Synthesis of Chromans via [3+3] Cyclocoupling of Phenols with Allylic Alcohols Using a Mo/*o*-Chloranil Catalyst System

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Supporting Information

Contents

I. General Considerations

Column chromatography was performed on silica gel with mixed solvents. ^{1}H and ^{13}C NMR spectra were obtained for samples in $CDCl_3$ solutions at 25 °C. ^{1}H NMR chemical shifts are reported in terms of chemical shift (δ, ppm) relative to the singlet at 7.26 ppm for chloroform. Splitting patterns are designated as follows: s, singlet; d, doublet; t, triplet; q, quartet; quint, quintet; sext, sextet; sept, septet; m, multiplet. Coupling constants are reported in Hz. ^{13}C NMR spectra were fully decoupled and are reported in terms of chemical shift (δ, ppm) relative to the triplet at 77.0 ppm for $CDCl_3$. EI mass measurements were performed with a Shimadzu GCMS-QP2010 plus mass spectrometer. Elemental analyses were performed at Center for Advanced Materials Analysis of Tokyo Institute of Technology. Melting points were obtained in capillary tubes and are uncorrected. $CpMoCl(CO)_3$, $[CpMo(CO)_3]_2$, $[Mo(OAc)_2]_2$, *o*-chloranil, chlorobenzene, and isoprene were purchased and used as received. Most of allylic alcohols were purchased and used as received except for **2c–d**, and **2f** which were prepared by reductions of the parent esters a or a ketone. Microwave irradiation experiments were carried out with a single-mode microwave reactor (CEM Discover LabMate). Closed reaction vessels were used, and the temperature was monitored by an on-line IR detector.

II. Synthesis of Chromans.

Representative Procedures for Cyclocoupling (1) – Synthesis of 3aa: In a 6-mL reaction tube, $CpMoCl(CO)_3$ (14.02 mg, 0.050 mmol) and *o*-chloranil (24.57 mg, 0.10 mmol) were mixed with *p*-cresol (3 mL) at room temperature under Ar atmosphere. After stirring for 30 min at room temperature, to this mixture prenyl alcohol (102 μL, 1.00 mmol) was added by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 1 h (Temperature-Time Profile 1). After cooling to room temperature, the solution was diluted with ether (5 mL), and was filtered through a pad of alumina. The insoluble materials were further washed with ether (40 mL). The filtrate was washed with 1 N NaOH (40 mL) and extracted with ether (20 mL × 2). The combined organic layer was dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by silica gel flash column chromatography (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 100:1) to give chroman **3aa** (147.64 mg, 84%) as a colorless oil. The following spectral data were in good agreement with those reported previously;[1] ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.32 (s, 6 H), 1.79 (t, J = 6.9 Hz, 2 H), 2.25 (s, 3 H), 2.74 (t, J = 6.9 Hz, 2 H), 6.68 (d, J = 7.8 Hz, 1 H), 6.87 (s, 1 H), 6.89 (d, J = 7.8 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ

20.4, 22.4, 26.8, 32.9, 73.8, 116.9, 120.5, 127.9, 128.6, 129.7, 151.7.

Analytical data for 3ba:[2] colorless oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 50:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.32 (s, 6 H), 1.78 (t, J = 6.9 Hz, 2 H), 2.74 (t, J = 6.9 Hz, 2 H), 6.70 (d, J = 9.6 Hz, 1 H), 7.03 (d, J = 9.6 Hz, 1 H), 7.04 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 22.3, 26.7, 32.4, 74.4, 118.5, 122.4, 124.2, 127.1, 128.9, 152.6.

Analytical data for 3da:[3] colorless oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 100:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.31 (s, 6 H), 1.77 (t, J = 6.9 Hz, 2 H), 2.14 (s, 3 H), 2.22 (S, 3 H), 2.73 (t, J = 6.9 Hz, 2 H), 6.72 (s, 1 H), 6.78 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 15.9, 20.4, 22.6, 27.0, 33.0, 73.6, 119.9, 125.9, 127.1, 127.8, 129.1, 149.9.

Analytical data for 3ab (all-rac): colorless oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 300:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.82–0.88 (m, 12 H), 1.00–1.61 (m, 21 H), 1.27 (s, 3 H), 1.74 (dt, J = 13.5, 6.6 Hz, 1 H), 1.83 (dt, J = 13.5, 6.6 Hz, 1 H), 2.24 (s, 3 H), 2.71 (t, J = 6.6 Hz, 2 H), 6.68 (d, J = 8.1 Hz, 1 H), 6.86 (s, 1 H), 6.88 (d, J = 8.1 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 19.6–19.7 (3 peak tops, CH_3), 20.4 (CH_3), 21.1 (CH_2), 22.2 (CH_2), 22.6 (CH_3), 22.7 (CH_3), 24.2 (CH_3), 24.5 (CH_2), 24.8 (CH_2), 28.0 (CH), 31.0 (2 peak tops, CH_2), 32.7–32.8 (4 peak tops, CH), 37.3–37.6 (5 peak tops, CH_2), 39.4 (CH_2), 40.0 (2 peak tops, CH_2), 76.0, 117.0 (CH), 120.8, 127.9 (CH), 128.5, 129.7 (CH), 151.8; MS (EI): *m/z* (%): 386 (41) $[M]^+$, 161 (89) $[M - (CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)_2]^+$, 121 (100) $[MH - CH_2{=}CH(CH_3)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)_2]^+$; EA calcd (%) for $C_{27}H_{46}O$ (386.65): C 83.87, H 11.99; found: C 83.87, H 11.17.

Analytical data for 3ac:[4] colorless oil (Kanto 60, spherical, 40–50 μm; eluent hexane); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.26–1.80 (m, 10 H), 1.77 (t, J = 6.9 Hz, 2 H), 2.25 (s, 3 H), 2.71 (t, J = 6.9 Hz, 2 H), 6.72 (d, J = 8.1 Hz, 1 H), 6.85 (s, 1 H), 6.89 (d, J = 8.1 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.4, 21.6, 21.8, 26.0, 31.7, 35.1, 74.3, 117.0, 121.2, 127.7, 128.6, 129.7, 151.5.

Analytical data for 3ad:[5] colorless oil (Kanto 60, spherical, 40–50 μm; eluent hexane–AcOEt 150:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.56 (s, 3 H), 0.89 (s, 3 H), 1.38 (s, 3 H), 1.58–1.86 (m, 6 H), 2.25 (s, 3 H), 2.98 (quint, J = 3.3 Hz, 1 H), 6.60 (d, J = 8.4 Hz, 1 H), 6.84 (d, J = 2.0 Hz, 1 H), 6.89 (dd, J = 8.4, 2.0 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.5, 29.3, 29.5, 30.2, 32.6, 36.0, 36.7, 45.2, 51.7, 74.8, 114.9, 127.3, 128.1, 128.2, 128.6, 153.4.

Analytical data for 3af: pale-yellow oil (Kanto 60N, spherical, 63–210 μm; eluent

hexane–AcOEt 100:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.63 (s, 3 H), 2.06 (ddd, *J* = 14.0, 11.0, 5.4 Hz, 1 H), 2.22 (s, 3 H), 2.30–2.47 (m, 2 H), 2.62 (dt, *J* = 16.5, 5.4 Hz, 1 H), 6.76 (s, 1 H), 6.88 (d, *J* = 8.2 Hz, 1 H), 6.94 (dd, *J* = 8.2, 1.5 Hz, 1 H), 7.16–7.40 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.4, 22.6, 30.2, 33.0, 78.1, 116.6, 121.2, 124.9, 126.6, 128.0, 128.3, 129.0, 129.7, 145.7, 151.9; MS (EI): *m/z* (%): 238 (100) $[M]^+$, 223 (50) $[M - Me]^+$, 209 (6) $[MH - 2\ CH_3]^+$, 147 (8) $[MH - Me - C_6H_5]^+$; EA calcd (%) for $C_{17}H_{18}O$ (238.32): C 85.67, H 7.61; found: C 85.62, H 7.75.

Analytical data for 5ag:[6] colorless oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 300:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.46 (s, 6 H), 2.27 (s, 3 H), 2.97 (s, 2 H), 6.62 (d, *J* = 8.4 Hz, 1 H), 6.90 (d, *J* = 8.4 Hz, 1 H), 6.95 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.7, 28.1, 43.0, 86.2, 109.0, 125.7, 127.0, 128.2, 129.1, 156.8.

Analytical data for 6ag:[7] white solid, mp 164.0–164.5 °C [lit.[9] mp 172–173 °C] (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 3:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.92 (d, *J* = 6.6 Hz, 6 H), 2.26 (s, 6 H), 2.64 (dsept, *J* = 10.8, 6.6 Hz, 1 H), 3.97 (d, *J* = 10.8 Hz, 1 H), 6.24 (s, 2 H), 6.68 (d, *J* = 8.4 Hz, 2 H), 6.82 (dd, *J* = 8.4, 1.8 Hz, 2 H), 7.09 (d, *J* = 1.8 H, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.8, 21.5, 30.1, 43.4, 115.7, 127.4, 127.8, 130.2, 130.6, 150.5.

Representative Procedures for Cyclocoupling (2) – Synthesis of 3ca: In a 6-mL reaction tube, $CpMoCl(CO)_3$ (14.00 mg, 0.050 mmol) and *o*-chloranil (24.62 mg, 0.10 mmol) were mixed with a solution of *p*-methoxyphenol (1.241 g, 10 mmol) in chlorobenzene (3 mL) at room temperature under Ar atmosphere. After stirring for 30 min at room temperature, to this mixture prenyl alcohol (102 μL, 1.00 mmol) was added by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 1 h (Temperature-Time Profile 2). After cooling to room temperature, the solution was diluted with ether (5 mL), and was filtered through a pad of alumina. The insoluble materials were further washed with ether (40 mL). The filtrate was washed with 1 N NaOH (40 mL) and extracted with ether (20 mL × 2). The combined organic layer was dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by silica gel flash column chromatography (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 80:1) to give chroman **3ca** (117.32 mg, 61%) as a colorless oil. The following spectral data were in good agreement with those reported previously;[2] ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.31 (s, 6 H), 1.78 (t, *J* = 6.9 Hz, 2 H), 2.75 (t, *J* = 6.9 Hz, 2 H), 3.75 (s, 3 H), 6.61 (dd, *J* = 2.4, 0.6 Hz, 1 H), 6.67 (dd, *J* = 8.7, 2.4 Hz, 1 H), 6.71 (dd, *J* = 8.7, 0.6 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 22.7,

26.7, 32.8, 55.6, 73.7, 113.3, 113.9, 117.7, 121.4, 147.9, 152.8.

Analytical data for 3ea:[8] pale-yellow oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 300:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.31 (s, 6 H), 1.81 (t, *J* = 6.9 Hz, 2 H), 2.18 (s, 3 H), 2.23 (S, 3 H), 2.59 (t, *J* = 6.9 Hz, 2 H), 6.49 (s, 1 H), 6.55 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 19.0, 20.0, 20.9, 26.7, 32.9, 73.2, 115.4, 116.6, 122.1, 136.4, 136.8, 153.7.

Analytical data for 3ga:[2] colorless oil (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 300:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.43 (s, 6 H), 1.90 (t, *J* = 6.6 Hz, 2 H), 2.89 (t, *J* = 6.6 Hz, 2 H), 7.16 (d, *J* = 8.4 Hz, 1 H), 7.31 (d, *J* = 8.4 Hz, 1 H), 7.38–7.45 (m, 2 H), 7.70–7.76 (m, 1 H), 8.19-8.23 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 22.8, 26.9, 32.8, 74.4, 114.3, 118.8, 121.6, 124.8, 125.4, 125.7, 127.3, 127.7, 133.3, 148.7.

Analytical data for 3ha:[9] colorless solid, mp 74–75 °C [lit.[10] mp 77–78 °C] (Kanto 60N, spherical, 63–210 μm; eluent hexane–AcOEt 300:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.41 (s, 6 H), 1.90 (t, *J* = 6.6 Hz, 2 H), 2.85 (t, *J* = 6.6 Hz, 2 H), 3.95 (s, 3 H), 6.50 (s, 1 H), 7.42 (dt, *J* = 6.0, 2.1 Hz, 1 H), 7.46 (dt, *J* = 6.0, 1.8 Hz, 1 H), 8.14 (dd, *J* = 6.0, 2.1 Hz, 1 H), 8.17 (dd, *J* = 6.0, 1.8 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 23.3, 26.7, 33.0, 55.7, 73.8, 105.4, 113.3, 121.3, 121.6, 124.9, 125.3, 125.5, 126.5, 142.5, 148.5.

Procedures for Synthesis of 3ae: In a 30-mL round bottom flask, $CpMoCl(CO)_3$ (14.00 mg, 0.050 mmol) and *o*-chloranil (24.57 mg, 0.10 mmol) were mixed with *p*-cresol (1 mL) at room temperature under Ar atmosphere. After stirring for 30 min at room temperature, to this mixture a solution of cinnamyl alcohol (134.19 mg, 1.00 mmol) in *p*-cresol (2 mL) was added by a syringe. Then, the reaction mixture was heated on an oil bath at 60 °C for 3 h. After cooling to room temperature, the solution was diluted with ether (5 mL), and filtered through a pad of alumina. The insoluble materials were further washed with ether (40 mL). The filtrate was washed with 1 N NaOH (40 mL) and extracted with ether (20 mL × 2). The combined organic layer was dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by silica gel flash column chromatography (Kanto 60N, spherical, neutral, 63–210 μm; eluent hexane–AcOEt 20:1) to give **4ae** (149.50 mg, 67%) as a colorless oil. The following spectral data were in good agreement with those reported previously;[10] ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.28 (s, 3 H), 3.54 (d, *J* = 6.0 Hz, 2 H), 4.76 (br s, 1 H), 6.38 (dt, *J* = 16.0, 6.0 Hz, 2 H), 6.51 (d, *J* = 16.0 Hz, 1 H), 6.72 (d, *J* = 8.1 Hz, 1 H),

6.95 (d, J = 8.1 Hz, 1 H), 6.98 (s, 1 H), 7.18–7.40 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.4, 33.9, 115.5, 125.5, 126.1, 127.1, 128.1, 128.4, 130.1, 130.9, 131.2, 137.2, 151.5.

In a 6-mL reaction tube, $CpMoCl(CO)_3$ (14.03 mg, 0.050 mmol) and *o*-chloranil (24.58 mg, 0.10 mmol) were mixed with chlorobenzene (1 mL) at room temperature under Ar atmosphere. After stirring for 30 min at room temperature, to this mixture a solution of above prepared **4ae** (224.78 mg, 1.00 mmol) in chlorobenzene (2 mL) was added by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 1 h (Temperature-Time Profile 3). After cooling to room temperature, the solution was diluted with ether (5 mL), and was filtered through a pad of alumina. The insoluble materials were further washed with ether (40 mL). The filtrate was concentrated in vacuo and was purified by silica gel flash column chromatography (Kanto 60N, spherical, neutral, 63–210 μm; eluent hexane–AcOEt 100:1) to give chroman **3ae** (166.20 mg, 74%) as a pale-yellow oil. The following spectral data were in good agreement with those reported previously;[11] ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.07 (dddd, J = 13.5, 11.1, 10.2, 5.2 Hz, 1 H), 2.20 (dddd, J = 13.5, 6.2, 3.4, 2.4 Hz, 1 H), 2.28 (s, 3 H), 2.76 (ddd, J = 16.8, 5.2, 3.4 Hz, 1 H), 2.97 (ddd, J = 16.8, 11.1, 6.2 Hz, 1 H), 5.04 (dd, J = 10.2, 2.4 Hz, 1 H), 6.82 (d, J = 8.2 Hz, 1 H), 6.91 (s, 1 H), 6.93 (d, J = 8.2 Hz, 1 H), 7.28–7.45 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.5, 25.0, 30.0, 77.6, 116.6, 121.4, 126.0, 127.7, 127.9, 128.4, 129.4, 129.8, 141.9, 152.9.

Procedures for Synthesis of 3fa: In a 30-mL round bottom flask, $CpMoCl(CO)_3$ (14.00 mg, 0.050 mmol) and *o*-chloranil (24.63 mg, 0.10 mmol) were mixed with a solution of β-naphthol (1.442 g, 10.0 mmol) in chlorobenzene (3 mL) at room temperature under Ar atmosphere. After stirring for 30 min at room temperature, to this mixture a solution of prenyl alcohol (102 μL, 1.00 mmol) was added by a syringe. Then, the reaction mixture was heated on an oil bath at 60 °C for 6 h. After cooling to room temperature, the solution was diluted with ether (5 mL), and filtered through a pad of alumina. The insoluble materials were further washed with ether (40 mL). The filtrate was washed with 1 N NaOH (40 mL) and extracted with ether (20 mL × 2). The combined organic layer was dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by silica gel flash column chromatography (Kanto 60N, spherical 63–210 μm; eluent hexane–AcOEt 200:1) to give **3fa** (147.97 mg, 70%) as white solid (mp 68–69 °C). The following spectral data were in good agreement with those reported previously;[2] ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.39 (s, 6 H), 1.96 (t, J

= 6.6 Hz, 2 H), 3.04 (t, J = 6.6 Hz, 2 H), 7.02 (d, J = 8.9 Hz, 1 H), 7.33 (ddd, J = 7.8, 6.8, 0.9 Hz, 1 H), 7.48 (ddd, J = 8.4, 6.8, 1.2 Hz, 1 H), 7.62 (d, J = 8.9 Hz, 1 H), 7.75 (d, J = 7.8 Hz, 1 H), 7.83 (d, J = 8.4 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 19.3, 26.5, 32.7, 74.0, 112.4, 119.7, 121.8, 122.9, 126.2, 127.7, 128.4, 128.7, 133.0, 151.3.

Representative Procedures for Cyclocoupling (3) – Synthesis of 8a: In a 6-mL reaction tube, $[CpMo(CO)_3]_2$ (12.23 mg, 0.025 mmol) and *o*-chloranil (24.55 mg, 0.10 mmol) were mixed with a solution of trimethylhydroquinone (152.18 mg, 1.00 mmol) in chlorobenzene (3 mL) at -78 °C, and the reaction mixture was degassed at this temperature. After stirring for 30 min at room temperature under Ar atmosphere, to this mixture degassed prenyl alcohol (205 μL, 2.00 mmol) was added by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 1 h (Temperature-Time Profile 4). After cooling to room temperature, the solution was diluted with AcOEt (5 mL), and was filtered through a pad of alumina. The insoluble materials were further washed with AcOEt (60 mL). The filtrate was concentrated in vacuo, and the residue was purified by silica gel flash column chromatography (Kanto 60, spherical, 40–50 μm; eluent hexane–AcOEt 100:1) to give chroman **8a** (176.86 mg, 80%) as a colorless needle (mp. 94.0–94.5 °C; lit.[12] mp 93-94 °C). The following spectral data were in good agreement with those reported previously;[13] ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.29 (s, 6 H), 1.79 (t, J = 6.9 Hz, 2 H), 2.11 (s, 6 H), 2.16 (s, 3 H), 2.62 (t, J = 6.9 Hz, 2 H), 4.18 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 11.2, 11.7, 12.2, 21.0, 26.6, 33.0, 72.4, 117.1, 118.6, 121.1, 122.5, 144.6, 145.7.

Analytical data for 8b (all-rac): pale-yellow oil (Kanto 60, spherical, 40–50 μm; eluent hexane–AcOEt 150:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.82–0.88 (m, 12 H), 1.00–1.60 (m, 21 H), 1.23 (s, 3 H), 1.75 (dt, J = 13.5, 6.9 Hz, 1 H), 1.82 (dt, J = 13.5, 7.2 Hz, 1 H), 2.11 (s, 6 H), 2.16 (s, 3 H), 2.60 (t, J = 6.6 Hz, 2 H), 4.17 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 11.2–12.2 (3 peak tops, CH_3), 19.6–19.74 (4 peak tops, CH_3), 20.8 (CH_2), 21.1 (CH_2), 22.6–22.7 (2 peak tops, CH_3), 23.8 (CH_3), 24.4 (CH_2), 28.0 (CH), 31.5–31.6 (2 peak tops, CH_2), 32.7–32.8 (3 peak tops, CH), 37.3–37.7 (7 peak tops, CH_2), 39.4 (CH_2), 39.8–39.9 (2 peak tops, CH_2), 74.5, 117.3, 118.5, 121.1, 122.6, 144.5, 145.6. These spectral data were in good agreement with an authentic sample (DL-α-tochopherol, purity >98%) purchased from Wako Pure Chemical Industries (cat. No. 209-01791).

Analytical data for 11: white solid, mp 103–104 °C [lit.[14] mp 107 °C] (Kanto 60, spherical,

40–50 μm; eluent hexane–CH_2Cl_2 20:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.39 (s, 12 H), 1.91 (t, *J* = 6.9 Hz, 4 H), 2.69 (t, *J* = 6.9 Hz, 4 H), 7.39 (dd, *J* = 6.3, 3.6 Hz, 2 H), 8.13 (dd, *J* = 6.3, 3.6 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.2, 26.7, 33.0, 72.9, 113.2, 121.2, 124.6, 125.1, 141.7; MS (EI): *m/z* (%): 296 (73) $[M]^+$, 240 (100) $[M - CH_2{=}CMe_2]^+$, 225 (25) $[M - H - CH_2CH_2CMe_2]^+$.

Representative Procedures for Cyclocoupling (4) – Synthesis of 8c: In a 6-mL reaction tube, $[CpMo(CO)_3]_2$ (12.26 mg, 0.025 mmol) and *o*-chloranil (24.57 mg, 0.10 mmol) were mixed with a solution of tetramethylhydroquinone (152.19 mg, 1.00 mmol) in chlorobenzene (3 mL) at -78 °C, and the reaction mixture was degassed at this temperature. After stirring for 30 min at room temperature under Ar atmosphere, to this mixture was added degassed cyclohexylideneethanol (270 μL, 2.00 mmol) by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 0.5 h (Temperature-Time Profile 5). After cooling to room temperature, to the reaction mixture was added degassed cyclohexylideneethanol (270 μL, 2.00 mmol) by a syringe. The mixture was again degassed at -78 °C and was subjected to the microwave heating at 150 °C for 0.5 h (Temperature-Time Profile 6). The crude mixture was diluted with AcOEt (5 mL), and was filtered through a pad of alumina. The insoluble materials were further washed with AcOEt (60 mL). The filtrate was concentrated in vacuo, and the residue was purified by silica gel flash column chromatography (Kanto 60, spherical, 40–50 μm; eluent hexane–CH_2Cl_2 10:1) to give chroman **8c** (160.93 mg, 62%) as a colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.23–1.37 (m, 3 H), 1.47–1.57 (m, 2 H), 1.62–1.85 (m, 5 H), 1.77 (t, *J* = 6.9 Hz, 2 H), 2.11 (s, 3 H), 2.18 (s, 3 H), 2.19 (s, 3 H), 2.62 (t, *J* = 6.9 Hz, 2 H), 4.19 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 11.2, 11.7, 12.2, 20.3, 21.9, 26.2, 32.6, 34.9, 73.0, 117.7, 118.6, 121.0, 122.8, 144.7, 145.2; MS (EI): *m/z* (%): 260 (51) $[M]^+$, 165 (100) [MH – methylenecyclohexane]$^+$; This compound is unstable and decompose to black viscous oil. Thus, elemental analysis was omitted.

Analytical data for 8d: white solid, mp 138–139 °C (This compound was purified twice. Kanto 60, spherical, 40–50 μm; eluent hexane–AcOEt 100:1; hexane–toluene 1:1); ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.50 (s, 3 H), 0.88 (s, 3 H), 1.37 (s, 3 H), 1.39 (d, *J* = 14.7 Hz, 1 H), 1.53–1.71 (m, 4 H), 1.79 (d, *J* = 14.7, 1 H), 2.08 (s, 3 H), 2.15 (s, 3 H), 2.17 (s, 3 H), 3.13–3.19 (m, 1 H), 4.11 (br s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 10.6, 11.7, 12.2, 29.1, 29.4, 29.8, 30.3, 36.4, 36.7, 43.1, 51.8, 73.4, 117.3, 120.6, 121.0, 122.8, 144.1, 147.5; MS (EI): *m/z* (%): 274 (100) $[M]^+$, 259 (7) $[M - Me]^+$, 203 (50) $[MH - CH_2C(CH_3)_2CH_2]^+$; EA calcd (%) for $C_{18}H_{26}O_2$ (274.40): C 78.79, H

9.55; found: C 78.74, H 9.59.

Procedures for Synthesis of 10: To a solution of naphthoic acid (4.08 g, 20 mmol) in a mixed solvent (dry ether 30 mL / dry methanol 10 mL) was added a solution of $TMSCHN_2$ in THF (2 M solution, 15 mL, 30 mmol) over 45 min via a syringe pump at -30 °C under Ar atmosphere. The solution was concentrated in vacuo and the residue was passed through a short silica gel column (Kanto 60N, spherical 63–210 μm; eluent hexane–AcOEt 1:1). Recrystallization of the crude product from hexane/AcOEt gave **9** (3.51 g, 80%) as colorless solid (mp 192.5–193.5 °C; lit.[15] mp 192–193.5 °C). The following spectral data were in good agreement with those reported previously;[15] ^{1}H NMR (300 MHz, $CDCl_3$): δ 3.98 (s, 3 H), 4.87 (s, 1 H), 7.11 (s, 1 H), 7.58 (t, J = 8.1 Hz, 1 H), 7.66 (t, J = 8.1 Hz, 1 H), 8.13 (d, J = 8.1 Hz, 1 H), 8.41 (d, J = 8.1 Hz, 1 H), 11.55 (s, 1 H); ^{13}C NMR (75 MHz, DMSO-d_6): δ 52.4, 103.9, 104.7, 122.2, 123.2, 124.9, 126.3, 128.6, 129.1, 145.2, 152.8, 170.6.

In a 6-mL reaction tube, $CpMoCl(CO)_3$ (28.05 mg, 0.10 mmol) and *o*-chloranil (49.18 mg, 0.20 mmol) were mixed with a solution of above prepared **9** (218.21 mg, 1.00 mmol) in chlorobenzene (3 mL) at -78 °C, and the reaction mixture was degassed at this temperature. After stirring for 30 min at room temperature under Ar atmosphere, to this mixture degassed isoprene (400 μL, 4.00 mmol) was added by a syringe. Then, the reaction tube was sealed with a teflon cap and heated in a microwave reactor at 150 °C for 30 min (Temperature-Time Profile 7). After cooling to room temperature, the solution was diluted with hexane (5 mL), and was filtered through a pad of alumina. The insoluble materials were washed with hexane (40 mL) to remove oligomeric byproducts. Then the crude product was eluted with AcOEt (60 mL). The filtrate was concentrated in vacuo, and the residue was purified by silica gel flash column chromatography (Kanto 60, spherical, 40–50 μm; eluent hexane–toluene 10:1) to give dihydromollugin **10** (155.25 mg, 54%) as a pale-yellow solid (mp. 96.5–97.0 °C; lit.[16] mp 98–99 °C). The following spectral data were in good agreement with those reported previously;[16] ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.41 (s, 6 H), 1.83 (t, J = 6.9 Hz, 2 H), 3.06 (t, J = 6.9 Hz, 2 H), 3.99 (s, 3 H), 7.49 (t, J = 8.4 Hz, 1 H), 7.60 (t, J = 8.4 Hz, 1 H), 8.18 (d, J = 8.4 Hz, 1 H), 8.37 (d, J = 8.4 Hz, 1 H), 12.16 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 23.3, 26.5, 33.3, 51.9, 73.0, 105.2, 111.6, 121.6, 123.7, 124.4, 125.6, 129.0, 129.5, 141.6, 156.2, 173.0.

VI. References.

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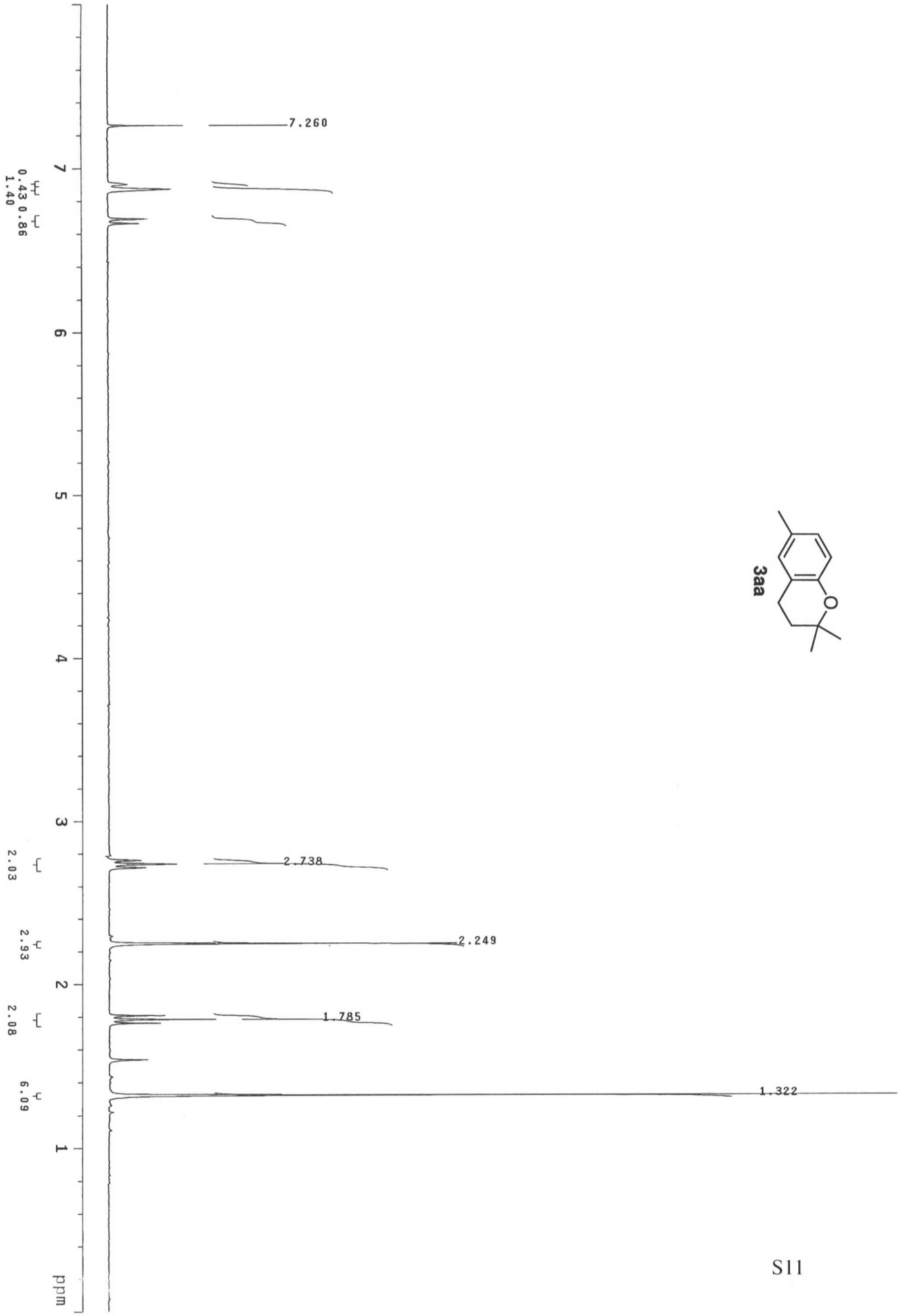
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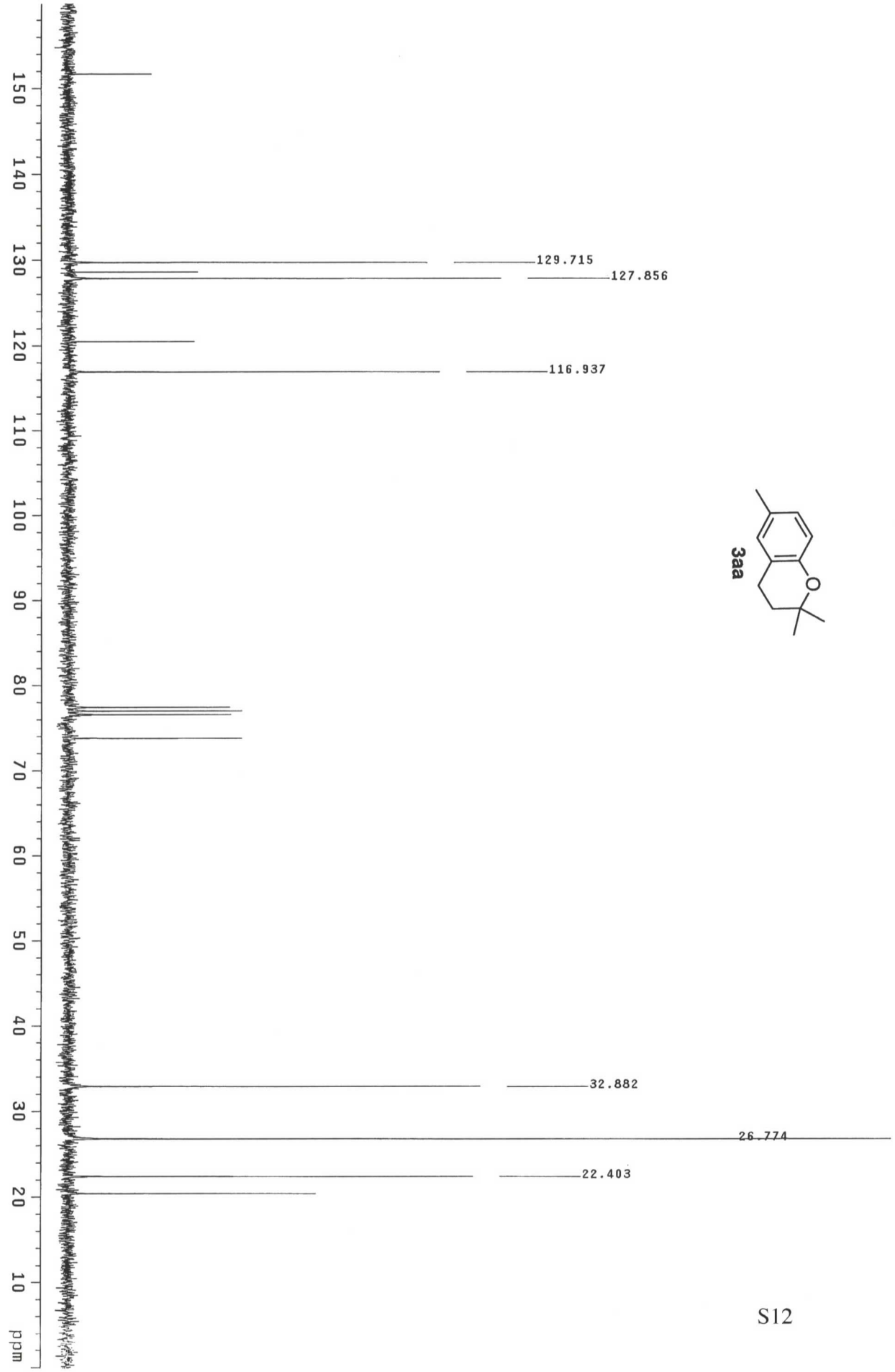
1.40



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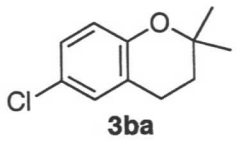

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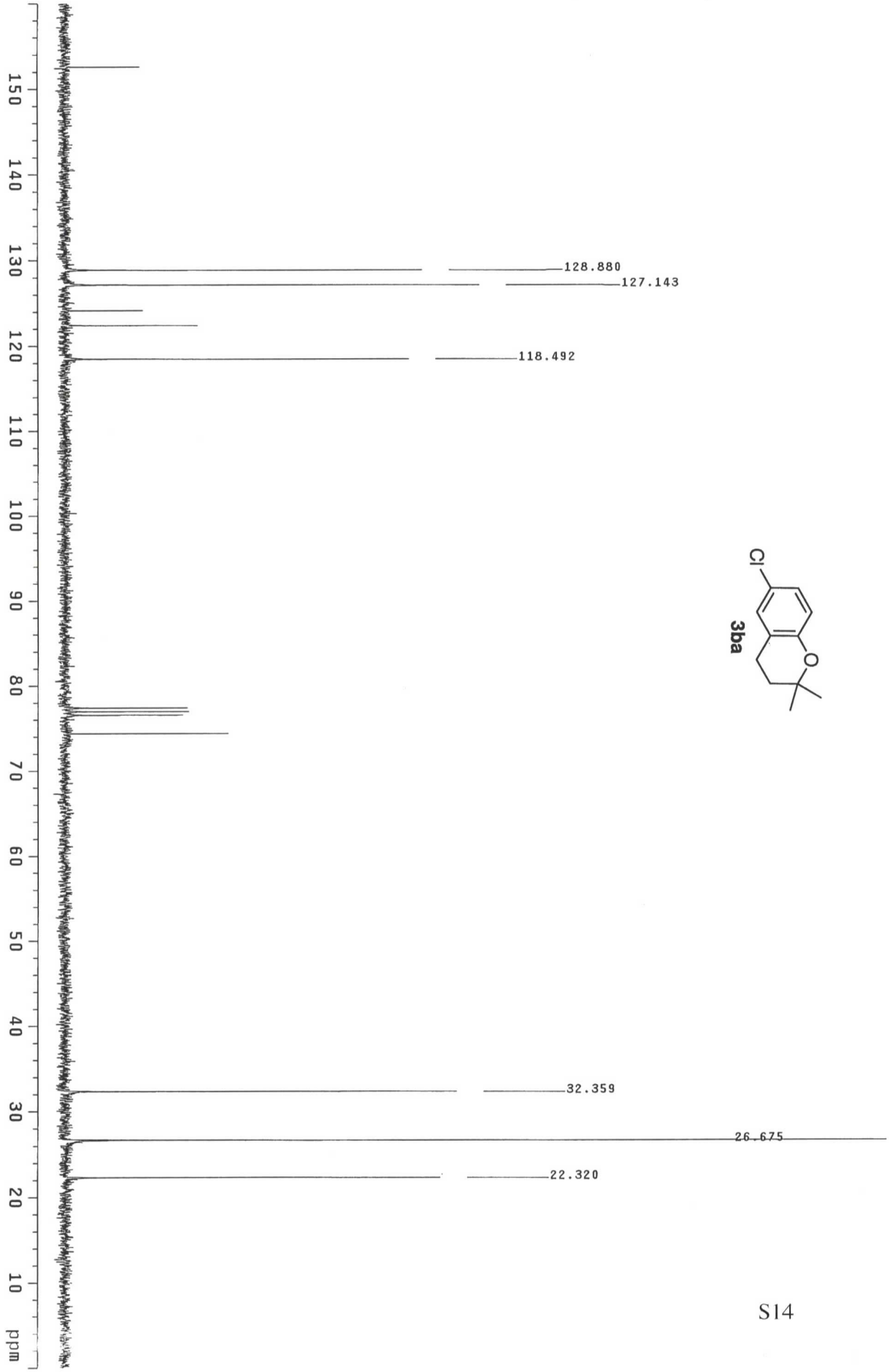
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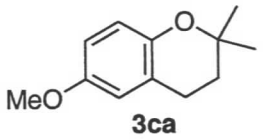
10
ppm

Cl
O

3ba



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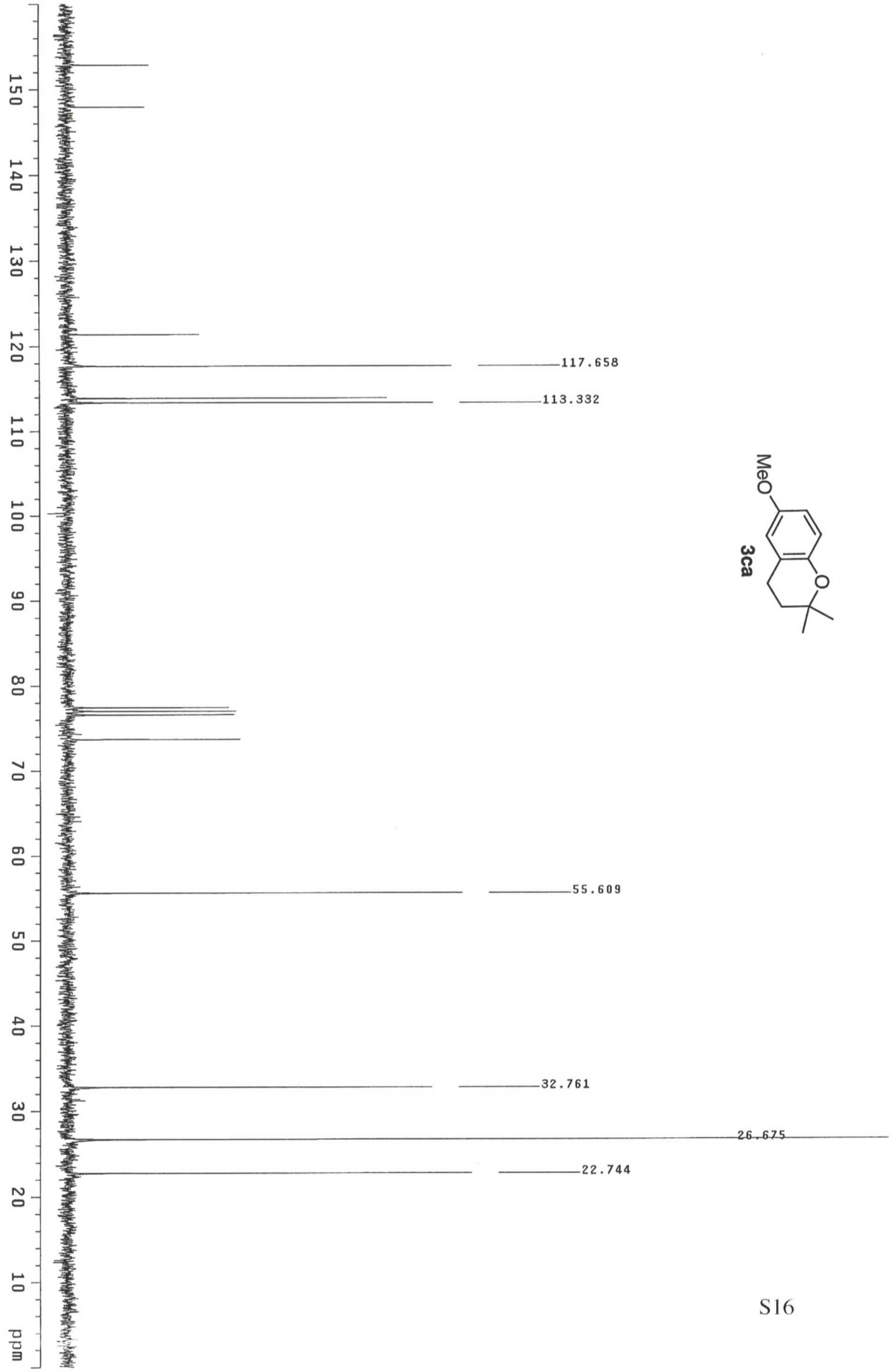
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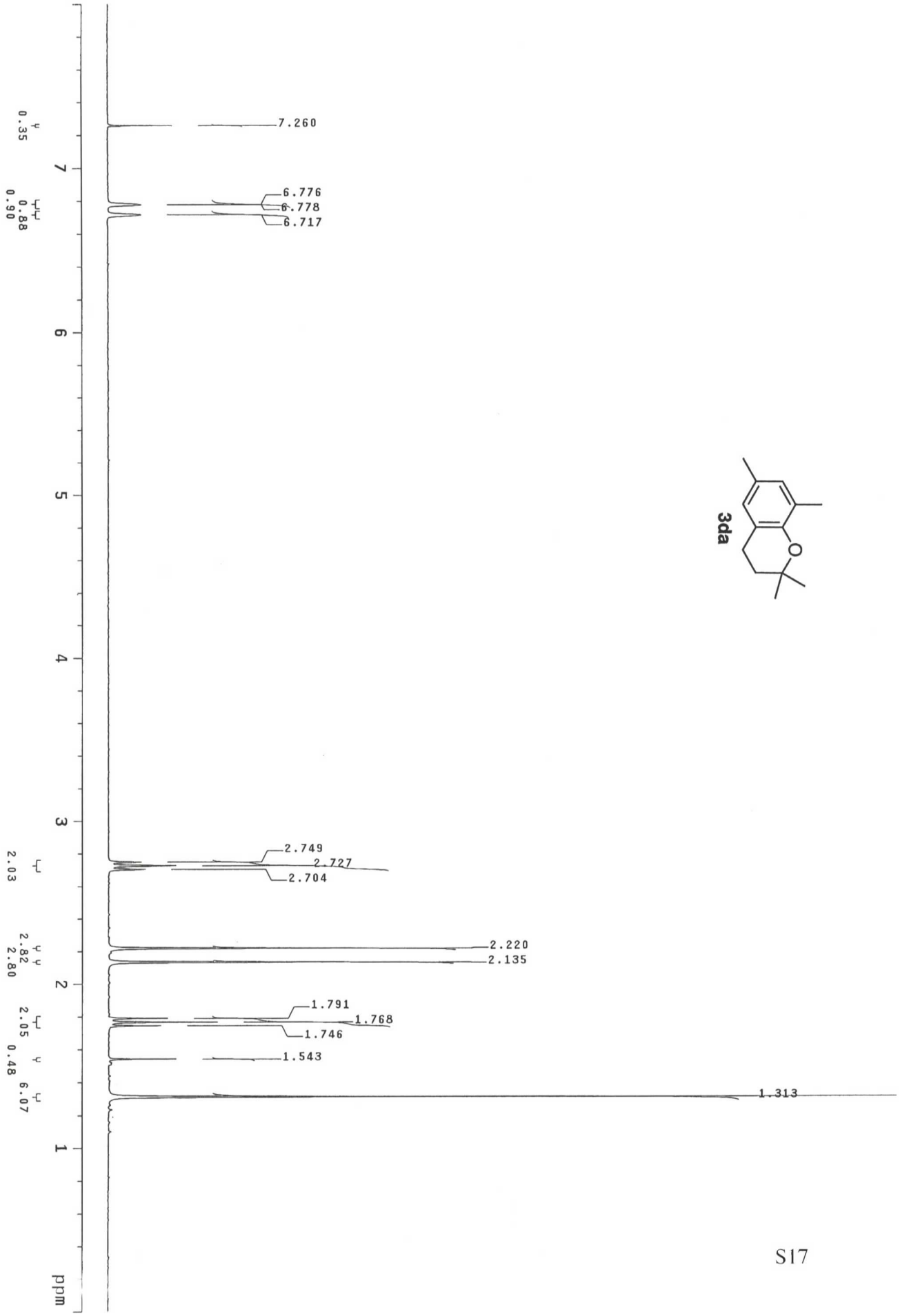
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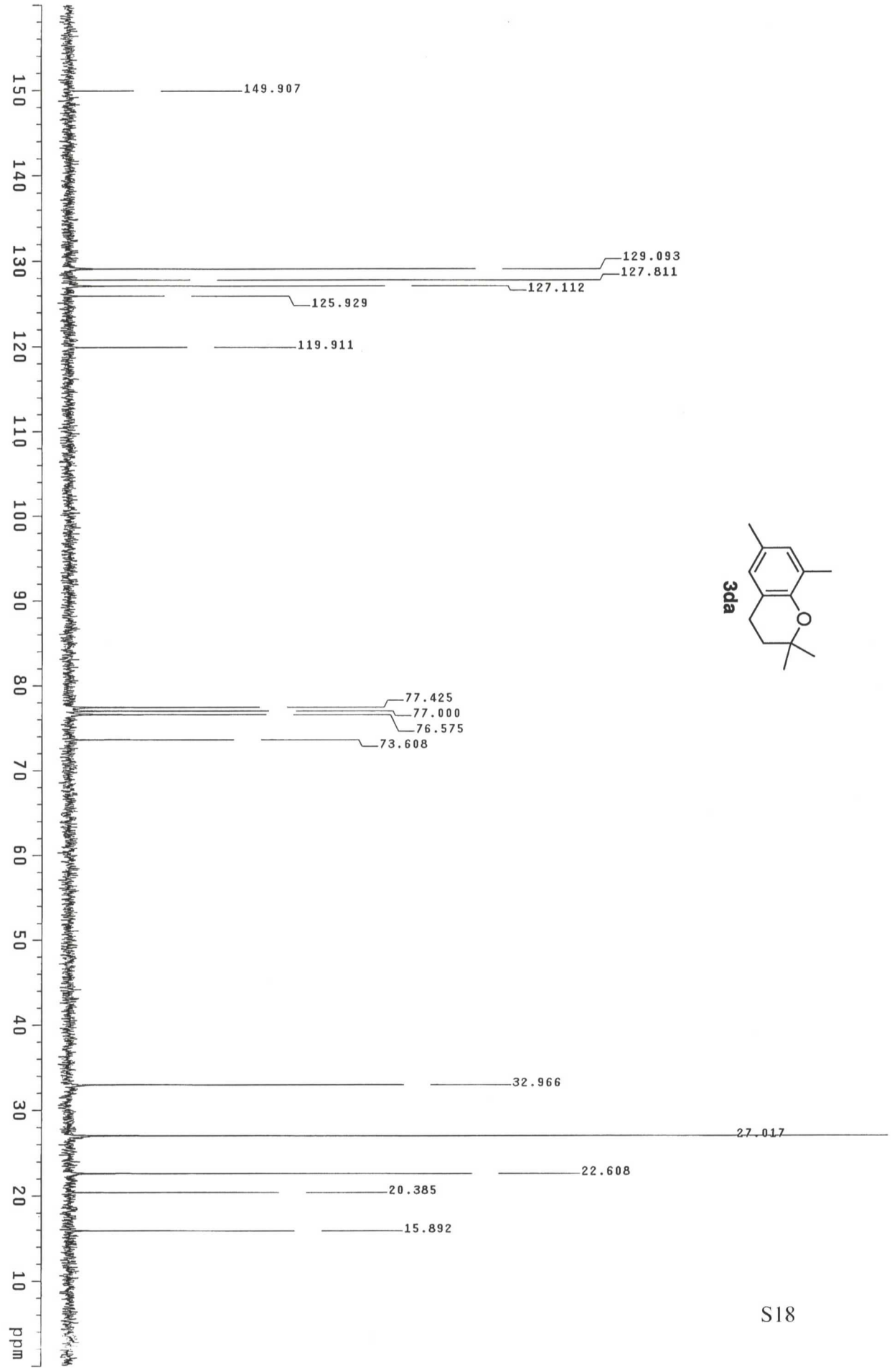
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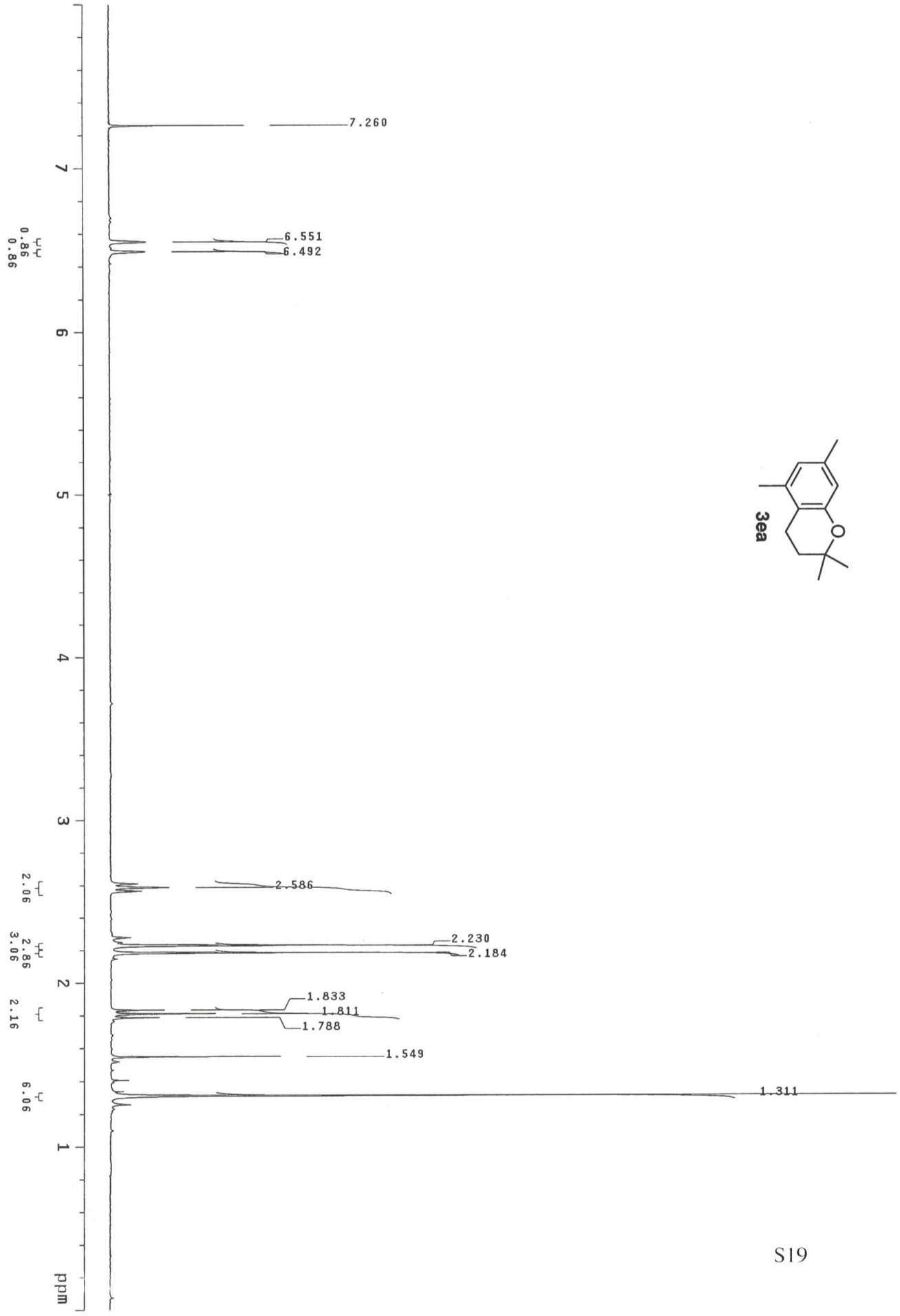
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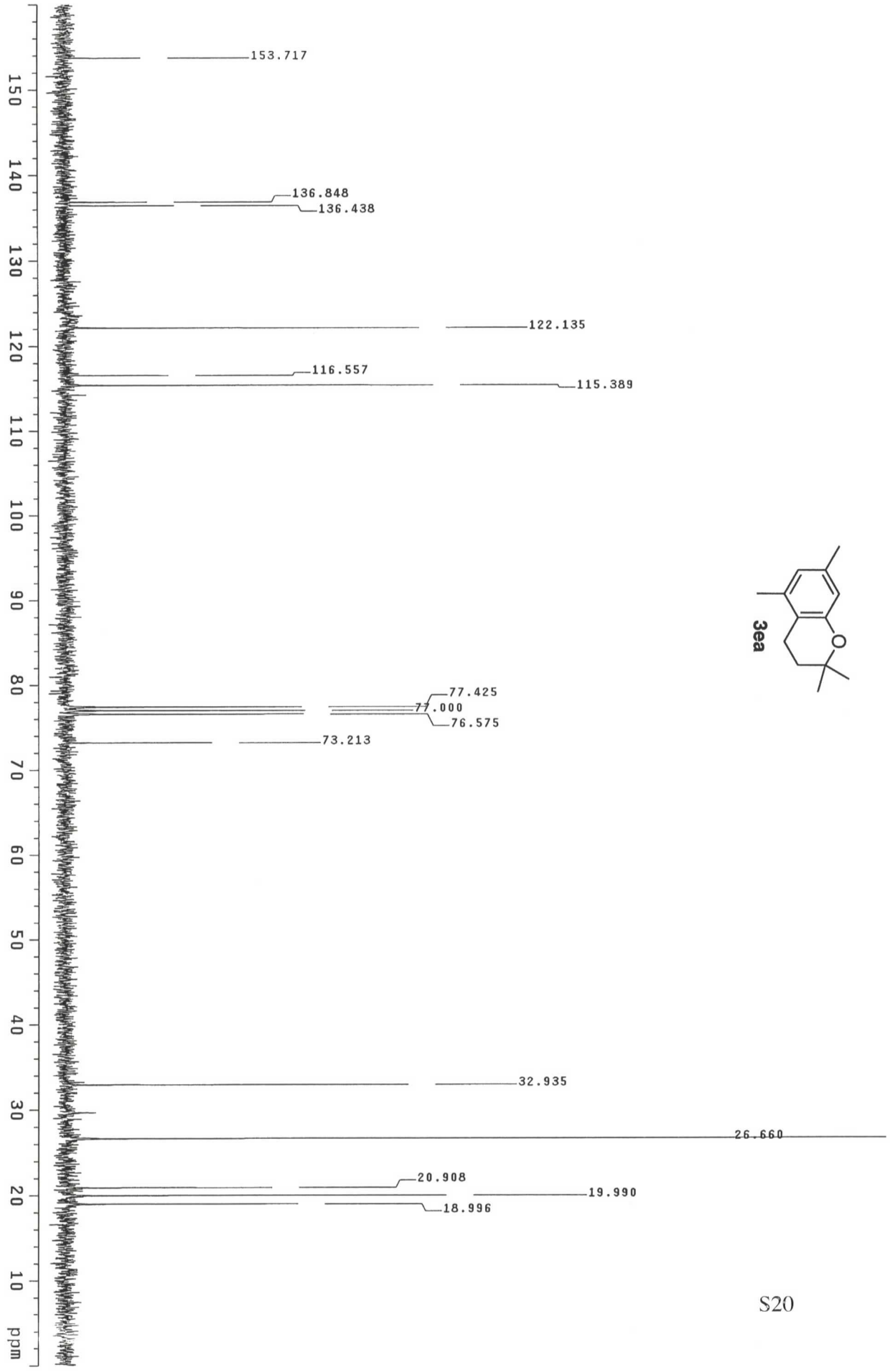
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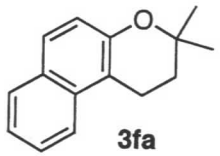

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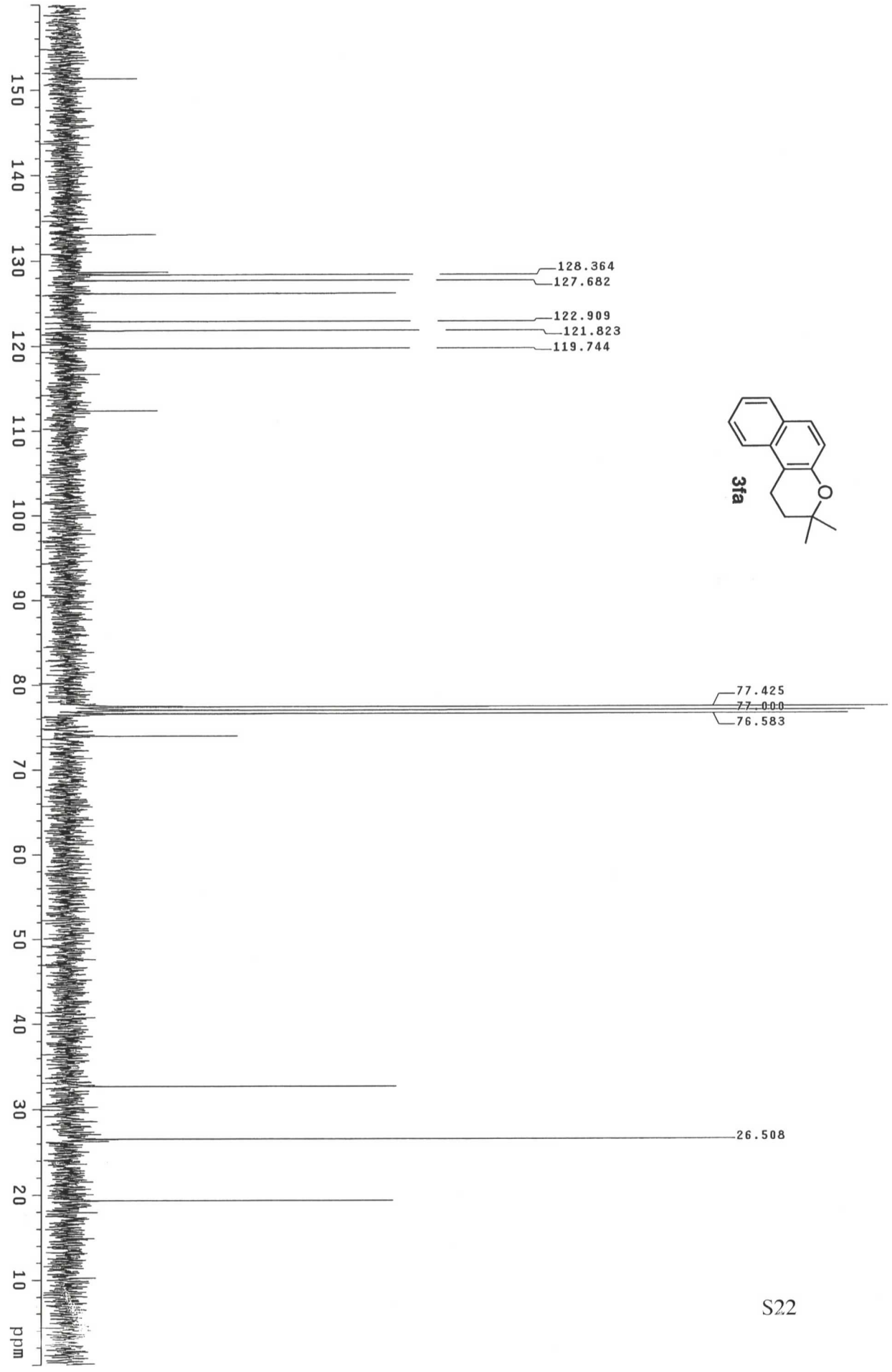
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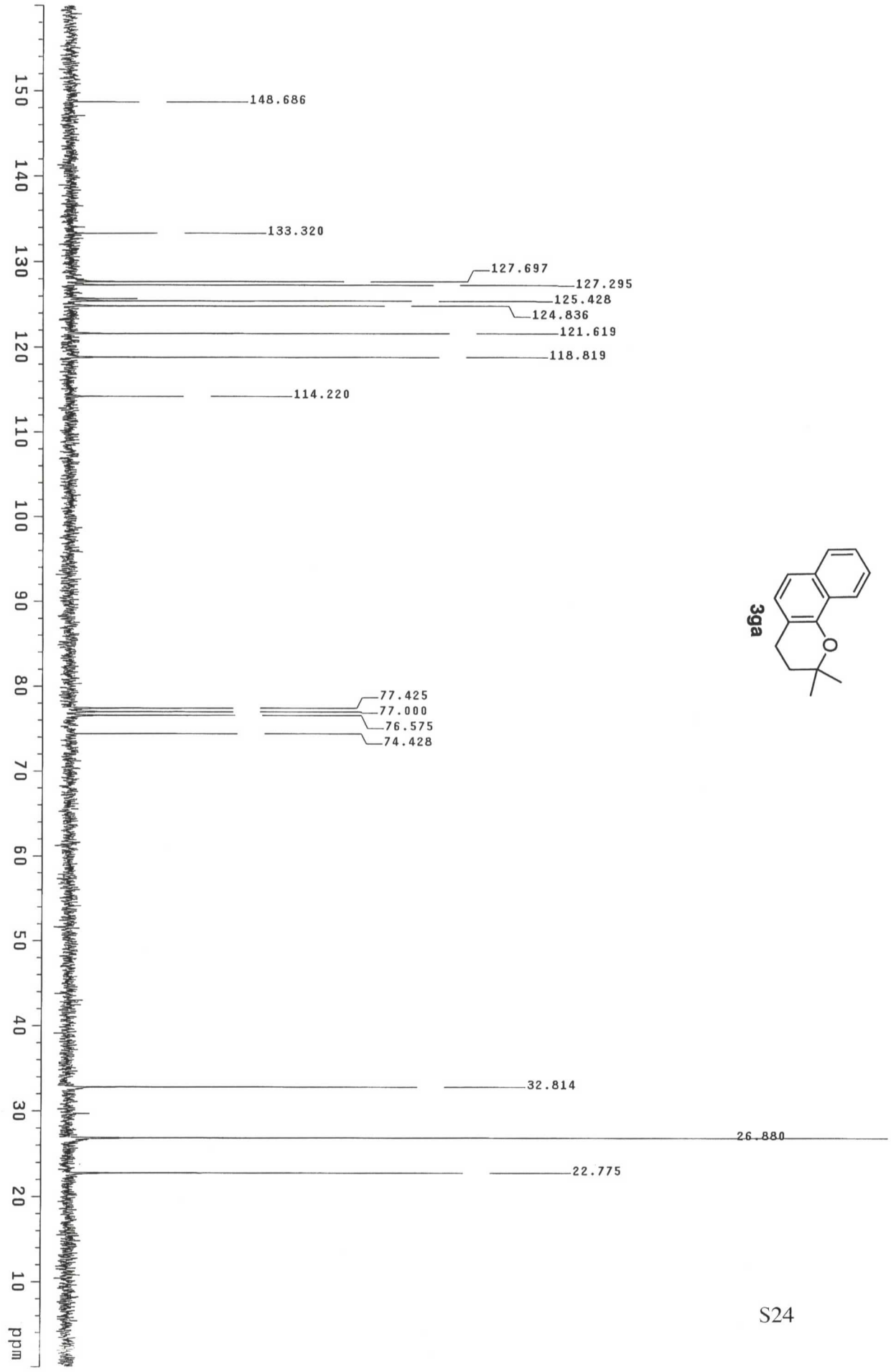
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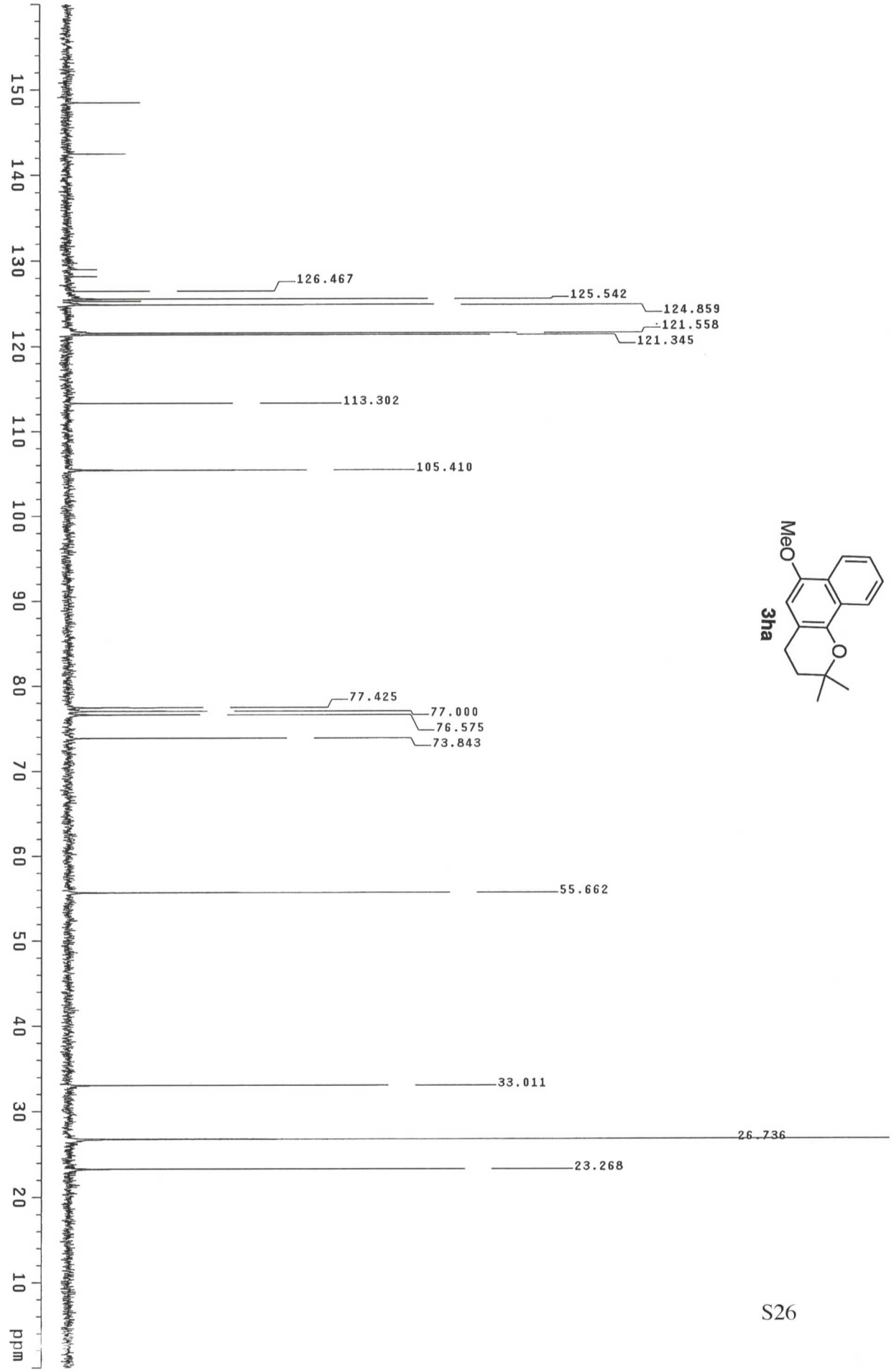
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O

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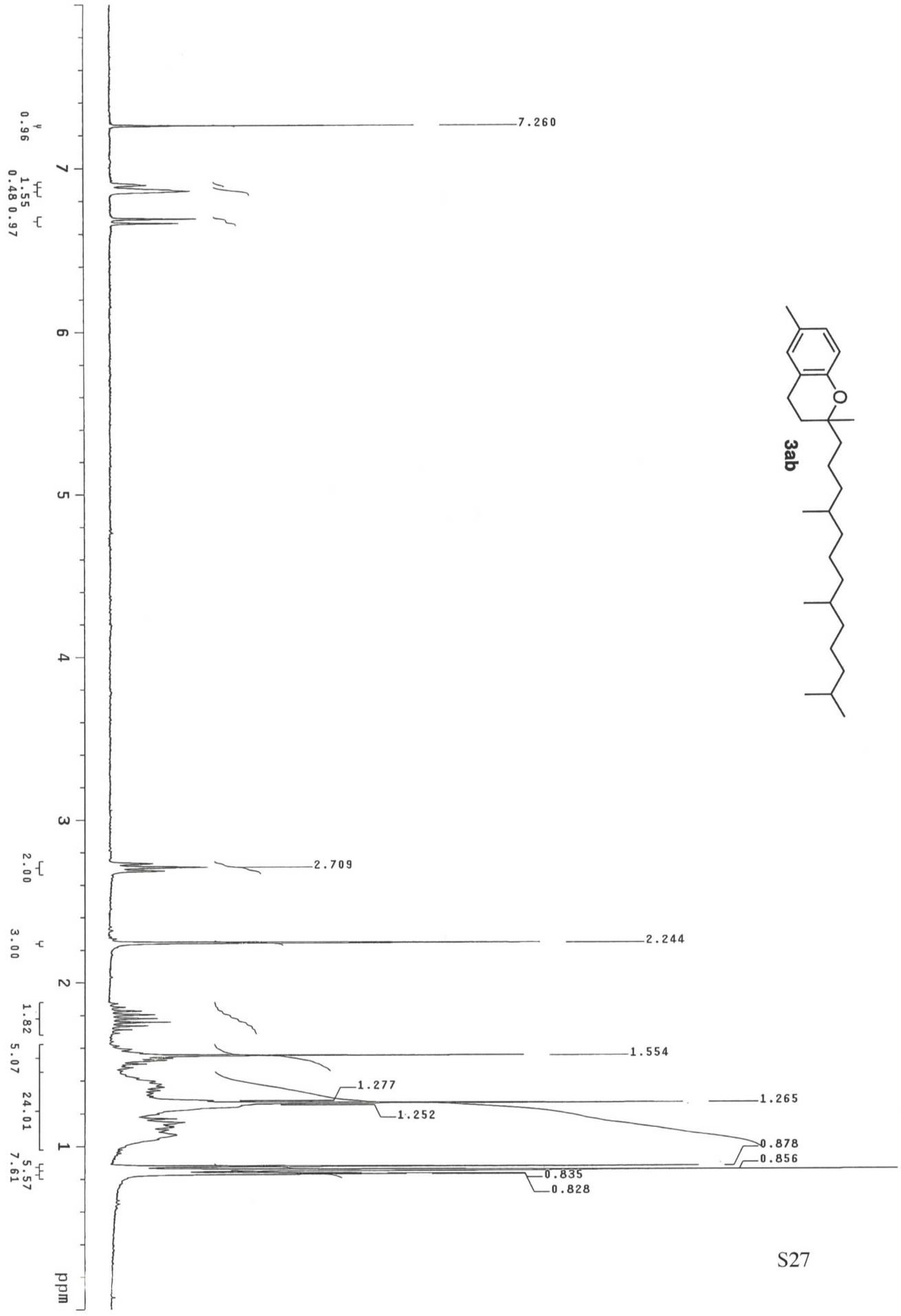
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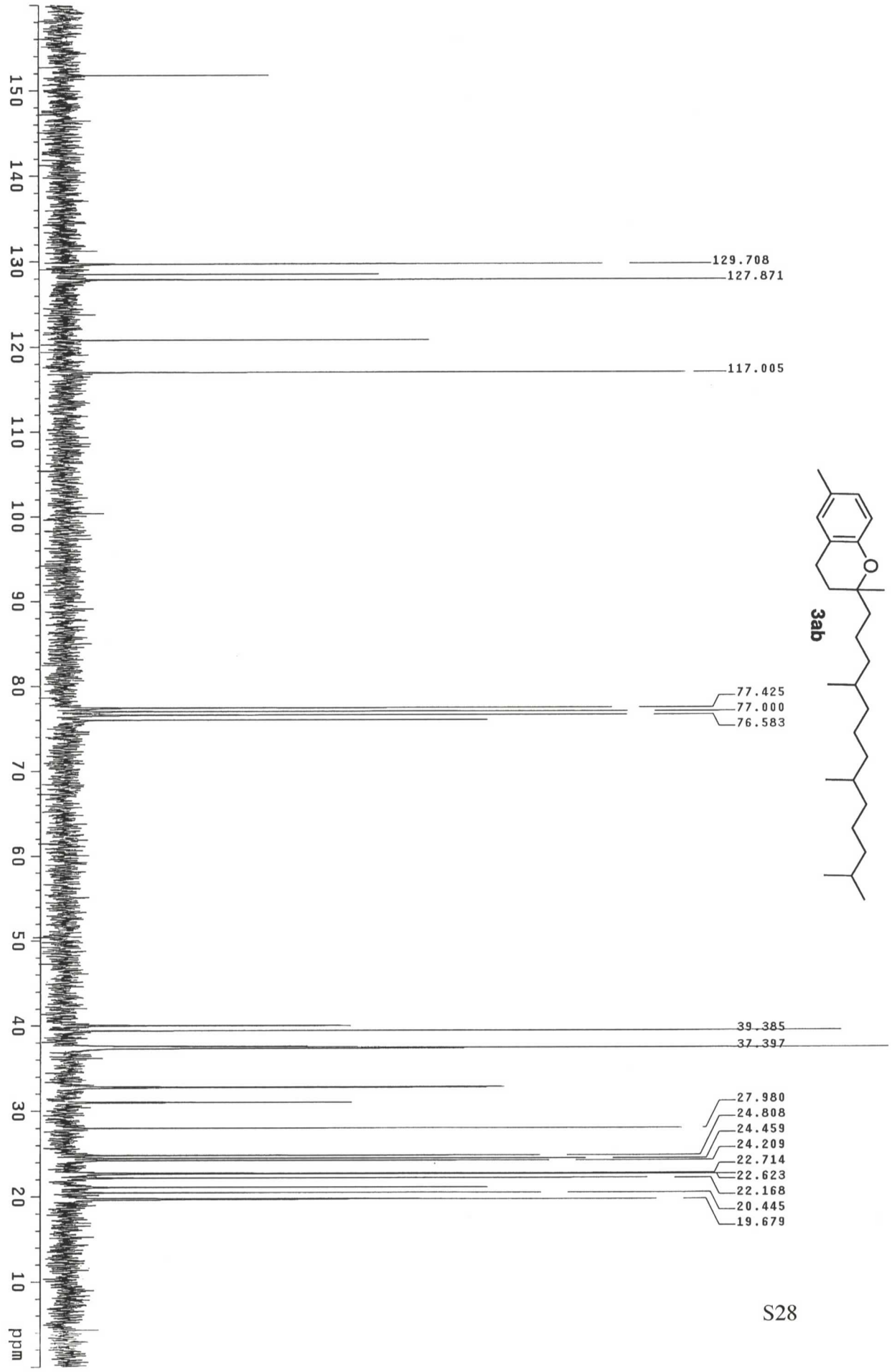
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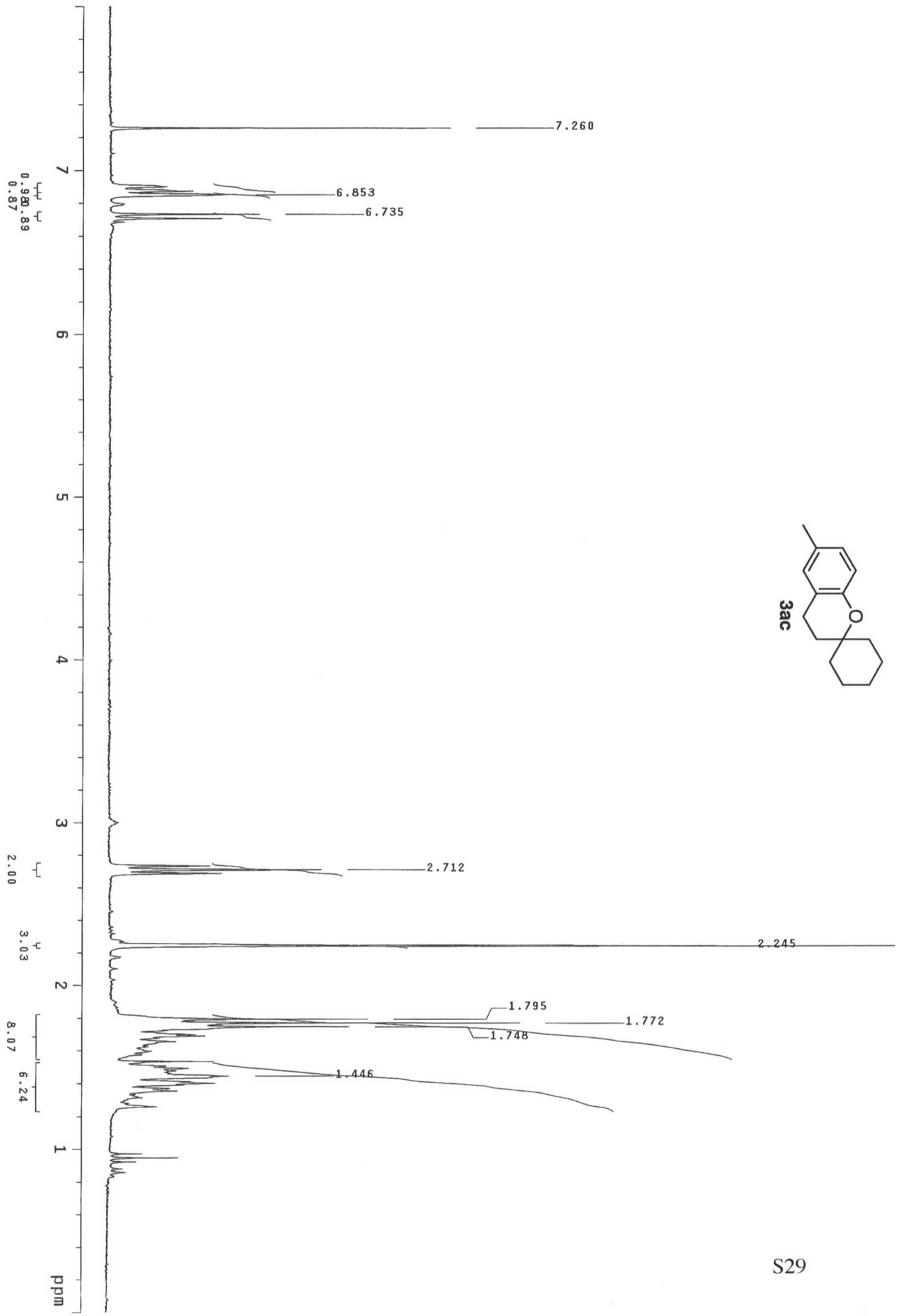
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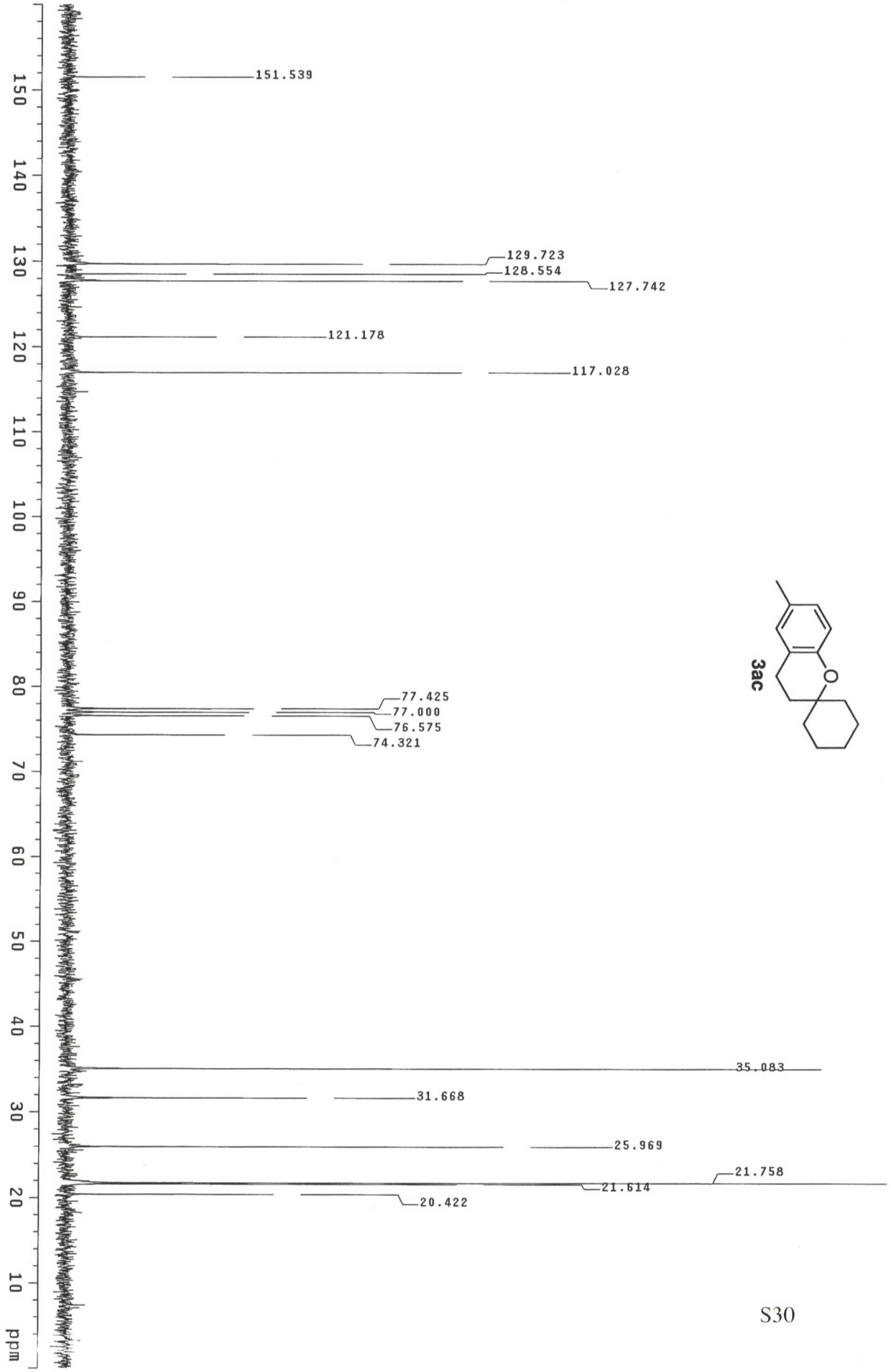
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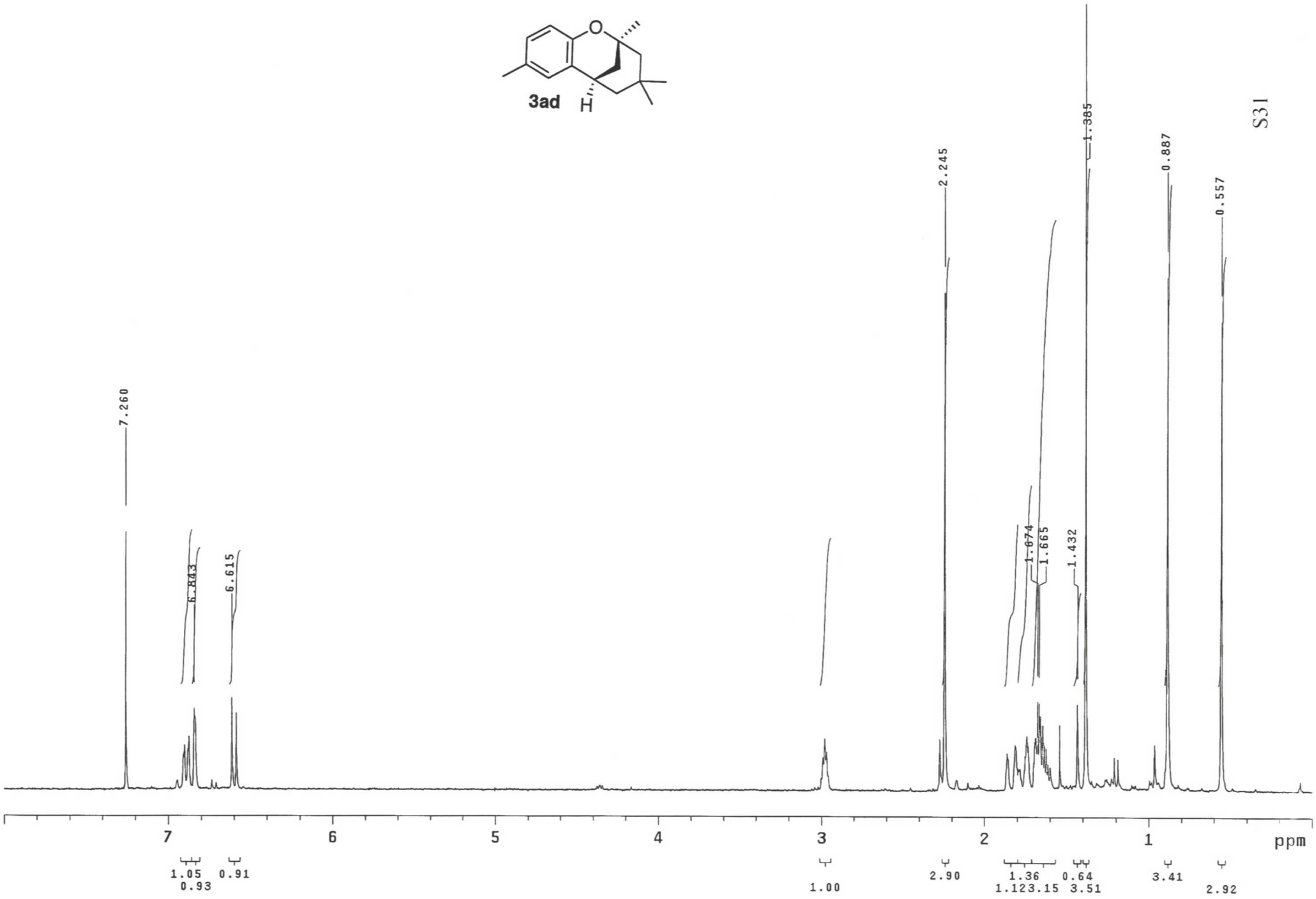
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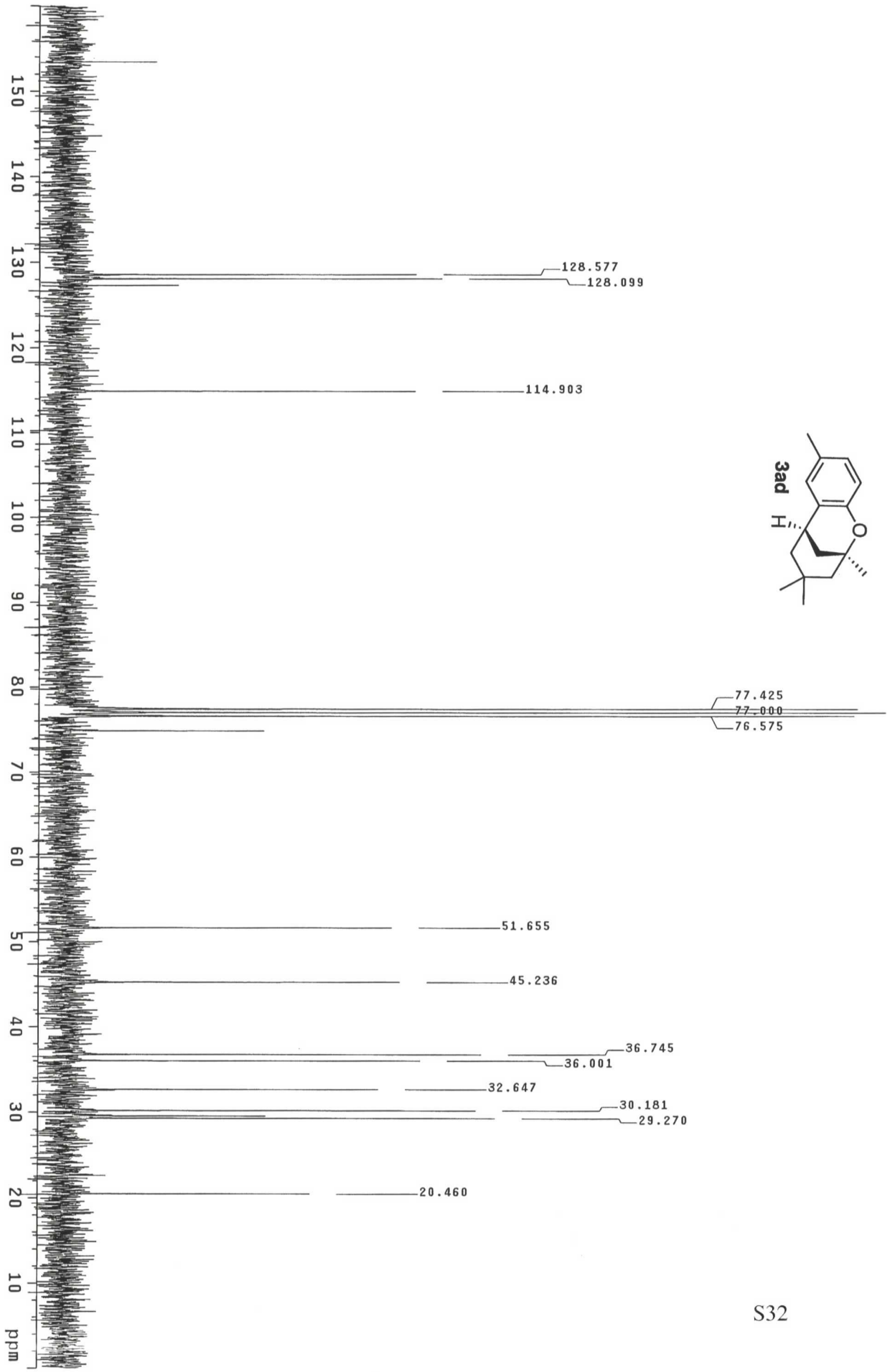
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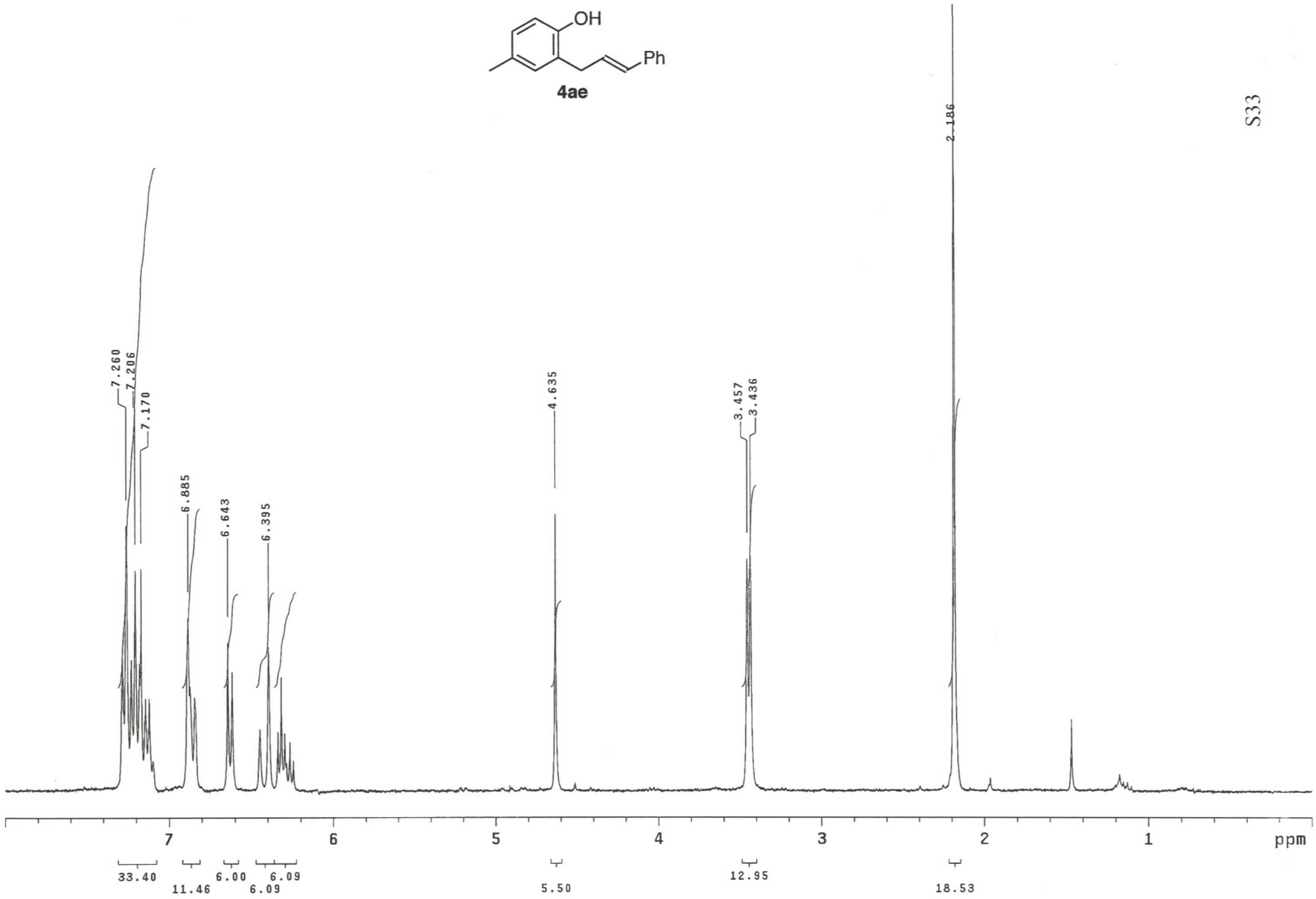
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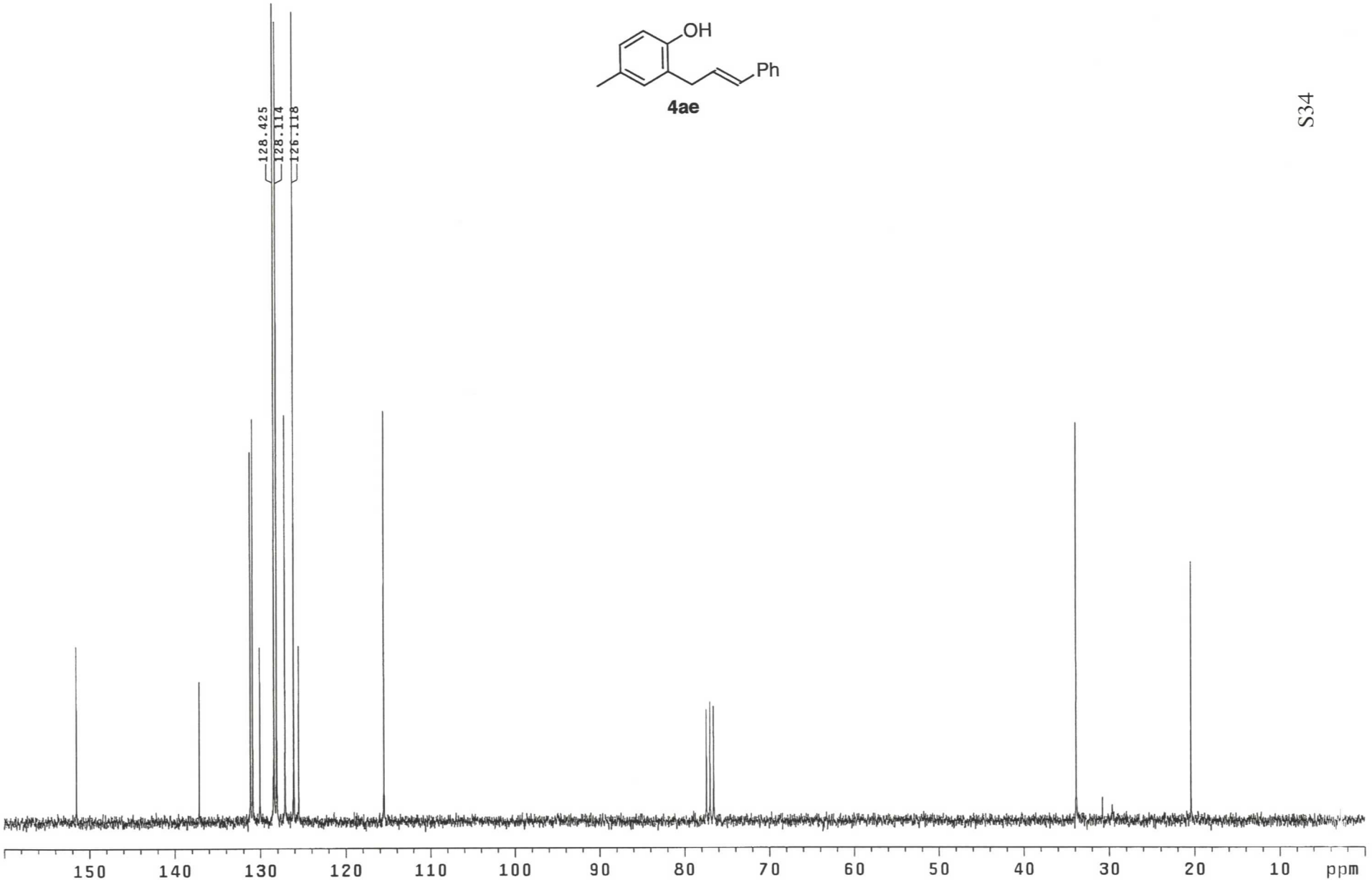
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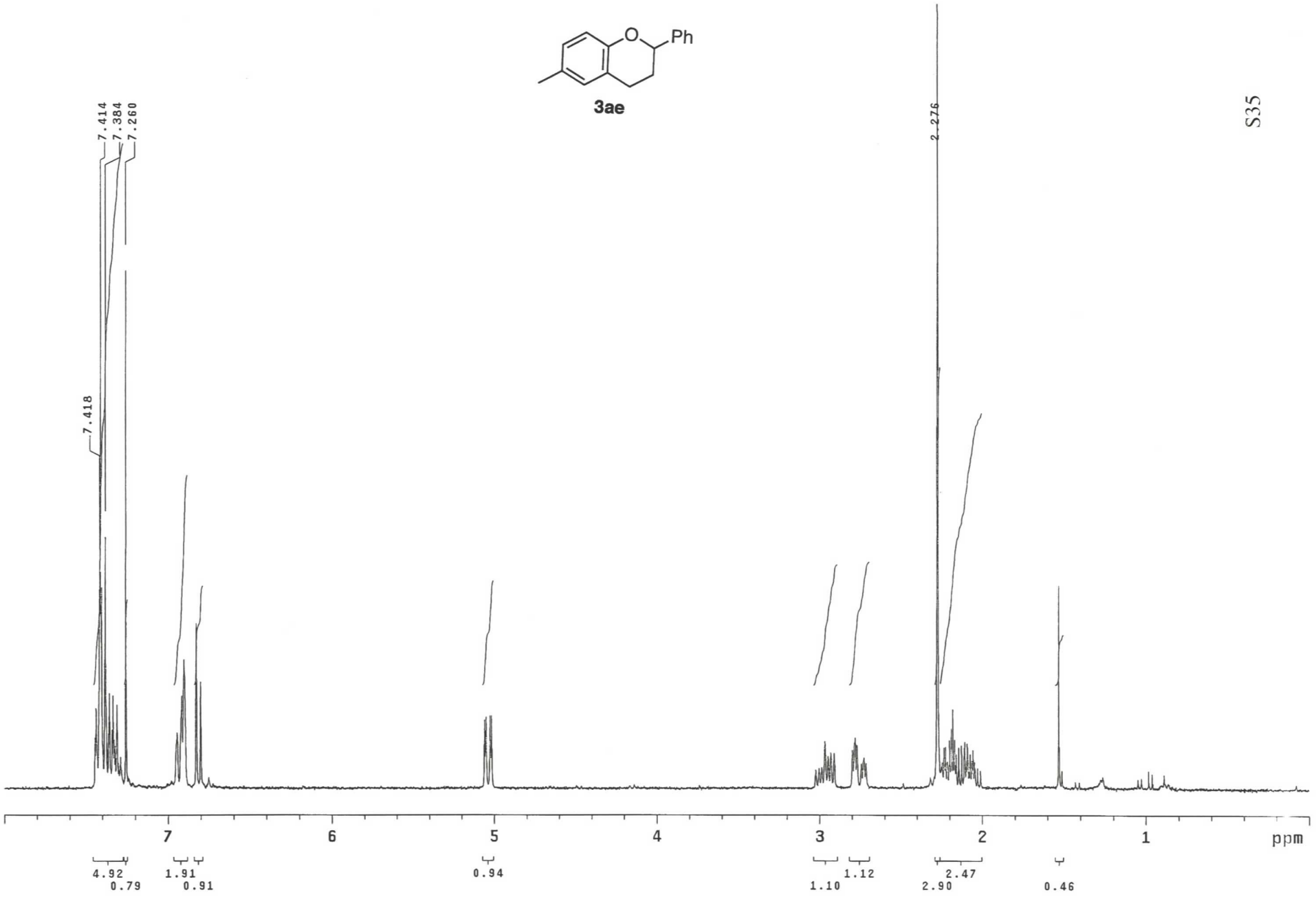
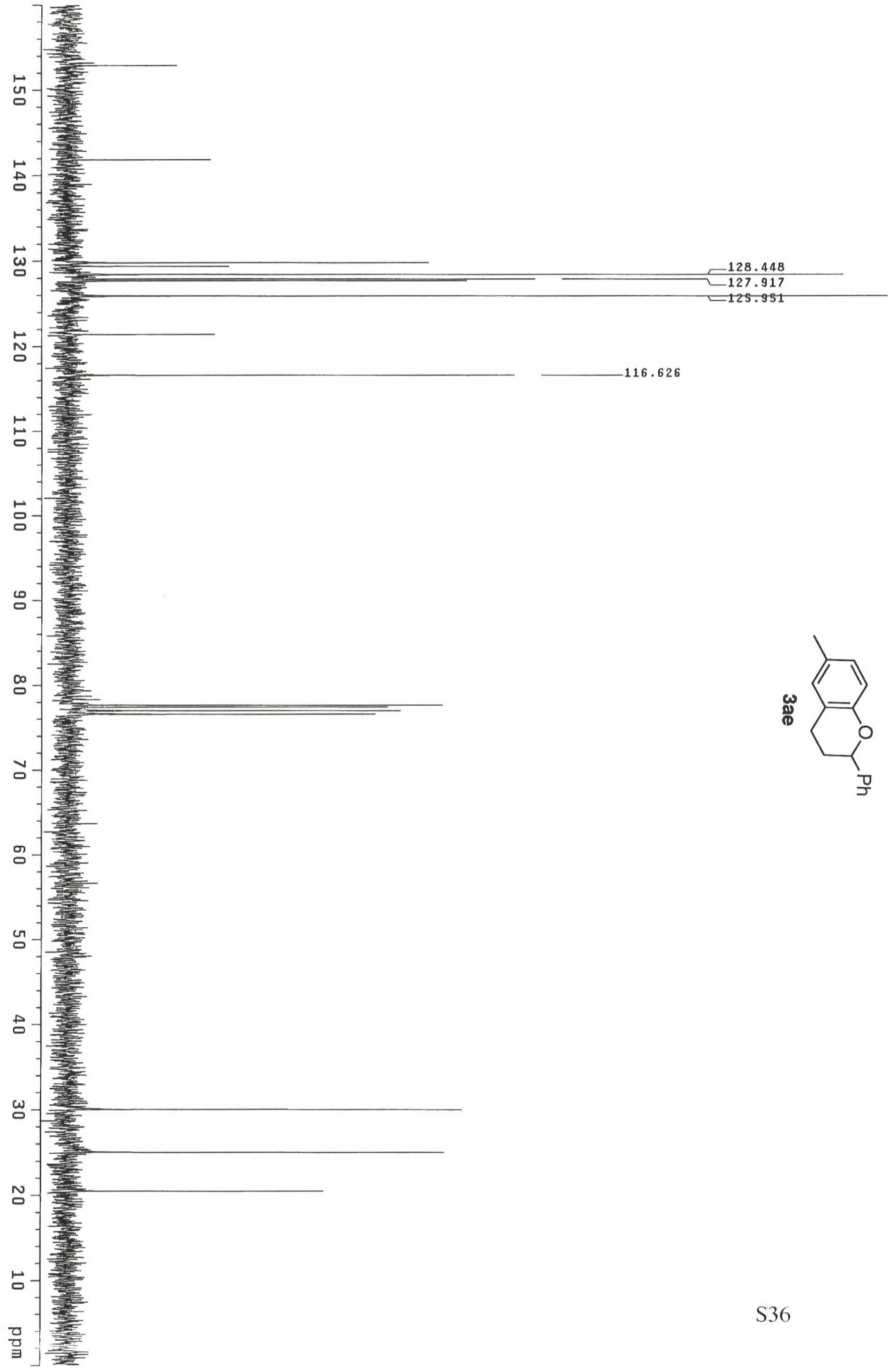
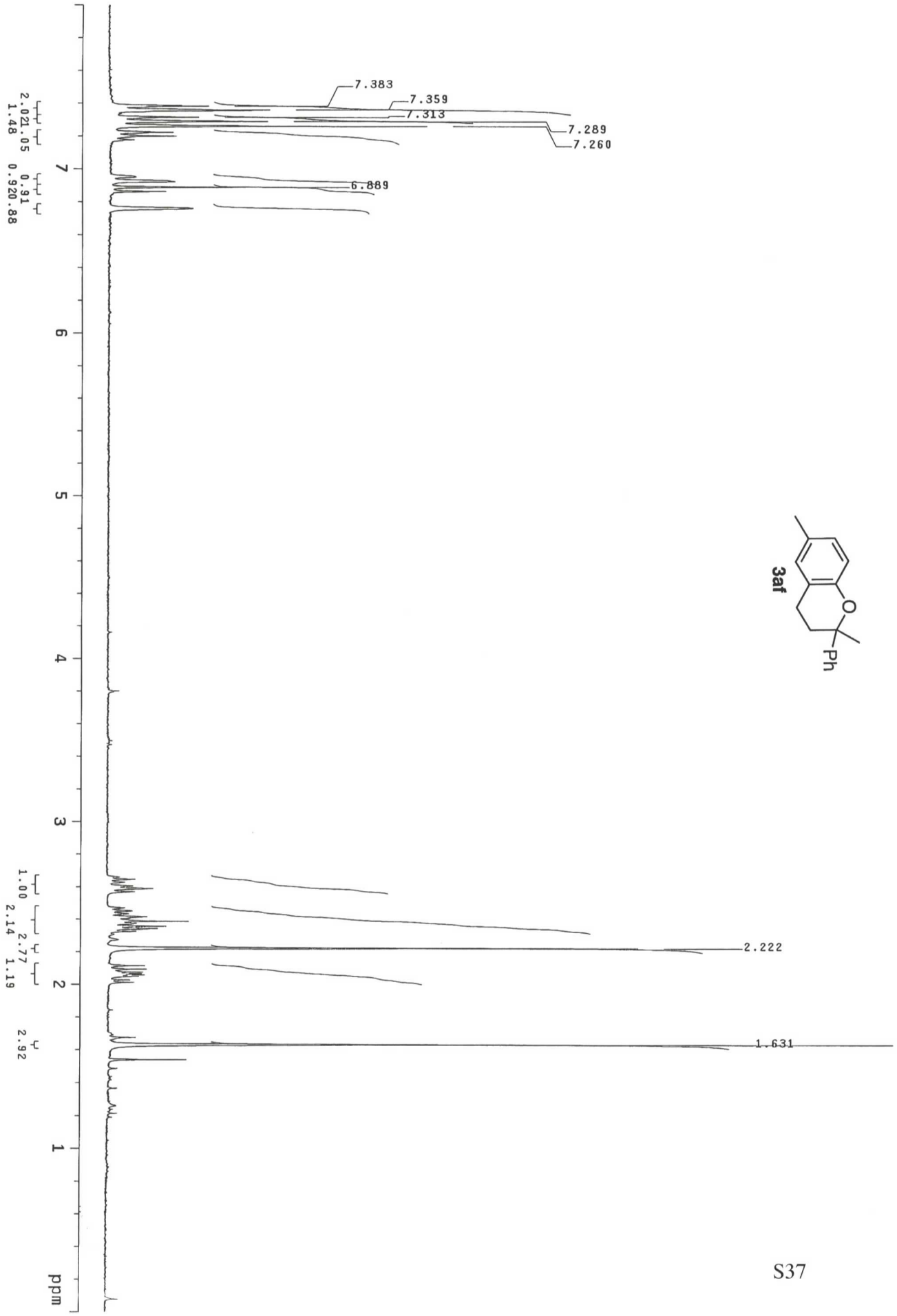
10
ppm

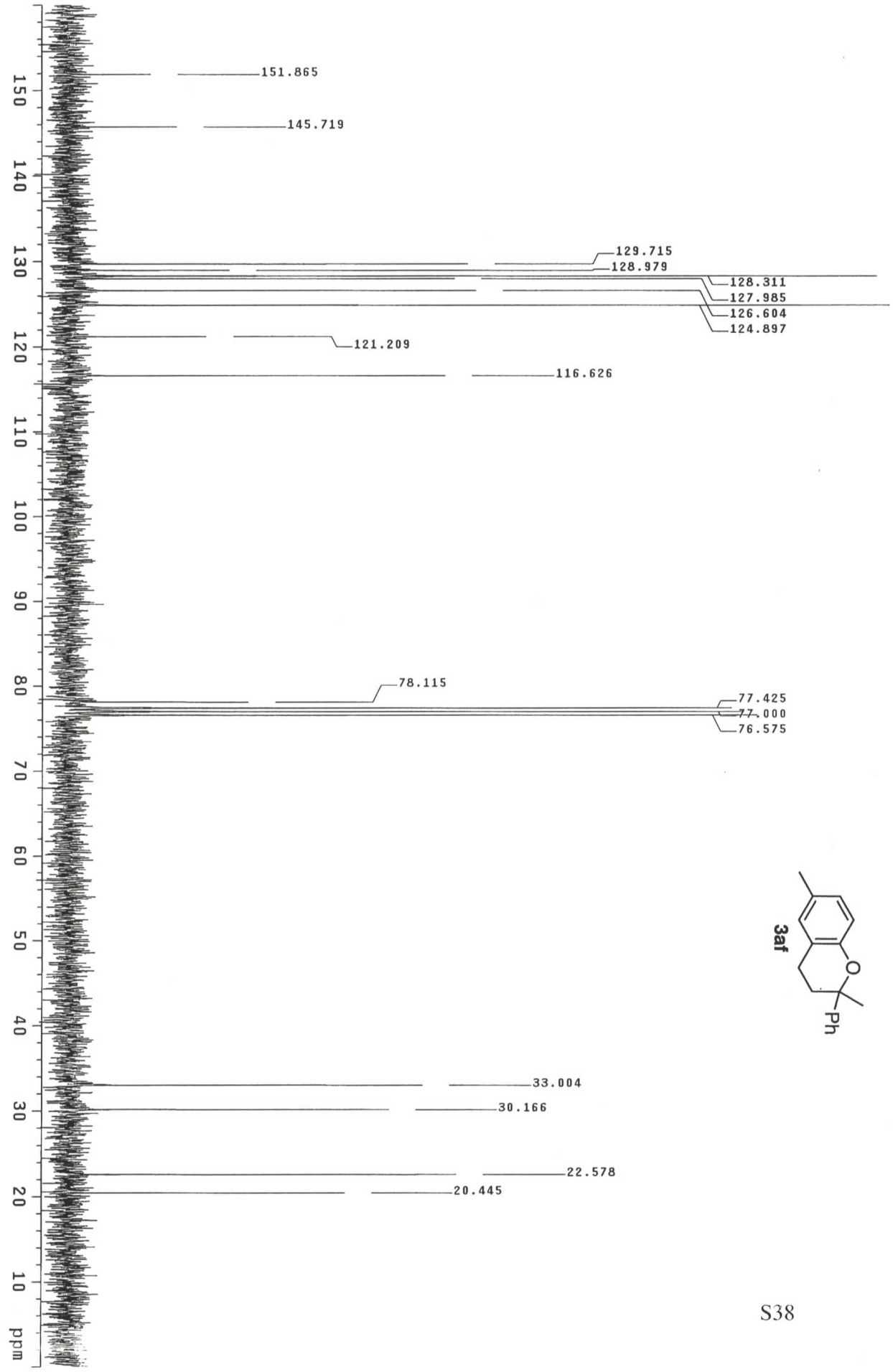

O
Ph
3ae
7.414
7.384
7.260
7.418
2.276
7
6
5
4
3
2
1
ppm
4.92
0.79
1.91
0.91
0.94
1.10
1.12
2.90
2.47
0.46


128.448
127.917
125.951
116.626
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

O
Ph

3ae

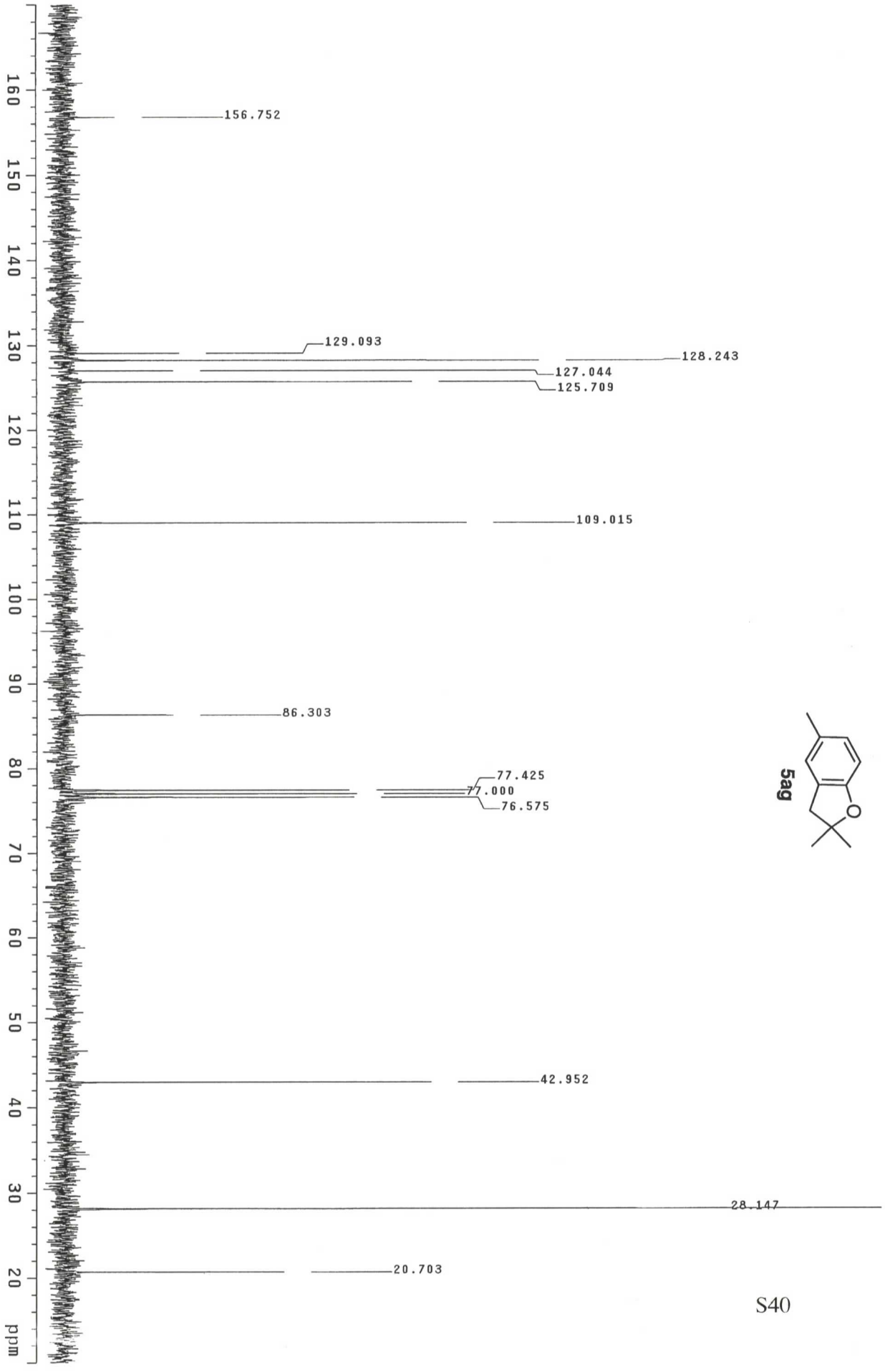

7.383
7.359
7.313
7.289
7.260
6.889
2.222
1.631
3af
O
Ph
ppm


151.865
145.719
129.715
128.979
128.311
127.985
126.604
124.897
121.209
116.626
78.115
77.425
77.000
76.575
33.004
30.166
22.578
20.445
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

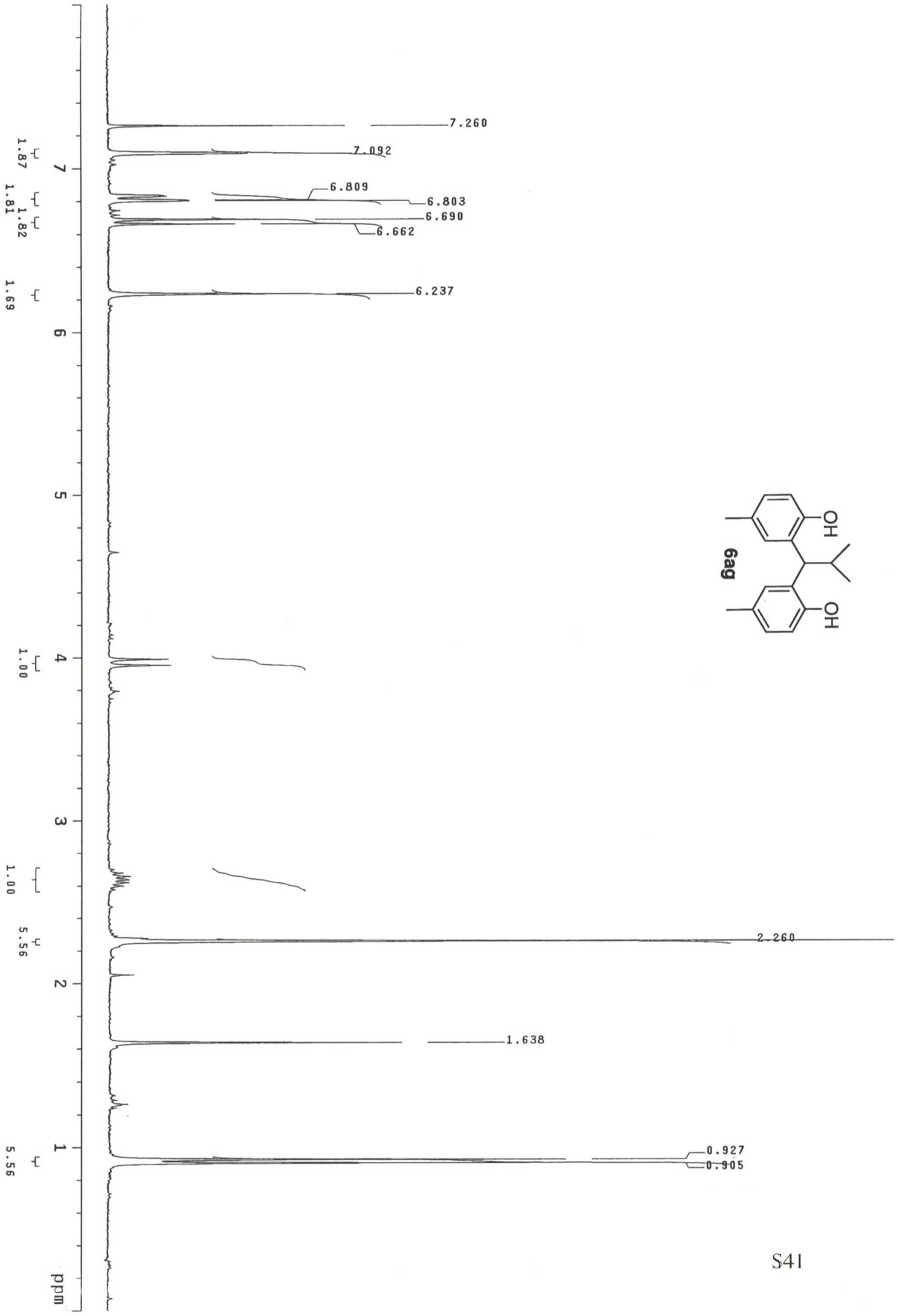
3af
O
Ph

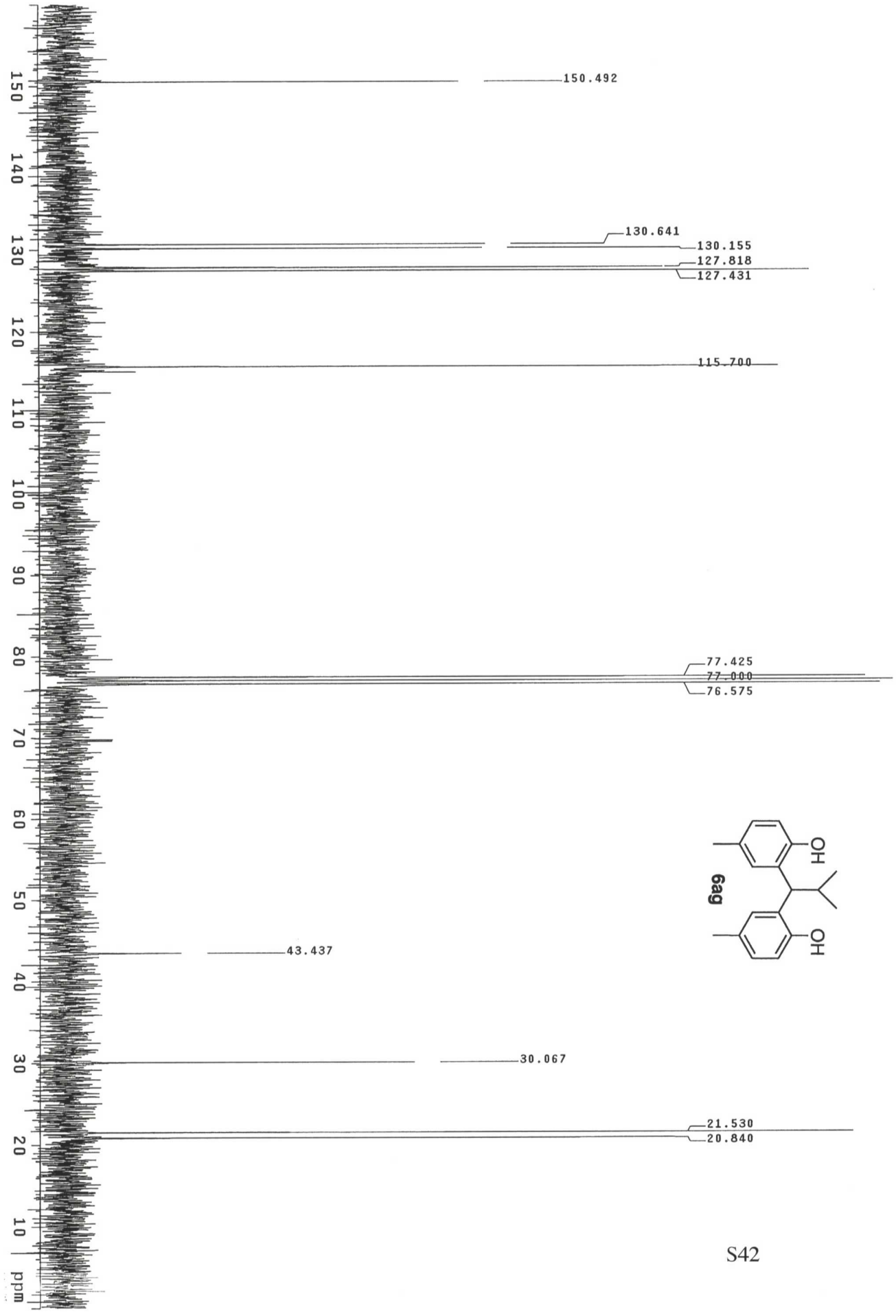
7.260
6.950
6.917
6.889
6.636
6.608
2.973
2.270
1.536
1.461
0.91
0.98
0.90
2.00
3.08
6.11
ppm

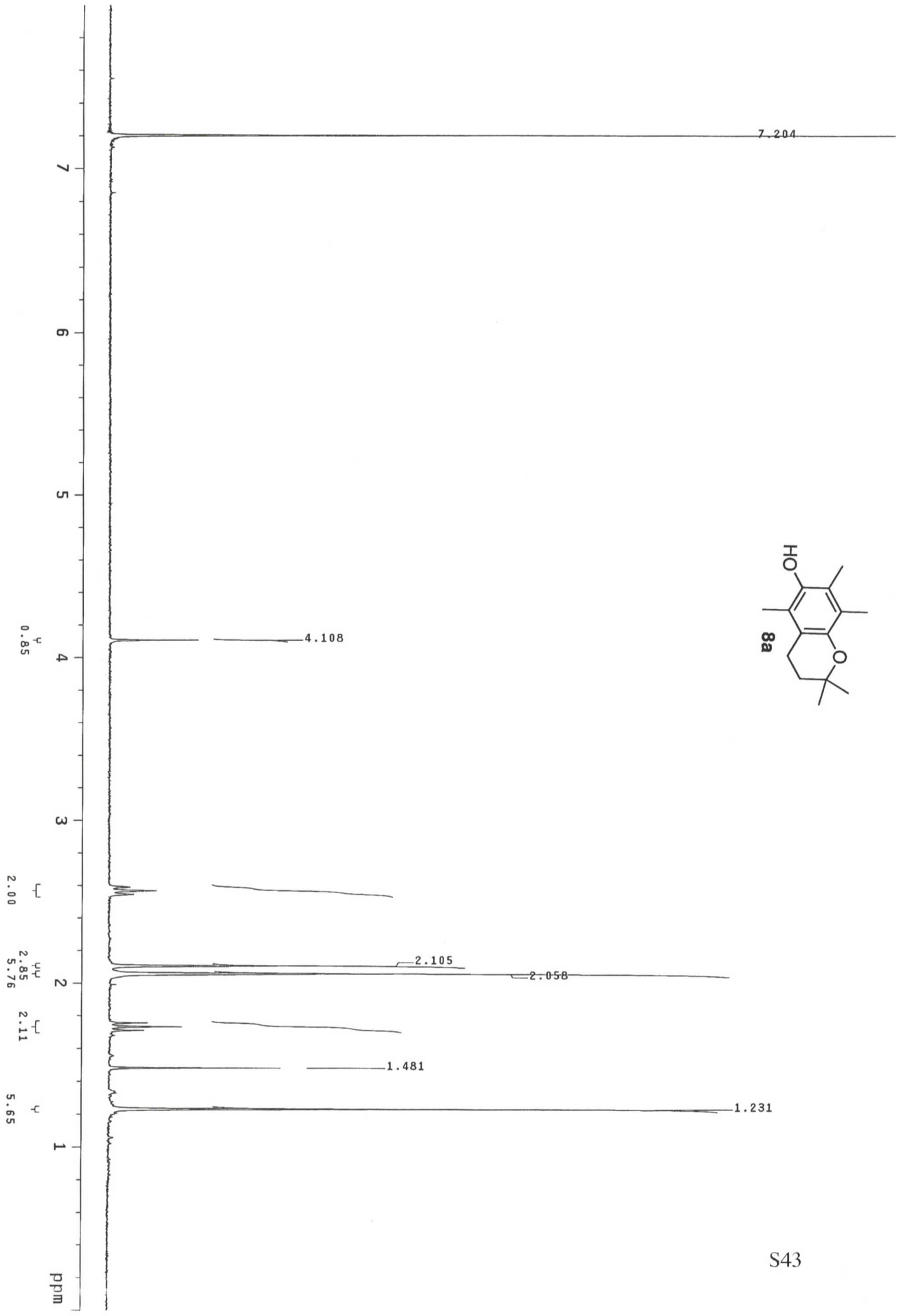
5ag
O

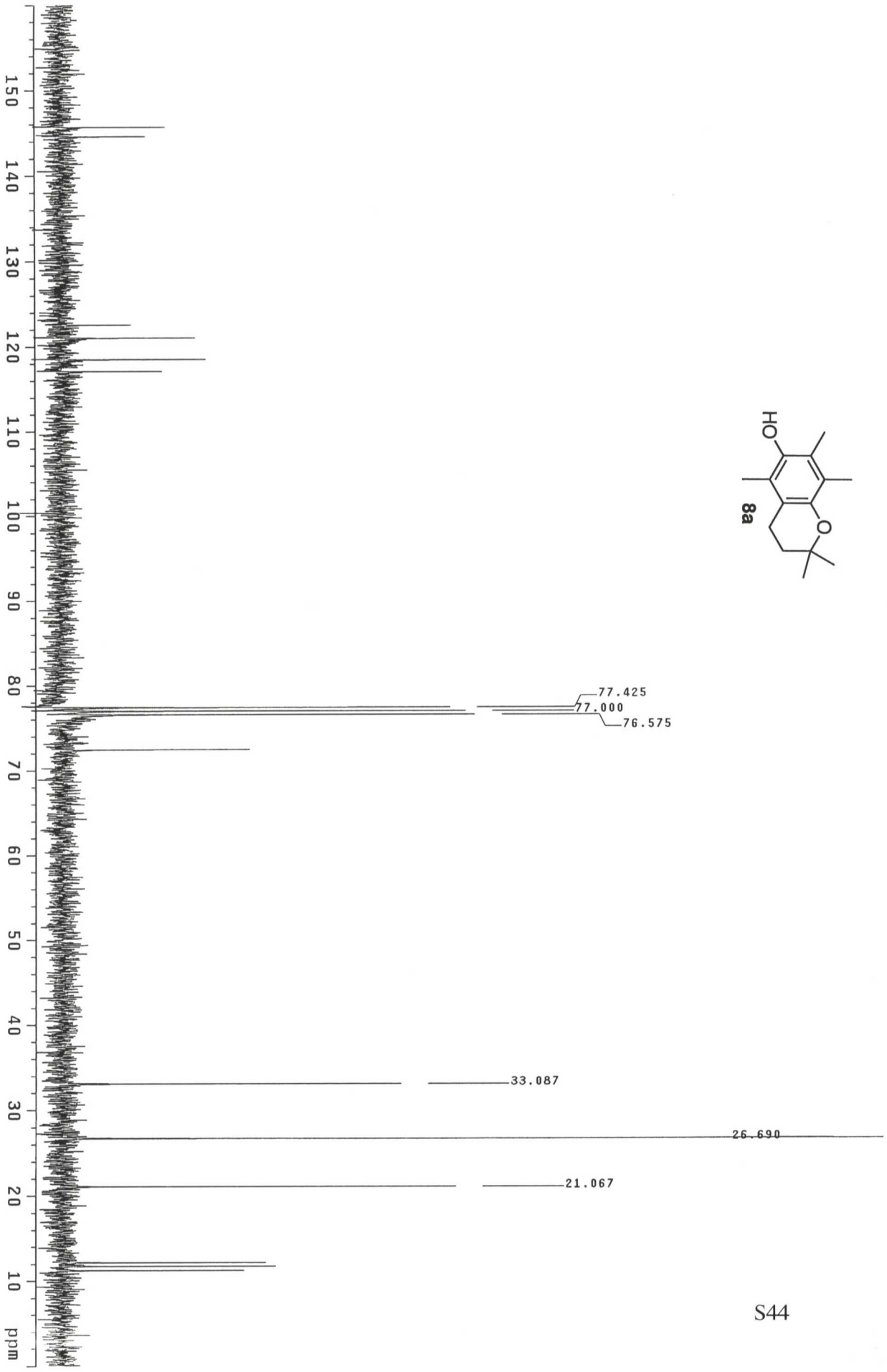

156.752
129.093
128.243
127.044
125.709
109.015
86.303
77.425
77.000
76.575
42.952
28.147
20.703
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
ppm

5ag

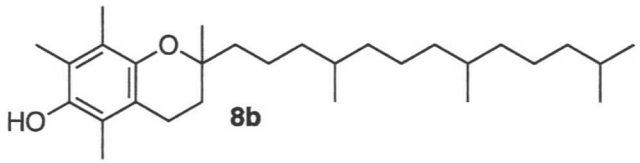

7.260
7.092
6.809
6.803
6.690
6.662
6.237
2.260
1.638
0.927
0.905
1.87
1.81
1.82
1.69
1.00
1.00
5.56
5.56
ppm
OH
OH
6ag


150.492
130.641
130.155
127.818
127.431
115.700
77.425
77.000
76.575
43.437
30.067
21.530
20.840
OH
OH
6ag
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


7.204
4.108
2.105
2.058
1.481
1.231
HO
O
8a
ppm
0.85
2.00
2.85
5.76
2.11
5.65

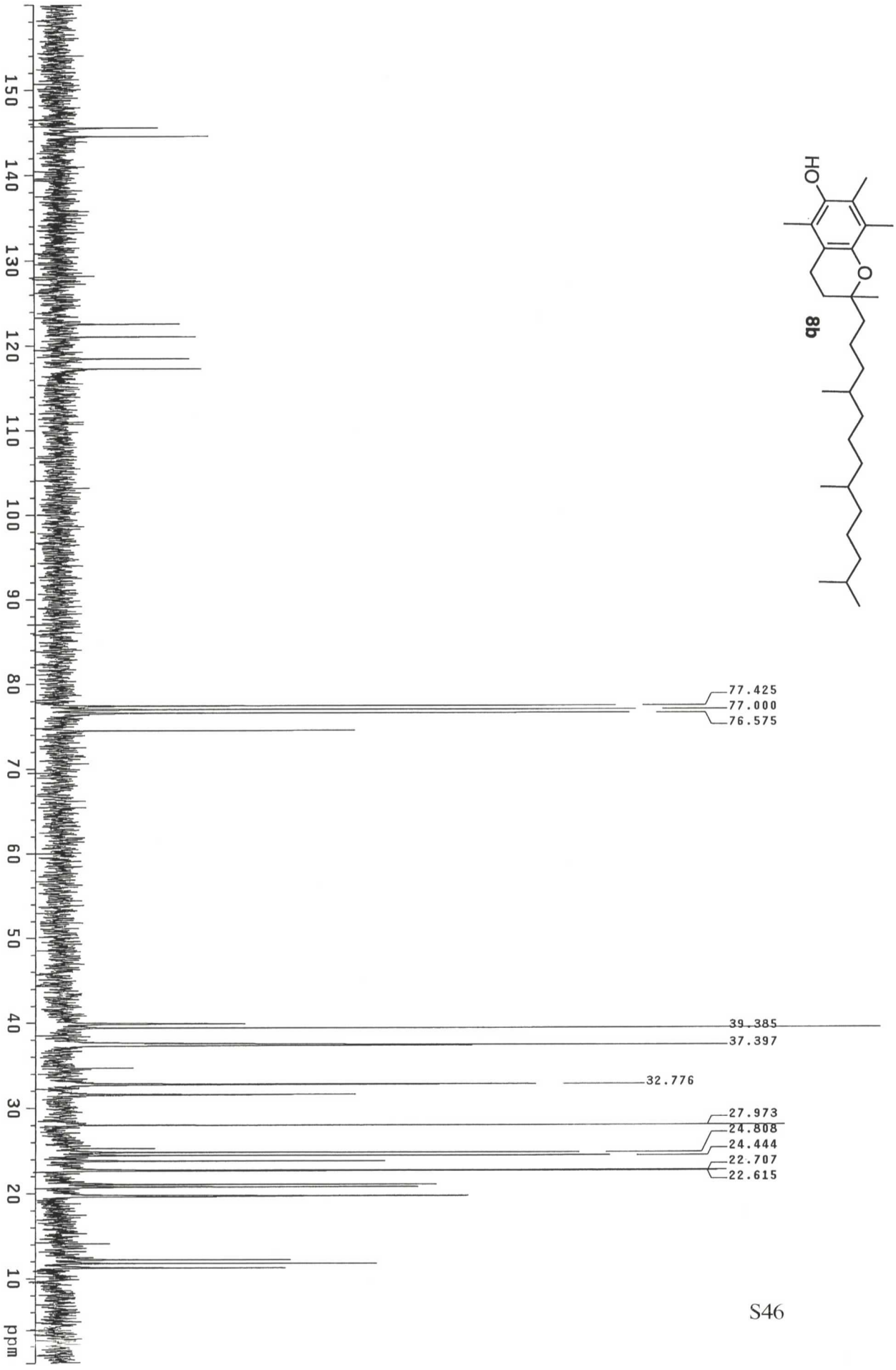


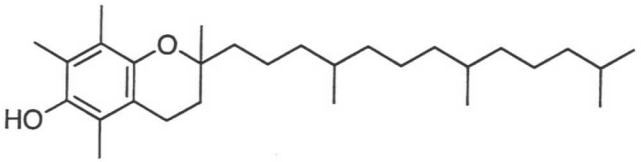
8a


HO
O

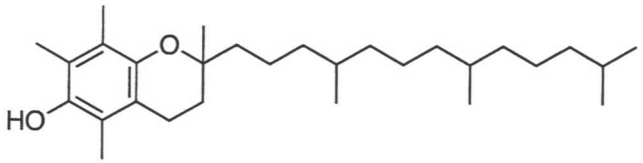
8b

7.260
2.159
2.110
1.550
1.227
0.878
0.856
0.838
0.831
7
6
5
4
3
2
1
ppm
0.79
2.00
3.33
6.54
2.41
33.59
14.30

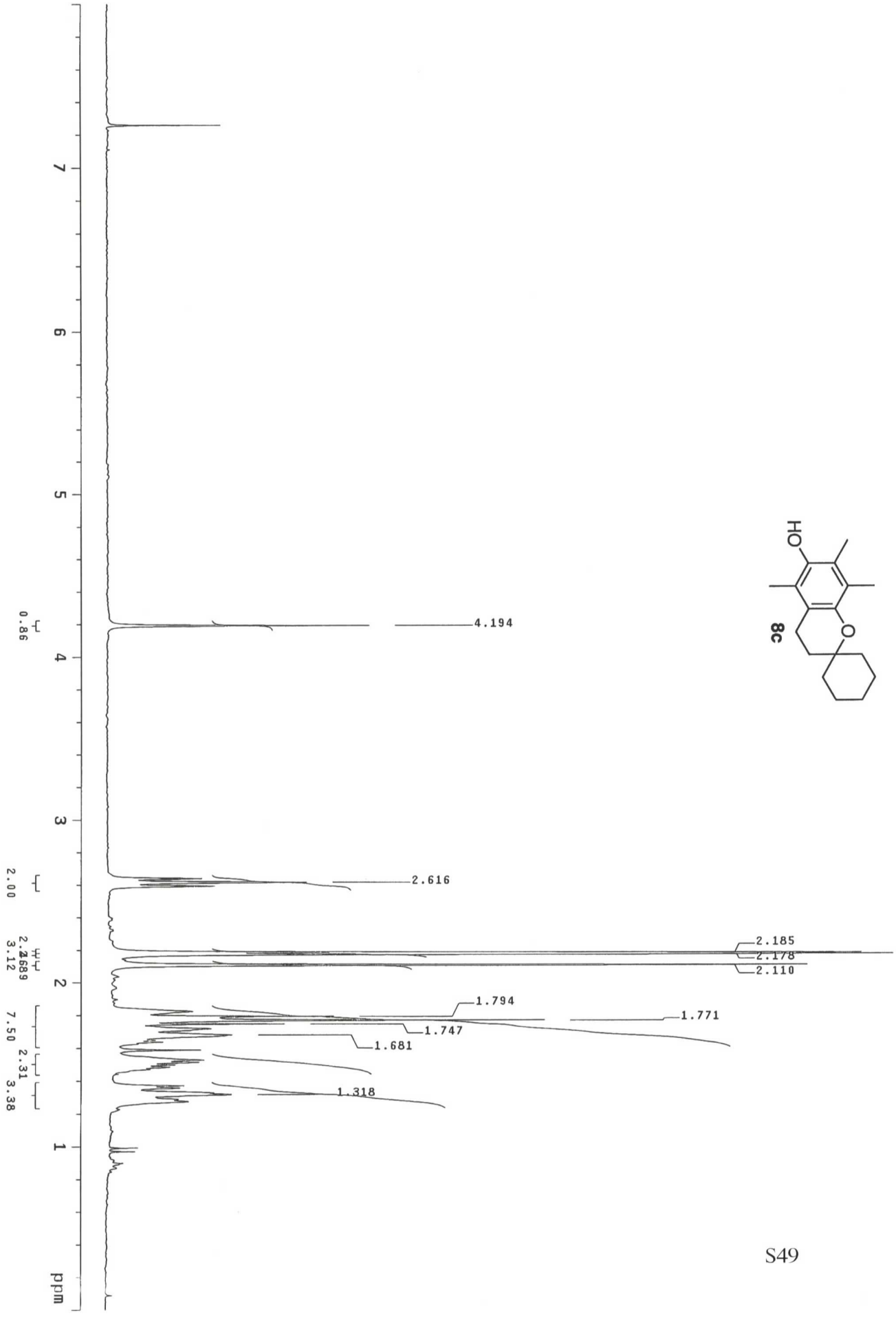

HO
O
8b
77.425
77.000
76.575
39.385
37.397
32.776
27.973
24.808
24.444
22.707
22.615
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

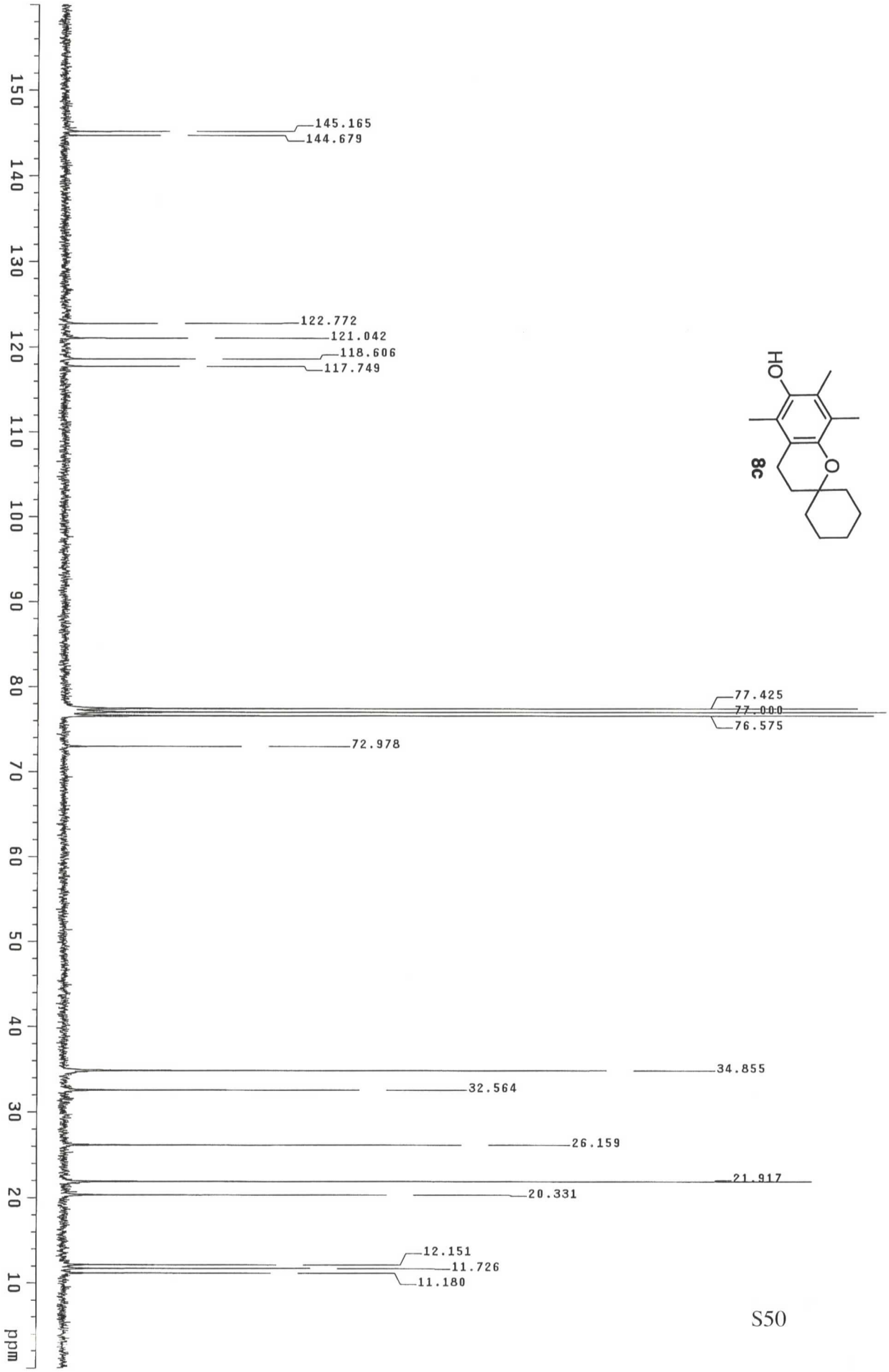


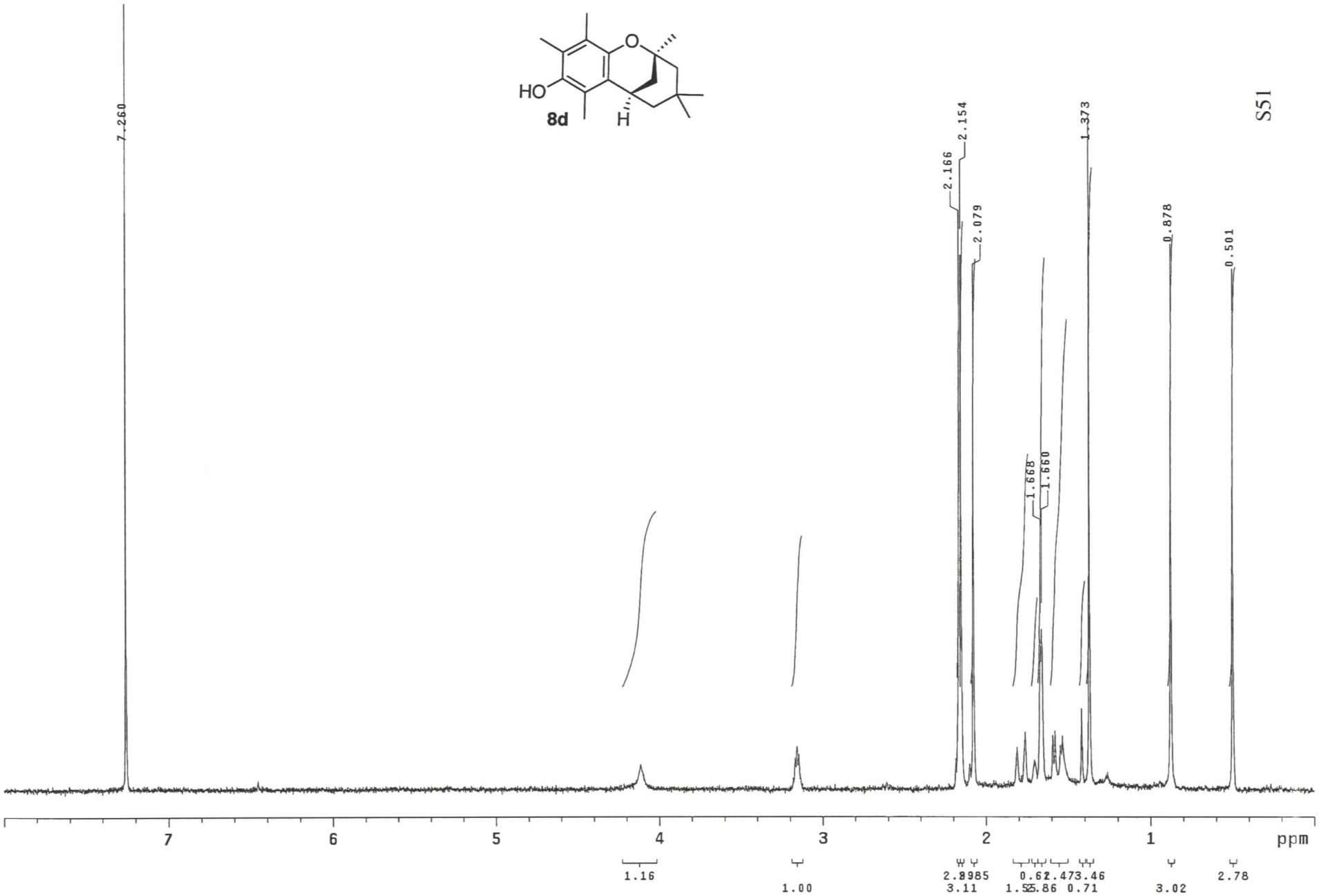
DL-α-tochopherol, purity >98%
Wako Pure Chemical Industries (cat. No. 209-01791)

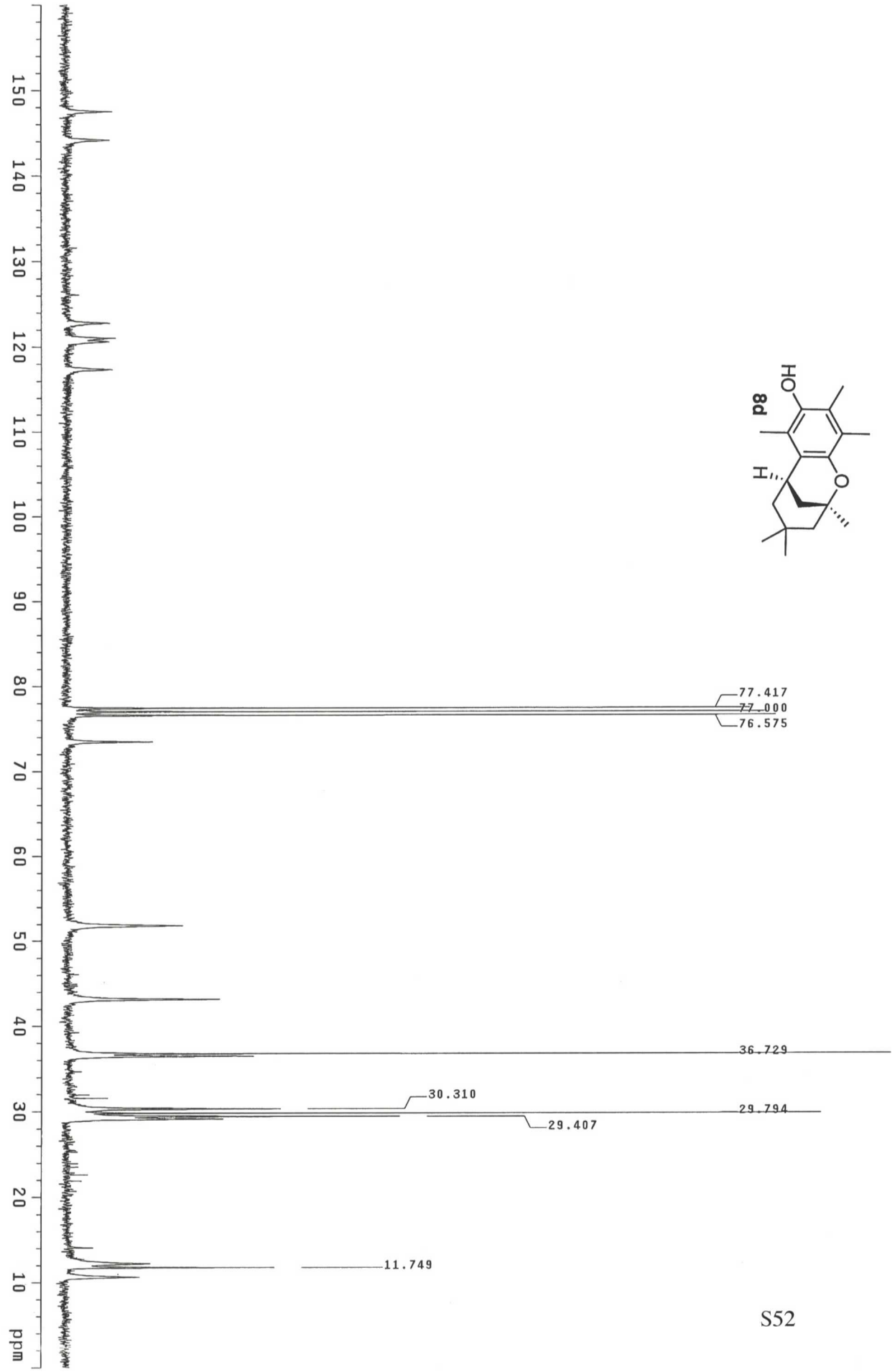


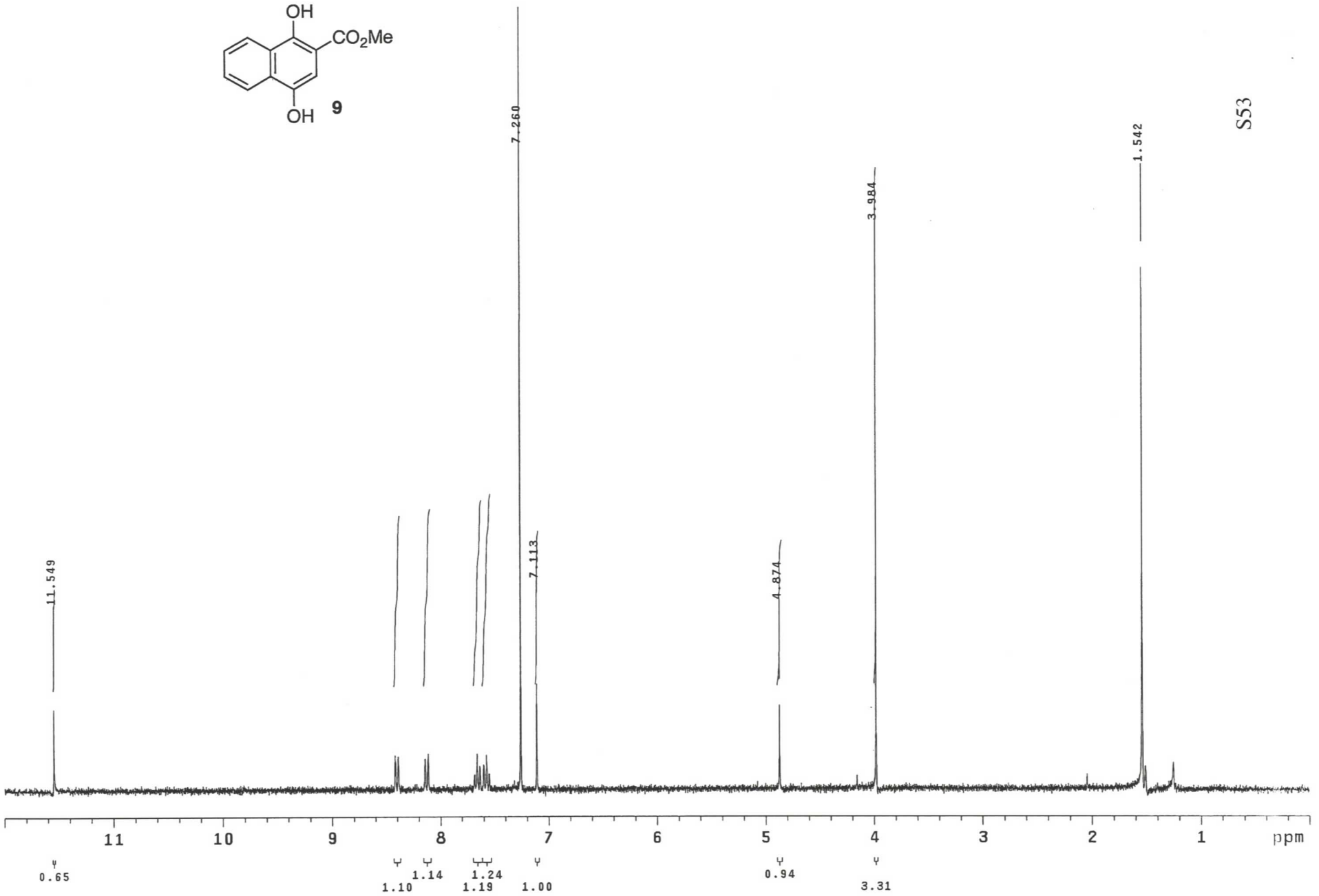
DL-α-tochopherol, purity >98%
Wako Pure Chemical Industries (cat. No. 209-01791)

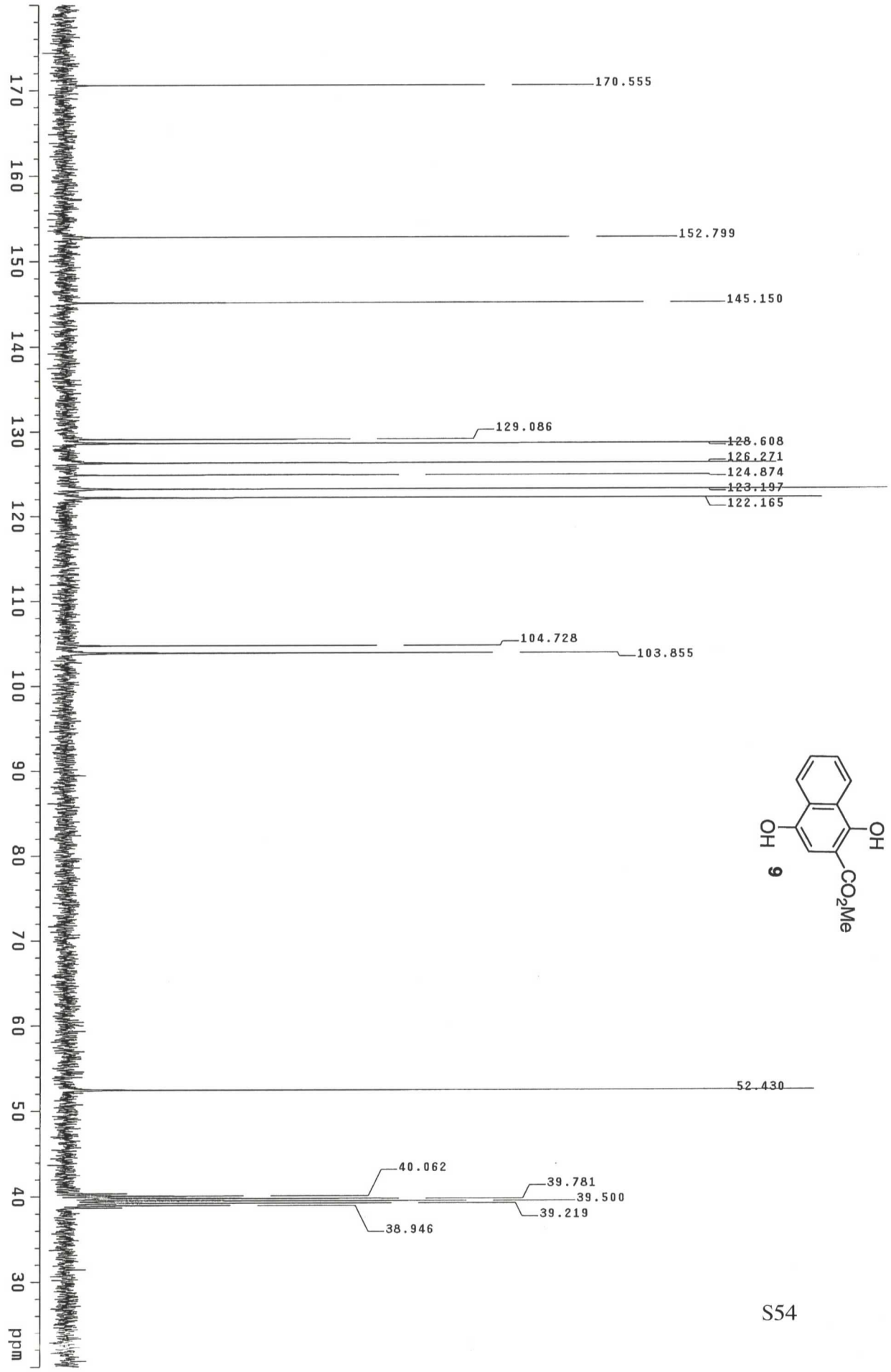

4.194
2.616
2.185
2.178
2.110
1.794
1.771
1.747
1.681
1.318
HO
O
8c
ppm


145.165
144.679
122.772
121.042
118.606
117.749
77.425
77.000
76.575
72.978
34.855
32.564
26.159
21.917
20.331
12.151
11.726
11.180
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm
HO
O
8c

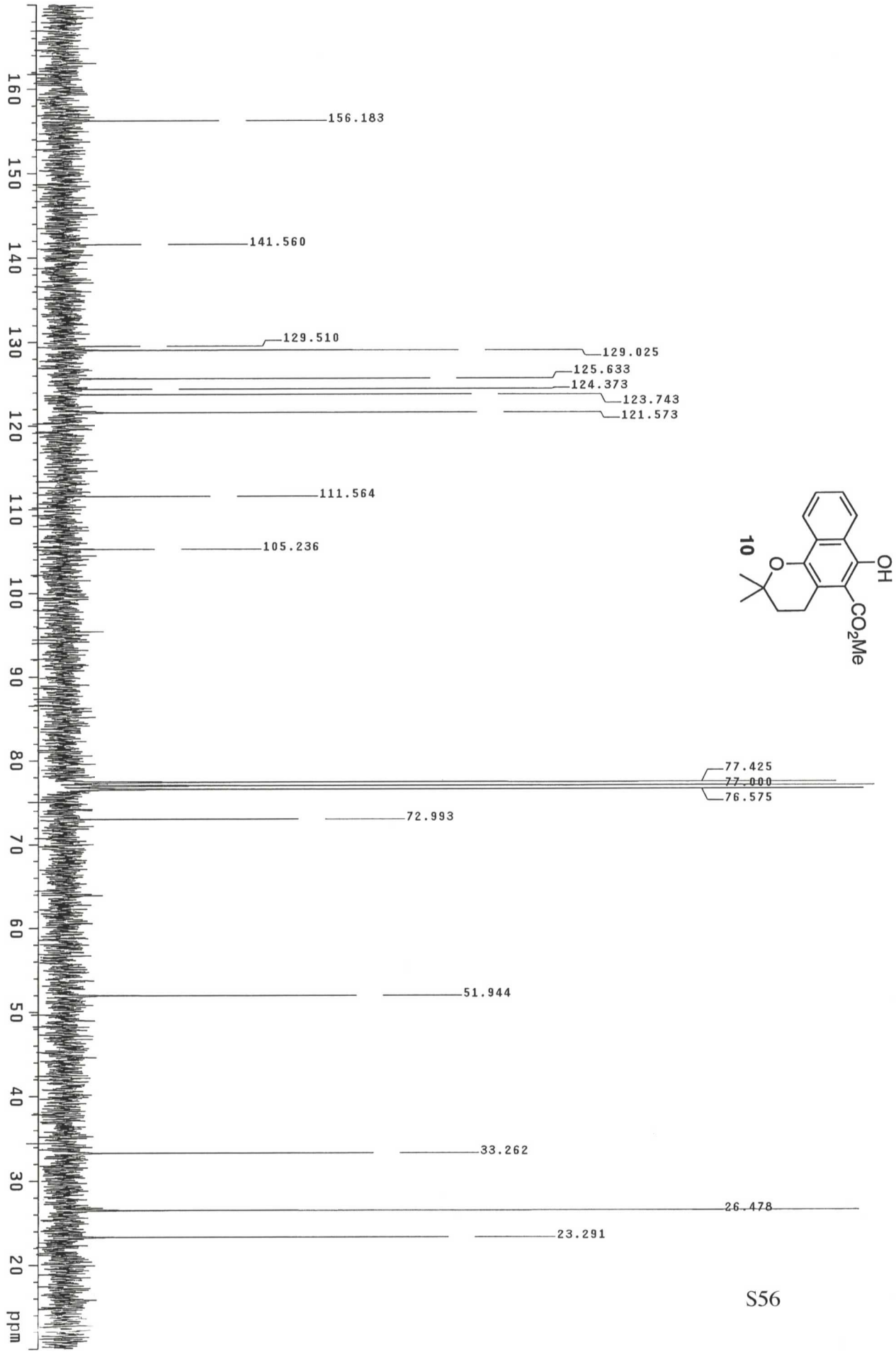

HO
O
H
8d
7.260
2.166
2.154
2.079
1.668
1.660
1.373
0.878
0.501
7
6
5
4
3
2
1
ppm
1.16
1.00
2.89
3.11
0.62
1.55
2.47
5.86
3.46
0.71
3.02
2.78

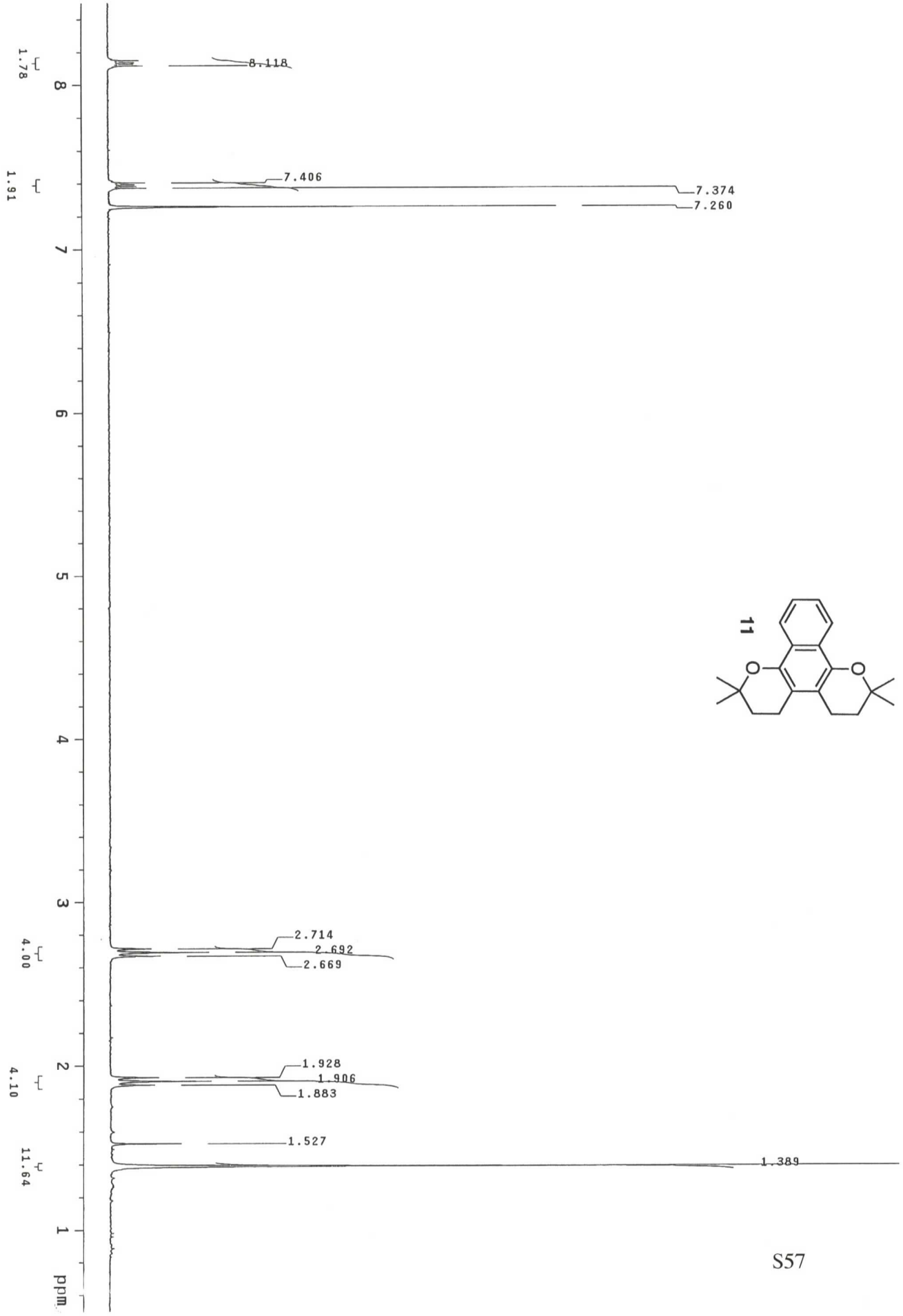

8d
OH
H
O
77.417
77.000
76.575
36.729
30.310
29.794
29.407
11.749
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


OH
CO2Me
OH
9
11.549
7.260
7.113
4.874
3.984
1.542
11
10
9
8
7
6
5
4
3
2
1
ppm
0.65
1.10
1.14
1.19
1.24
1.00
0.94
3.31

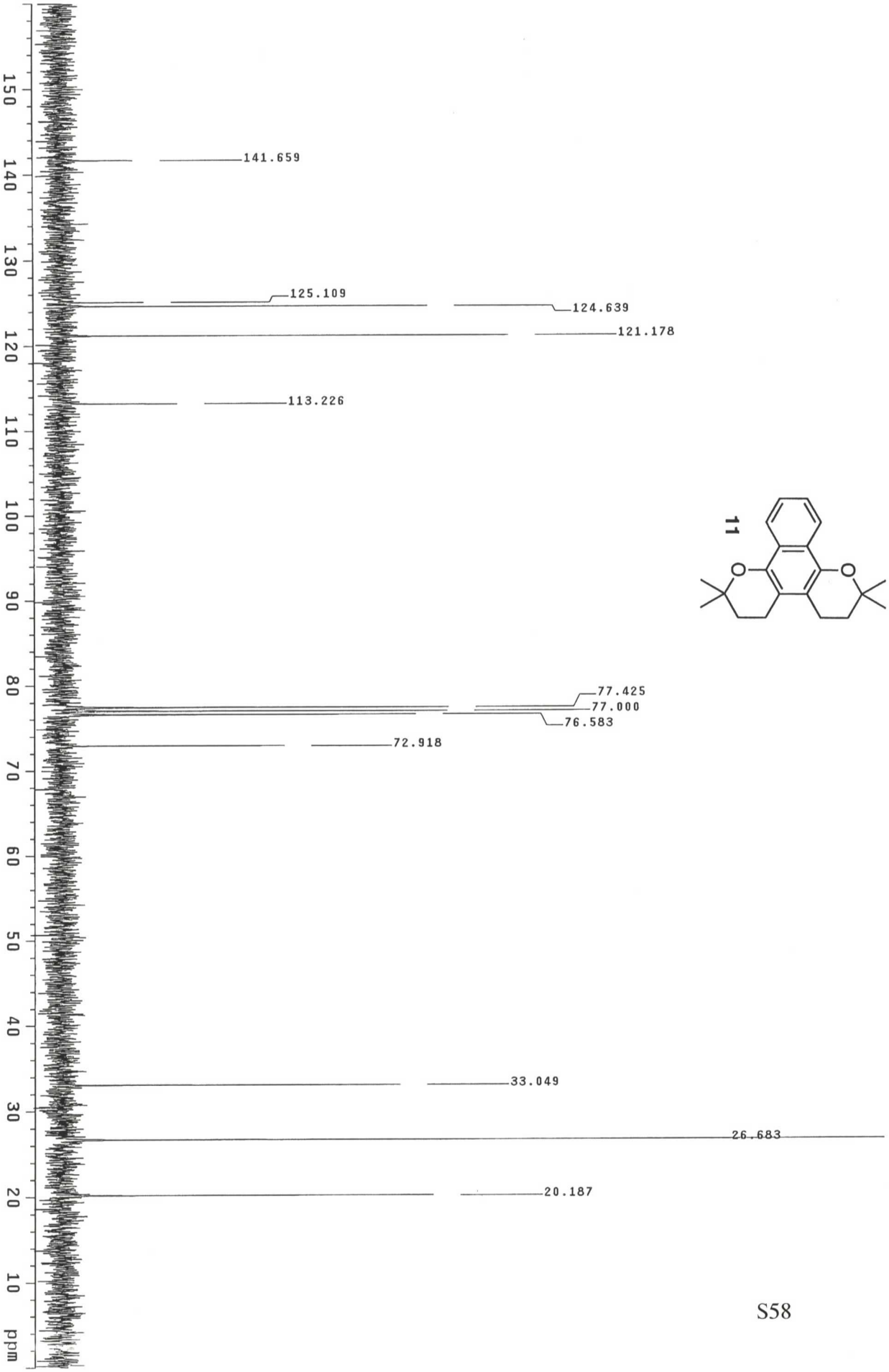

170.555
152.799
145.150
129.086
128.608
126.271
124.874
123.197
122.165
104.728
103.855
52.430
40.062
39.781
39.500
39.219
38.946
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
ppm
OH
OH
CO2Me
9

12.164
3.993
3.061
1.834
1.408
0.53
0.89
0.87
0.98
0.94
2.91
2.00
2.06
5.59
ppm
10
OH
CO2Me


156.183
141.560
129.510
129.025
125.633
124.373
123.743
121.573
111.564
105.236
77.425
77.000
76.575
72.993
51.944
33.262
26.478
23.291
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
ppm
10
O
OH
CO2Me

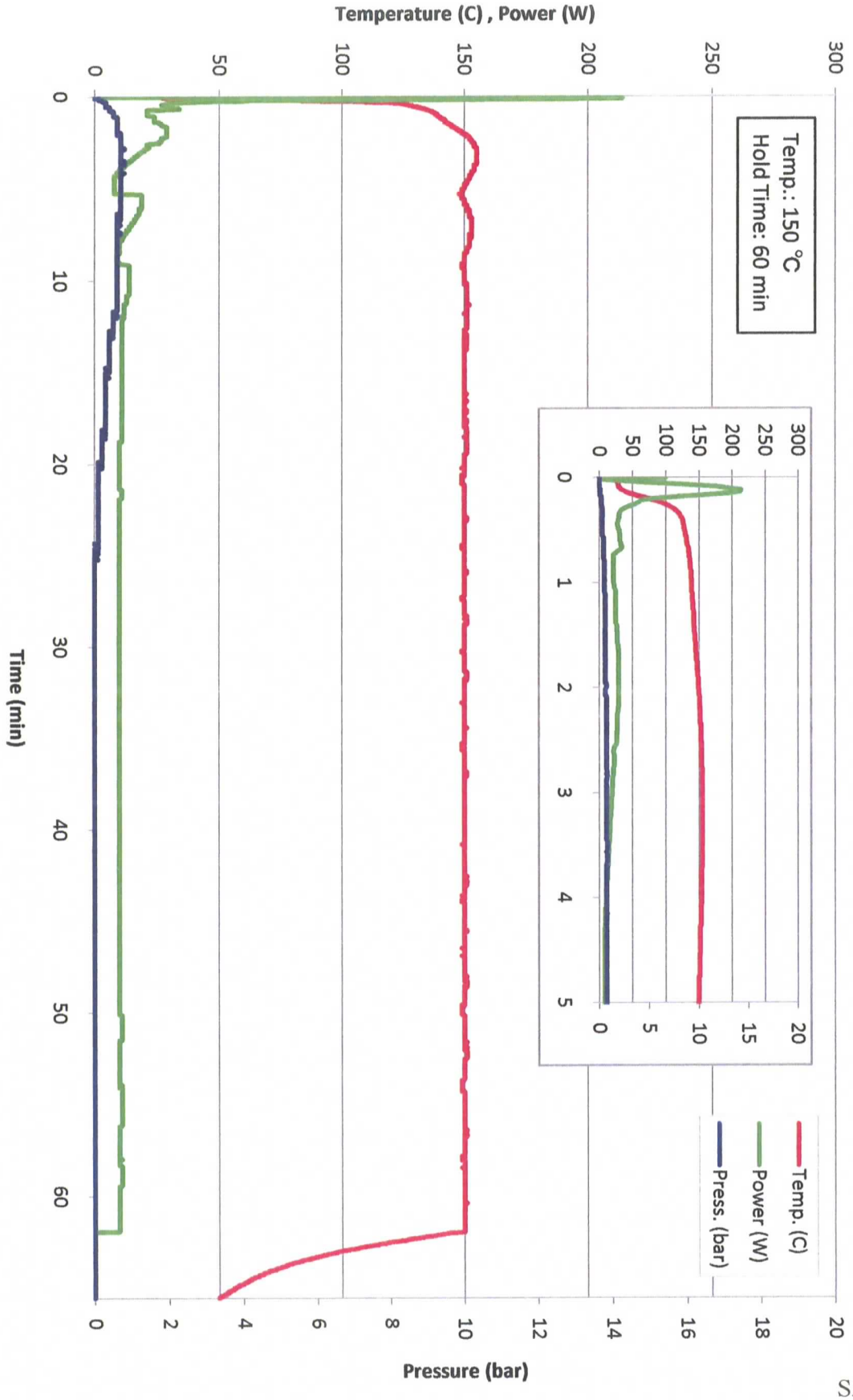

8.118
7.406
7.374
7.260
2.714
2.692
2.669
1.928
1.906
1.883
1.527
1.389
1.78
1.91
4.00
4.10
11.64
ppm

11
O
O

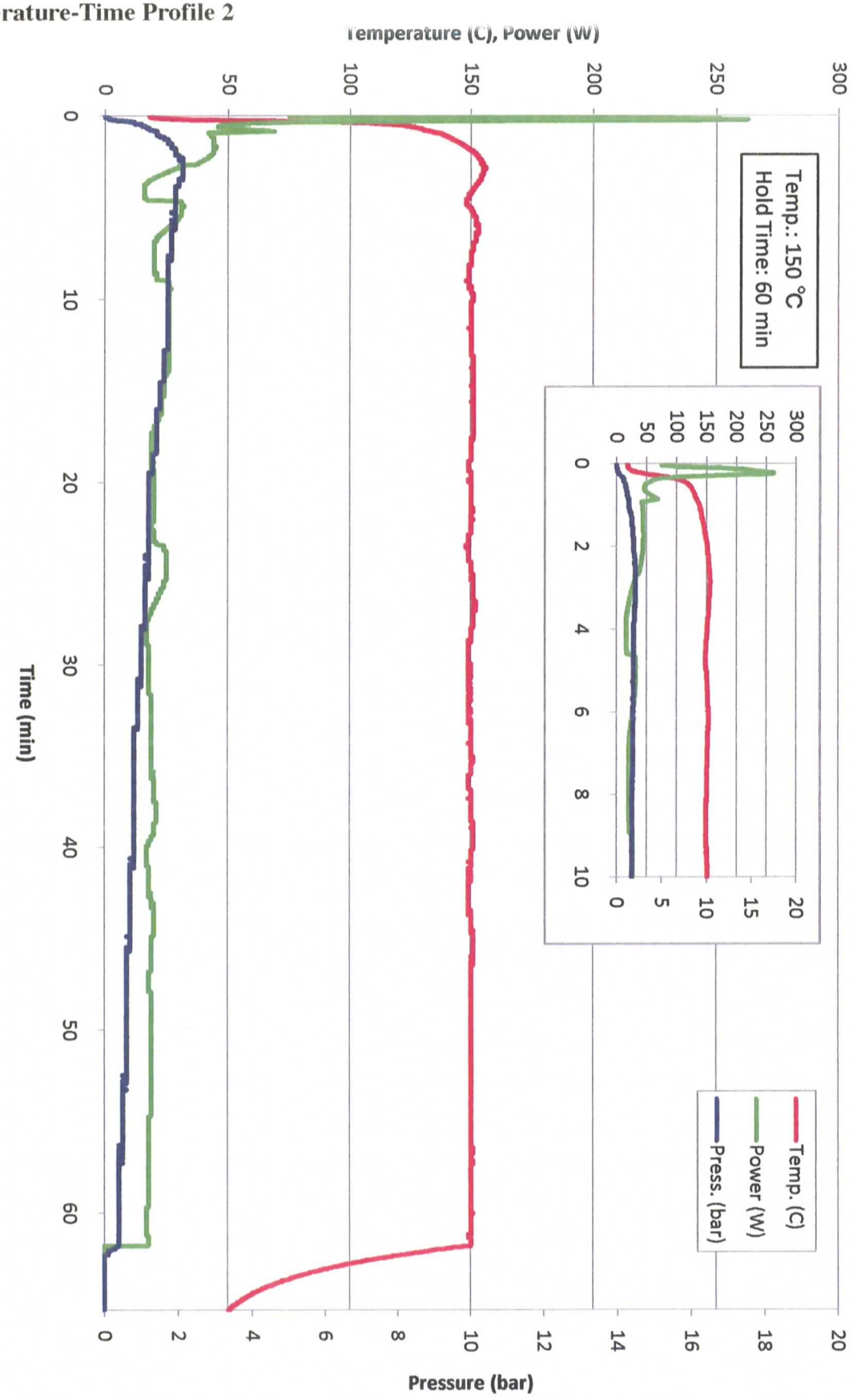

141.659
125.109
124.639
121.178
113.226
77.425
77.000
76.583
72.918
33.049
26.683
20.187
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

11
O
O

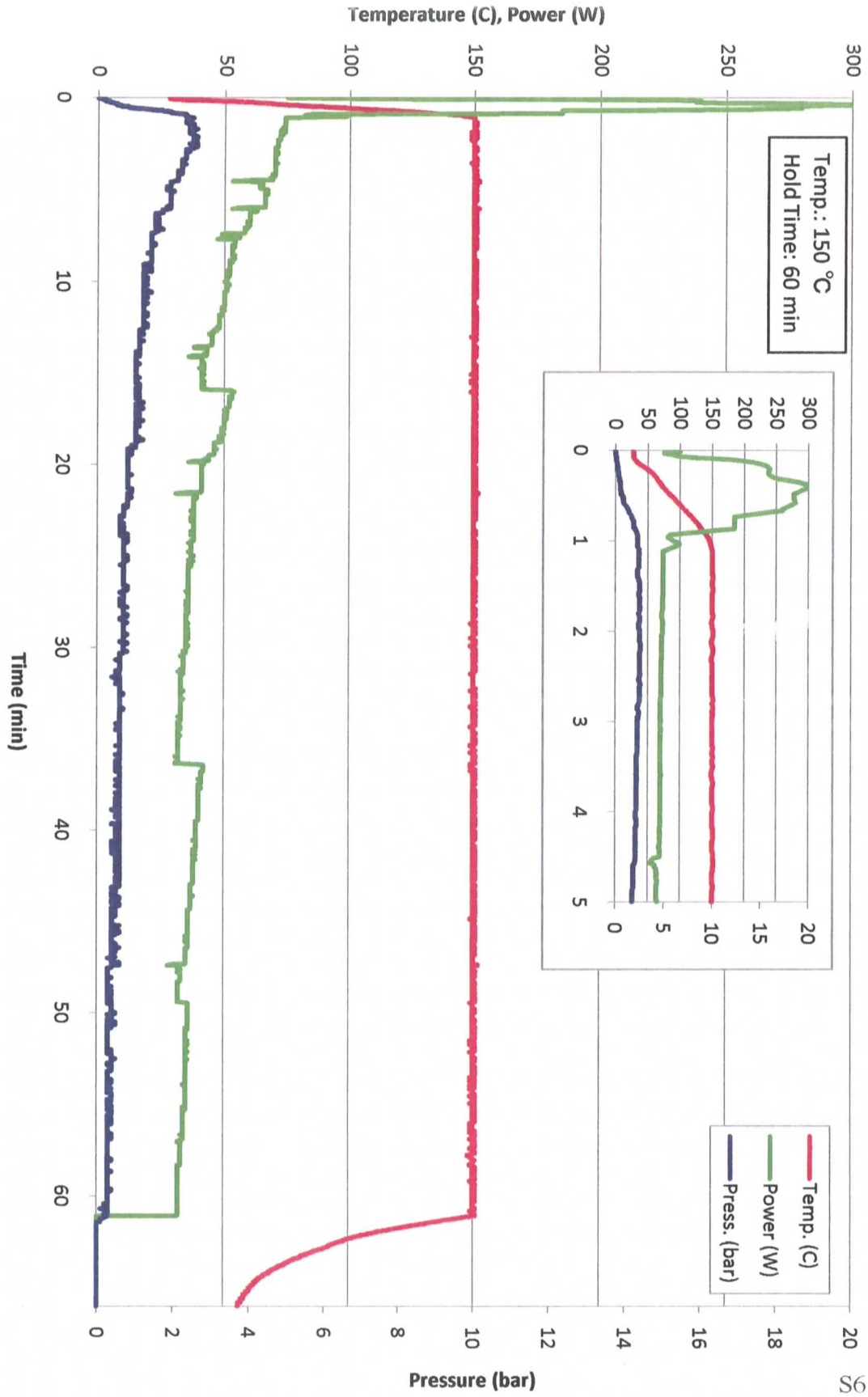
Temperature-Time Profile 1



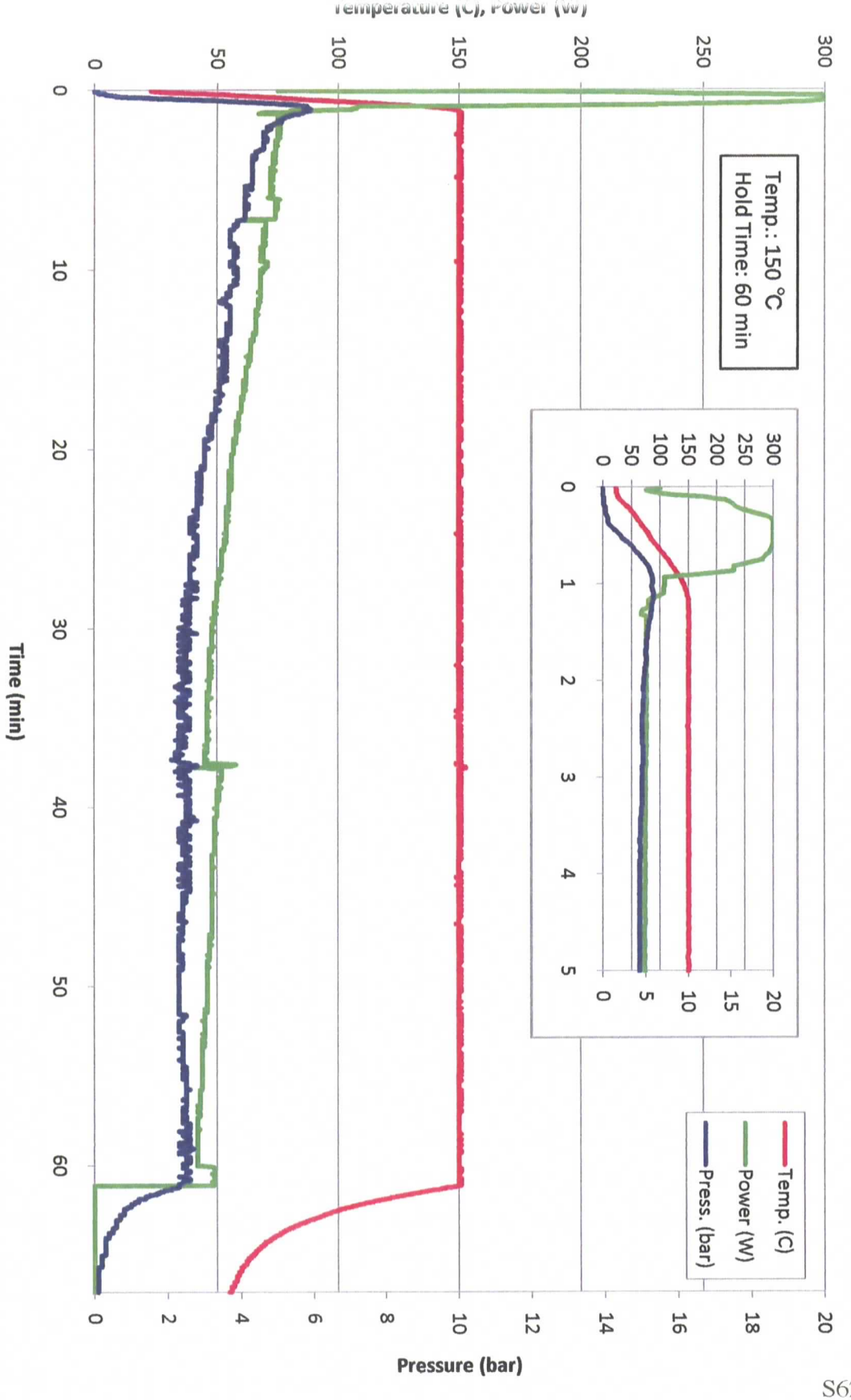
Temperature-Time Profile 2



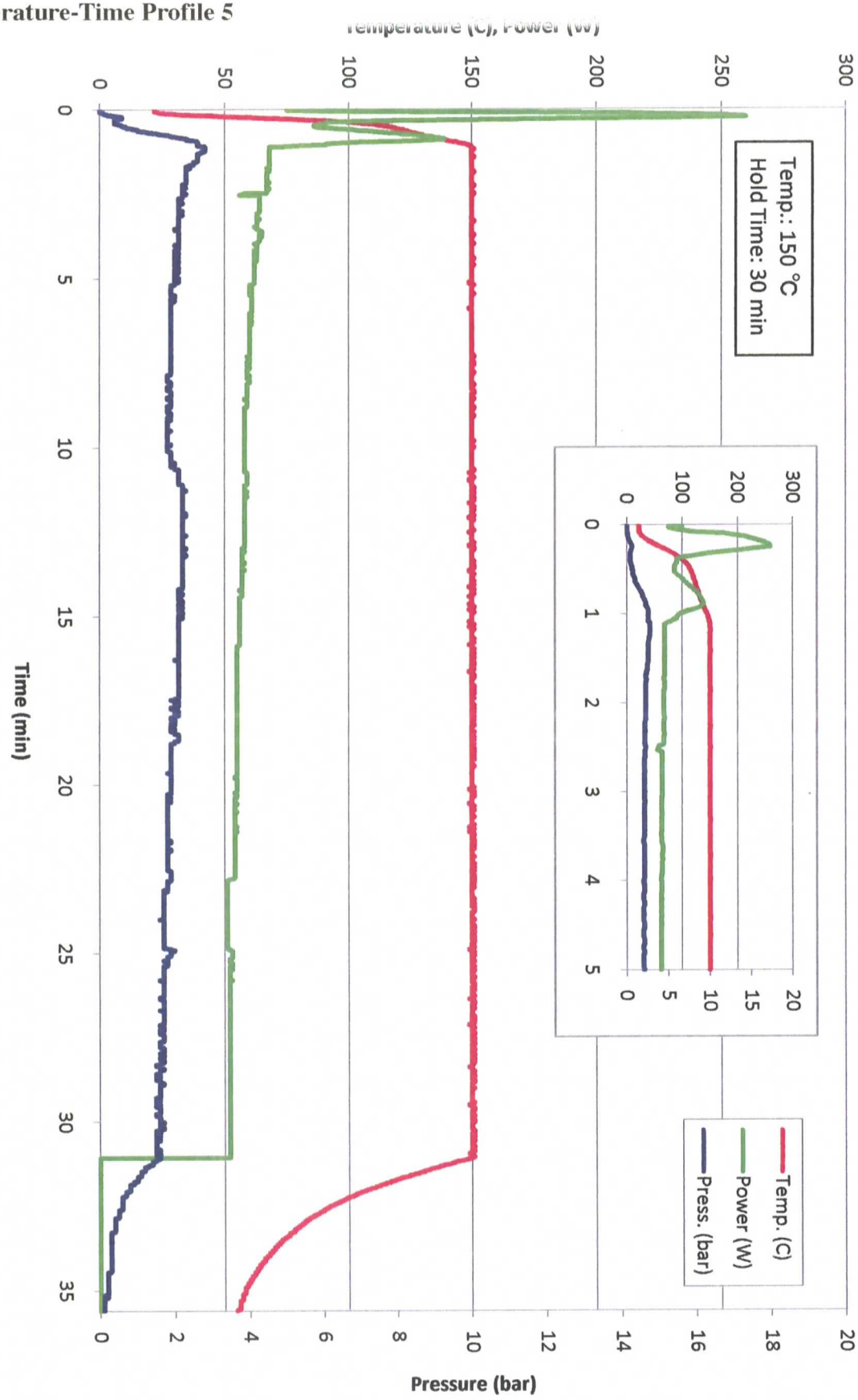
Temperature-Time Profile 3



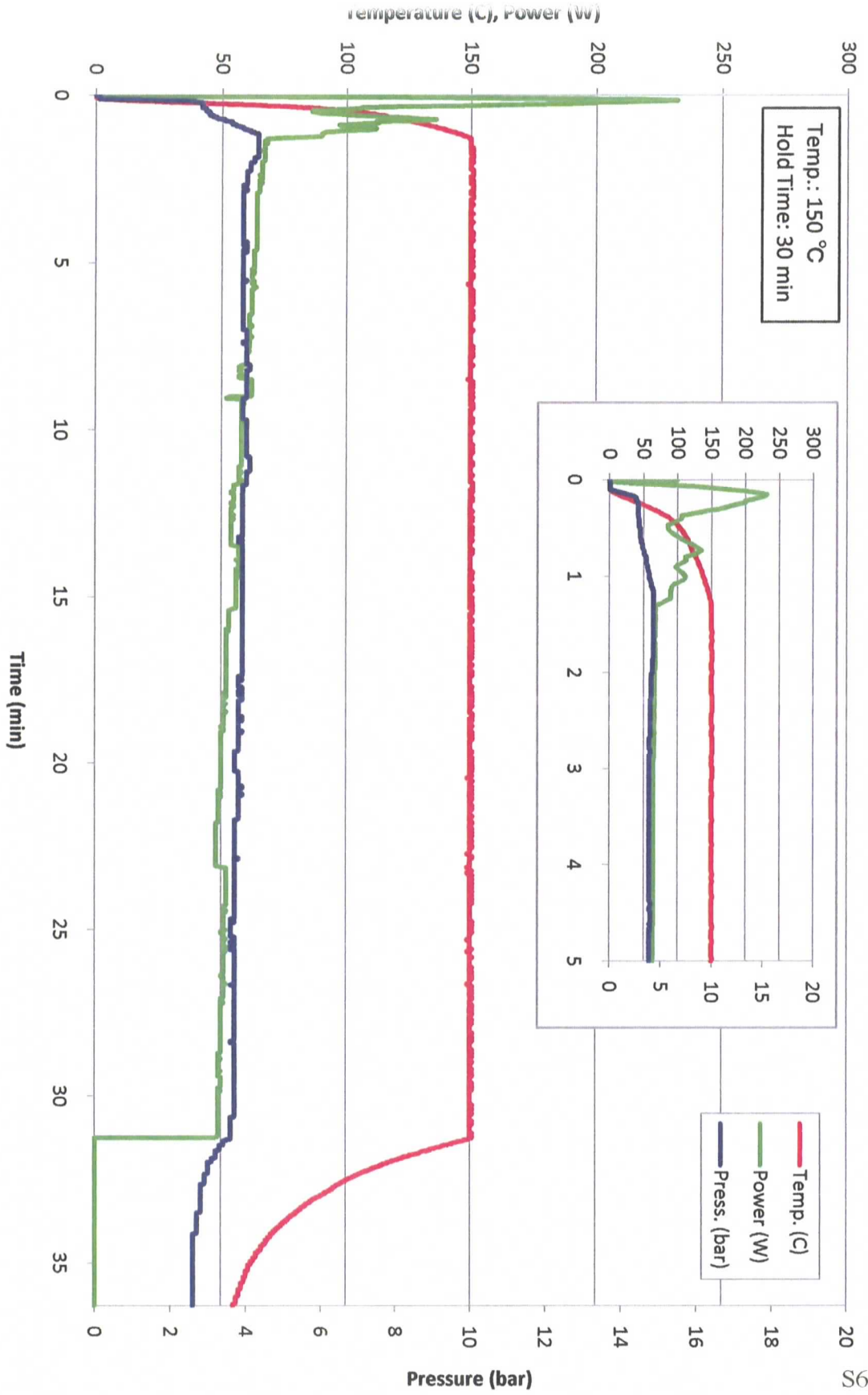
Temperature-Time Profile 4



Temperature-Time Profile 5



Temperature-Time Profile 6



Temperature-Time Profile 7