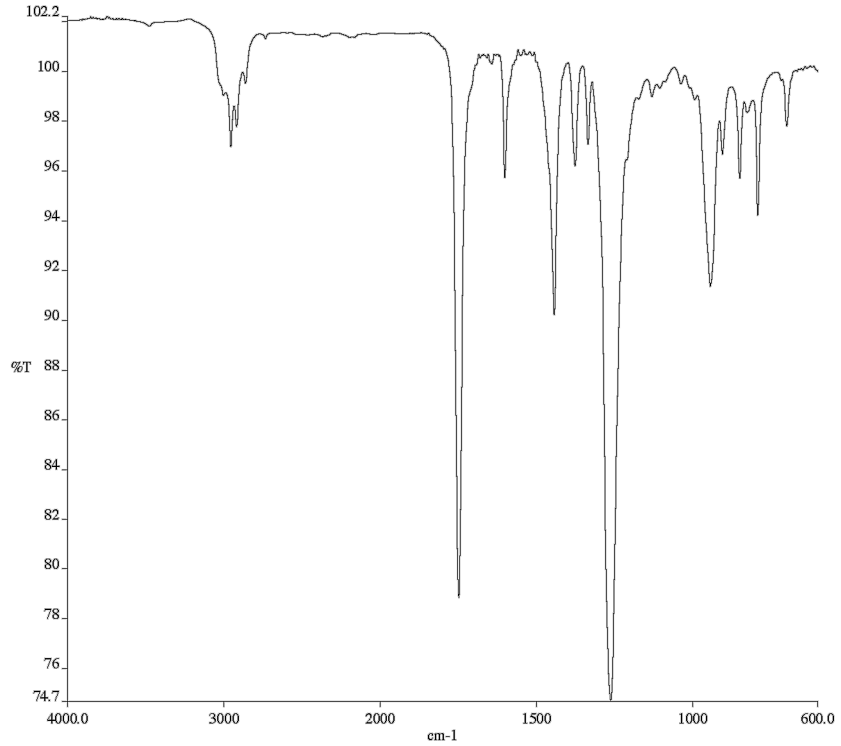
Infrared spectrum (Thin Film, NaCl) of compound **6i**.



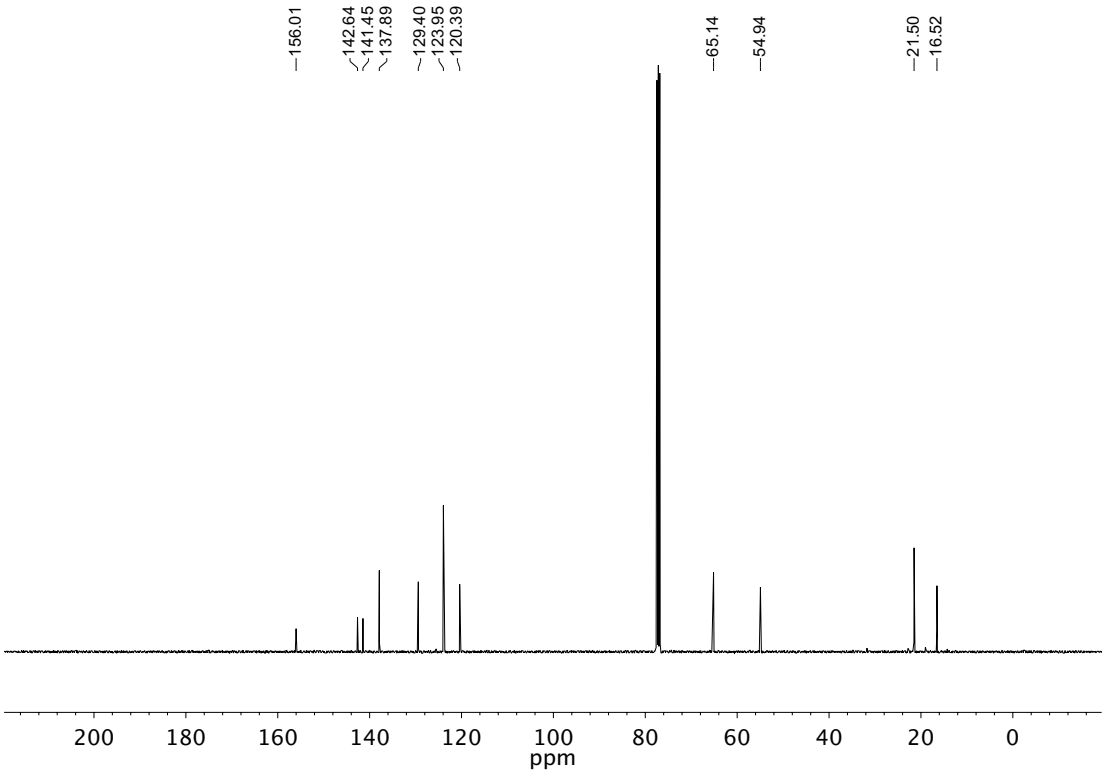
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6i**.



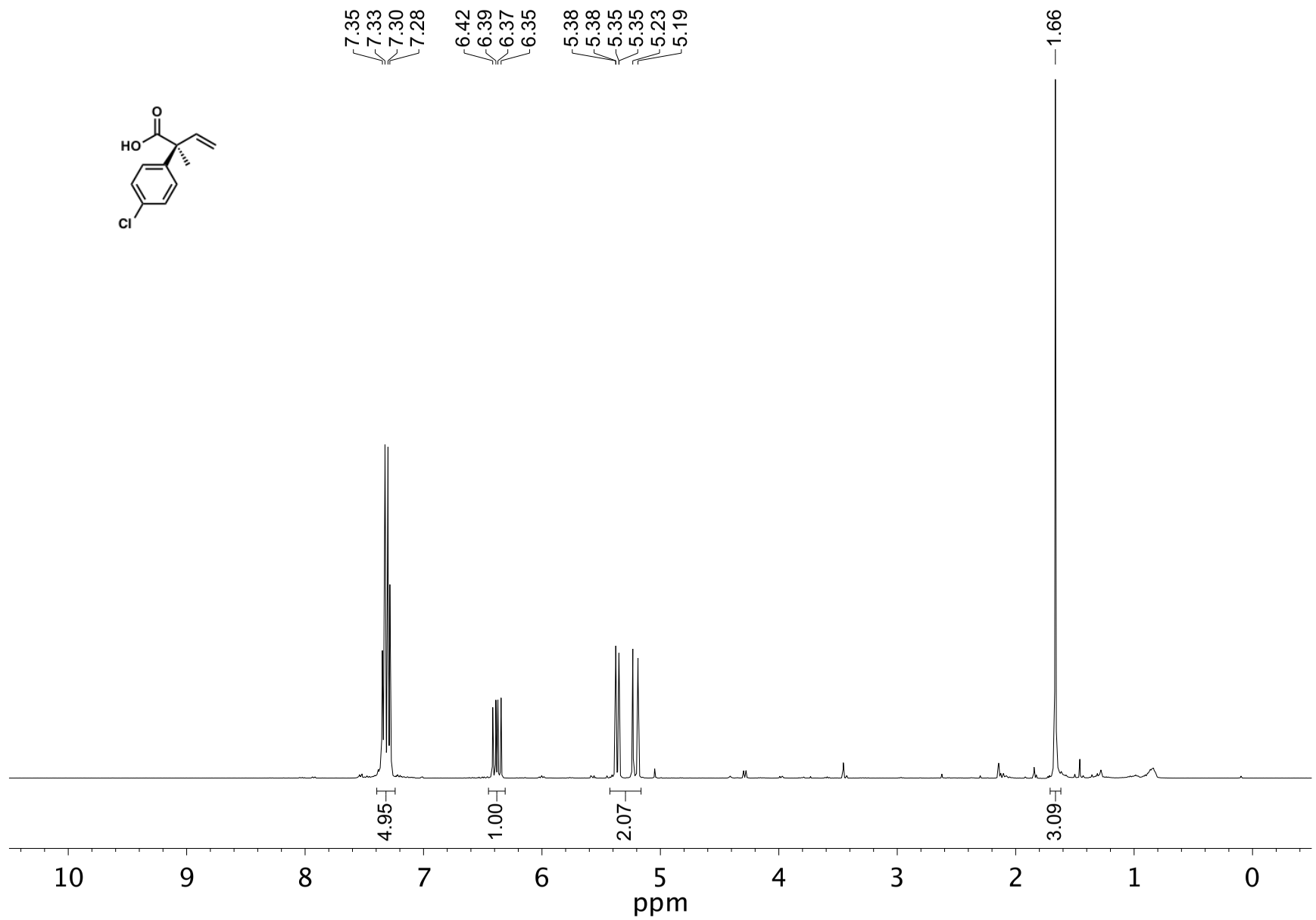
^{1}H NMR (400 MHz, $CDCl_3$) of compound **6k**.



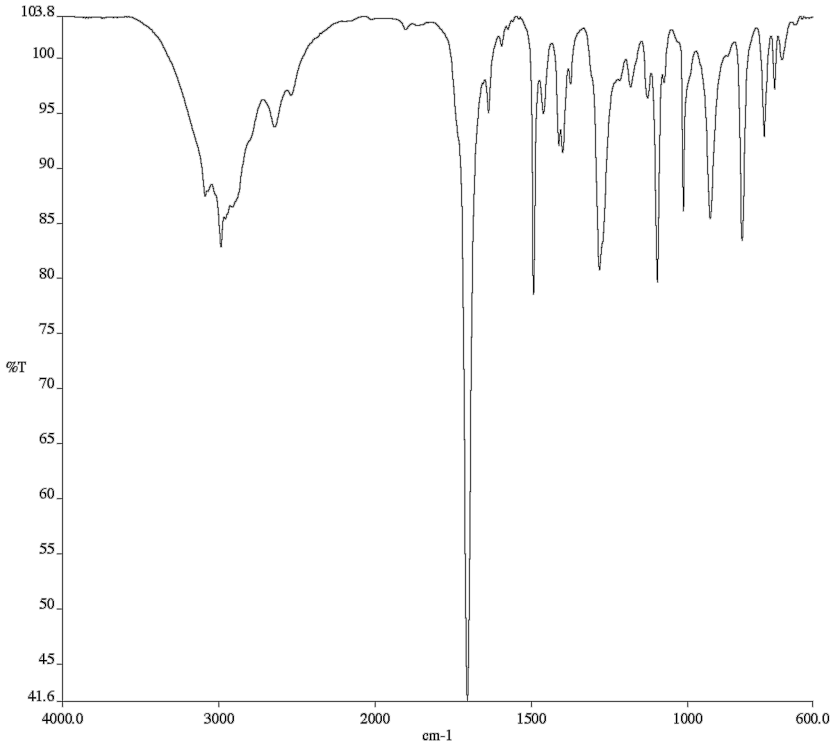
Infrared spectrum (Thin Film, NaCl) of compound **6k**.



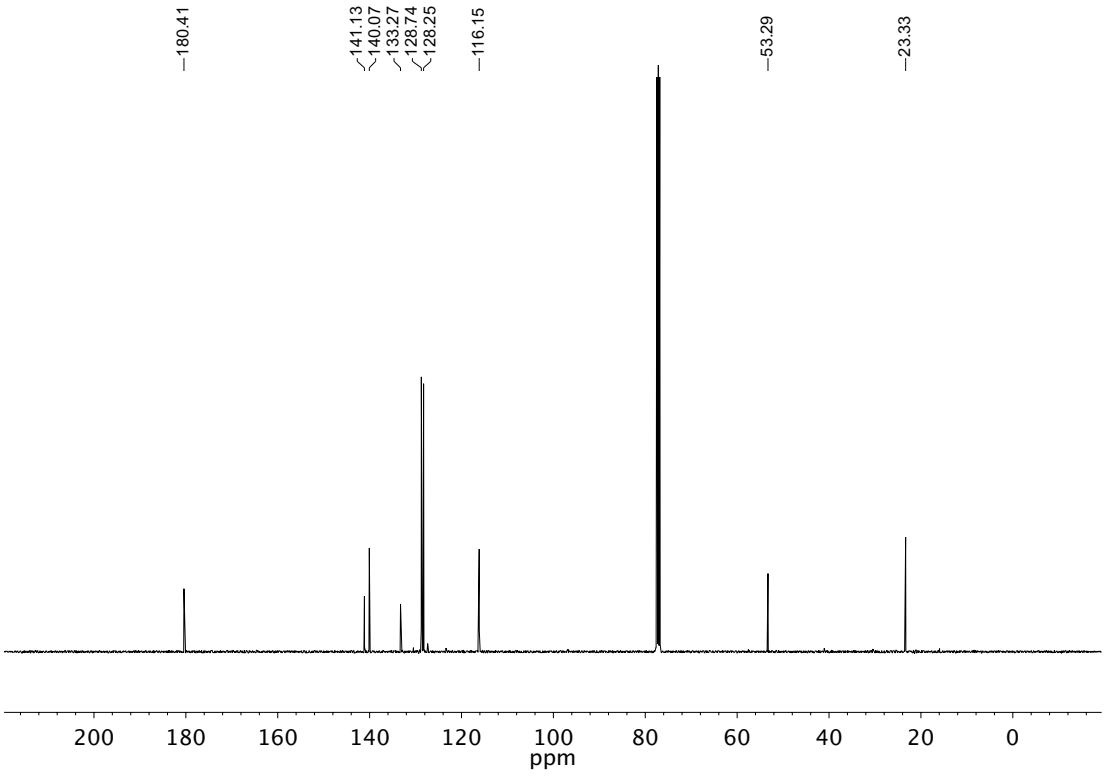
^{13}C NMR (101 MHz, $CDCl_3$) of compound **6k**.



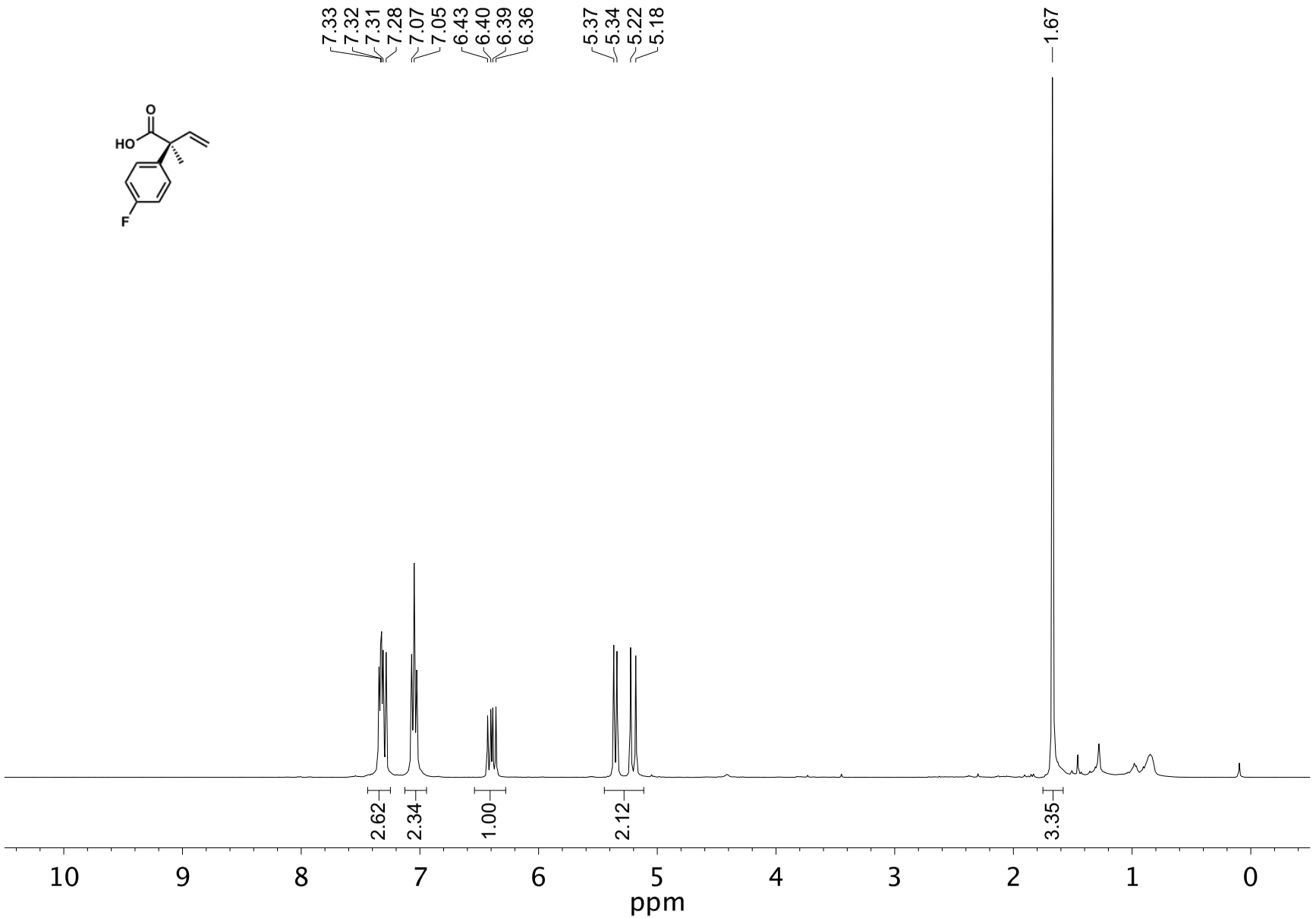
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7b**.



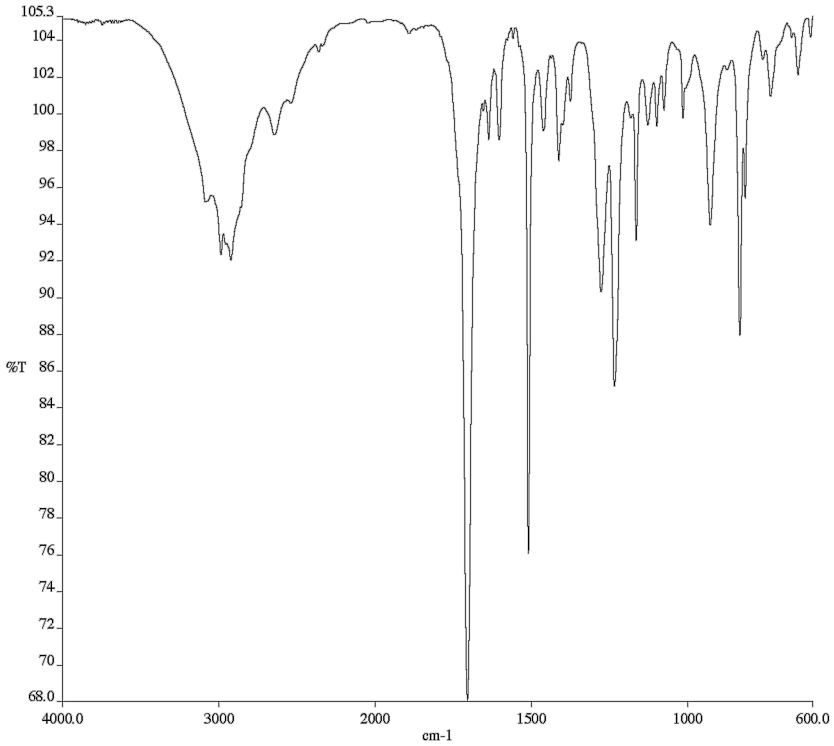
Infrared spectrum (Thin Film, NaCl) of compound **7b**.



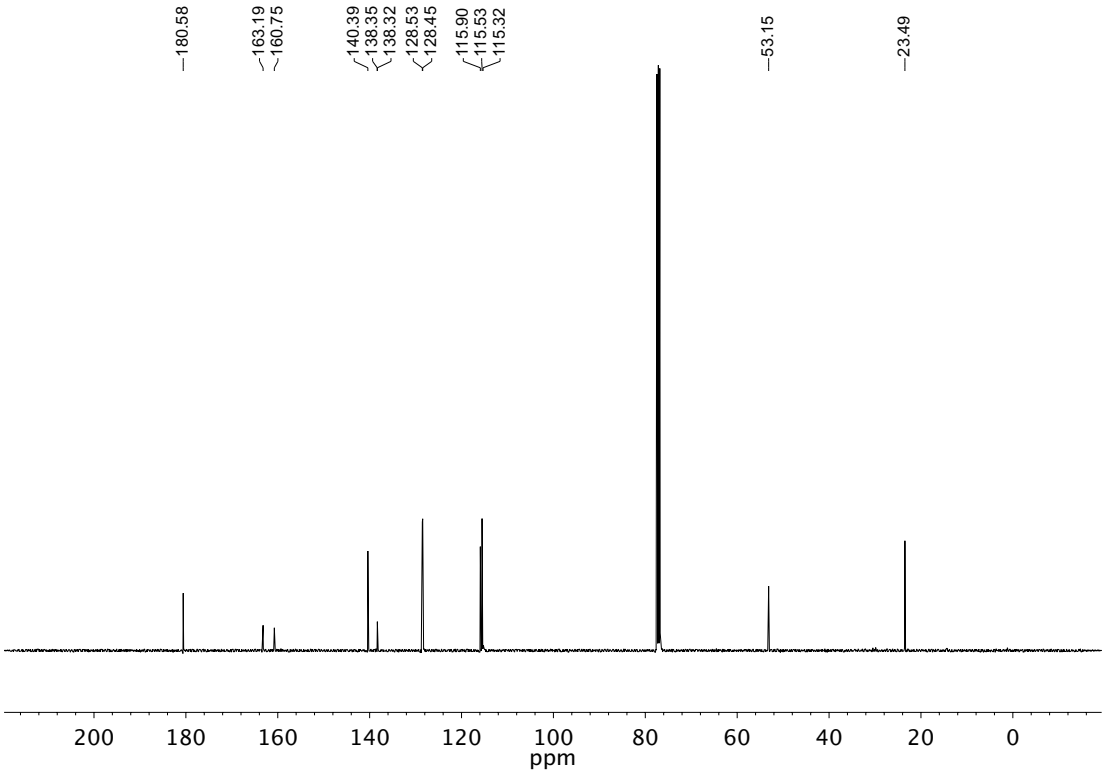
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7b**.



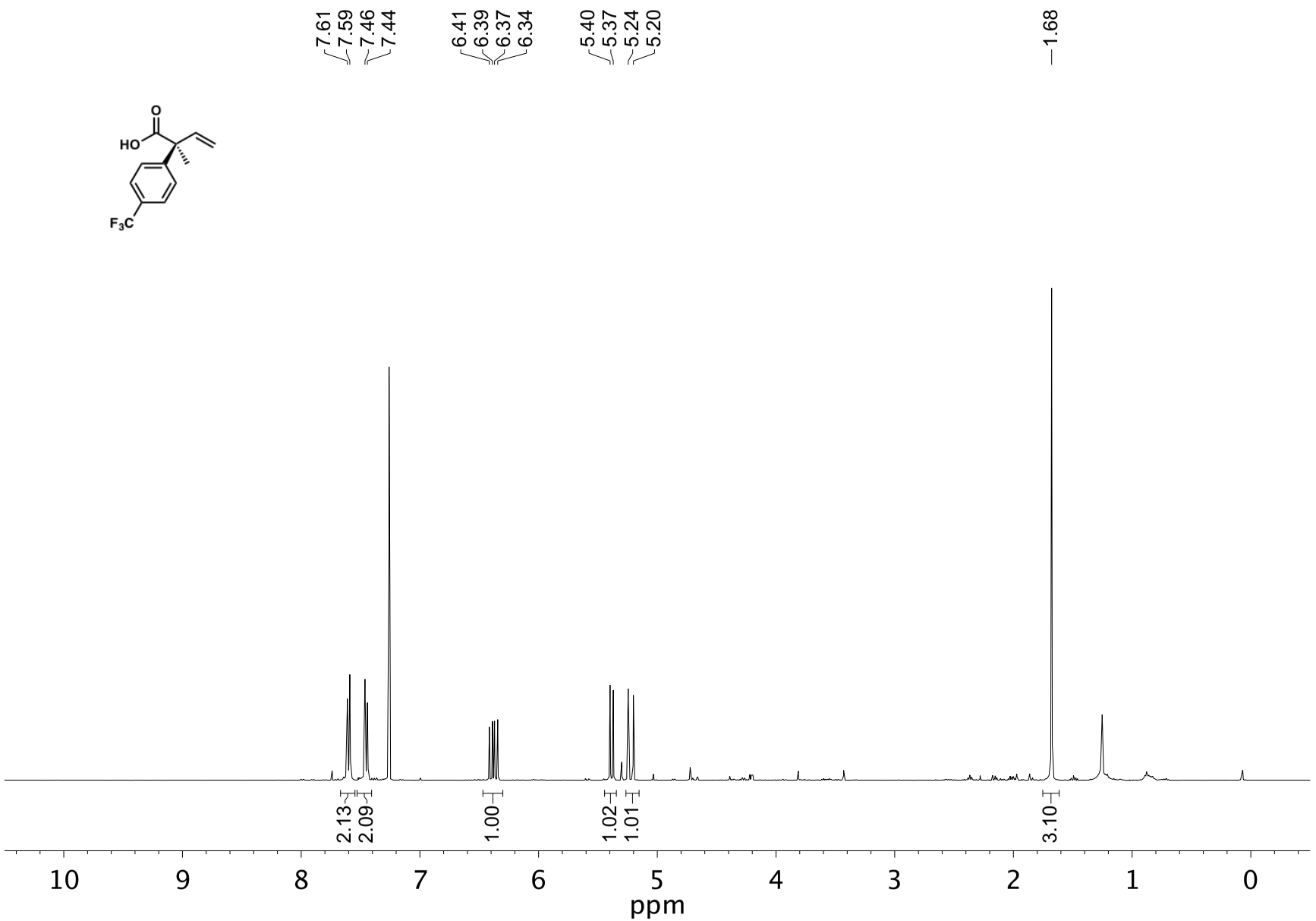
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7c**.



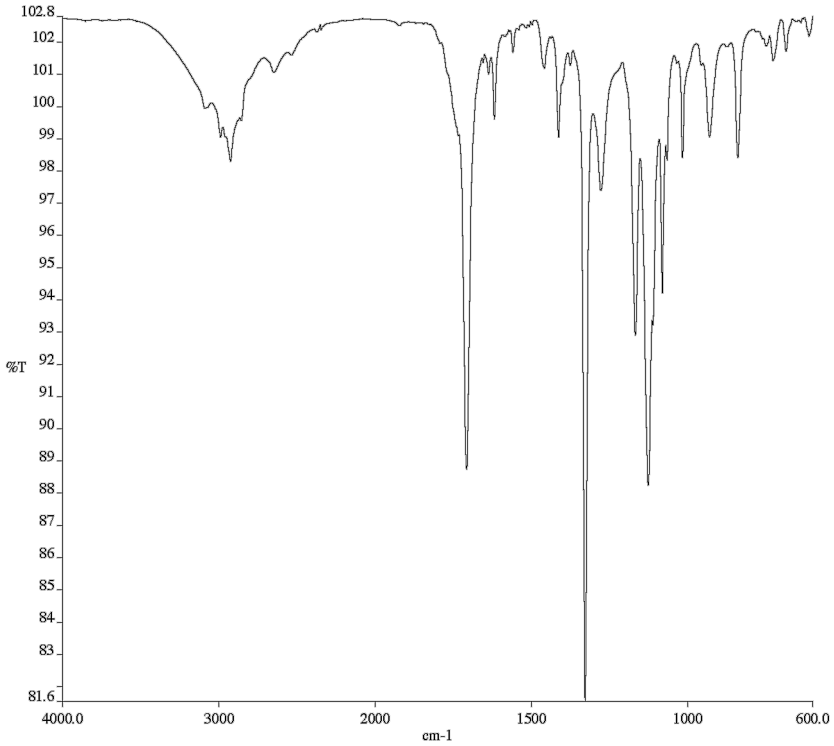
Infrared spectrum (Thin Film, NaCl) of compound **7c**.



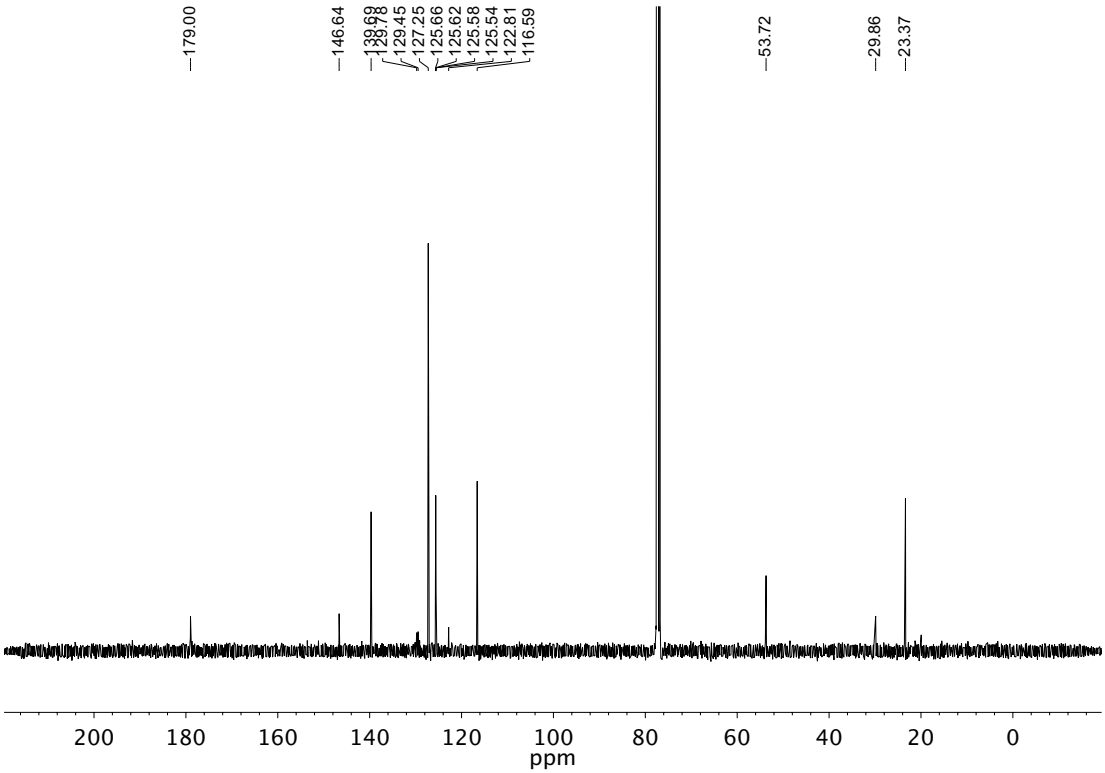
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7c**.



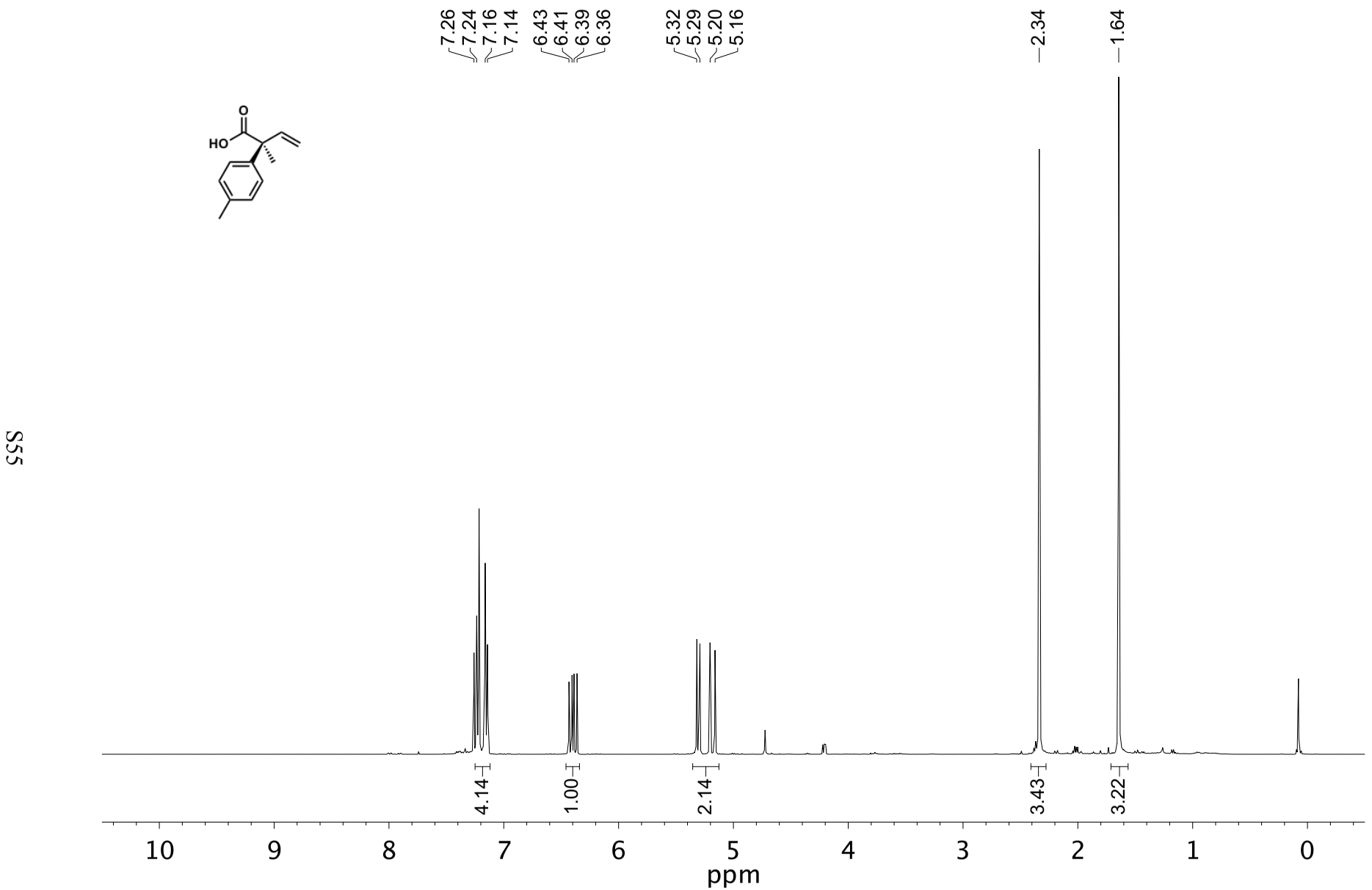
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7d**.



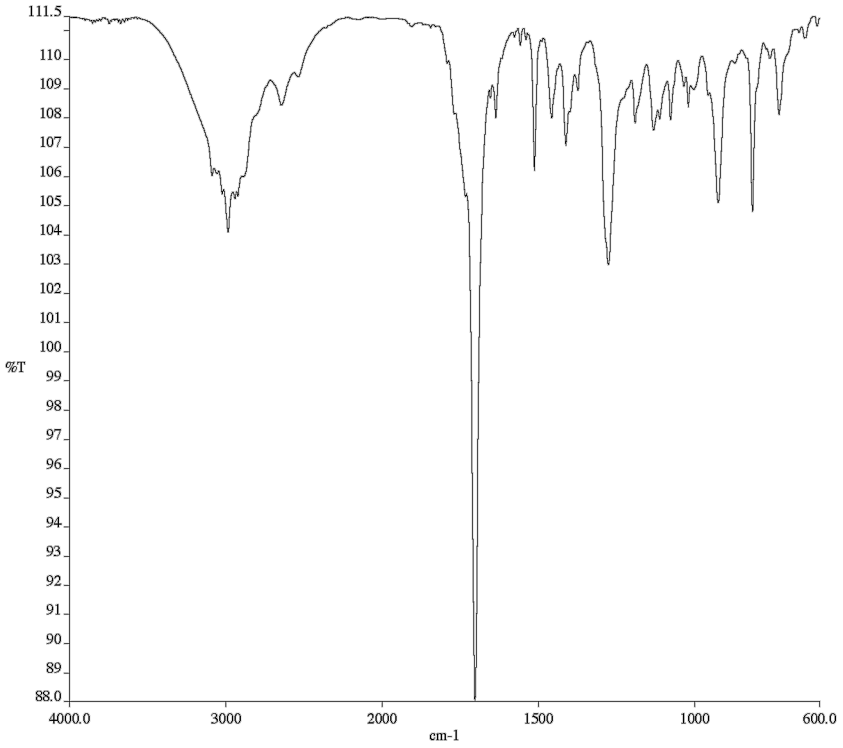
Infrared spectrum (Thin Film, NaCl) of compound **7d**.



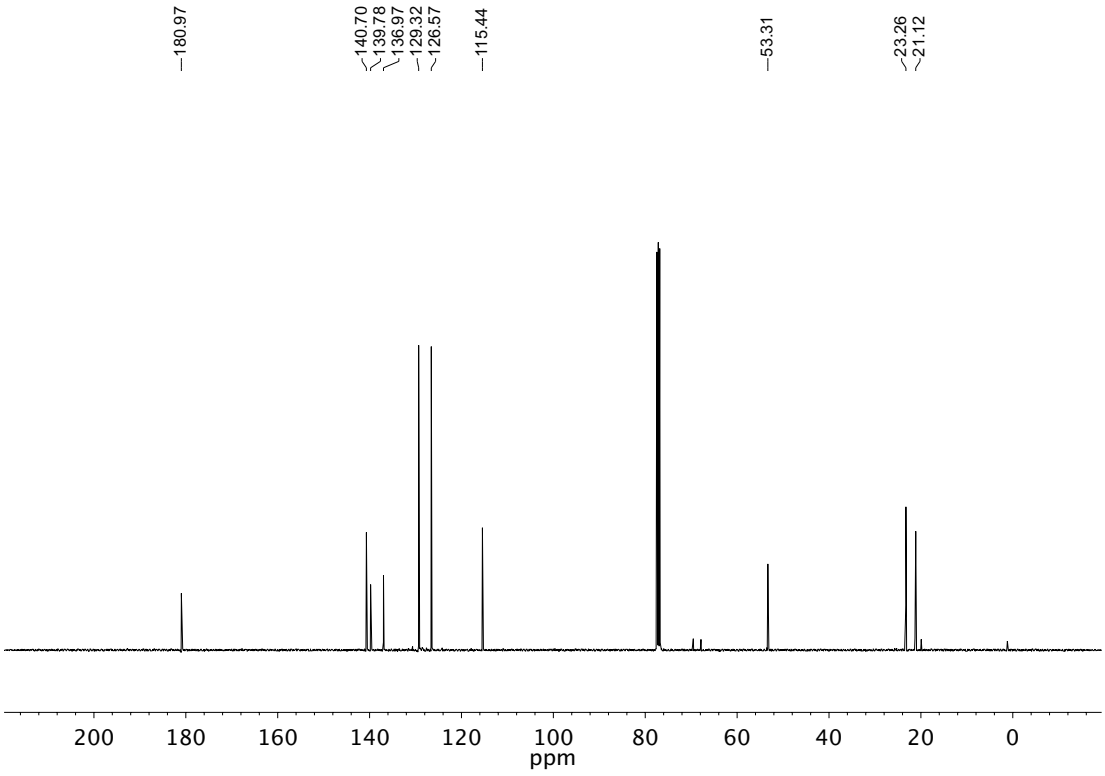
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7d**.



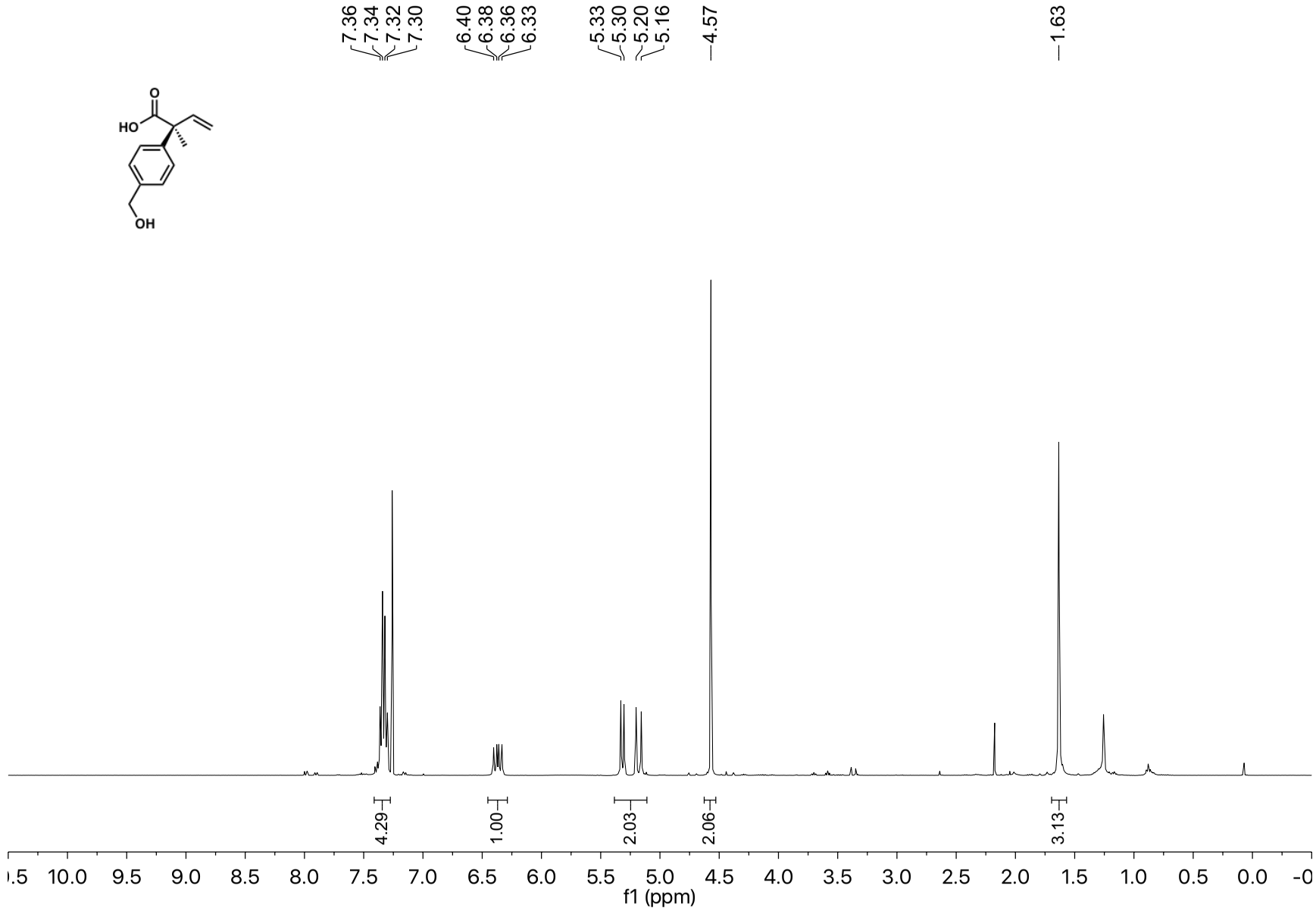
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7e**.



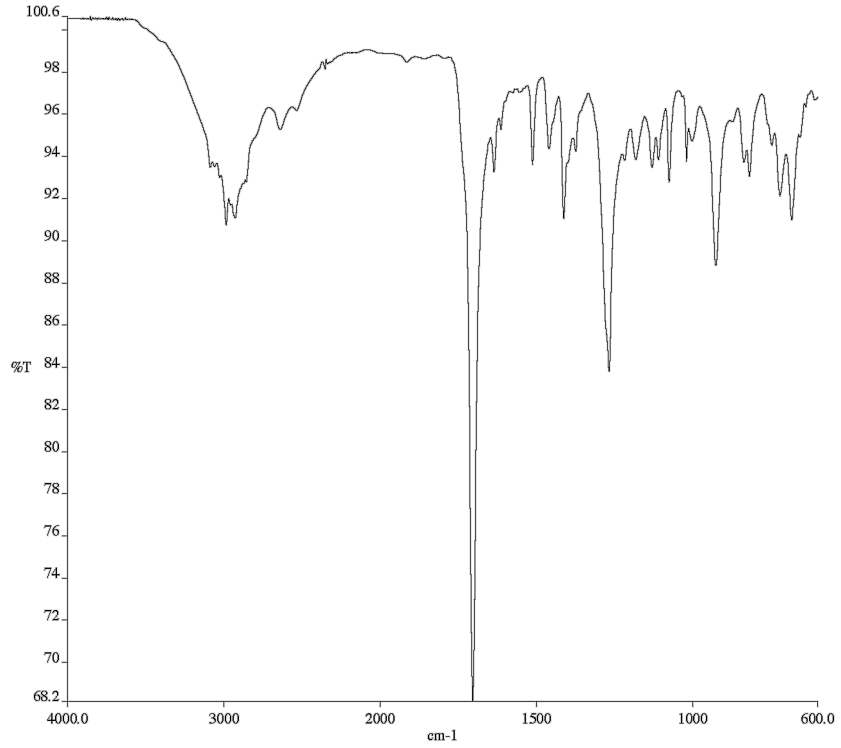
Infrared spectrum (Thin Film, NaCl) of compound **7e**.



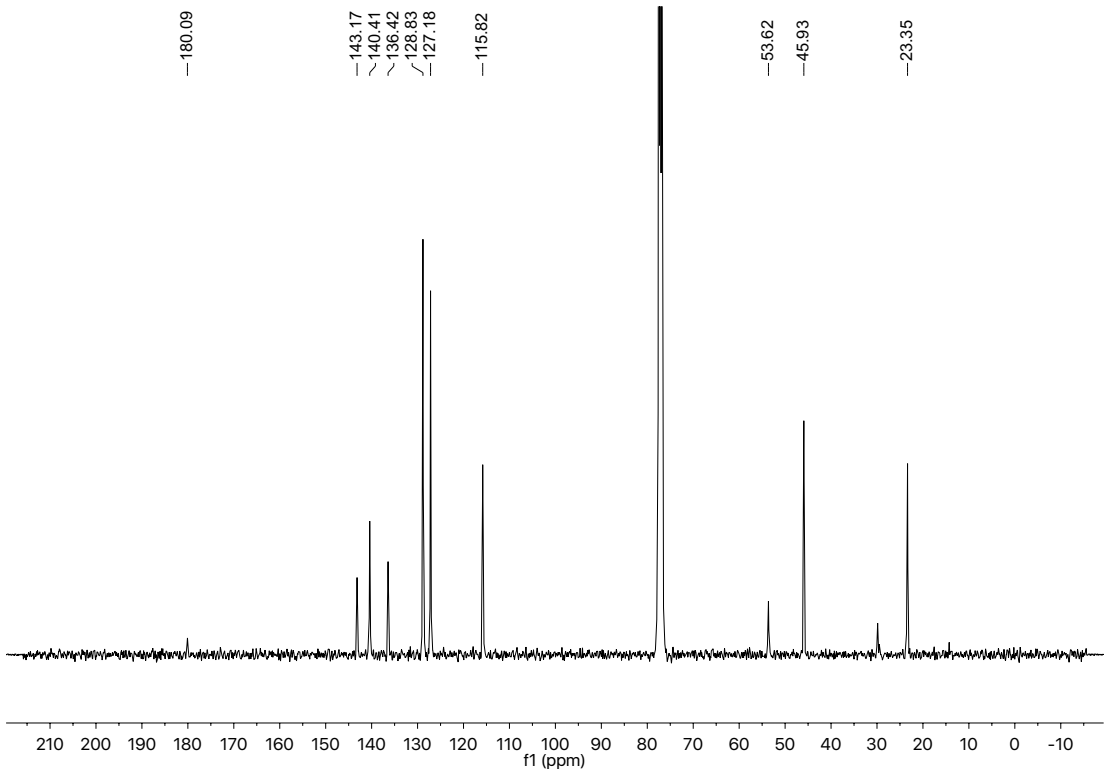
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7e**.



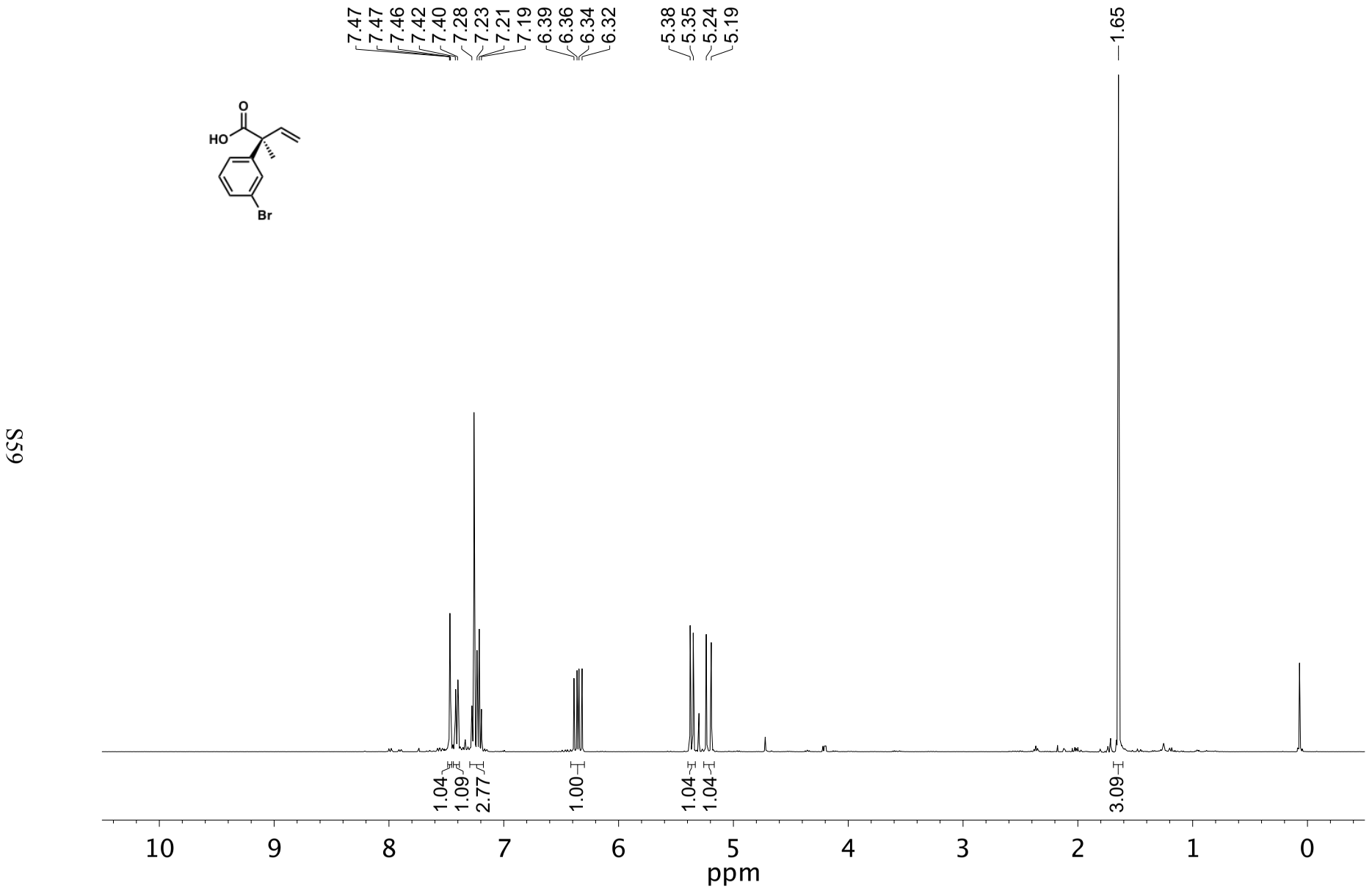
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7f**.



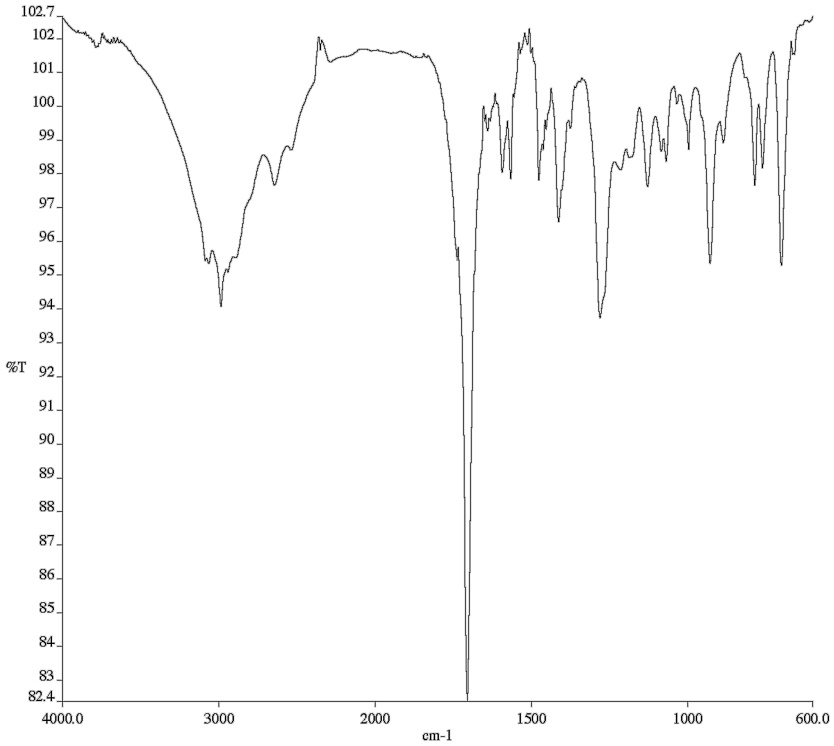
Infrared spectrum (Thin Film, NaCl) of compound **7f**.



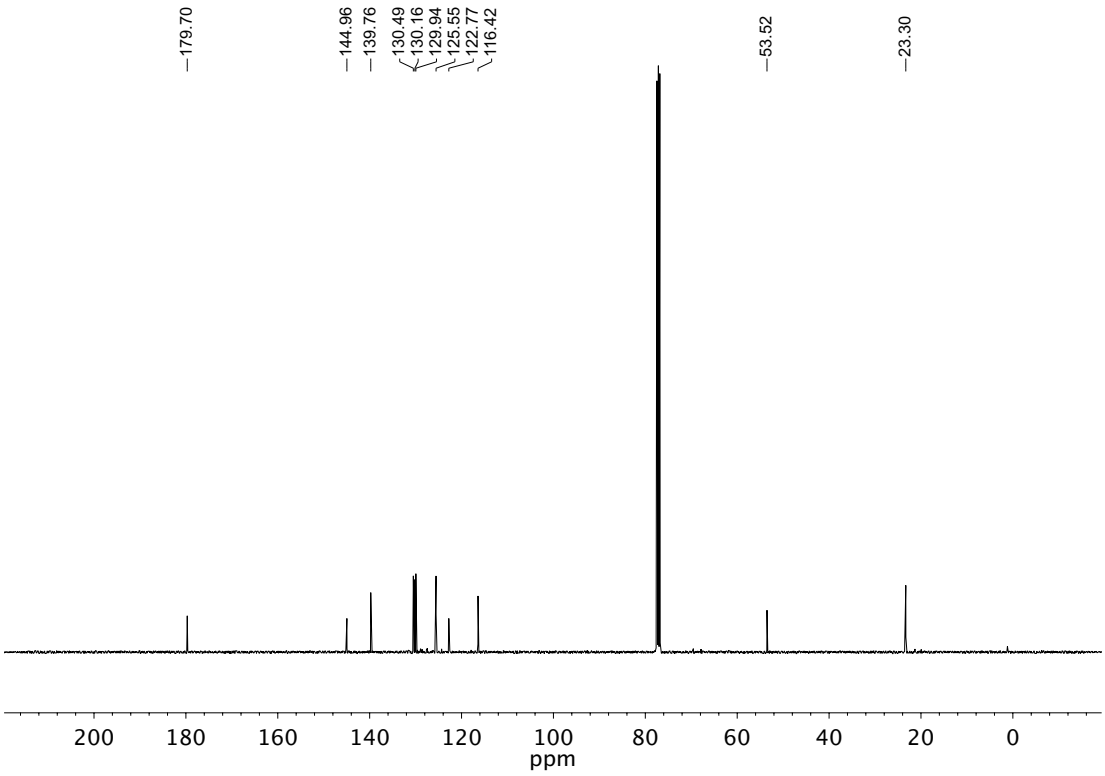
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7f**.



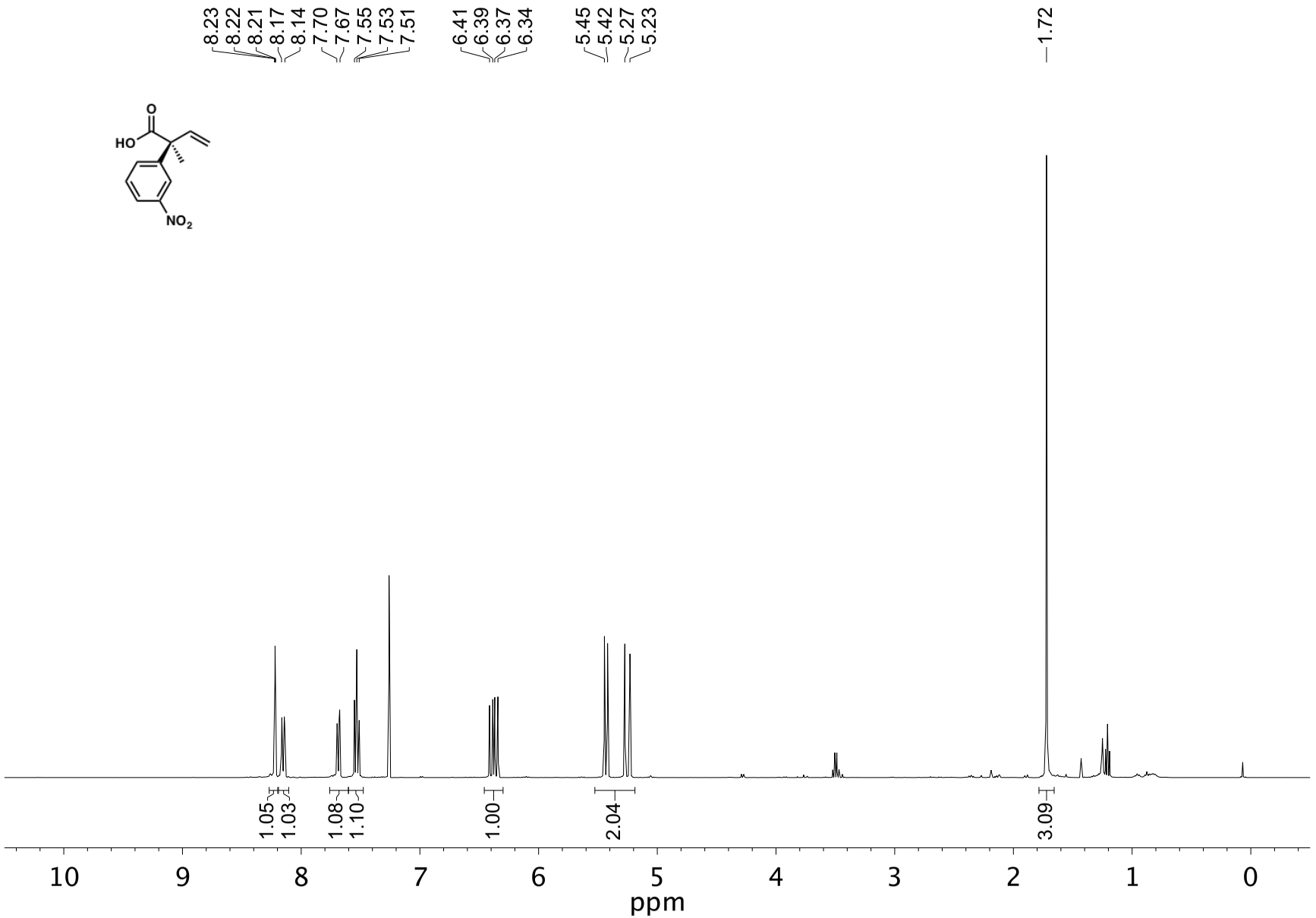
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7g**.



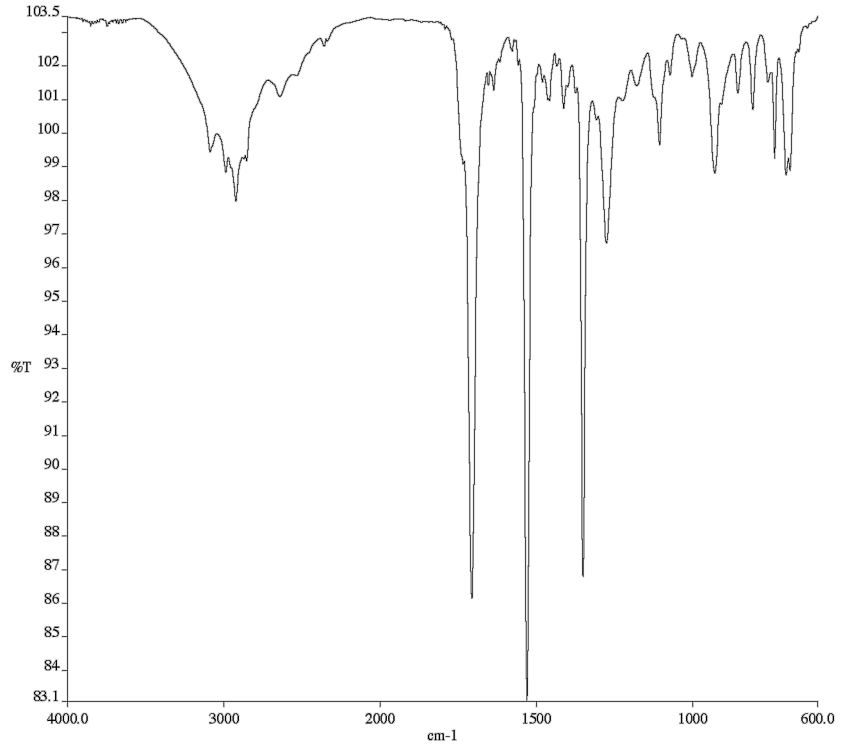
Infrared spectrum (Thin Film, NaCl) of compound **7g**.



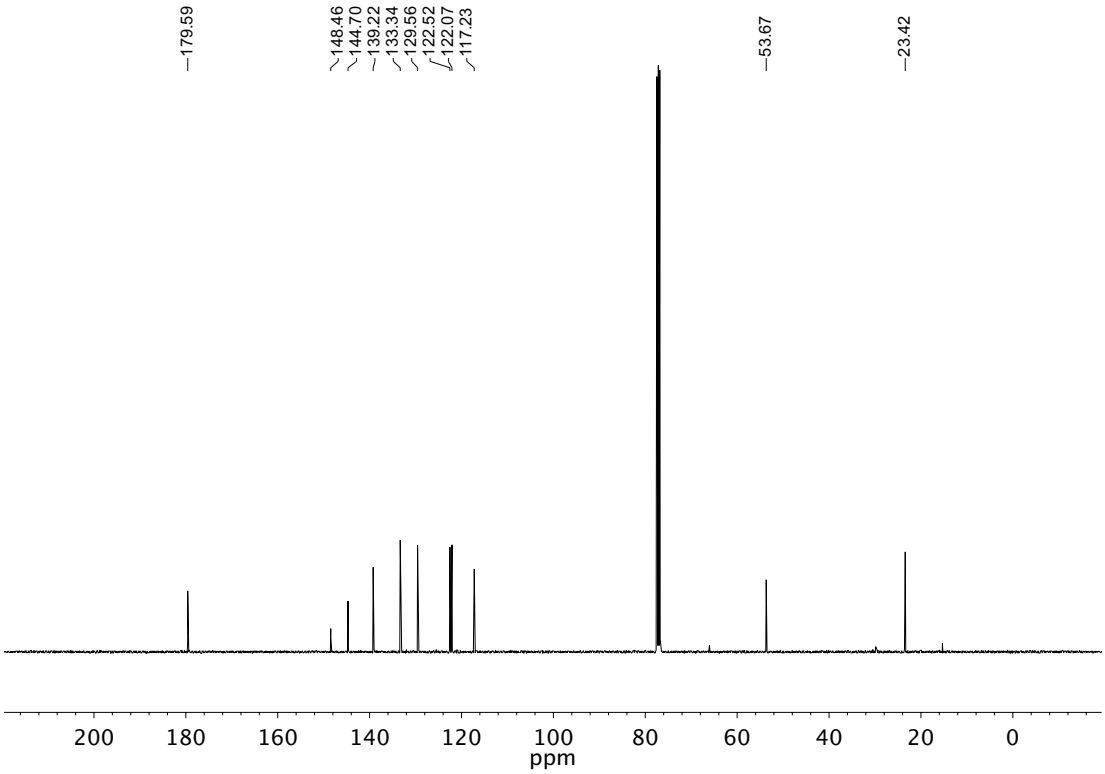
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7g**.



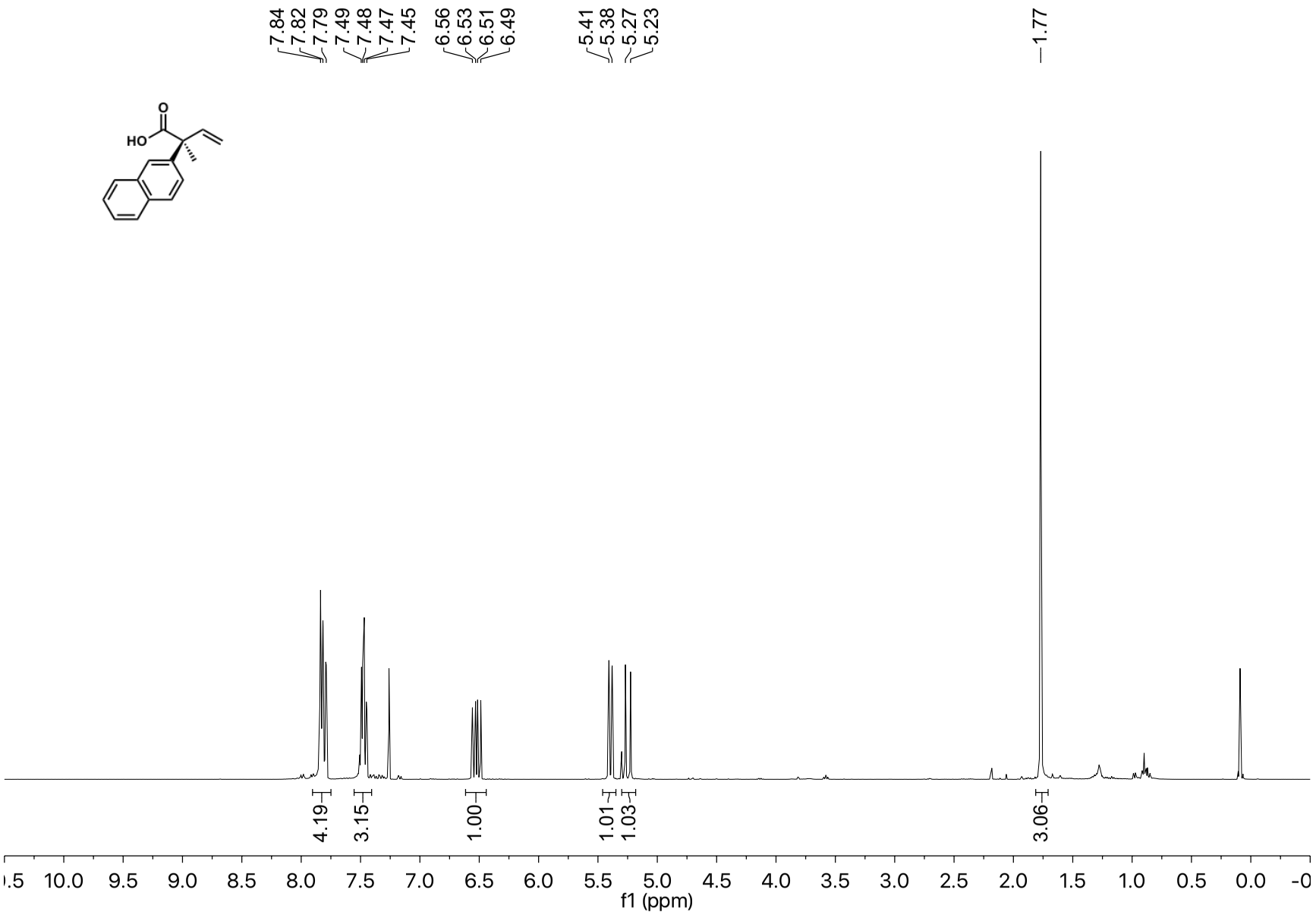
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7h**.



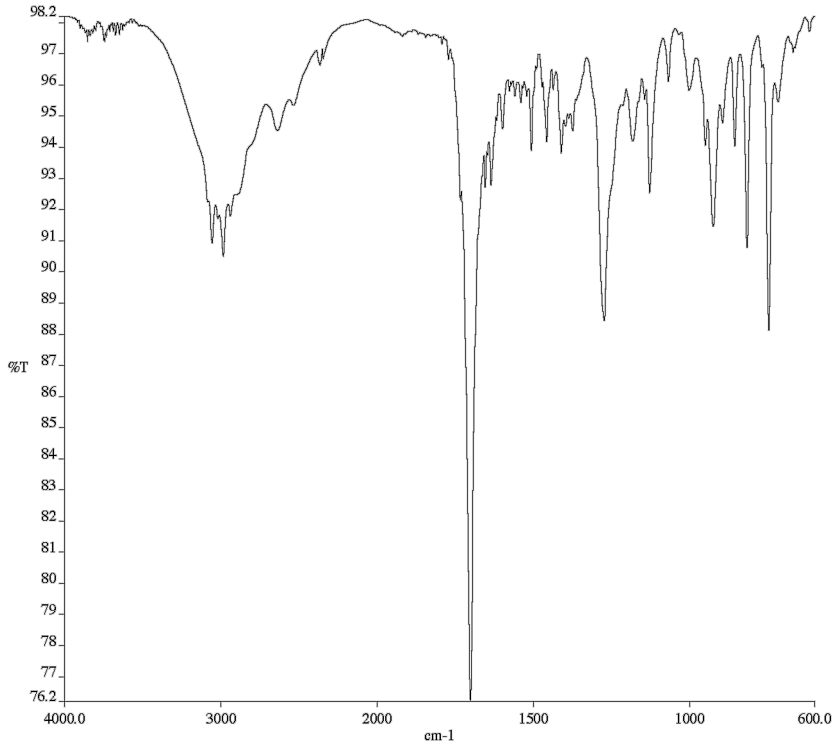
Infrared spectrum (Thin Film, NaCl) of compound **7h**.



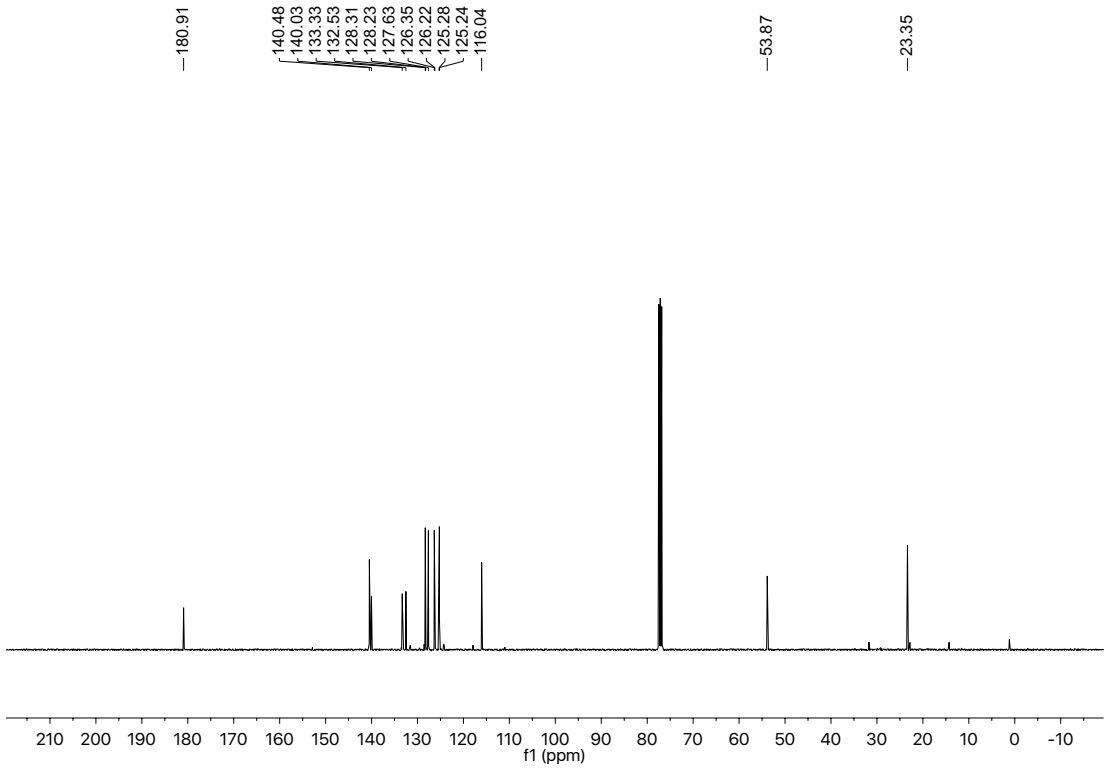
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7h**.



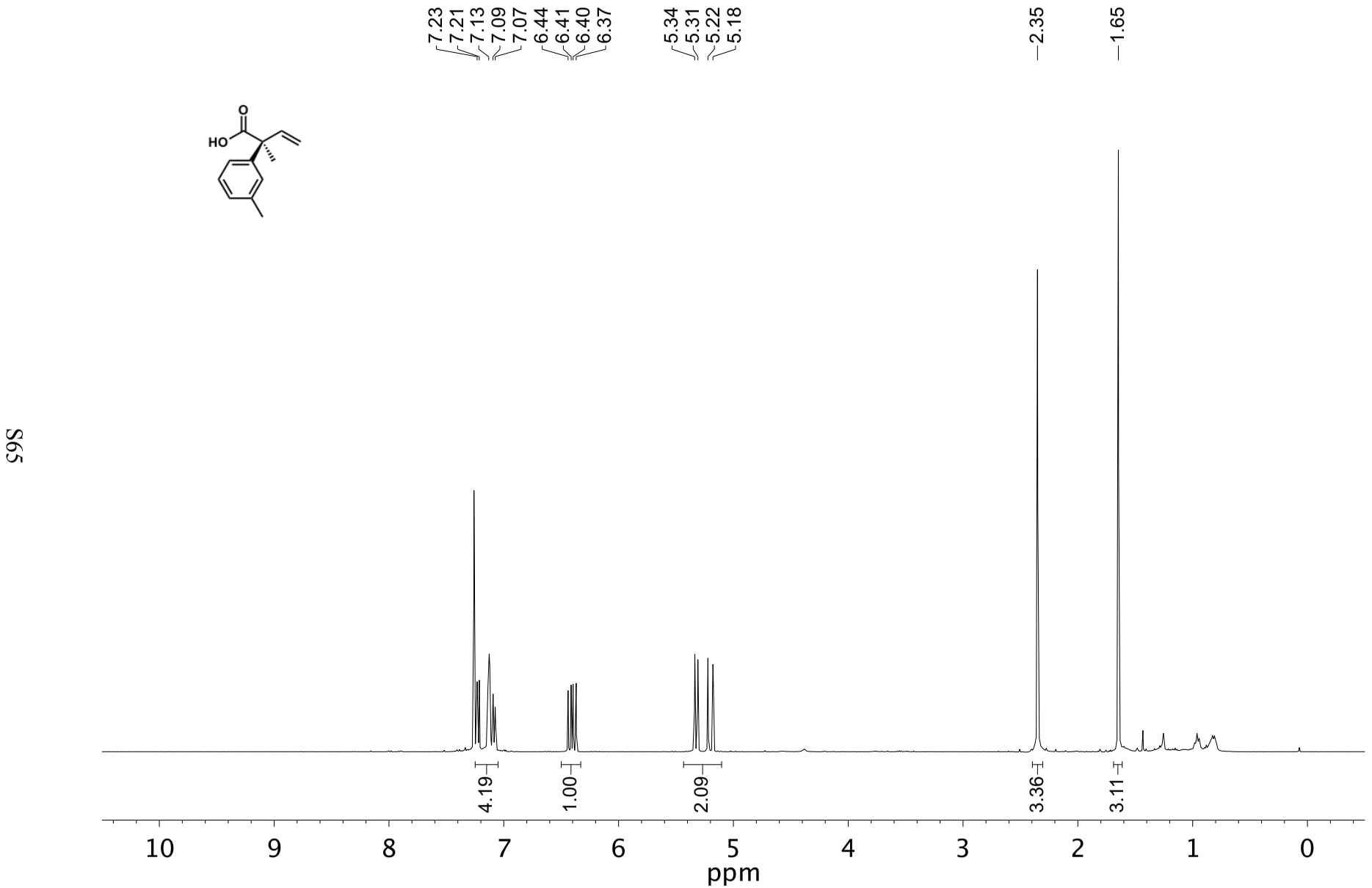
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7i**.



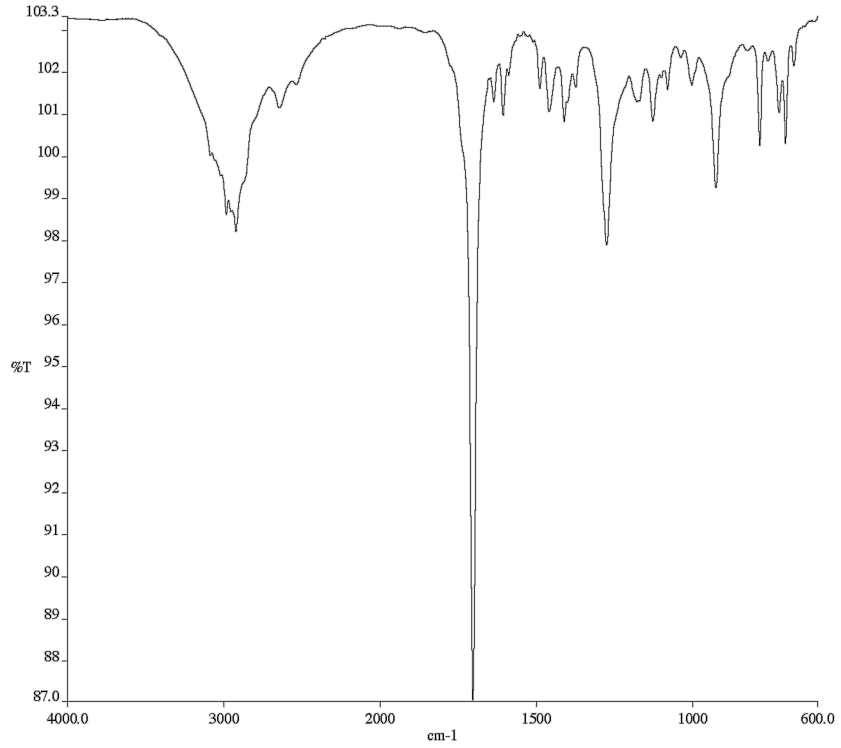
Infrared spectrum (Thin Film, NaCl) of compound **7i**.



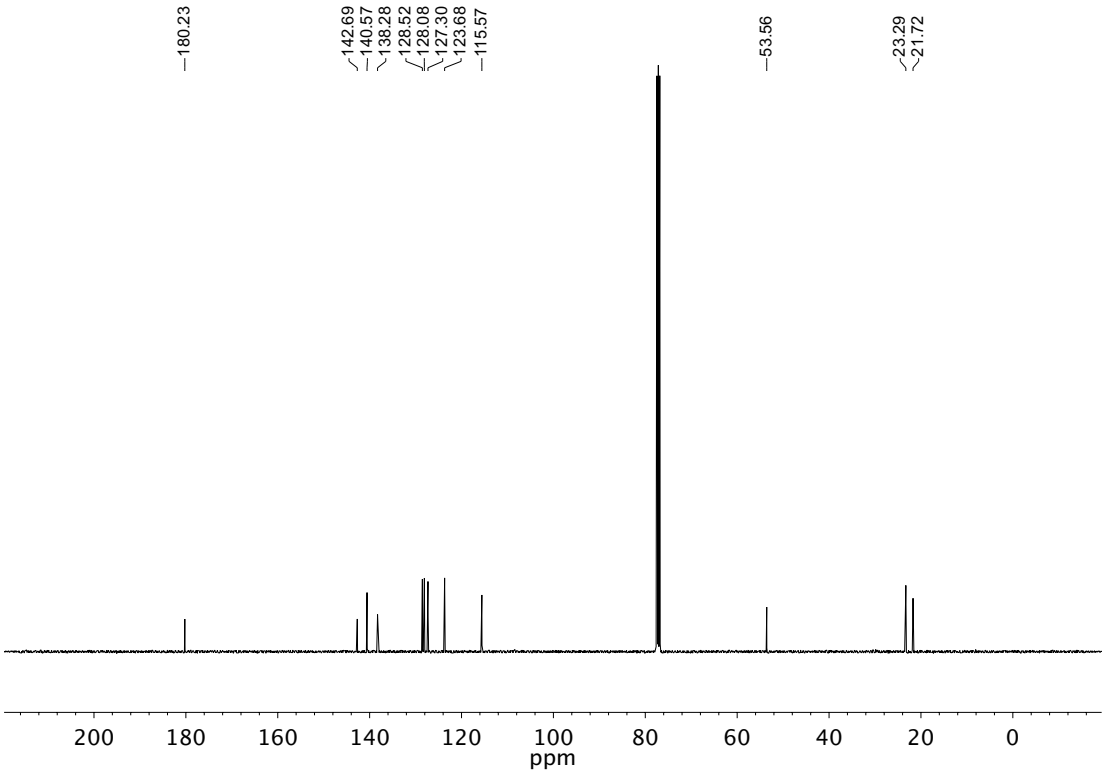
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7i**.



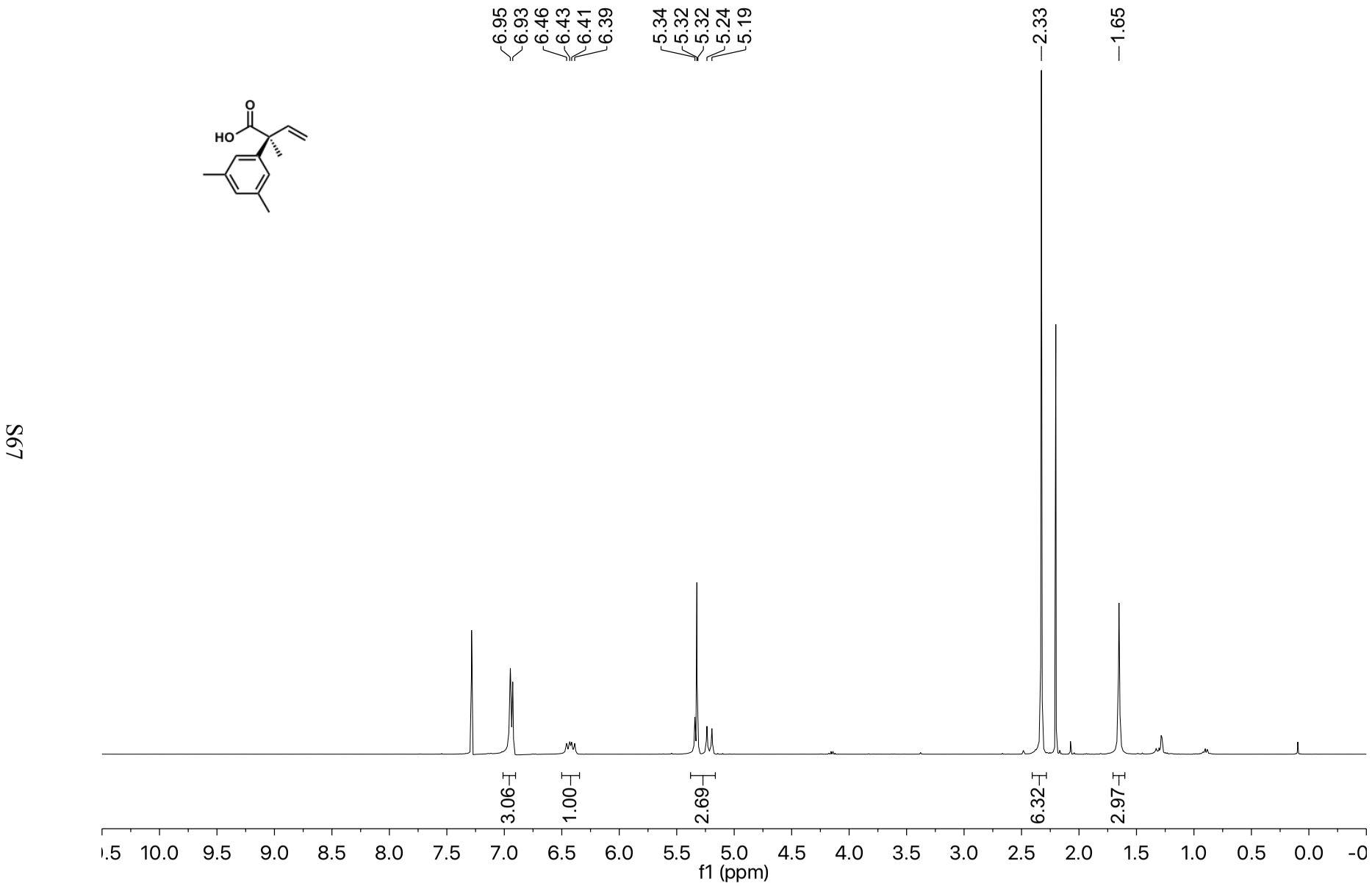
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7j**.



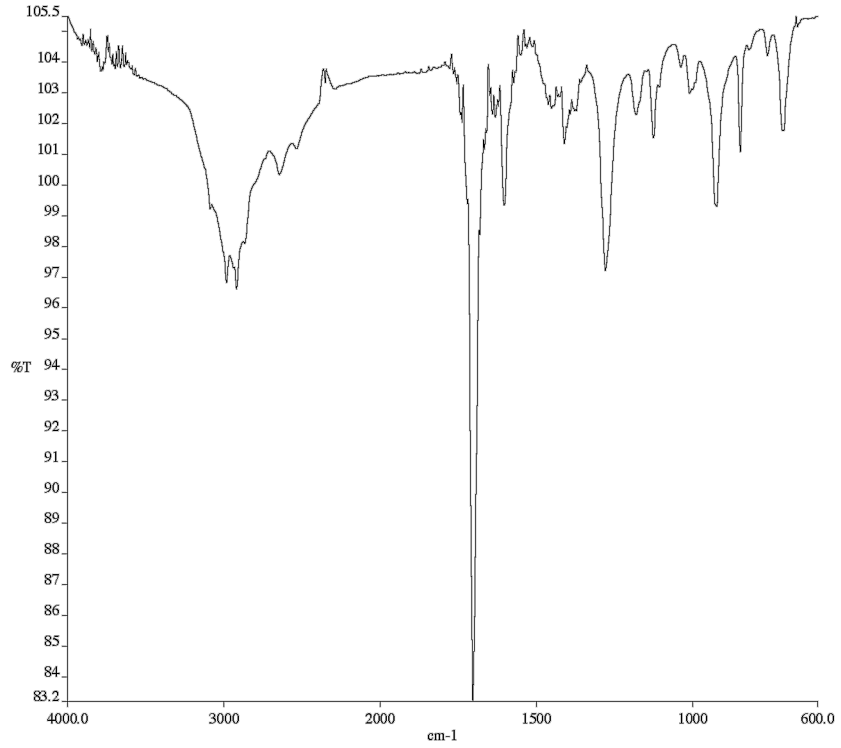
Infrared spectrum (Thin Film, NaCl) of compound **7j**.



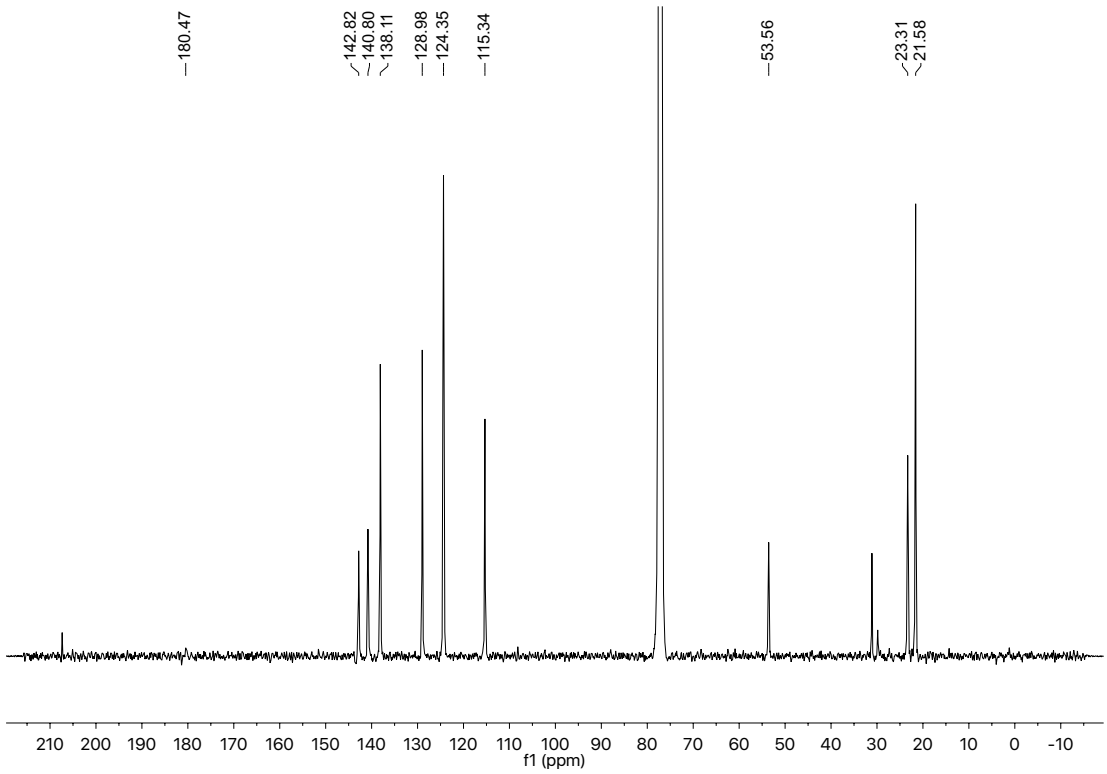
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7j**.



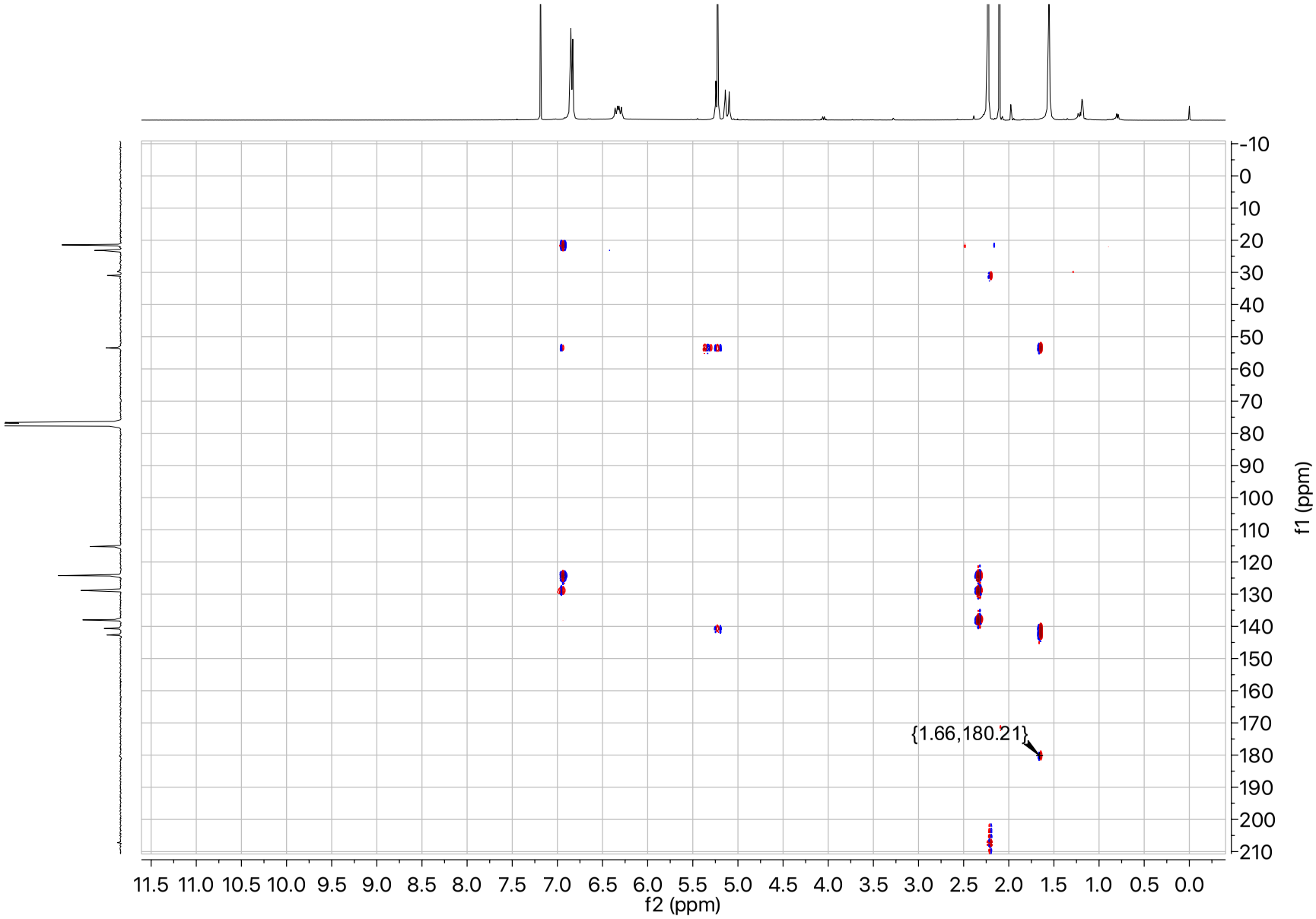
^{1}H NMR (400 MHz, $CDCl_3$) of compound **7k**.



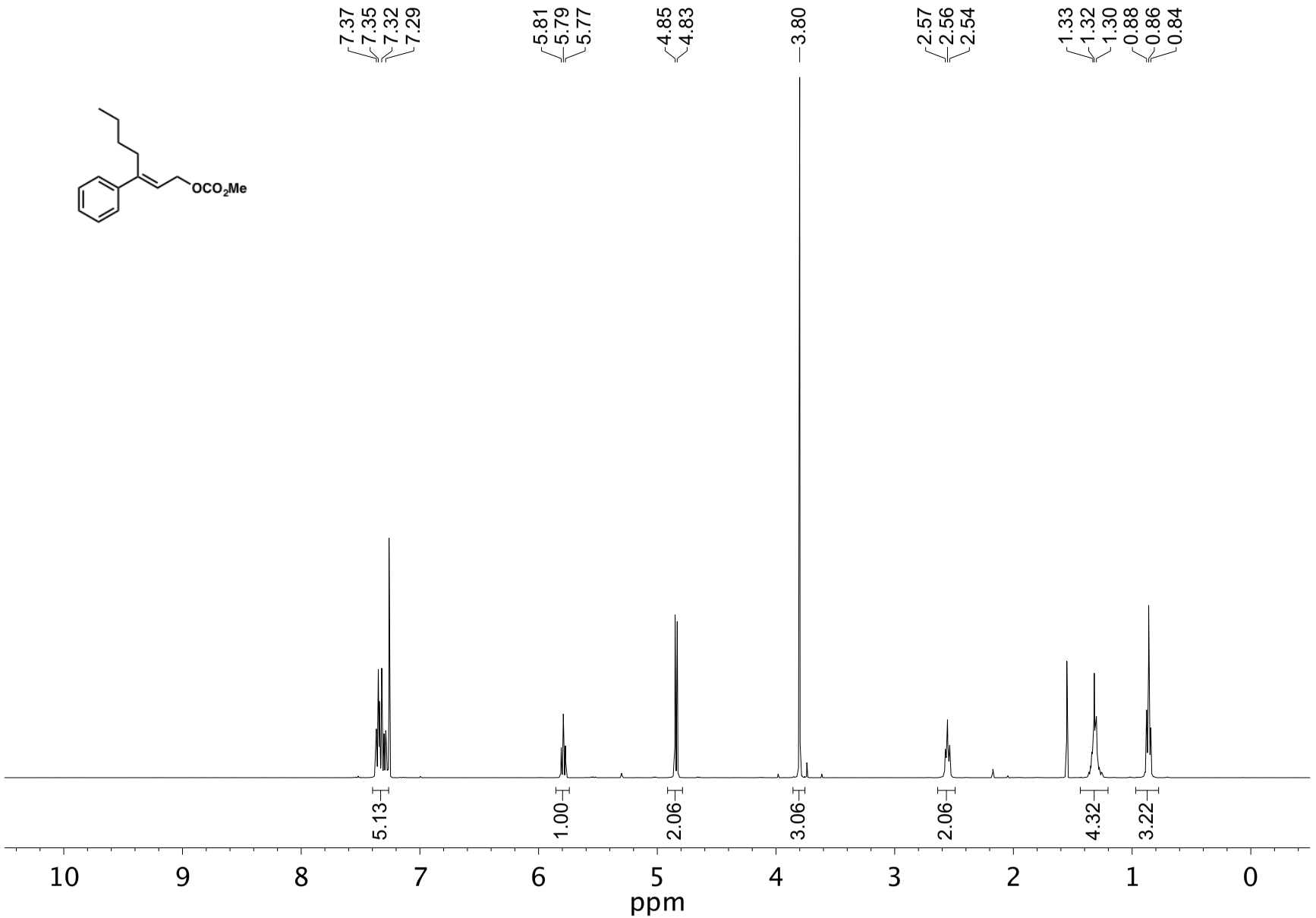
Infrared spectrum (Thin Film, NaCl) of compound **7k**.



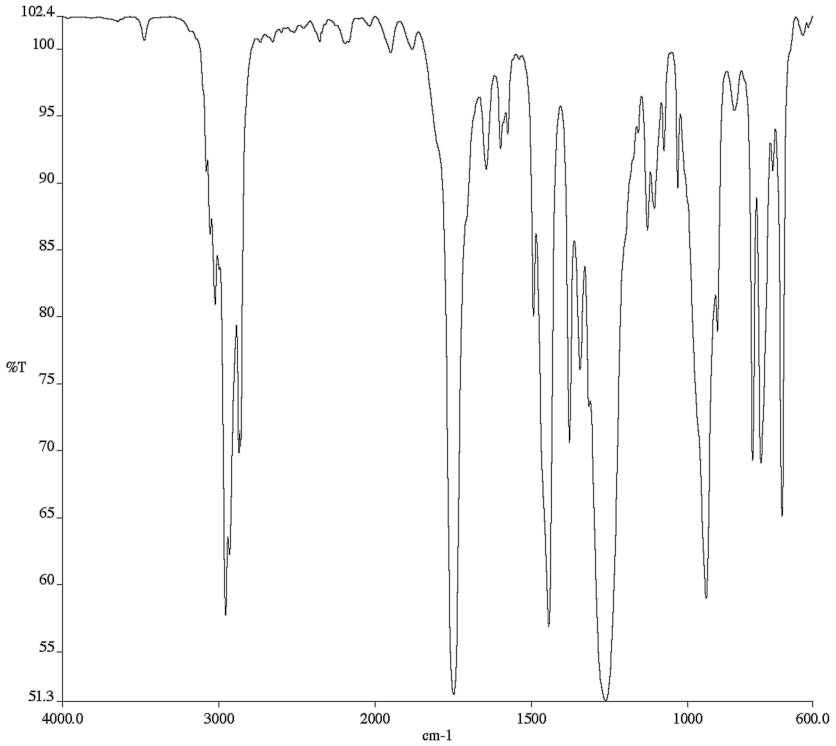
^{13}C NMR (101 MHz, $CDCl_3$) of compound **7k**.



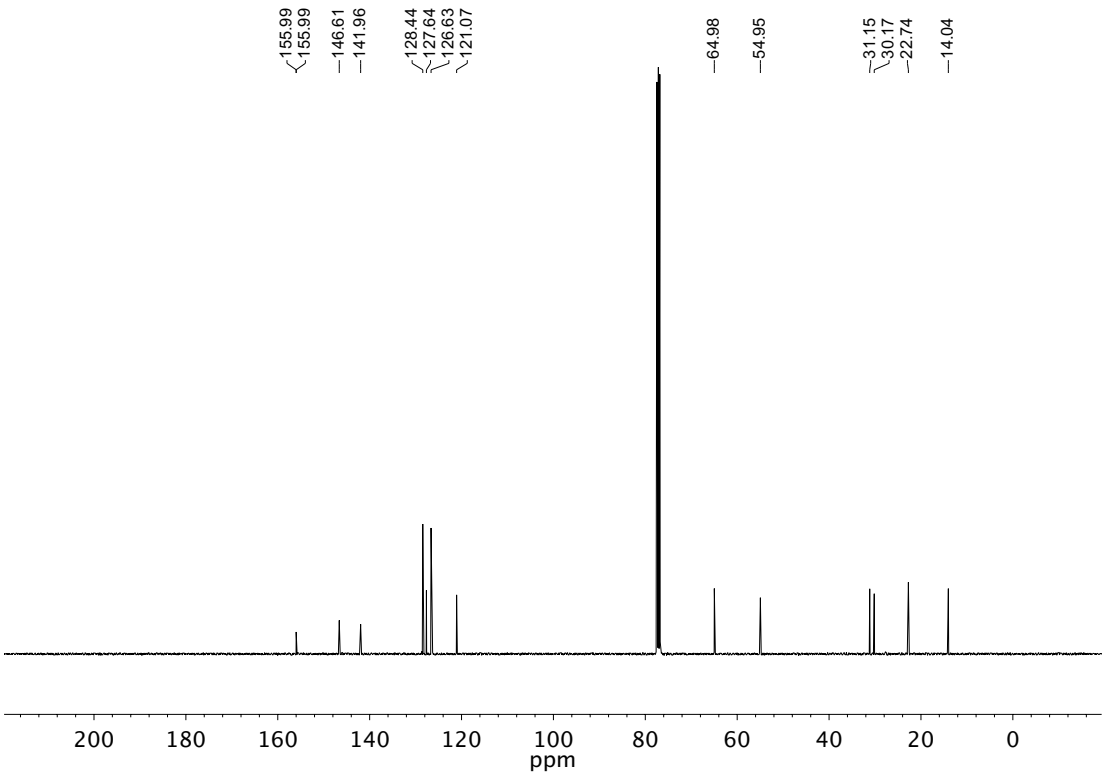
HMBC (400 MHz, $CDCl_3$) of compound **7k**.



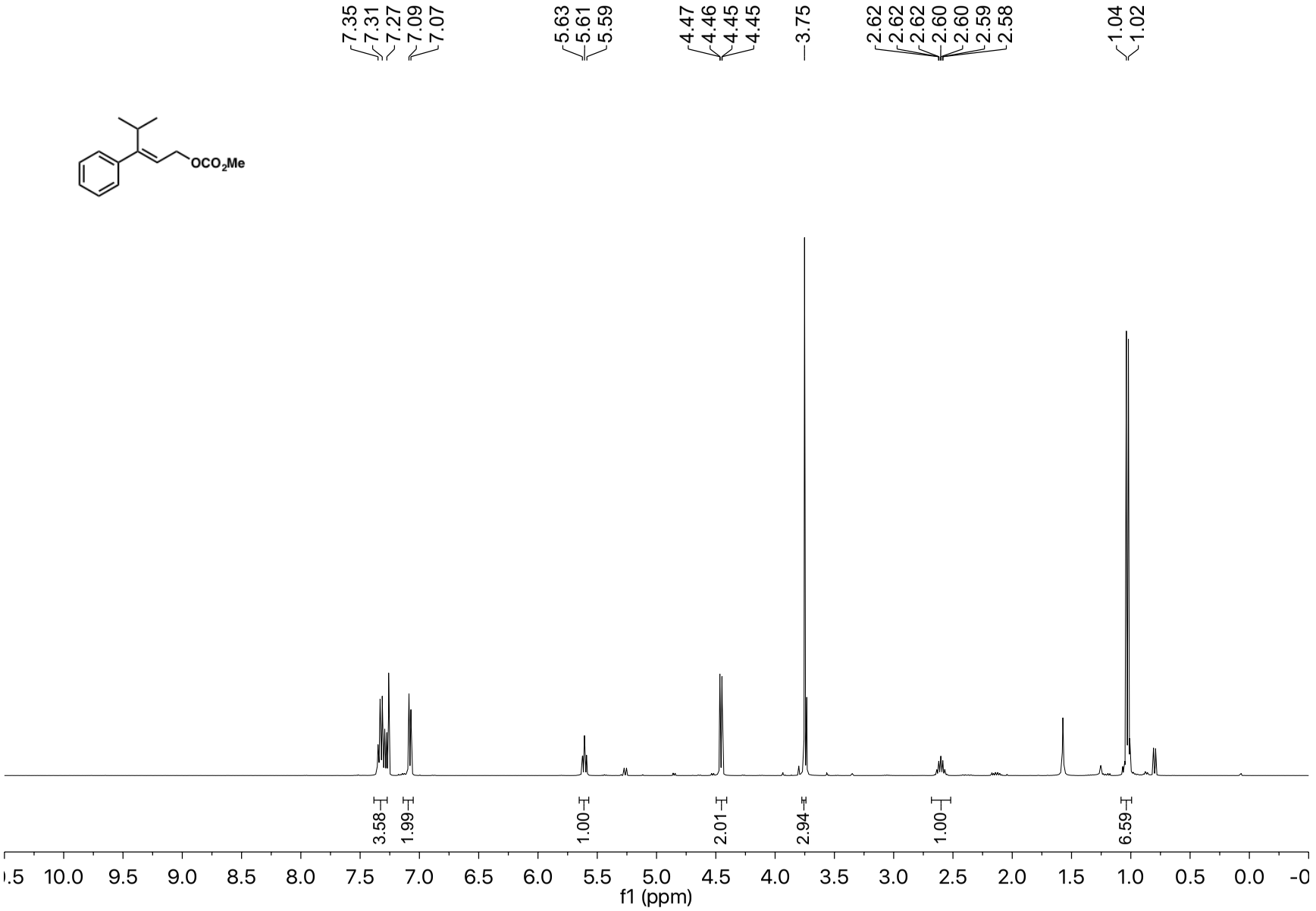
^{1}H NMR (400 MHz, $CDCl_3$) of compound **8b**.



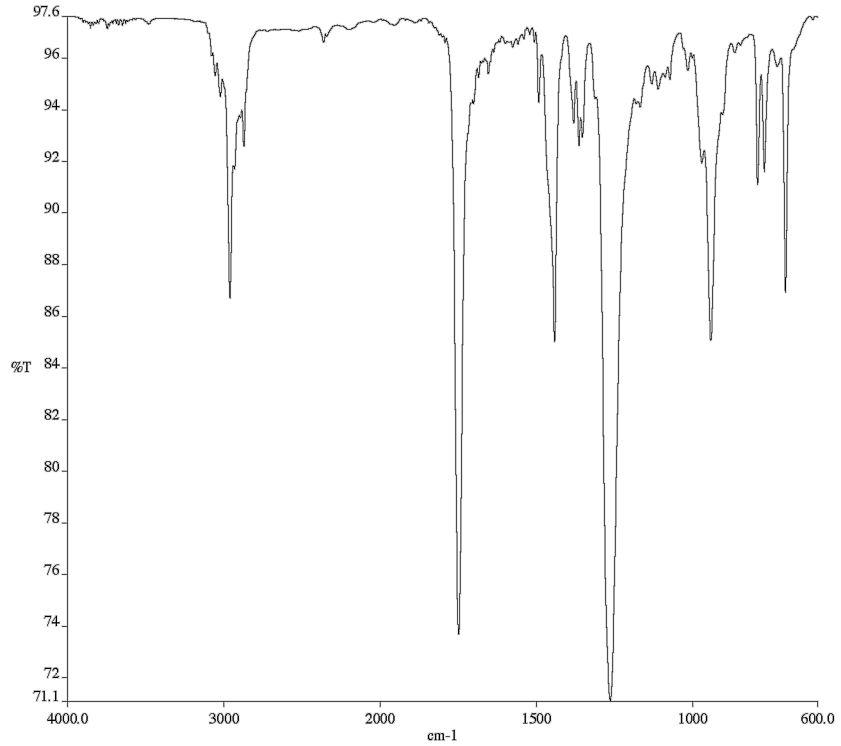
Infrared spectrum (Thin Film, NaCl) of compound **8b**.



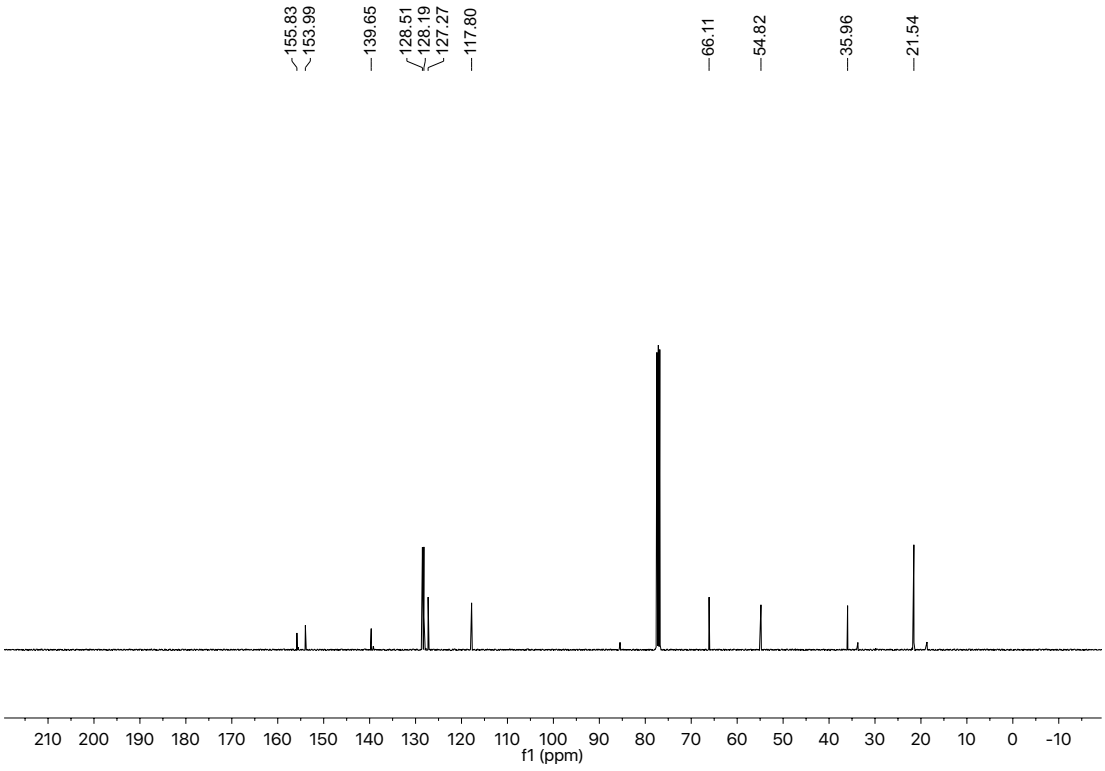
^{13}C NMR (101 MHz, $CDCl_3$) of compound **8b**.



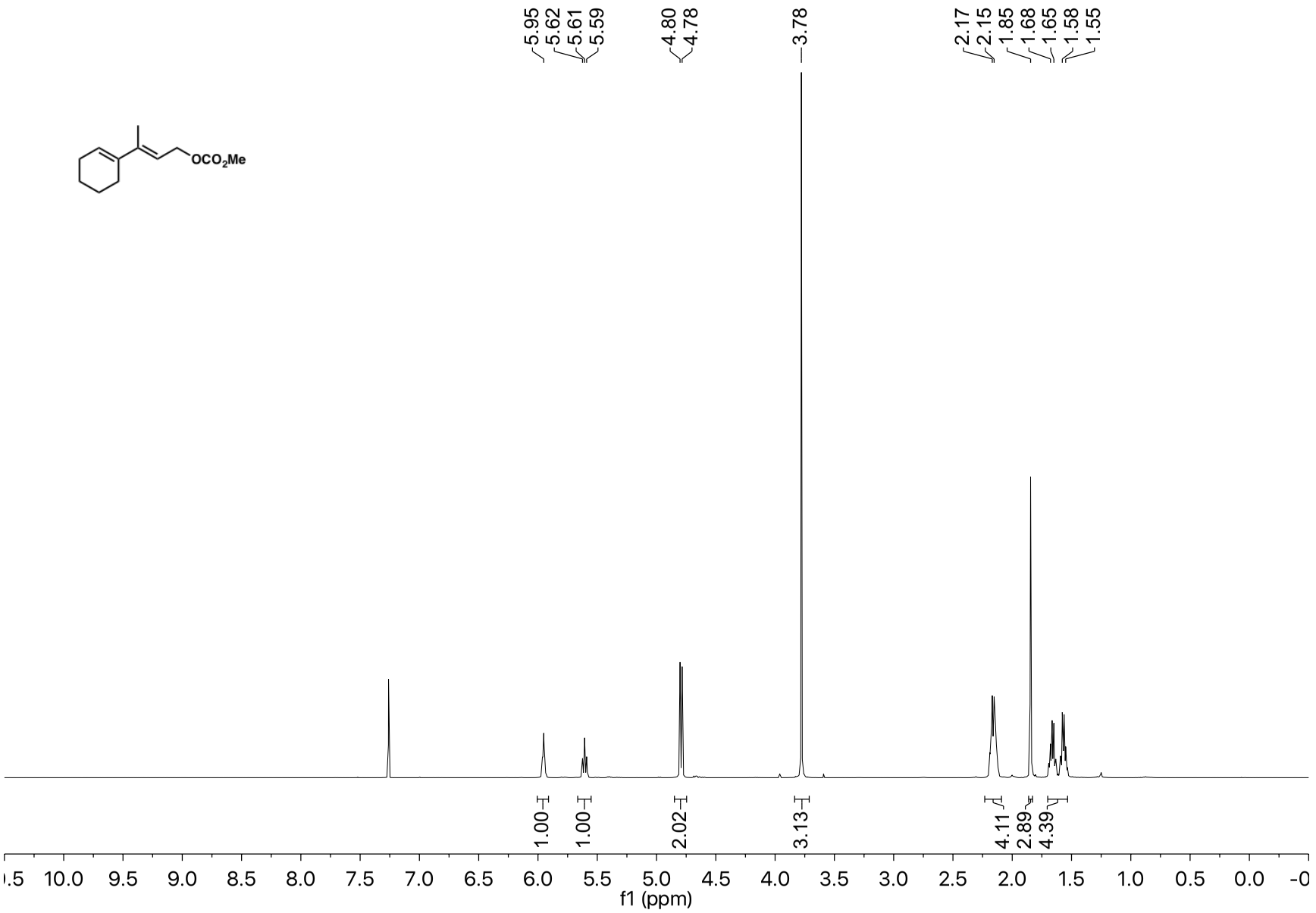
^{1}H NMR (400 MHz, $CDCl_3$) of compound **8c**.



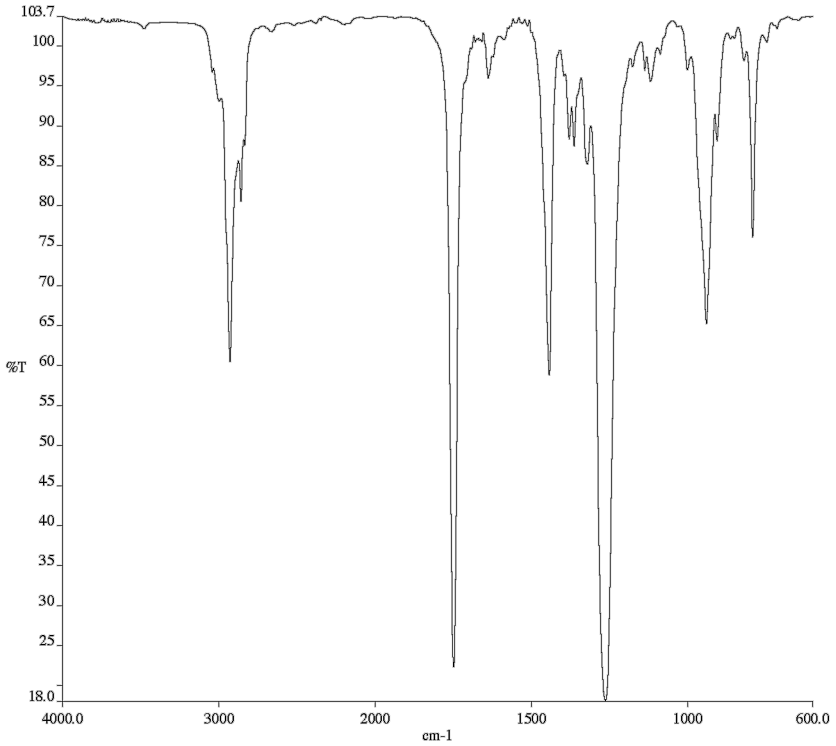
Infrared spectrum (Thin Film, NaCl) of compound **8c**.



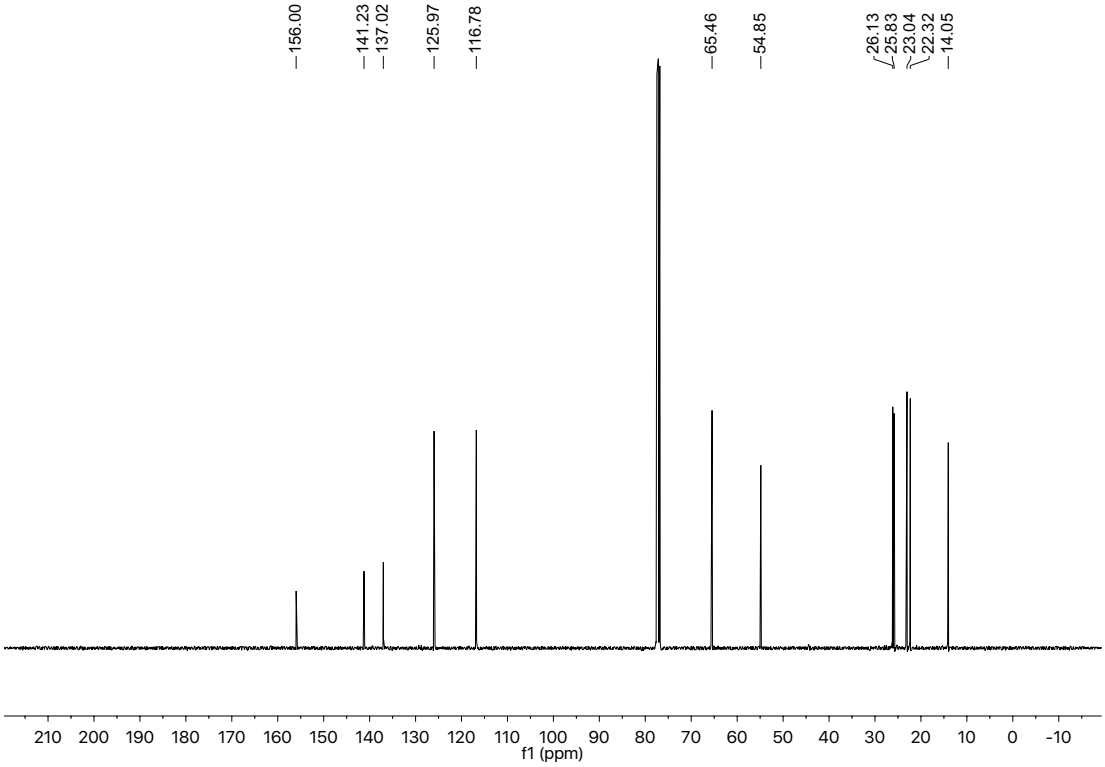
^{13}C NMR (101 MHz, $CDCl_3$) of compound **8c**.



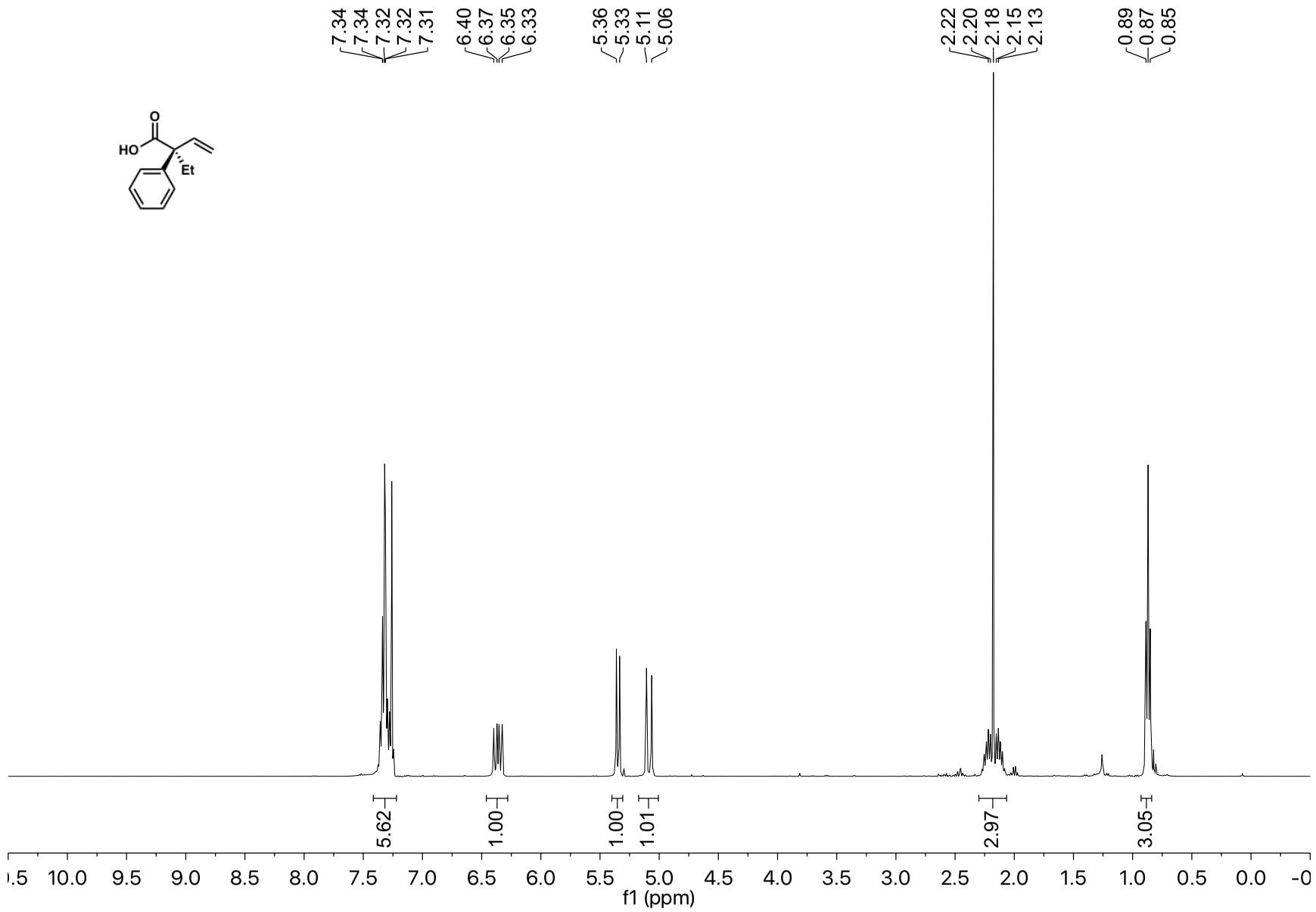
^{1}H NMR (400 MHz, $CDCl_3$) of compound **8e**.



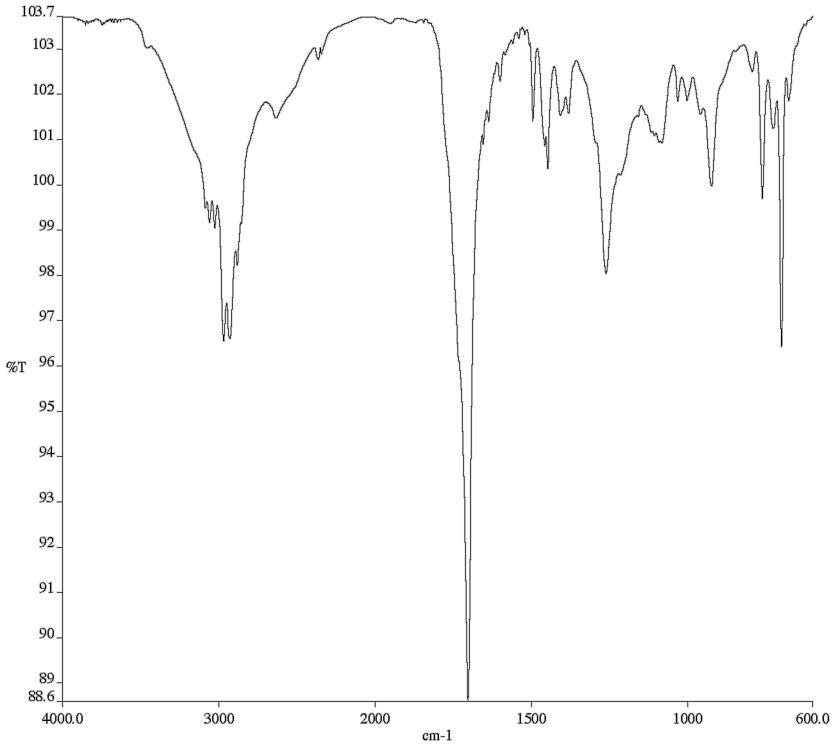
Infrared spectrum (Thin Film, NaCl) of compound **8e**.



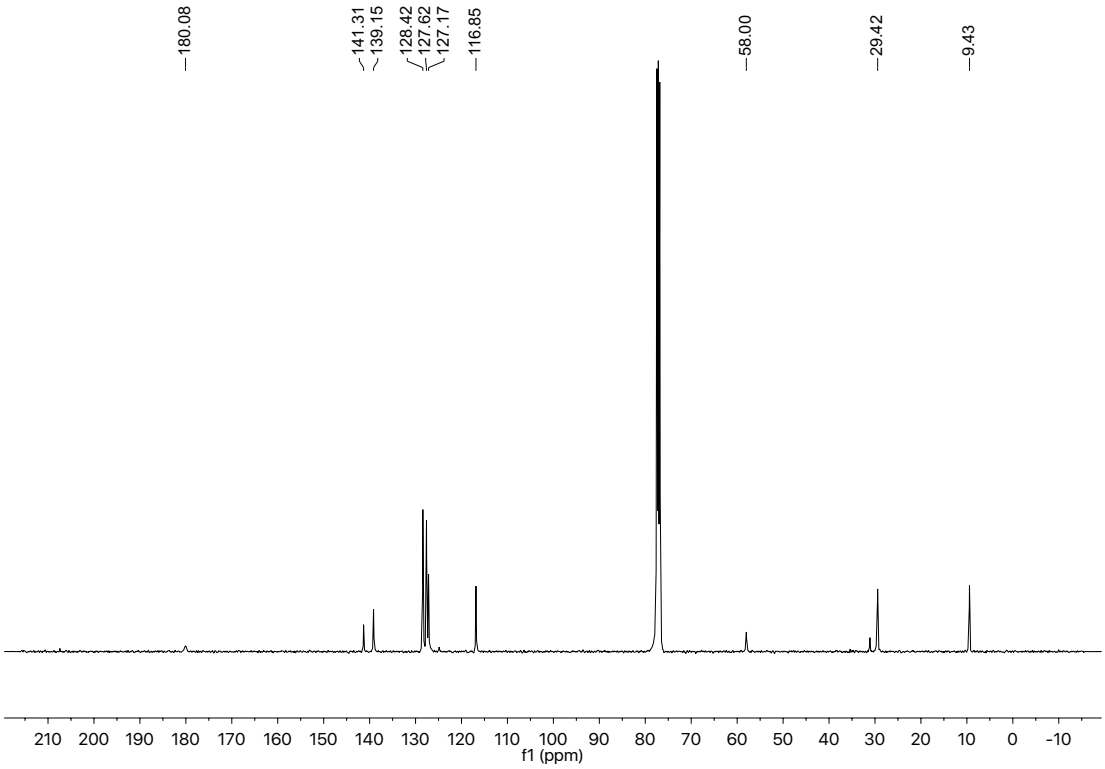
^{13}C NMR (101 MHz, $CDCl_3$) of compound **8e**.



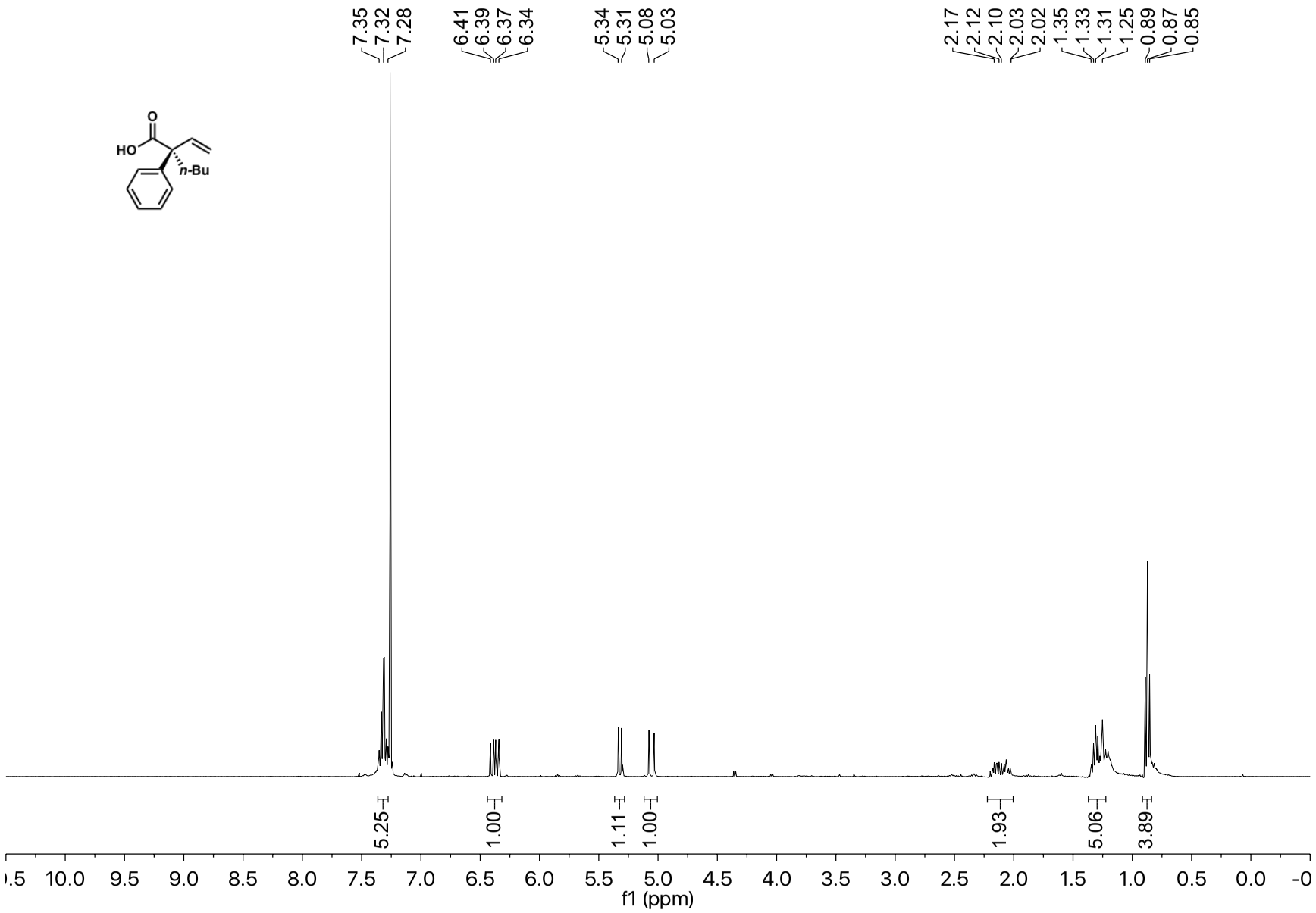
^{1}H NMR (400 MHz, $CDCl_3$) of compound **9a**.



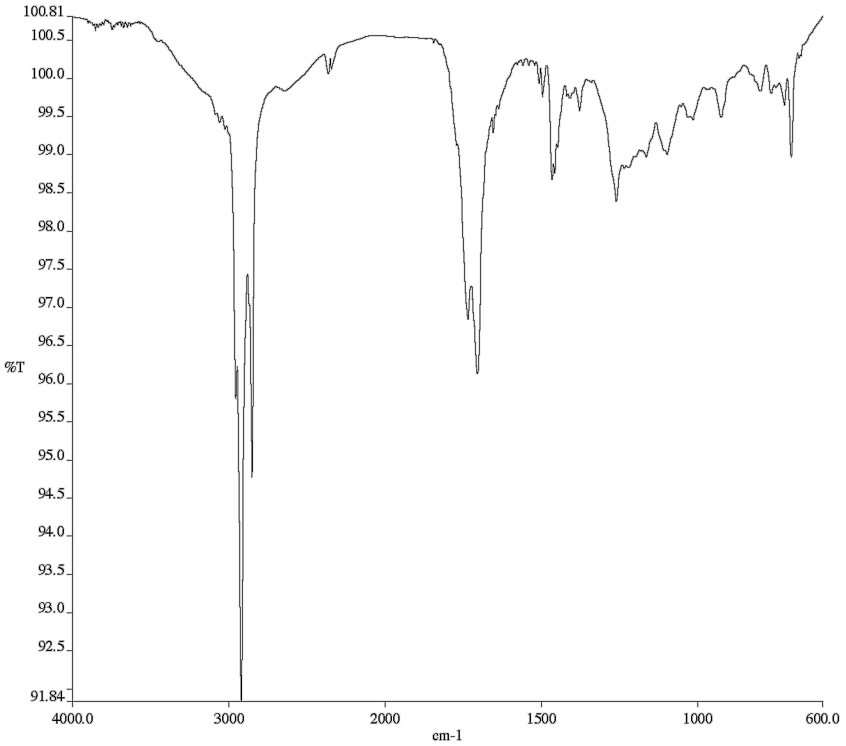
Infrared spectrum (Thin Film, NaCl) of compound **9a**.



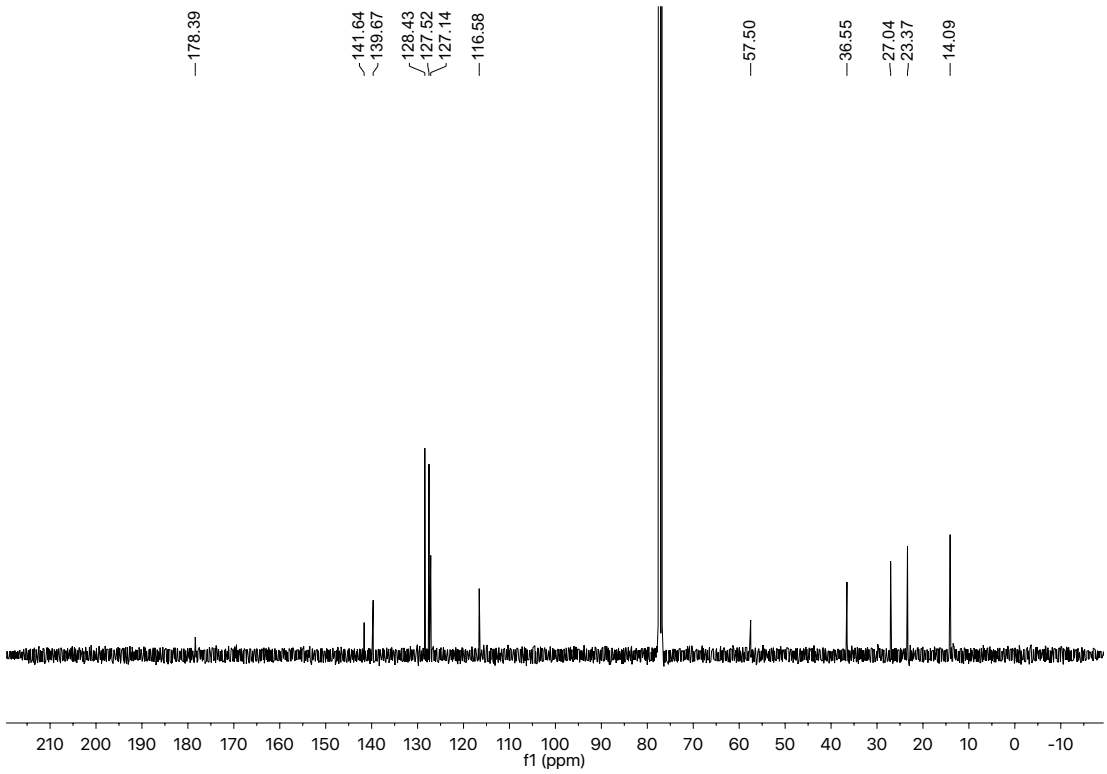
^{13}C NMR (101 MHz, $CDCl_3$) of compound **9a**.



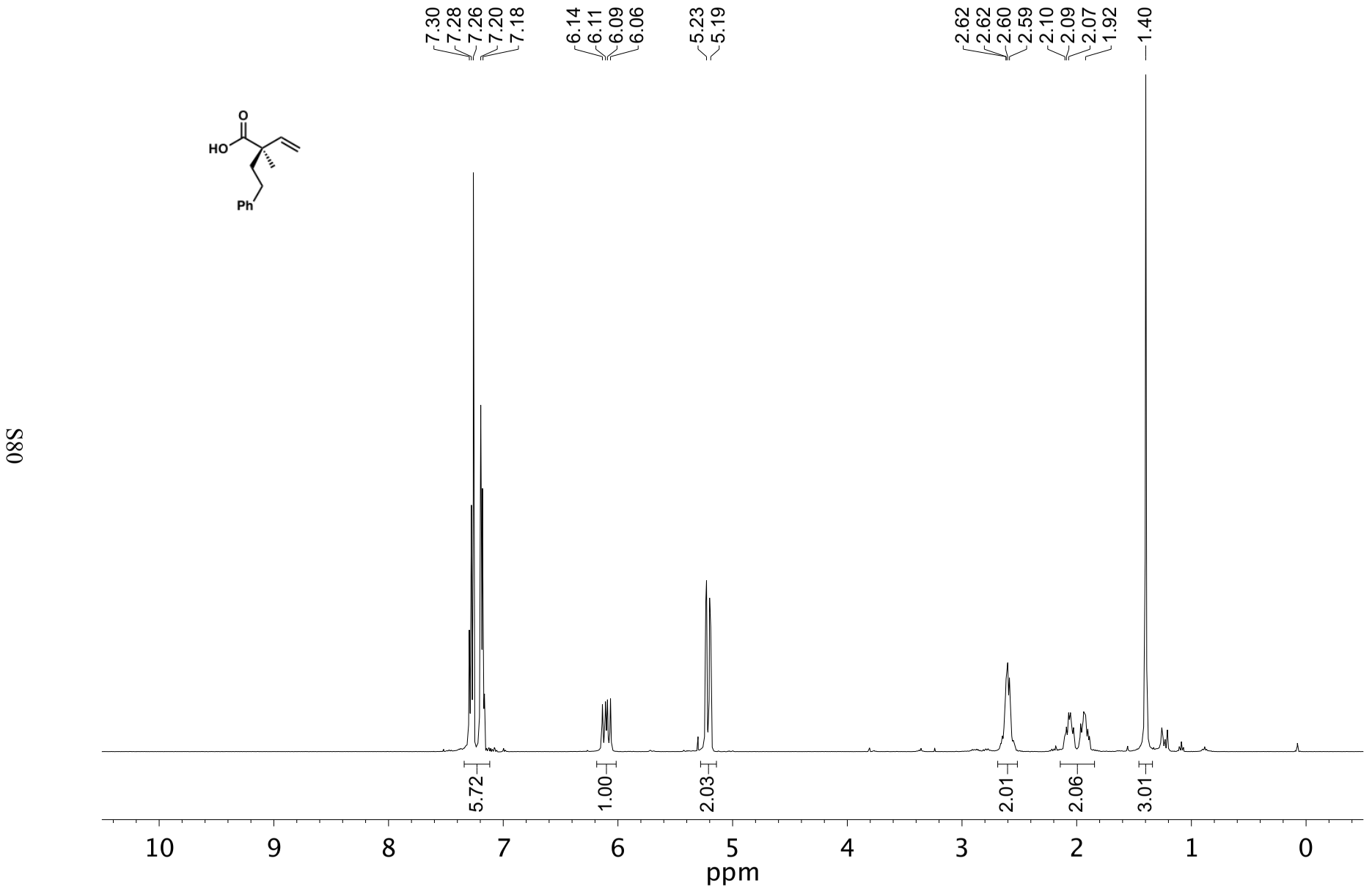
^{1}H NMR (400 MHz, $CDCl_3$) of compound **9b**.



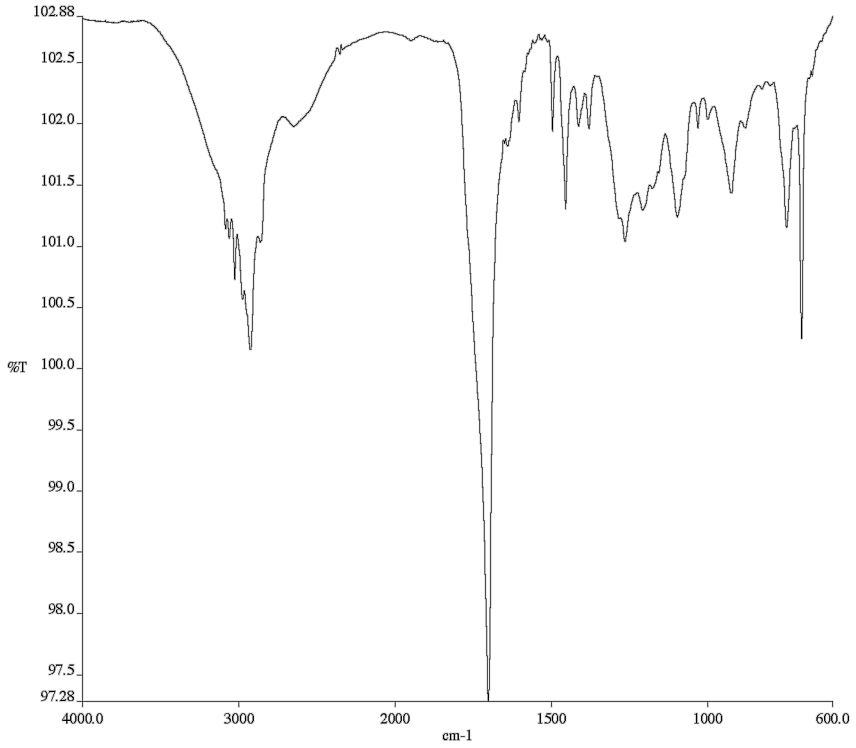
Infrared spectrum (Thin Film, NaCl) of compound **9b**.



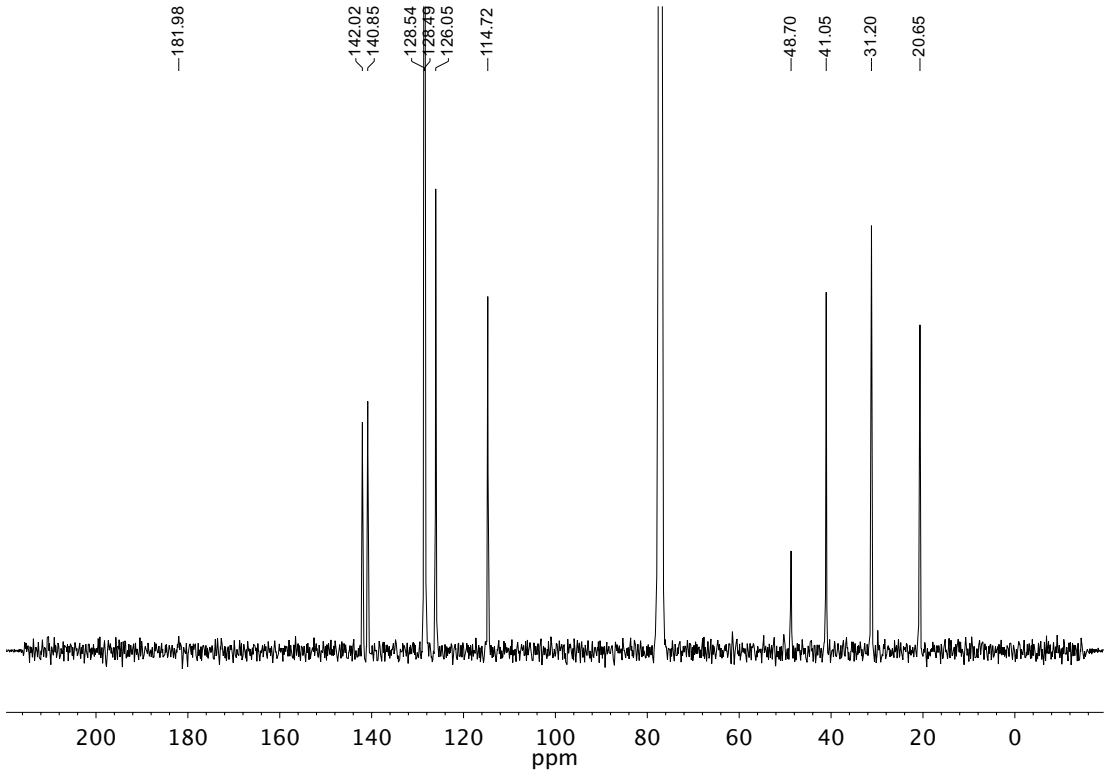
^{13}C NMR (101 MHz, $CDCl_3$) of compound **9b**.



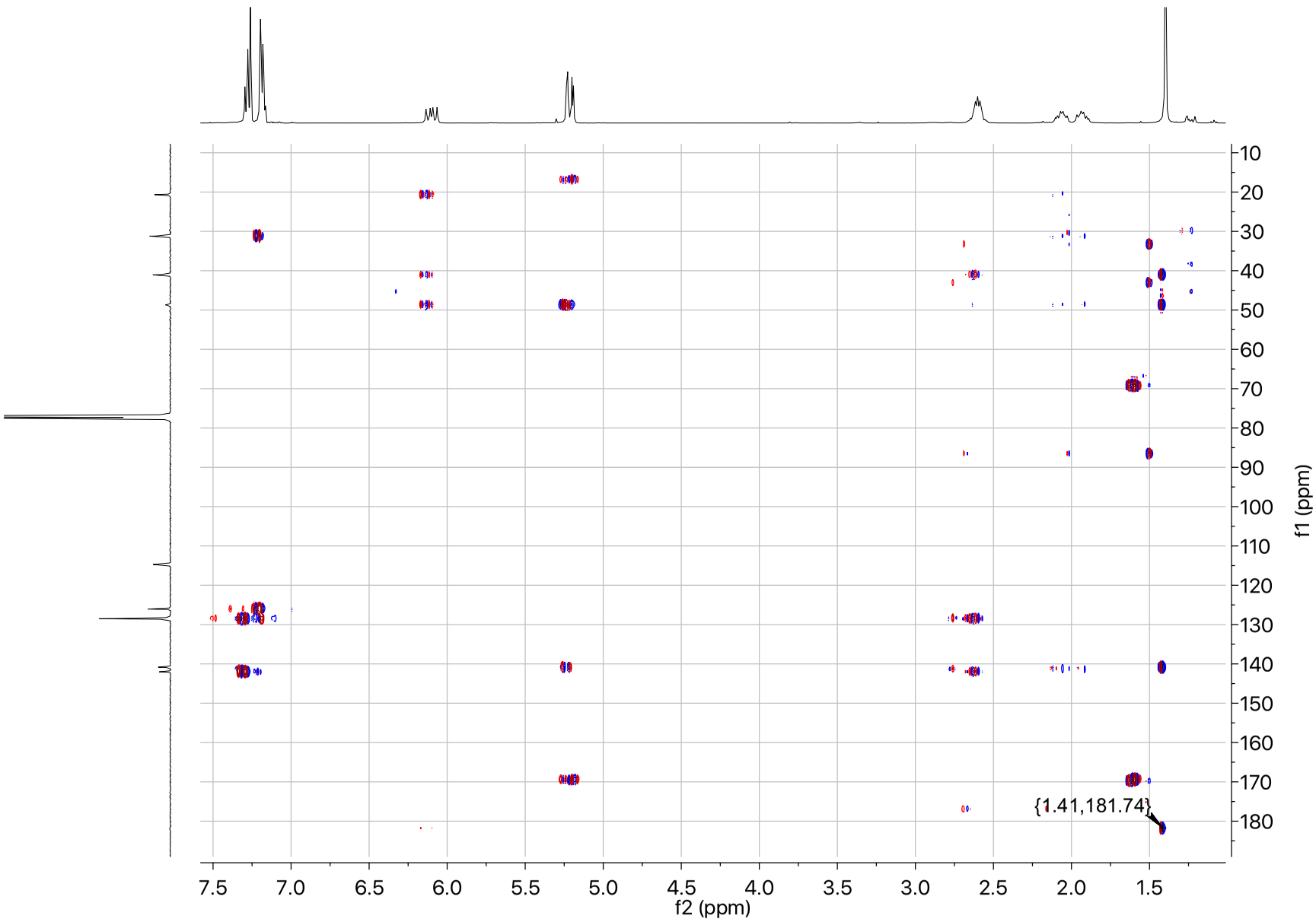
^{1}H NMR (400 MHz, $CDCl_3$) of compound **9f**.



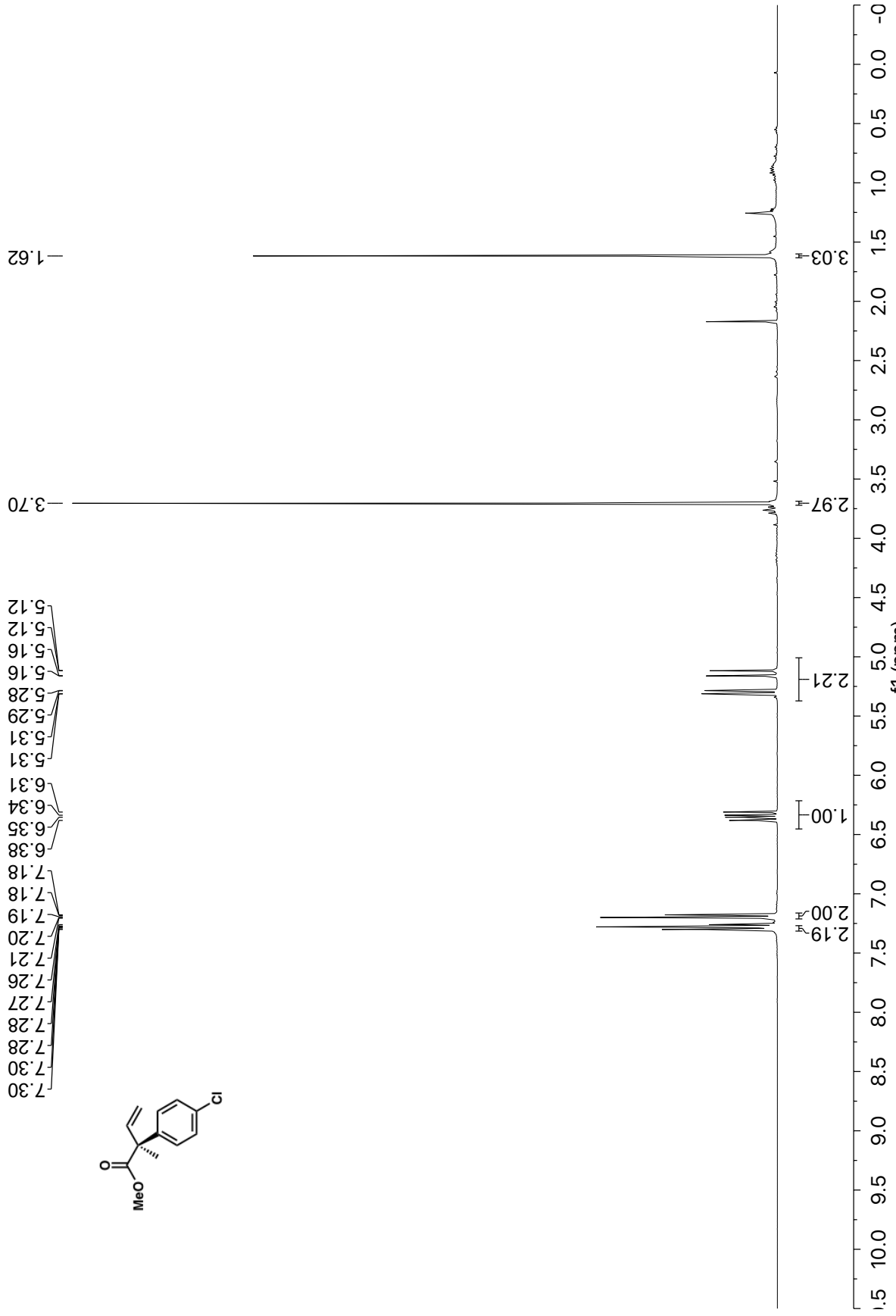
Infrared spectrum (Thin Film, NaCl) of compound **9f**.



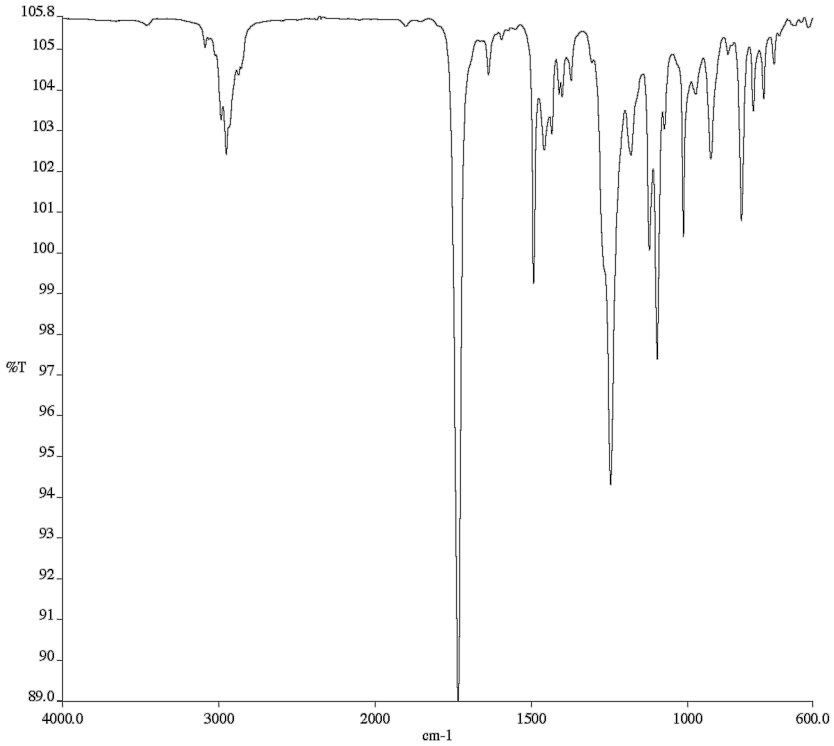
^{13}C NMR (101 MHz, $CDCl_3$) of compound **9f**.



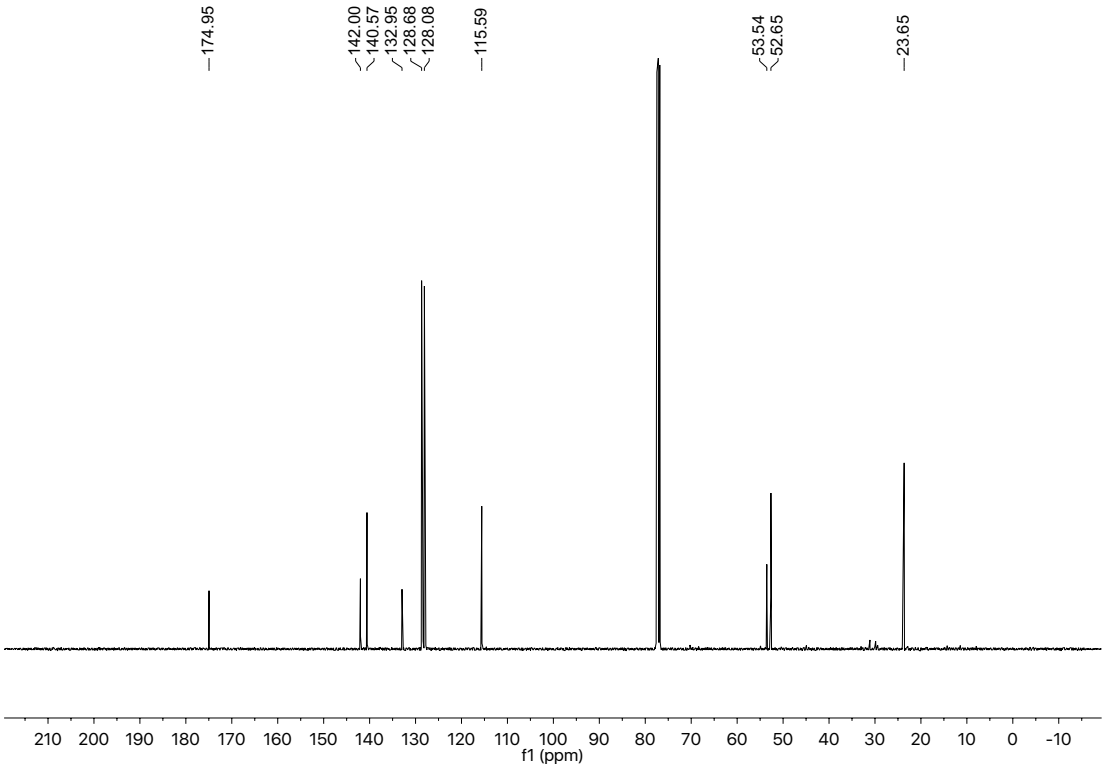
HMBC (400 MHz, $CDCl_3$) of compound **9f**.



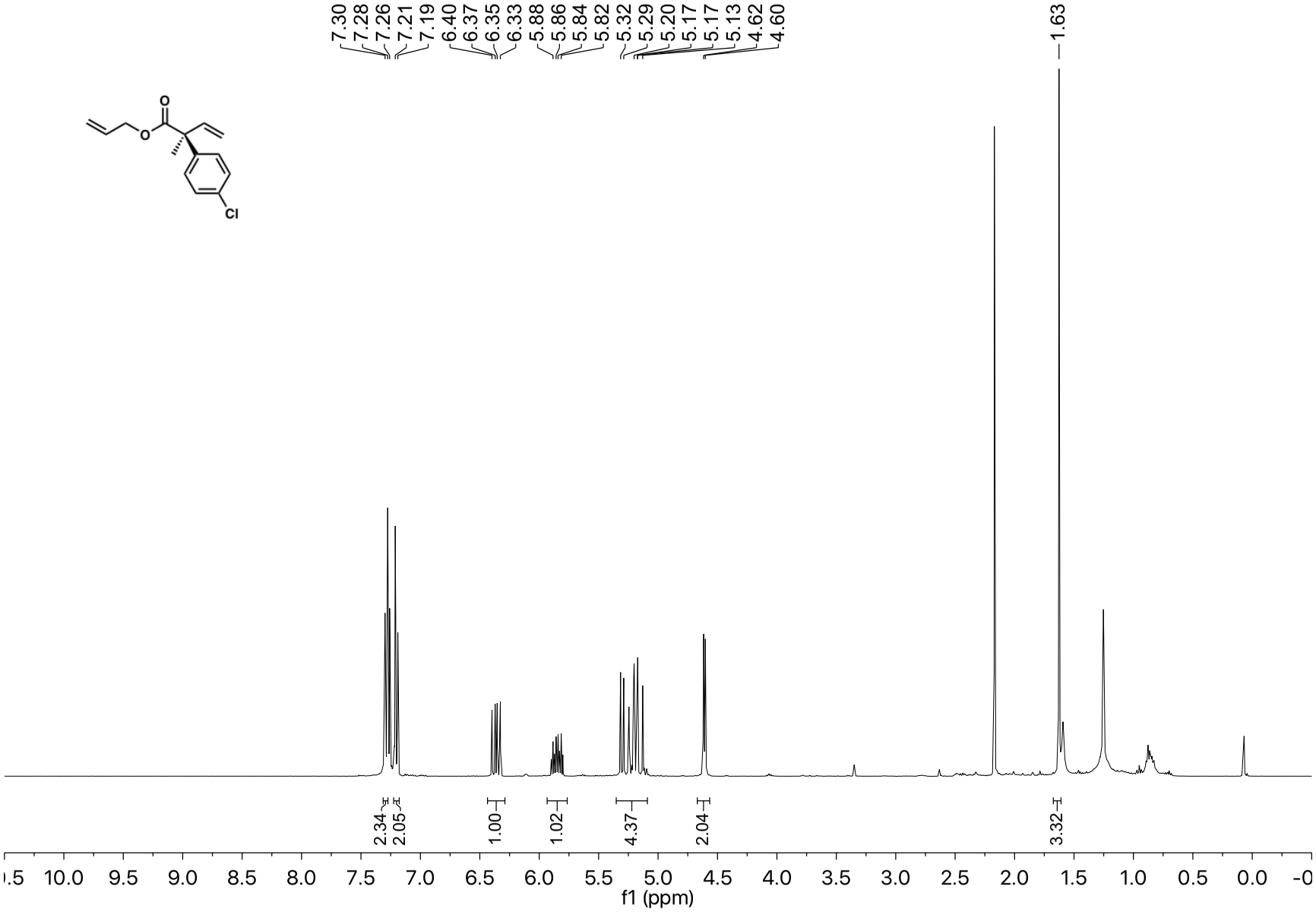
^{1}H NMR (400 MHz, $CDCl_3$) of compound **10**.



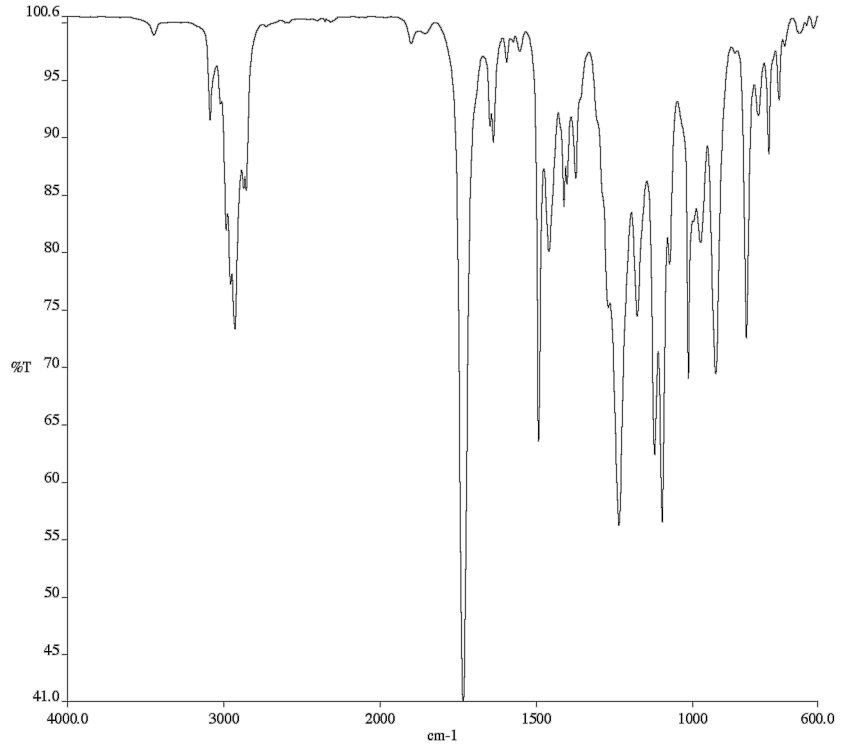
Infrared spectrum (Thin Film, NaCl) of compound **10**.



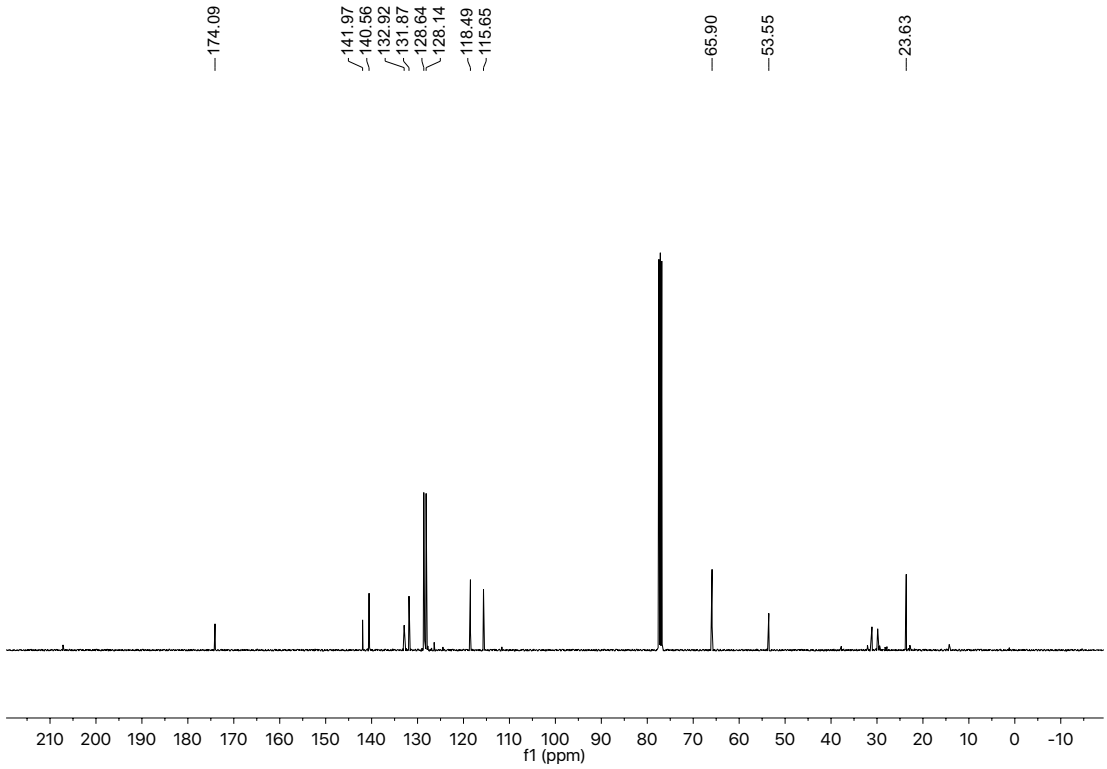
^{13}C NMR (101 MHz, $CDCl_3$) of compound **10**.



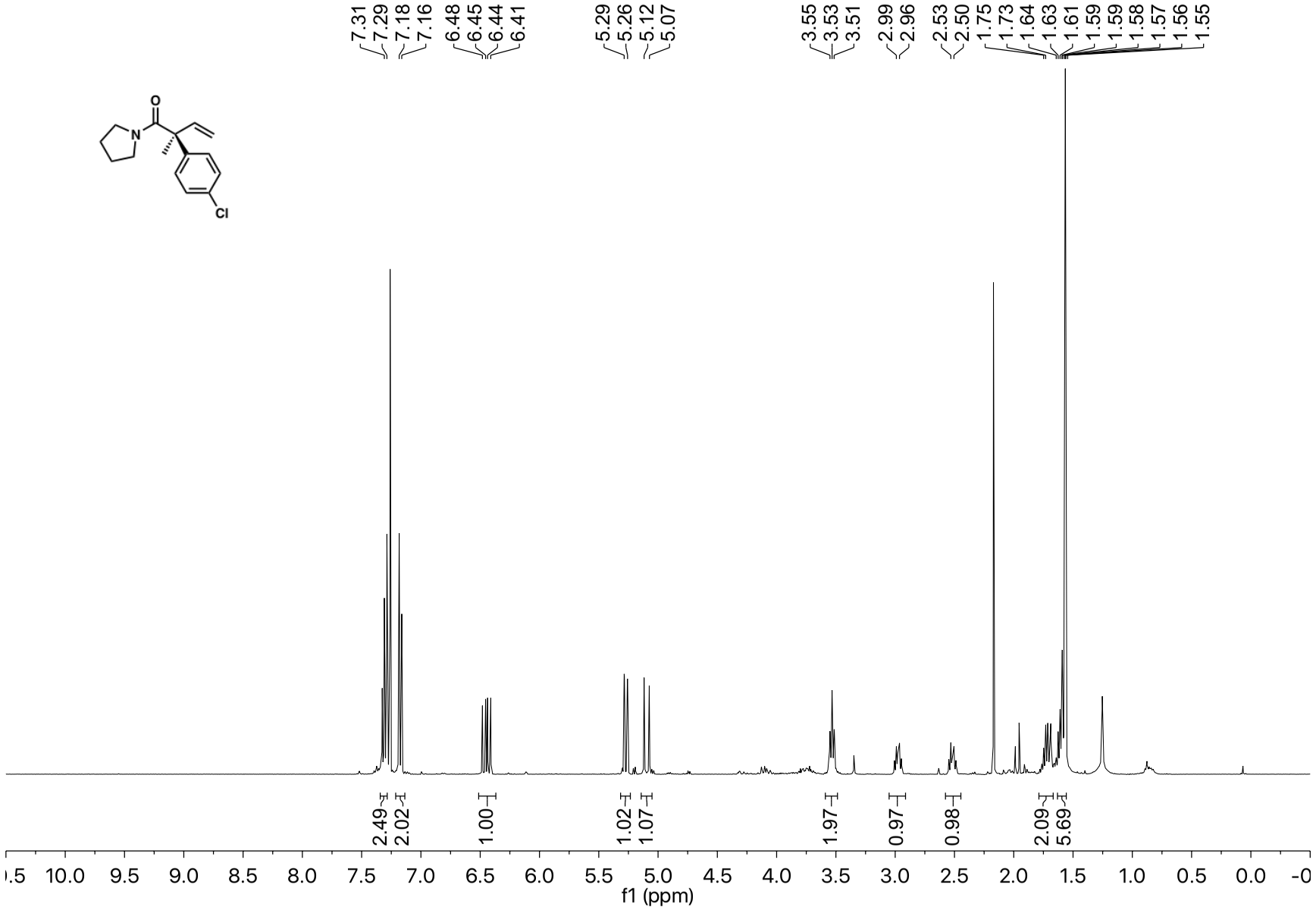
^{1}H NMR (400 MHz, $CDCl_3$) of compound **11**.



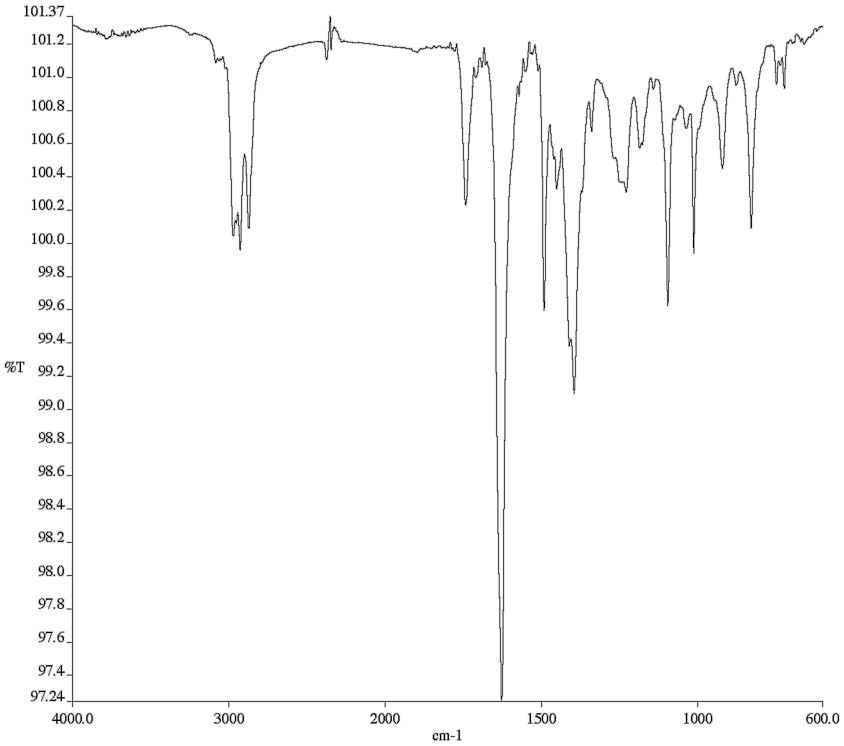
Infrared spectrum (Thin Film, NaCl) of compound **11**.



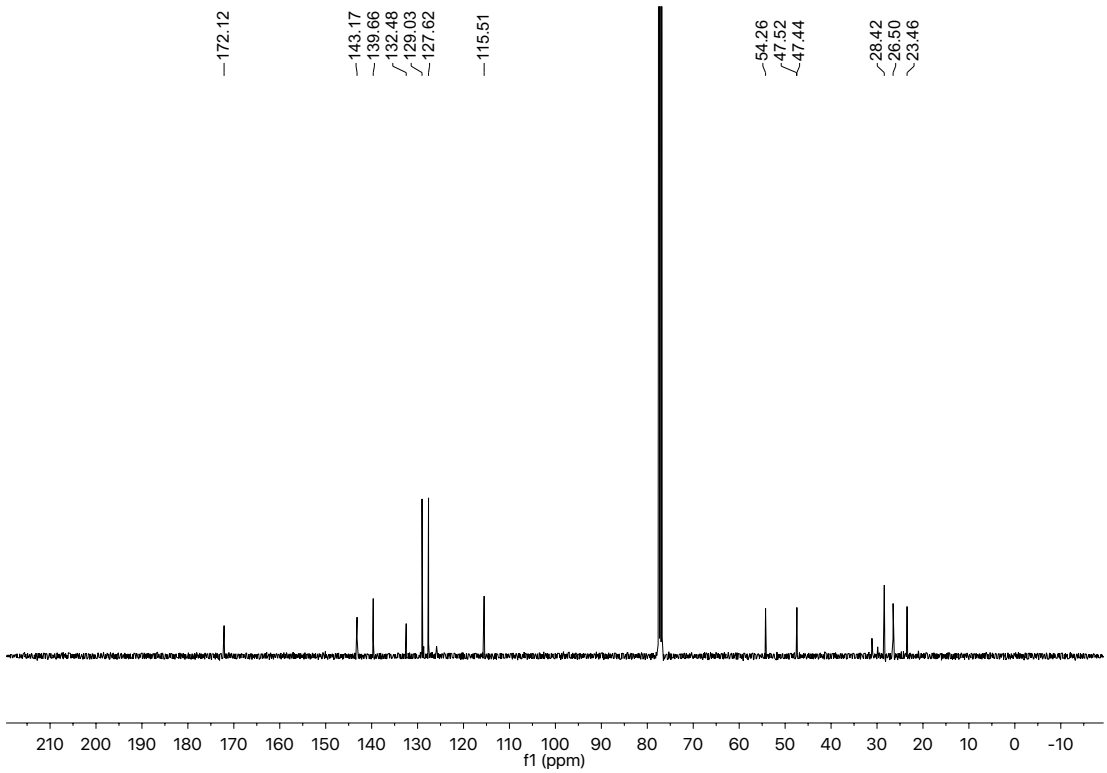
^{13}C NMR (101 MHz, $CDCl_3$) of compound **11**.



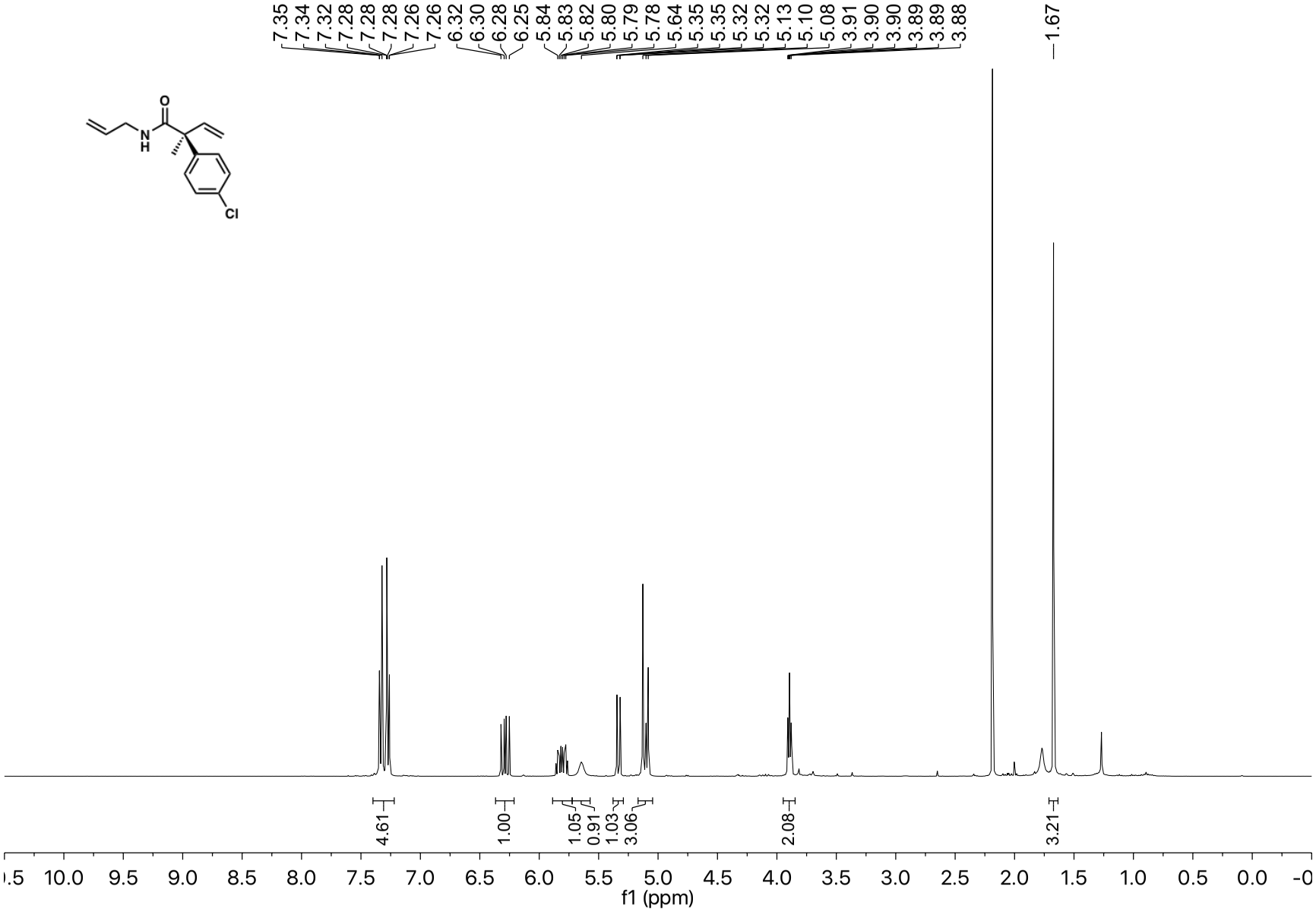
^{1}H NMR (400 MHz, $CDCl_3$) of compound **12**.



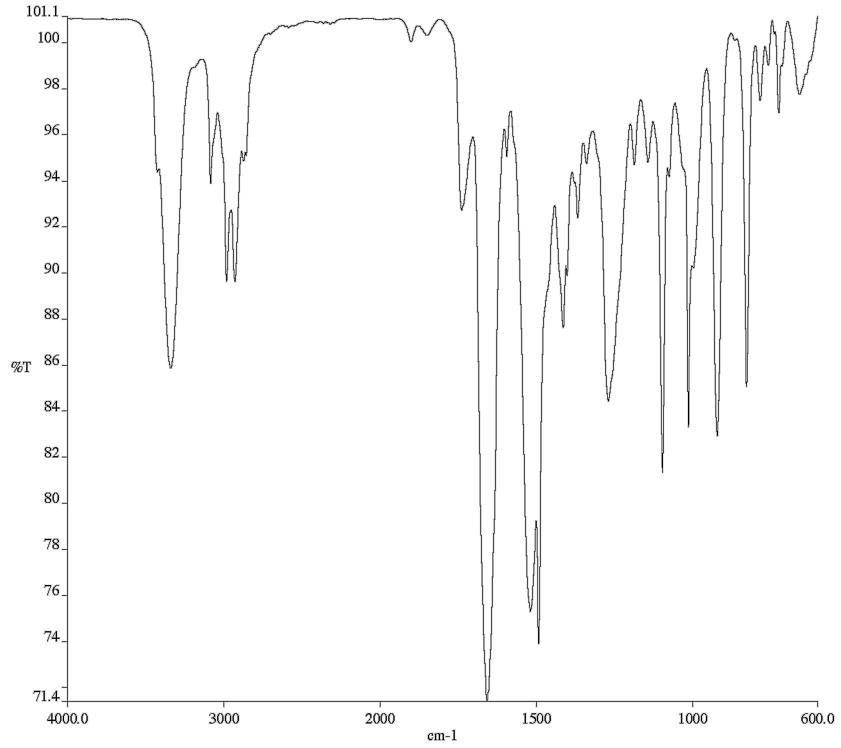
Infrared spectrum (Thin Film, NaCl) of compound **12**.



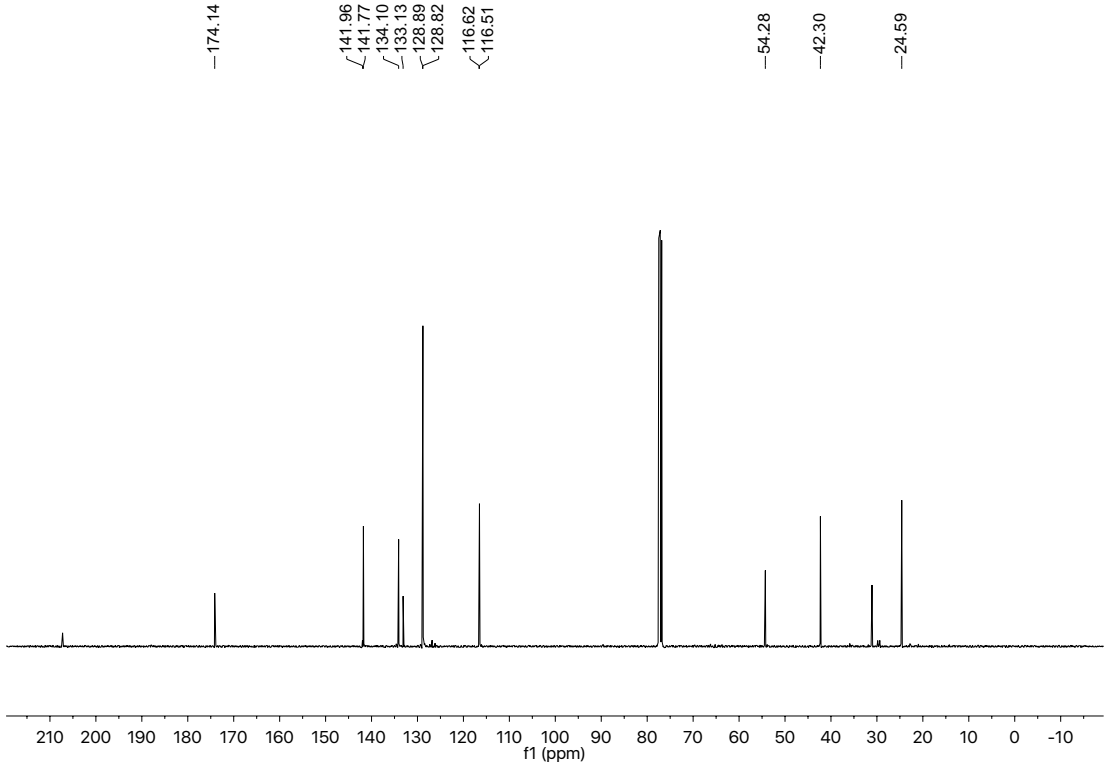
^{13}C NMR (101 MHz, $CDCl_3$) of compound **12**.



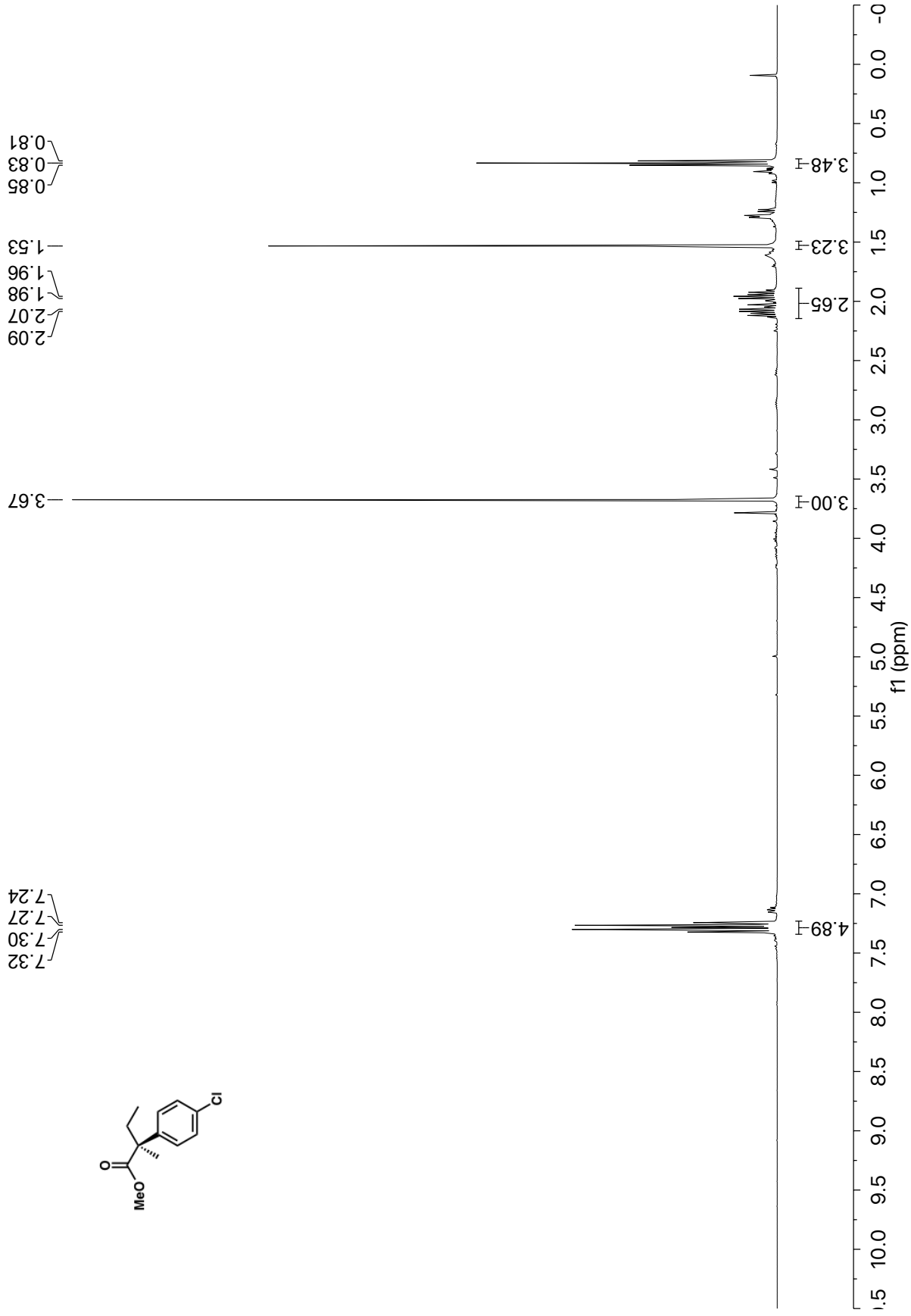
^{1}H NMR (400 MHz, $CDCl_3$) of compound **13**.



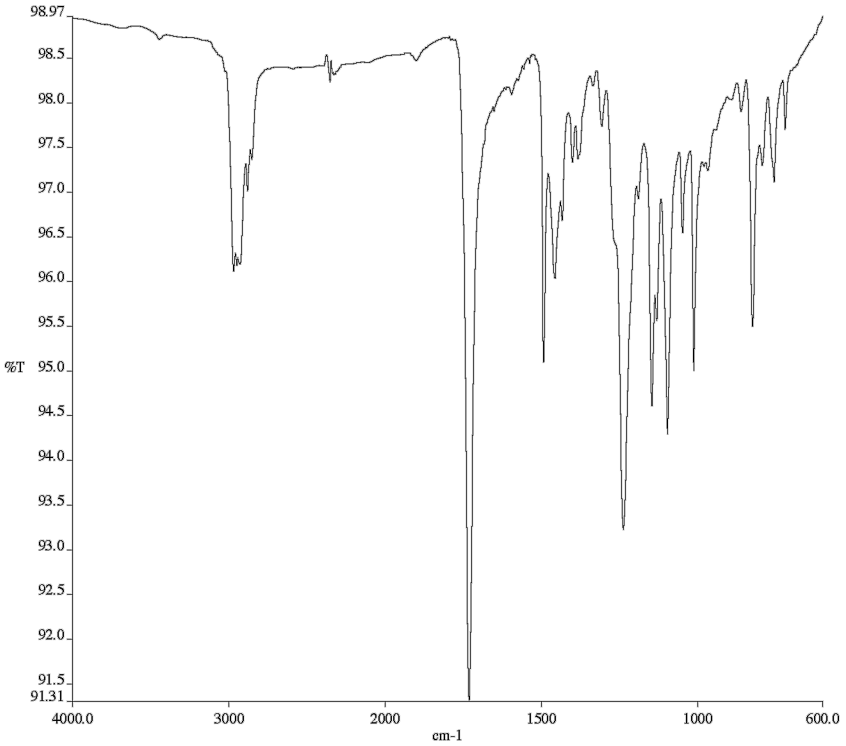
Infrared spectrum (Thin Film, NaCl) of compound **13**.



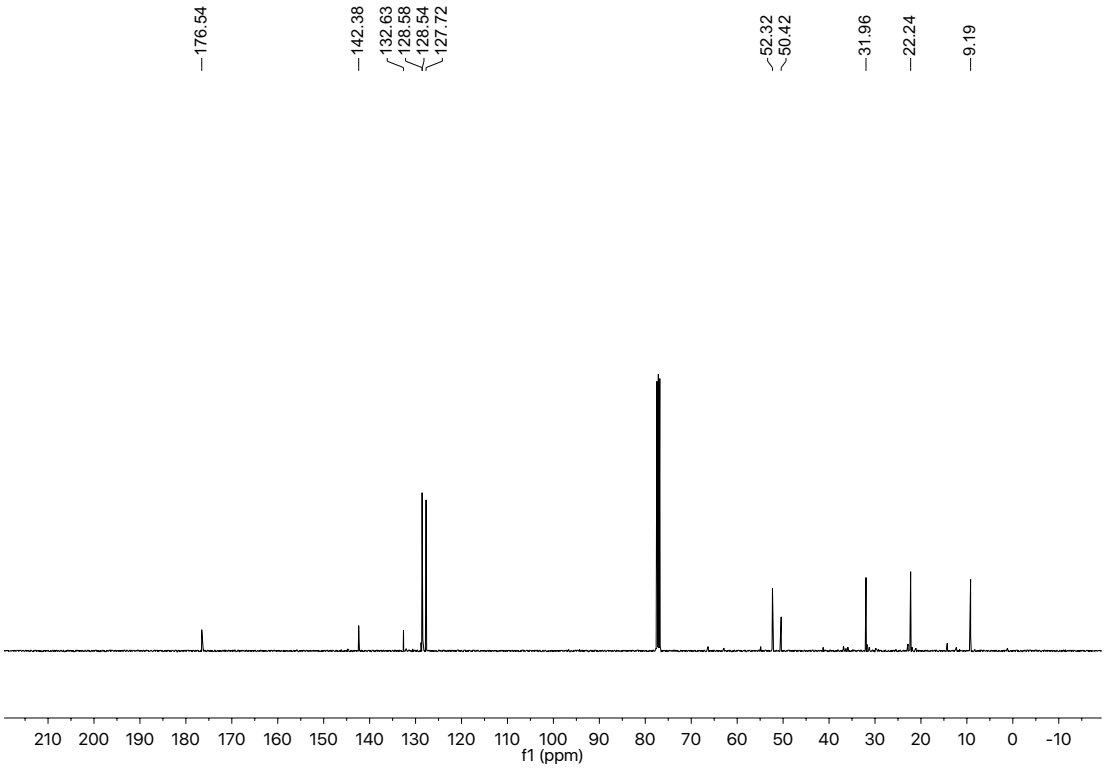
^{13}C NMR (101 MHz, $CDCl_3$) of compound **13**.



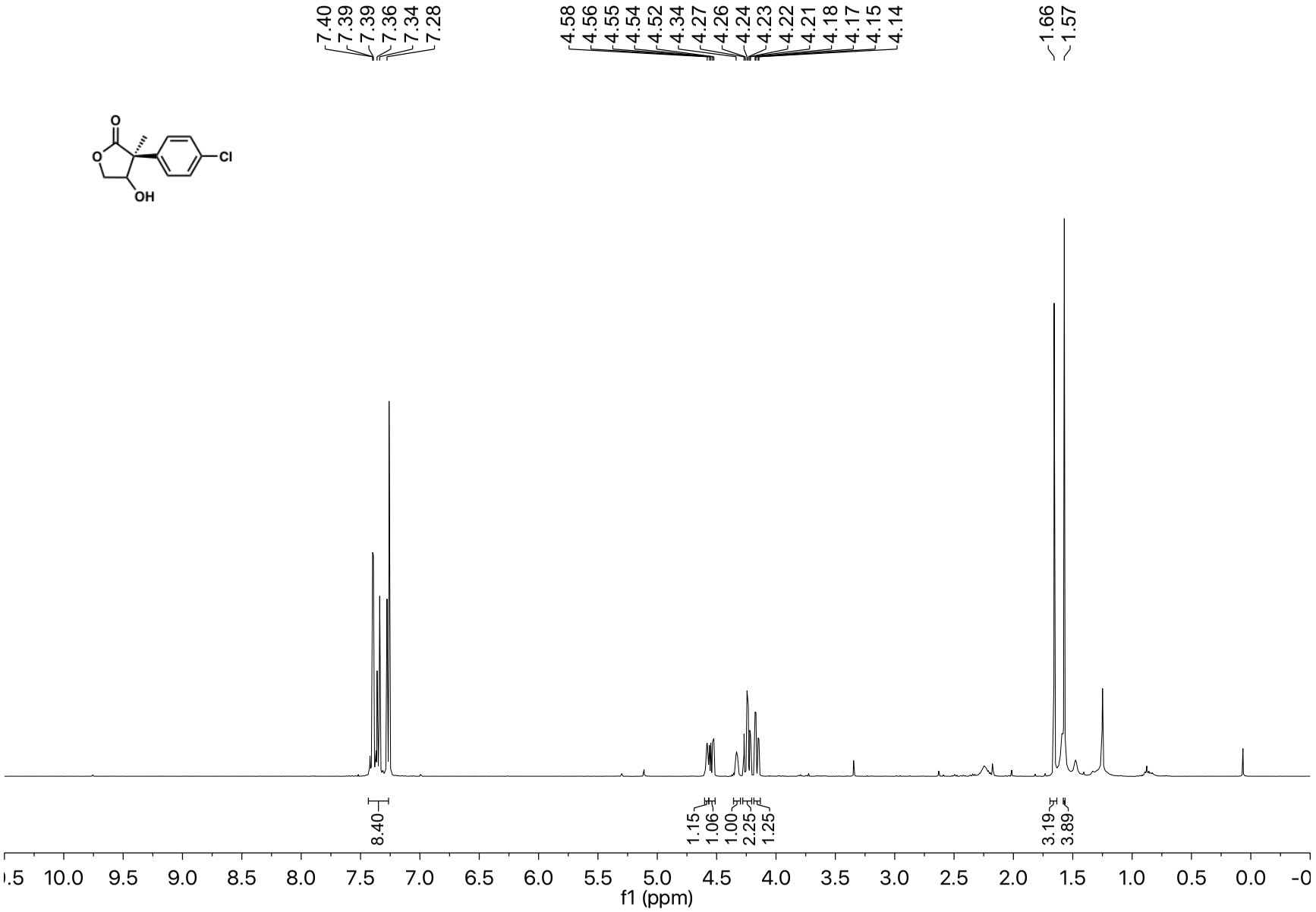
^{1}H NMR (400 MHz, $CDCl_3$) of compound **14**.



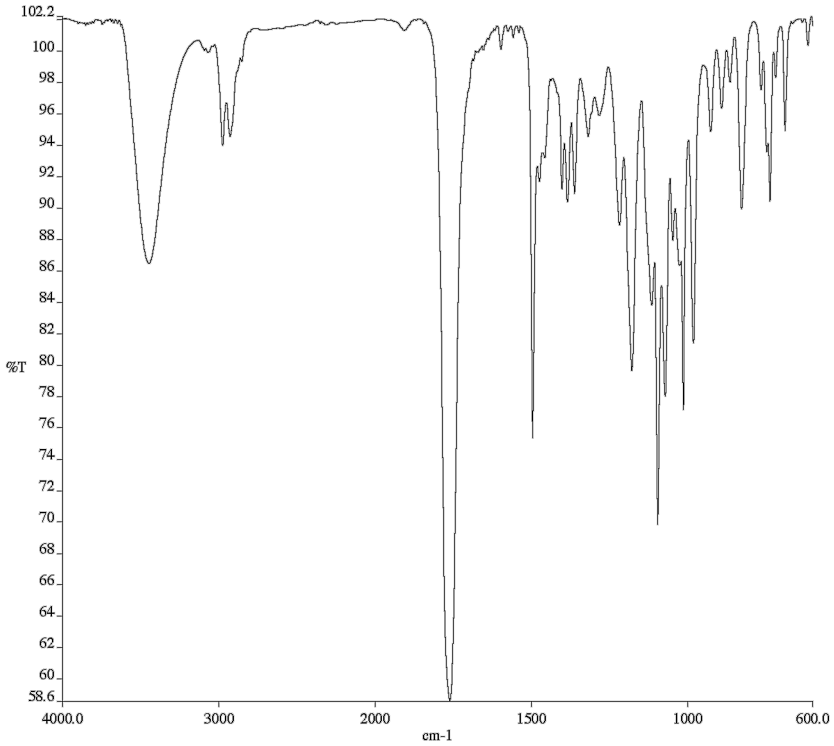
Infrared spectrum (Thin Film, NaCl) of compound **14**.



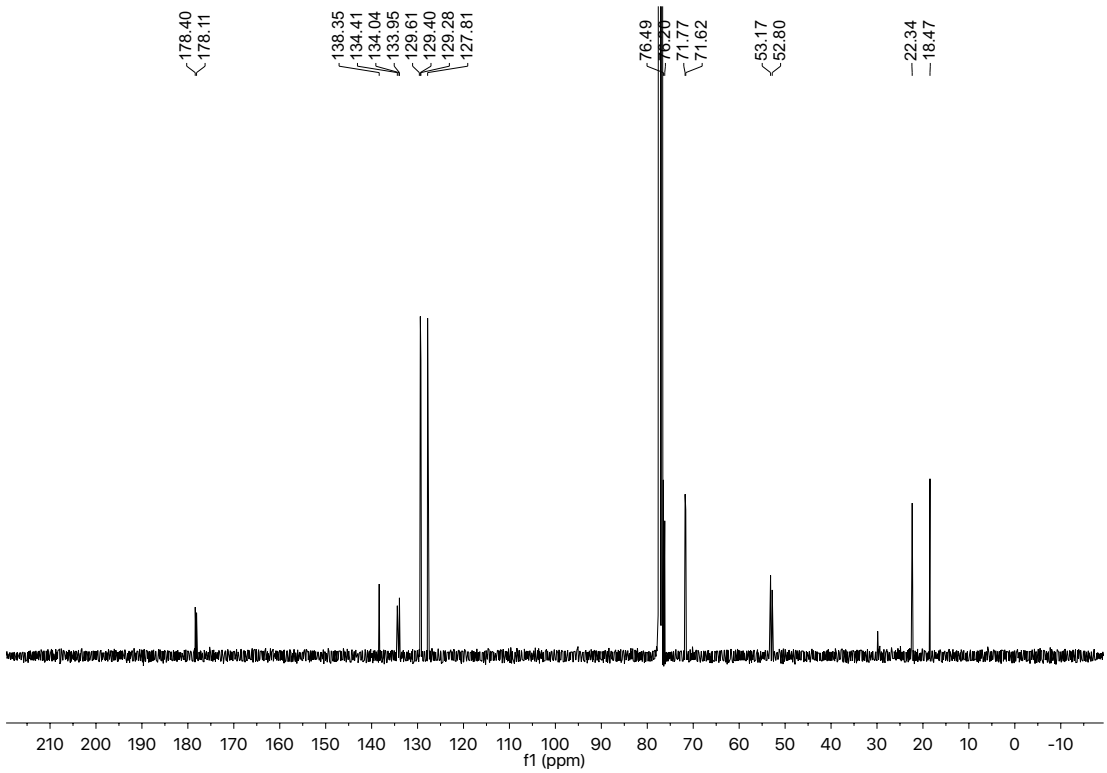
^{13}C NMR (101 MHz, $CDCl_3$) of compound **14**.



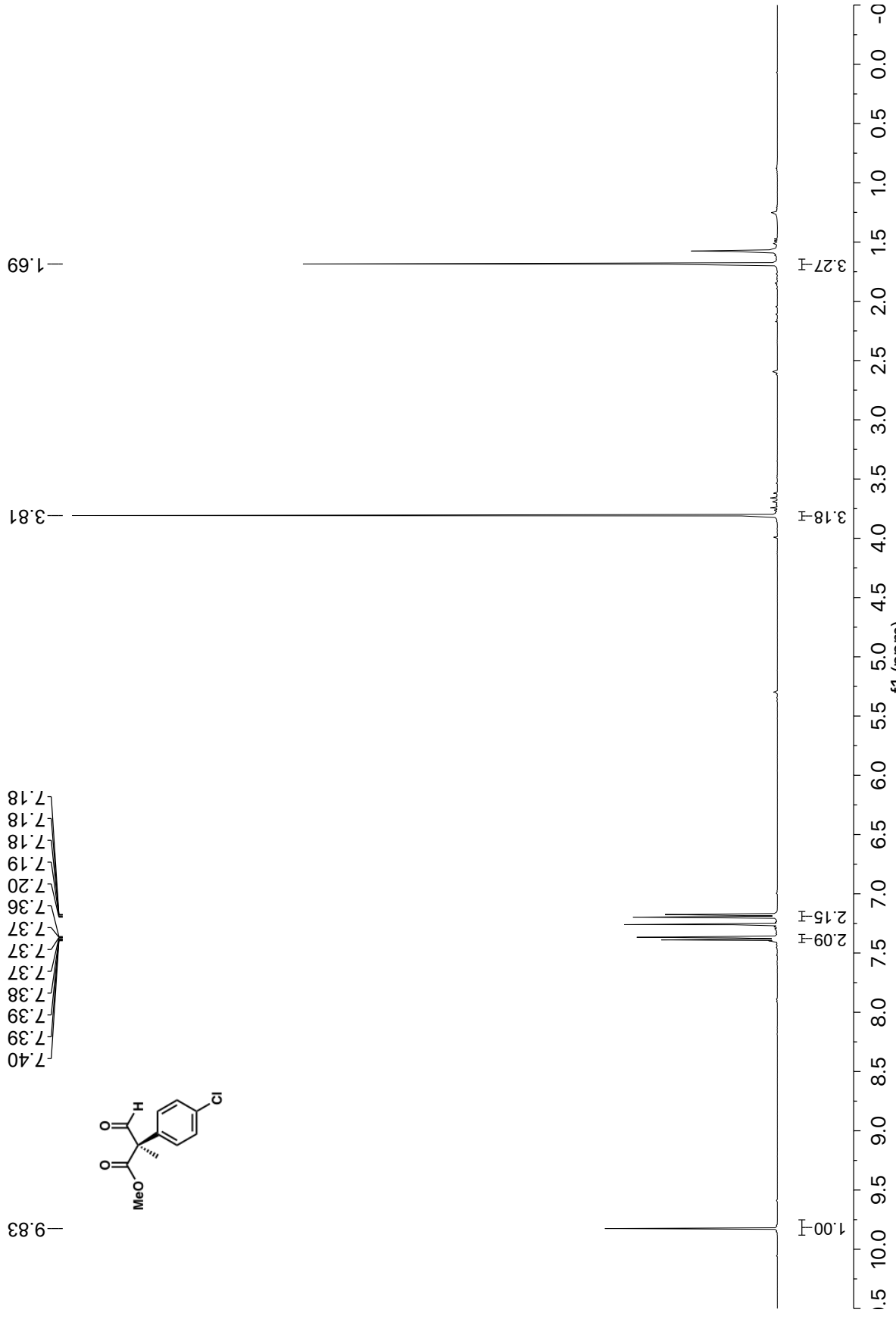
^{1}H NMR (400 MHz, $CDCl_3$) of compound **16**.



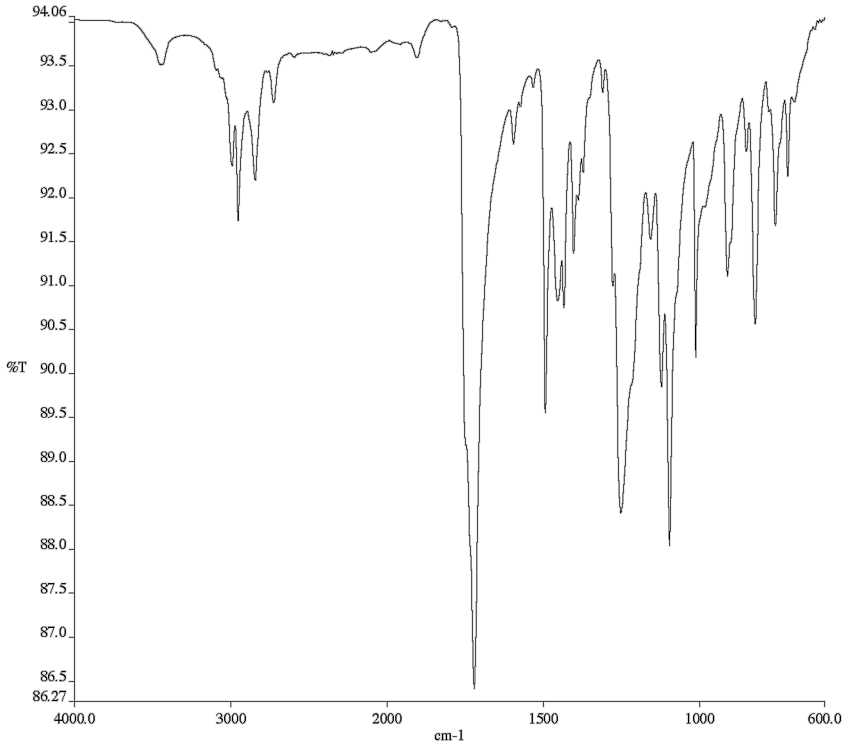
Infrared spectrum (Thin Film, NaCl) of compound **16**.



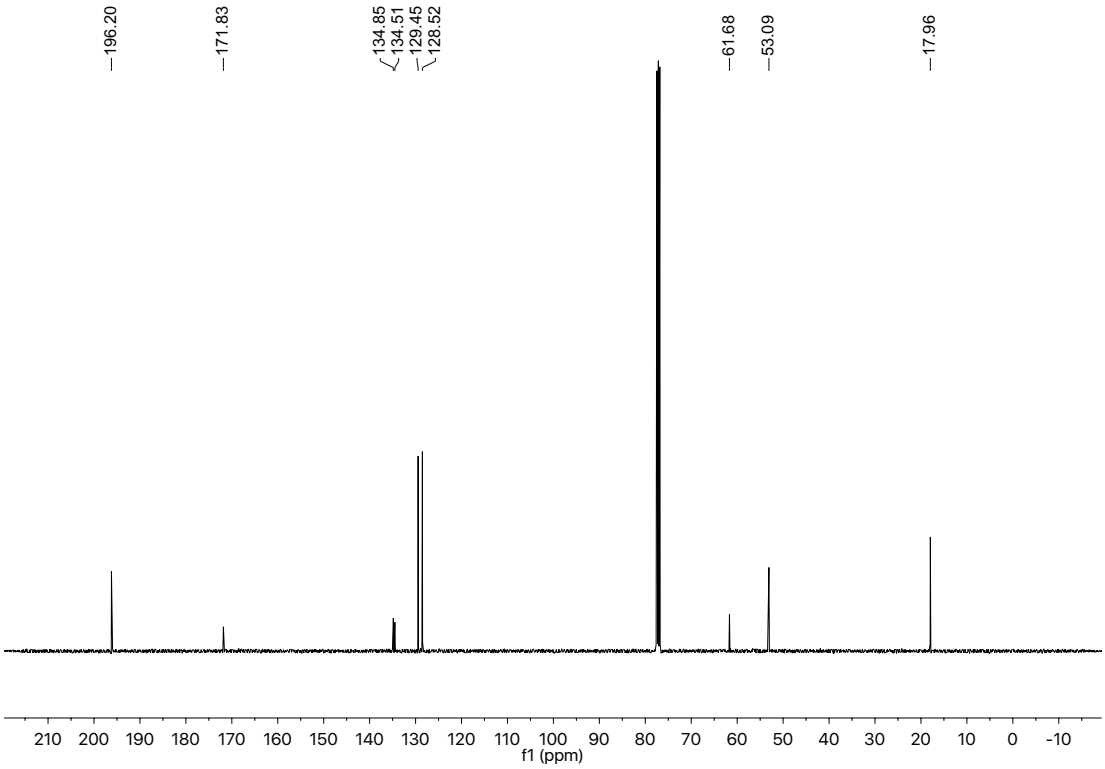
^{13}C NMR (101 MHz, $CDCl_3$) of compound **16**.



^{1}H NMR (400 MHz, $CDCl_3$) of compound **17**.



Infrared spectrum (Thin Film, NaCl) of compound **17**.



^{13}C NMR (101 MHz, $CDCl_3$) of compound **17**.