Reinvestigation of a Catalytic, Enantioselective Alkene Dibromination and Chlorohydroxylation

Scott E. Denmark* and Nessa Carson

Roger Adams Laboratory, University of Illinois, 600 South Mathews Avenue, Urbana, Illinois 61801

SUPPORTING INFORMATION

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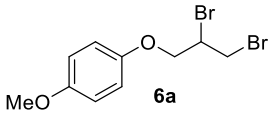
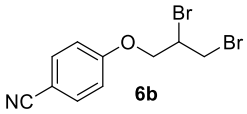
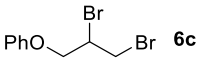
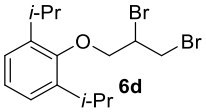
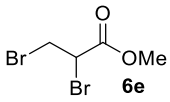
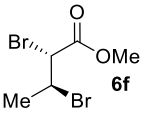
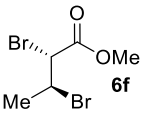
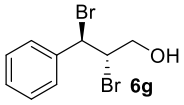
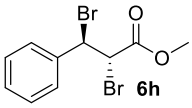
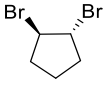
Henry's Dibromination Results[1]

Table S1. Henry's Reported Asymmetric Dibromination Results

Entry	Product[a]	Nuclearity of catalyst	Ligand	Recovered starting material	Dibromide yield, %[b]	er[c]
1	 **6a**	*Ambiguous in original text*	(*S*)-BINAP	NR	95	98:2
2	 **6b**	2	(*S*)-Tol-BINAP	NR	95	98.5:1.5
3	 **6c**	2	(*S*)-BINAP	NR	95	97.5:2.5
4	 **6d**	1	(*S*)-BINAP	NR	95	97:3
5	 **6e**	2	(*S*)-METBOX	63%	31	97:3
6	 **6f**	1	(*S*)-BZOX	30%	80[d]	92:8
7	 **6f**	2	(*S*)-METBOX	21%	70	91:9
8	 **6g**	2	(*R*)-BINAM	24%	77	90:10
9	 **6h**	2	(*R*)-BINAM	12%	83	57:43
10	 **6i**	2	(*S*)-Tol-BINAP	NR	85[e]	-

NR = not reported. [a] Absolute configuration not determined. [b] Isolated yield. Yields differ from the values in the original paper since they are calculated from the amount of olefin substrate used rather than the amount that was converted under the reaction conditions, where this information is available. [c] er of dibromide products determined by ^{1}H chiral shift reagent NMR. [d] Yield calculated from oxygen uptake. [e] An unnamed byproduct was formed in approximately 14% yield by GC analysis.

General Experimental

Reaction Setup: Reactions were performed in oven-dried glassware. Room temperature (rt) was approximately 23 °C. Solvent evaporation was performed on a rotary evaporator at 30 °C unless otherwise specified.

NMR Spectroscopy: Spectra were recorded on Varian 500 MHz spectrometers. ^{1}H and ^{13}C spectra were referenced to residual non-deuterated chloroform (7.26 ppm, ^{1}H; 77.02 ppm, ^{13}C) or d_6-DMSO
(2.49 ppm, ^{1}H; 39.52 ppm, ^{13}C). ^{31}P spectra were referenced to an external standard of 85% H_3PO_4 in H_2O (0 ppm). ^{13}C spectra were recorded with broadband decoupling of the ^{1}H nucleus, and ^{31}P spectra with broadband decoupling of the ^{13}C nucleus. Chemical shifts are reported in parts per million (ppm), multiplicities indicated by s (singlet), d (doublet), t (triplet), sext (sextet), sept (septet), br (broad), and m (multiplet). Coupling constants, *J*, are reported in Hz with integration provided and assignments indicated.

Infrared Spectroscopy: Infrared spectra (IR) were recorded using a Perkin-Elmer FTIR instrument. Peaks are reported in cm^{-1} with indicated relative absorption intensities: s (strong, 67–100%); m (medium, 34–66%); w (weak, 0–33%) and sh (sharp) and br (broad) assignments.

Mass Spectrometry: Matrix-assisted laser desorption/ionization (MALDI) spectrometry was performed on an AB Voyager instrument. Electron Impact (EI) spectrometry was performed at 70 eV using methane as the carrier gas, with a time-of-flight (TOF) mass analyzer. Data are reported in the form of m/z (intensity relative to the base peak = 100).

Distillation: Bulb-to-bulb distillation was performed using a Kugelrohr, with boiling points (bp) corresponding to uncorrected air bath temperatures (ABT) under vacuum.

Gas Chromatography: Analytical gas chromatography (GC) was performed using a flame ionization detector and an Agilent CycloSil-B column. Injector temperature was 250 °C, and detector temperature was 300 °C, with a H_2 carrier gas flow of 4.7 mL min^{-1}.

Liquid Chromatography: Analytical thin-layer chromatography (TLC) was performed on silica gel 60 F_{254} plates. Retention factor (R_f) values reported were measured using 10 × 2 cm silica TLC plates in a developing chamber containing the solvent system described. Visualization was accomplished with UV light and cerium(IV) ammonium molybdate solution (CAM), acidic 2,4-dinitrophenylhydrazine solution (DNP), or a solution of silver nitrate and 2-phenoxyethanol with one drop of 30% aqueous hydrogen peroxide and UV irradiation for several minutes ($AgNO_3$-H_2O_2). Flash column chromatography

was performed using 40–63 μm particle size (230–400 mesh, 60 Å pore size) SiO_2. Analytical high-performance liquid chromatography (HPLC) was performed on an Agilent 1100 system using a UV detector (254 nm) and a Chiralpak IB-3 or OJ-H column. Analytical supercritical fluid chromatography (SFC) was performed on an Agilent 1100 HPLC equipped with an Aurora Systems A-5 supercritical CO_2 adapter for SFC, using a UV detector (220 nm) and a Daicel Chiralcel OD column.

Solvents: Anhydrous toluene (ACS grade), anhydrous benzene, anhydrous diethyl ether (ACS grade, BHT-stabilized), anhydrous 1,2-dimethoxyethane (DME), and anhydrous tetrahydrofuran (THF, HPLC grade) were dried by percolation through two columns packed with neutral alumina, under a positive pressure of argon. Anhydrous acetonitrile was freshly distilled from sodium. Anhydrous acetone was prepared by stirring acetone (Optima grade) with 10 g L^{-1} anhydrous calcium sulfate for 4 h under Ar, followed by distillation from fresh anhydrous calcium sulfate.[2] Other solvents for reaction, filtration, transfers and chromatography were hexane (Optima grade), toluene (ACS grade), dichloromethane (ACS grade), chloroform (ACS grade), ethyl acetate (ACS grade), acetone (Optima grade), 95% or 100% ethanol (USP grade), and methanol (Optima grade). Degassing of solvents was achieved by sparging with Ar.

Chemicals: Copper(II) bromide, lithium bromide, sodium hydride and tetrakis(acetonitrile)palladium(II) tetrafluoroborate were stored in a glove box under Ar. (*R*)-BINAP and (*R*)-Tol-BINAP were purified by basic aqueous extraction from toluene, trituration with degassed MeOH and subsequent recrystallization from 1:1 toluene:EtOH.[2] Anhydrous triethylamine was freshly distilled from calcium hydride. All other reagents were used as received.

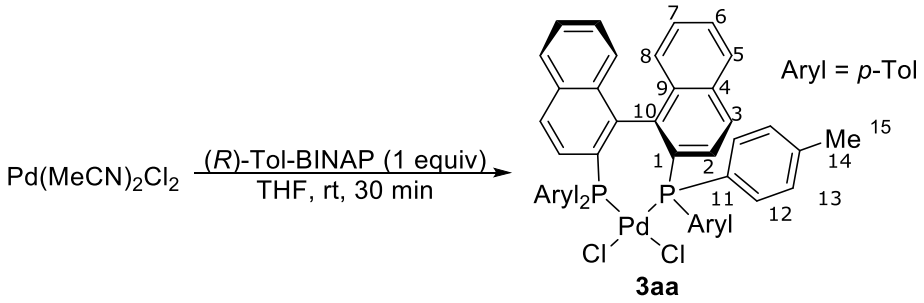
Literature Preparations

Allyl aryl ethers **1c** and **5a**–**5d** were prepared according to a literature procedure,[3,4] were purified *via* Kugelrohr distillation or sublimation, and had spectroscopic data consistent with literature.

(*R*)-BINAP bis(acetonitrile)palladium(II) tetrafluoroborate 3b[5] (highly air-sensitive) and **1-phenylhexane-1,3,5-trione**[6] were also prepared according to literature procedures, and had spectroscopic data consistent with literature.

Experimental Procedures

Preparation and Isolation of Palladium Catalyst 3aa



3aa

Complex **3aa** was generated *in situ* for Table 1, Entries 8 and 10, and a sample was isolated for characterization purposes.

Bis(acetonitrile)dichloropalladium(II) (20 mg, 77 μmol) was charged to a 10-mL, two-necked, round-bottomed flask, in a glove box. Anhydrous, degassed THF (0.5 mL) was added, followed by (*R*)-Tol-BINAP (51 mg, 77 μmol, 1.0 equiv), washing with further anhydrous, degassed THF (0.5 mL). The clear, orange-yellow solution was stirred at rt for 30 min. Anhydrous, degassed Et_2O (3 mL) was added, and a yellow precipitate was immediately produced. The solution was filtered, and the filtrand dried *in vacuo* to 62 mg (77 μmol, **97%** yield) of a bright yellow powder. Further drying under high vacuum (50 Pa) for over 24 h did not remove residual Et_2O.

Data for **3b**:

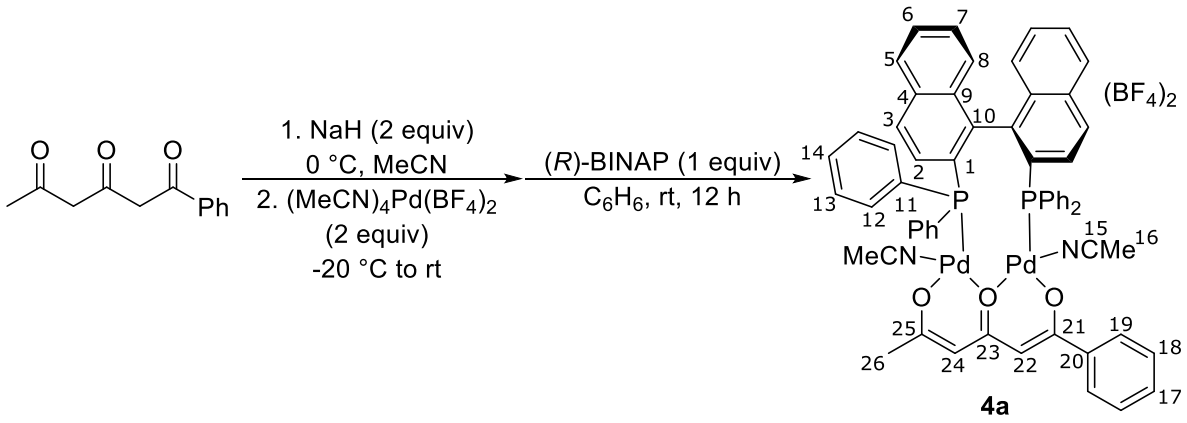
^{1}H NMR: (500 MHz, d_6-DMSO)
δ 7.73 (d, J = 8.9 Hz, 2 H), 7.70 (d, J = 8.2 Hz, 2 H), 7.61 (dd, J = 11.7, 8.2 Hz, 4 H), 7.50 (t, J = 7.5 Hz, 2 H), 7.39 (br s, 4 H), 7.33 (d, J = 7.4 Hz, 4 H), 7.14–7.24 (m, 4 H), 6.63 (d, J = 8.7 Hz, 2 H), 6.53 (br s, 4 H), 2.38 (s, 6 H, $H_{3,A}C(15)$), 1.98 (s, 6 H, $H_{3,B}C(15)$)

^{31}P NMR: (202 MHz, d_6-DMSO)
28.62

IR: (KBr; pressed under Ar)
3416 (s, v br), 3055 (s), 2976 (s), 2920 (s), 2866 (s), 1597 (s), 1557 (m), 1498 (s), 1444 (m), 1397 (m), 1308 (m), 1224 (w), 1192 (m), 1159 (w), 1101 (s), 1020 (w), 870 (w), 846 (w), 803 (s), 746 (s), 707 (m), 697 (m), 670 (m), 652 (m), 636 (m), 621 (m), 614 (m), 602 (m), 530 (m), 523 (m), 508 (s), 475 (m), 454 (m)

MS: (MALDI; THF)
819.96 ($[M-Cl]^+$)

Henry's Preparation of μ-(*R*)-BINAP μ-1-Phenylhexane-1,3,5-triketone Bis[(acetonitrile)palladium(II)] Tetrafluoroborate 4a



The procedure was followed as closely as possible to that in Henry's report.[1]

To a stirred so lution of tetrakis(acetonitrile)palladium(II) tetrafluoroborate (100 mg, 226 μmol, 2 equiv) in anhydrous acetonitrile (4.3 mL) under Ar in a 25-mL, round-bottomed flask was added, dropwise, a solution of 1-phenylhexane-1,3,5-trione (23 mg, 113 μmol) in anhydrous acetonitrile (2.0 mL). Anhydrous triethylamine (210 μL, 152 mg, 13.4 equiv) was then added dropwise, causing a color change from yellow to bold orange. The solution was stirred at rt for 30 min. A solution of (*R*)-BINAP (70 mg, 113 μmol, 1 equiv) in anhydrous benzene (1.3 mL) was then added dropwise to the reaction mixture, which was next stirred at rt for 12 h. The mixture was concentrated under high vacuum (50 Pa) to a pasty, brick red residue. Anhydrous Et_2O (10 mL) was added, and the suspension stirred at high frequency for 15 min. Solvent was removed under high vacuum to yield a brick red powder. This was washed in a glove box with anhydrous Et_2O (5 × 30 mL) to give a yellow-brown powder, which was dried briefly *in vacuo* to 131 mg yellow-brown powder (100 μmol, **90%** yield. Residual Et_2O was not removed by further drying a sample *in vacuo* for over 24 h, and the ^{31}P NMR spectrum did not change after this process.

^{1}H NMR: (500 MHz, d_6-DMSO)
δ 6.95-8.19 (m, 12.09 H), 6.83 (m, 0.41 H), 6.60 (m, 0.01 H), 6.40 (m, 0.12 H), 6.20 (m, 0.01 H), 5.87 (br s, 0.13 H), 5.43 (br s, 0.04 H), 3.33 (br m, 1.00 H), 3.07 (br q, J = 6.9 Hz, 11.86 H), 2.92 (br s, 0.14 H), 2.49 (s, 2.99 H), 2.23 (br m, 0.12 H), 2.06 (s, 0.47 H), 1.74 (s, 0.22 H), 1.67 (s, 0.03 H), 1.16 (t, J = 6.9 Hz, 20.70 H)

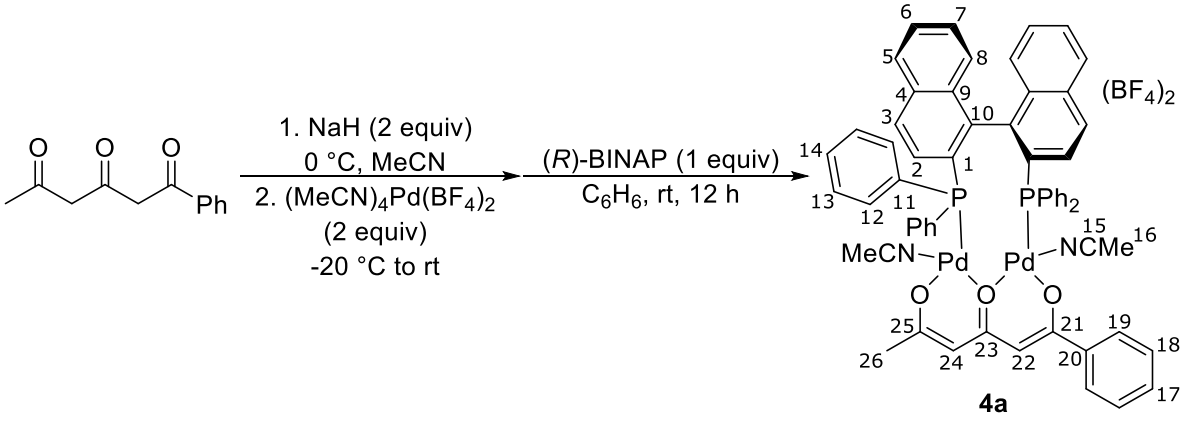
^{31}P NMR: (202 MHz, d_6-DMSO)
33.28, 33.09, 32.72, 32.51, 32.30 (major peak), 31.76, 31.54, 31.26, 31.06, 28.29, 25.36, 25.05, 22.32

IR: (KBr; pressed under Ar)
3169 (m), 3055 (m), 2986 (m), 2943 (m), 2680 (m), 2492 (m), 1673 (m), 1586 (m), 1531 (s), 1507 (s), 1478 (s), 1437 (s), 1399 (m), 1384 (m), 1311 (m), 1056 (s, v br), 872 (w), 847 (w), 815 (m), 746 (m), 697 (s), 668 (m), 619 (w), 609 (w), 582 (w), 552 (w), 523 (m), 501 (m), 475 (w)

New Preparation of Dinuclear Palladium Catalysts 4

To a two-necked, 15-mL, pear-shaped flask charged with a suspension of sodium hydride (5.4 mg, 226 μmol, 2 equiv) in anhydrous acetonitrile (1.0 mL) at 0 °C was added 1-phenylhexane-1,3,5-trione (23 mg, 113 μmol) portion wise under Ar, and the mixture stirred at rt for 15 min. The solution turned clear, bright yellow, and H_2 evolution was observed. Tetrakis(acetonitrile)palladium(II) tetrafluoroborate (100 mg, 226 μmol, 2 equiv) was dissolved in anhydrous acetonitrile (1.5 mL) under Ar in a separate 10-mL Schlenk flask, and cooled to −20 °C. The solution of deprotonated triketone was added slowly to the palladium-containing solution *via* cannula at −20 °C, washing with anhydrous acetonitrile (0.5 mL). The mixture was brought to rt, and stirred for 30 min. This was accompanied by a color change to orange. The mixture was cooled to −20 °C, then a solution of bisphosphine ligand (113 μmol, 1 equiv) in anhydrous benzene (0.9 mL, 0.2 M in ligand) was added dropwise over 3 min. The reaction mixture was stirred at rt for 12 h. It was then concentrated under high vacuum (120 Pa) to a brown powder. This was washed in a glove box with anhydrous Et_2O (10 mL), then anhydrous toluene (3 × 10 mL), removing a yellow filtrate. The solids were dissolved in anhydrous acetone to yield a yellow-brown solution, which was quickly filtered to remove a white solid. The filtrate was concentrated under high vacuum (120 Pa), and washed with anhydrous Et_2O (4 × 10 mL), then anhydrous toluene (3 × 10 mL). The solid was collected. The dinuclear palladium catalysts decompose quickly, and decomposition appears to be accelerated under vacuum. The complexes must be kept under inert atmosphere, and should be used and characterized without delay.

Preparation of μ-(*R*)-BINAP μ-1-Phenylhexane-1,3,5-triketone Bis[(acetonitrile)palladium(II)] Tetrafluoroborate 4a



Dinuclear complex **4a** was synthesized from tetrakis(acetonitrile)palladium(II) tetrafluoroborate (226 μmol), producing 131 mg (101 μmol, **90%** yield) of a yellow-brown powder.

Data for **4a**:

^{1}H NMR: (500 MHz, d_6-DMSO)

δ 8.04 (br d), 7.65–8.00 (br m), 7.60 (br s), 7.52 (br t), 7.38 (br m), 7.13–7.28 (br m), 7.04 (br), 6.72–6.95 (br m), 6.54 (br d, J = 6.2 Hz), 6.35 (br), 2.28 (s), 2.06 (s), 1.82 (s), 1.74 (s), 1.67 (s), 1.07 (t, H_3C(16))

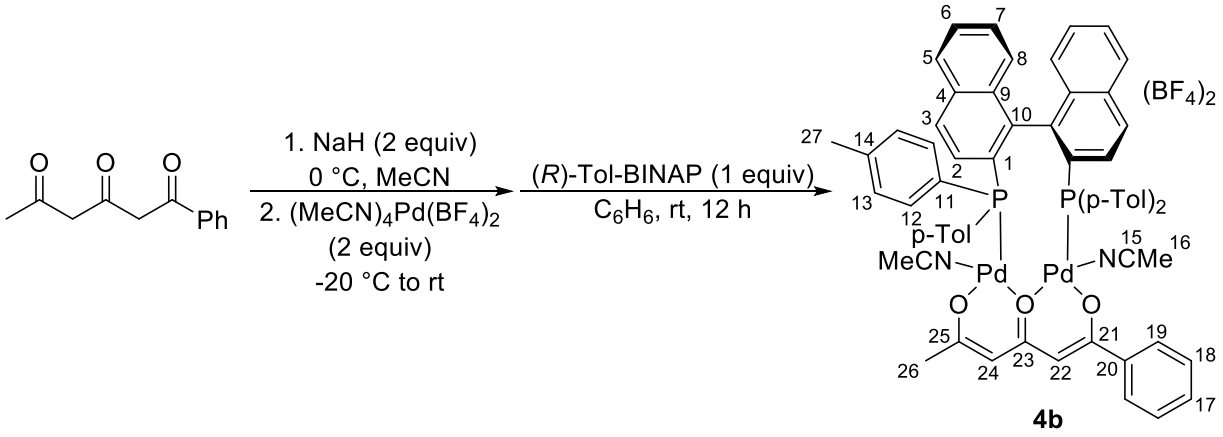
^{31}P NMR: (202 MHz, d_6-DMSO)

33.10

IR: (powder, under air)

3694 (w), 3434 (br w), 2924.16 (w), 1439 (w), 1376 (w), 1084 (w), 1023 (w), 1003 (w), 833 (w), 697 (w), 558 (w), 539 (w), 498 (w), 470 (w)

Preparation of μ-(*R*)-Tol-BINAP μ-1-Phenylhexane-1,3,5-triketone Bis[(acetonitrile)palladium(II)] Tetrafluoroborate 4b



Dinuclear complex **4b** was synthesized from tetrakis(acetonitrile)palladium(II) tetrafluoroborate (108 μmol) to yield 64 mg (47 μmol, **88%** yield) of a light brown powder.

Data for **4b**:

^{1}H NMR: (500 MHz, d_6-DMSO)

δ 8.04 (d, J = 7.5 Hz), 7.89 (d, J = 8.6 Hz), 7.73–7.87 (m), 7.35–7.70 (m), 7.12–7.32 (m), 7.09 (t, J = 7.9 Hz), 6.79 (d, J = 8.5 Hz), 6.49–6.75 (m), 6.40 (s), 6.31 (s), 5.73 (s), 2.07 (s), 2.06 (s), 1.74 (s, $H_{3,A}C(27)$), 1.64 (s, $H_{3,B}C(27)$)

^{31}P NMR: (202 MHz, d_6-DMSO)

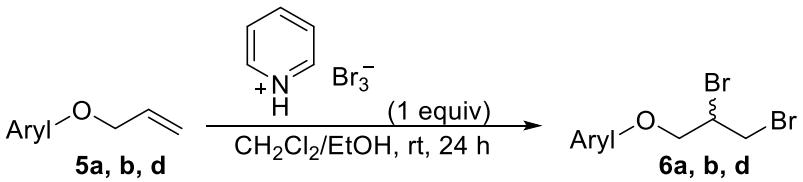
32.39

IR: (powder, under air)

3427 (br w), 3058 (w), 1590 (w), 1557 (w), 1437 (w), 1313 (w), 1238 (w), 1055 (w), 1022 (w), 997 (w), 745 (w), 696 (w), 523 (w), 498 (w)

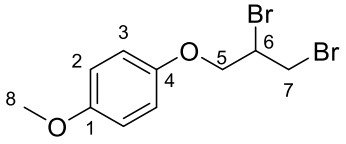
Preparation of Racemic Dibromide Standards

Preparation of *rac*-6a, *rac*-6b and *rac*-6d



A 20-mL scintillation vial was charged with allylic ether **5** (0.50 mmol) and CH_2Cl_2 (1.5 mL, 0.33 M in **5**). Pyridinium tribromide (88% active, 182 mg, 0.50 mmol, 1.0 equiv) was then added in one portion, followed by 95% ethanol (1.5 mL, 0.33 M in **5**). The vial was capped with a plastic-lined cap, and the orange-yellow solution stirred for 24 h, during which time the color is lost. Reaction progress was monitored by TLC. The reaction was quenched by the addition of saturated aqueous $Na_2S_2O_3$ solution (1.0 mL), and the mixture diluted with CH_2Cl_2 (10 mL) and H_2O (10 mL). The layers were separated, and the organic phase was extracted with CH_2Cl_2 (3 × 10 mL). The organic extracts were dried over $MgSO_4$, filtered, and concentrated *in vacuo* to give racemic dibromides **6**.

Preparation of *rac*-1-(2,3-Dibromopropoxy)-4-Methoxybenzene (6a)



Dibromide **6a** was synthesized from **5a** (0.3 mmol) to yield 94 mg (290 μmol, **97%** yield) of a white solid. Spectroscopic data were consistent with those of Henry.[1]

Data for **6a**:

^{1}H NMR: (500 MHz, $CDCl_3$)
δ 6.82–6.91 (m, 4 H, HC(2,3)), 4.38–4.44 (ABX, 1 H, HC(6)), 4.28–4.36 (ABX, 2 H, H_2C(5)), 3.86–3.95 (ABX, 2 H, H_2C(7)), 3.78 (s, 3 H, H_3C(8))

^{13}C NMR: (126 MHz, $CDCl_3$)
δ 154.5 (C(1)), 152.1 (C(4)), 116.2 (C(3)), 114.7 (C(2)), 70.1 (C(5)), 55.7 (C(8)), 48.0 (C(6)), 32.8 (C(7))

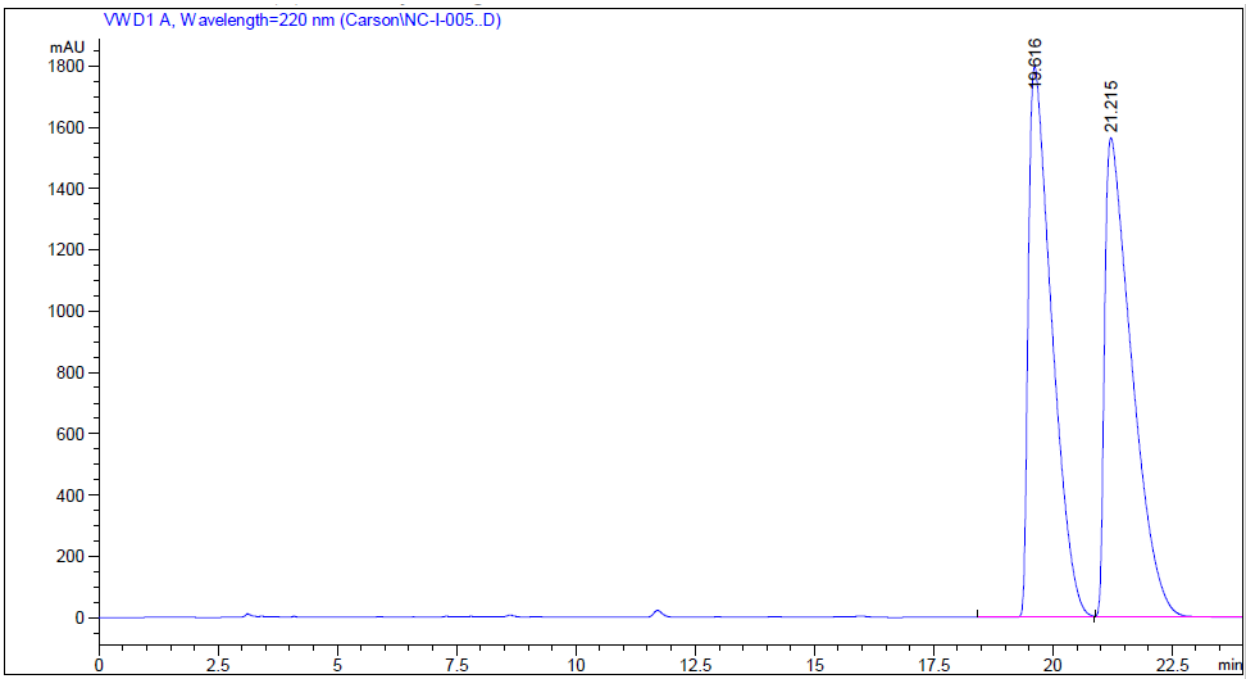
IR: (neat)
2999 (w), 2932 (2), 2968 (w), 1593 (w), 1505 (s), 1456 (m), 1290 (w), 1223 (s), 1108 (w), 1034 (m), 822 (s), 751 (m), 574 (m), 522 (w)

MS: (EI)

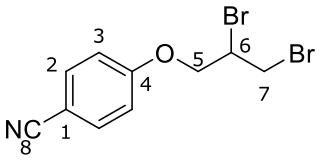
325.9 (11, M^+), 323.9 (20, M^+), 321.9 (11, M^+), 164.1 (9, $[M-Br_2]^+$), 124.1 (90), 123.1 (100, $[M-C_3H_5Br_2]^+$), 109.0 (15), 95.0 (19), 62.0 (11)

TLC: R_f 0.36 (90:10 hexane/EtOAc) [UV/CAM]

HPLC: t_R 19.6 min (49.8%); t_R 21.2 min (50.2%) (OJ-H, hexane/*i*-PrOH = 95.5:4.5, 1.0 mL min^{-1}, 220 nm, 20 °C)



Preparation of 1-(2,6-Dibromopropoxy)-4-Cyanobenzene (6b)



Dibromide **6b** was synthesized from **5b** (0.3 mmol) to yield 92 mg (288 µmol, **96%** yield) of a white solid. Spectroscopic data were consistent with those of Henry.[1]

Data for **6b**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 7.61 (d, *J* = 9.0 Hz, 2 H, HC(2)), 7.00 (d, *J* = 9.0 Hz, 2 H, HC(3)), 4.39–4.48 (m, 3 H, $H_2C(5)$, HC(6)), 3.87–3.93 (m, 2 H, $H_2C(7)$)

^{13}C NMR: (126 MHz, $CDCl_3$)

δ 161.1 (C(4)), 134.1 (C(2)), 118.8 (C(1)), 115.4 (C(3)), 105.1 (C(8)), 69.2 (C(5)), 46.6 (C(6)), 32.1 (C(7))

IR: (powder)

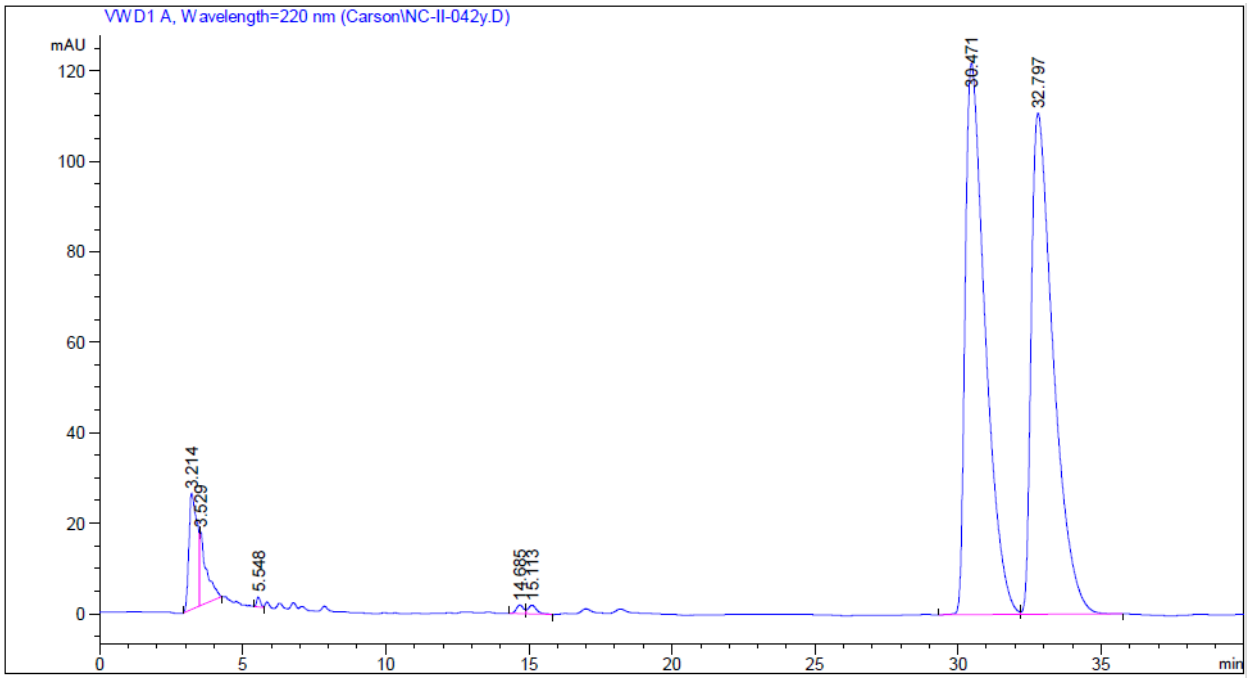
2924 (w), 2227 (m), 1904 (w), 1651 (w), 1605 (m), 1509 (m), 1453 (w), 1302 (w), 1270 (m), 1253 (m), 1173 (m), 1119 (w), 1043 (w), 990 (w), 834 (m), 575 (m), 546 (m)

MS: (EI)

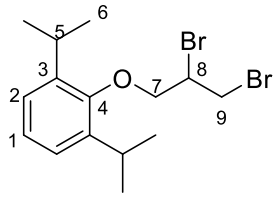
320.9 (11, M^+), 318.9 (22, M^+), 316.9 (11, M^+), 240.0 (2, $[M-HBr]^+$), 238.0 (2, $[M-HBr]^+$), 202.9 (39, $[M-OAryl^+]$, 200.9 (82, $[M-OAryl^+]$, 198.9 (42, $[M-OAryl^+]$, 120.9 (36, $[M-BrOAryl]^+$), 119.0 (100, $[M-BrOAryl]^+$), 102.0 (14, $[C_6H_4CN]^+$), 90.0 (8), 62.1 (45)

TLC: R_f 0.15 (90:10 hexane/EtOAc) [$AgNO_3$-H_2O_2]

HPLC: t_R 30.5 min (50.0%); t_R 32.8 min (50.0%) (IB-3, hexane/*i*-PrOH = 92:8, 1.0 mL min^{-1}, 220 nm, 20 °C)



Preparation of *rac*-1-(2,3-Dibromopropoxy)-2,6-Diisopropylbenzene (6d)



Dibromide **6d** was synthesized from **5d** (0.2 mmol) to yield 73 mg (193 μmol, **97%** yield) of colorless needles. Spectroscopic data were consistent with those of Henry.[1]

Data for **6d**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 7.09–7.13 (m, 3 H, HC(1,2)), 4.45 (AB<u>X</u>, 1 H, HC(8)), 4.15 (<u>AB</u>X, 2 H, H_2C(7)), 3.96 (<u>AB</u>X, 2 H, H_2C(9)), 3.42 (sept, J = 6.8 Hz, 2 H, HC(5)), 1.24 (d, J = 6.8 Hz, 12 H, H_3C(6))

^{13}C NMR: (126 MHz, $CDCl_3$)

δ 151.7 (C(4)), 141.9 (C(3)), 125.2 (C(2)), 124.1 (C(1)), 74.1 (C(7)), 48.6 (C(8)), 32.3 (C(9)), 26.3 (C(5)), 24.1 (C(6))

IR: (neat)

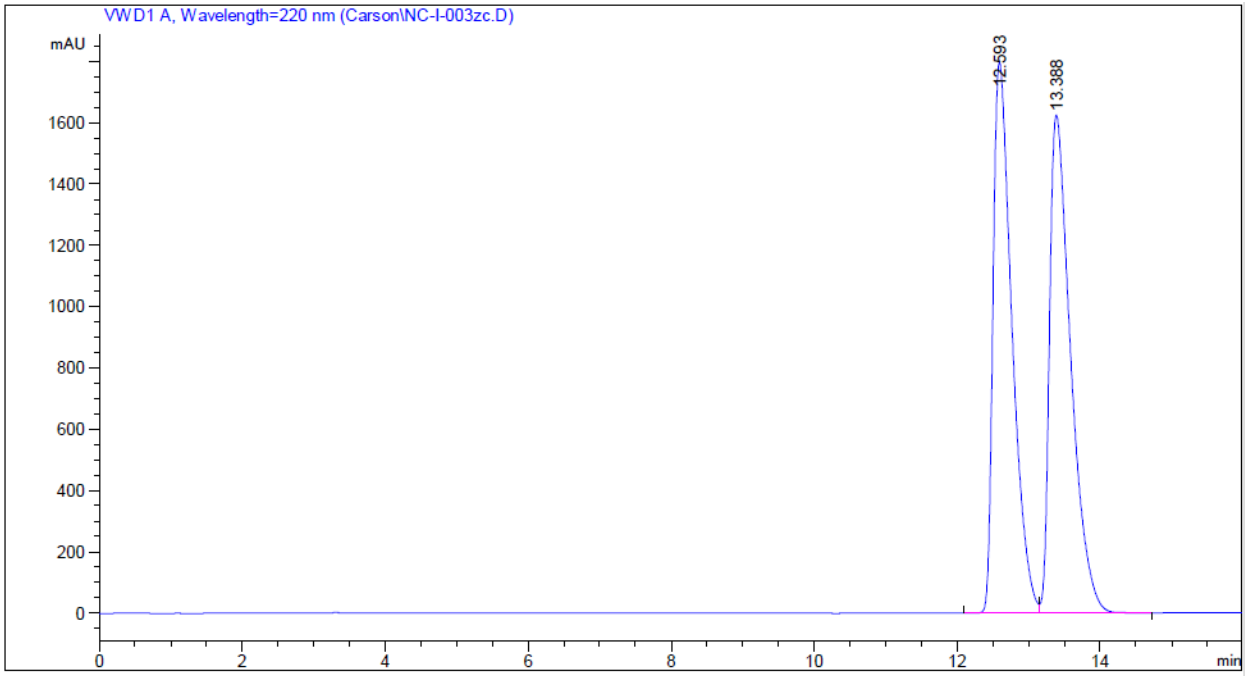
2962 (w), 2927 (w), 2868 (w), 1589 (w), 1457 (w), 1442 (w), 1328 (w), 1256 (w), 1180 (m), 1035 (w), 981 (w), 914 (w), 799 (w), 759 (m), 577 (m)

MS: (EI)

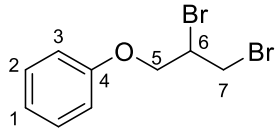
380.0 (11, M^+), 378.0 (22, M^+), 376.0 (11, M^+), 218.2 (5), 202.9 (6, $[M-Aryl]^+$), 200.9 (12, $[M-Aryl]^+$), 198.9 (6, $[M-Aryl]^+$), 178.1 (100, $[M-C_3H_4Br_2]^+$), 163.1 (92), 147.1 (10), 135.1 (47), 121.0 (12), 107.1 (13), 91.1 (17), 77.1 (7), 62.1 (6)

TLC: R_f 0.60 (90:10 hexane/EtOAc) [UV/CAM]

HPLC: t_R 12.5 min (49.7%); t_R 13.9 min (50.3%) (IB-3, hexane/*i*-PrOH = 99.9:0.1, 1.0 mL min^{-1}, 220 nm, 20 °C)



Preparation of *rac*-(2,3-Dibromopropoxy)benzene (6c)



Dibromide **6c** was prepared according to a literature procedure,[7] and had spectroscopic data consistent with the literature.

Data for **6c**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 7.31 (dd, *J* = 8.5, 7.5 Hz, 2 H, HC(2)), 7.00 (t, *J* = 7.4 Hz, 1 H, HC(1)), 6.94 (d, *J* = 7.9 Hz, 2 H, HC(3)), 4.35–4.47 (m, 3 H, H_2C(6), HC(7)), 3.88–3.96 (m, 2 H, H_2C(8))

^{13}C NMR: (126 MHz, $CDCl_3$)

δ 157.9 (C(4)), 129.6 (C(2)), 121.7 (C(1)), 114.8 (C(3)), 69.0 (C(5)), 47.7 (C(6)), 32.8 (C(7))

IR: (neat)

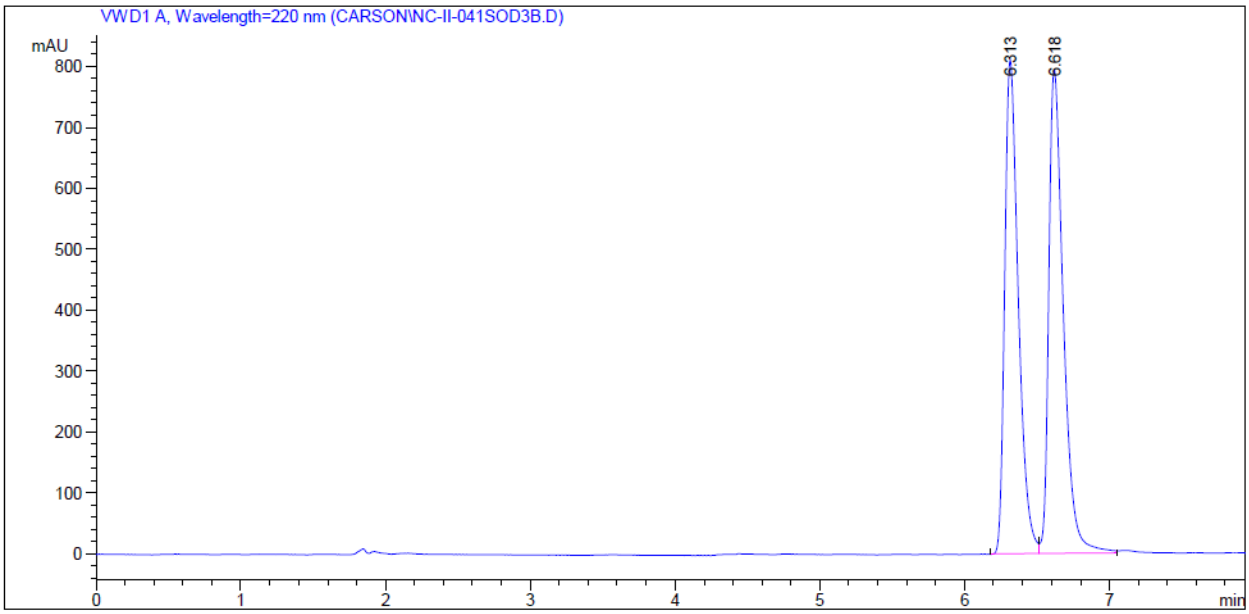
2927 (w), 2869 (w), 1598 (m), 1495 (m), 1240 (m), 1047 (w), 908 (w), 884 (w), 814 (w), 752 (s), 690 (m), 509 (w)

MS: (EI)

295.9 (10, M^+), 293.9 (21, M^+), 291.9 (11, M^+), 202.9 (6, $[M-OPh]^+$), 200.9 (13, $[M-OPh]^+$), 198.9 (7, $[M-OPh]^+$), 121.0 (14, $[M-BrOPh]^+$), 119.0 (14, $[M-BrOPh]^+$), 95.0 (11), 94.0 (100), 77.1 (16.9, Ph^+), 65.1 (13)

TLC: R_f 0.78 (90:10 hexane/Et_2O) [UV/CAM]

SFC: t_R 6.3 min (49.8%); t_R 6.6 min (50.2%) (OD, MeOH:CO_2 = 3:97, 2.5 mL min^{-1}, 220 nm, 40 °C)

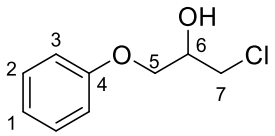


Preparation of Racemic Chlorohydrin Standards

Preparation of *rac*-2a and *rac*-2c

Racemic standards of chlorohydrins **2a** and **2c** were prepared according to a literature procedure[8] and had spectroscopic data consistent with literature.

Preparation of *rac*-(2-Chloro-3-hydroxypropoxy)benzene (2a)



Data for **2a**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 7.31 (m, 2 H, HC(2)), 7.00 (tt, J = 7.4, 1.0 Hz, 1 H, HC(1)), 6.93 (m, 2 H, HC(3)), 4.23 (sext, J = 5.5 Hz, 1 H, HC(6), 4.10 (m, 2 H, H_2C(5)), 3.77 (m, 2 H, H_2C(7)), 2.59 (d, J = 5.8 Hz, 1 H, OH)

^{13}C NMR: (126 MHz, $CDCl_3$)

δ 158.1 (C(4)), 129.6 (C(2)), 121.4 (C(1)), 114.5 (C(3)), 69.9 (C(5)), 68.4 (C(6)), 46.0 (C(7))

IR: (neat)

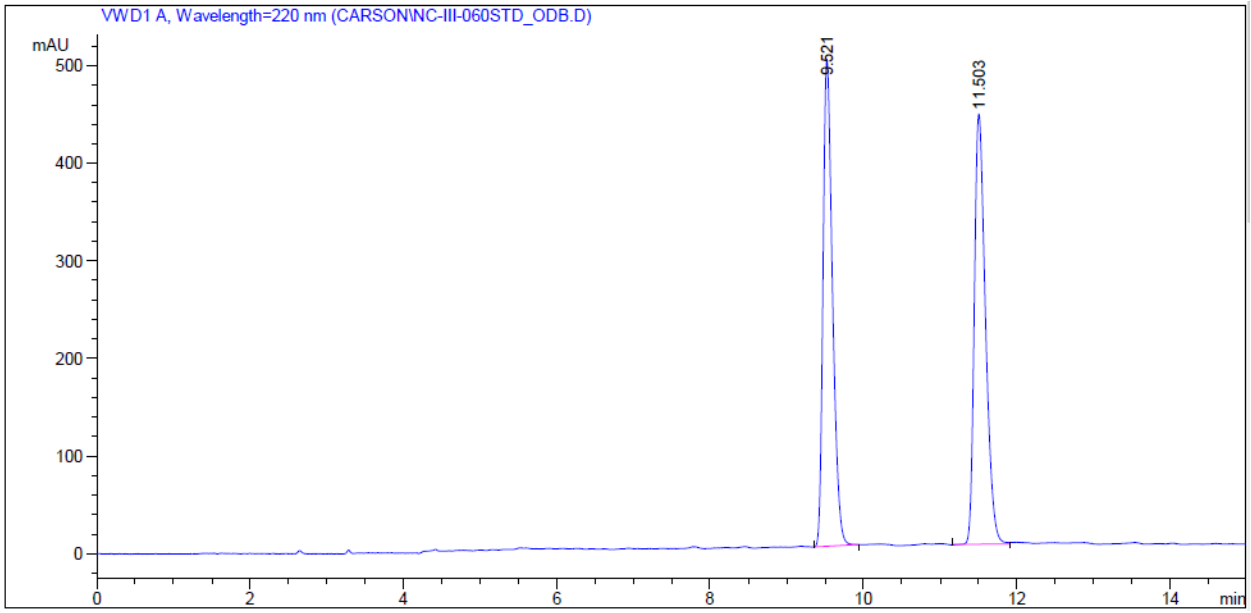
3407 (br, w), 2928 (w), 1739 (w), 1599 (m), 1588 (w), 1495 (m), 1457 (w), 1240 (m), 1173 (w), 1078 (m), 1042 (m), 751 (s), 690 (m), 509 (m)

MS: (EI)

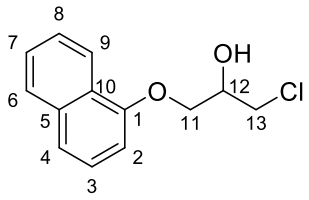
188.0 (22, M^+), 186.0 (59, M^+), 144.0 (9), 142.0 (30), 137.0 (18), 119.0 (18), 108.0 (11), 107.0 (63), 95.0 (61), 94 (100), 79.1 (20), 78.1 (13), 77.0 (69, Ph^+), 66.1 (14), 65.1 (18), 51.0 (23)

TLC: R_f 0.78 (90:10 hexane/Et_2O) [UV/CAM]

SFC: t_R 9.5 min (49.8%); t_R 11.5 min (50.2%) (OD, MeOH:CO_2 = 1:99 for 10 min then 10:90 for 6 min then 5:95 for 4 min, 2.5 mL min^{-1}, 220 nm, 40 °C)



Preparation of *rac*-1-(2-Chloro-3-hydroxypropoxy)naphthalene (2c)



Data for **2c**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 8.21 (d, *J* = 7.1 Hz, 1 H, HC(9)), 7.82 (d, *J* = 6.9 Hz, 1 H, HC(6)), 7.45–7.54 (m, 3 H), HC(4), HC(7), HC(8)), 7.39 (t, *J* = 7.9 Hz, 1 H, HC(3)), 6.85 (d, *J* = 7.5 Hz, 1 H, HC(2)), 4.39 (sext, *J* = 5.5 Hz, 1 H, HC(12)), 4.28 (m, 2 H, H_2C(11)), 3.89 (m, 2 H, H_2C(13)), 2.59 (d, *J* = 6.1 Hz, OH)

^{13}C NMR: (126 MHz, $CDCl_3$)

δ 153.7 (C(10)), 134.5 (C(5)), 127.6 (C(6)), 126.5 (C(7)), 125.7 (C(3)), 125.4 (C(8)), 125.3 (C(1)), 121.5 (C(9)), 121.0 (C(4)), 105.0 (C(2)), 69.9 (C(11)), 68.6 (C(12)), 46.3 (C(13))

IR: (powder)

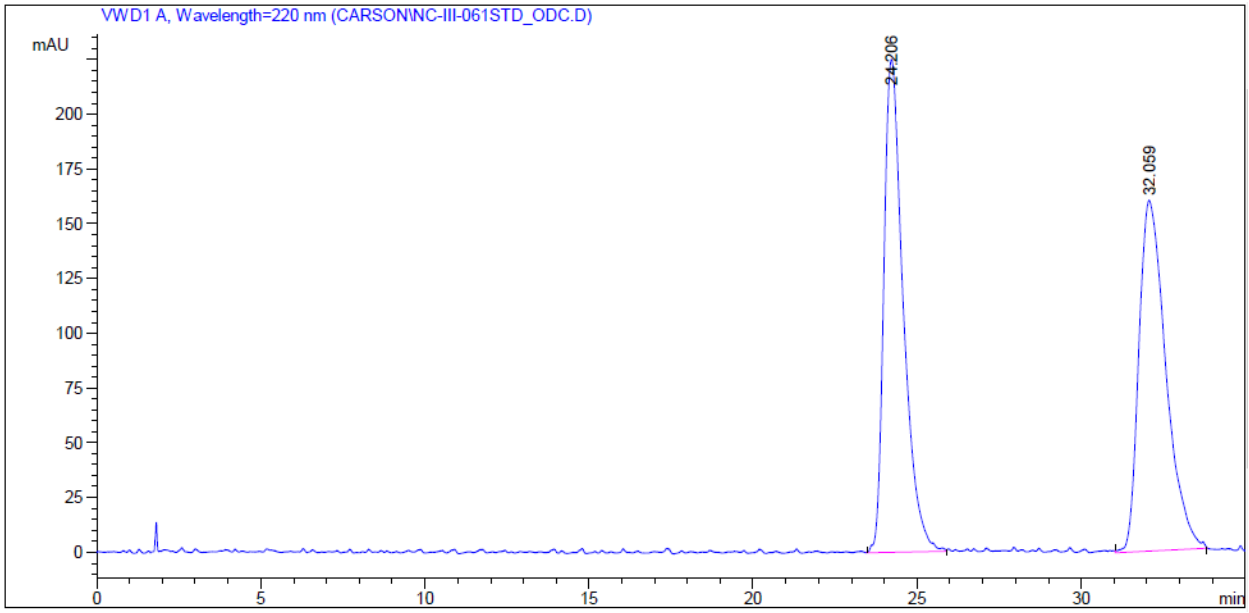
3312 (br, w), 3056 (w), 2926 (w), 2853 (w), 1738 (w), 1627 (w), 1577 (m), 1509 (w), 1456 (w), 1393 (m), 1322 (w), 1270 (m), 1208 (m), 1100 (m), 1021 (m), 904 (m), 793 (m), 770 (s), 707 (m), 574 (m), 514 (w)

MS: (EI)

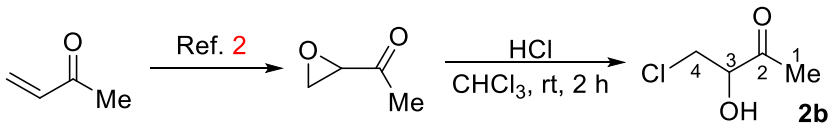
238.0 (8, M^+), 236.0 (25, M^+), 145.0 (13), 144.0 (100), 127.0 (10, $Naph^+$), 116 (15), 115 (25), 94.0 (10)

TLC: R_f 0.78 (90:10 hexane/Et_2O) [UV/CAM]

SFC: t_R 24.2 min (50.2%); t_R 32.1 min (49.8%) (OD, MeOH:CO_2 = 10:90, 2.5 mL min^{-1}, 220 nm, 40 °C)



Preparation of *rac*-4-Chloro-3-hydroxybutan-2-one (2b)



1-(Oxiran-2-yl)ethanone was prepared on a 2 mmol scale, according to a literature procedure.[9] The crude, colorless oil produced in this reaction was then cooled to 0 °C in a 7-mL vial, and $CHCl_3$ (0.5 mL) and concentrated HCl (0.25 mL) were added to form a colorless/yellow biphase. The mixture was stirred at rt for 2 h. H_2O (3 mL) was added, and the organic components were extracted with $CHCl_3$ (3 × 5 mL). The organic extracts were dried over $CaCl_2$, filtered, and concentrated *in vacuo* to a crude, dark, brown oil. This complex mixture was separated *via* column chromatography using an eluent gradient from 95:5 to 80:20 hexane/ethyl acetate, to yield 71 mg (0.58 mmol, **29%** yield over two steps) of a volatile, colorless oil **2b**.

Data for **2b**:

^{1}H NMR: (500 MHz, $CDCl_3$)

δ 4.29 (t, J = 5.6 Hz, 1 H, HC(3)), 3.92 (m, 2 H, H_2C(4)), 3.02 (br s, 1 H, OH), 2.33 (s, 3 H, H_3C(1))

^{13}C NMR: (126 MHz, $CDCl_3$)

203.39 (C(2)), 63.42 (C(3)), 62.54 (C(4)), 27.40 (C(1))

IR: (neat)

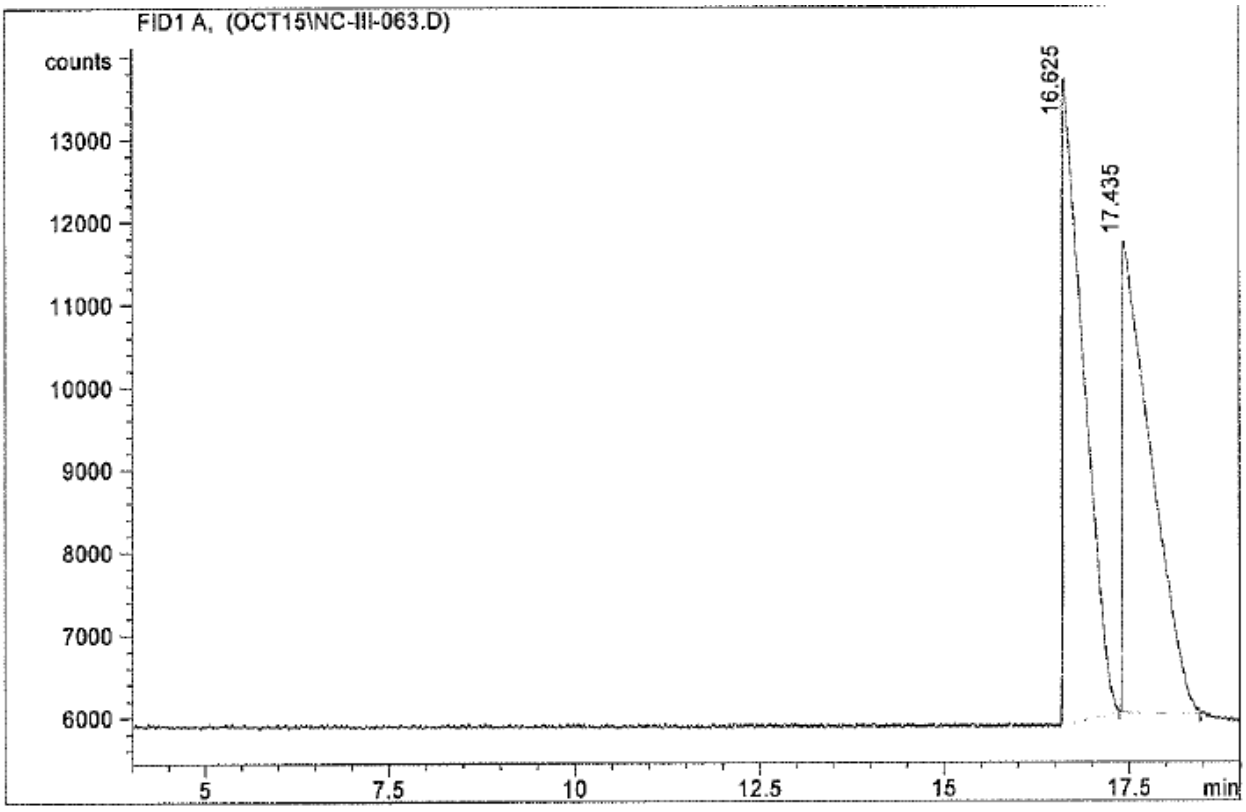
3419 (br, w), 2941 (w), 1715 (s), 1420 (m), 1358 (m), 1224 (m), 1162 (w), 1075 (m), 1041 (m), 929 (w), 796 (w), 733 (m), 680 (m), 629 (m), 593 (m), 559 (m), 474 (s)

MS: (EI)

128.0 (10), 126.0 (16), 109.1 (7.4, $[M\text{-}Me]^+$), 107.0 (23.0, $[M\text{-}Me]^+$), 94.0 (12), 92.0 (37.6), 91.1 (11.9), 87.1 (20.2, $[M\text{-}Cl]^+$), 86.1 (13.5), 81.1 (16.3, $[M\text{-}Ac]^+$), 79.0 (53.8, $[M\text{-}Ac]^+$), 77.0 (17.2), 76.0 (11.2), 71.1 (21.2), 69.1 (15.2), 64.1 (47.7), 62.1 (100), 57.2 (15.9), 55.1 (14.2)

TLC: R_f 0.37 (70:30 hexane/EtOAc) [DNP]

GC: t_R 16.6 min (50.3%); t_R 17.4 min (49.7%) (CycloSil-B, 70 °C)



Conditions and Spectra for Dibromination Reactions:

Reactions were run according to Henry's procedures.[1] The procedures were all reproduced as rigorously as the described procedures allow, other than changing the scale and reaction time – with the

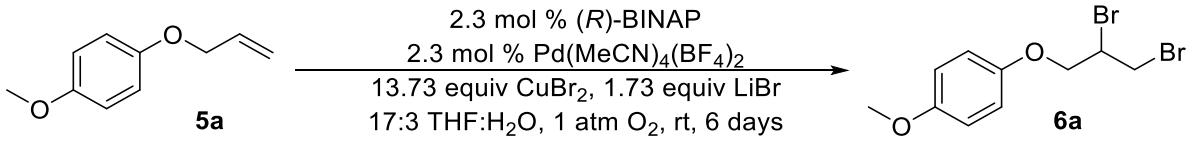
exception of Run 3. Reaction progress was monitored by TLC. Concentrations are calculated with respect to total solvent volume.

Table S2. Conditions for Dibromination Reactions

Run	Substrate	Amount of substrate, mmol	Pd complex, mol %	$CuBr_2$ equiv	$CuBr_2$ molarity, M	LiBr equiv	LiBr molarity, M	THF/H_2O	Time, h
1	**5a**[†]	0.25	2.3	13.74	2.0 M	1.75	0.26 M	17:3	28
2	**5a**[†]	0.25	2.3	13.74	2.0 M	1.75	0.26 M	17:3	28
3	**5a**[†]	3.0	2.3	13.73	2.1 M	1.73	0.26 M	17:3	144
4	**5a**[†]	0.25	2.3	13.75	2.1 M	1.75	0.27 M	17:3	6
5	**5b**	0.25	2.4	15.83	2.0 M	1.01	0.13 M	1:9	24
6	**5c**	0.25	1.4	10.65	2.0 M	1.11	0.20 M	17:3	24
7	**5d**	0.25	2.5	15.83	2.2 M	1.24	0.17 M	87:13	24

[†]Nuclearity of palladium(II) catalyst is ambiguous in the original text for dibromination of **5a**.

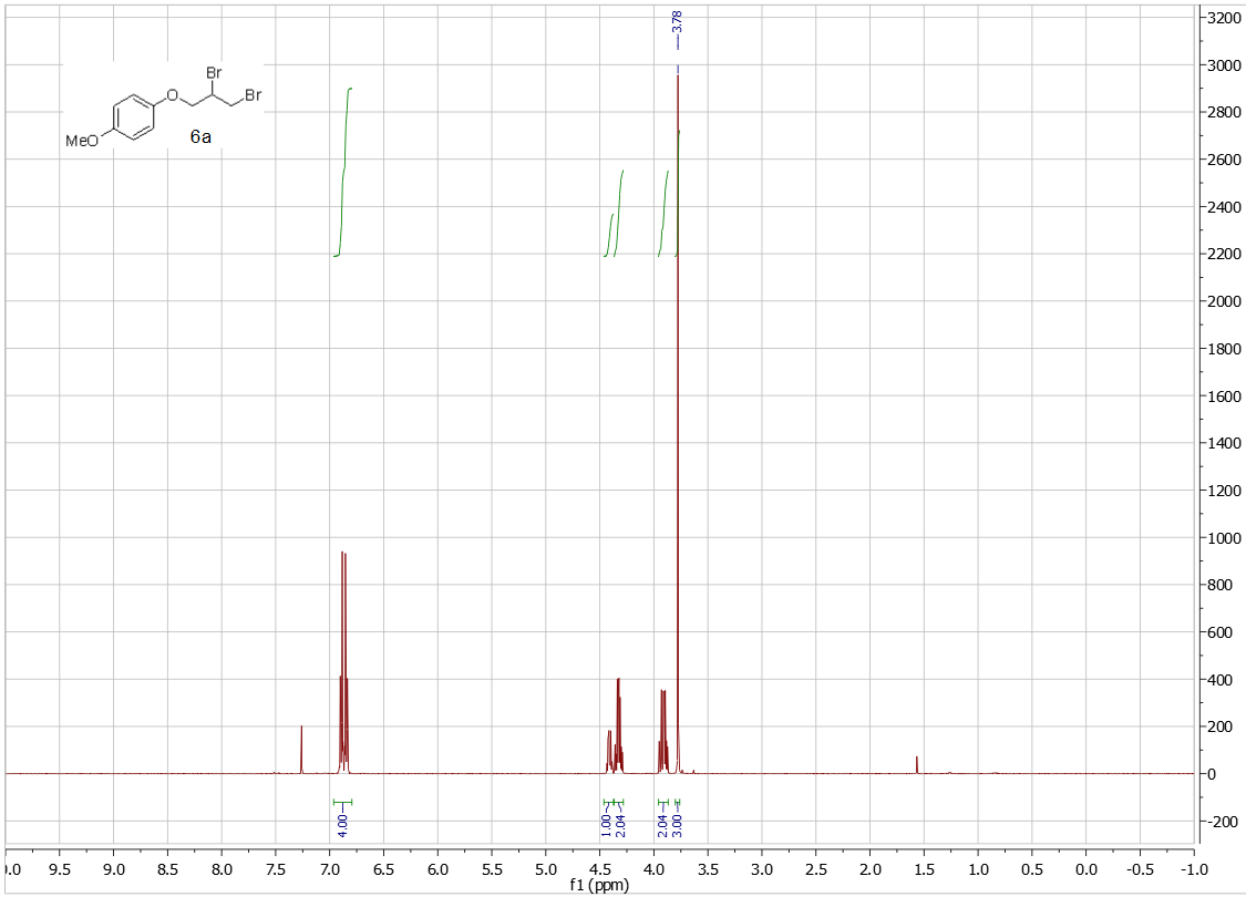
Run 1: Dibromination of 5a, 3.00 mmol, 6 days[†]

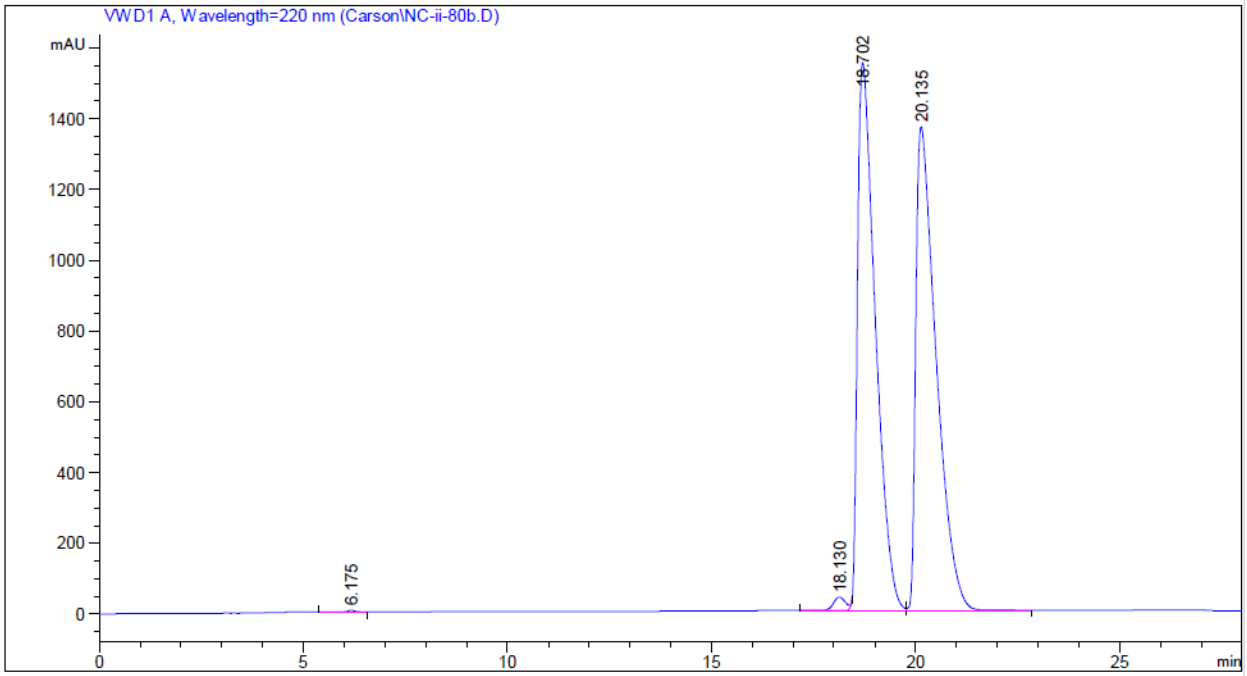


An oven-dried, 50-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with tetrakis(acetonitrile)palladium(II) tetrafluoroborate (31 mg, 69 μmol, 2.3 mol %) and (*R*)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl ((*R*)-BINAP) (43 mg, 69 μmol, 2.3 mol %) in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 17:3 THF/H_2O (15 mL) injected. The solution was stirred at rt for 10 min, and turned from light to dark orange color. Then, copper(II) bromide (9.20 g, 41.2 mmol, 13.73 equiv, 2.1 M) was added in one portion to form a deep green solution, followed by lithium bromide (450 mg, 5.2 mmol, 1.73 equiv, 0.26 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5a** (493 mg, 3.00 mmol) was then added to the mixture, washing with 17:3 THF/H_2O (5 mL). The mixture was left to stir at rt. After 6 days, the mixture was extracted with CH_2Cl_2 (3 × 50 mL), then dried over $MgSO_4$. Hexane (15 mL) was added, and the precipitated orange Pd complex removed by filtration, washing with hexane (3 × 10 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using 95:5 hexane/ethyl acetate as eluent, to yield dibromide **6a**, 754 mg (2.33 mmol, **78%** yield) of a white solid. This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

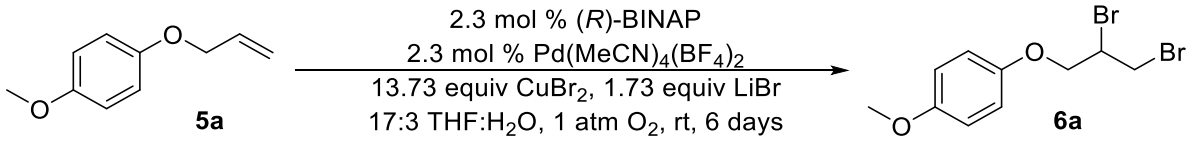
Data for **6a**:

HPLC: t_R 18.7 min (49.9%); t_R 20.1 min (50.1%) (OJ-H, hexane/*i*-PrOH = 95.5:4.5, 1.0 mL min^{-1}, 220 nm, 20 °C)


Br
Br
O
MeO
6a
3.78
4.00
1.00
2.04
2.04
3.00
f1 (ppm)


VWD1 A, Wavelength=220 nm (Carson\NC-ii-80b.D)
mAU
6.175
18.130
18.702
20.135
min

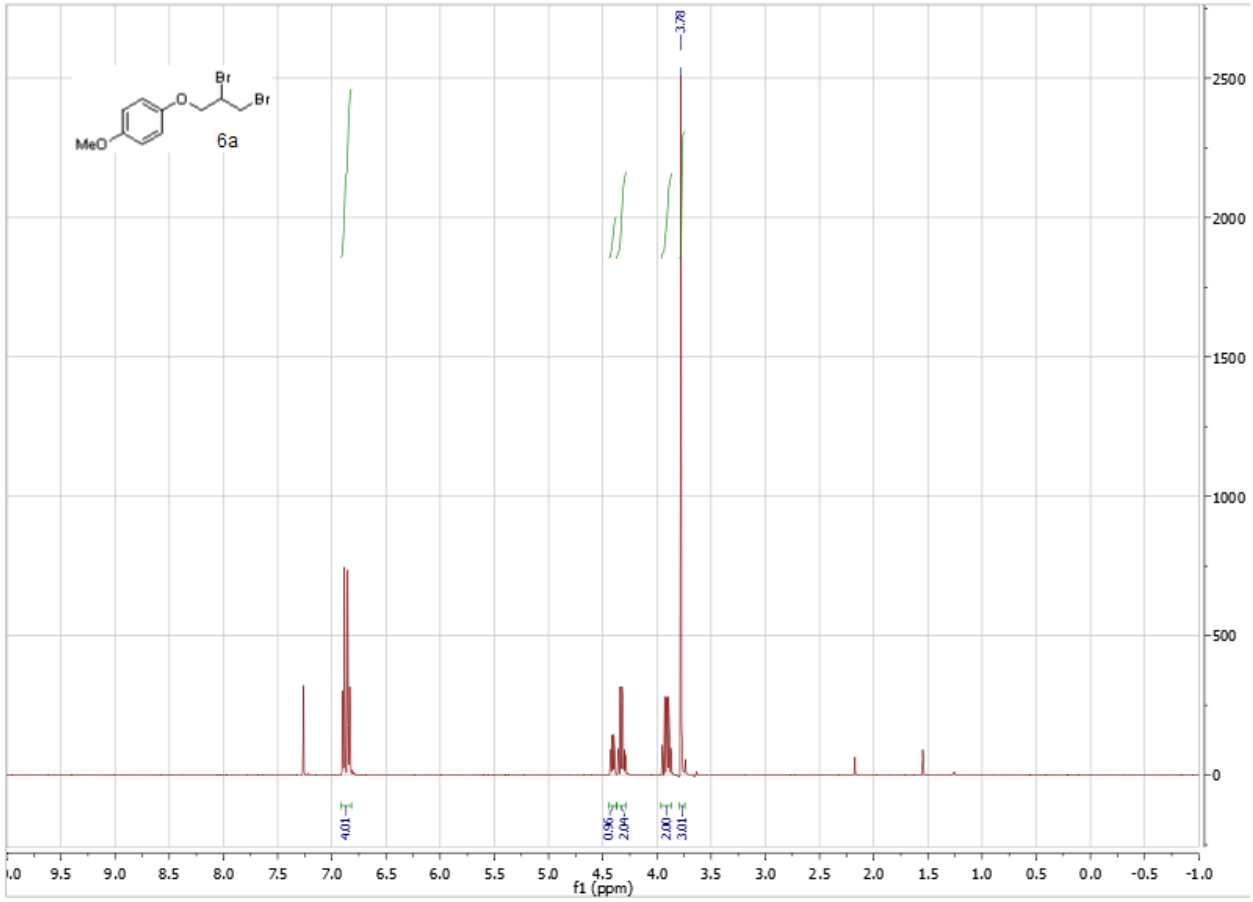
Run 2: Dibromination of 5a, 0.25 mmol, 6 h[†]

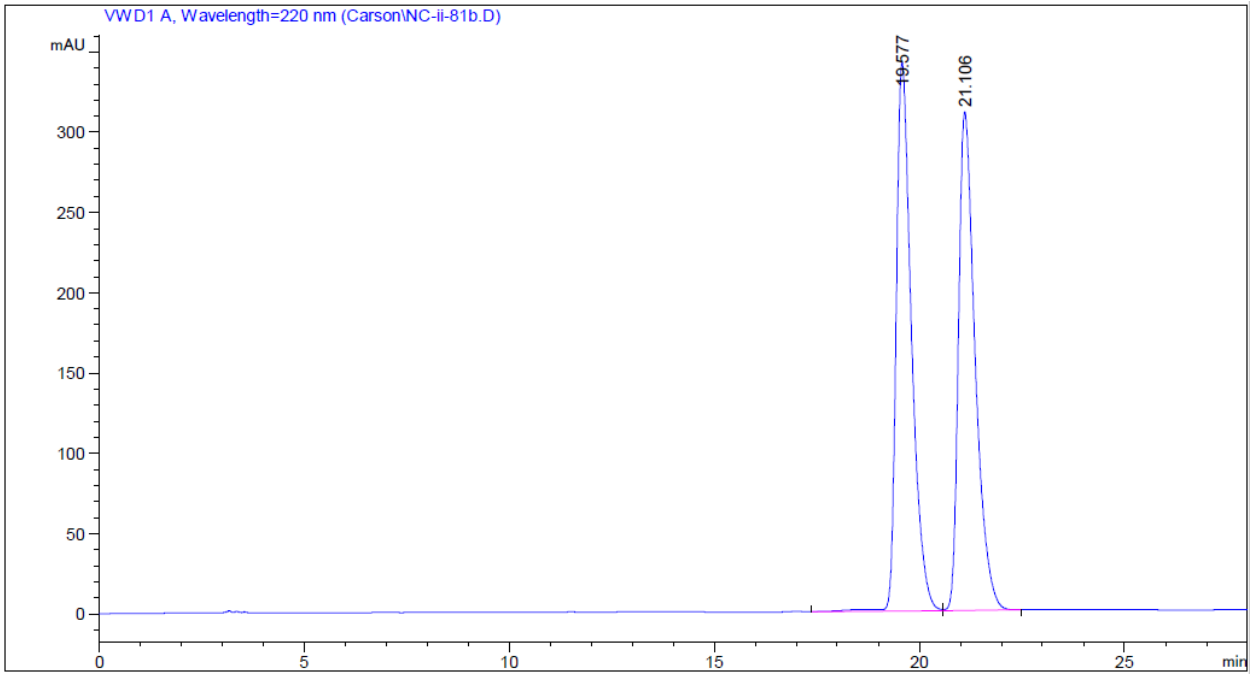


An oven-dried, 15-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with tetrakis(acetonitrile)palladium(II) tetrafluoroborate (2.6 mg, 5.7 μmol, 2.3 mol %) and (*R*)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl ((*R*)-BINAP) (3.6 mg, 5.7 μmol, 2.3 mol %) in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 17:3 THF/H_2O (1.0 mL) injected. The solution was stirred at rt for 10 min, and turned from light to dark orange color. Then, copper(II) bromide (758 mg, 3.43 mmol, 13.75 equiv, 2.1 M) was added in one portion to form a deep green solution, followed by lithium bromide (38 mg, 0.43 mmol, 1.75 equiv, 0.27 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5a** (41 mg, 0.25 mmol) was then added to the mixture, washing with 17:3 THF/H_2O (0.6 mL). The mixture was left to stir at rt, and stopped after 6 h. The mixture was extracted with CH_2Cl_2 (3 × 15 mL), then dried over $MgSO_4$. Hexane (5 mL) was added, and the precipitated orange Pd complex removed by filtration, washing with hexane (3 × 5 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using 93:7 hexane/ethyl acetate as eluent, to yield dibromide **6a**, 54 mg (0.17 mmol, **67%** yield) as a white solid. This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

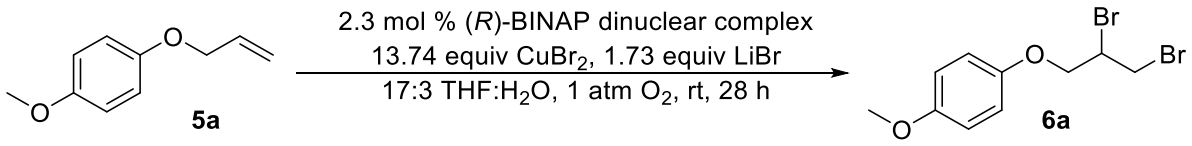
Data for **6a**:

HPLC: t_R 19.6 min (50.3%); t_R 21.1 min (49.7%) (OJ-H, hexane/*i*-PrOH = 95.5:4.5, 1.0 mL min^{-1}, 220 nm, 20 °C)


Br
Br
O
MeO
6a
3.78
4.01
0.96
2.04
2.00
3.01
f1 (ppm)


VWD1 A, Wavelength=220 nm (Carson\NC-ii-81b.D)
mAU
19.577
21.106
min

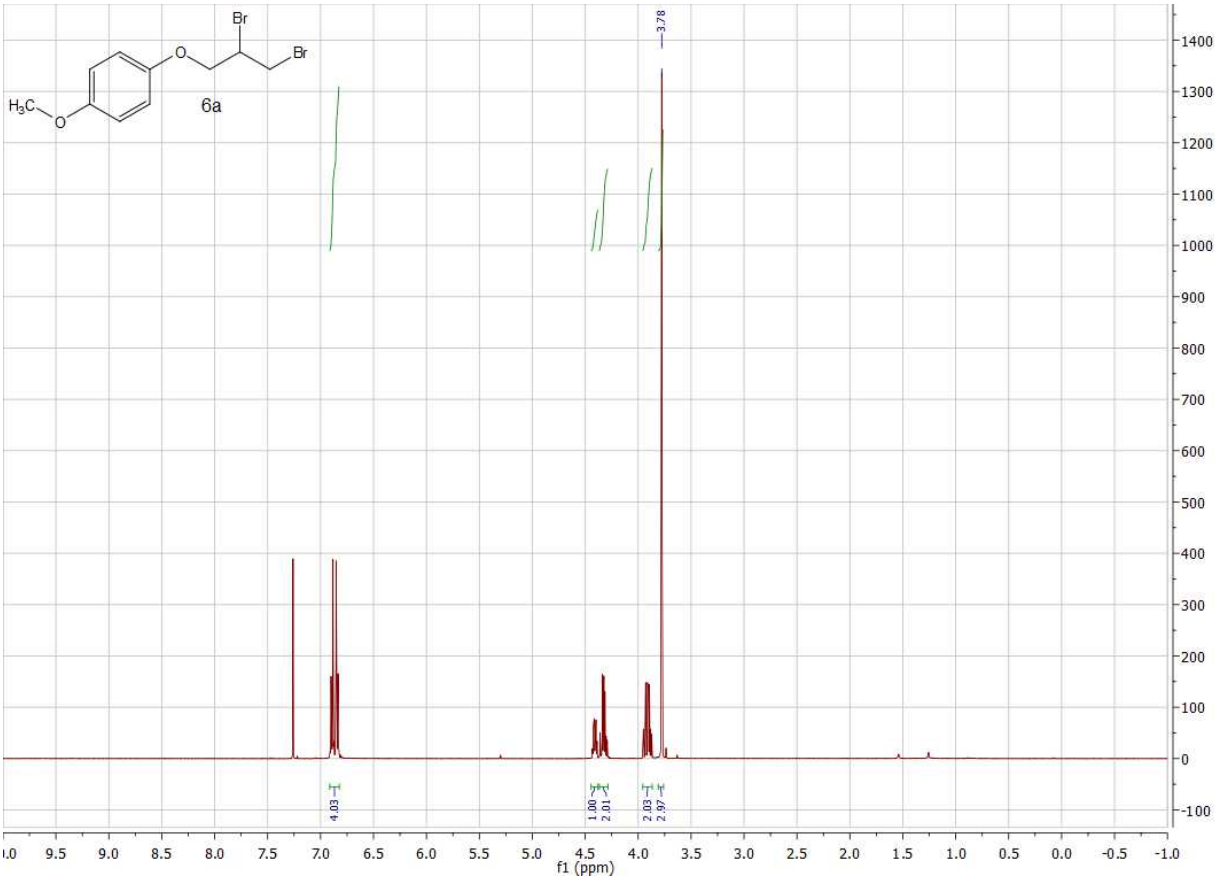
Run 3: Dibromination of 5a with Henry's catalyst preparation, 0.25 mmol, 28 h[†]

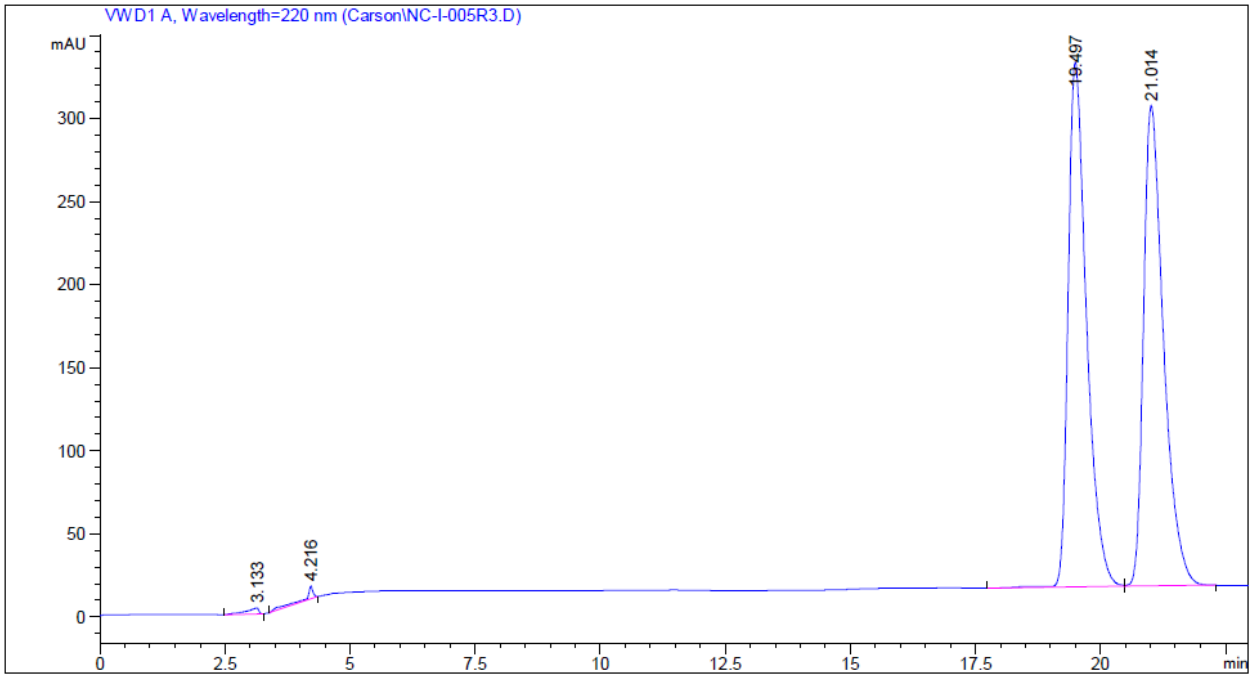


A 25-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with **4a**,[†] freshly prepared according to Henry's method (7.5 mg, 5.8 μmol, 2.3 mol %), and weighed out in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 17:3 THF/H_2O (1.0 mL) injected to give a yellow solution. Then, copper(II) bromide (767 mg, 3.43 mmol, 13.74 equiv, 2.0 M) was added in one portion to form a deep green solution, followed by lithium bromide (38 mg, 0.43 mmol, 1.73 equiv, 0.26 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5a** (41 mg, 0.25 mmol) was then added to the mixture, washing with 17:3 THF/H_2O (0.7 mL). The mixture was left to stir at rt, monitoring periodically by TLC. Completion was reached at 28 h, and the mixture was extracted with CH_2Cl_2 (3 × 20 mL), then dried over $MgSO_4$. Hexane (5 mL) was added, and the precipitated orange Pd complex removed by filtration, washing with hexane (3 × 5 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using 93:7 hexane/ethyl acetate as eluent, to yield dibromide **6a** as a white solid, 70 mg (0.22 mmol, **86%** yield). This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

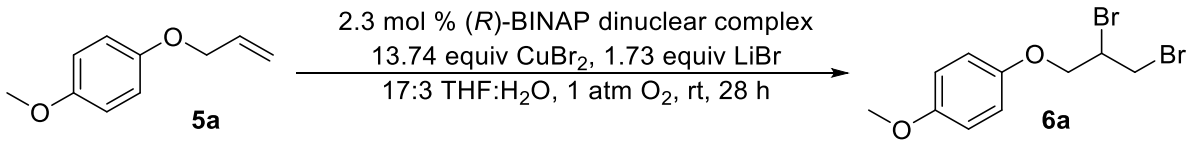
Data for **6a**:

HPLC: t_R 19.5 min (50.1%); t_R 21.0 min (49.9%) (OJ-H, hexane/*i*-PrOH = 95.5:4.5, 1.0 mL min^{-1}, 220 nm, 20 °C)


Br
O
Br
H_3C
O
6a
3.78
4.03
1.00
2.01
2.03
2.97
f1 (ppm)


VWD1 A, Wavelength=220 nm (Carson\NC-I-005R3.D)
mAU
3.133
4.216
19.497
21.014
min

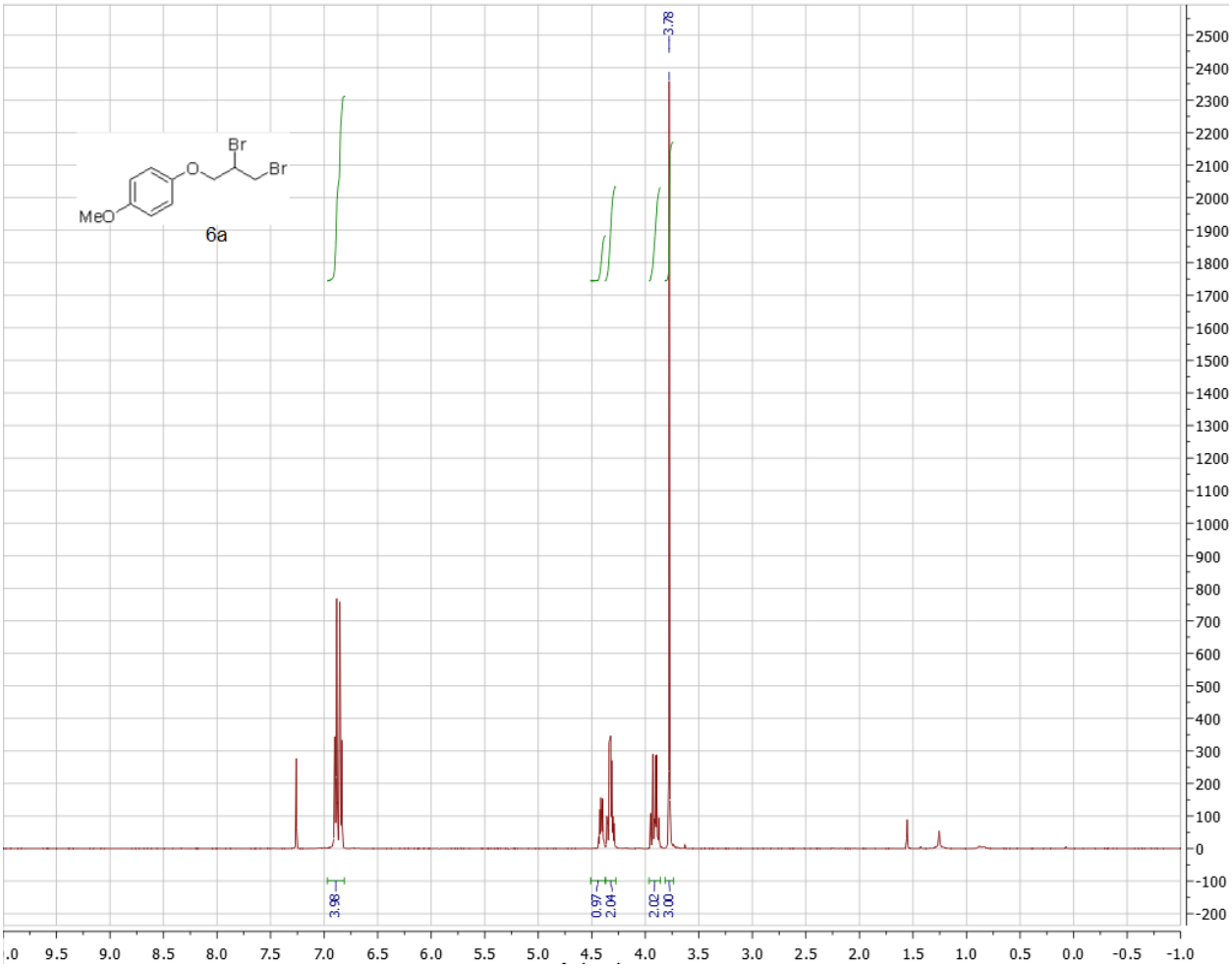
Run 4: Dibromination of 5a with New Catalyst Preparation, 0.25 mmol, 28 h[†]

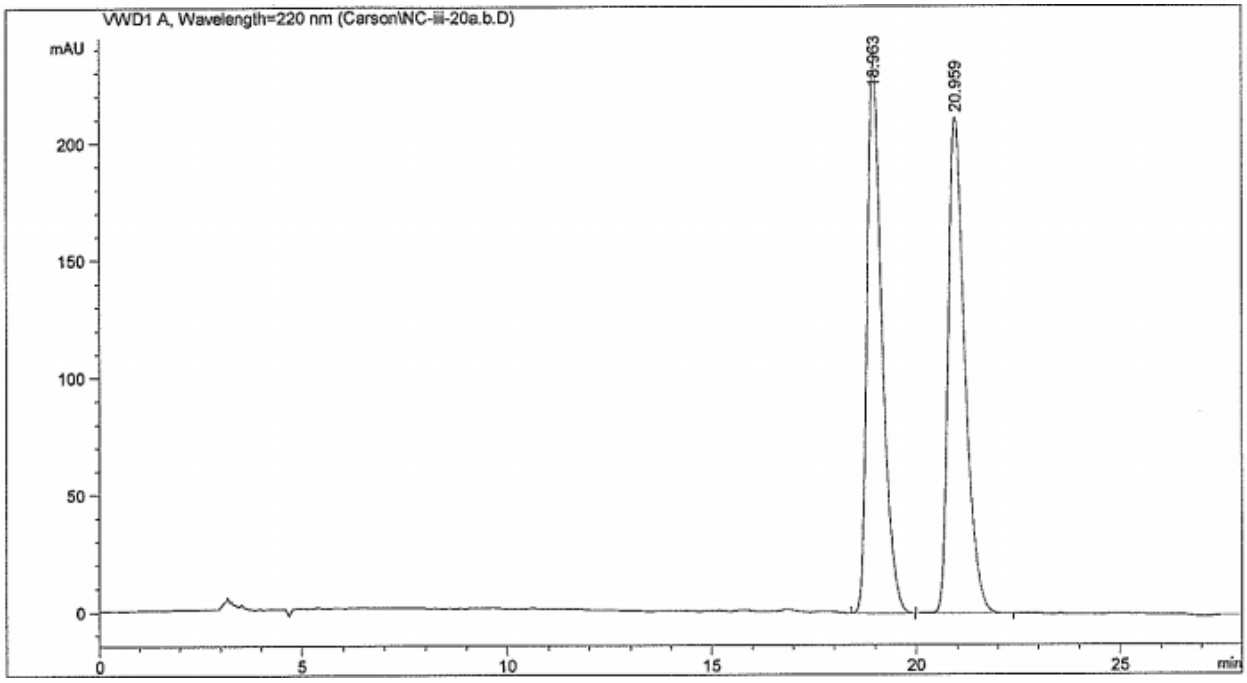


Run 3 was replicated, with the exception of using **4a** prepared by the new method described above. Dibromide **6a** was produced as a white solid, 69 mg (0.21 mmol, **85%** yield). This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

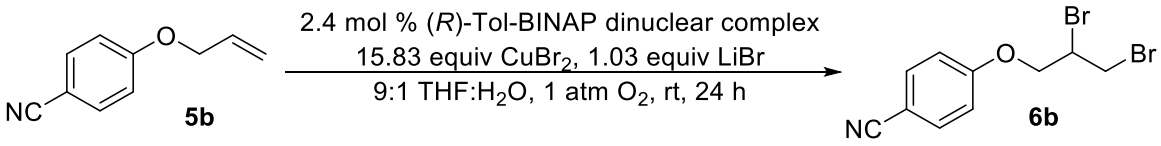
Data for **6a**:

HPLC: t_R 19.0 min (50.0%); t_R 21.0 min (50.0%) (OJ-H, hexane/*i*-PrOH = 95.5:4.5, 1.0 mL min^{-1}, 220 nm, 20 °C)




VWD1 A, Wavelength=220 nm (Carson\NC-iii-20a.b.D)
mAU
200
150
100
50
0
18.963
20.959
0
5
10
15
20
25
min

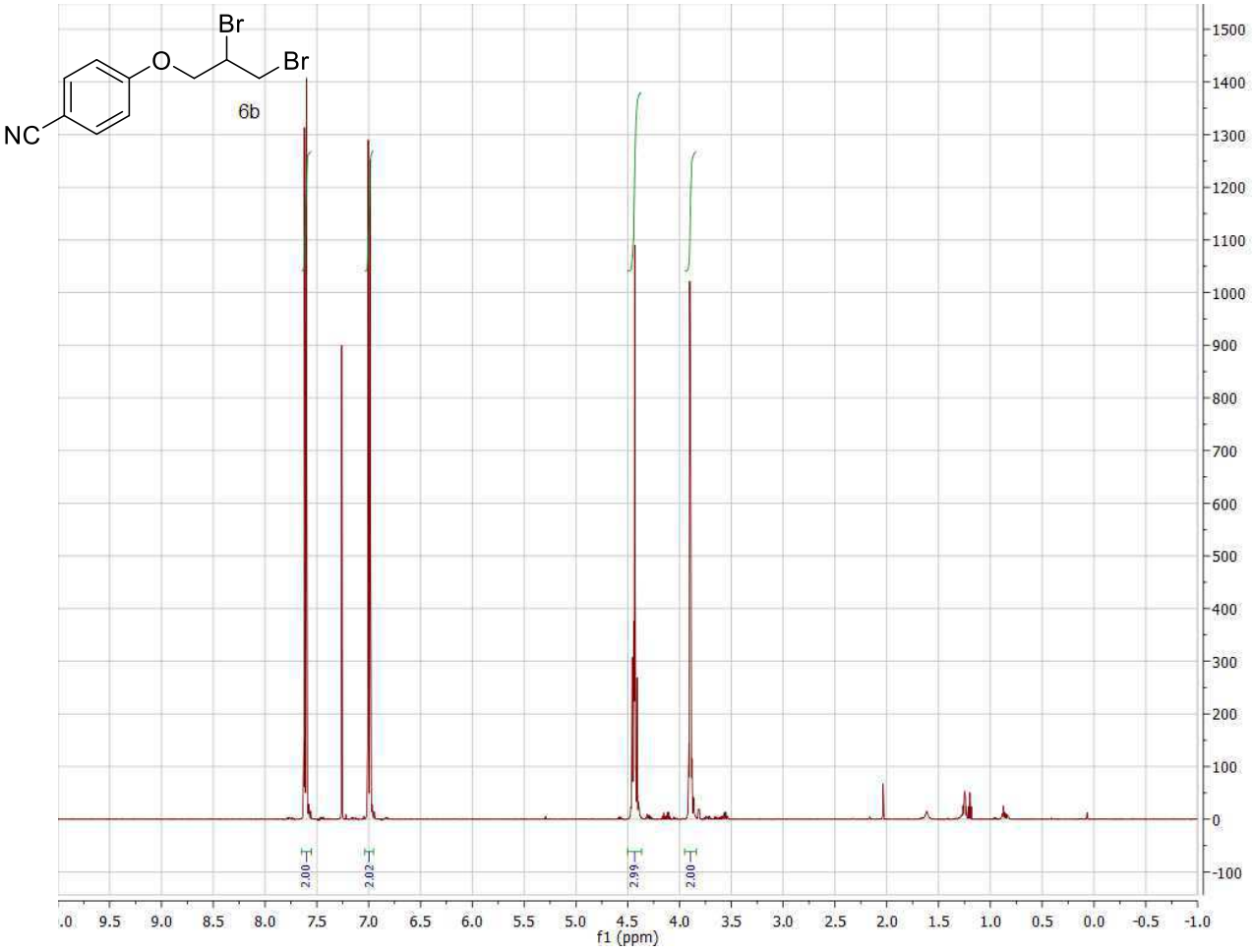
Run 5: Dibromination of 5b, 0.25 mmol, 24 h

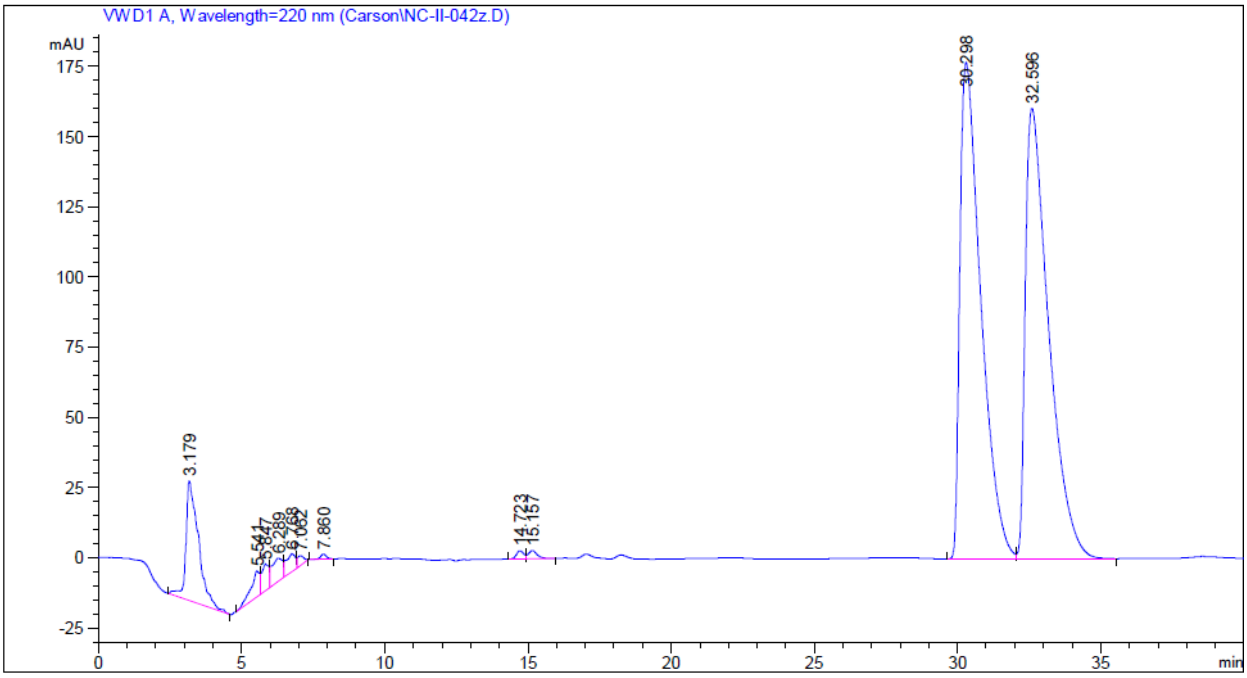


A 25-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with freshly-prepared **4b** (8.1 mg, 6.0 μmol, 2.4 mol %), weighed out in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 9:1 THF/H_2O (1.0 mL) injected. Then, copper(II) bromide (884 mg, 3.96 mmol, 15.83 equiv, 2.0 M) was added in one portion to form a deep green solution, followed by lithium bromide (22 mg, 0.26 mmol, 1.03 equiv, 0.13 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5b** (40 mg, 0.25 mmol) was then added to the mixture, washing with 9:1 THF/H_2O (1.0 mL). The mixture was left to stir at rt, monitoring periodically by TLC. Completion was reached at 24 h, and the mixture was extracted with CH_2Cl_2 (3 × 20 mL), then dried over $MgSO_4$. Hexane (5 mL) was added, and the precipitated yellow Pd complex removed by filtration, washing with hexane (3 × 5 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using 9:1 hexane/ethyl acetate as eluent, to yield dibromide **6b** as a white solid, 68 mg (0.21 mmol, **85%** yield). This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

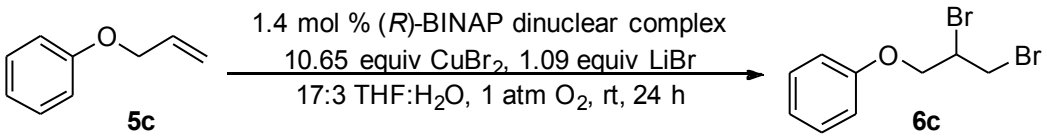
Data for **6b**:

HPLC: t_R 30.3 min (49.8%); t_R 32.6 min (50.2%) (IB-3, hexane/*i*-PrOH = 92:8, 1.0 mL min^{-1}, 220 nm, 20 °C)


Br
O
Br
NC
6b
2.00
2.02
2.99
2.00
f1 (ppm)


VWD1 A, Wavelength=220 nm (Carson\NC-II-042z.D)
mAU
3.179
7.860
14.723
15.157
30.298
32.596
min

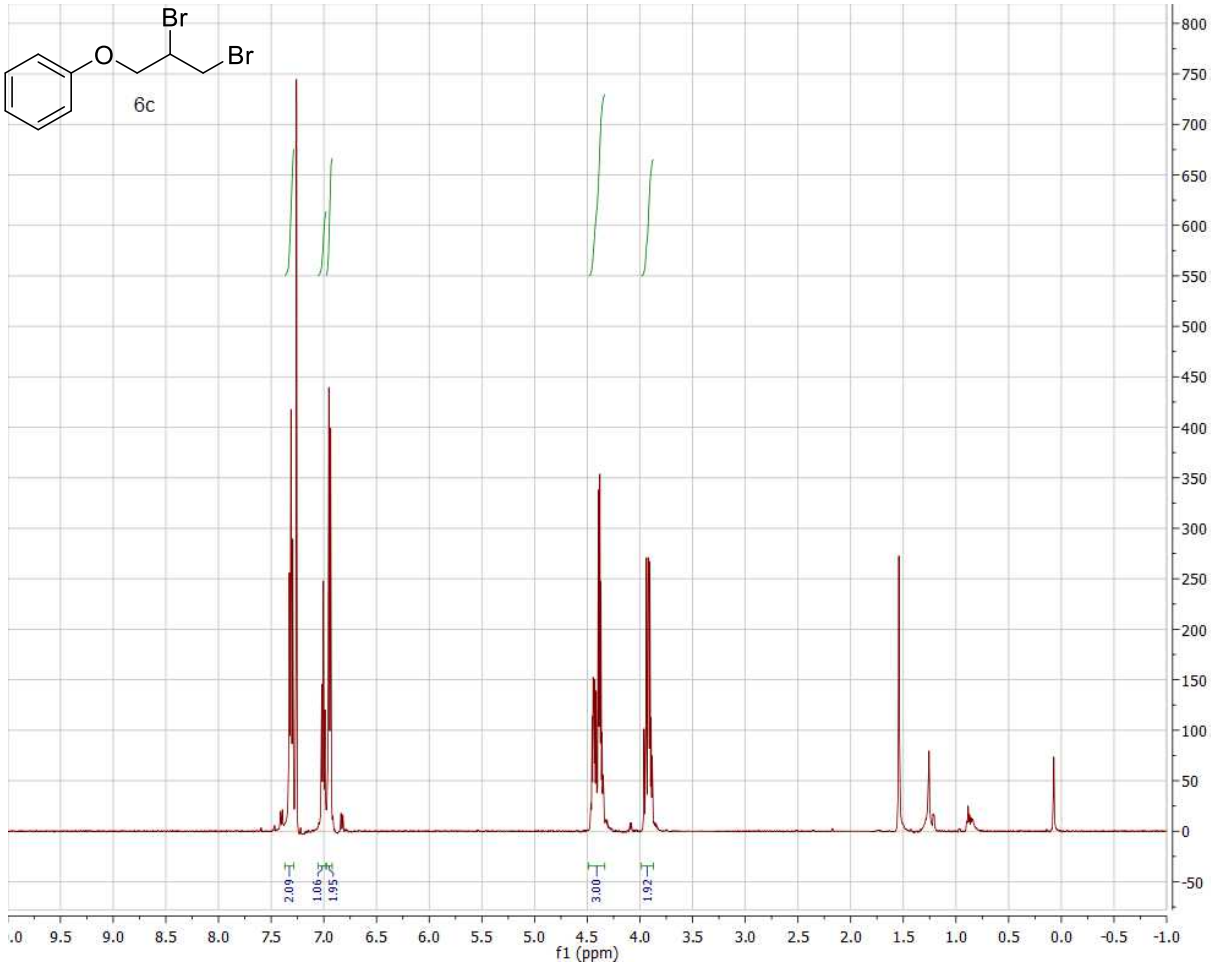
Run 6: Dibromination of 5c, 0.25 mmol, 24 h

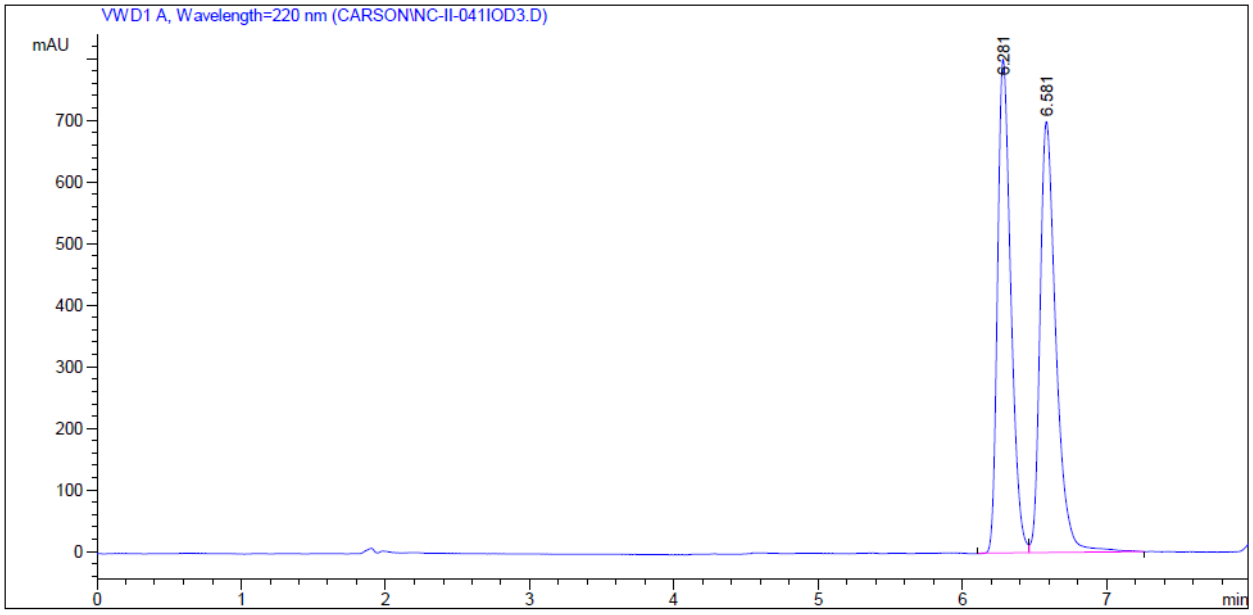


A 25-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with **4a**, freshly prepared according to the new method described above (4.4 mg, 3.4 μmol, 1.4 mol %), and weighed out in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 17:3 THF/H_2O (1.0 mL) injected. Then, copper(II) bromide (595 mg, 2.66 mmol, 10.65 equiv, 2.0 M) was added in one portion to form a deep green solution, followed by lithium bromide (24 mg, 0.27 mmol, 1.09 equiv, 0.20 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5c** (34 mg, 0.25 mmol) was then added to the mixture, washing with 17:3 THF/H_2O (0.35 mL). The mixture was left to stir at rt, monitoring periodically by TLC. Completion was reached at 24 h, and the mixture was extracted with CH_2Cl_2 (3 × 20 mL), then dried over $MgSO_4$. Hexane (5 mL) was added, and the precipitated orange Pd complex removed by filtration, washing with hexane (3 × 5 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using hexane as eluent, to yield dibromide **6c** as a pale yellow oil, 51 mg (0.17 mmol, **69%** yield). This was found to be racemic by CSP-SFC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

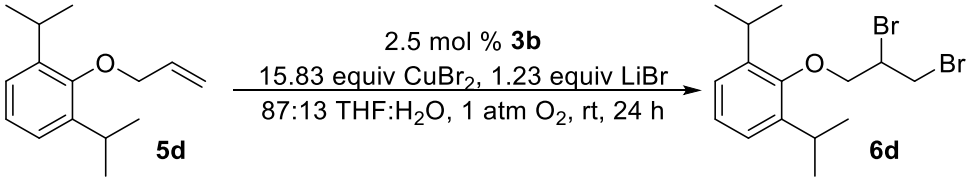
Data for **6c**:

SFC: t_R 6.3 min (49.9%); t_R 6.6 min (50.1%) (OD, MeOH:CO_2 = 3:97, 2.5 mL min^{-1}, 220 nm, 40 °C)


Br
O
Br
6c
2.09
1.06
1.95
3.00
1.92
f1 (ppm)


VWD1 A, Wavelength=220 nm (CARSON\NC-II-041IOD3.D)
mAU
6.281
6.581
min

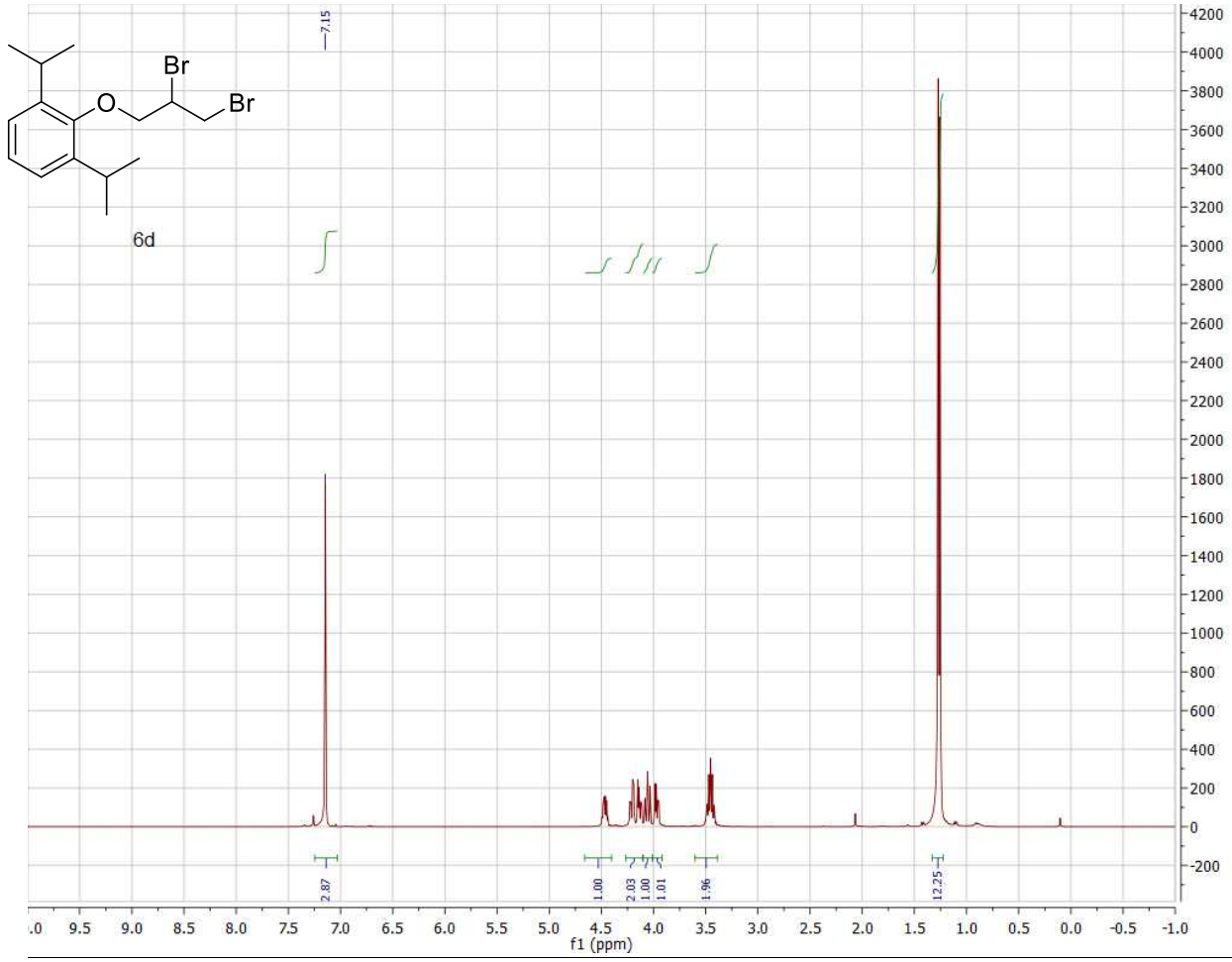
Run 7: Dibromination of 5d, 0.25 mmol, 24 h

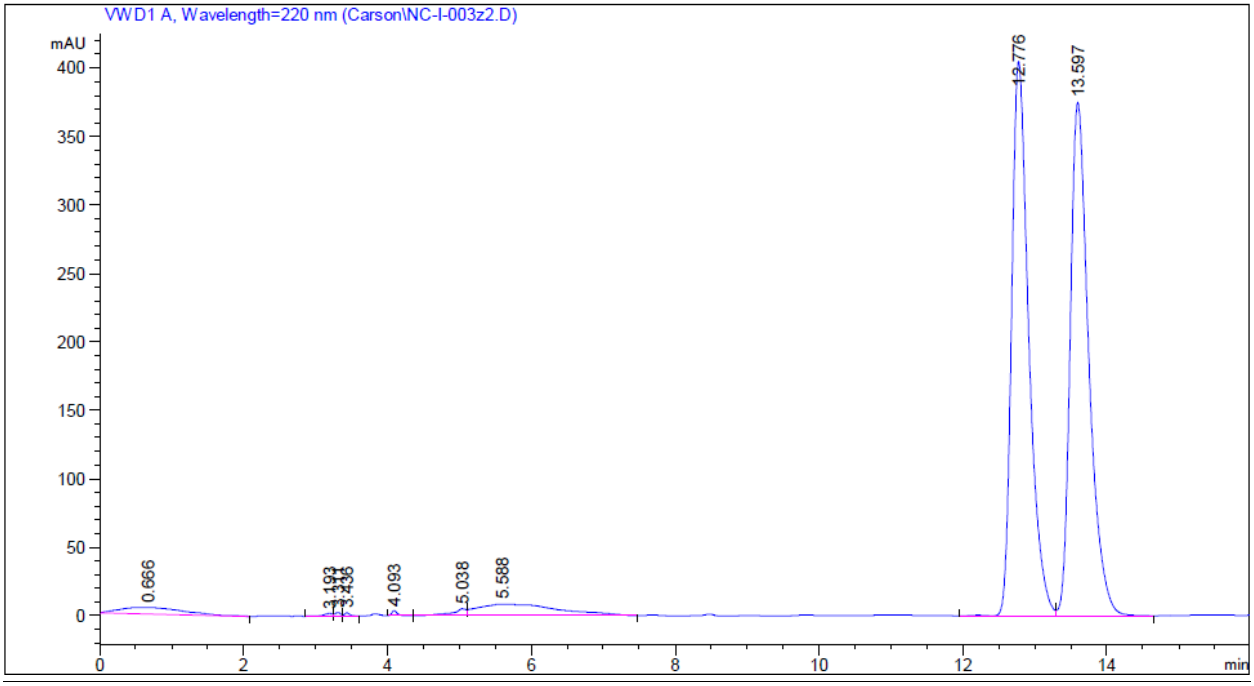


A 25-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with freshly-prepared **3b** (6.2 mg, 6.3 μmol, 2.5 mol %), weighed out in a glove box. The system was sealed under Ar, and removed from the glove box, then an Ar line inserted, and 87:13 THF/H_2O (1.0 mL) injected to give a bright yellow solution. Then, copper(II) bromide (884 mg, 3.96 mmol, 15.83 equiv, 2.2 M) was added in one portion to form a deep green solution, followed by lithium bromide (27 mg, 0.31 mmol, 1.23 equiv, 0.17 M) in one portion, which gave slight yellowing of the solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5d** (55 mg, 0.25 mmol) was then added to the mixture, washing with 87:13 THF/H_2O (0.8 mL). The mixture was left to stir at rt, monitoring periodically by TLC. Completion was reached at 24 h, and the mixture was extracted with CH_2Cl_2 (3 × 20 mL), then dried over $MgSO_4$. Hexane (5 mL) was added, and the precipitated yellow Pd complex removed by filtration, washing with hexane (3 × 5 mL). Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using 99:1 hexane/ethyl acetate as eluent, to yield dibromide **6d** as colorless needles, 85 mg (0.22 mmol, **90%** yield). This was found to be racemic by CSP-HPLC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

Data for **6d**:

HPLC: t_R 12.8 min (49.9 %); t_R 13.6 min (50.1%) (IB-3, hexane/*i*-PrOH = 99.9:0.1, 1.0 mL min^{-1}, 220 nm, 20 °C)


Br
O
Br
6d
7.15
2.87
1.00
2.03
1.00
1.01
1.96
12.25
f1 (ppm)


VWD1 A, Wavelength=220 nm (Carson\NC-I-003z2.D)
mAU
0.666
3.193
3.371
3.438
4.093
5.038
5.588
12.776
13.597
min

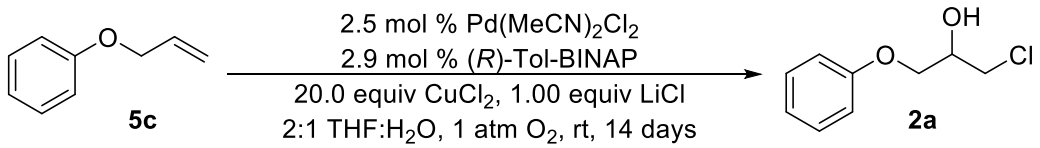
Conditions and Spectra for Chlorohydroxylation Reactions:

Reactions were run according to Henry's procedures.[1] The procedures were all reproduced as rigorously as the described procedures allow, other than changing the scale. Reaction progress was monitored by ^{1}H NMR of aliquots. Concentrations are calculated with respect to total solvent volume.

Table S3. Conditions for Chlorohydroxylation Reactions

Run	Substrate	Amount of substrate, mmol	Pd complex, mol %	$CuCl_2$ equiv	$CuCl_2$ molarity, M	LiCl equiv	LiCl molarity, M	THF/H_2O	Time, days
8	**2a**	0.5	2.5	20.00	4.0	1.00	0.20	2:1	14
9	**2a**	0.5	1.2	14.59	1.8	2.43	0.30	92:8	5
10	**2b**	1.0	1.0	8.00	8.0	0.40	0.40	2:1	10
11	**2c**	0.5	1.5	13.38	2.9	0.92	0.20	90:10	10

Run 8: Chlorohydroxylation of 5c with Catalyst 3a, 0.50 mmol, 14 days

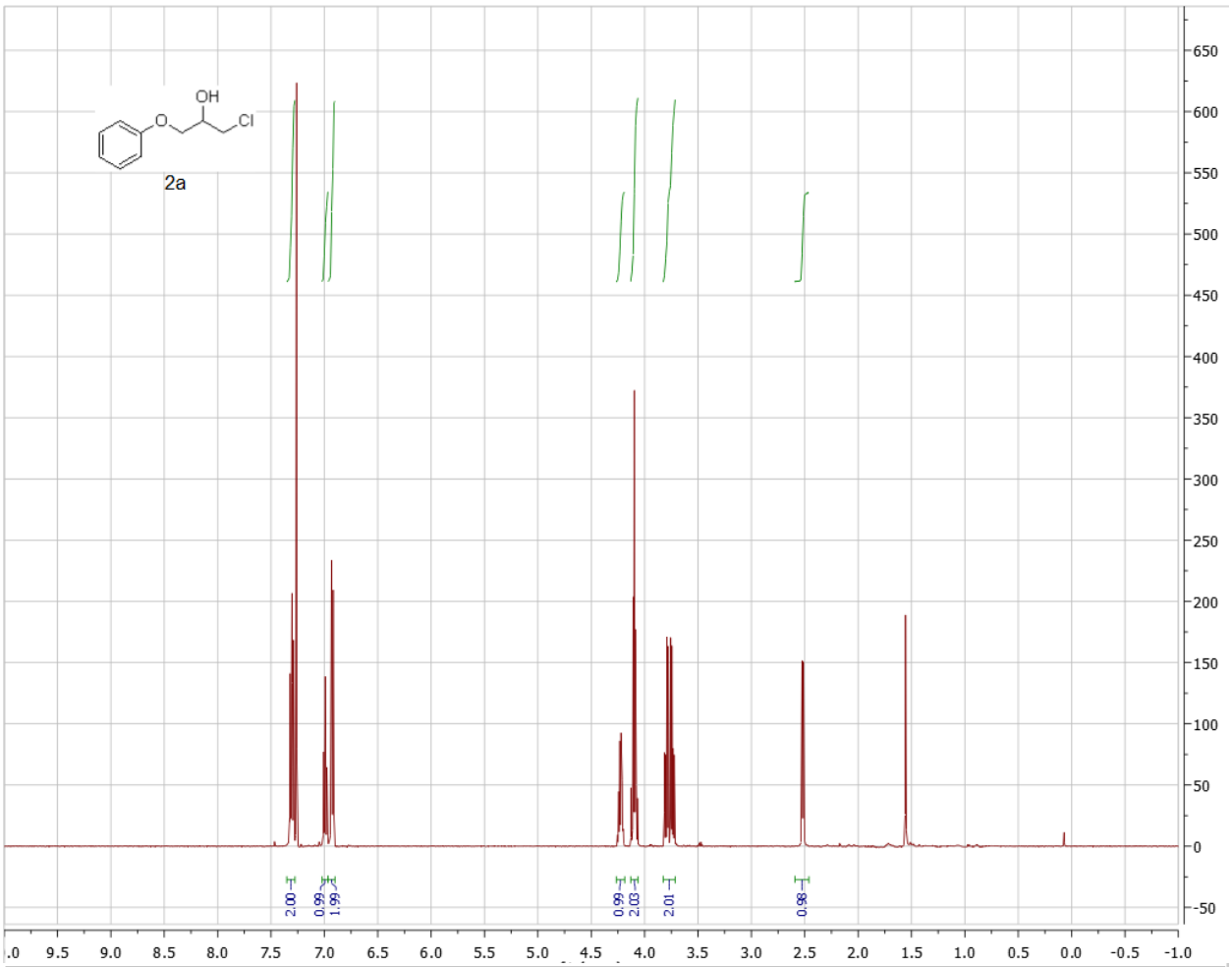


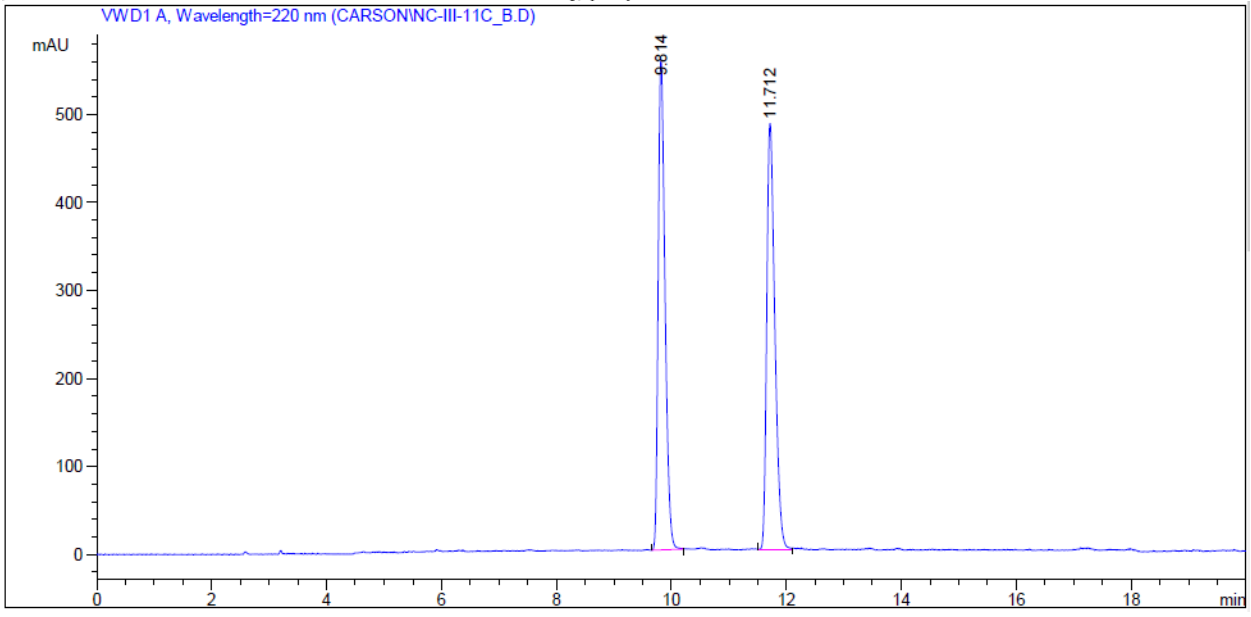
In a glove box, a 10-mL, two-necked flask containing a Teflon-coated, magnetic stir bar was charged with bis(acetonitrile)dichloropalladium(II) (3.2 mg, 12 μmol, 2.5 mol %). The flask was sealed under Ar and removed from the glove box. An Ar line was inserted, and anhydrous THF (1.0 mL) was injected. (*R*)-Tol-BINAP (9.5 mg, 14 μmol, 2.9 mol %) was added to form a yellow solution, which was stirred at rt for 30 min. Then, a separate 10-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with anhydrous copper(II) chloride (1.344 g, 10.0 mmol, 20.0 equiv) and lithium chloride (21 mg, 0.5 mmol, 1.00 equiv), and 45:55 THF/H_2O (0.5 mL) was added to form a green solution. The catalyst solution was cannulated into the second flask, washing with 45:55 THF/H_2O (0.5 mL). The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5c** (67 mg, 0.5 mmol) was then added to the mixture, washing with 45:55 THF/H_2O (0.5 mL). The eventual solvent mixture was 2:1 THF/H_2O . The mixture was left to stir at rt, monitoring periodically by NMR spectroscopy of aliquots. Despite low conversion, the reaction was stopped after 14 days. H_2O (10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 × 10 mL), then dried over $CaCl_2$. Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using a gradient from 93:7 to 85:15 hexane/ethyl acetate as eluent, to yield chlorohydrin **2a** as a pale yellow oil,

14 mg (0.075 mmol, **15%** yield). This was found to be racemic by CSP-SFC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

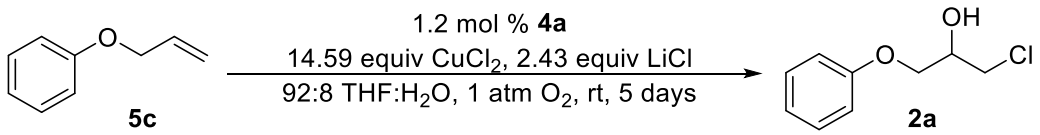
Data for **2a**:

SFC: t_R 9.8 min (49.5%); t_R 11.7 min (50.5%) (OD, MeOH:CO_2 = 1:99 for 10 min then 10:90 for 6 min then 5:95 for 4 min, 2.5 mL min^{-1}, 220 nm, 40 °C)


OH
O
Cl
2a
2.00
0.99
1.99
0.99
2.03
2.01
0.88


VWD1 A, Wavelength=220 nm (CARSON\NC-III-11C_B.D)
mAU
9.814
11.712
min

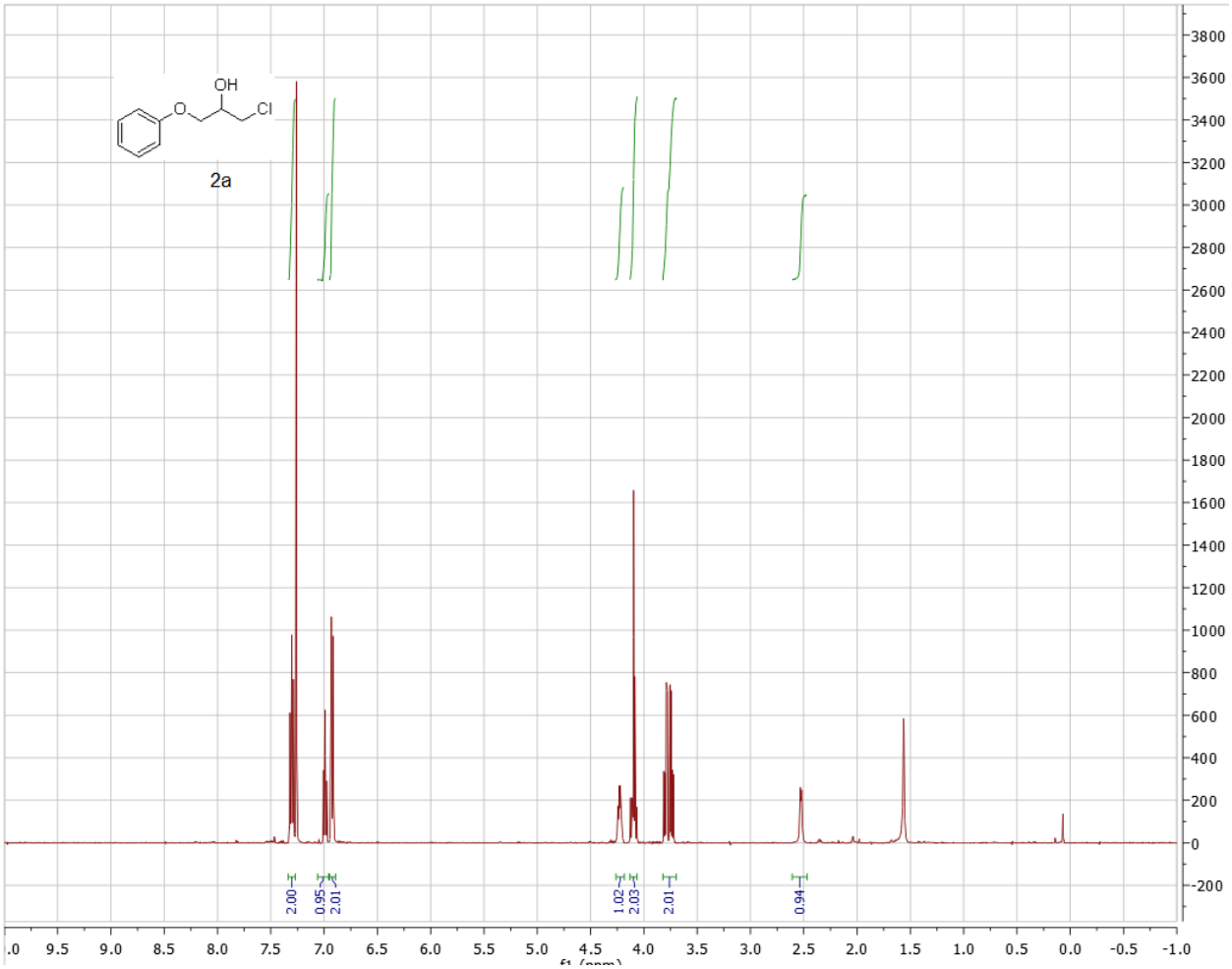
Run 9: Chlorohydroxylation of 5c with Catalyst 4a, 0.50 mmol, 5 days

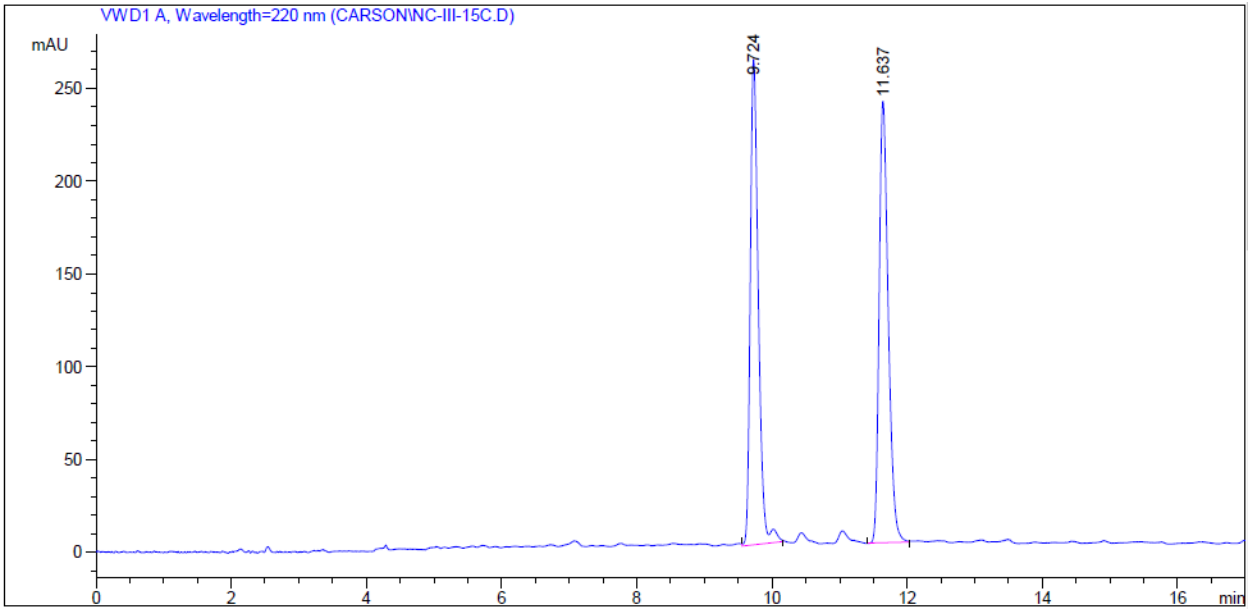


In a glove box, a 10-mL, two-necked flask containing a Teflon-coated, magnetic stir bar was charged with **4a**, freshly prepared according to Henry's method (7.9 mg, 6.1 μmol, 1.2 mol %). The flask was sealed under Ar and removed from the glove box. An Ar line was inserted, and anhydrous THF (1.0 mL) was injected. Anhydrous copper(II) chloride (981 mg, 7.30 mmol, 14.59 equiv) and lithium chloride (52 mg, 1.21 mmol, 2.43 equiv) were then added, followed by 89:11 THF/H_2O (2.05 mL), to form a green solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5c** (67 mg, 0.5 mmol) was then added to the mixture, washing with 92:8 THF/H_2O (1.0 mL). The eventual solvent mixture was 92:8 THF/H_2O . The mixture was left to stir at rt, monitoring periodically by NMR spectroscopy of aliquots, and stopped after 5 days. H_2O (10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 × 10 mL), then dried over $CaCl_2$. Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using a gradient from 93:7 to 85:15 hexane/ethyl acetate as eluent, to yield chlorohydrin **2a** as a pale yellow oil, 37 mg (0.20 mmol, **40%** yield). This was found to be racemic by CSP-SFC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

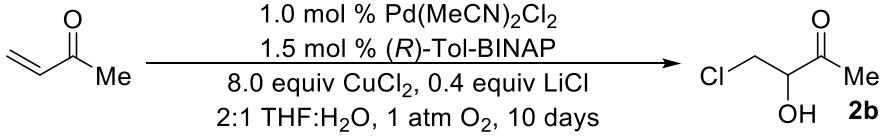
Data for **2a**:

SFC: t_R 9.7 min (49.5%); t_R 11.6 min (50.5%) (OD, MeOH:CO_2 = 1:99 for 10 min then 10:90 for 6 min then 5:95 for 4 min, 2.5 mL min^{-1}, 220 nm, 40 °C)


OH
O
Cl
2a
2.00
0.95
2.01
1.02
2.03
2.01
0.94


VWD1 A, Wavelength=220 nm (CARSON\NC-III-15C.D)
mAU
9.724
11.637
min

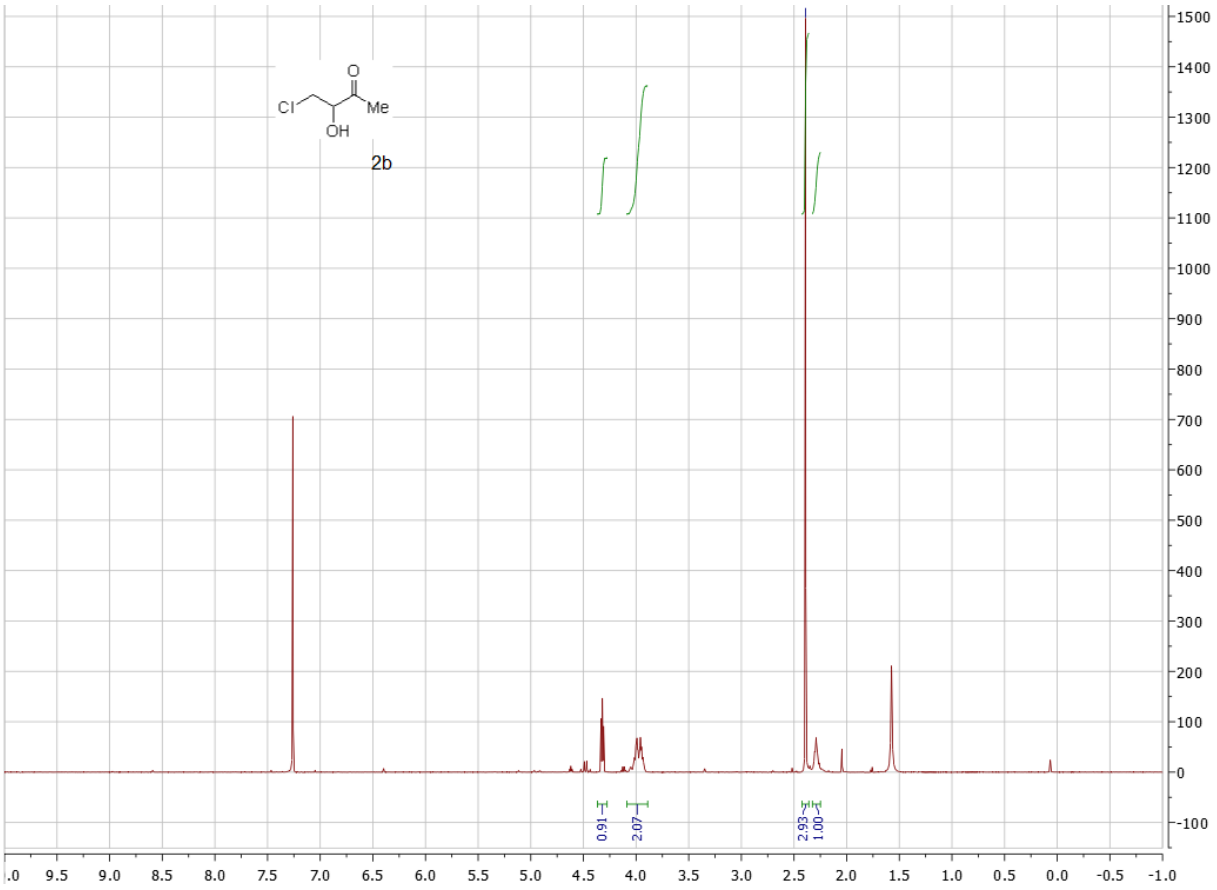
Run 10: Chlorohydroxylation of Methyl Vinyl Ketone with Catalyst 3a, 1.00 mmol, 10 days

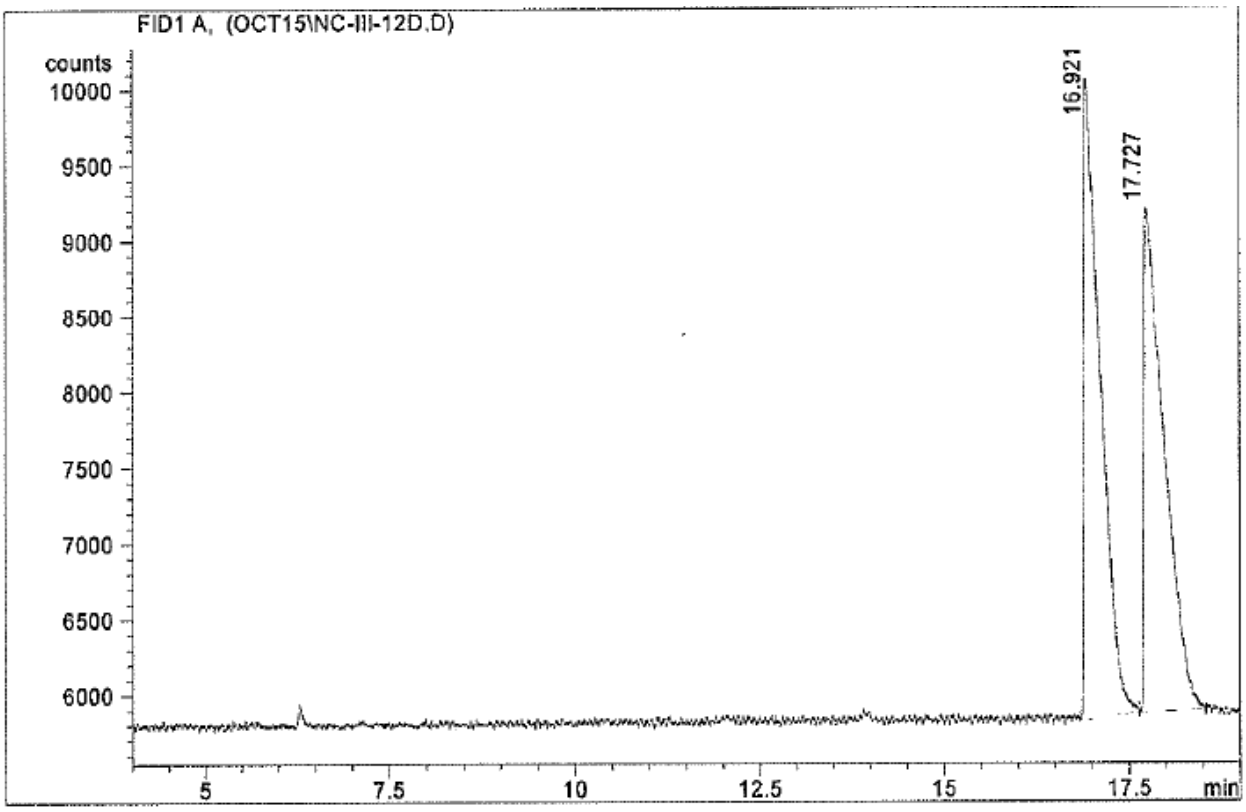


In a glove box, a 10-mL, two-necked flask containing a Teflon-coated, magnetic stir bar was charged with bis(acetonitrile)dichloropalladium(II) (2.6 mg, 10 μmol, 1.0 mol %). The flask was sealed under Ar and removed from the glove box. An Ar line was inserted, and anhydrous THF (1.0 mL) was injected. (*R*)-Tol-BINAP (9.9 mg, 15 μmol, 1.5 mol %) was added to form a yellow solution, which was stirred at rt for 30 min. Then, a separate 10-mL, round-bottomed flask containing a Teflon-coated, magnetic stir bar was charged with anhydrous copper(II) chloride (1.076 g, 8.0 mmol, 8.0 equiv) and lithium chloride (17 mg, 0.4 mmol, 0.4 equiv), then 1:2 THF/H_2O (0.3 mL) was added to form a green solution. The catalyst solution was cannulated into the second flask, washing with 1:2 THF/H_2O (0.3 mL). The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. Methyl vinyl ketone (70 mg, 1.0 mmol) was then injected into the mixture, washing with 1:2 THF/H_2O (0.4 mL). The eventual solvent mixture was 2:1 THF/H_2O . The mixture was left to stir at rt, monitoring periodically by NMR spectroscopy of aliquots, and stopped after 10 days. H_2O (10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 × 10 mL), then dried over $CaCl_2$. Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using a gradient from 95:5 to 80:20 hexane/ethyl acetate as eluent, to yield chlorohydrin **2b** as a colorless oil, 40 mg (0.33 mmol, **33%** yield). This was found to be racemic by CSP-GC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

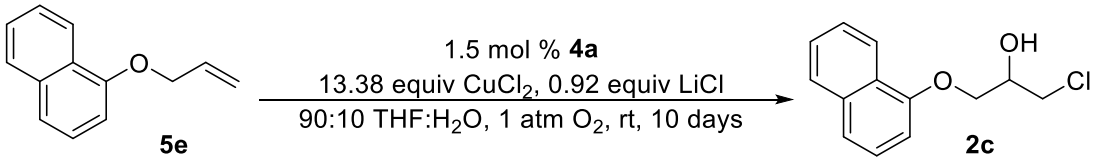
Data for **2b**:

GC: t_R 16.9 min (50.3%); t_R 17.7 min (49.7%) (CycloSil-B, 70 °C)


O
Cl
Me
OH
2b
0.91
2.07
2.93
1.00


FID1 A, (OCT15\NC-III-12D.D)
counts
16.921
17.727
min

Run 11: Chlorohydroxylation of 5e with Catalyst 4a, 0.50 mmol, 14 days

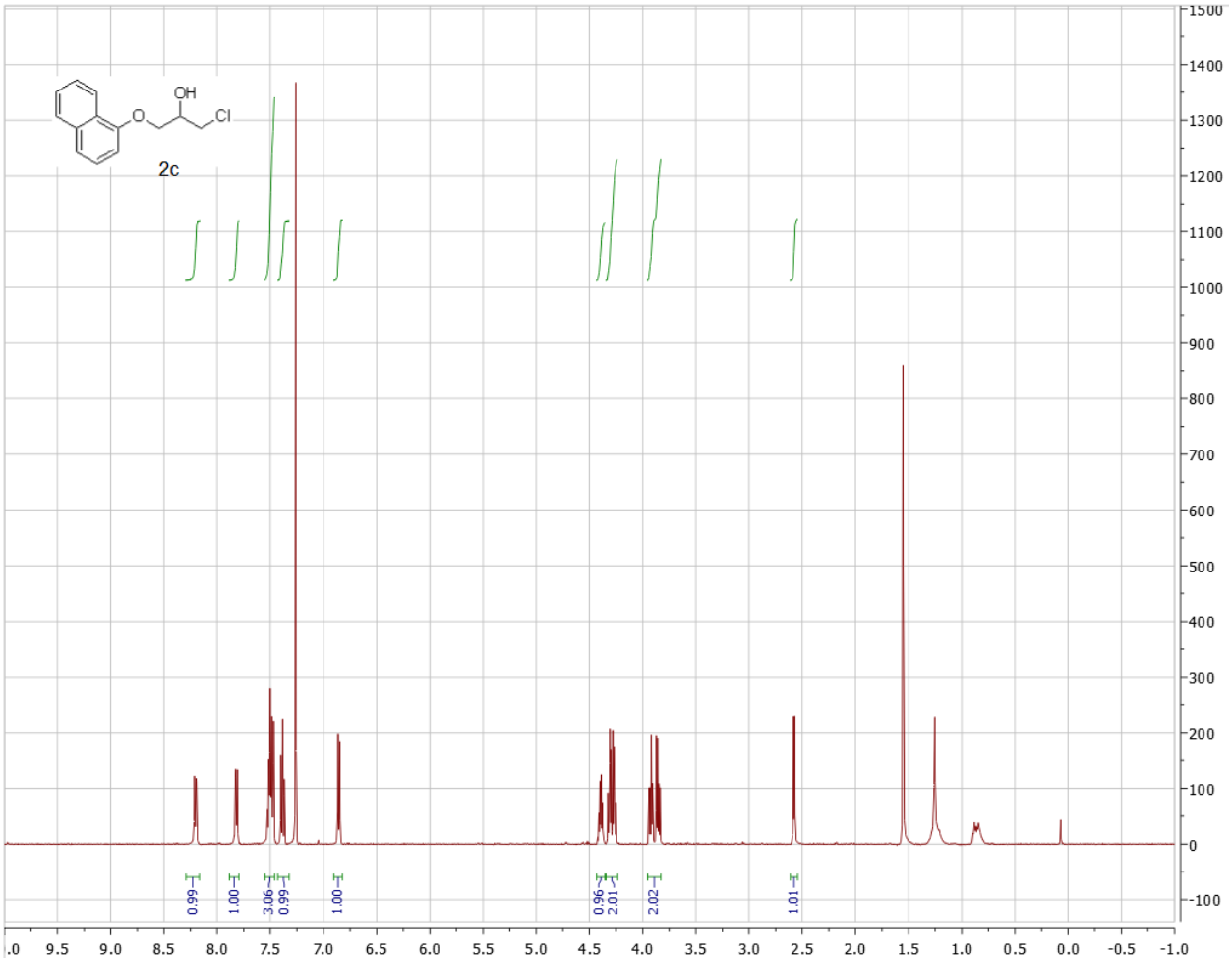


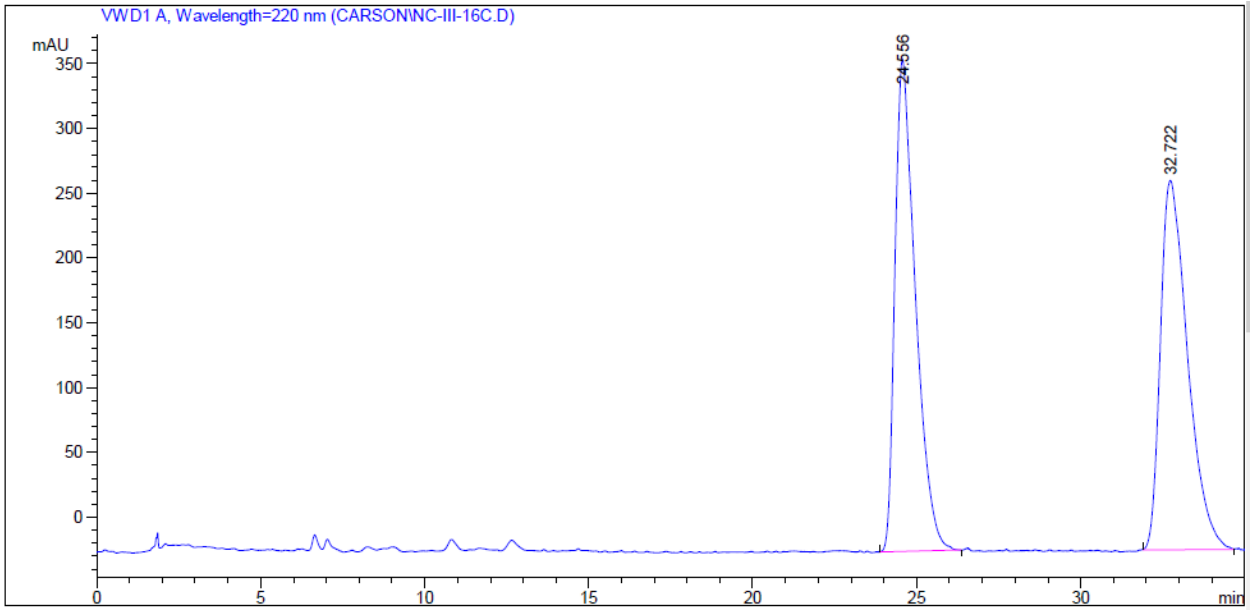
NOTE: The product was mischaracterized in Henry and coworkers' original report. The product there characterized was present in small amounts (roughly 9%) in the crude reaction mixture and is proposed to be the constitutionally isomeric chlorohydroxylation product.

In a glove box, a 10-mL, two-necked flask containing a Teflon-coated, magnetic stir bar was charged with **4a**, freshly prepared according to Henry's method (9.9 mg, 7.7 μmol, 1.5 mol %). The flask was sealed under Ar and removed from the glove box. An Ar line was inserted, and anhydrous THF (1.0 mL) was injected. Anhydrous copper(II) chloride (900 mg, 6.69 mmol, 13.38 equiv) and lithium chloride (20 mg, 0.46 mmol, 0.92 equiv) were then added, followed by 82:18 THF/H_2O (0.7 mL), to form a green solution. The atmosphere was replaced with 1 atm O_2 by sparging, and the reaction run under 1 atm O_2 from an oxygen manifold. **5e** (92 mg, 0.5 mmol) was then added to the mixture, washing with 82:18 THF/H_2O (0.6 mL). The eventual solvent mixture was 90:10 THF/H_2O . The mixture was left to stir at rt, monitoring periodically by NMR spectroscopy of aliquots. Despite incomplete conversion, the reaction was stopped after 10 days. H_2O (10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 × 10 mL), then dried over $CaCl_2$. Solvent was removed *in vacuo*, then the mixture purified *via* column chromatography using a gradient from 90:10 to 30:70 hexane/Et_2O as eluent, to yield firstly recovered 54 mg of pink solid **5e** (0.29 mmol, 59% yield of recovered starting material), and secondly chlorohydrin **2c** as a pale yellow oil, 34 mg (0.14 mmol, **29%** yield). This was found to be racemic by CSP-SFC. ^{1}H NMR spectroscopic data were identical to those of the racemic standard.

Data for **2c**:

SFC: t_R 24.6 min (50.1%); t_R 32.7 min (49.9%) (OD, MeOH:CO_2 = 10:90, 2.5 mL min^{-1}, 220 nm, 40 °C)


OH
O
Cl
2c
0.99
1.00
3.06
0.99
1.00
0.96
2.01
2.02
1.01


VWD1 A, Wavelength=220 nm (CARSON\NC-III-16C.D)
mAU
24.556
32.722
min

Chiral Shift Reagent NMR Experiment

$CDCl_3$ was purified by passing through a dry neutral Al_2O_3 column (70 × 7 mm diameter). Eu(hfc)$_3$ (448 mg, 375 μmol) was dissolved in 2.0 mL of purified $CDCl_3$, and the bright yellow solution filtered through a Celite column (25 × 6 mm diameter) with a slight positive Ar flow. Dibromide **5a** (40.5 mg, 125 μmol) was dissolved in purified $CDCl_3$ (0.5 mL) in an NMR tube. The Eu(hfc)$_3$ solution was added portionwise to the solution of **5a**, and ^{1}H NMR spectra (400 MHz) were taken after each addition (see page S48). The spectrum corresponding to 4 equiv Eu(hfc)$_3$ was taken in $CDCl_3$ (0.8 mL), containing **5a** (23.8 mg, 70 μmol) and Eu(hfc)$_3$ (334 mg, 280 μmol). The processing parameters for this spectrum were:

Spectrometer frequency	400 MHz
Delay time	10 s
Number of scans	16

References

(1) El-Qisairi, A. K.; Qaseer, H. A.; Katsigras, G.; Lorenzi, P.; Trivedi, U.; Tracz, S.; Hartman, A.; Miller, J. A.; Henry, P. M. *Org. Lett.* **2003**, *5*, 439–441.

(2) Armarego, W. L. F.; Chai, C. L. L. *Purification of Laboratory Chemicals*, Sixth Ed.; Butterworth-Heinemann, 2009.

(3) El-Qisairi, A. K.; Qaseer, H. A.; Henry, P. M. *J. Organomet. Chem.* **2002**, *656*, 168–176.

(4) Marcinkiewicz, S.; Green, J.; Mamalis, P. *Tetrahedron* **1961**, *14*, 208–222.

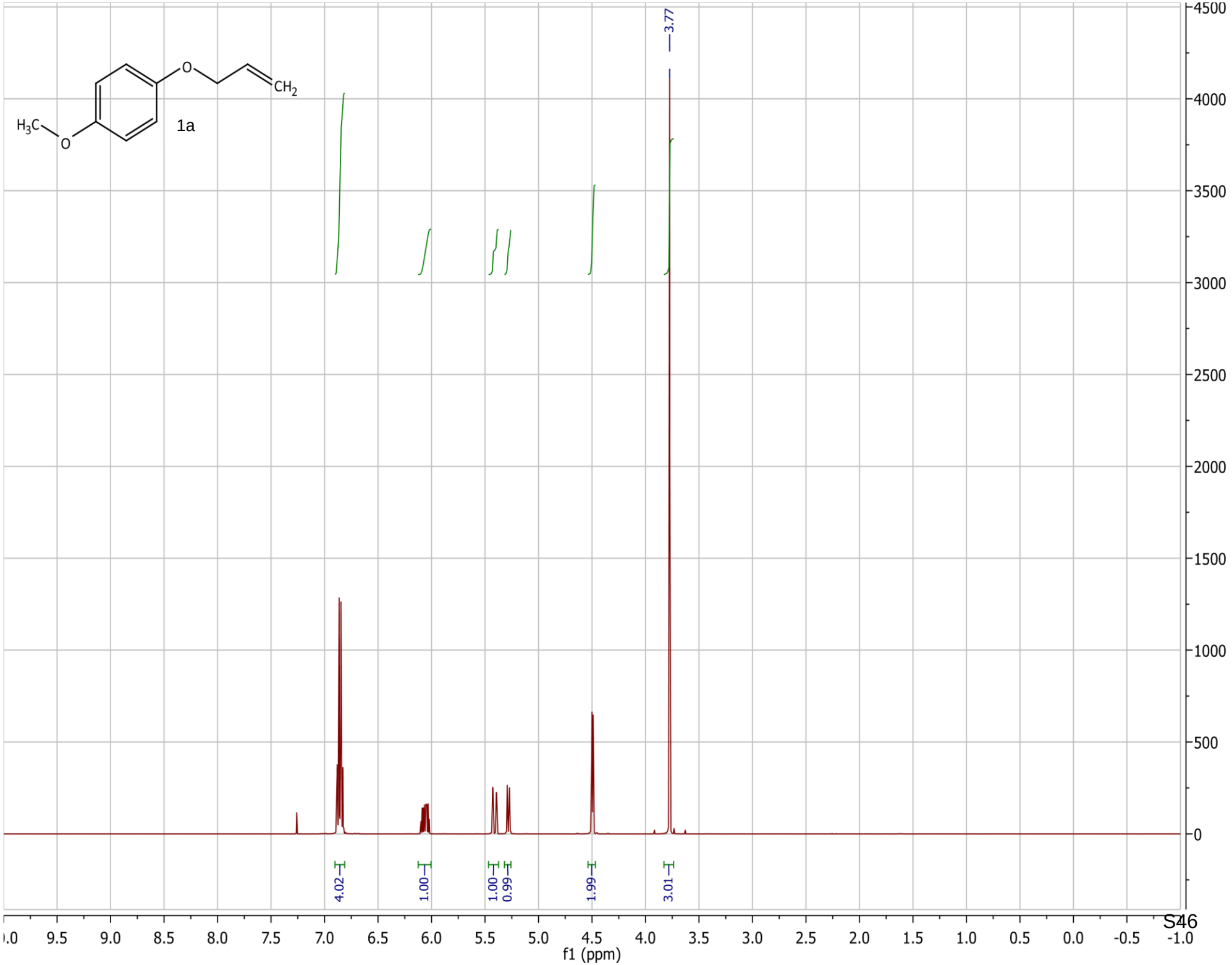
(5) Nesper, R.; Pregosin, P. S.; Püntener, K.; Wörle, M. *Helv. Chim. Acta* **1993**, *76*, 2239–2249.

(6) El-Qisairi, A.; Henry, P. M. *J. Organomet. Chem.* **2000**, *603*, 50–60.

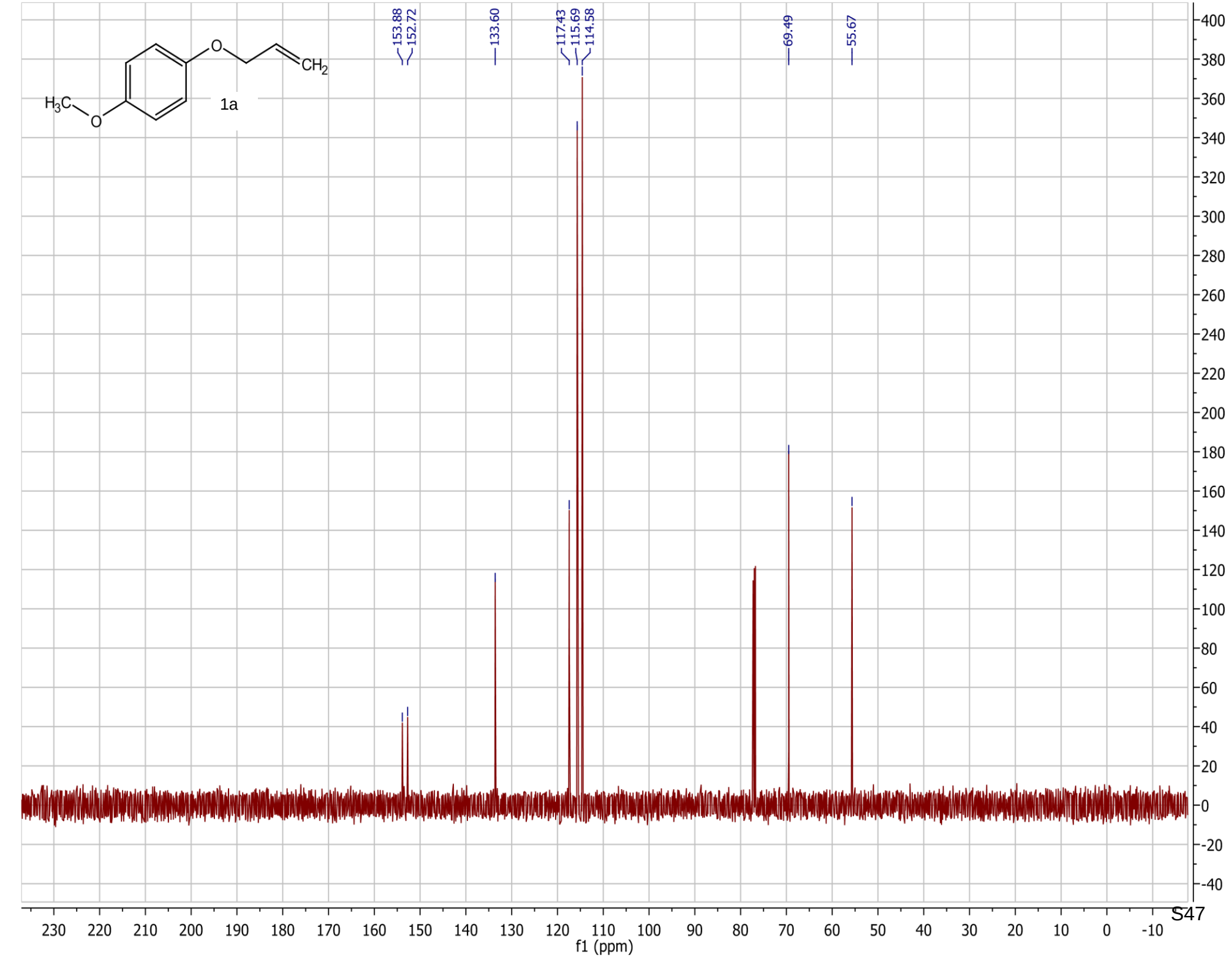
(7) Braddock, D. C.; Cansell, G.; Hermitage, S. A. *Synlett* **2004**, 461–464.

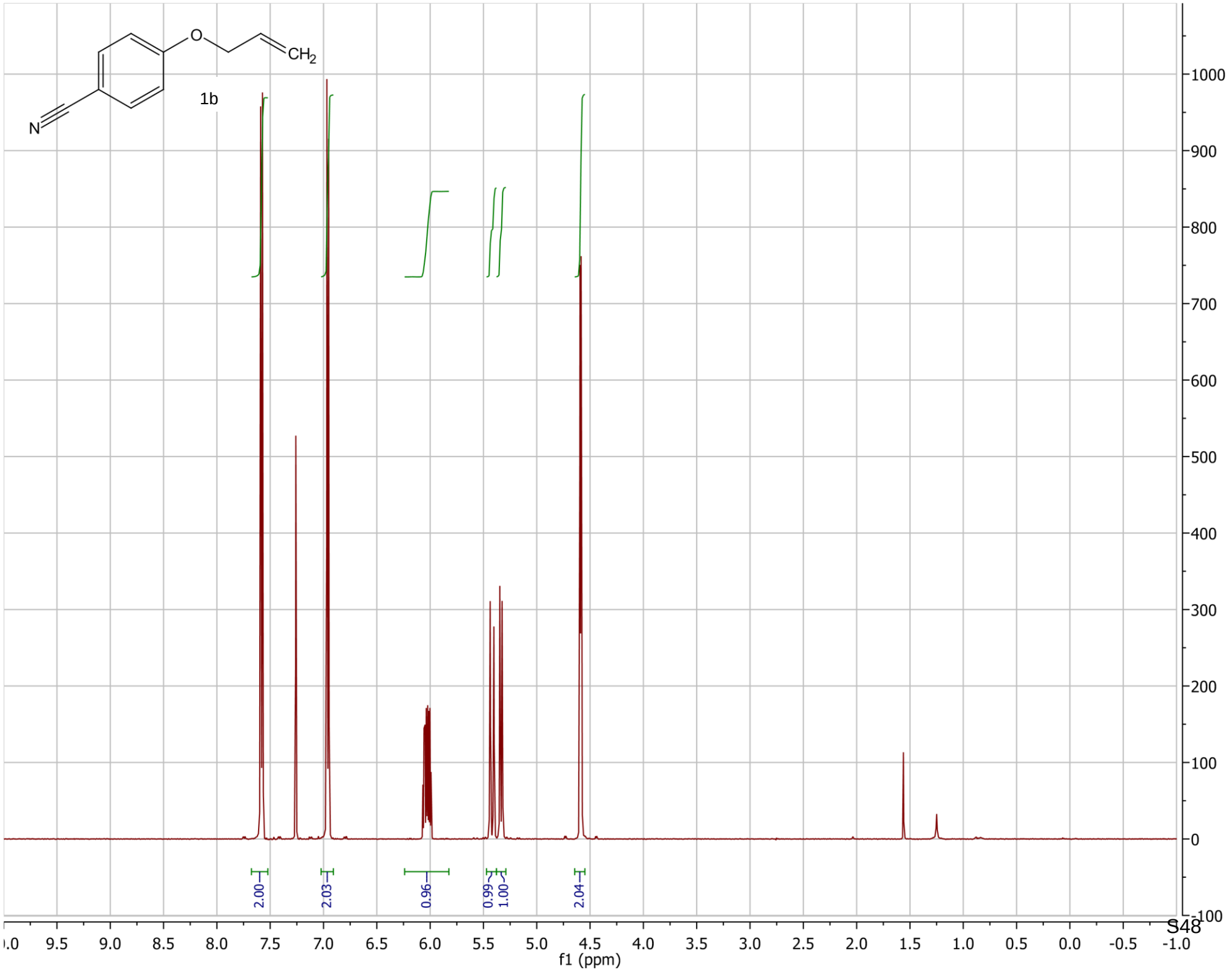
(8) Martínez, F.; Del Campo, C.; Sinisterra, J. V.; Llama, E. F. *Tetrahedron Asymmetry* **2000**, *11*, 4651–4660.

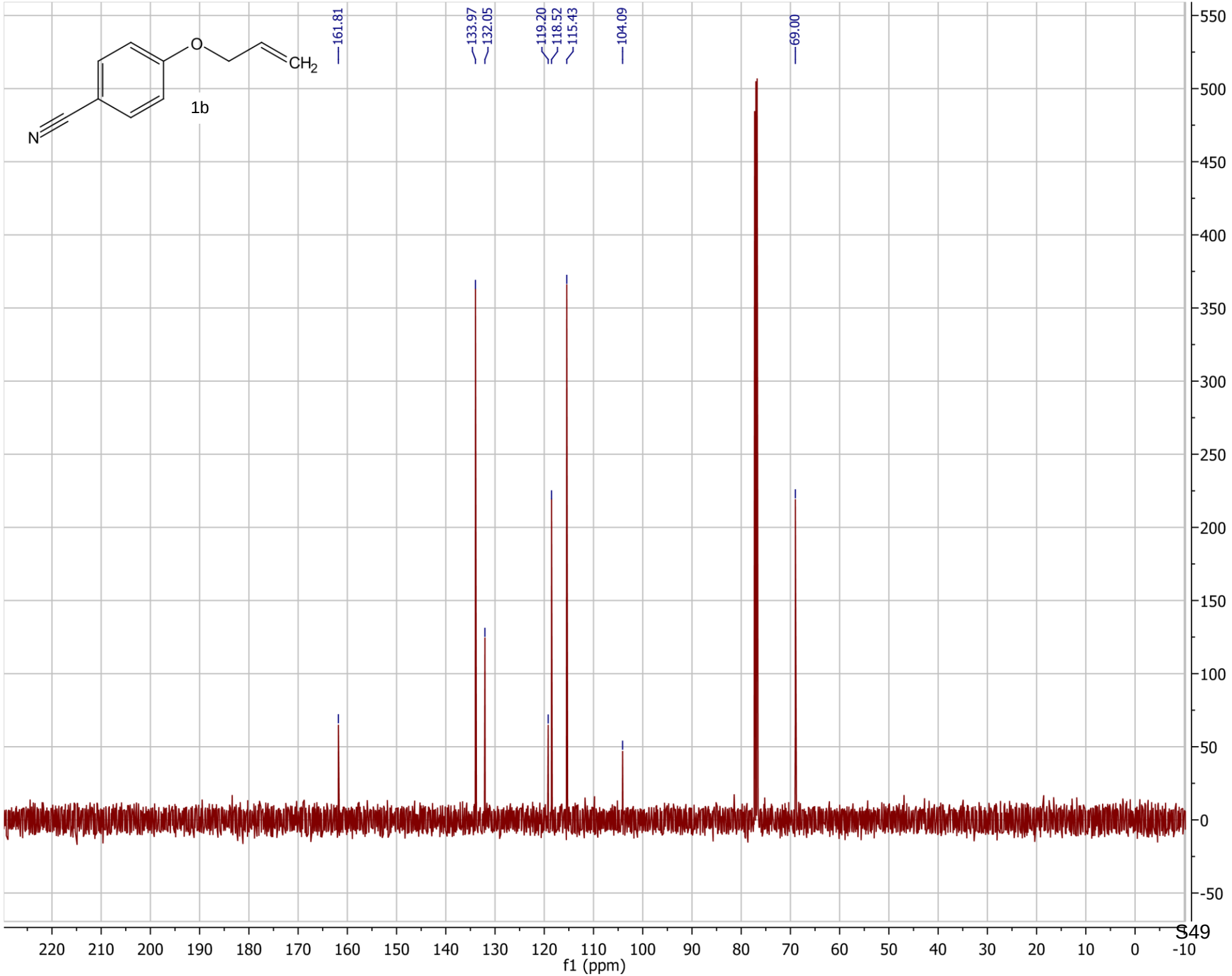
(9) Limnios, D.; Kokotos, C. G. *J. Org. Chem.* **2014**, *79*, 4270–4276.

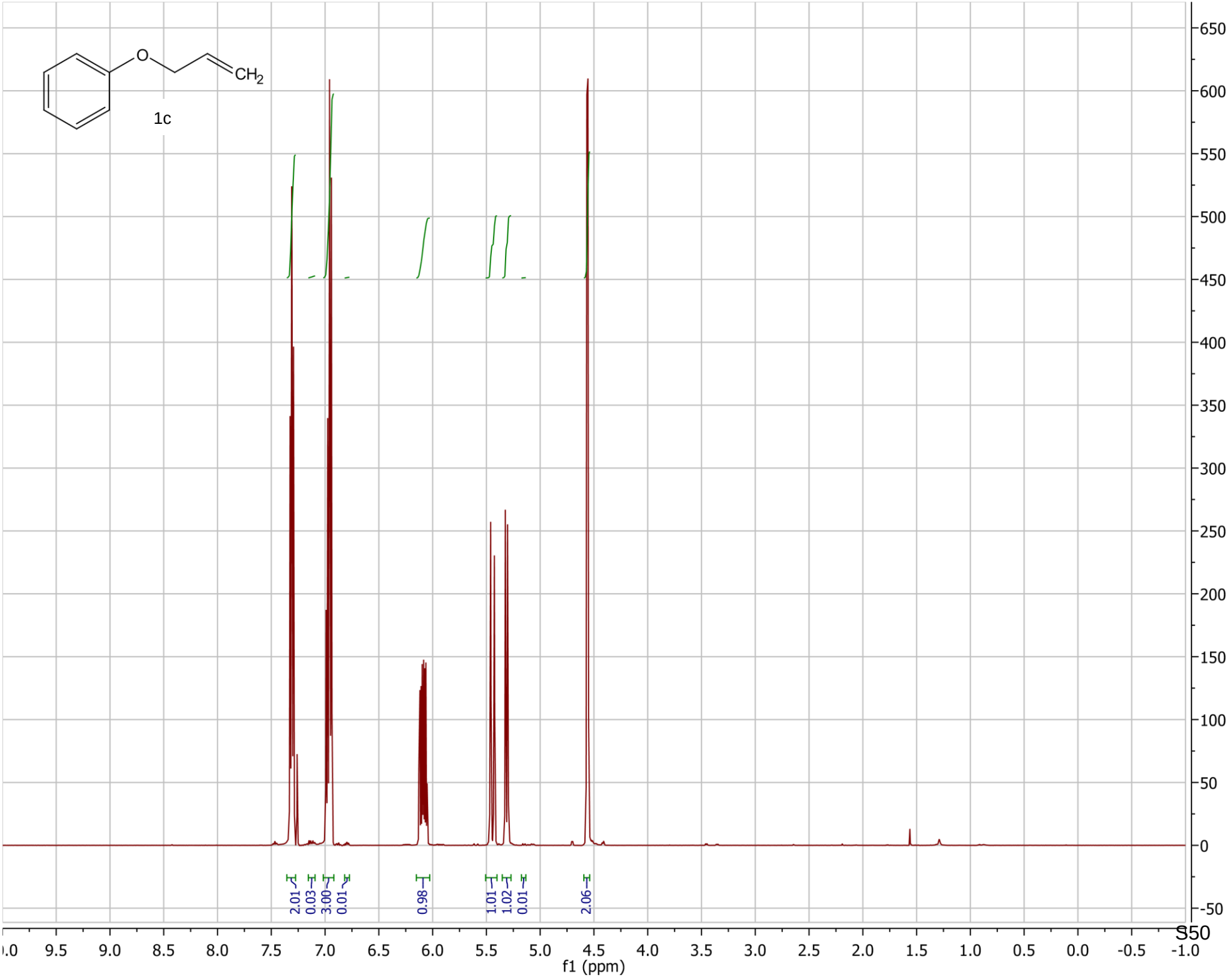


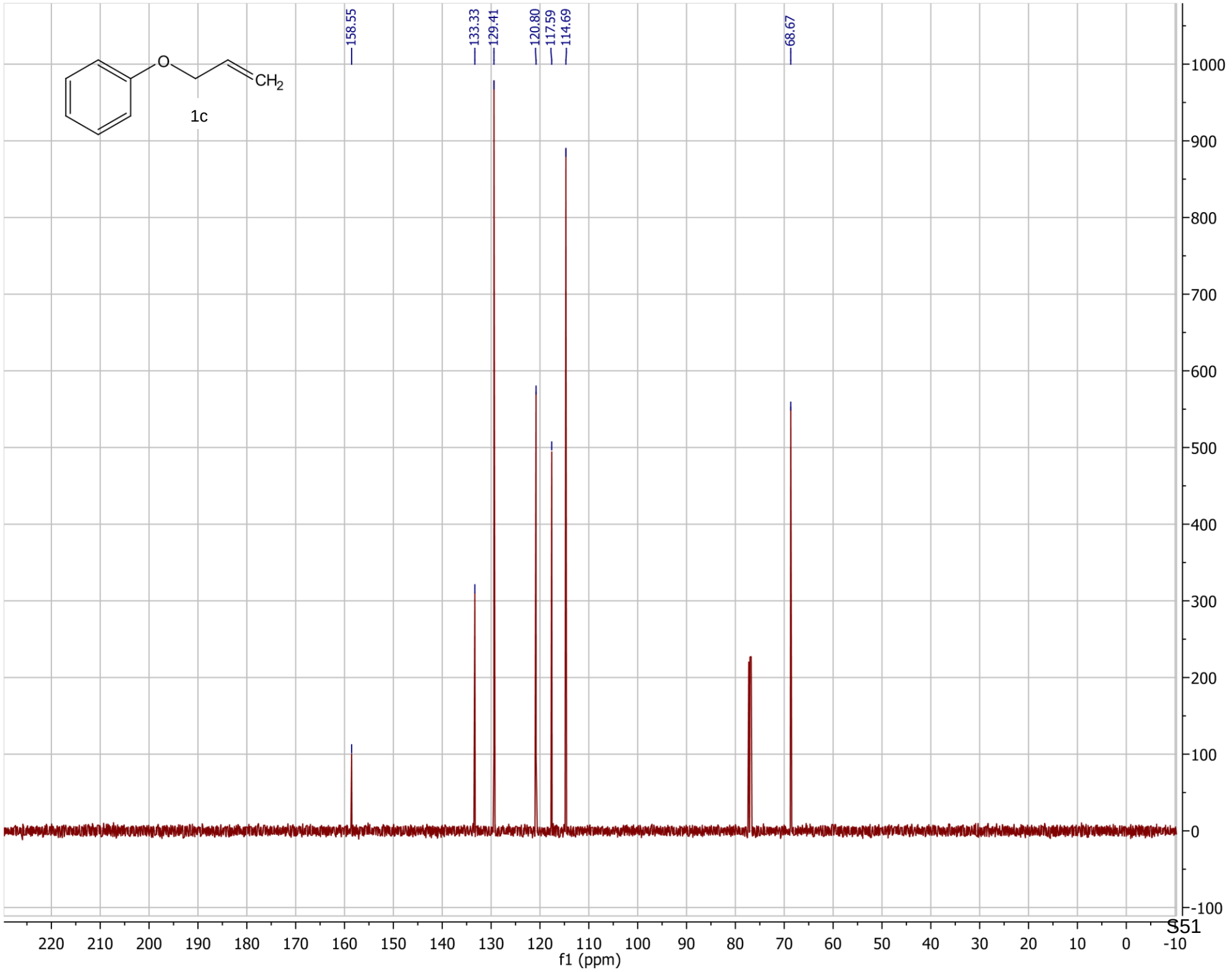
1a

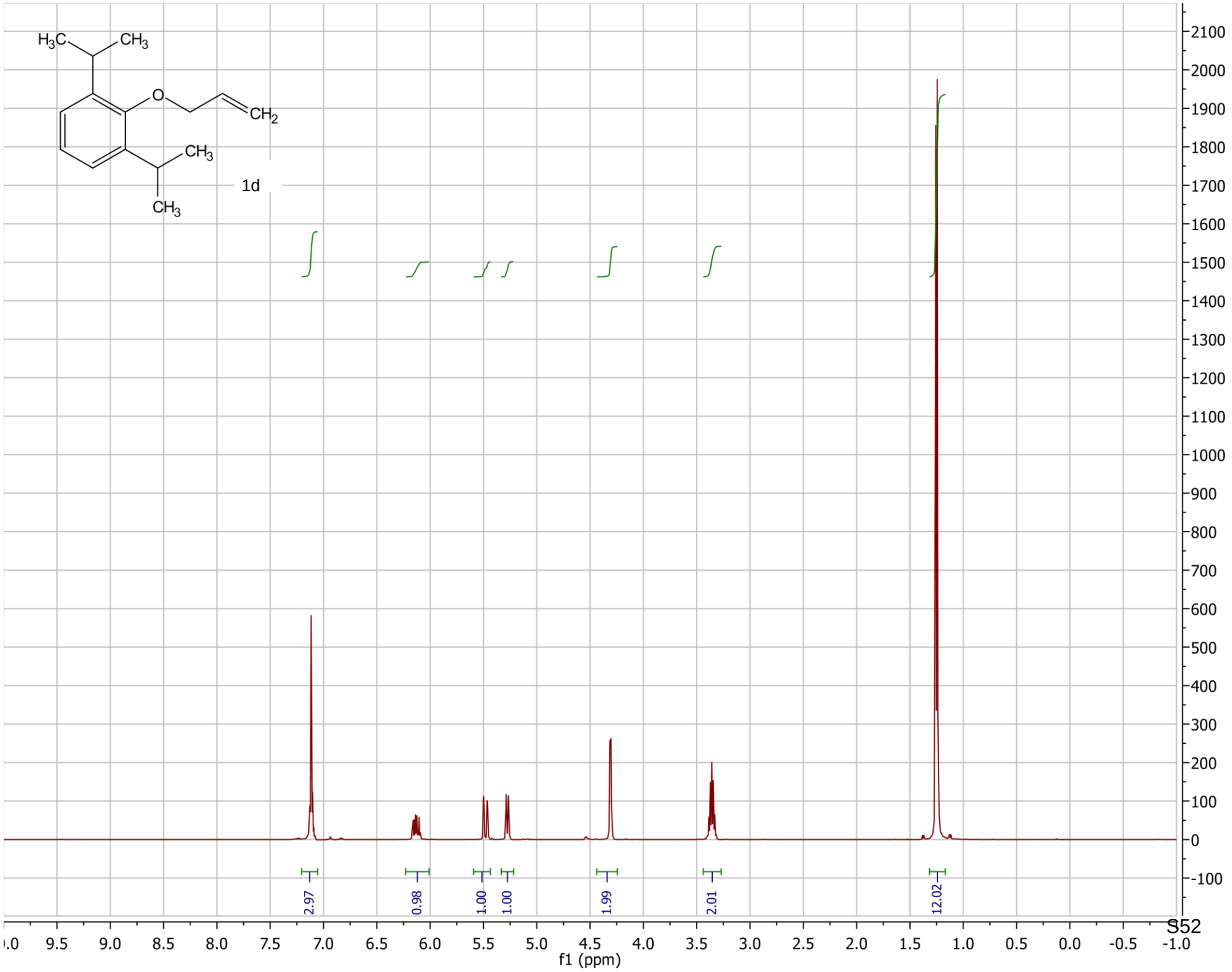

153.88
152.72
133.60
117.43
115.69
114.58
69.49
55.67
O
CH2
H3C
O
1a
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-20
-40
230 220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

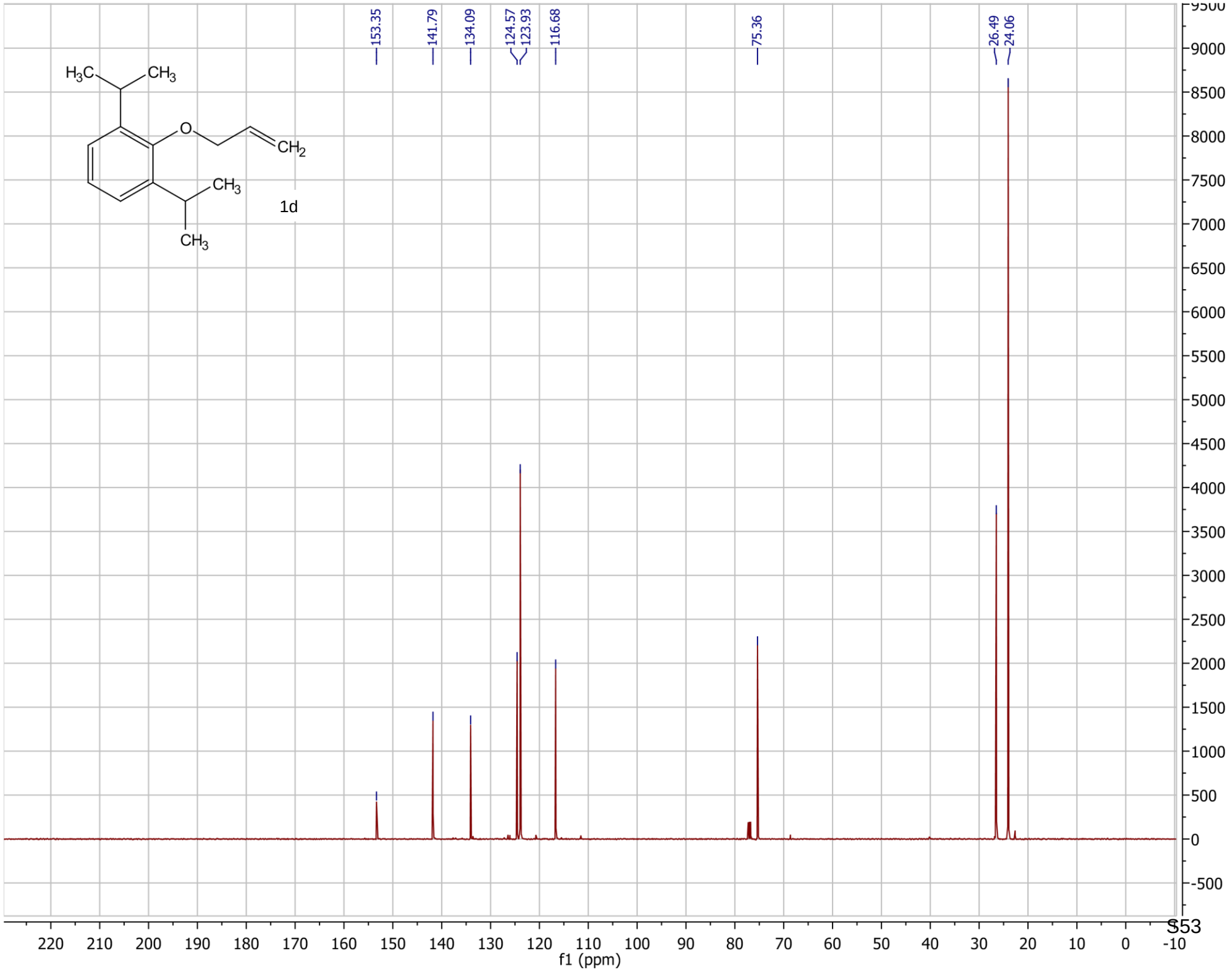

O
CH2
N
1b
2.00
2.03
0.96
0.99
1.00
2.04
1000
900
800
700
600
500
400
300
200
100
0
-100
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
f1 (ppm)

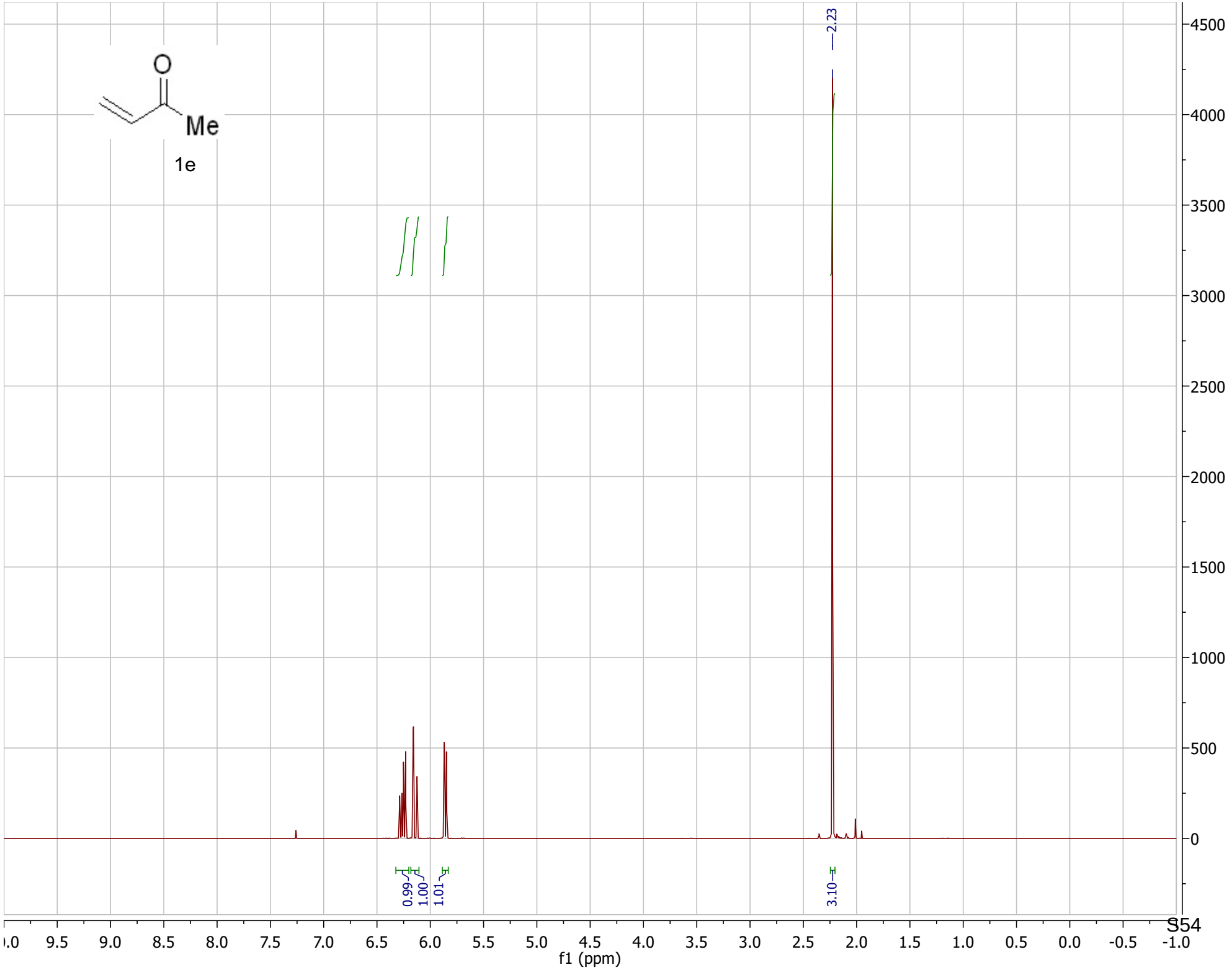

161.81
133.97
132.05
119.20
118.52
115.43
104.09
69.00
O
CH2
N
1b
f1 (ppm)


O
CH2
1c
2.01
0.03
3.00
0.01
0.98
1.01
1.02
0.01
2.06
f1 (ppm)


158.55
133.33
129.41
120.80
117.59
114.69
68.67
O
CH2
1c
1000
900
800
700
600
500
400
300
200
100
0
-100
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)


H3C
CH3
O
CH2
CH3
CH3
1d
2.97
0.98
1.00
1.00
1.99
2.01
12.02
f1 (ppm)


153.35
141.79
134.09
124.57
123.93
116.68
75.36
26.49
24.06
H3C
CH3
O
CH2
CH3
CH3
1d
f1 (ppm)


O
Me
1e
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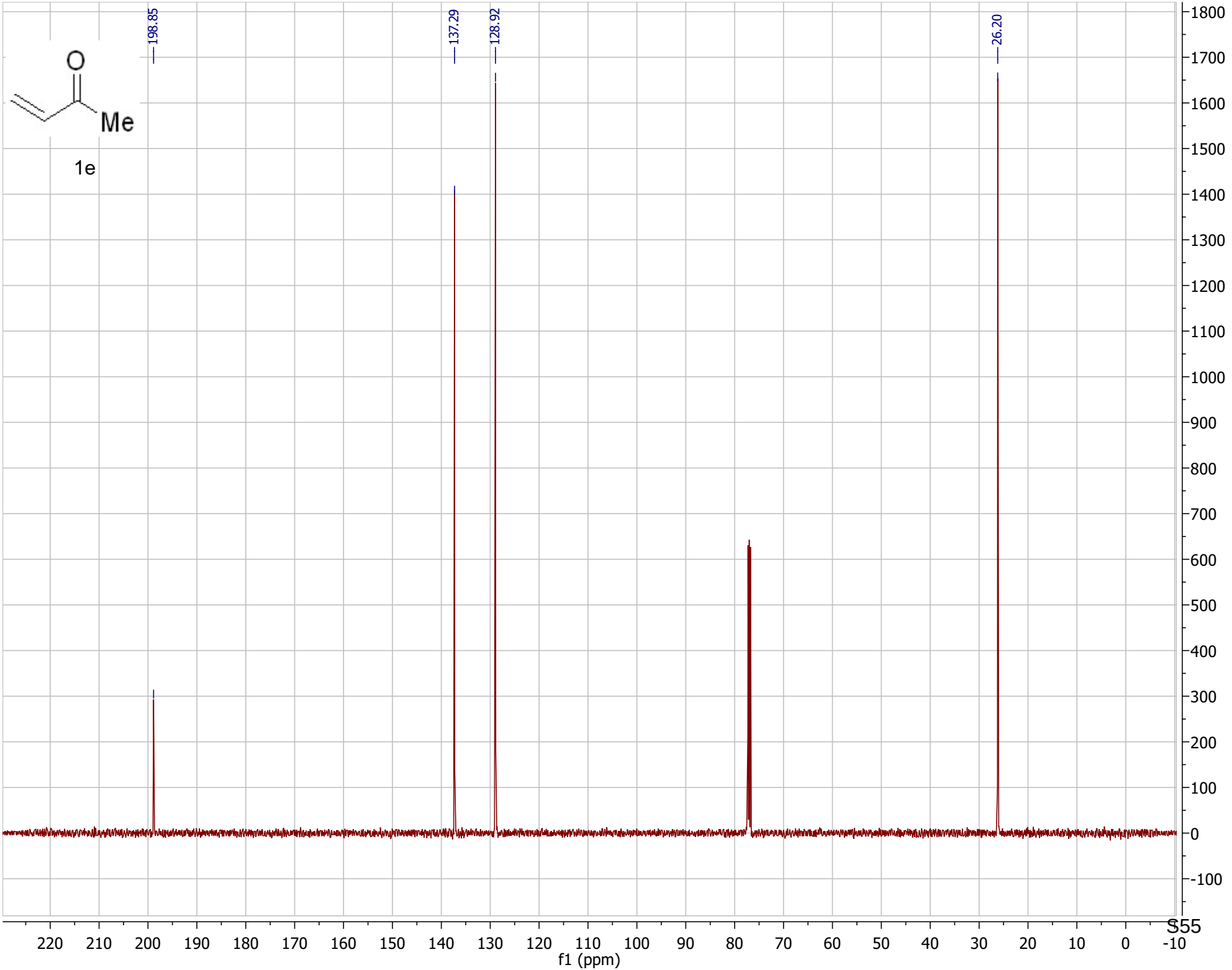
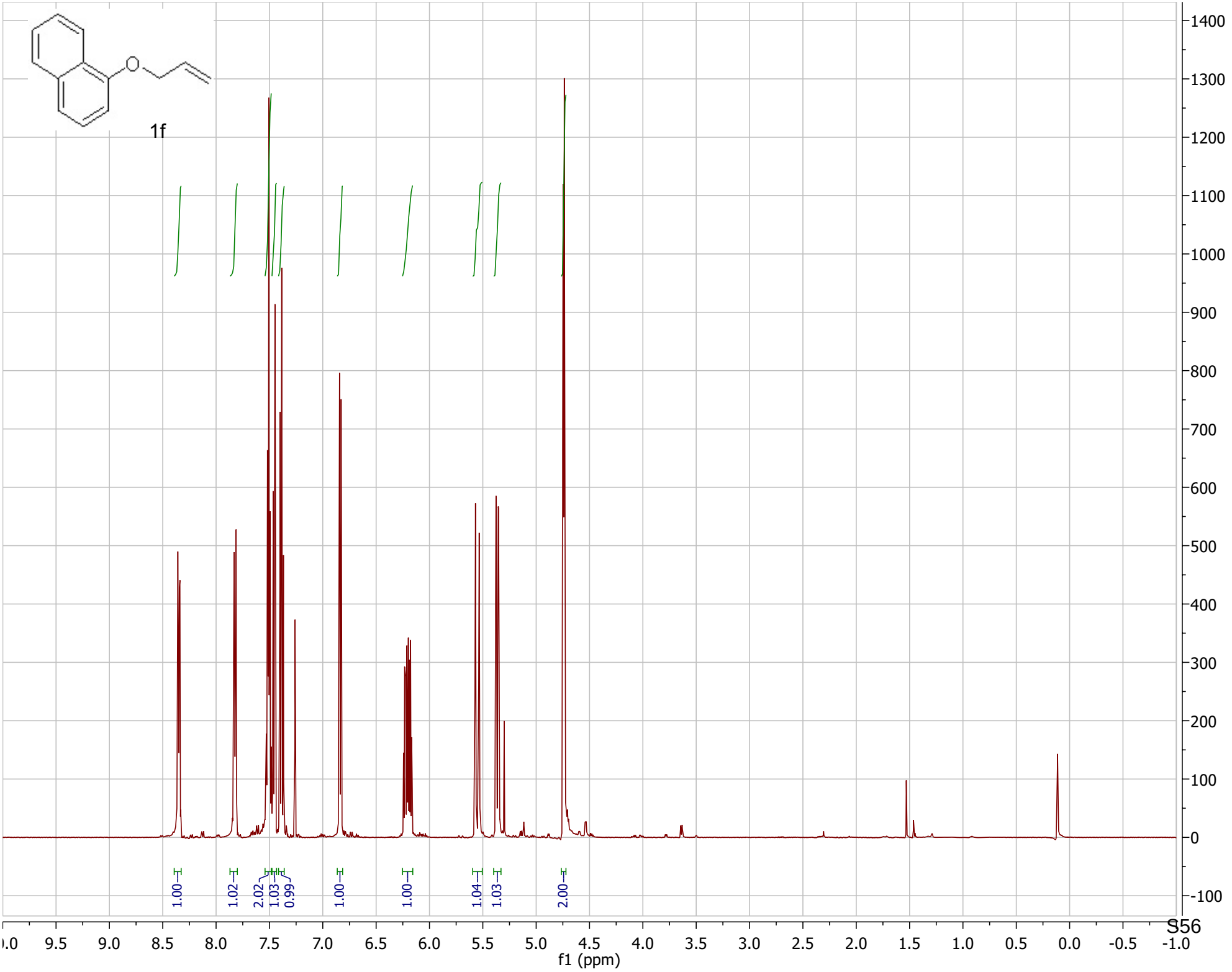
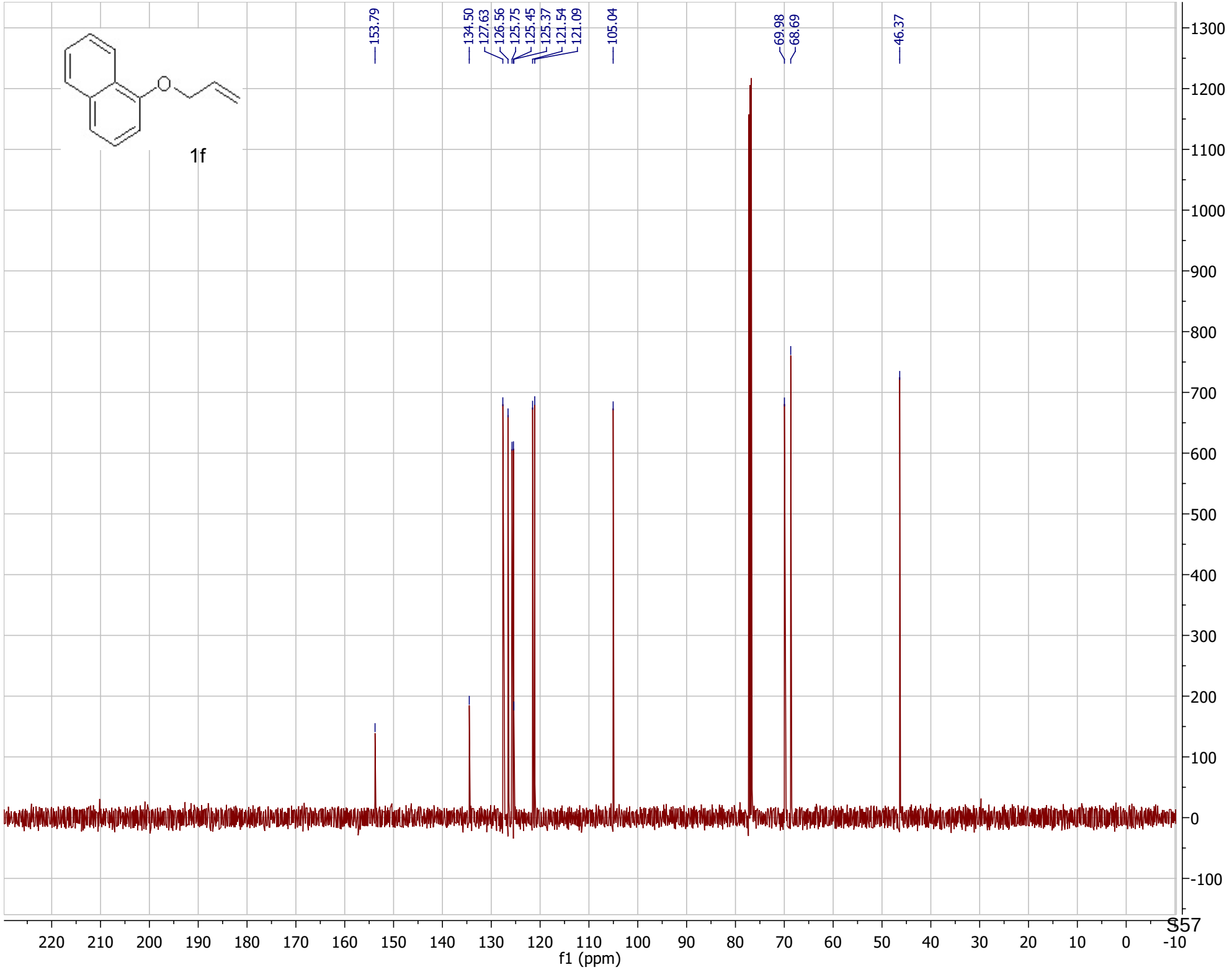
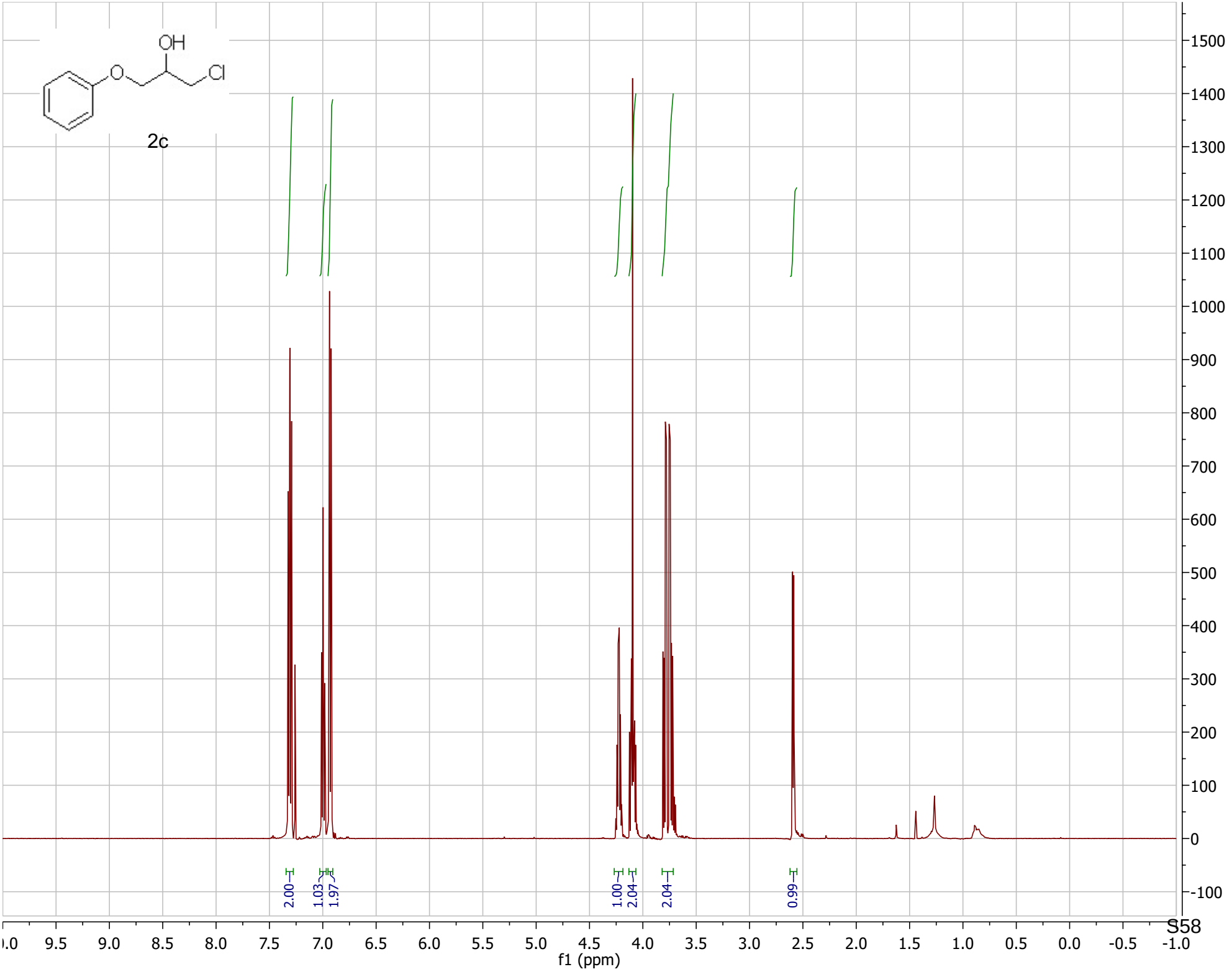
0.99
1.00
1.01
3.10
f1 (ppm)


198.85
137.29
128.92
26.20
O
Me
1e
f1 (ppm)


1f
1.00
1.02
2.02
1.03
0.99
1.00
1.00
1.04
1.03
2.00
f1 (ppm)


153.79
134.50
127.63
126.56
125.75
125.45
125.37
121.54
121.09
105.04
69.98
68.69
46.37
1f
f1 (ppm)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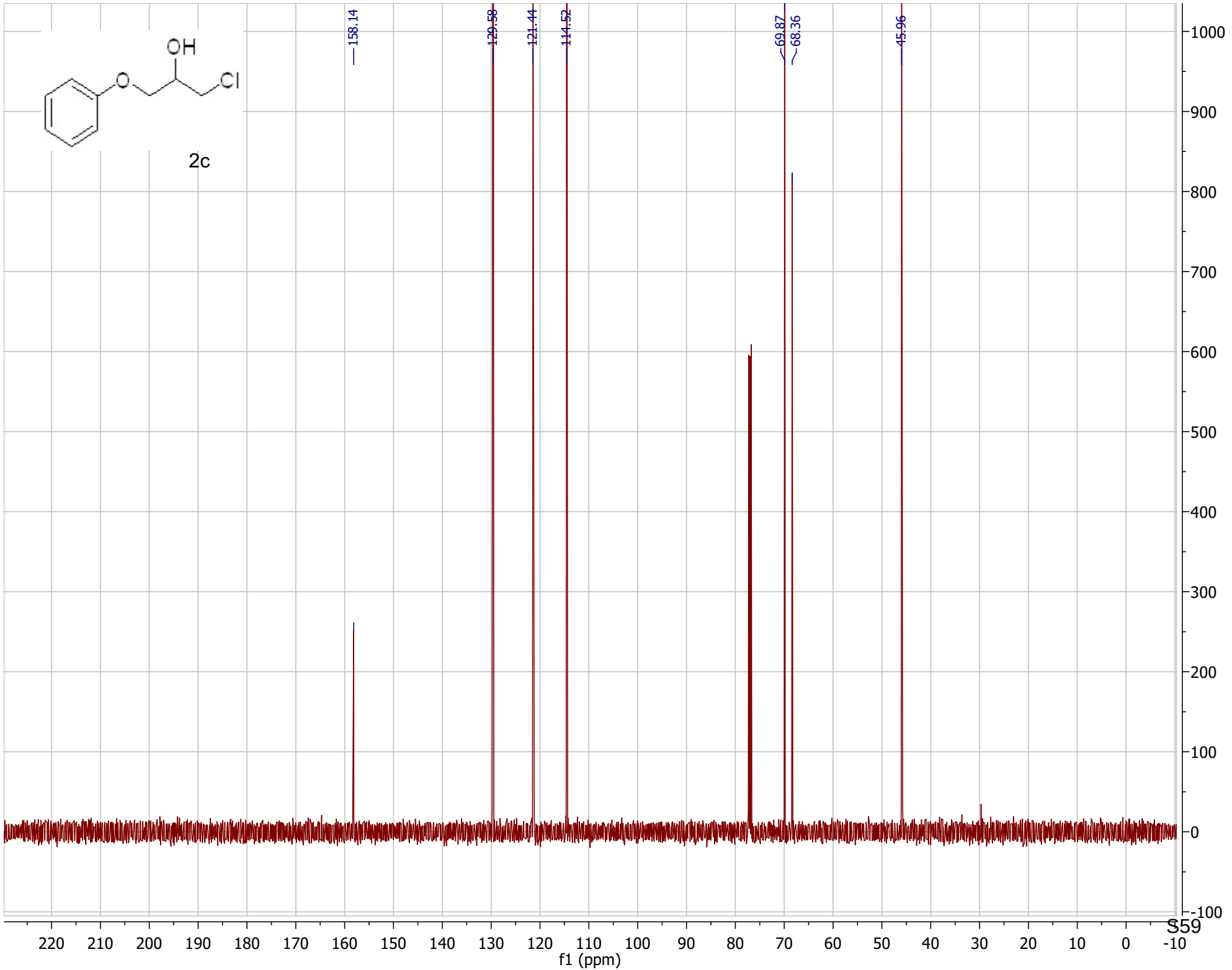
O
Cl
2c
2.00
1.03
1.97
1.00
2.04
2.04
0.99
f1 (ppm)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O
Cl
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121.44
114.52
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45.96
1000
900
800
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600
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400
300
200
100
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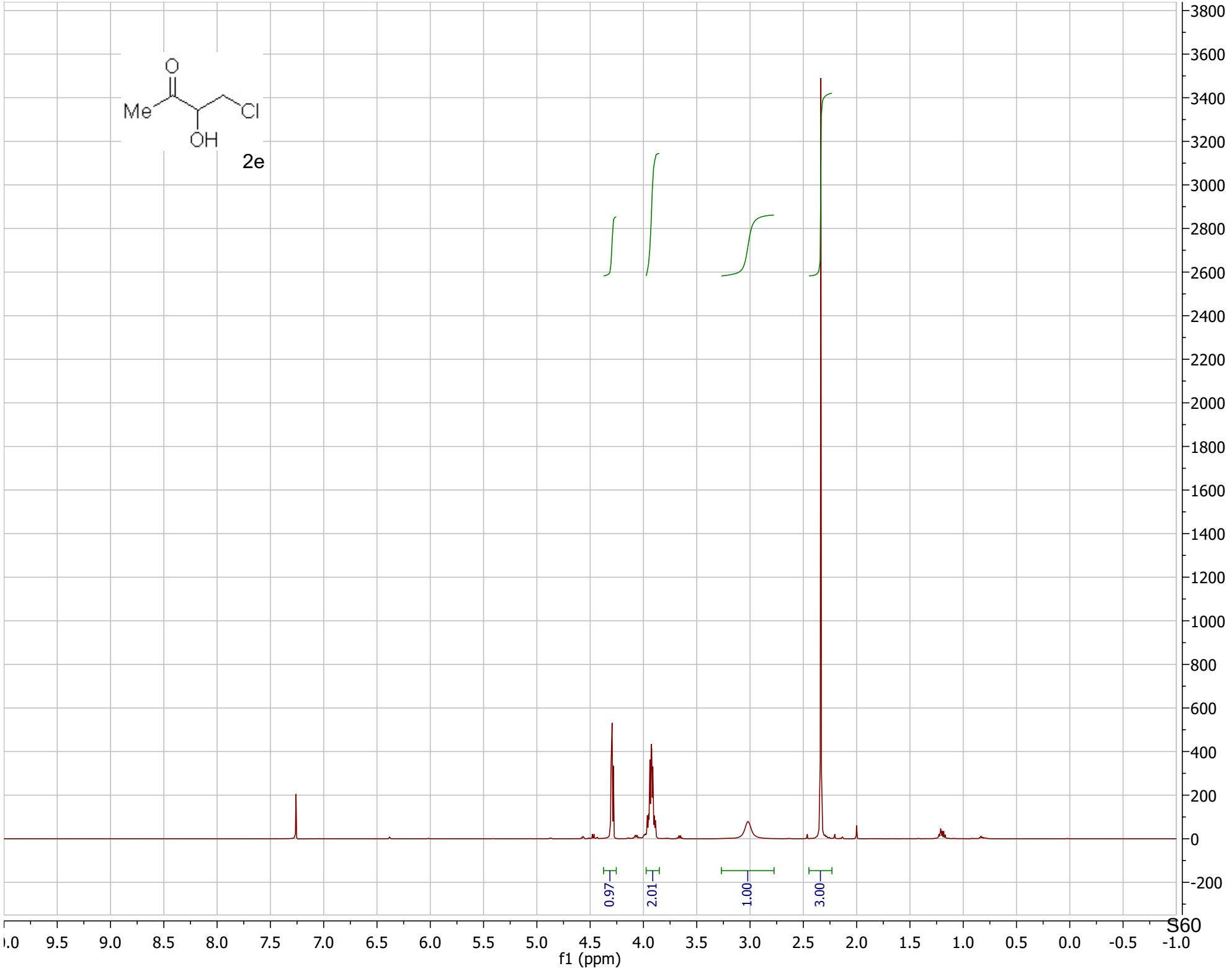
-100
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)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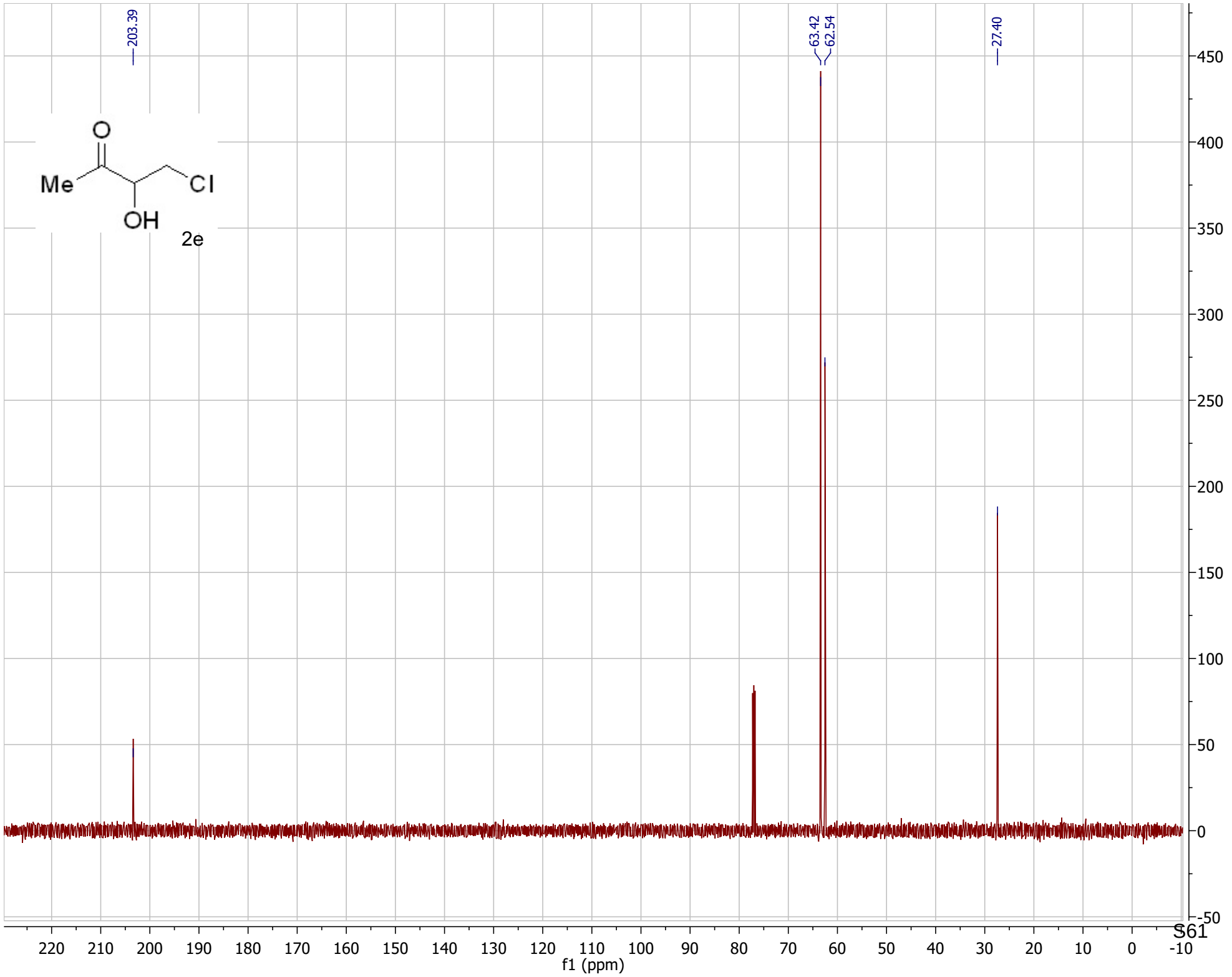
Me
Cl
OH
2e
0.97
2.01
1.00
3.00
f1 (ppm)


203.39
63.42
62.54
27.40
O
Me
Cl
OH
2e
450
400
350
300
250
200
150
100
50
0
-50
220
210
200
190
180
170
160
150
140
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120
110
100
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80
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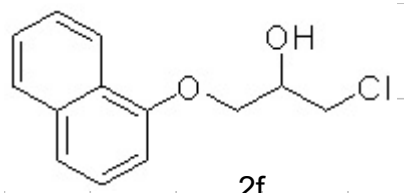
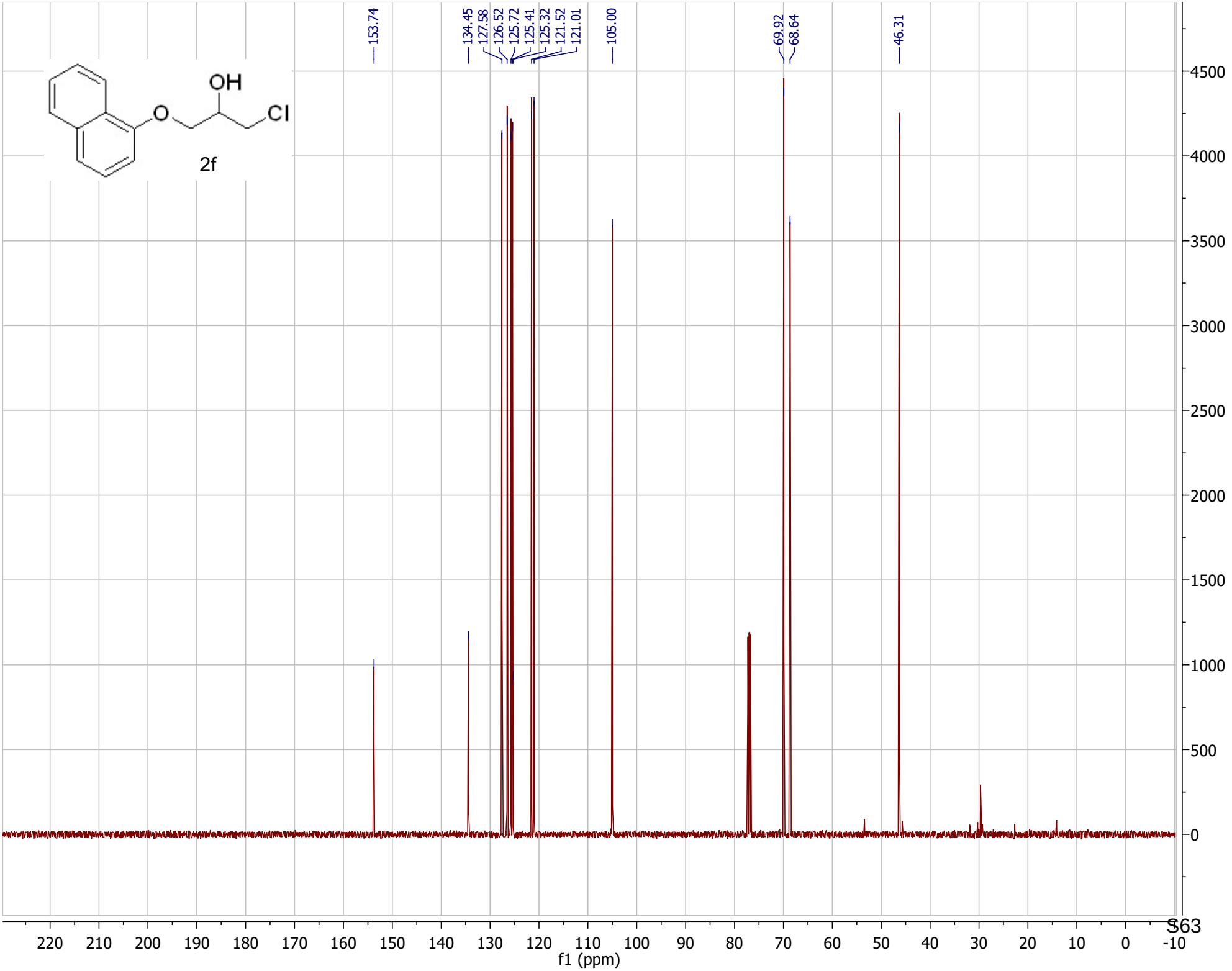
60
50
40
30
20
10
0
-10
f1 (ppm)



2f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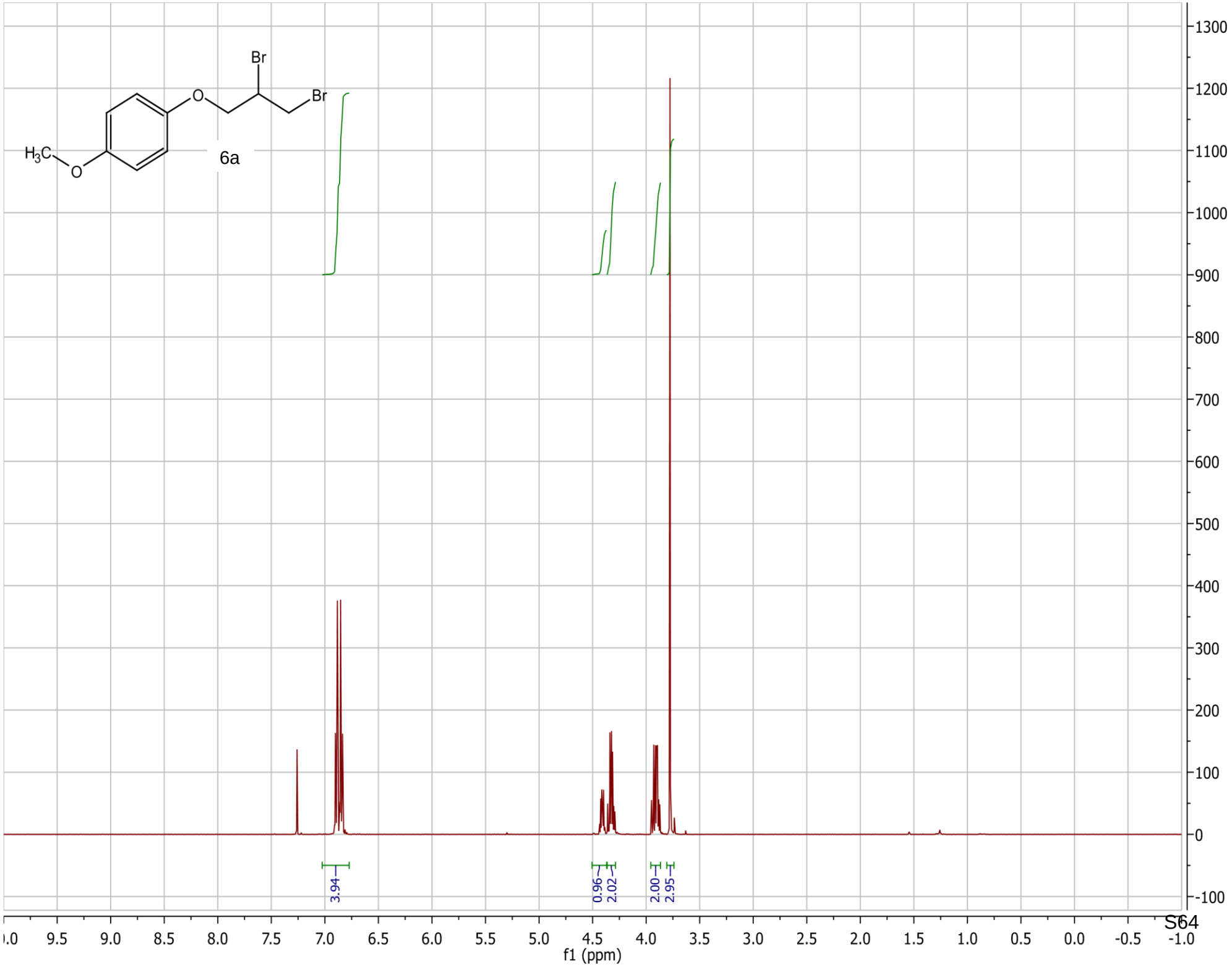
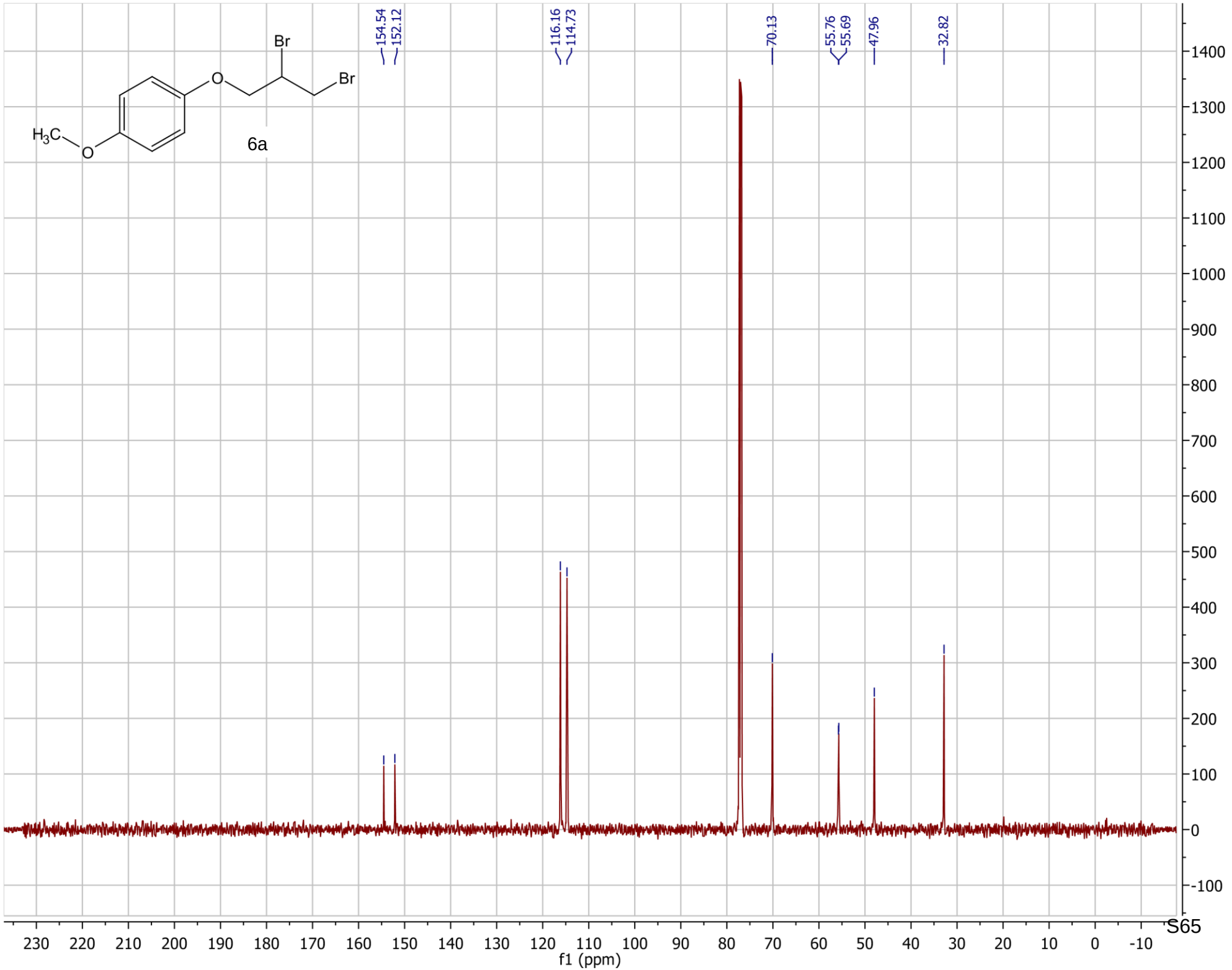
134.45
127.58
126.52
125.72
125.41
125.32
121.52
121.01
105.00
69.92
68.64
46.31
OH
O
Cl
2f
4500
4000
3500
3000
2500
2000
1500
1000
500
0
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)


Br
Br
O
O
H3C
6a
3.94
0.96
2.02
2.00
2.95
f1 (ppm)


154.54
152.12
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114.73
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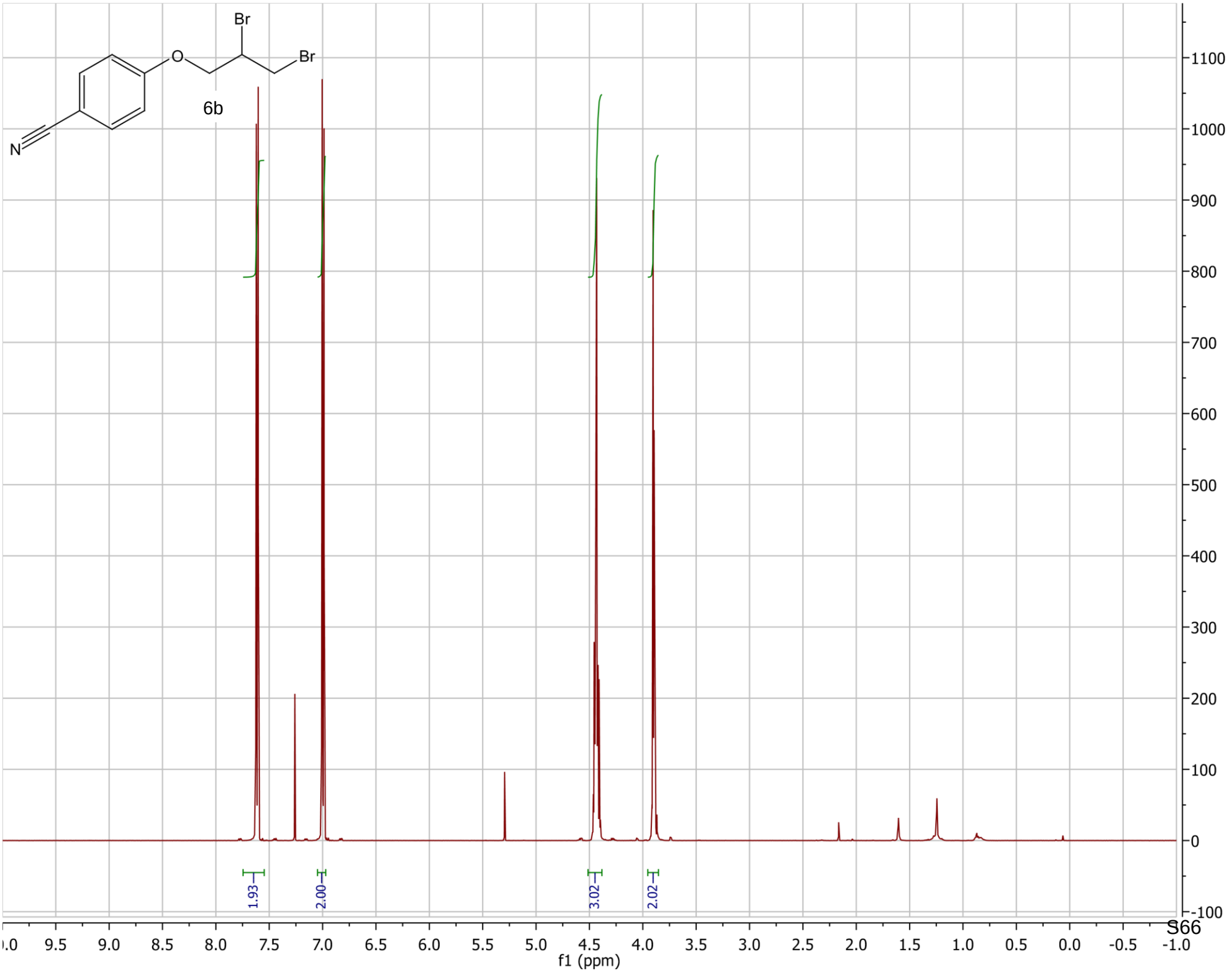
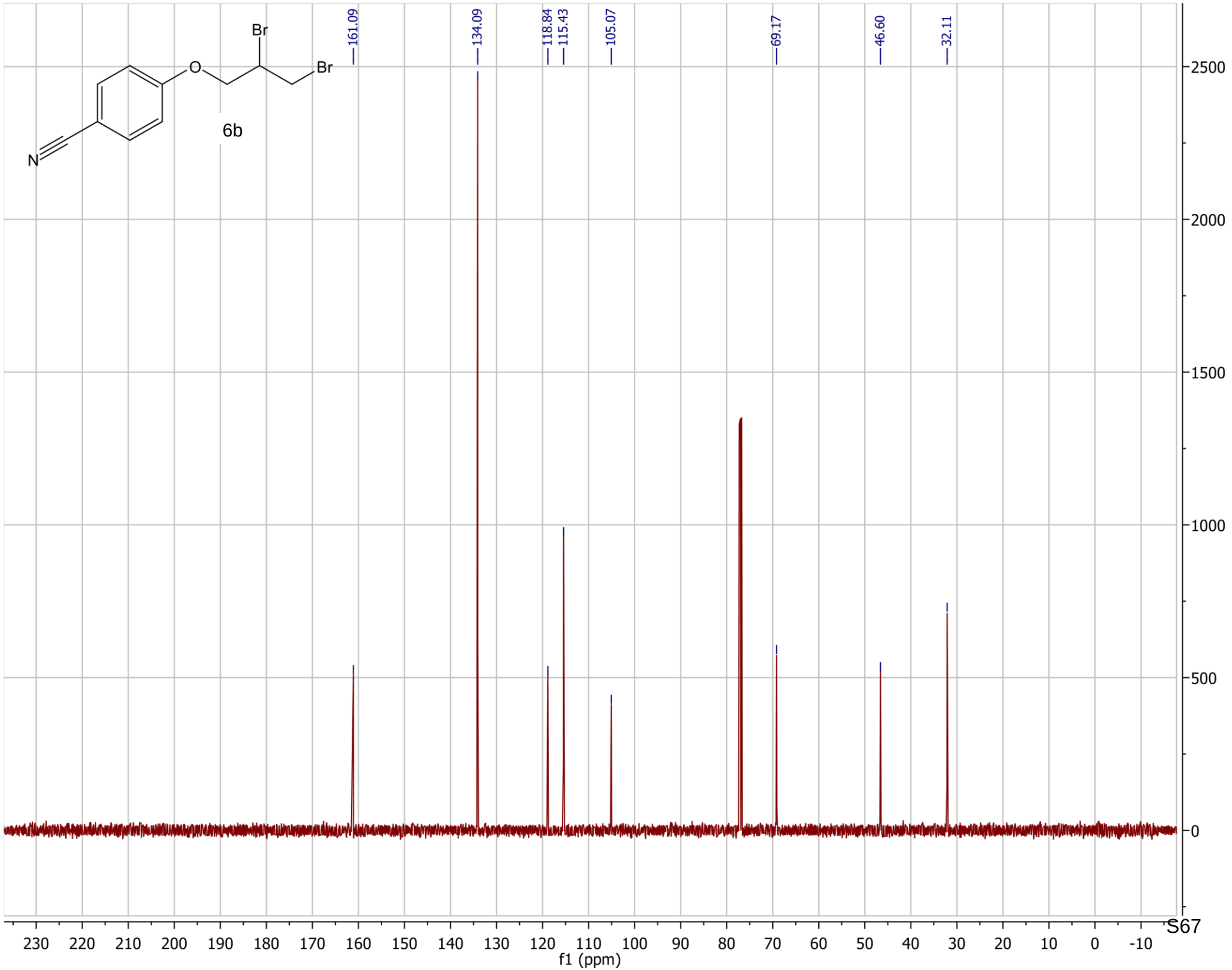
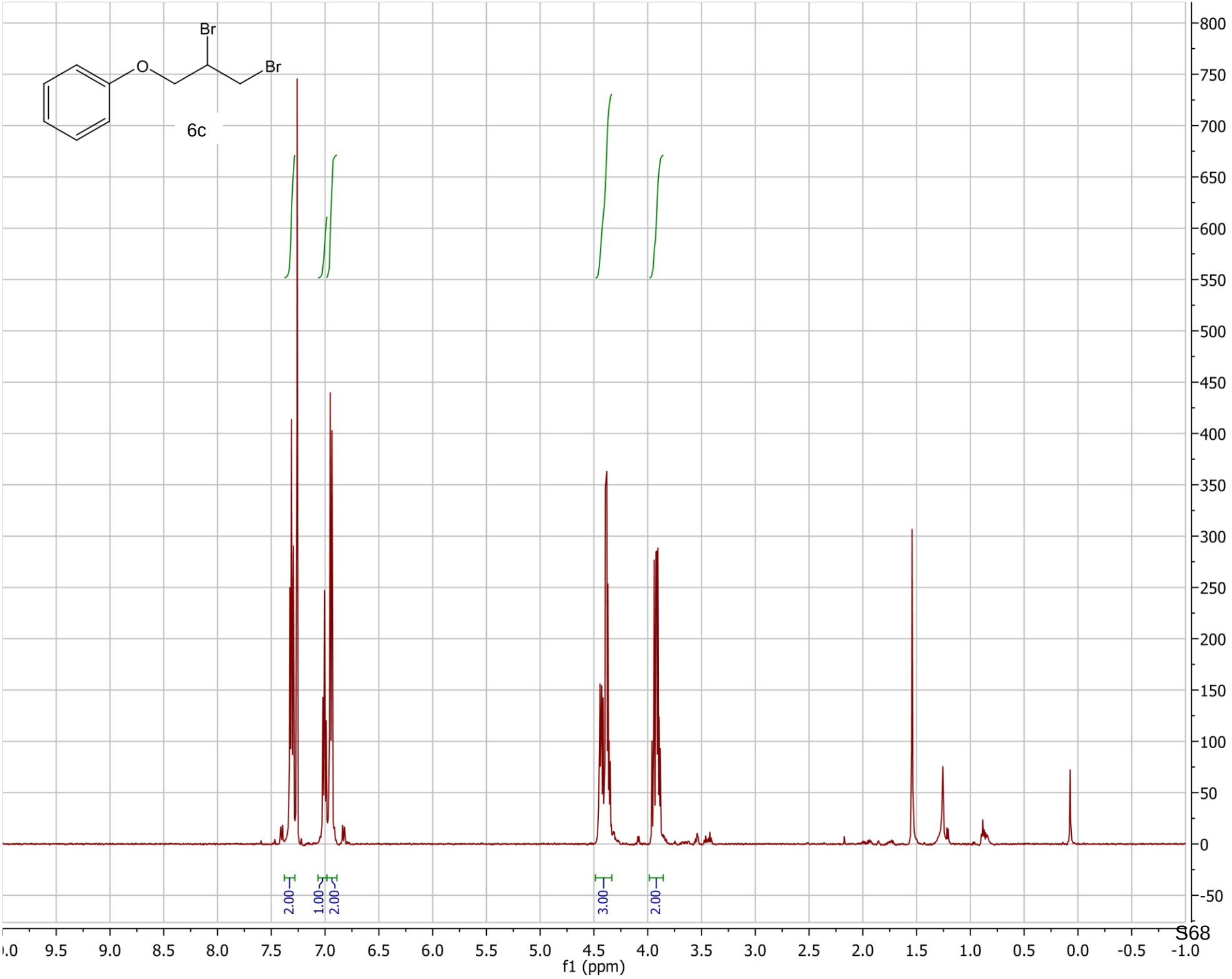
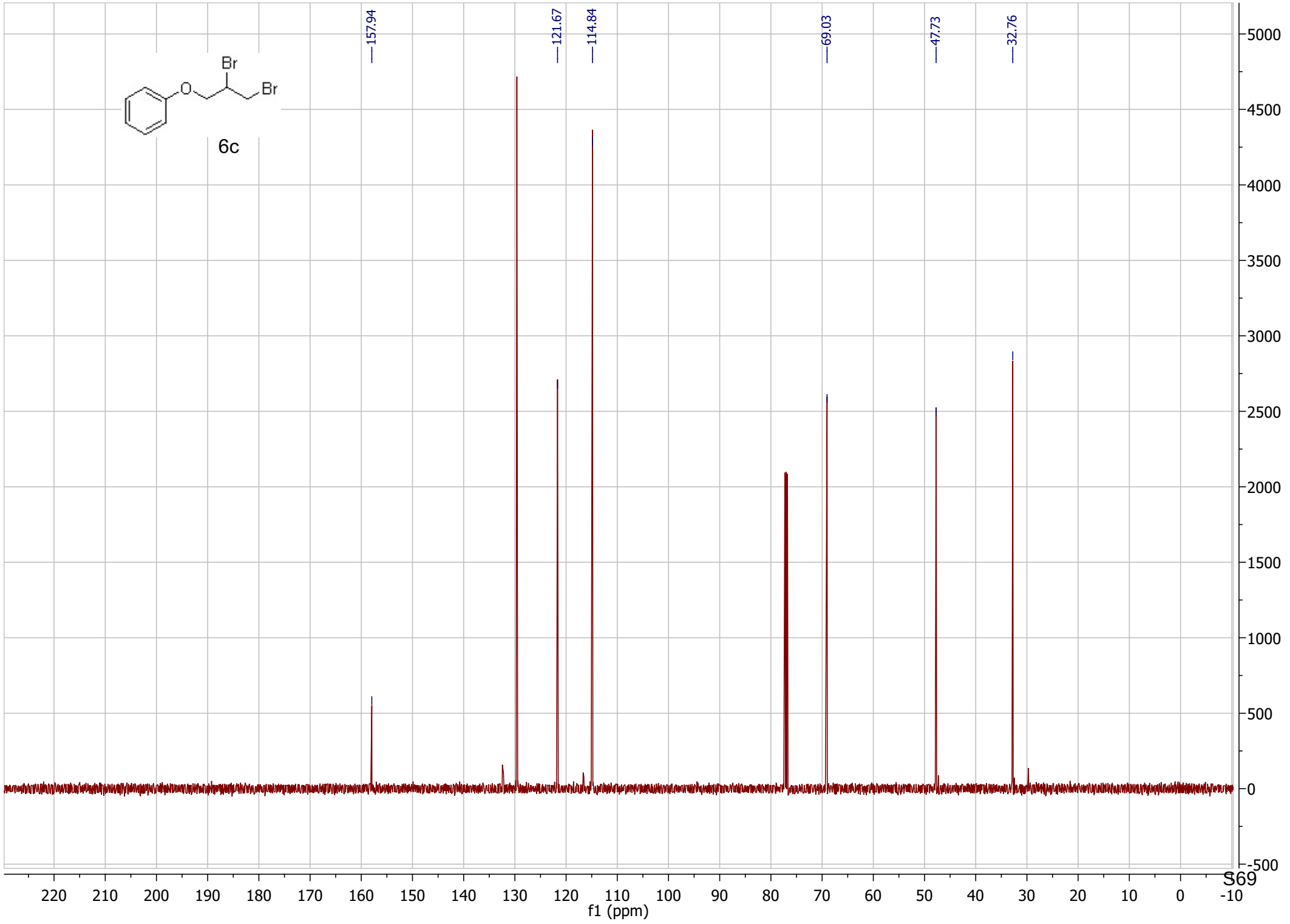
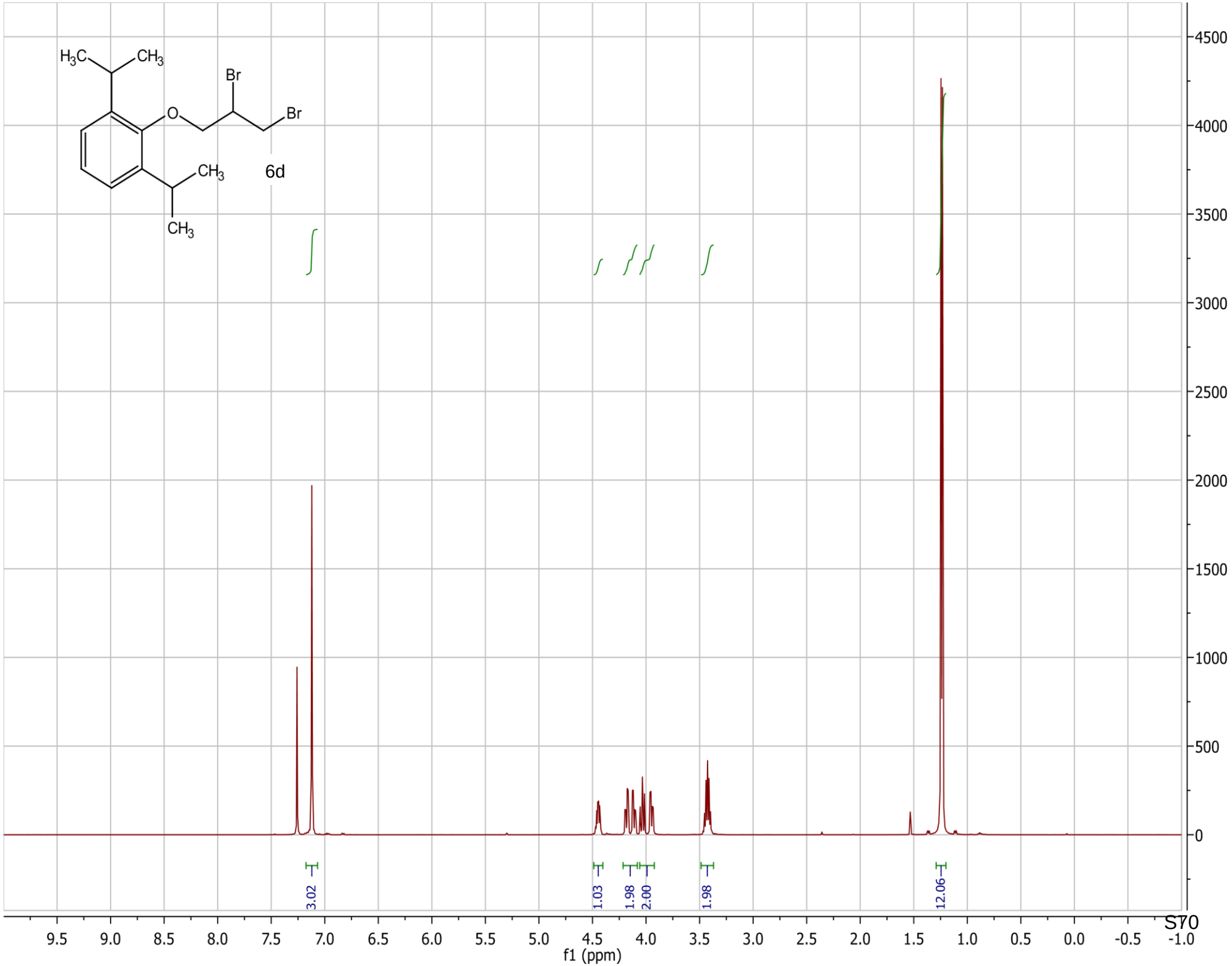
55.69
47.96
32.82
Br
Br
O
O
H3C
6a
f1 (ppm)

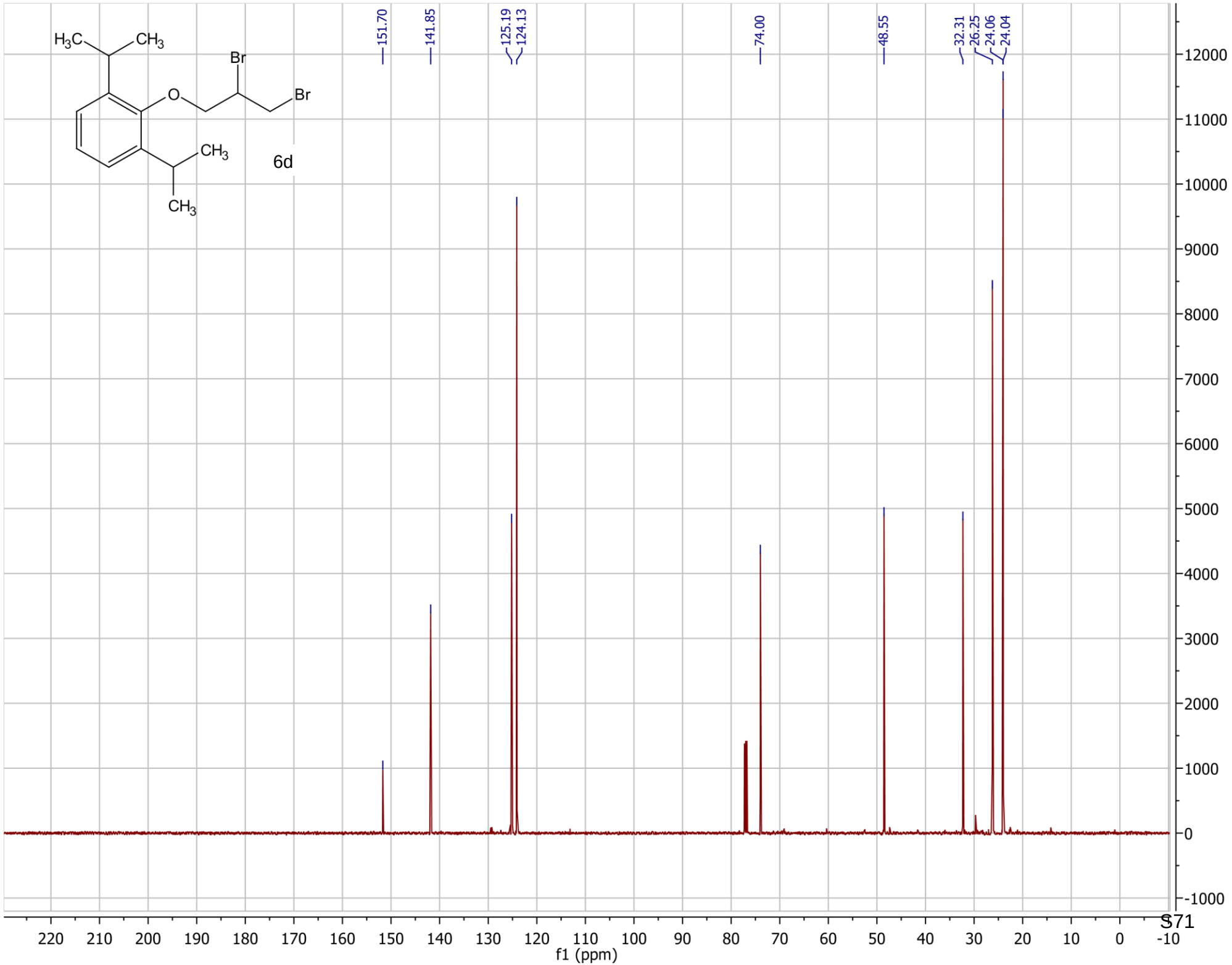

Br
O
Br
N
6b
1.93
2.00
3.02
2.02
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
f1 (ppm)

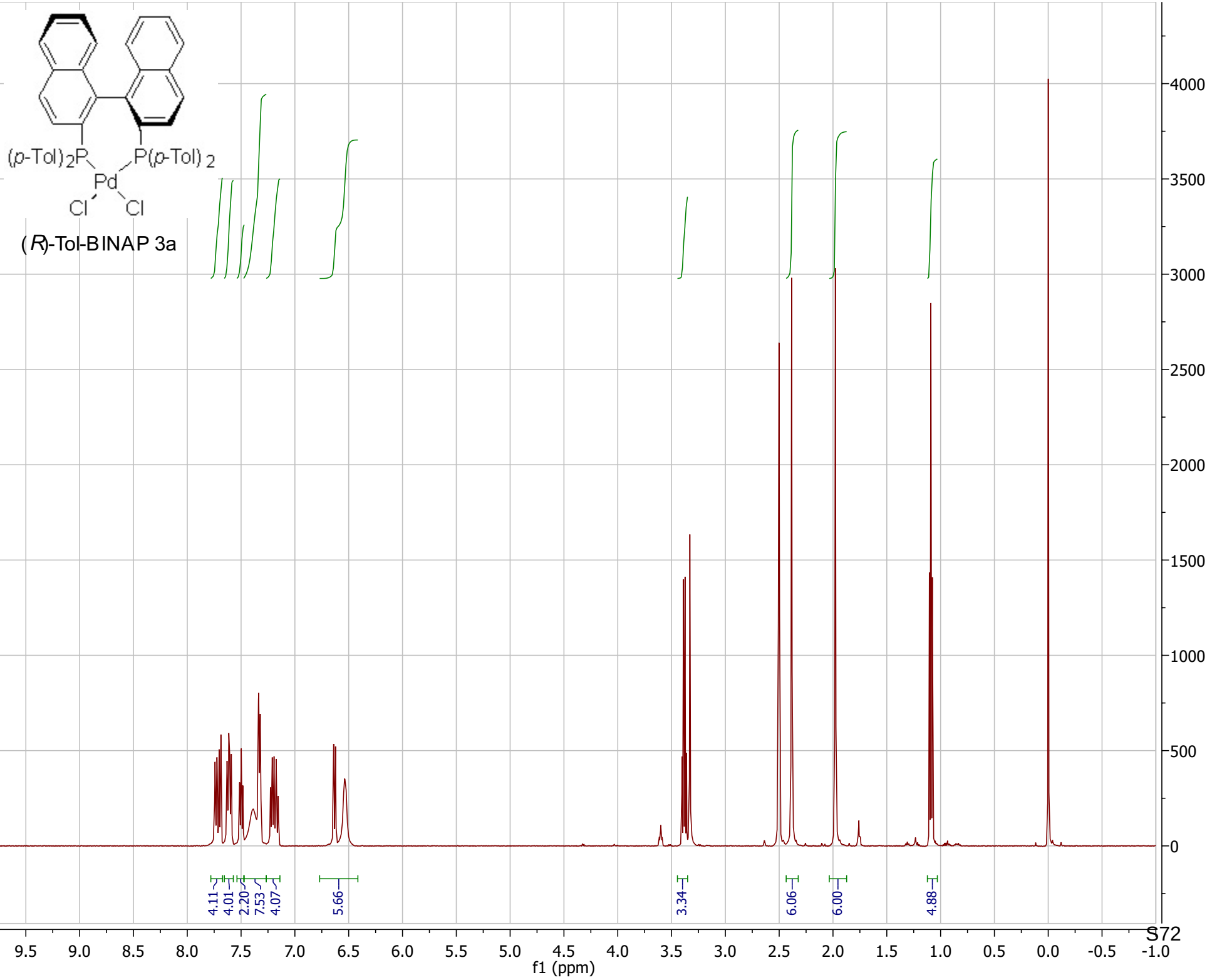

161.09
134.09
118.84
115.43
105.07
69.17
46.60
32.11
Br
O
Br
N
6b
2500
2000
1500
1000
500
0
230 220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

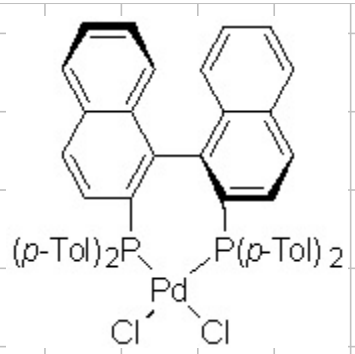

Br
O
Br
6c
2.00
1.00
2.00
3.00
2.00
f1 (ppm)


157.94
121.67
114.84
69.03
47.73
32.76
Br
O
Br
6c
f1 (ppm)


H3C
CH3
Br
O
Br
CH3
CH3
6d
3.02
1.03
1.98
2.00
1.98
12.06
f1 (ppm)


H3C
CH3
Br
O
Br
CH3
CH3
6d
151.70
141.85
125.19
124.13
74.00
48.55
32.31
26.25
24.06
24.04
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

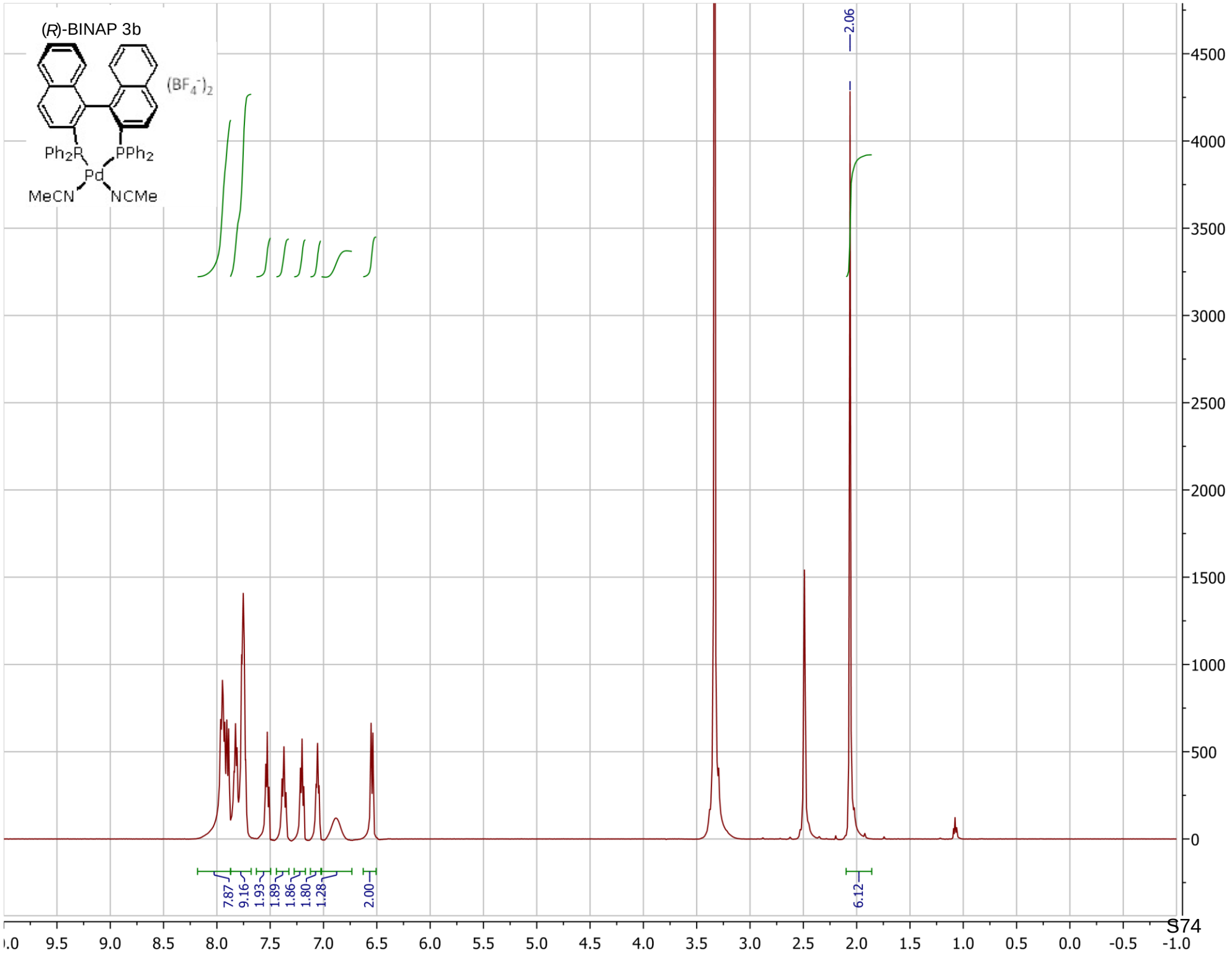

(p-Tol)2P
P(p-Tol)2
Pd
Cl
Cl
(R)-Tol-BINAP 3a
4.11
4.01
2.20
7.53
4.07
5.66
3.34
6.06
6.00
4.88
f1 (ppm)

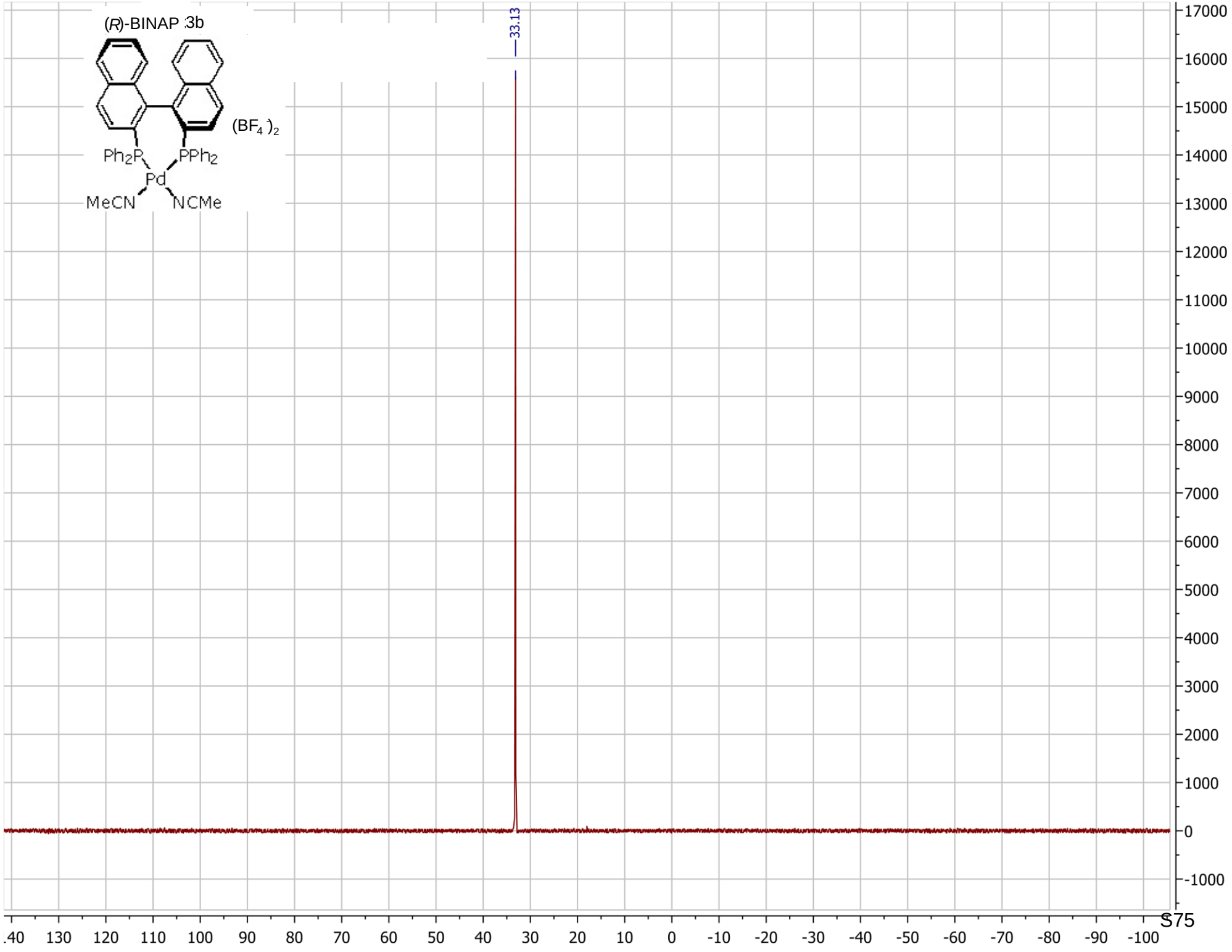


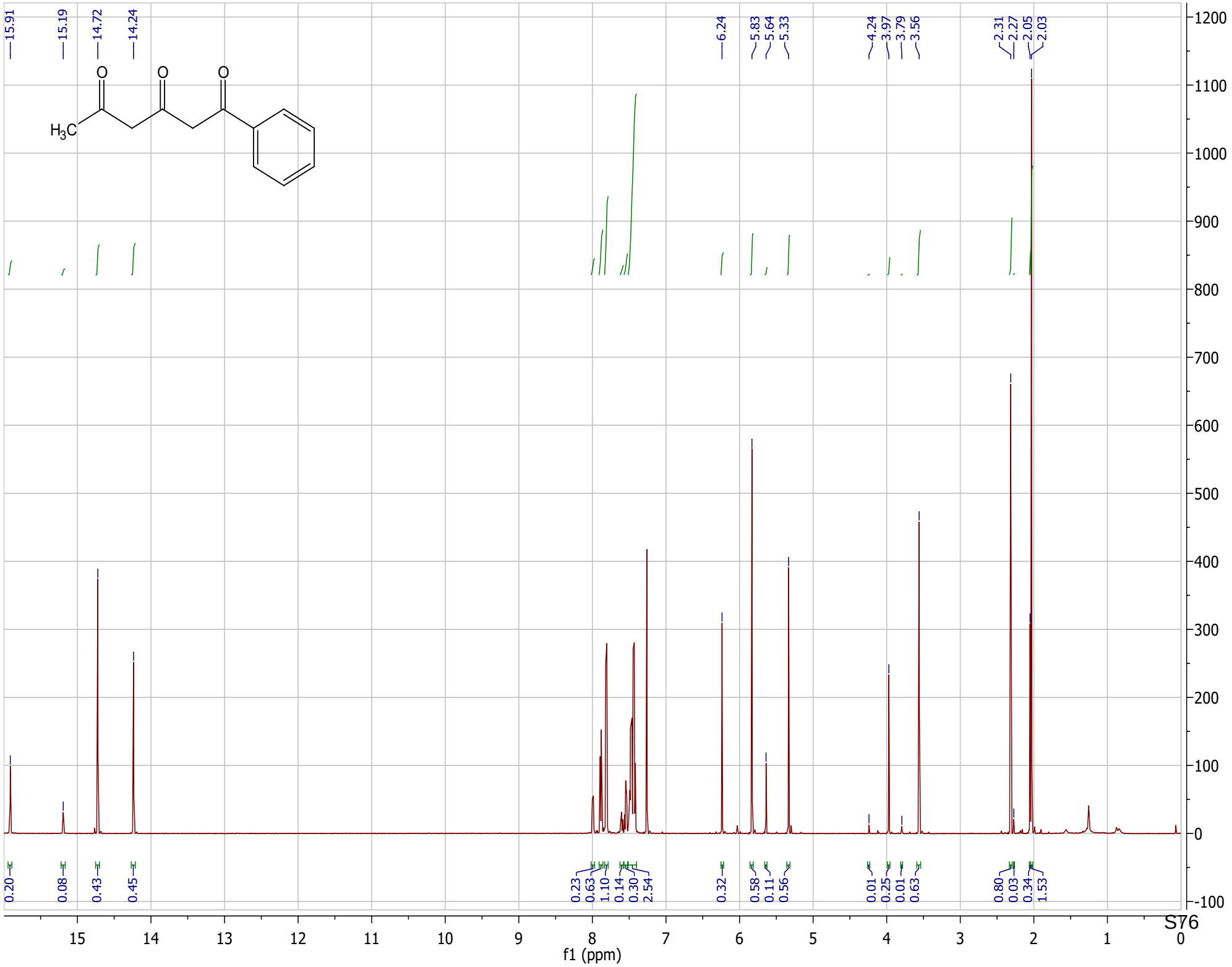
(*R*)-Tol-BINAP 3a

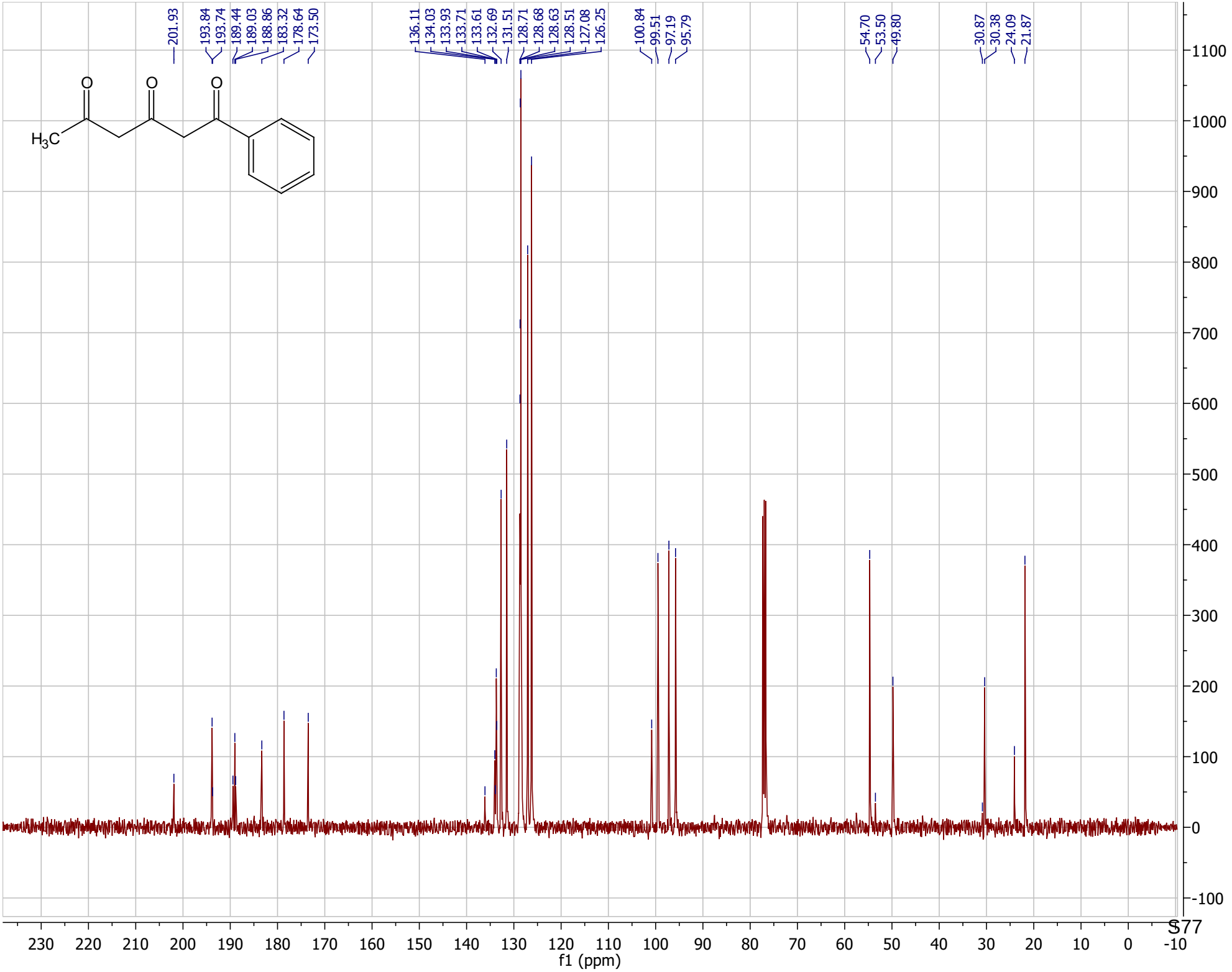
28.62

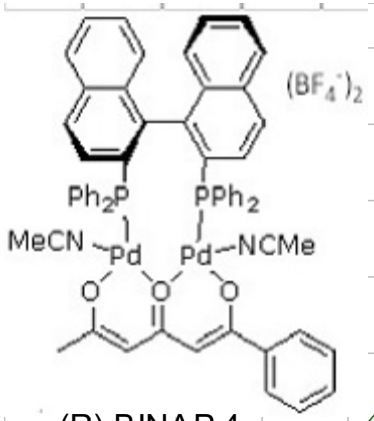
f1 (ppm)


(R)-BINAP 3b
(BF4-)2
Ph2P
PPh2
Pd
MeCN
NCMe
2.06
7.87
9.16
1.93
1.89
1.86
1.80
1.28
2.00
6.12
4500
4000
3500
3000
2500
2000
1500
1000
500
0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0

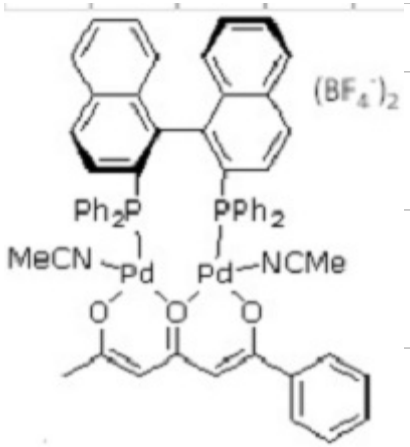

(R)-BINAP 3b
(BF4)2
Ph2P
PPh2
Pd
MeCN
NCMe
33.13
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100


15.91
15.19
14.72
14.24
6.24
5.83
5.64
5.33
4.24
3.97
3.79
3.56
2.31
2.27
2.05
2.03
O
O
O
H3C
0.20
0.08
0.43
0.45
0.23
0.63
1.10
0.14
0.30
2.54
0.32
0.58
0.11
0.56
0.01
0.25
0.01
0.63
0.80
0.03
0.34
1.53
f1 (ppm)


201.93
193.84
193.74
189.44
189.03
188.86
183.32
178.64
173.50
136.11
134.03
133.93
133.71
133.61
132.69
131.51
128.71
128.68
128.63
128.51
127.08
126.25
100.84
99.51
97.19
95.79
54.70
53.50
49.80
30.87
30.38
24.09
21.87
O
O
O
H3C
f1 (ppm)



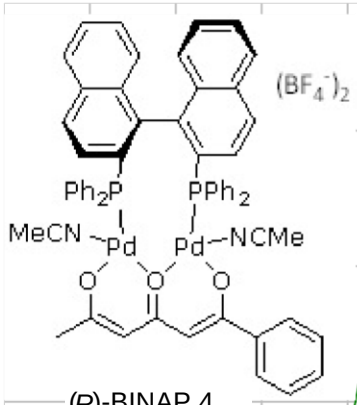
(R)-BINAP 4
Prepared according to Henry's method



(R)-BINAP 4
Prepared by Henry's method

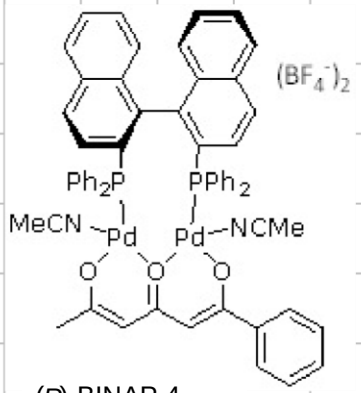
33.28
33.09
32.72
32.51
32.30
31.76
31.54
31.26
31.06
28.29
25.36
25.05
22.32

f1 (ppm)



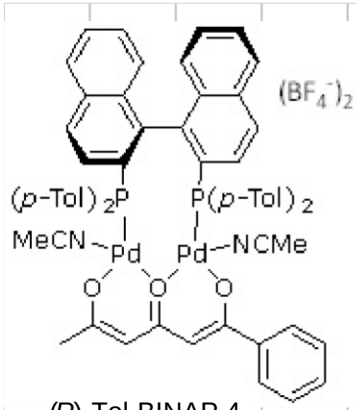
(*R*)-BINAP 4

prepared by new method

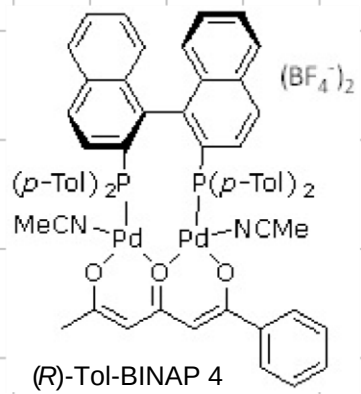


(*R*)-BINAP 4

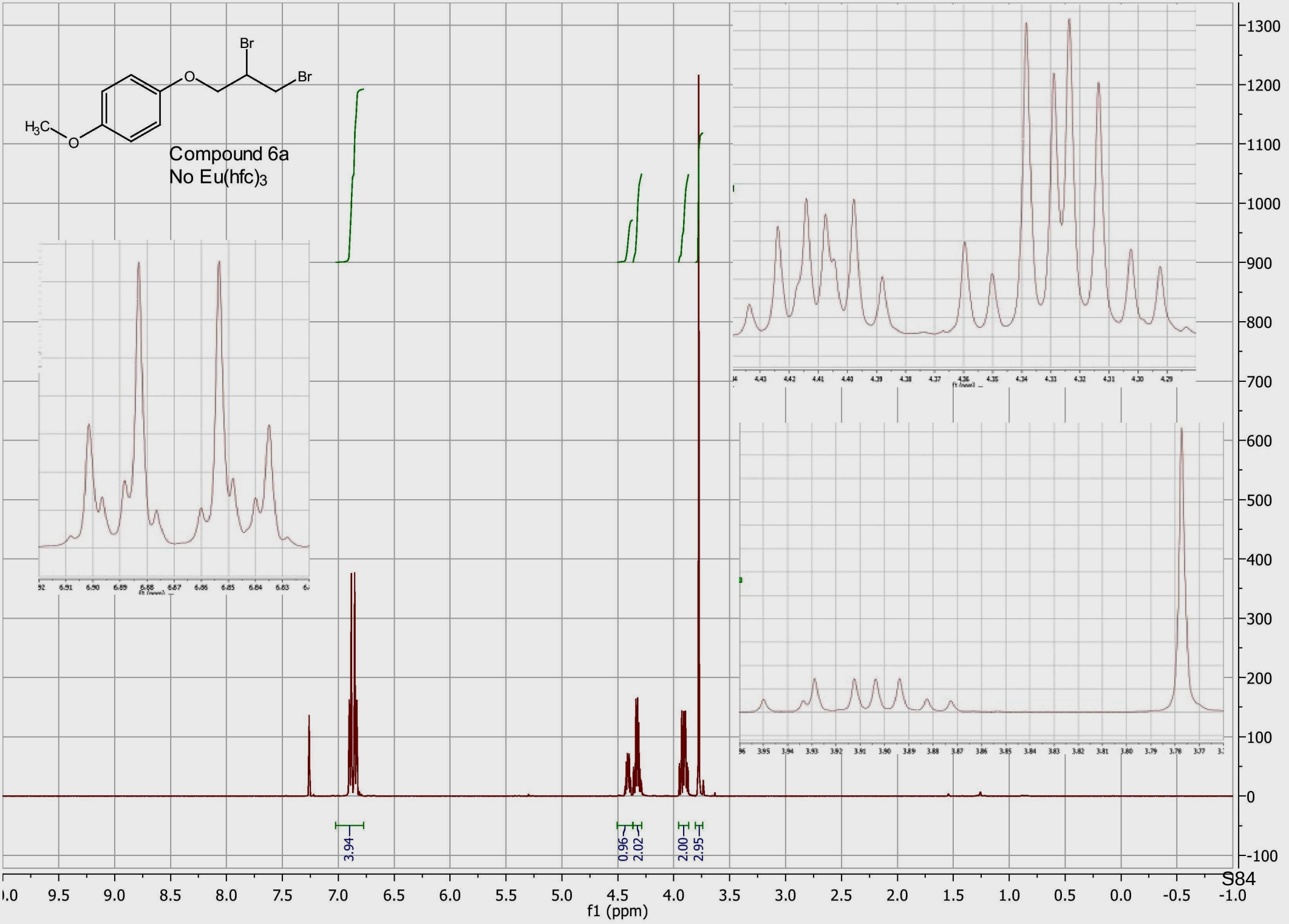
prepared by new method

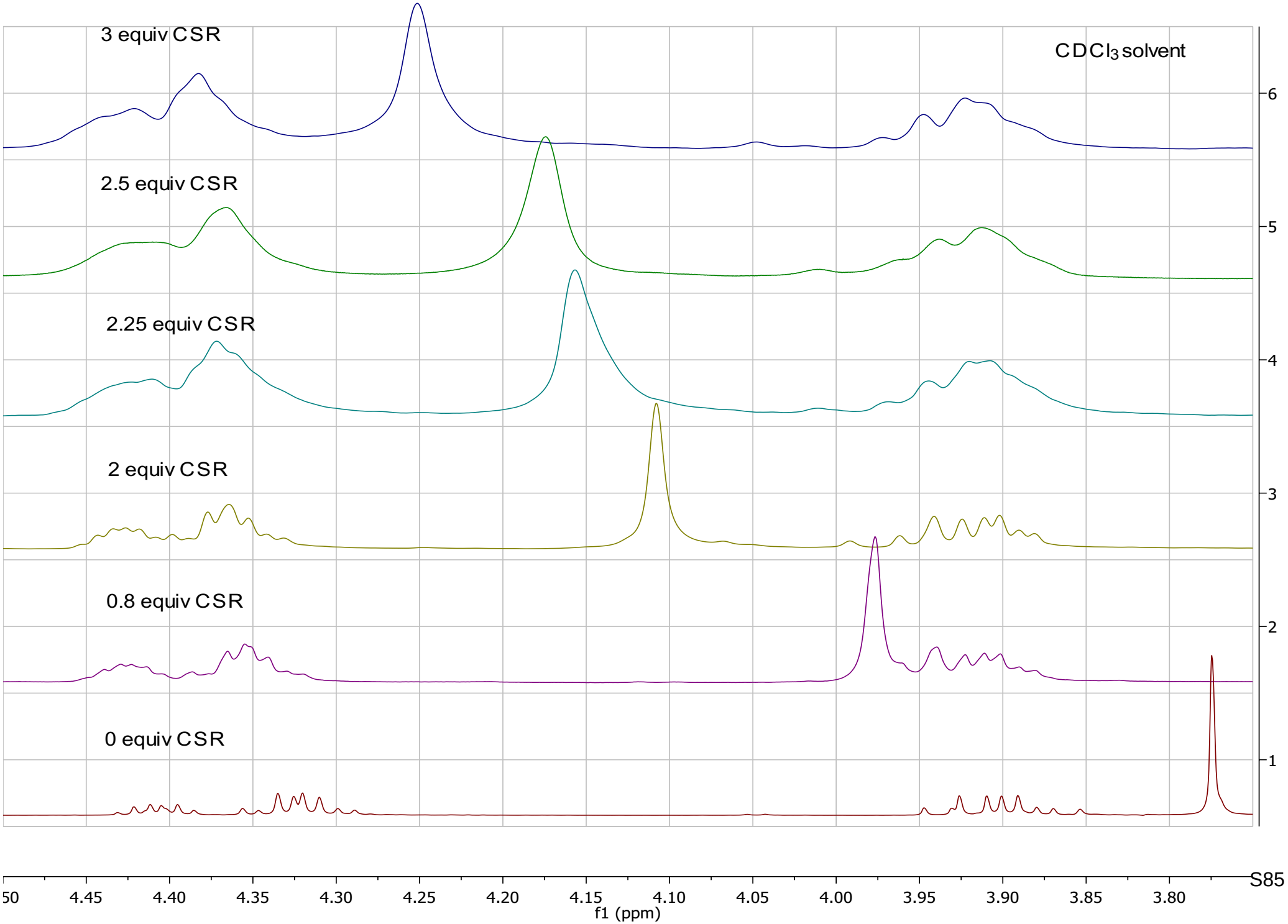


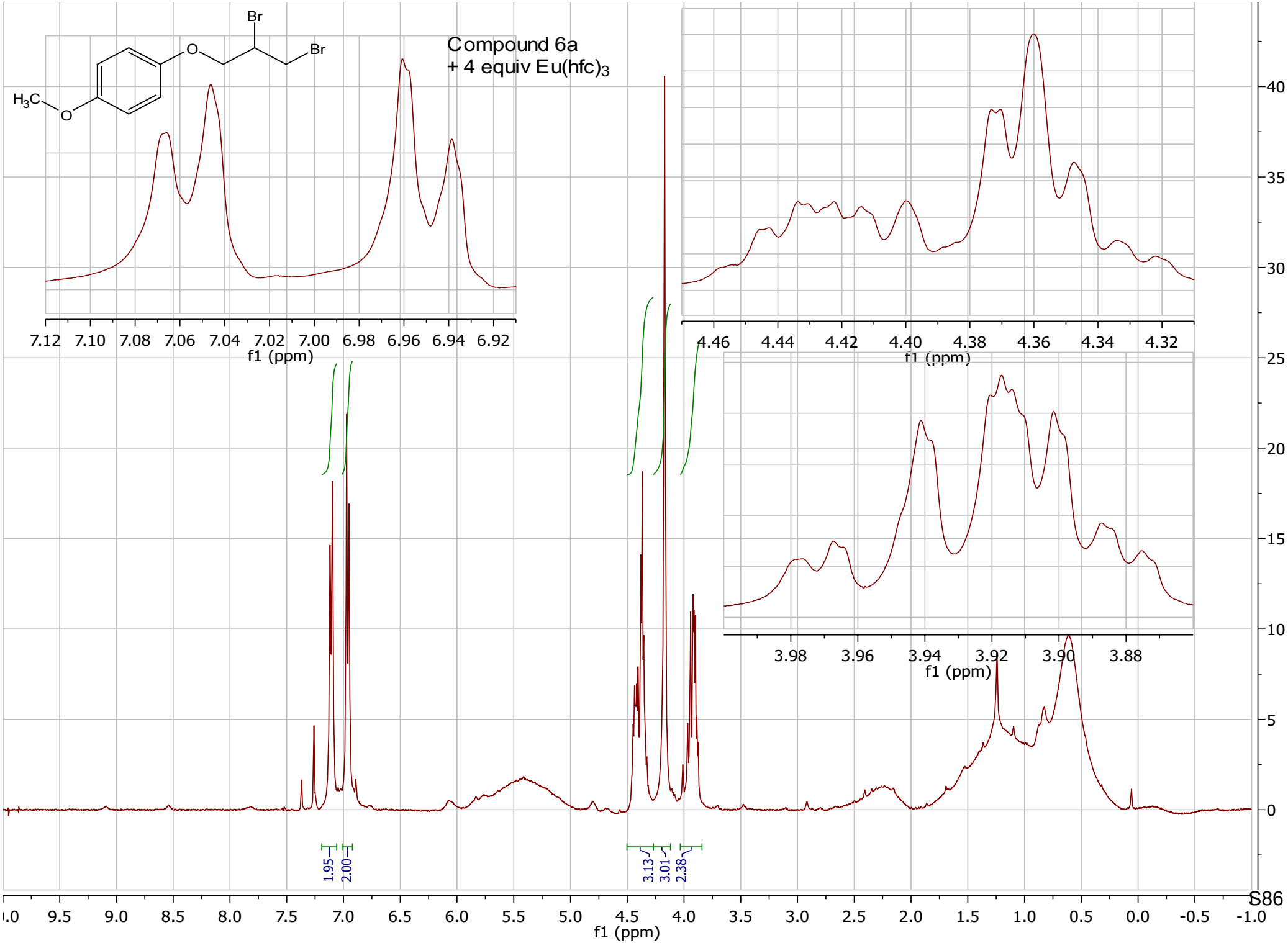
(*R*)-Tol-BINAP 4

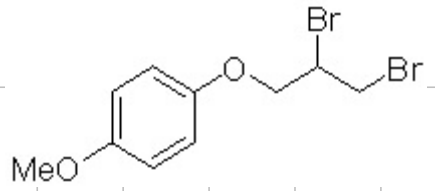


(*R*)-Tol-BINAP 4

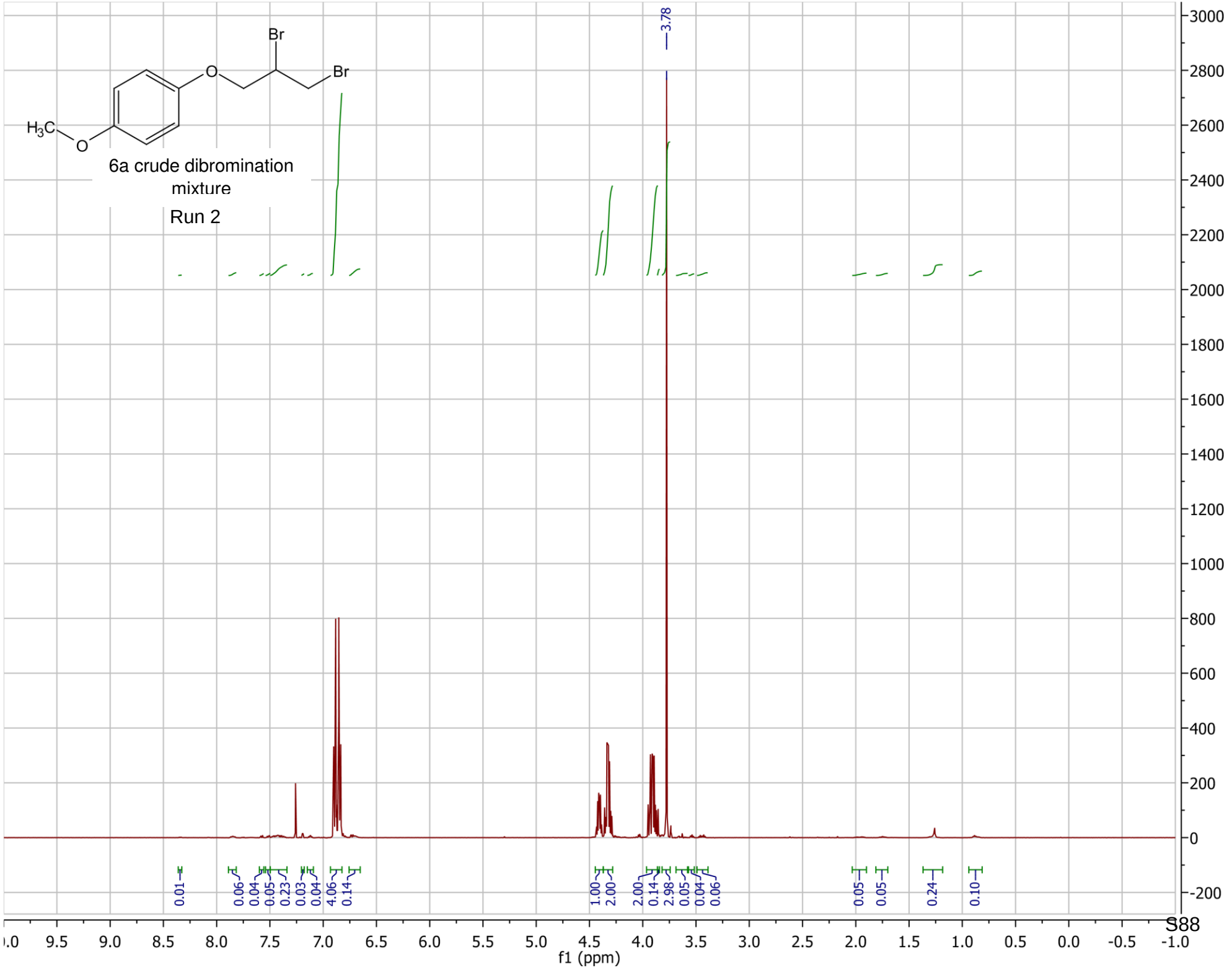

Br
O
Br
H3C
O
Compound 6a
No Eu(hfc)3
3.94
0.96
2.02
2.00
2.95
f1 (ppm)

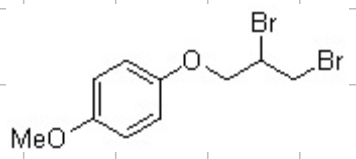

3 equiv CSR
CDCl3 solvent
2.5 equiv CSR
2.25 equiv CSR
2 equiv CSR
0.8 equiv CSR
0 equiv CSR
6
5
4
3
2
1
50
4.45
4.40
4.35
4.30
4.25
4.20
4.15
4.10
4.05
4.00
3.95
3.90
3.85
3.80
f1 (ppm)


Br
O
Br
H3C
O
Compound 6a
+ 4 equiv Eu(hfc)3
7.12 7.10 7.08 7.06 7.04 7.02 7.00 6.98 6.96 6.94 6.92
f1 (ppm)
4.46 4.44 4.42 4.40 4.38 4.36 4.34 4.32
f1 (ppm)
3.98 3.96 3.94 3.92 3.90 3.88
f1 (ppm)
1.95
2.00
3.13
3.01
2.38
40 35 30 25 20 15 10 5 0
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5 -1.0
f1 (ppm)

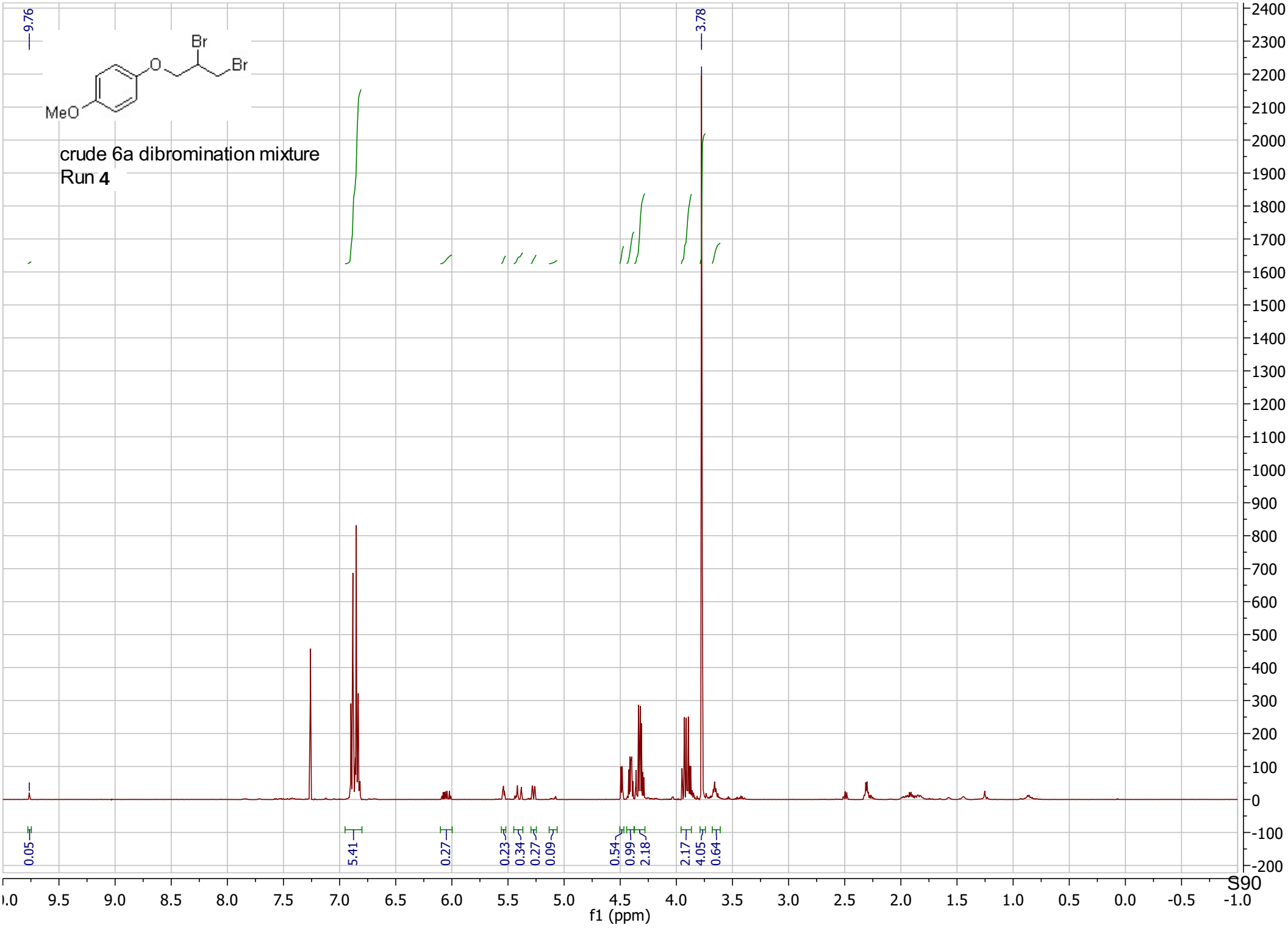


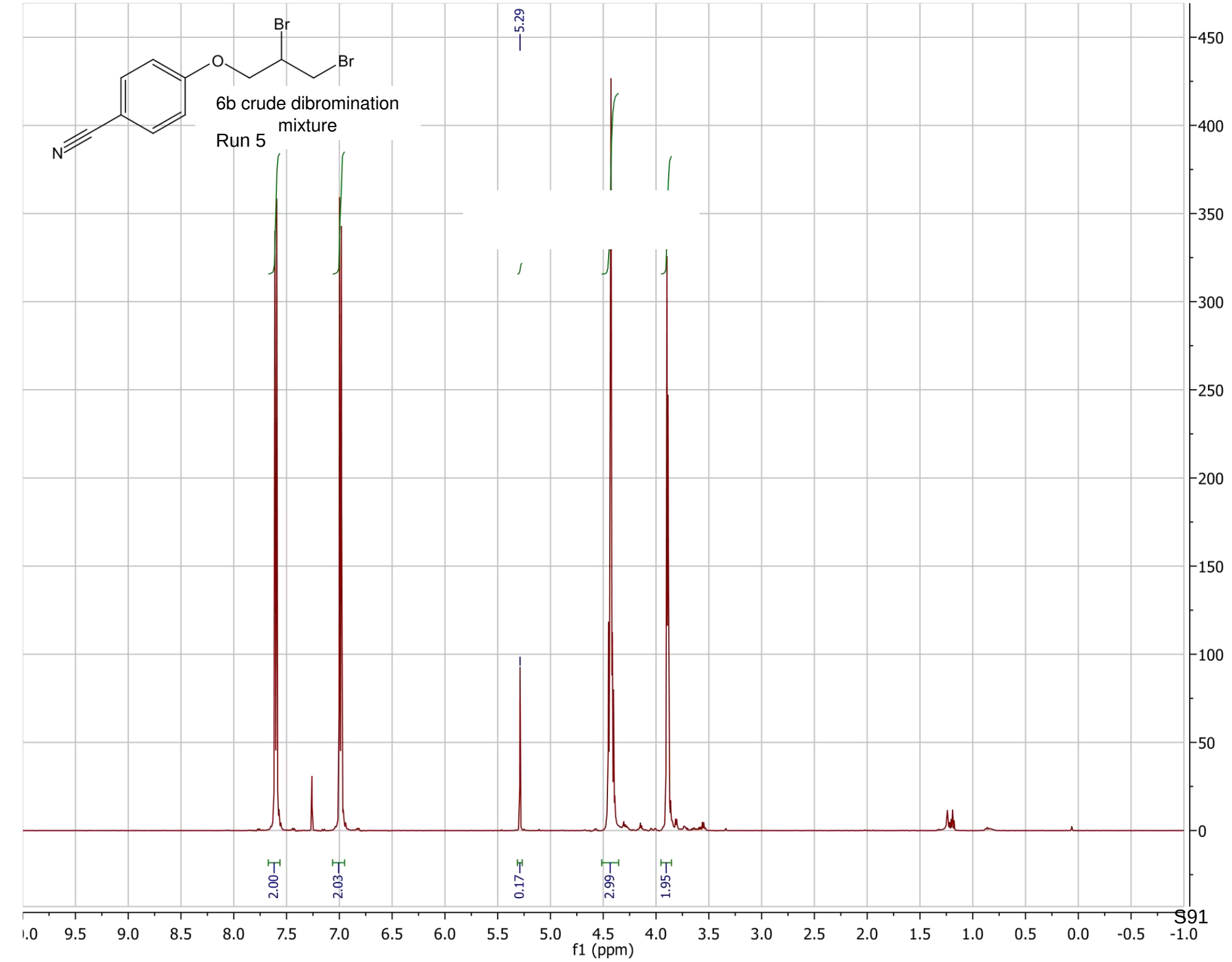
crude 6a dibromination mixture
Run 1

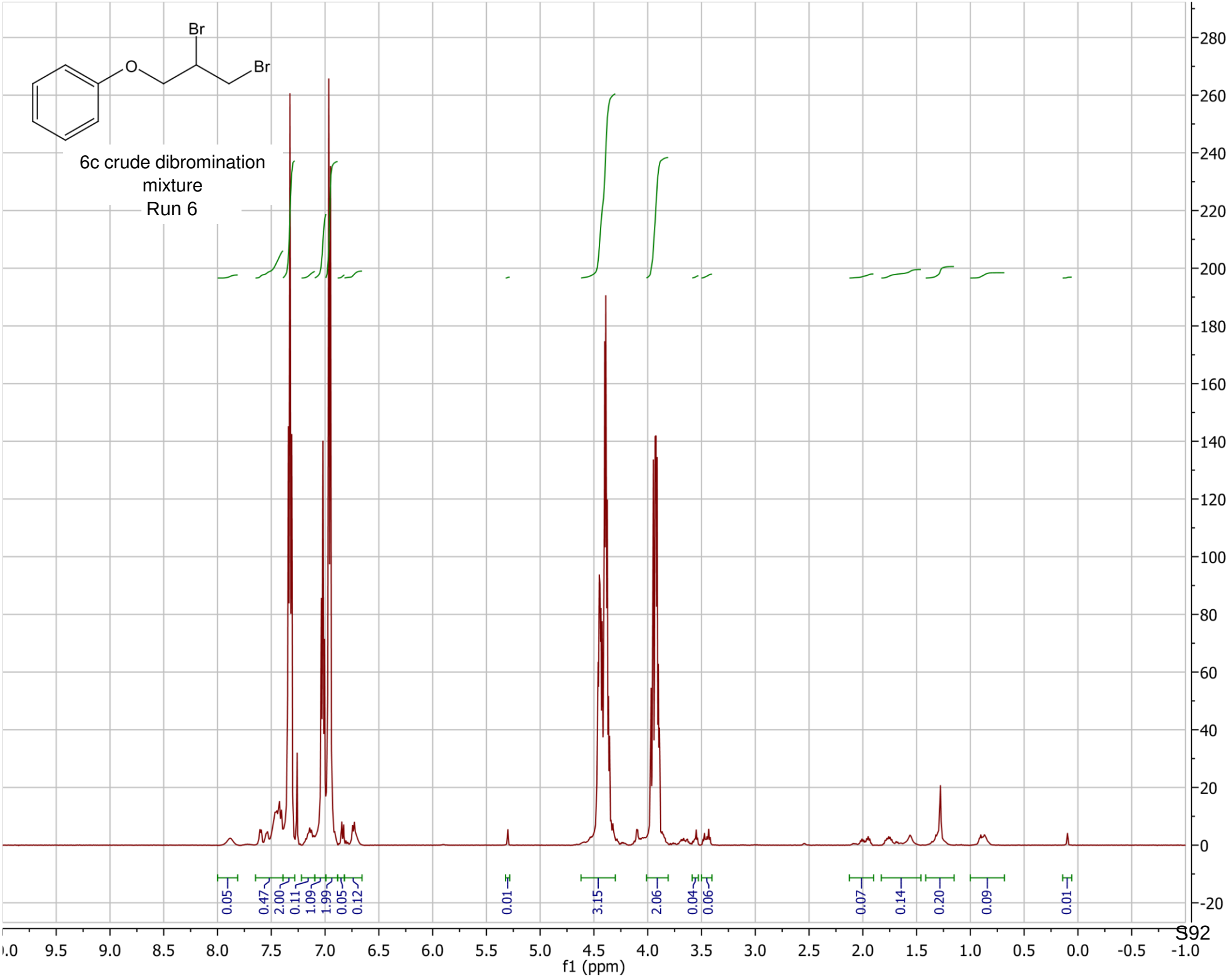

Br
O
Br
H3C
O
6a crude dibromination mixture
Run 2
3.78
0.01
0.06
0.04
0.05
0.23
0.03
0.04
4.06
0.14
1.00
2.00
2.00
0.14
2.98
0.05
0.04
0.06
0.05
0.05
0.24
0.10
f1 (ppm)

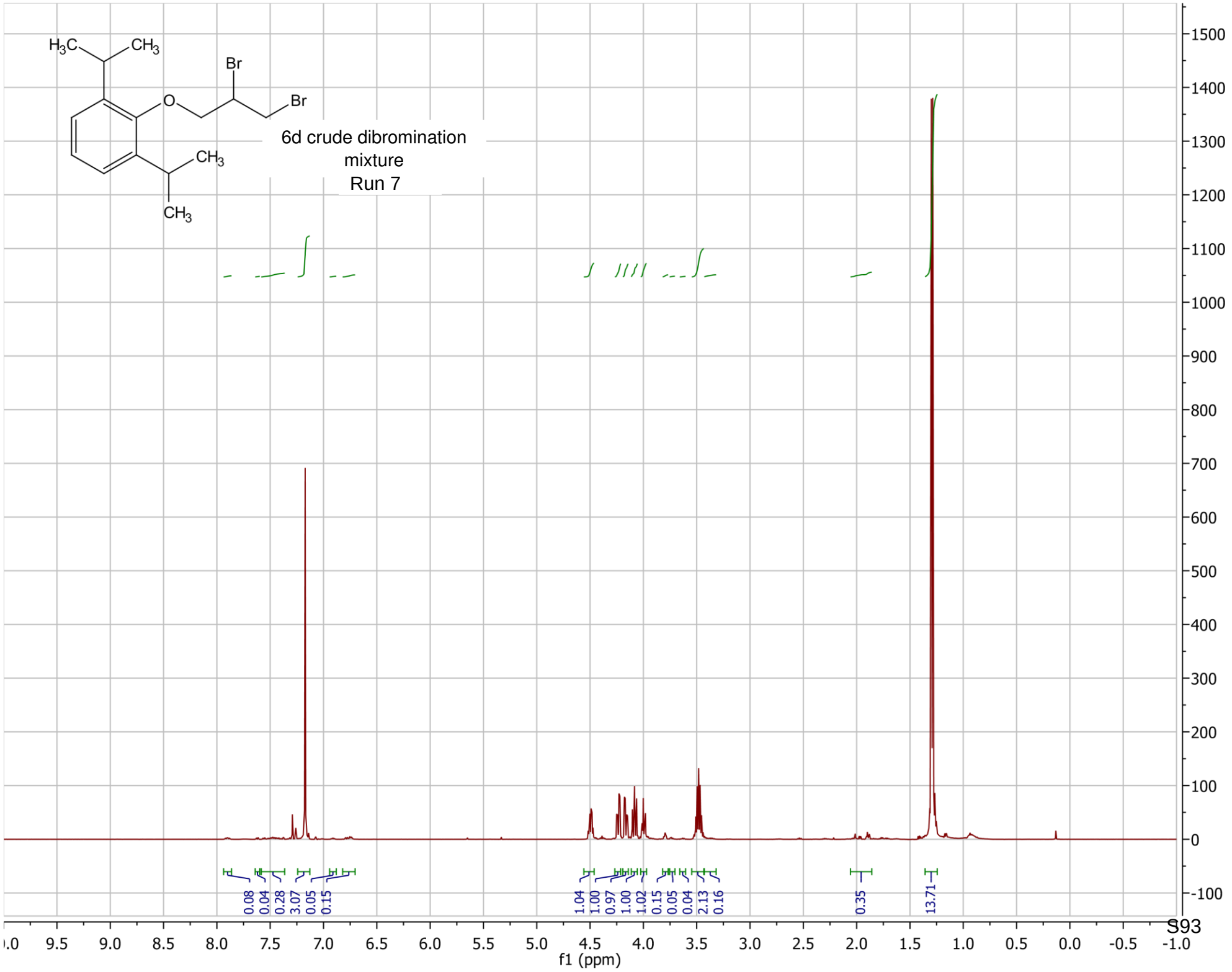


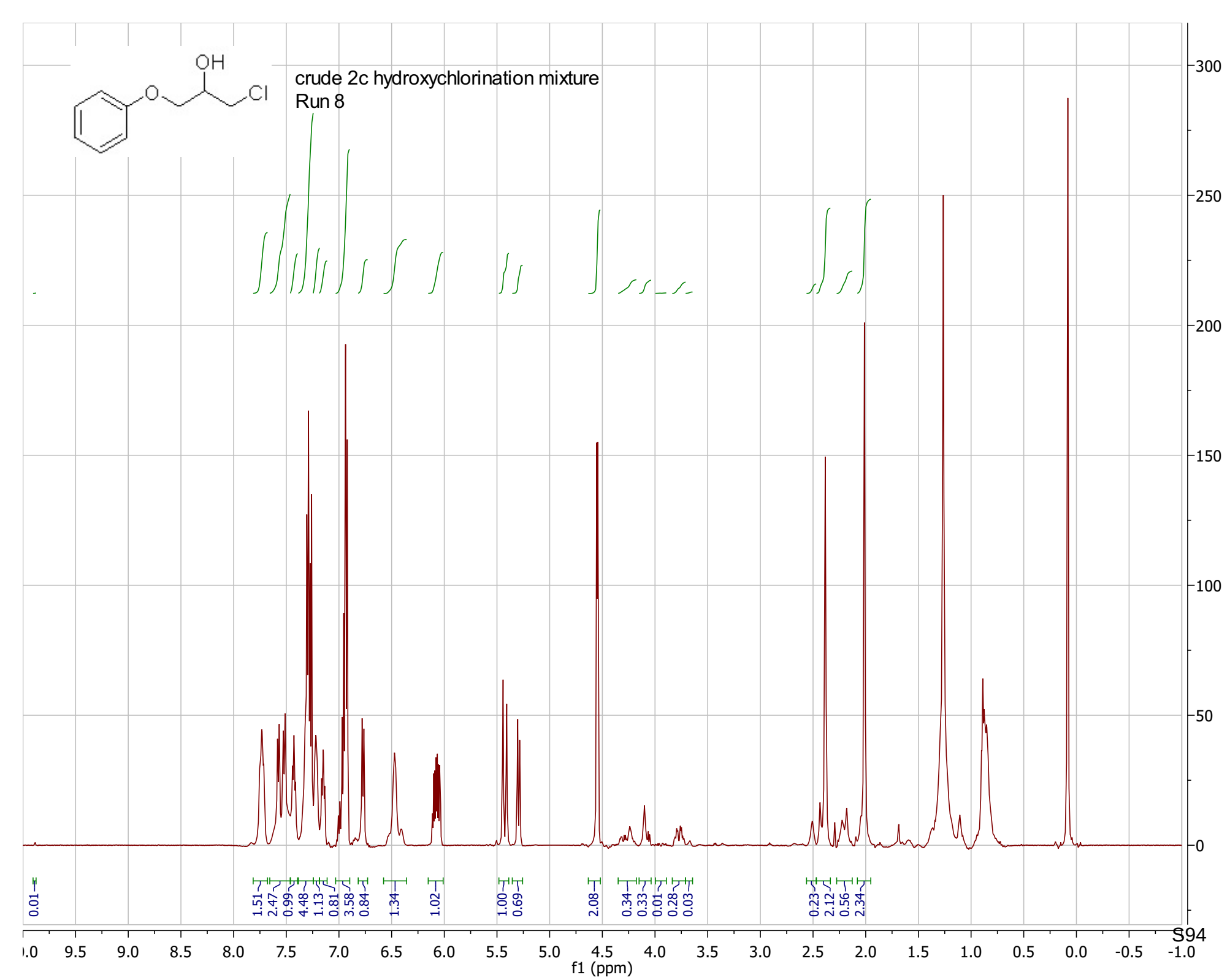
crude 6a dibromination mixture
Run **3**

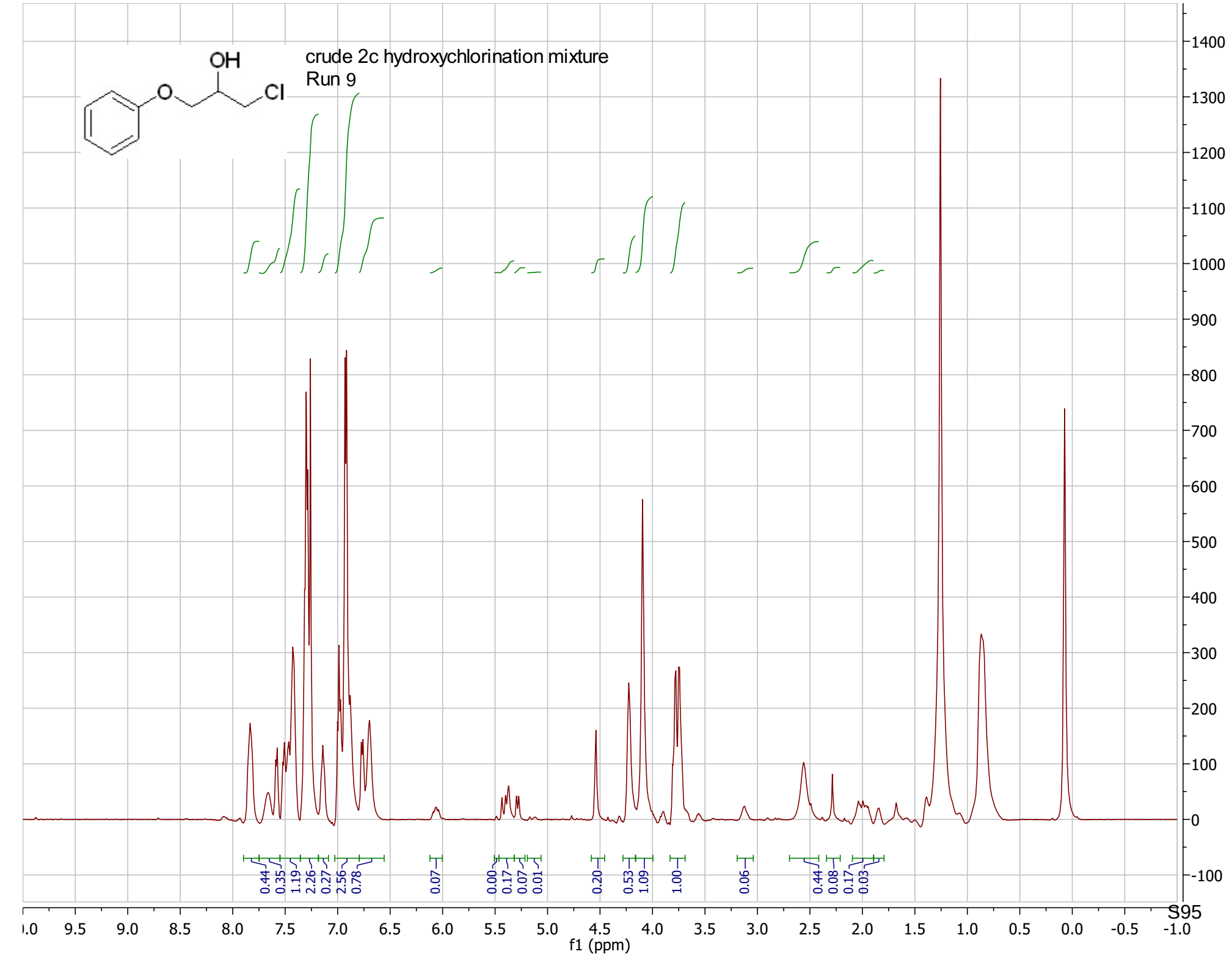

9.76
3.78
Br
O
Br
MeO
crude 6a dibromination mixture
Run 4
0.05
5.41
0.27
0.23
0.34
0.27
0.09
0.54
0.99
2.18
2.17
4.05
0.64
f1 (ppm)

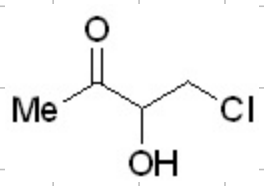

Br
O
Br
N
6b crude dibromination mixture
Run 5
5.29
2.00
2.03
0.17
2.99
1.95
f1 (ppm)


Br
O
Br
6c crude dibromination mixture
Run 6
0.05
0.47
2.00
0.11
1.09
1.99
0.05
0.12
0.01
3.15
2.06
0.04
0.06
0.07
0.14
0.20
0.09
0.01
f1 (ppm)

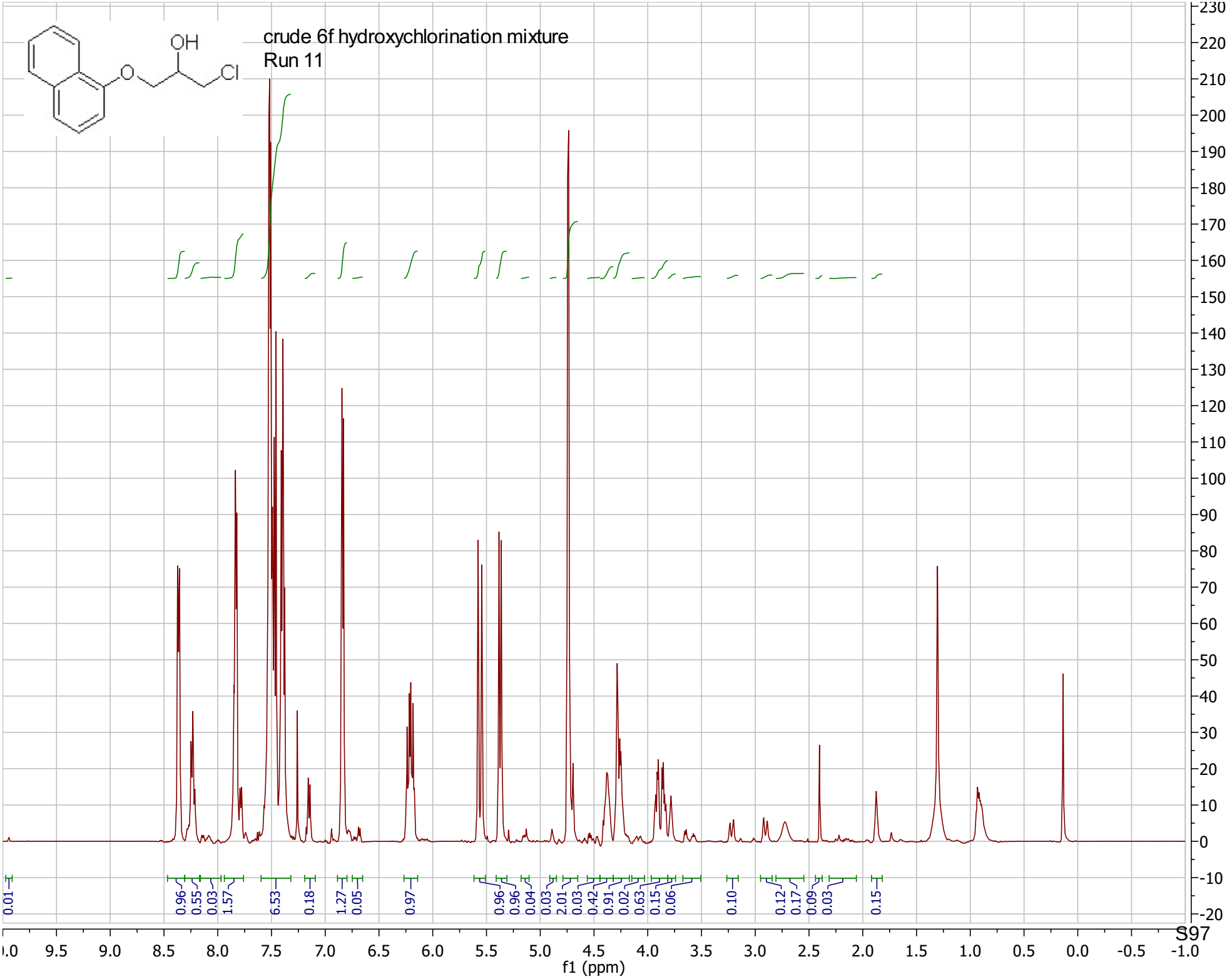

6d crude dibromination mixture
Run 7
f1 (ppm)


OH
O
Cl
crude 2c hydroxychlorination mixture
Run 8
0.01
1.51
2.47
0.99
4.48
1.13
0.81
3.58
0.84
1.34
1.02
1.00
0.69
2.08
0.34
0.33
0.01
0.28
0.03
0.23
2.12
0.56
2.34
f1 (ppm)


OH
O
Cl
crude 2c hydroxychlorination mixture
Run 9
0.44
0.35
1.19
2.26
0.27
2.56
0.78
0.07
0.00
0.17
0.07
0.01
0.20
0.53
1.09
1.00
0.06
0.44
0.08
0.17
0.03
f1 (ppm)



crude 2e hydroxychlorination mixture
Run 10


OH
O
Cl
crude 6f hydroxychlorination mixture
Run 11
0.01
0.96
0.55
0.03
1.57
6.53
0.18
1.27
0.05
0.97
0.96
0.96
0.04
0.03
2.01
0.03
0.42
0.91
0.02
0.63
0.15
0.06
0.10
0.12
0.17
0.09
0.03
0.15
f1 (ppm)