Scandium pre-catalysed deoxygenative allylation of benzylic alcohols

Ivan Šolić,[a] Pattarakiat Seankongsuk,[b] Joanna Kejun Loh,[a] Tirayut Vilaivan,[b] Roderick W. Bates*[a]

a: Division of Chemistry and Biological Chemistry, School of Physical and Mathematcal Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371

b: Organic Synthesis Research Unit, Department of Chemistry, Faculty of Science, Chulalongkorn University, Phayathai Road, Patumwan, Bangkok 10330, Thailand

Procedures

^1H and ^{13}C NMR Spectra

General Experimental Methods

All reactions requiring anhydrous conditions were carried out under nitrogen gas atmosphere using oven-dried glassware. Anhydrous diethyl ether and tetrahydrofuran were distilled from sodium metal and benzophenone. All other solvents and reagents were used as received. Column chromatography was carried out on silica gel 230-400 mesh, and analytical TLC on precoated glass plates (silica gel 60, F_{254}). ^{1}H NMR and ^{13}C spectra were recorded on a JEOL ECA 400 MHz in $CDCl_3$ solutions. Chemical shifts are recorded in ppm and coupling constants are recorded in Hz.

Preparation of the benzylic alcohol derivatives

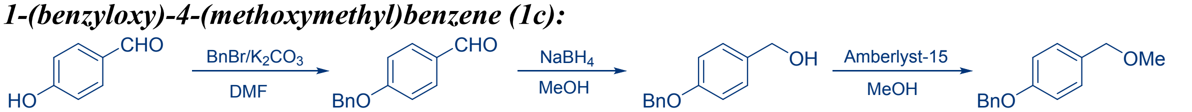
General procedure for the $NaBH_4$ reduction (GP1)

Sodium borohydride (1 eq.) was added portionwise to a solution of the corresponding carbonyl compound (1 mmol, 1eq.) in methanol (5 mL), cooled with an ice bath. The mixture was stirred for an additional one hour at room temperature and progress was monitored by TLC. The reaction mixture was quenched with saturated NH_4Cl solution, concentrated under reduced pressure, extracted with ethyl acetate, washed with water and brine, dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. When necessary, the residue was purified by flash chromatography.

General procedure for the Grignard reaction (GP2)

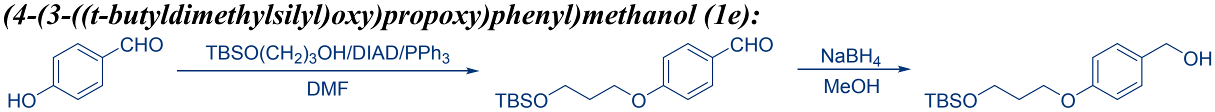
Magnesium turnings (1.2 eq.) were added into the oven dried, two-necked round-bottom flask equipped with reflux condenser and rubber septum. Anhydrous Et_2O (5 mL) was added together with one crystal of iodine. The mixture was stirred for 15 minutes, followed by dropwise addition of the corresponding aryl halide (1.2 eq.). The reaction mixture was stirred for an additional one hour at room temperature. The corresponding aryl aldehyde (1 eq.) was added dropwise by syringe. The reaction was monitored by TLC analysis and after completion, the reaction was quenched with H_2O and HCl (2M). The aqueous layer was extracted with Et_2O, and the combined organic layer were washed with brine and dried over anhydrous $MgSO_4$, filtered and concentrated under reduced pressure. The residue was purified by flash chromatography.

1-(benzyloxy)-4-(methoxymethyl)benzene (1c):



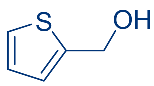
This compound was prepared from 4-hydroxybenzaldehyde according to the reported procedure[1], followed by $NaBH_4$ reduction using general procedure GP1, and methylation with Amberlyst-15. The product was obtained as a colourless liquid. Yield 80%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.22 (m, 7H), 6.98 – 6.92 (m, 2H), 5.06 (s, 2H), 4.38 (s, 2H), 3.36 (s, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 158.5, 137.1, 130.7, 129.5, 128.7, 128.1, 127.6, 114.9, 74.5, 70.1, 58.0).

(4-(3-((t-butyldimethylsilyl)oxy)propoxy)phenyl)methanol (1e):

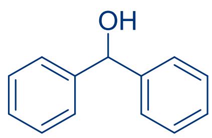


Diisopropyl azodicarboxylate (DIAD) (1.77 mL, 9.1 mmol, 1.1 eq) was added dropwise to a solution of 3-((*t*-butyldimethylsilyl)oxy)propan-1-ol (1.71 g, 9.1 mmol, 1.1 eq.), PPh_3 (2,36 g, 9.01 mmol, 1.1 eq) and 4-hydroxybenzaldehyde (1 g, 8.2 mmol, 1 eq.) in dry tetrahydrofuran (30 mL) at 0 °C. The mixture was stirred at room temperature for 4 hours. The solvent was removed in vacuo, and the residual thick yellow oil was purified by column chromatography. The product was reduced with

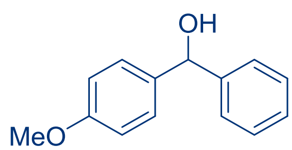
$NaBH_4$ according to general procedure GP1 to give alcohol **1e** as a yellow oil. Yield 64%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.24 (m, 2H), 6.90 – 6.86 (m, 2H), 4.60 (s, 2H), 4.05 (t, *J* = 6.2 Hz, 2H), 3.79 (t, *J* = 6.0 Hz, 2H), 1.97 (p, *J* = 6.1 Hz, 2H), 0.88 (s, 9H), 0.03 (s, 6H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 158.9, 133.1, 128.8, 114.7, 65.2, 64.7, 59.6, 32.5, 26.1, 18.5, -5.2; **HRMS (EI):** Exact mass calcd for $C_{16}H_{29}O_3Si$ $(M+H)^+$: 297.1886, Found: 297.1890; **MS (ESI):** 297.49 $(M+H)^+$; IR (NaCl): 3381.21, 2951.09, 2927.94, 2879.72, 2854.65, 1714.72, 1614.42, 1514.12, 1172.72



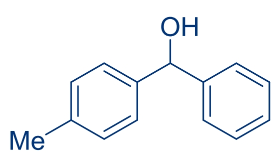
Thiophen-2-ylmethanol (1l): $LiAlH_4$ was added in a small portions under a stream of nitrogen gas to a stirred solution of thiophene-2-carboxylic acid (1 g, 7.8 mmol, 1 eq.) in anhydrous THF (10 mL). The mixture was stirred for 30 minutes at room temperature, then quenched with water, 2 M NaOH, and again with water. After quenching, the mixture was filtered, concentrated under reduced pressure, extracted with DCM, dried over $MgSO_4$ and concentarted under reduced pressure. The residue was purified by column chromatography to give thiophen-2-ylmethanol as a yellow oil. Yield 64%. The obtained NMR data are in agreement with those previously reported in the literature.[2] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.24 (m, 1H), 7.01 – 6.95 (m, 2H), 4.79 (s, 2H), 2.19 (s, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 144.1, 127.0, 125.7, 125.6, 60.0.



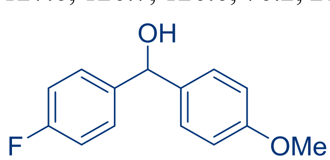
Diphenylmethanol (8a): This compound was synthesized from benzophenone according to the general procedure **GP1**. White solid. Quantitative yield. The obtained NMR data are in agreement with those previously reported in the literature.[3] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.42 – 7.13 (m, 10H), 5.84 (d, *J* = 3.4 Hz, 1H), 2.23 (d, *J* = 3.6 Hz, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 143.9, 128.6, 127.71, 126.7, 76.8, 76.4.



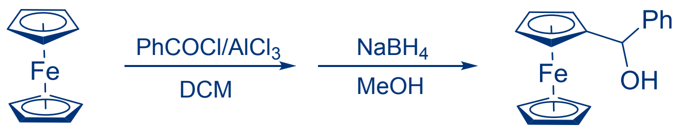
(4-methoxyphenyl)(phenyl)methanol (8b): This compound was synthesized from bromobenzene and 4-methoxybenzaldehyde according to the general procedure **GP2**. White solid. Yield 98%. The obtained NMR data are in agreement with those previously reported in the literature.[4] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.40 – 7.23 (m, 7H), 6.89 – 6.84 (m, 2H), 5.80 (s, 1H), 3.78 (s, 3H), 2.22 (d, *J* = 2.7 Hz, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 159.1, 144.1, 136.3, 128.5, 128.0, 127.5, 126.5, 114.0, 75.9, 55.4.



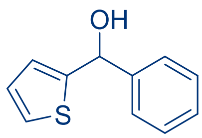
Phenyl(p-tolyl)methanol (8c): This compound was synthesized from bromobenzene and 4-methylbenzaldehyde according to the general procedure **GP2**. White solid. Yield 68%. The obtained NMR data are in agreement with those previously reported in the literature.[4] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.41 – 7.29 (m, 4H), 7.27 – 7.23 (m, 3H), 7.14 (d, *J* = 7.9 Hz, 2H), 5.80 (s, 1H), 2.33 (s, 3H), 2.25 (s, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 144.1, 141.1, 137.4, 129.3, 128.6, 127.6, 126.7, 126.6, 76.2, 21.2.



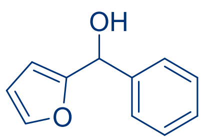
(4-fluorophenyl)(4-methoxyphenyl)methanol (8d): This compound was synthesized from 4-bromoanisole and 4-fluorobenzaldehyde according to the general procedure **GP2**. Yellow oil. Quantitative yield. The obtained ^{1}H NMR data are in agreement with those previously reported in the literature. On the other hand, ^{13}C NMR data are not in agreement with the literature because those authors disregarded coupling between ^{13}C and ^{19}F nuclei in the benzene ring.[4,5] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.29 (m, 2H), 7.24 (d, *J* = 8.8 Hz, 2H), 7.00 (t, *J* = 8.7 Hz, 2H), 6.85 (d, *J* = 8.8 Hz, 2H), 5.75 (s, 1H), 3.77 (s, 3H), 2.43 (d, *J* = 2.4 Hz, 1H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 162.2 (d, *J* = 245.7 Hz), 159.3, 139.9, 136.1, 128.2 (d, *J* = 8.0 Hz), 128.0, 115.3 (d, *J* = 21.3 Hz), 114.1, 75.3, 55.4.



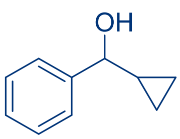
Ferrocenyl(phenyl)methanol (8e): This compound was prepared from ferrocene according the reported procedure[6] followed by $NaBH_4$ reduction (general procedure **GP1**). Orange solid. Yield 60%. The obtained NMR data are in agreement with those previously reported in the literature.[7] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.42 – 7.36 (m, 2H), 7.36 – 7.29 (m, 2H), 7.28 – 7.22 (m, 1H), 5.47 (d, *J* = 3.2 Hz, 1H), 4.24 – 4.15 (m, 9H), 2.45 (d, *J* = 3.1 Hz, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 143.4, 128.4, 127.6, 126.4, 72.2, 68.6, 68.3, 68.2, 67.6, 66.1.



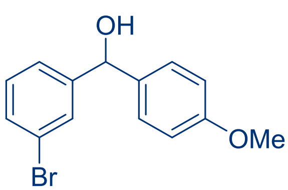
Phenyl(thiophen-2-yl)methanol (8f): This compound was synthesized from bromobenzene and 2-thiophenecarboxaldehyde according to the general procedure **GP2**. Yellow oil. Yield 54%. The obtained NMR data are in agreement with those previously reported in the literature.[8] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.47 – 7.43 (m, 2H), 7.37 (tt, *J* = 8.0, 1.7 Hz, 2H), 7.34 – 7.28 (m, 1H), 7.27 – 7.24 (m, 1H), 6.94 (dd, *J* = 5.0, 3.5 Hz, 1H), 6.89 (dt, *J* = 3.5, 1.1 Hz, 1H), 6.06 (d, *J* = 4.0 Hz, 1H), 2.40 (d, *J* = 4.0 Hz, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 148.3, 143.3, 128.7, 128.2, 126.8, 126.4, 125.6, 125.0, 72.6.



Furan-2-yl(phenyl)methanol (8g): This compound was synthesized from bromobenzene and furfural according to the general procedure **GP2**. Yellow oil. Yield 63%. The obtained NMR data are in agreement with those previously reported in the literature.[9] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.44 – 7.26 (m, 6H), 6.29 (dd, *J* = 3.1, 1.9 Hz, 1H), 6.09 (d, *J* = 3.2 Hz, 1H), 5.77 (d, *J* = 3.9 Hz, 1H), 2.64 (s, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 156.1, 142.6, 140.9, 128.5, 128.1, 126.7, 110.3, 107.5, 70.2.



Cyclopropyl(phenyl)methanol (8h): This compound was synthesized from bromobenzene and cyclopropanecarboxaldehyde according to the general procedure **GP2**. Yellow oil. Yield 47%. The obtained NMR data are in agreement with those previously reported in the literature.[10] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.24 (m, 5H), 4.01 (d, *J* = 8.3 Hz, 1H), 2.01 (s, 1H), 1.28 – 1.17 (m, 1H), 0.68 – 0.33 (m, 4H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 143.9, 128.5, 127.6, 126.1, 78.6, 19.3, 3.7, 2.9.



(3-bromophenyl)(4-methoxyphenyl)methanol[11] (8i): This compound was synthesized from 4-bromoanisole and 3-bromobenzaldehyde according to the general procedure **GP2**. Colourless oil. Yield 98%. The obtained NMR data are in agreement with those previously reported in the literature.[11] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.52 (t, *J* = 1.6 Hz, 1H), 7.36 (dt, *J* = 7.9, 1.3 Hz, 1H), 7.27 – 7.19 (m, 3H), 7.16 (t, *J* = 7.8 Hz, 1H), 6.87 – 6.80 (m, 2H), 5.68 (s, 1H), 3.76 (s, 3H), 2.50 (s, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 159.3, 146.4, 135.6, 130.5, 130.1, 129.5, 128.1, 125.1, 122.7, 114.1, 75.2, 55.4.

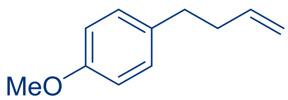
Methyl 3-(methoxy(4-methoxyphenyl)methyl)benzoate (8j):

a

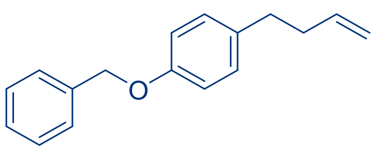
This compound was prepared by methylation of **8i** using modified procedure[12], followed by carbonylation. A solution of previously prepared bromide (1 eq., 250 mg, 0.8 mmol), *i*-Pr_2NEt (1.2 eq., 976 µL, 0.98 mmol) and $Pd(PPh_3)_2Cl_2$ (2 mol%, 14.3 mg, 0.02 mmol) in MeOH (5 mL) was heated at 100 °C under CO (100 psi) in a Fischer-Porter tube for 20 hours. The reaction mixture was filtered, concentrated *in vacuo* and purified by flash chromatography. Yellow oil. Yield 62%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.03 (t, *J* = 1.8 Hz, 1H), 7.92 (dt, *J* = 7.7, 1.5 Hz, 1H), 7.55 – 7.52 (m, 1H), 7.39 (t, *J* = 7.7 Hz, 1H), 7.27 – 7.22 (m, 2H), 6.89 – 6.83 (m, 2H), 5.24 (s, 1H), 3.90 (s, 3H), 3.78 (s, 3H), 3.36 (s, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 167.2, 159.3, 143.1, 133.8, 131.3, 130.4, 128.7, 128.6, 128.4, 128.0, 114.0, 84.6, 57.0, 55.4, 52.2; **HRMS (EI):** Exact mass calcd for $C_{17}H_{19}O_4$ $(M+H)^+$: 287.1283, Found: 287.1273; **MS (ESI):** $(M)^+$; **IR (NaCl):** 3419.79, 2991.59, 2902.87, 2665.62, 2048.40, 1940.39, 1722.42, 1612.49, 1510.26, 1247.94, 1172.72.

General procedure for the scandium pre-catalysed deoxygenative allylation

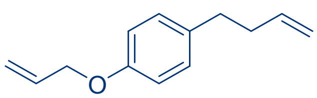
Scandium triflate (0.05 mmol, 5 mol%), followed by allyltrimethylsilane (4 mmol, 4 eq.) was added to a solution of the benzylic alcohol (1 mmol, 1 eq.) in acetonitrile (2 mL) in a 1-dram vial. The mixture was stirred at 40°C for 15-45 minutes until the starting material was consumed based on TLC analysis. The reaction mixture was concentrated *in vacuo* and subjected to flash chromatography on silica gel.



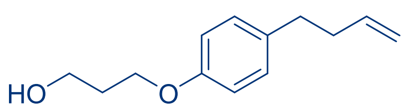
1-(but-3-en-1-yl)-4-methoxybenzene (2a): Yield 77%. Clear oil. The obtained NMR data are in agreement with those previously reported in the literature.[13] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.16 – 7.04 (m, 1H), 6.86 – 6.77 (m, 1H), 5.91 – 5.78 (m, 1H), 5.09 – 4.91 (m, 1H), 3.77 (s, 1H), 2.68 – 2.61 (m, 1H), 2.38 – 2.27 (m, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 157.9, 138.3, 134.1, 129.4, 115.0, 113.8, 55.3, 35.9, 34.6.



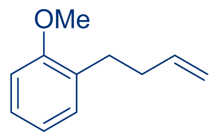
1-(benzyloxy)-4-(but-3-en-1-yl)benzene (2c): Pale yellow oil. Yield 97%. The obtained NMR data are in agreement with those previously reported in the literature.[14] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.47 – 7.29 (m, 5H), 7.14 – 7.07 (m, 2H), 6.93 – 6.88 (m, 2H), 5.86 (ddt, J = 16.8, 10.3, 6.5 Hz, 1H), 5.08 – 4.96 (m, 4H), 2.69 – 2.63 (m, 2H), 2.35 (dd, J = 14.8, 7.3 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 157.1, 138.3, 137.4, 134.4, 129.5, 128.7, 128.0, 127.6, 115.0, 114.8, 70.2, 35.9, 34.6.



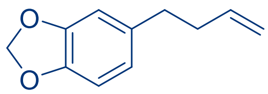
1-(allyloxy)-4-(but-3-en-1-yl)benzene (2d): Yield 94%. The obtained NMR data are in agreement with those previously reported in the literature.[15] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.12 – 7.06 (m, 2H), 6.87 – 6.81 (m, 2H), 6.11 – 6.00 (m, 1H), 5.85 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 5.45 – 5.35 (m, 1H), 5.31 – 5.23 (m, 1H), 5.08 – 4.93 (m, 2H), 4.51 (d, J = 5.3 Hz, 2H), 2.68 – 2.61 (m, 2H), 2.34 (dt, J = 14.3, 7.1 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 156.9, 138.3, 134.3, 133.6, 129.4, 117.6, 115.0, 114.7, 69.0, 35.9, 34.6.



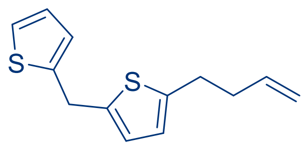
3-(4-(but-3-en-1-yl)phenoxy)propan-1-ol (2f): Colourless oil**.** Yield 51%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.09 – 7.03 (m, 2H), 6.83 – 6.76 (m, 2H), 5.81 (ddt, J = 16.8, 10.2, 6.6 Hz, 1H), 5.04 – 4.89 (m, 2H), 4.06 (t, J = 5.7 Hz, 2H), 3.81 (t, J = 5.9 Hz, 2H), 2.67 – 2.56 (m, 2H), 2.34 – 2.26 (m, 2H), 1.99 (p, J = 5.7 Hz, 2H), 1.85 (s, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 157.0, 138.3, 134.4, 129.5, 115.0, 114.5, 66.1, 60.9, 35.9, 34.6, 32.1; **HRMS (EI):** Exact mass calcd for $C_{13}H_{19}O_2$ $(M+H)^+$: 207.1385, Found: 207.1374; **MS (ESI):** 207.28 $(M+H)^+$; **IR (NaCl):** 3414.00, 3396.64, 1612.49, 1508.33, 1473.62, 1388.75, 1240.23.



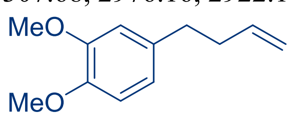
1-(but-3-en-1-yl)-2-methoxybenzene (2h): Yield 24%. The obtained NMR data are in agreement with those previously reported in the literature.[16] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.21 – 7.10 (m, 2H), 6.91 – 6.83 (m, 2H), 5.88 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 5.08 – 4.93 (m, 2H), 3.82 (s, 3H), 2.74 – 2.67 (m, 2H), 2.38 – 2.30 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 157.6, 138.9, 130.4, 130.0 (s), 127.2, 120.4, 114.6, 110.4, 55.4, 34.0, 29.9.



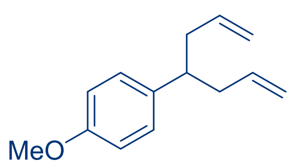
5-(but-3-en-1-yl)benzo[d][1,3]dioxole (2j): Yield 10%. Colourless oil. The obtained NMR data are in agreement with those previously reported in the literature.[13] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.76 – 6.61 (m, 3H), 5.92 (s, 2H), 5.91 – 5.78 (m, 1H), 5.07 – 4.94 (m, 2H), 2.65 – 2.61 (m, 2H), 2.38 – 2.28 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 147.6, 145.7, 138.1, 135.9, 121.3, 115.1, 109.0, 108.2, 100.9, 35.9, 35.3.



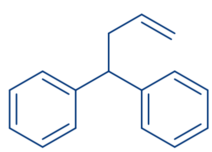
2-(but-3-en-1-yl)thiophene (2l'): Yield 41%. Colourless oil. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.17 – 7.12 (m, 1H), 6.94 – 6.90 (m, 1H), 6.88 – 6.85 (m, 1H), 6.66 (d, J = 3.5 Hz, 1H), 6.60 (d, J = 3.5 Hz, 1H), 5.84 (ddt, J = 16.9, 10.3, 6.6 Hz, 1H), 5.10 – 4.96 (m, 2H), 4.27 (s, 2H), 2.87 – 2.80 (m, 2H), 2.43 – 2.34 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 143.8, 143.5, 140.9, 137.6, 126.9, 125.3, 124.9, 124.2, 123.9, 115.5, 35.7, 30.6, 29.8; **MS (ESI):** 235.17 $(M+H)^+$; **IR (NaCl):** 307.68, 2976.16, 2922.16, 1639.49, 1487.12, 1431.18



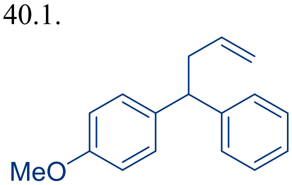
4-(but-3-en-1-yl)-1,2-dimethoxybenzene (2m): Colourless oil. Yield 15%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.84 – 6.66 (m, 3H), 5.86 (ddt, J = 17.0, 10.2, 6.6 Hz, 1H), 5.14 – 4.93 (m, 2H), 3.87 (s, 3H), 3.86 (s, 3H), 2.71 – 2.60 (m, 2H), 2.40 – 2.33 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 148.8, 147.3, 138.2, 134.6, 120.3, 115.0, 111.9, 111.3, 56.0, 55.9, 35.8, 35.1; **HRMS (EI):** Exact mass calcd for $C_{12}H_{17}O_2$ $(M+H)^+$: 193.1229, Found: 193.1217; **MS (ESI):** 193.13 $(M+Na)^+$; **IR (NaCl):** 3442.94, 2065.76, 1637.56, 1516.05, 1463.97, 1261.45, 1234.44.



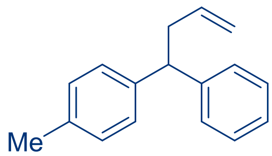
1-(hepta-1,6-dien-4-yl)-4-methoxybenzene (4): Colourless oil. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.10 – 7.04 (m, 2H), 6.86 – 6.81 (m, 2H), 5.66 (ddt, J = 17.3, 10.1, 7.0 Hz, 2H), 5.00 – 4.89 (m, 4H), 3.78 (s, 3H), 2.72 – 2.62 (m, 1H), 2.44 – 2.26 (m, 4H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 158.0, 137.1, 136.8, 128.7, 116.1, 113.7, 55.3, 44.9, 40.6.



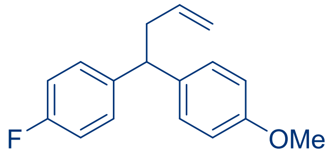
But-3-ene-1,1-diyldibenzene (9a): Colourless oil. Yield 96%. The obtained NMR data are in agreement with those previously reported in the literature.[17] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.21 (m, 8H), 7.20 – 7.13 (m, 2H), 5.72 (ddt, J = 17.1, 10.2, 6.8 Hz, 1H), 5.07 – 4.91 (m, 2H), 4.00 (t, J = 7.9 Hz, 1H), 2.84 – 2.79 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 144.6, 137.0, 128.5, 128.1, 126.3, 116.4, 51.4, 40.1.



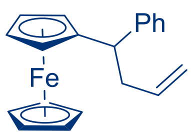
1-methoxy-4-(1-phenylbut-3-en-1-yl)benzene (9b): Colourless oil. Yield 94%. The obtained NMR data are in agreement with those previously reported in the literature.[18] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.30 – 7.12 (m, 7H), 6.85 – 6.79 (m, 2H), 5.71 (ddt, J = 17.1, 10.2, 6.8 Hz, 1H), 5.07 – 4.90 (m, 2H), 3.96 (t, J = 7.9 Hz, 1H), 3.76 (s, 3H), 2.78 (t, J = 7.3 Hz, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 158.1, 145.1, 137.1, 136.8, 129.0, 128.5, 128.0, 126.2, 116.3, 113.9, 55.3, 50.5, 40.3.



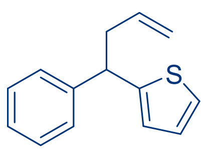
1-methyl-4-(1-phenylbut-3-en-1-yl)benzene (9c): Colourless oil. Yield 95%. The obtained NMR data are in agreement with those previously reported in the literature.[18] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.19 (m, 4H), 7.19 – 7.05 (m, 5H), 5.72 (ddt, *J* = 17.1, 10.2, 6.8 Hz, 1H), 4.98 (ddd, *J* = 13.6, 11.2, 1.1 Hz, 2H), 3.97 (t, *J* = 7.9 Hz, 1H), 2.79 (t, *J* = 7.3 Hz, 2H), 2.29 (s, 3H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 144.9, 141.6, 137.1, 135.8, 129.2, 128.5, 128.0, 128.0, 126.2, 116.3, 51.0, 40.1, 21.1.



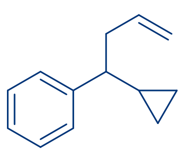
1-fluoro-4-(1-(4-methoxyphenyl)but-3-en-1-yl)benzene (9d): Yellow solid. Yield 84%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.21 – 7.09 (m, 4H), 6.99 – 6.91 (m, 2H), 6.85 – 6.80 (m, 2H), 5.75 – 5.63 (m, 1H), 5.07 – 4.91 (m, 2H), 3.95 (t, *J* = 7.9 Hz, 1H), 3.77 (s, 3H), 2.78 – 2.72 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 161.4 (d, *J* = 244.1 Hz), 158.1, 140.7 (d, *J* = 3.2 Hz), 136.8, 136.6, 129.3 (d, *J* = 7.8 Hz), 128.9, 116.5, 115.2 (d, *J* = 21.0 Hz), 114.0, 55.3, 49.7, 40.4; **HRMS (EI):** Exact mass calcd for $C_{17}H_{18}OF$ $(M+H)^+$: 257.1342; Found: 257.1344; **MS (ESI):** 279.38 $(M+Na)^+$; **IR (NaCl):** 3415.93. 1633.71, 1504.48, 1296.16, 1222.87. **Melting point:** 41-44 °C.



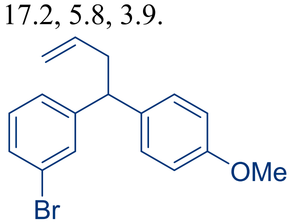
(1-ferrocenylbut-3-en-1-yl)benzene (9e): Orange solid. Yield 93%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.30 – 7.23 (m, 2H), 7.20 – 7.14 (m, 3H), 5.69 (ddt, *J* = 17.1, 10.1, 7.0 Hz, 1H), 5.03 – 4.89 (m, 2H), 4.18 (dt, *J* = 2.4, 1.3 Hz, 1H), 4.10 (td, *J* = 2.4, 1.3 Hz, 1H), 4.06 (s, 5H), 4.05 (td, *J* = 2.3, 1.2 Hz, 1H), 3.95 (dt, *J* = 2.5, 1.3 Hz, 1H), 3.68 (dd, *J* = 10.3, 4.7 Hz, 1H), 2.88 – 2.80 (m, 1H), 2.66 – 2.56 (m, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 145.0, 137.2, 128.3, 128.1, 126.3, 116.0, 93.9, 68.7, 67.7 (d, *J* = 10.2 Hz), 67.1 (d, *J* = 3.6 Hz), 46.4, 41.6; **HRMS (EI):** Exact mass calcd for $C_{20}H_{20}Fe$ $(M)^+$: 316.0914, Found: 316.0912; **MS (ESI):** 316.41 $(M)^+$; **IR (NaCl):** 3450.65, 3070.68, 3022.45, 1489.05, 1444.68, 1232.51, 1178.51, 1101.06, 1001.06; **Melting point:** 47-49 °C.



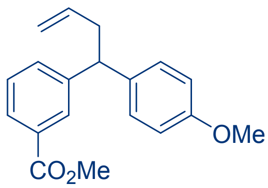
2-(1-phenylbut-3-en-1-yl)thiophene (9f): Yield 52%. The obtained NMR data are in agreement with those previously reported in the literature.[19] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.16 (m, 5H), 7.12 (dt, *J* = 2.0, 0.9 Hz, 1H), 6.90 (dd, *J* = 5.1, 3.5 Hz, 1H), 6.83 (dt, *J* = 3.2, 0.9 Hz, 1H), 5.72 (ddt, *J* = 17.0, 10.2, 6.9 Hz, 1H), 5.09 – 4.93 (m, 2H), 4.22 (t, *J* = 7.8 Hz, 1H), 2.93 – 2.73 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 148.9, 144.1, 136.3, 128.6, 127.9, 126.8, 126.6, 124.1, 123.7, 116.9, 47.0, 41.7.



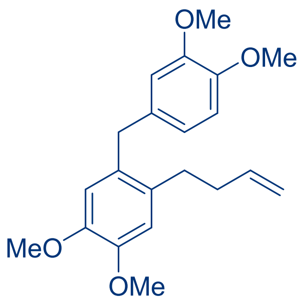
(1-cyclopropylbut-3-en-1-yl)benzene (9h): Yield 48%. Colourless oil. The obtained NMR data are in agreement with those previously reported in the literature.[20] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.36 – 7.25 (m, 2H), 7.23 – 7.16 (m, 3H), 5.80 – 5.67 (m, 1H), 5.03 – 4.87 (m, 2H), 2.62 – 2.44 (m, 2H), 1.88 (dt, *J* = 11.3, 7.2 Hz, 1H), 1.07 – 0.94 (m, 1H), 0.65 – 0.56 (m, 1H), 0.44 – 0.34 (m, 1H), 0.29 – 0.19 (m, 1H), 0.14 – 0.03 (m, 1H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 145.3, 137.2, 128.3, 127.7, 126.1, 115.7, 51.1, 41.3, 17.2, 5.8, 3.9.



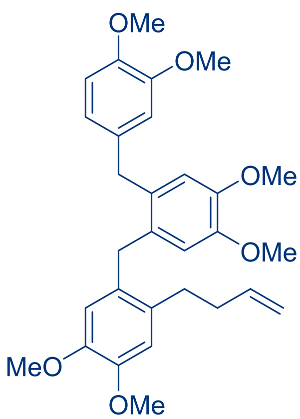
1-bromo-3-(1-(4-methoxyphenyl)but-3-en-1-yl)benzene (9i): Colourless oil. Yield 94%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 (s, 1H), 7.31 – 7.27 (m, 1H), 7.16 – 7.09 (m, 4H), 6.86 – 6.80 (m, 2H), 5.68 (ddt, *J* = 17.0, 10.2, 6.8 Hz, 1H), 5.06 – 4.92 (m, 2H), 3.92 (t, *J* = 7.9 Hz, 1H), 3.76 (s, 3H), 2.78 – 2.72 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 158.25 (s), 147.47 (s), 136.52 (s), 135.86 (s), 131.03 (s), 130.1, 129.3, 128.9, 126.7, 122.6, 116.7, 114.0, 55.3, 50.2, 40.0; **HRMS (EI):** Exact mass calcd for $C_{17}H_{18}O^{79}Br$ $(M+H)^+$: 317.0541, Found: 317.0565; **MS (ESI):** 317.65 $(M+H)^+$; **IR (NaCl):** 3421.72, 3074.53, 2833.43, 1639.49, 1610.56, 1510.26, 1473.62, 1249.87.



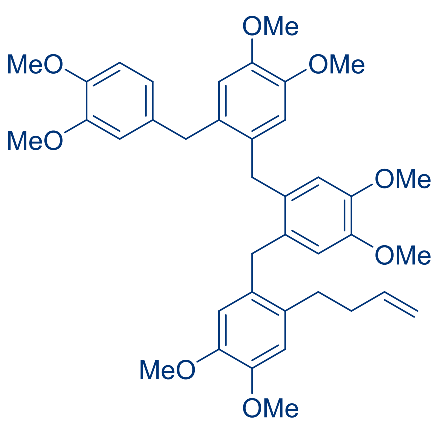
Methyl 3-(1-(4-methoxyphenyl)but-3-en-1-yl)benzoate (9j): Colourless oil. Yield 97%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.93 (t, J = 1.7 Hz, 1H), 7.85 (dt, J = 7.6, 1.5 Hz, 1H), 7.42 – 7.37 (m, 1H), 7.33 (t, J = 7.6 Hz, 1H), 7.17 – 7.12 (m, 2H), 6.85 – 6.80 (m, 2H), 5.69 (ddt, J = 17.0, 10.2, 6.8 Hz, 1H), 5.06 – 4.92 (m, 2H), 4.02 (t, J = 7.9 Hz, 1H), 3.89 (s, 3H), 3.76 (s, 3H), 2.82 – 2.78 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 167.3, 158.2, 145.4, 136.6, 136.2, 132.7, 130.4, 129.0, 128.9, 128.6, 127.6, 116.7, 114.0, 55.3, 52.2, 50.3, 40.1; **HRMS (EI):** Exact mass calcd for $C_{19}H_{21}O_3$ $(M+H)^+$: 297.1491, Found: 297.1515; **MS (ESI):** 297.23 $(M+H)^+$; **IR(NaCl):** 3427.51, 2999.31, 2949.16, 2927.94, 2061.90, 1720.50, 1610.56, 1510.26, 1435.04, 1280.73.



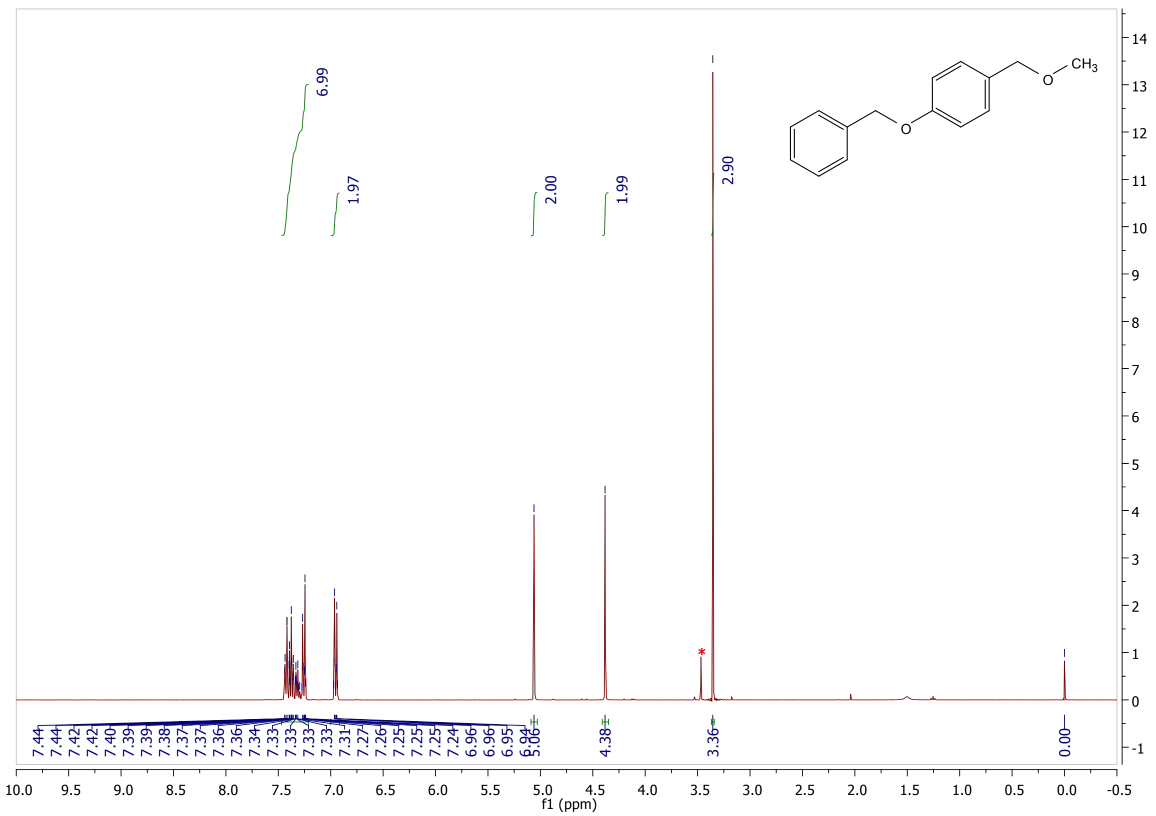
1-(but-3-en-1-yl)-2-(3,4-dimethoxybenzyl)-4,5-dimethoxybenzene (5): Yield 5%. Yellow oil. **^{1}H NMR** (400 MHz, C_6D_6) δ 6.75 – 6.58 (m, 5H), 5.82 (ddt, J = 16.9, 10.1, 6.5 Hz, 1H), 5.09 – 4.94 (m, 2H), 3.91 (s, 2H), 3.50 (s, 3H), 3.44 (s, 3H), 3.43 (s, 3H), 3.42 (s, 3H), 2.69 – 2.64 (m, 2H), 2.25 (dt, J = 14.6, 7.2 Hz, 2H); **^{13}C NMR** (100 MHz, C_6D_6) δ 150.3, 148.9, 148.7, 148.6, 138.6, 134.3, 132.7, 131.2, 121.0, 115.4, 115.0, 114.3, 113.3, 112.6, 55.9 (2 C), 55.7, 55.6, 38.5, 35.8, 32.5; **HRMS (EI):** Exact mass calcd for $C_{21}H_{26}O_4Na$ $(M+Na)^+$: 365.1729, Found: 365.1739; **MS (ESI):** 365.41 $(M+Na)^+$.

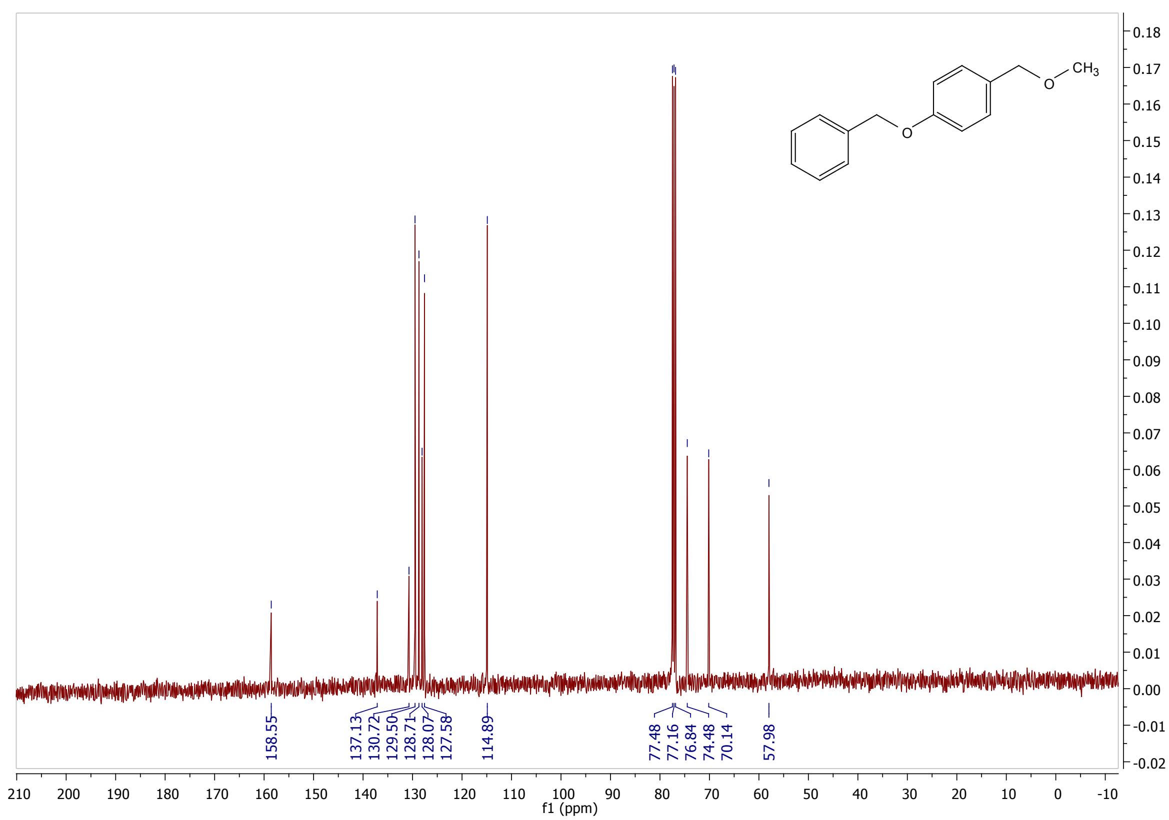


1-(but-3-en-1-yl)-2-(2-(3,4-dimethoxybenzyl)-4,5-dimethoxybenzyl)-4,5-dimethoxybenzene (6): Yellow oil. Yield 4%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.77 (d, J = 7.8 Hz, 1H), 6.70 (d, J = 1.2 Hz, 2H), 6.63 – 6.59 (m, 2H), 6.46 (s, 1H), 6.41 (s, 1H), 5.76 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 4.99 – 4.90 (m, 2H), 3.89 – 3.78 (m, 16H), 3.71 (s, 3H), 3.70 (s, 3H), 2.52 (dd, J = 9.1, 6.7 Hz, 2H), 2.25 – 2.14 (m, 2H);); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 149.0, 147.5, 147.4, 147.3, 147.3, 147.2, 138.2, 133.4, 132.4, 131.3, 131.1, 130.2, 120.6, 115.0, 113.9, 113.3, 113.3, 112.8, 112.0, 111.3, 56.1, 56.0 (2 C), 56.0 (2 C), 55.9, 38.4, 35.1 (2 C), 32.2; **HRMS (EI):** Exact mass calcd for $C_{30}H_{36}O_6Na$ $(M+Na)^+$: 515.2410, Found: 515.2403; **MS (ESI):** 515.63 $(M+Na)^+$.

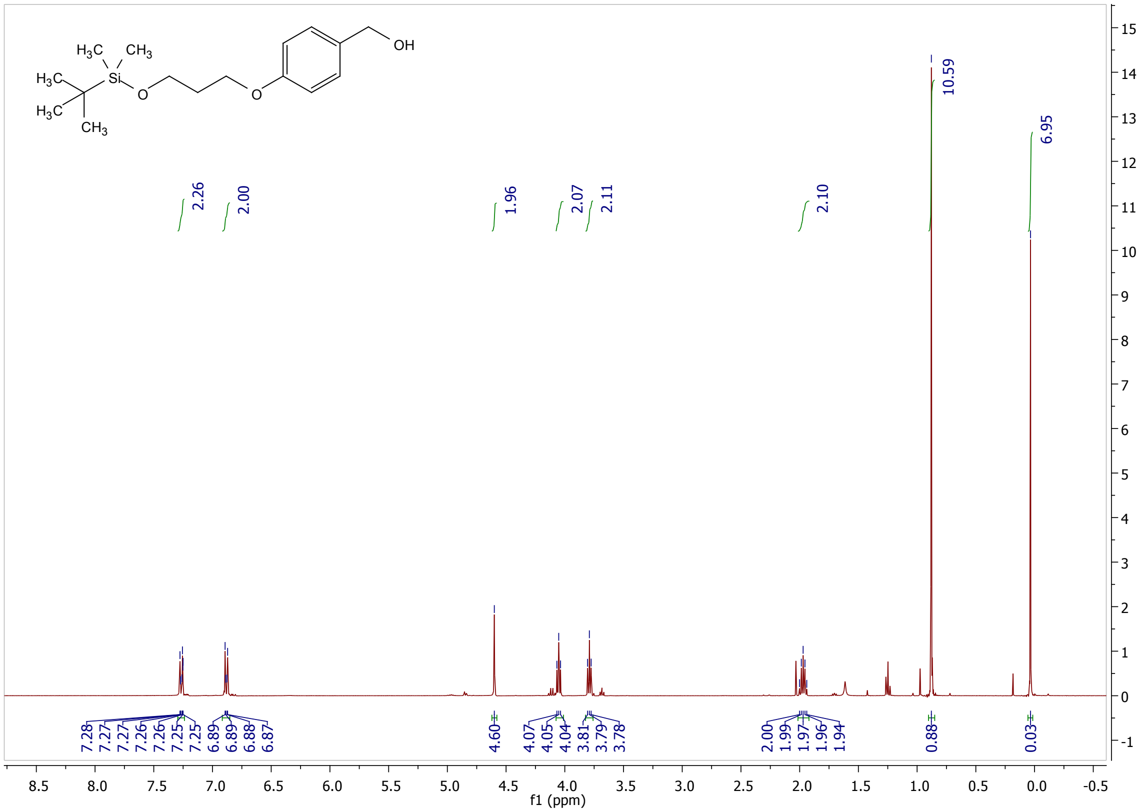


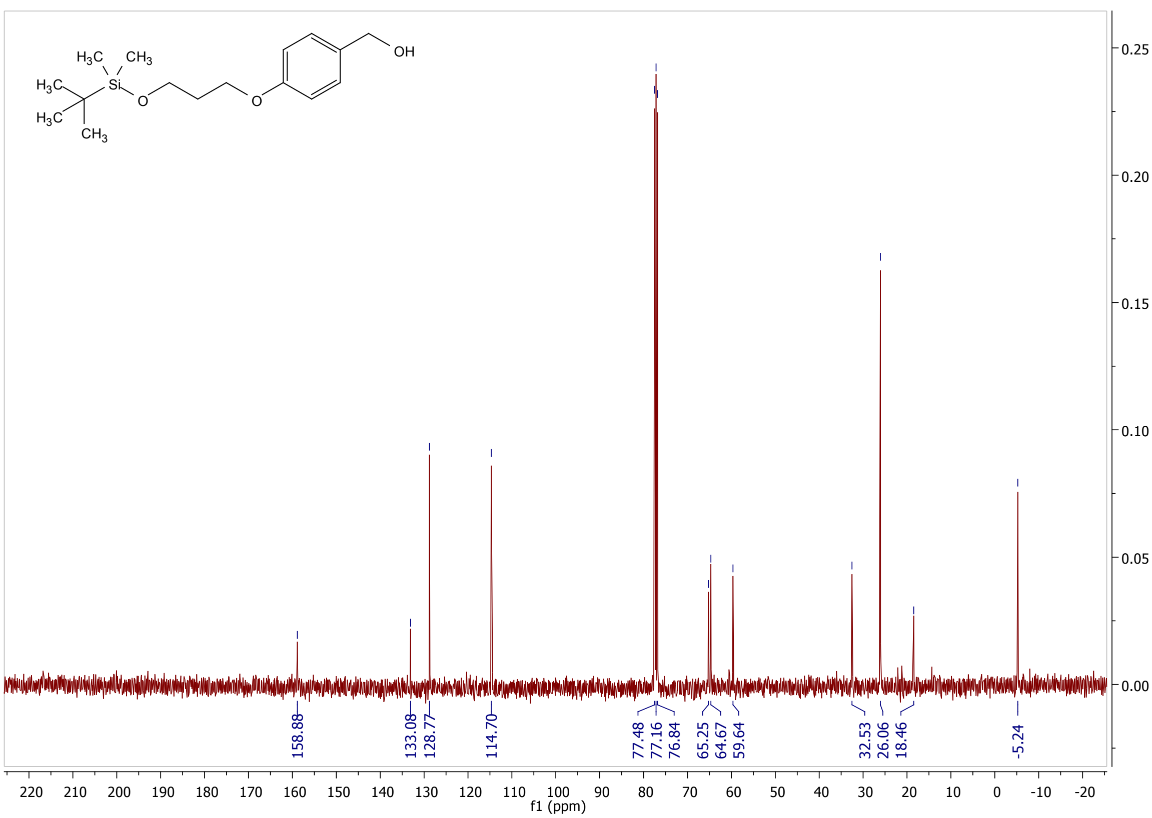
1-(but-3-en-1-yl)-2-(2-(2-(3,4-dimethoxybenzyl)-4,5-dimethoxybenzyl)-4,5-dimethoxybenzyl)-4,5-dimethoxy benzene (7): Yellow oil. Yield 5%. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.72 (d, J = 8.1 Hz, 1H), 6.68 (s, 2H), 6.60 – 6.52 (m, 2H), 6.51 – 6.43 (m, 3H), 6.39 (s, 1H), 5.74 (ddt, J = 16.9, 10.3, 6.6 Hz, 1H), 4.98 – 4.89 (m, 2H), 3.87 (s, 3H), 3.84 – 3.65 (m, 27H), 2.51 – 2.46 (m, 2H), 2.22 – 2.13 (m, 2H); **^{13}C NMR** (100 MHz, $CDCl_3$) δ 149.0, 147.6, 147.4, 147.4, 147.4, 147.4, 147.3, 147.2, 138.1, 133.2, 132.4, 131.3, 131.3, 130.9, 130.8, 130.0, 120.6, 115.1, 113.9, 113.4, 113.2, 113.2, 113.1, 112.8, 112.0, 111.2, 56.1, 56.1, 56.0 (2 C), 56.0, 56.0, 56.0, 55.9, 38.4, 35.4, 35.1, 35.0, 32.2; **HRMS (EI):** Exact mass calcd for $C_{39}H_{46}O_8Na$ $(M+Na)^+$: 665.3090, Found: 665.3082; **MS (ESI):** 665.81 $(M+Na)^+$.



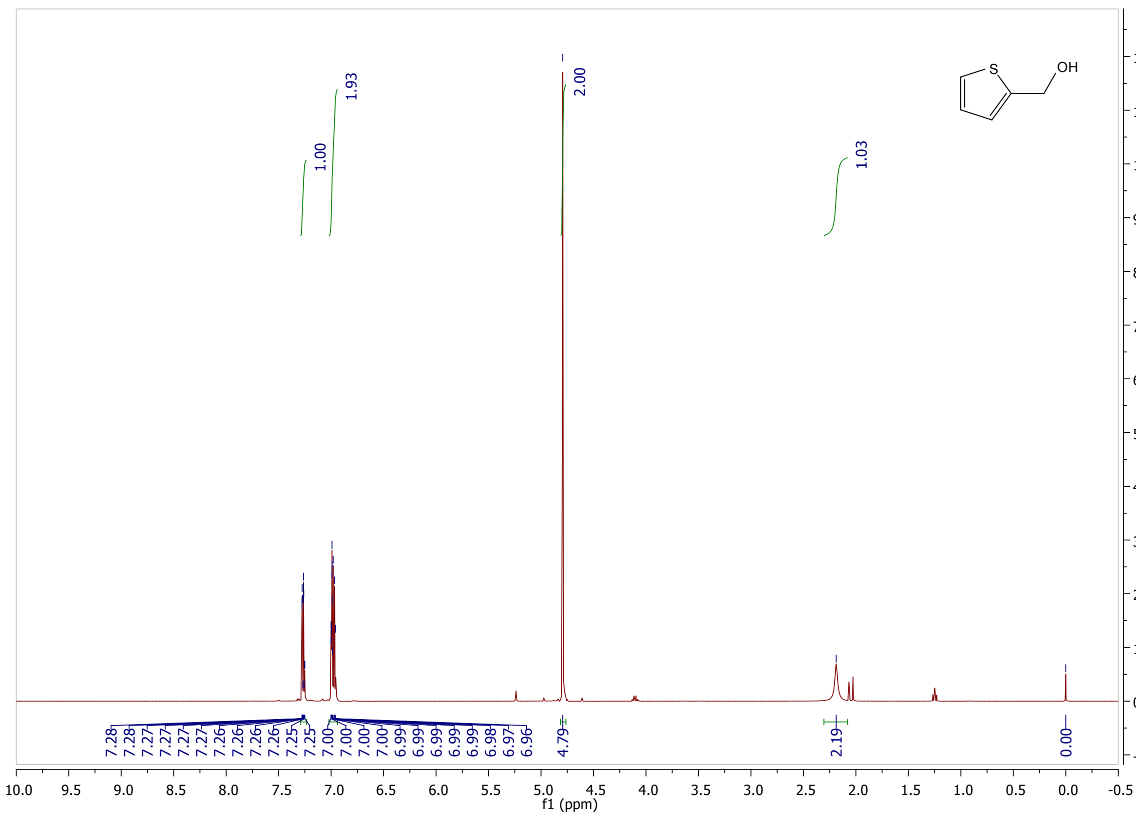


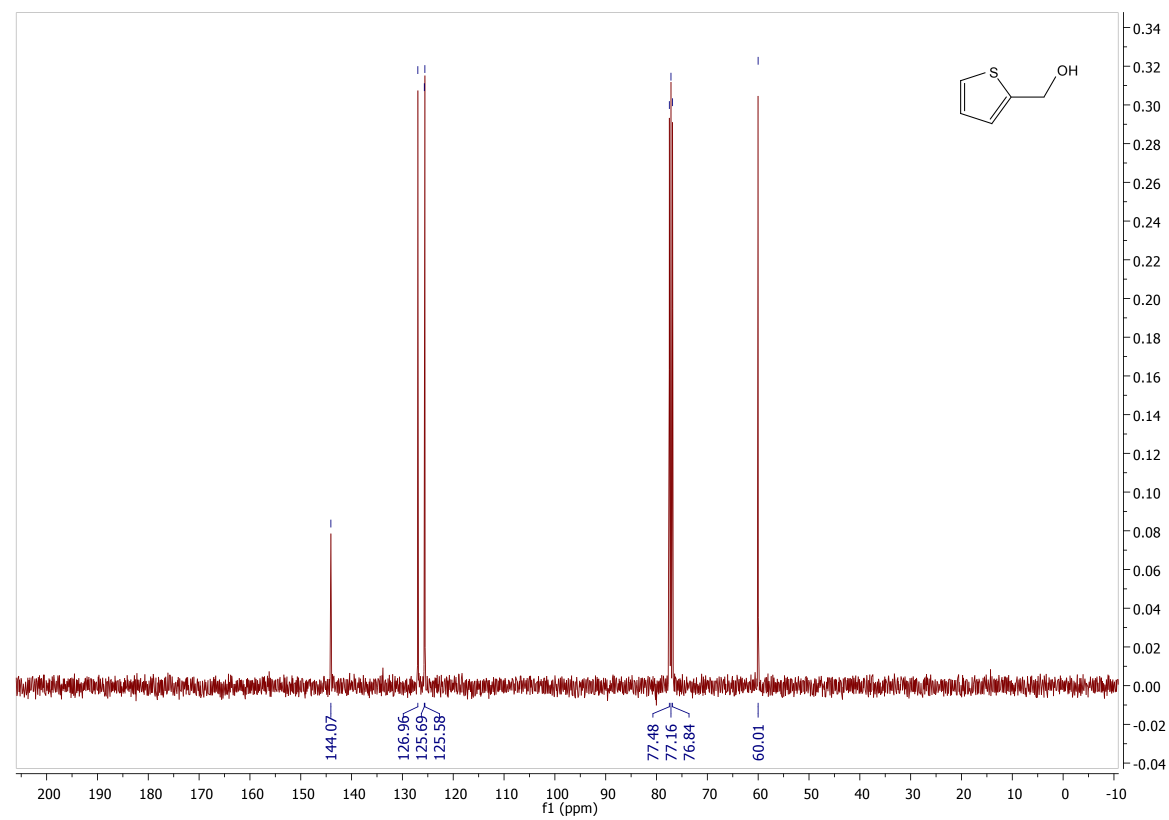
[1]H and [13]C spectra of **1c**.



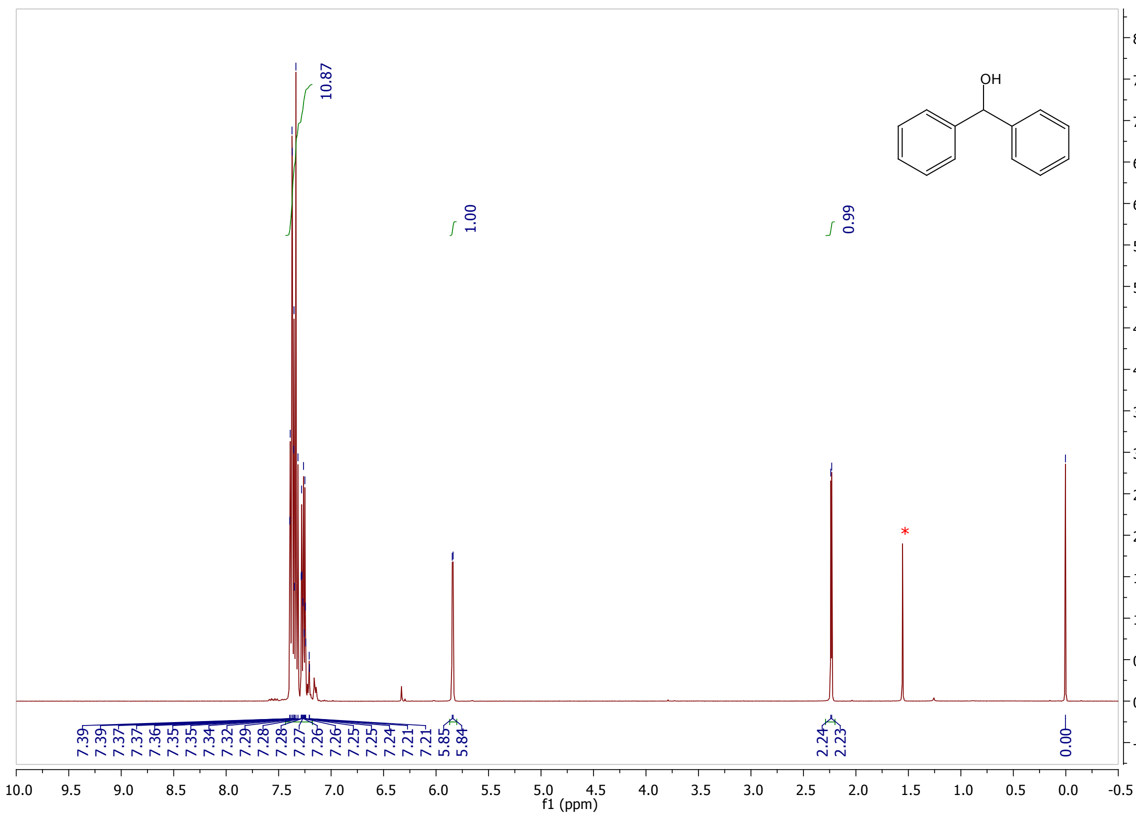


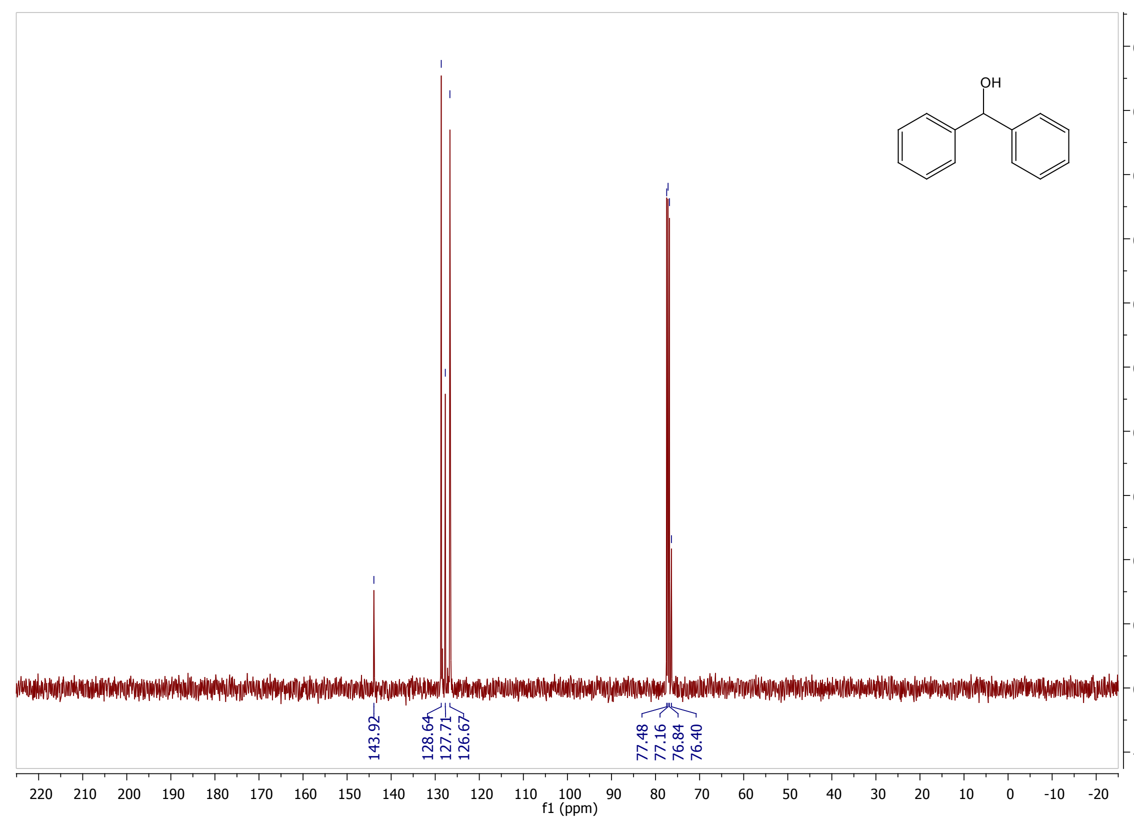
[1]H and [13]C spectra of **1e**.



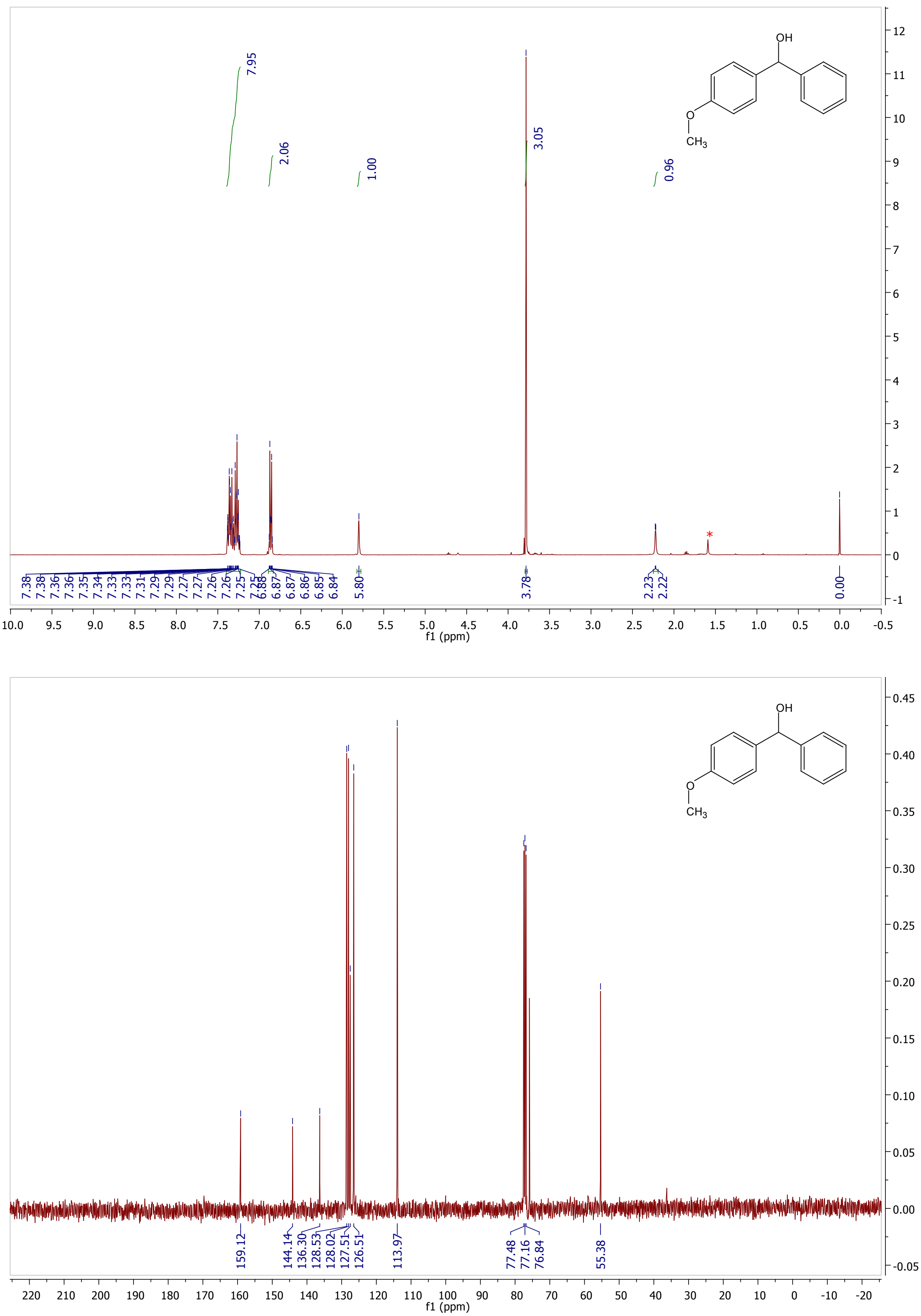


^{1}H and ^{13}C spectra of **1l**.

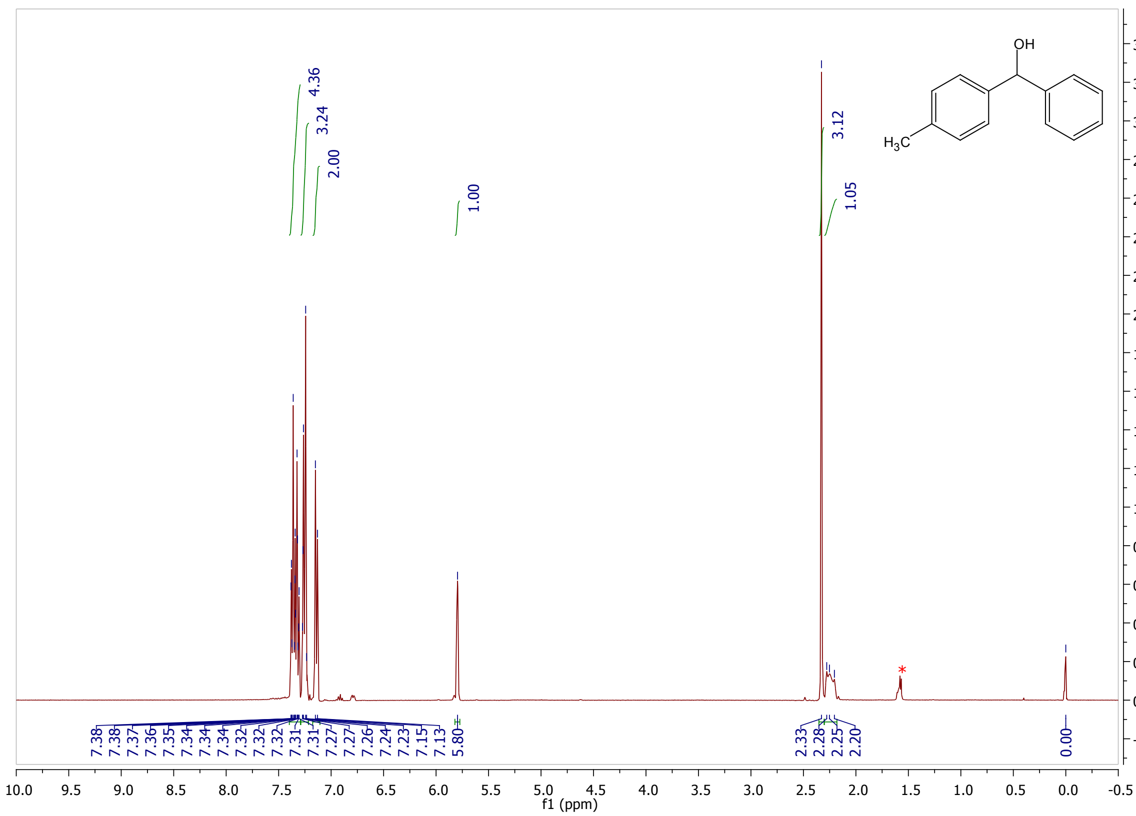


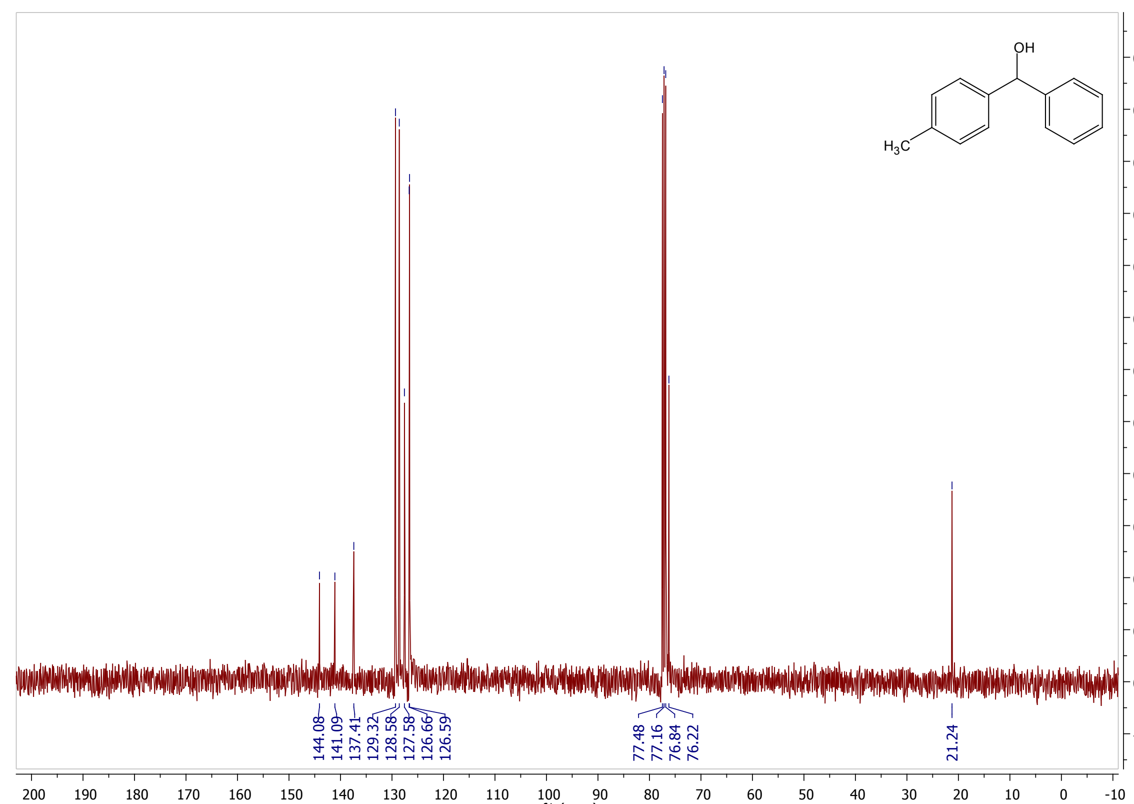


^{1}H and ^{13}C spectra of **8a**.

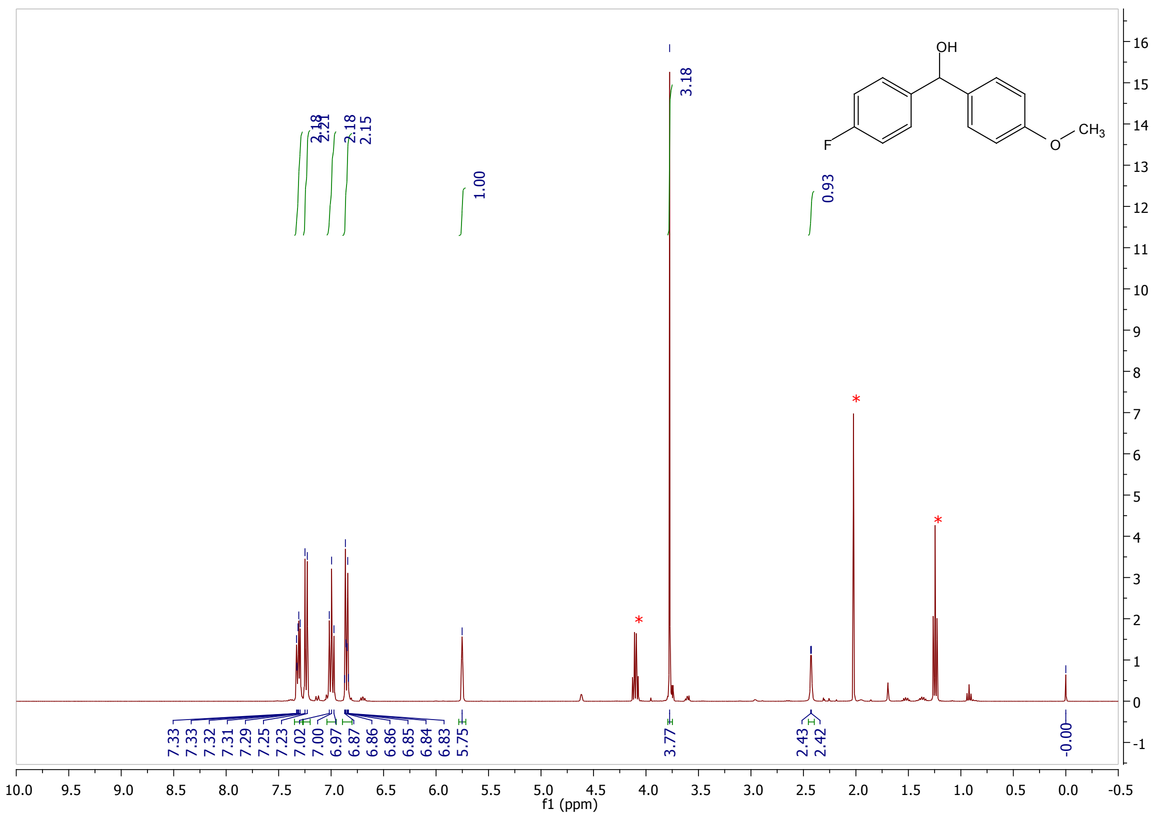


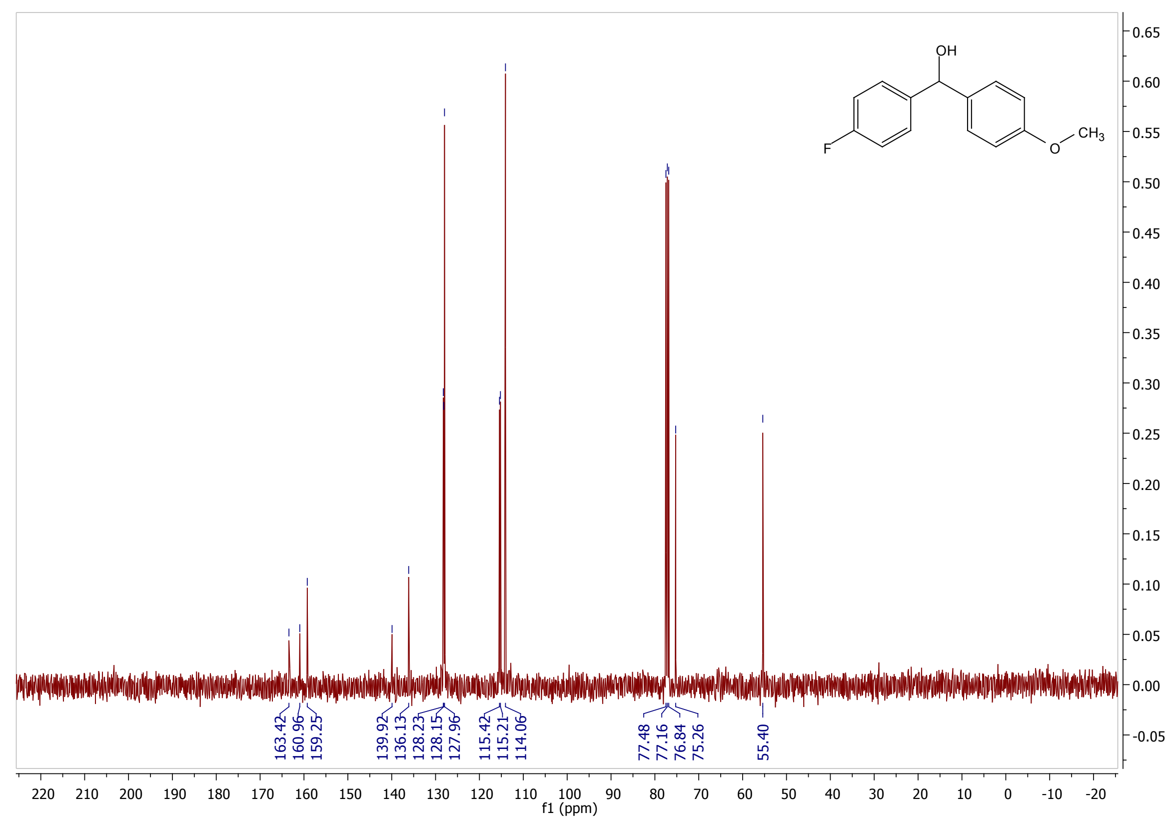
^{1}H and ^{13}C spectra of **8b**.



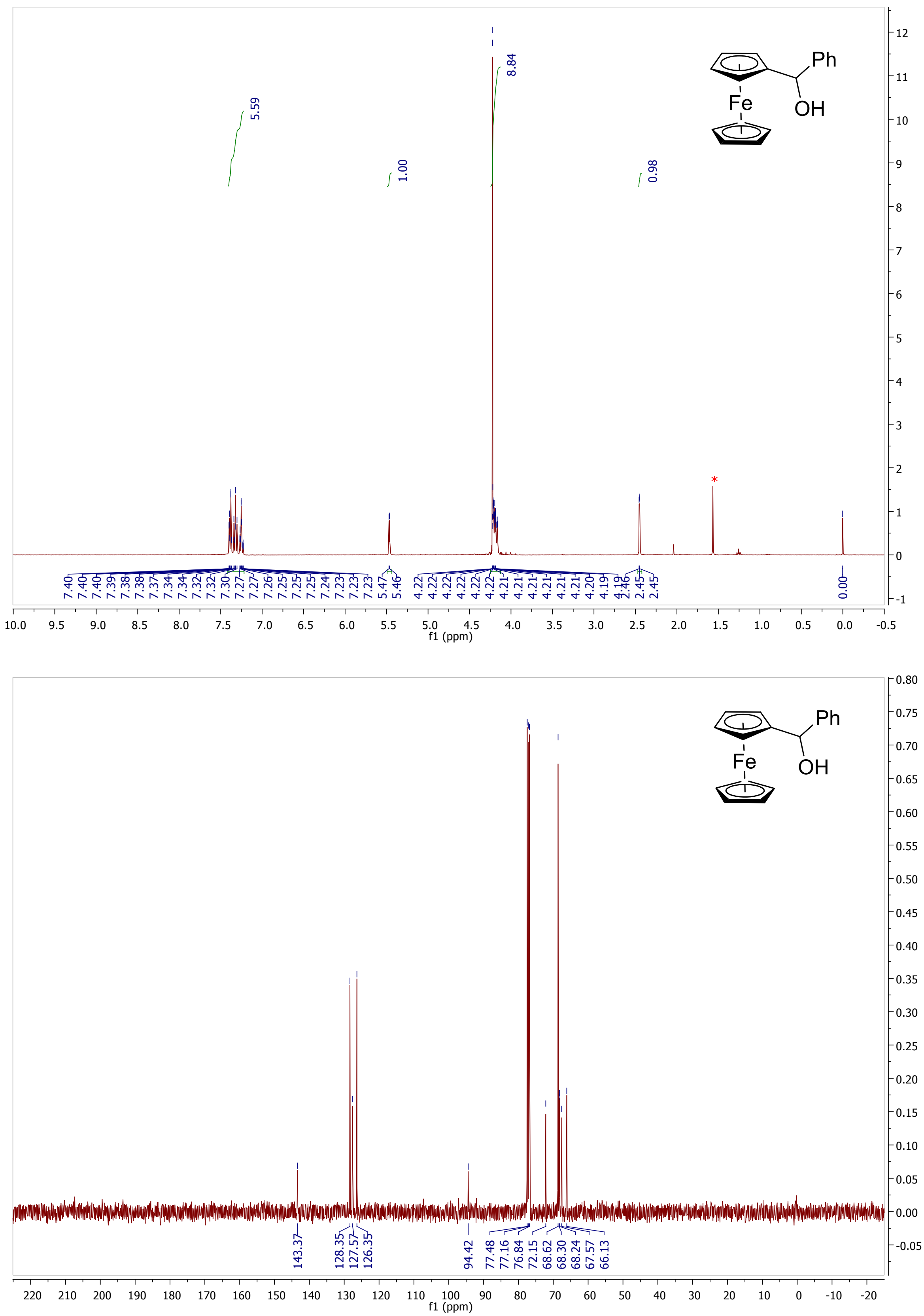


^1H and ^{13}C spectra of **8c**.

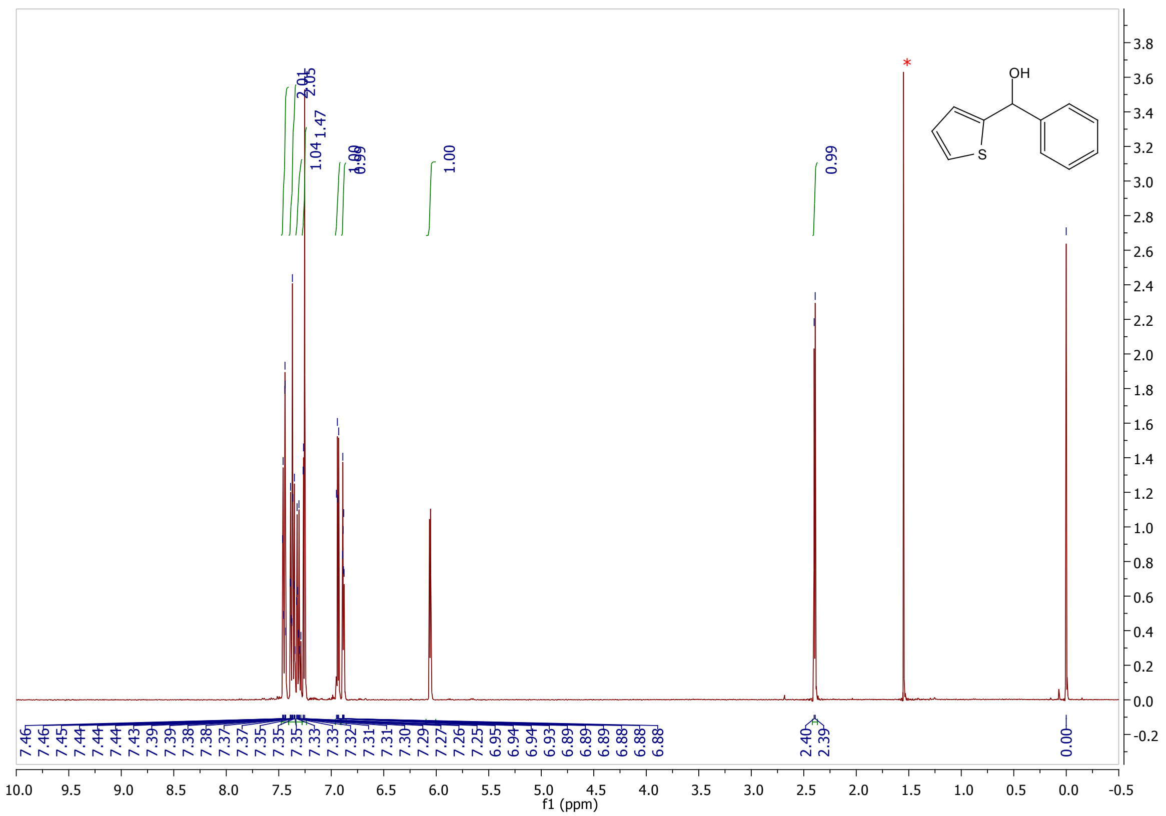


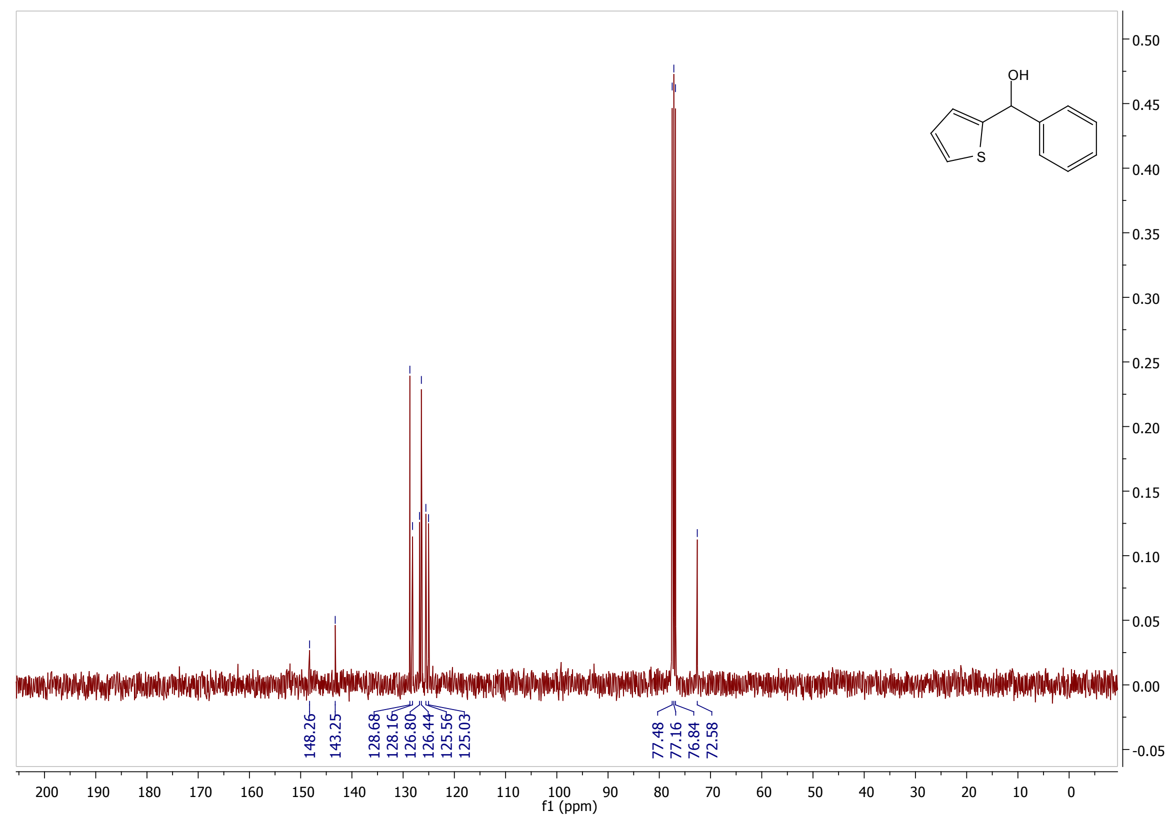


[1]H and [13]C spectra of **8d**.

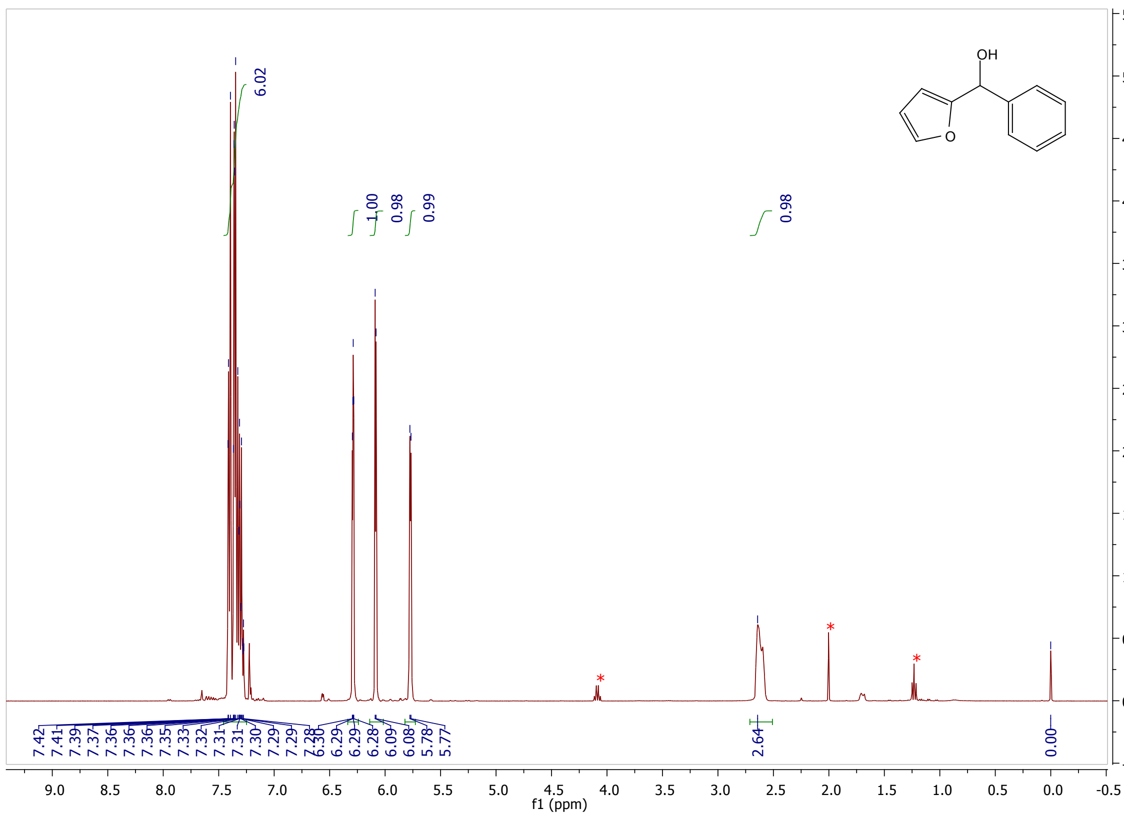


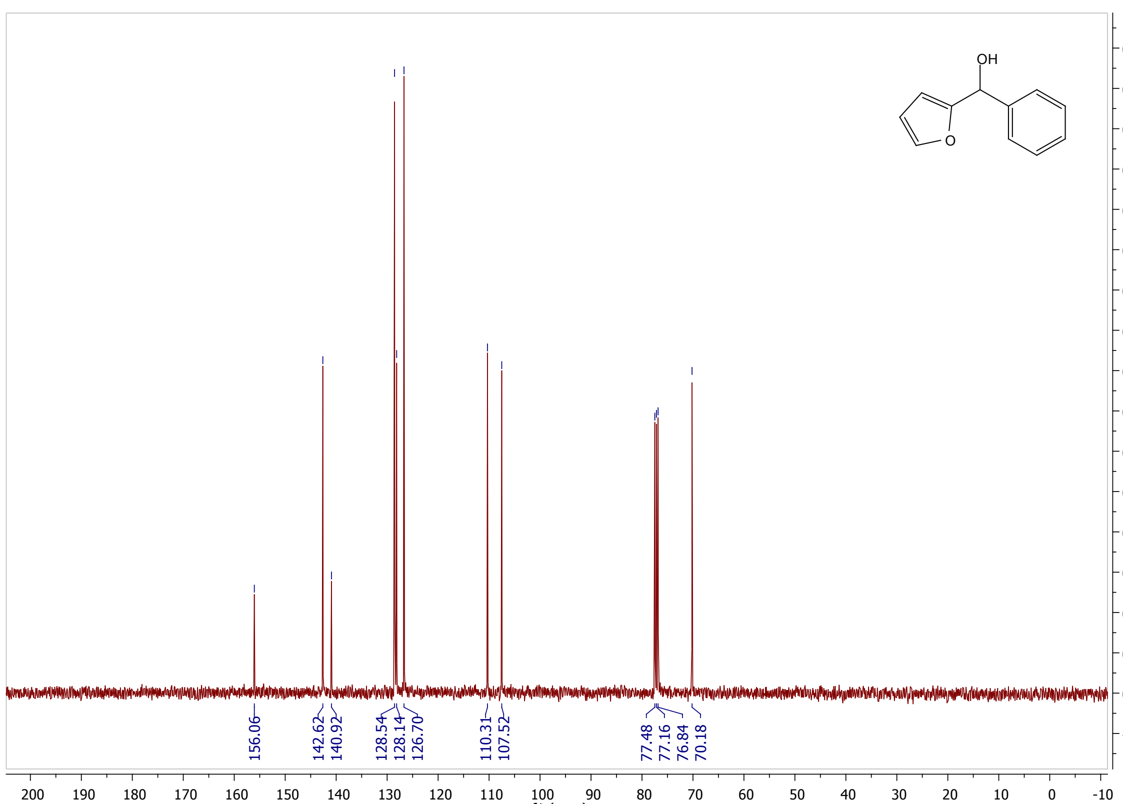
^{1}H and ^{13}C spectra of **8e**.



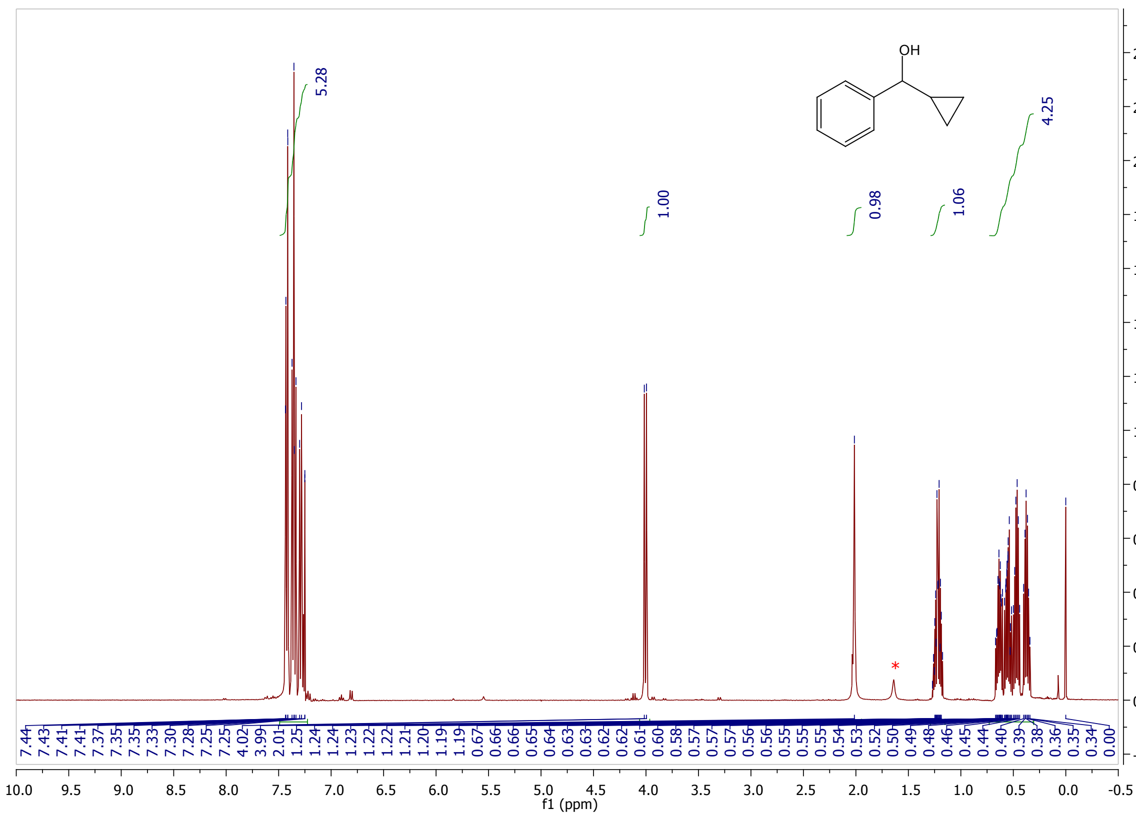


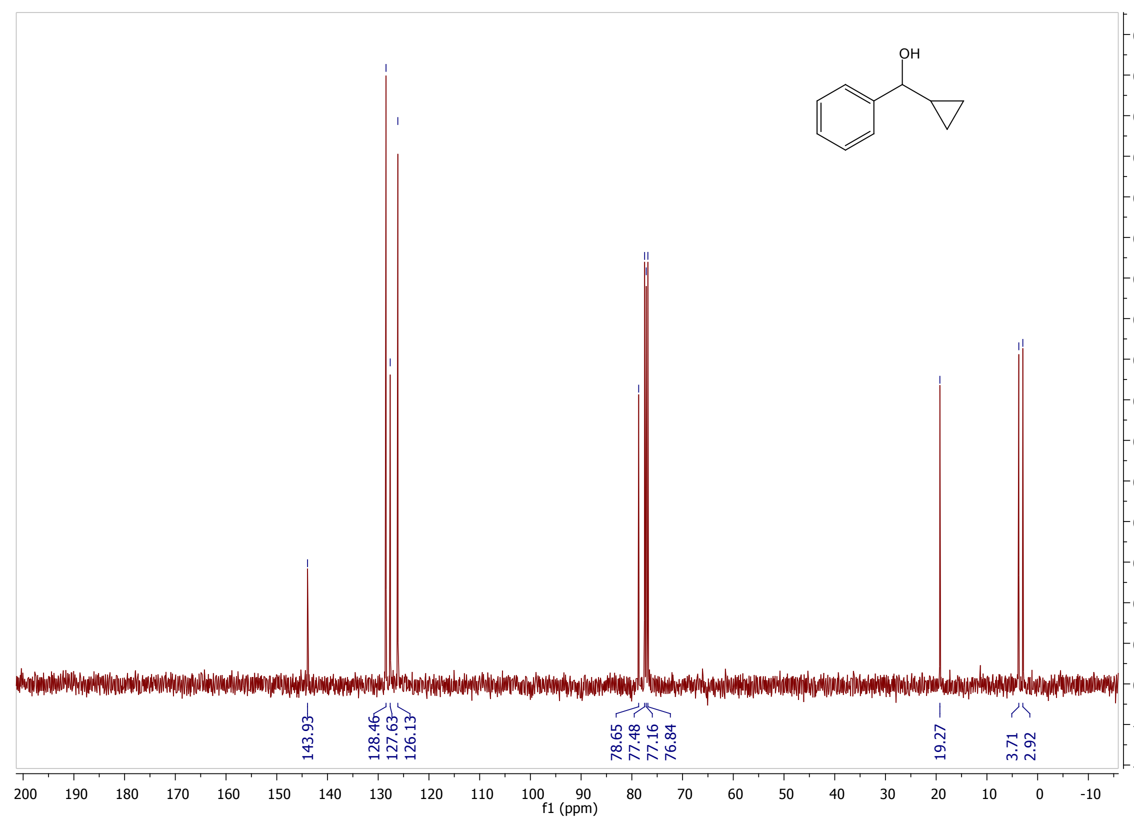
[1]H and [13]C spectra of **8f**.



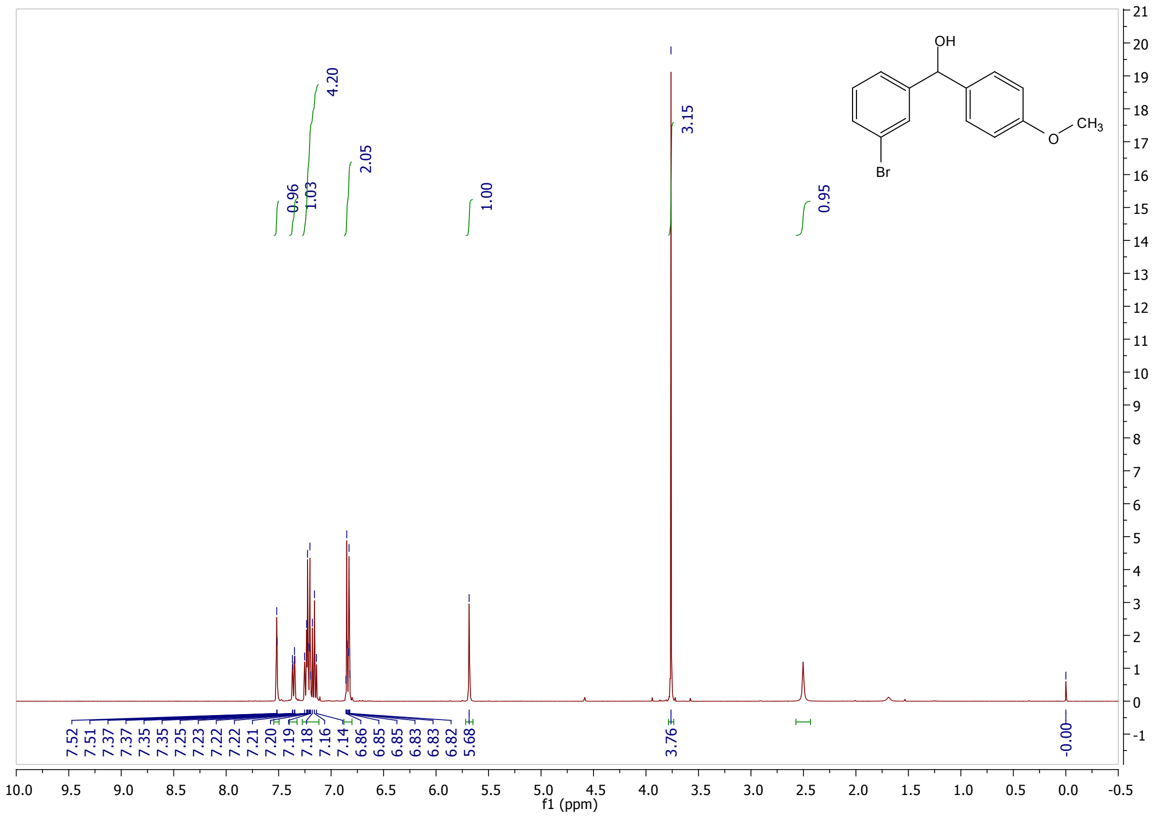


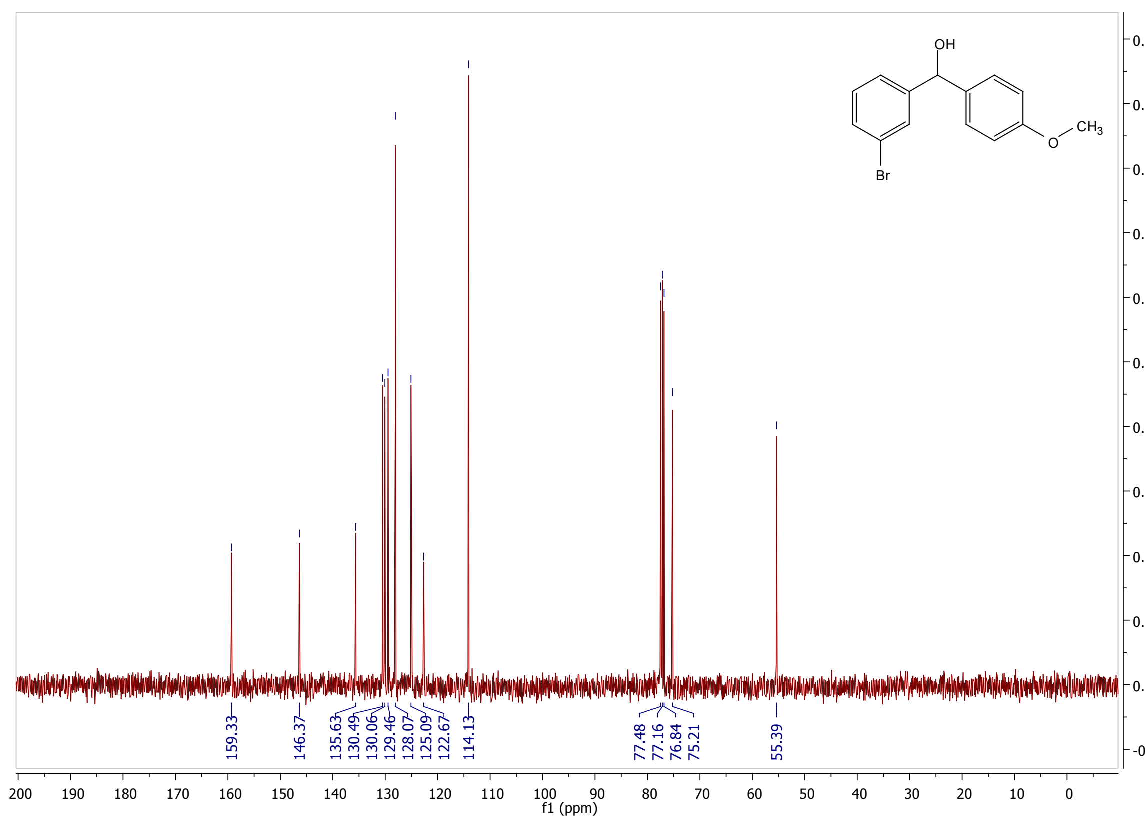
[1]H and [13]C spectra of **8g**.



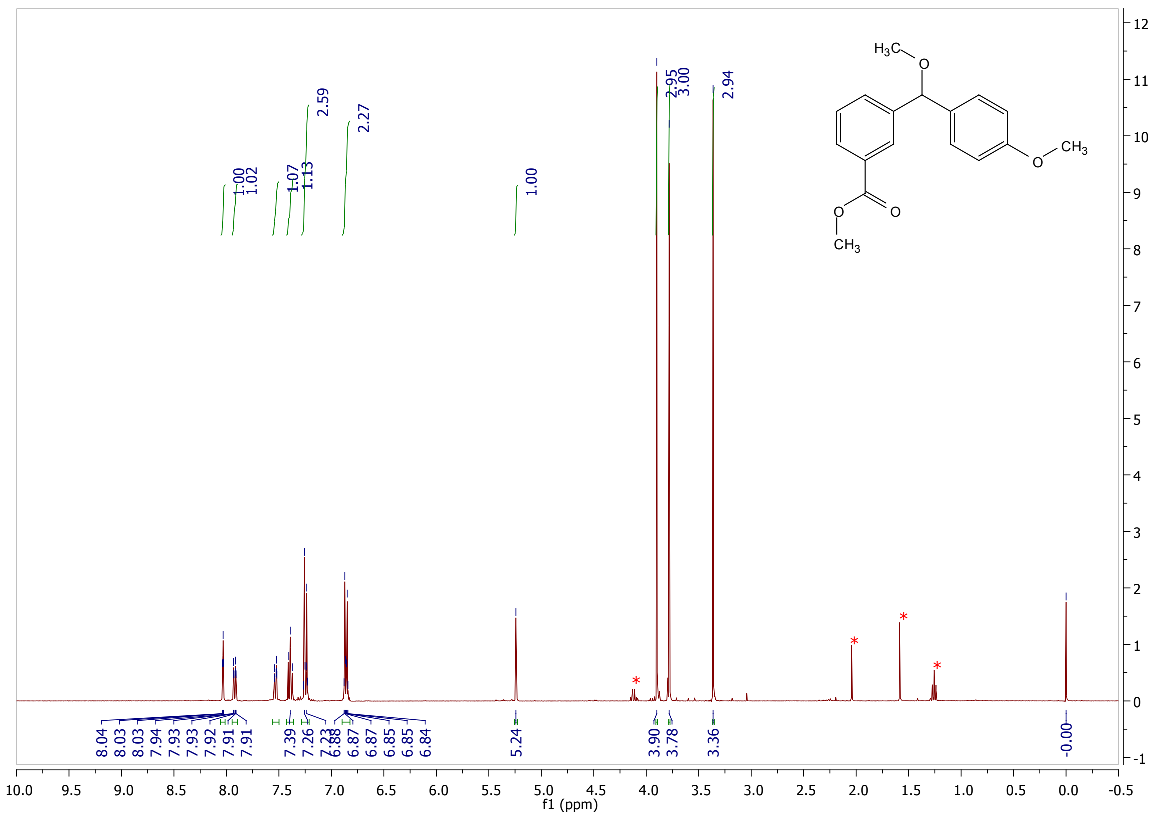


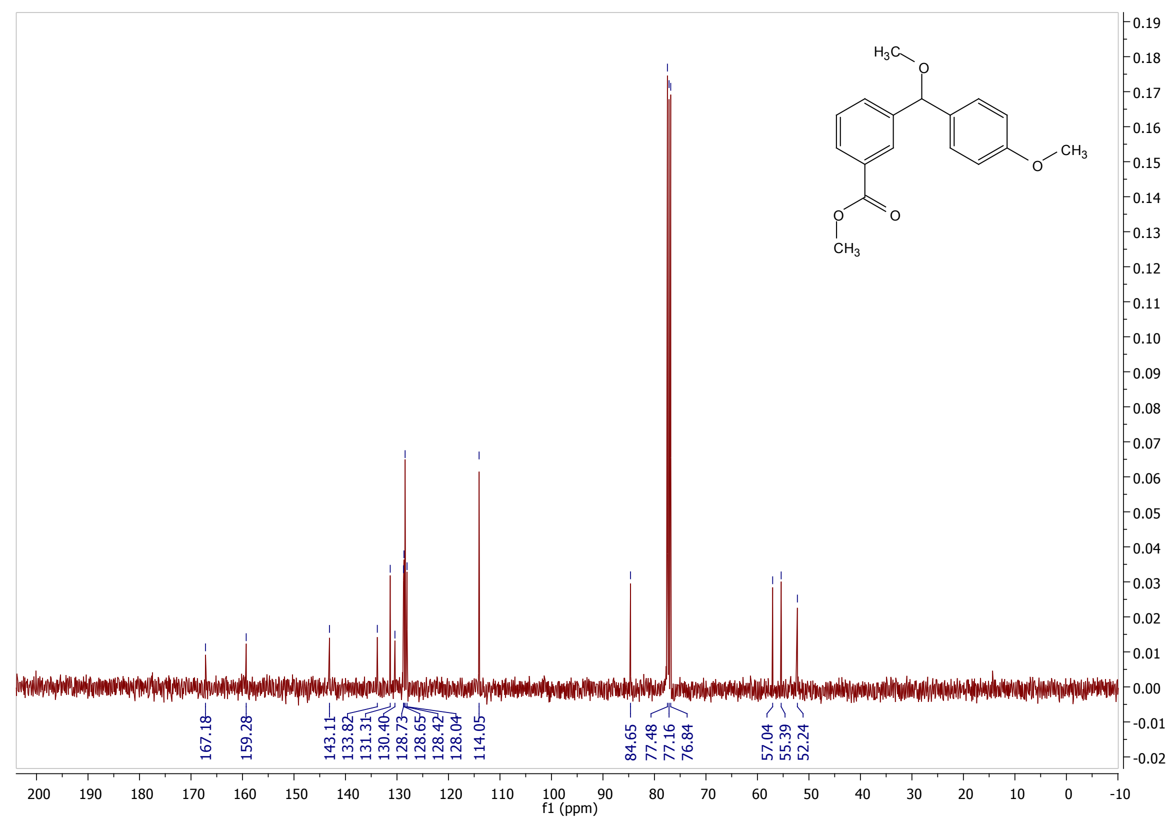
^{1}H and ^{13}C spectra of **8h**.



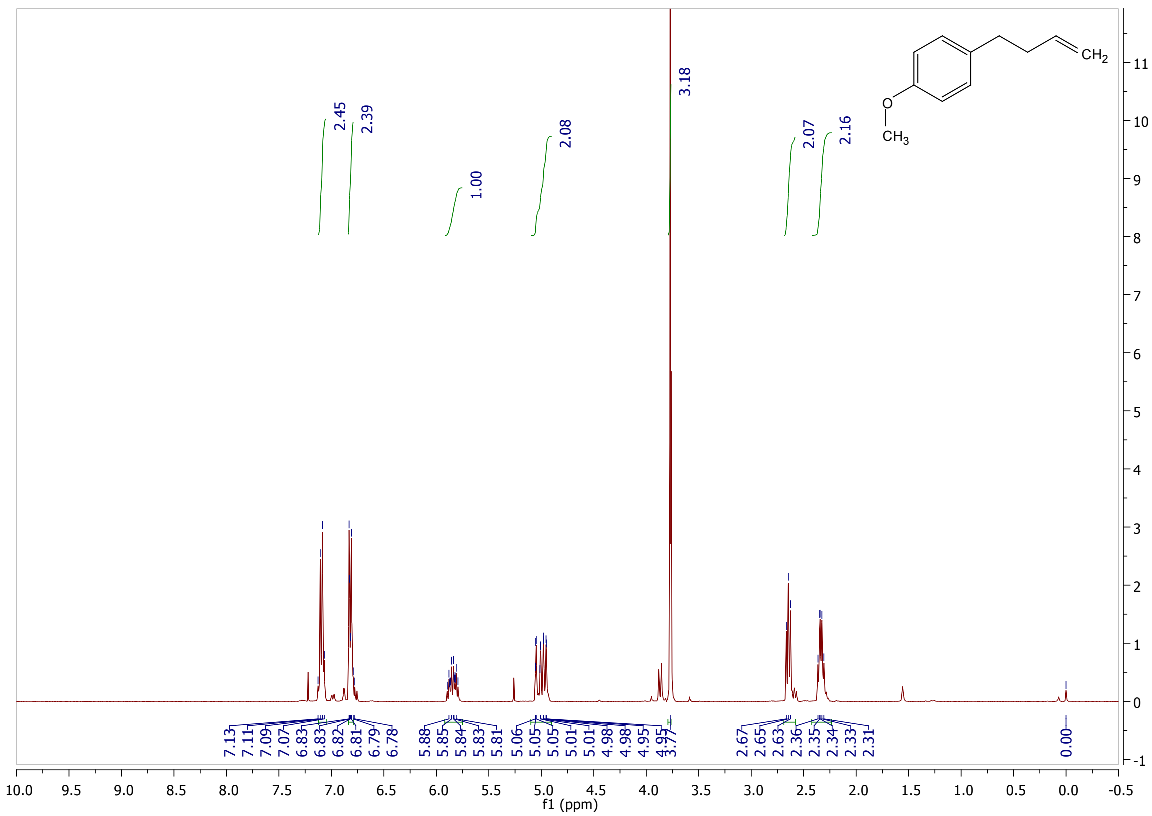


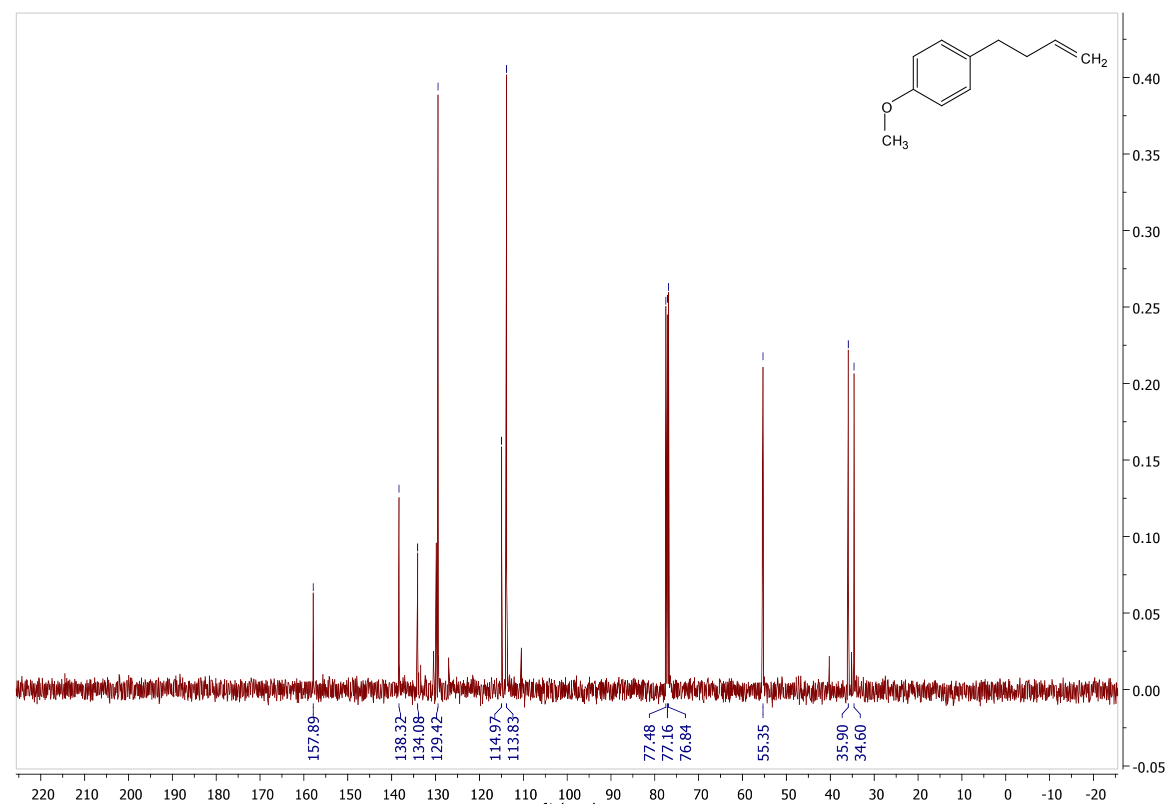
^{1}H and ^{13}C spectra of **8i**.



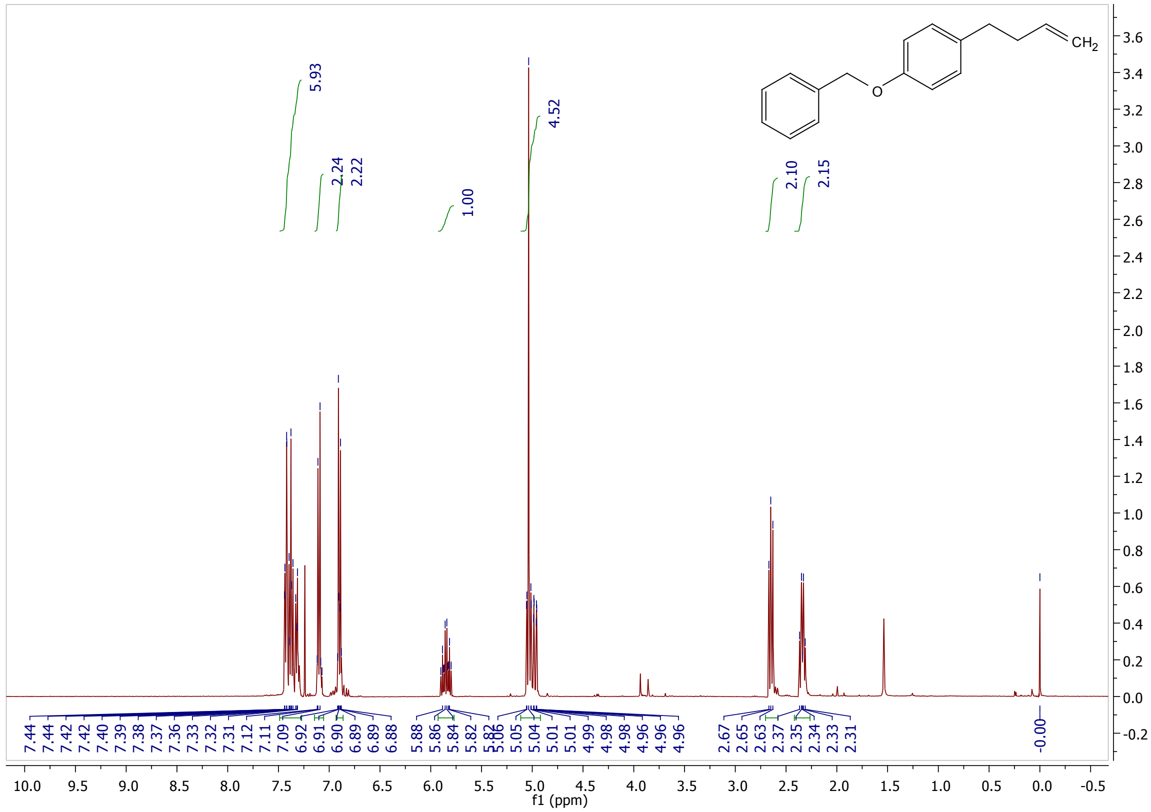


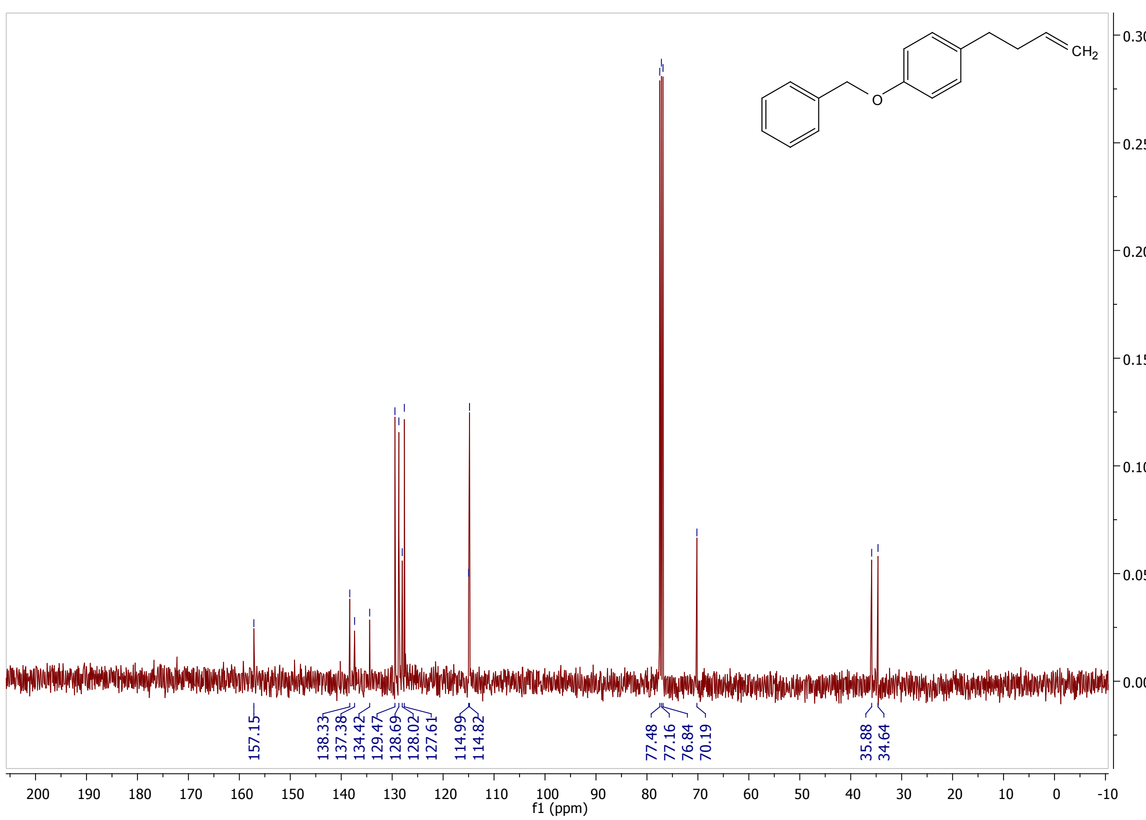
[1]H and [13]C spectra of **8j**.



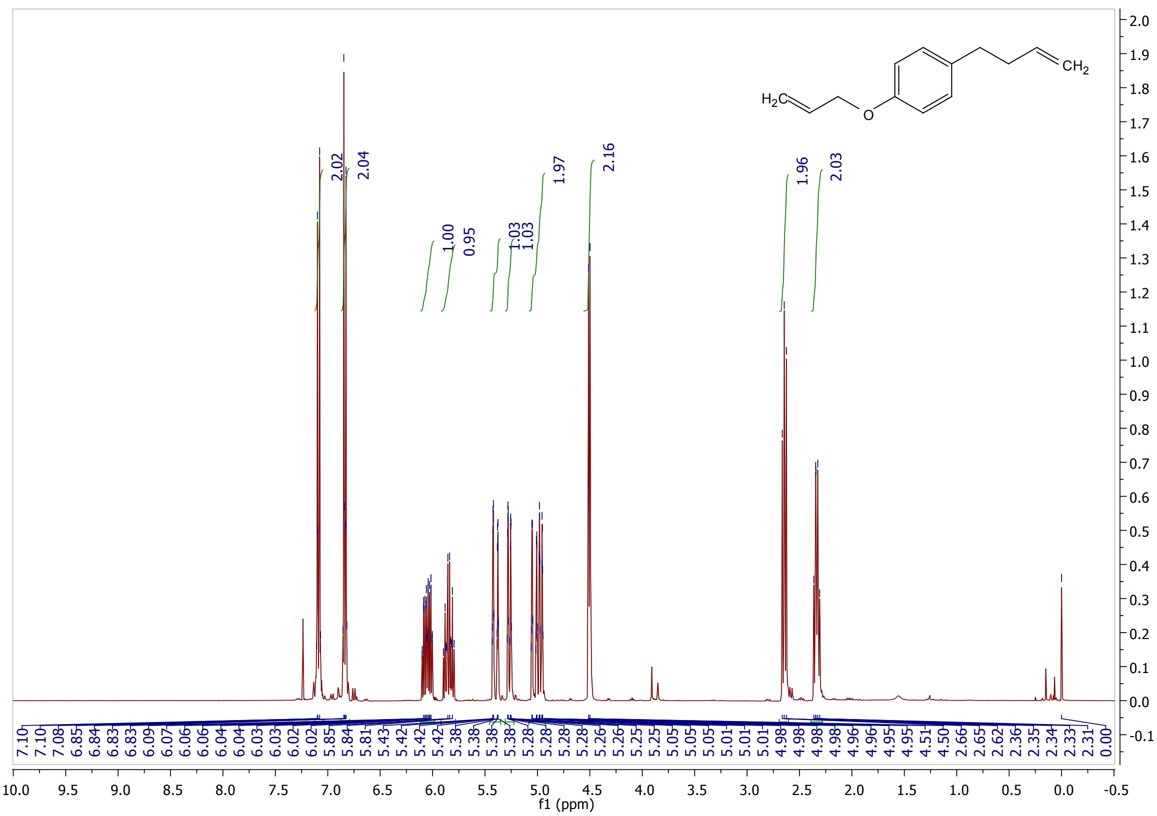


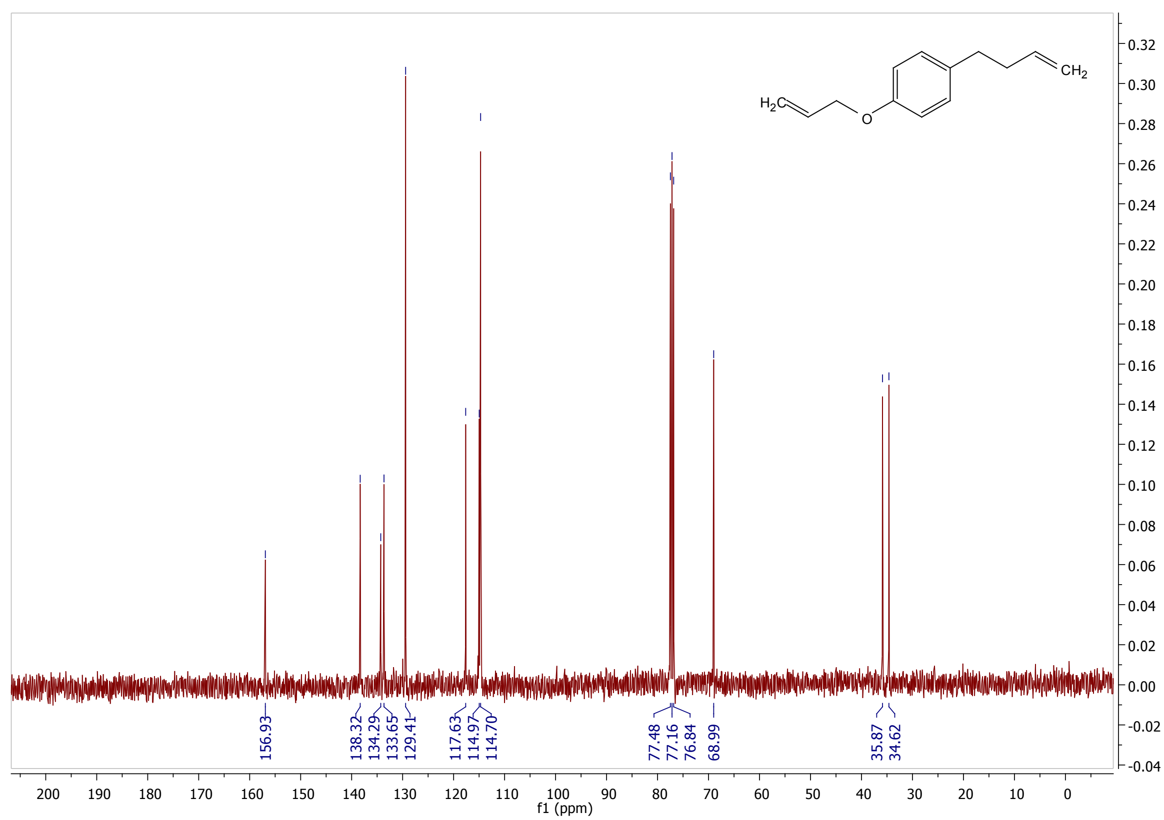
^{1}H and ^{13}C spectra of **2a**.



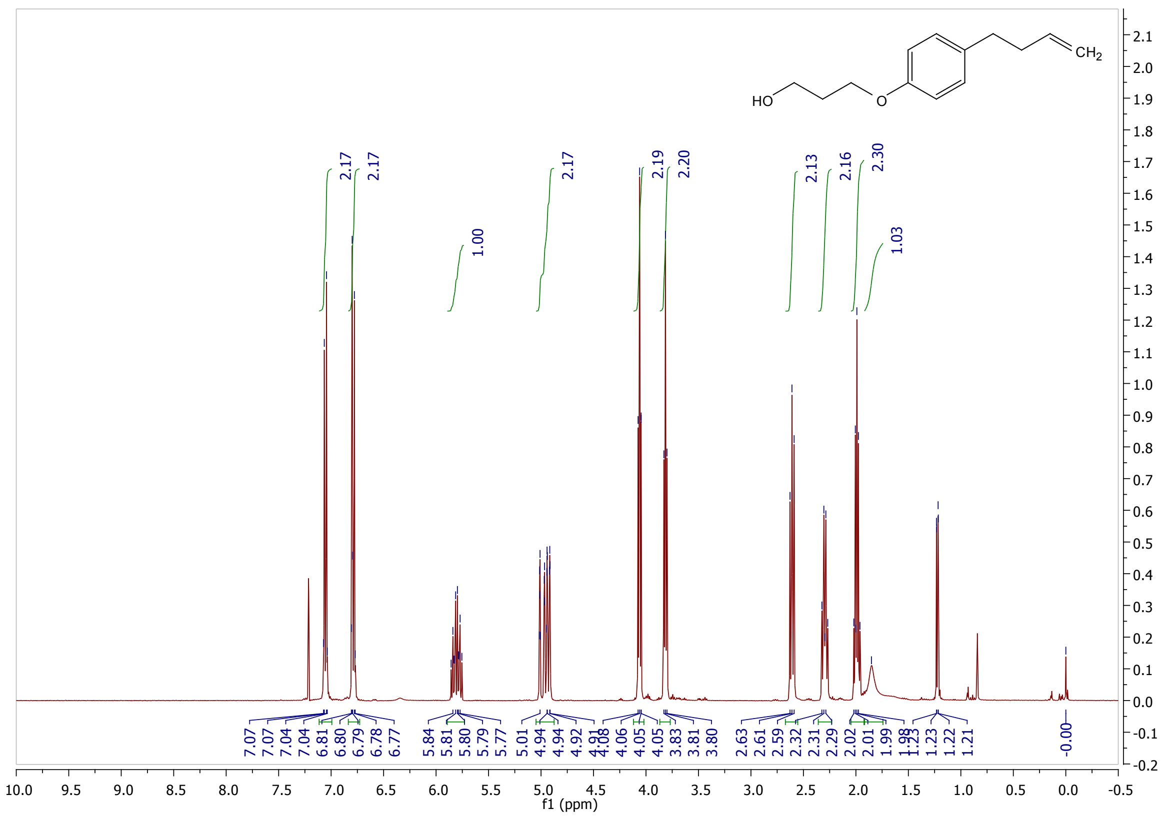


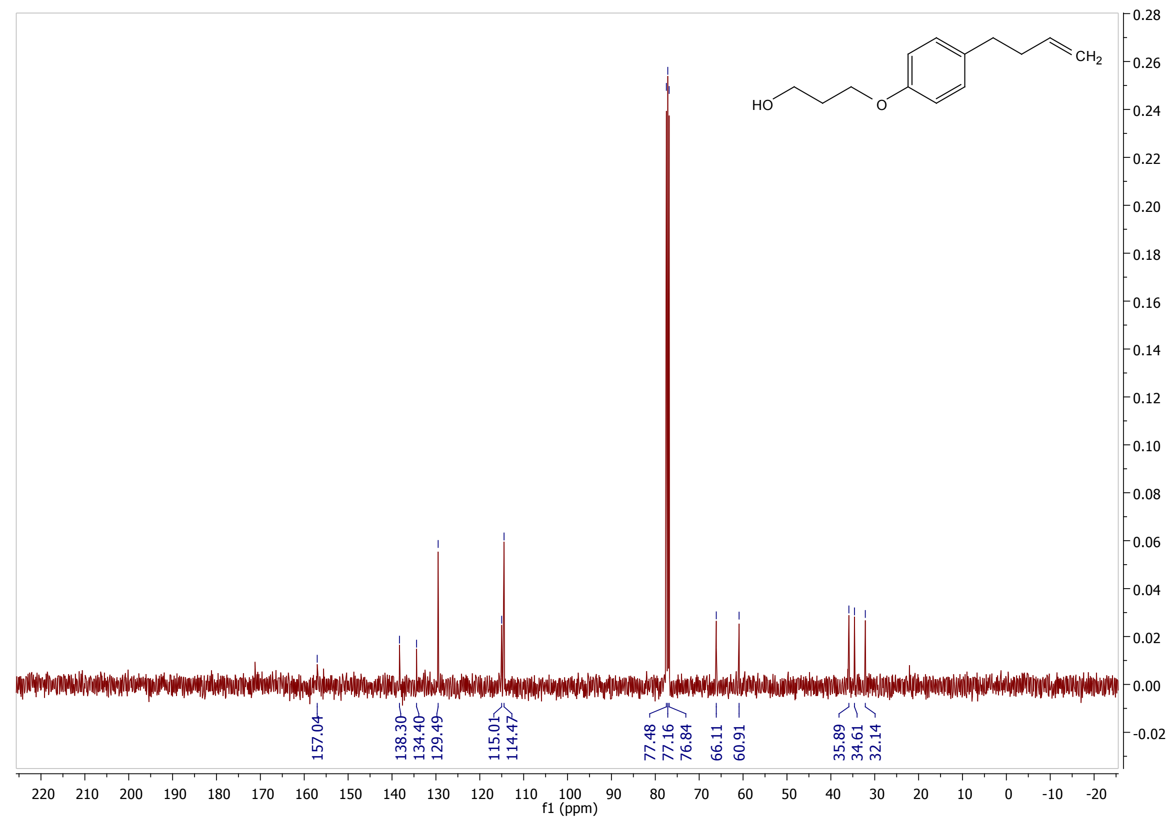
[1]H and [13]C spectra of **2c**.



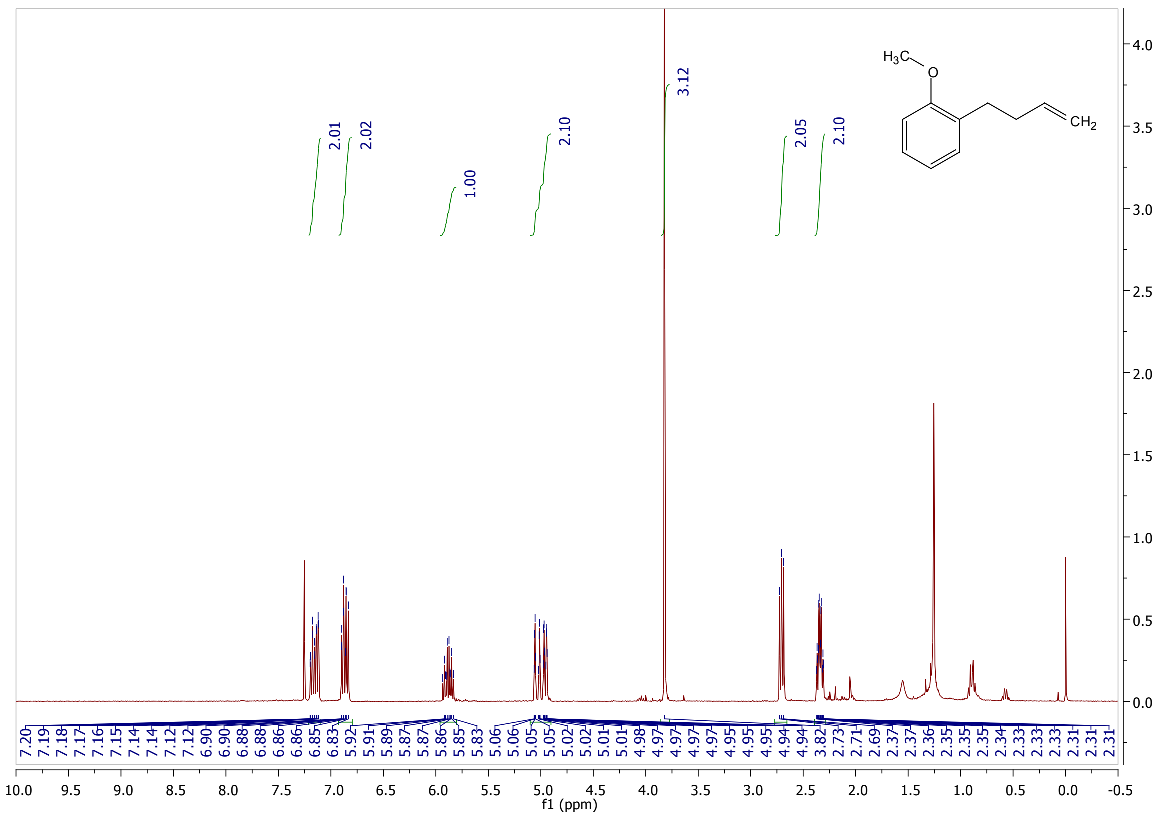


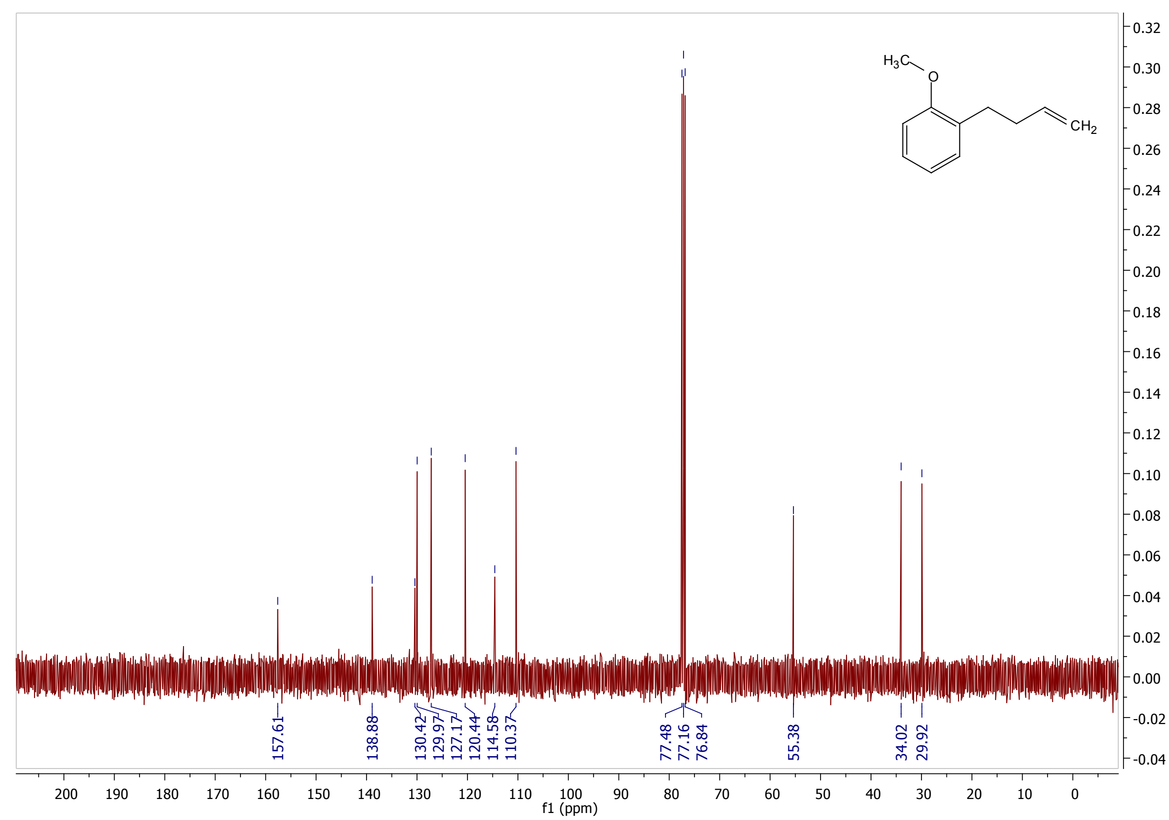
^1H and ^{13}C spectra of **2d**.



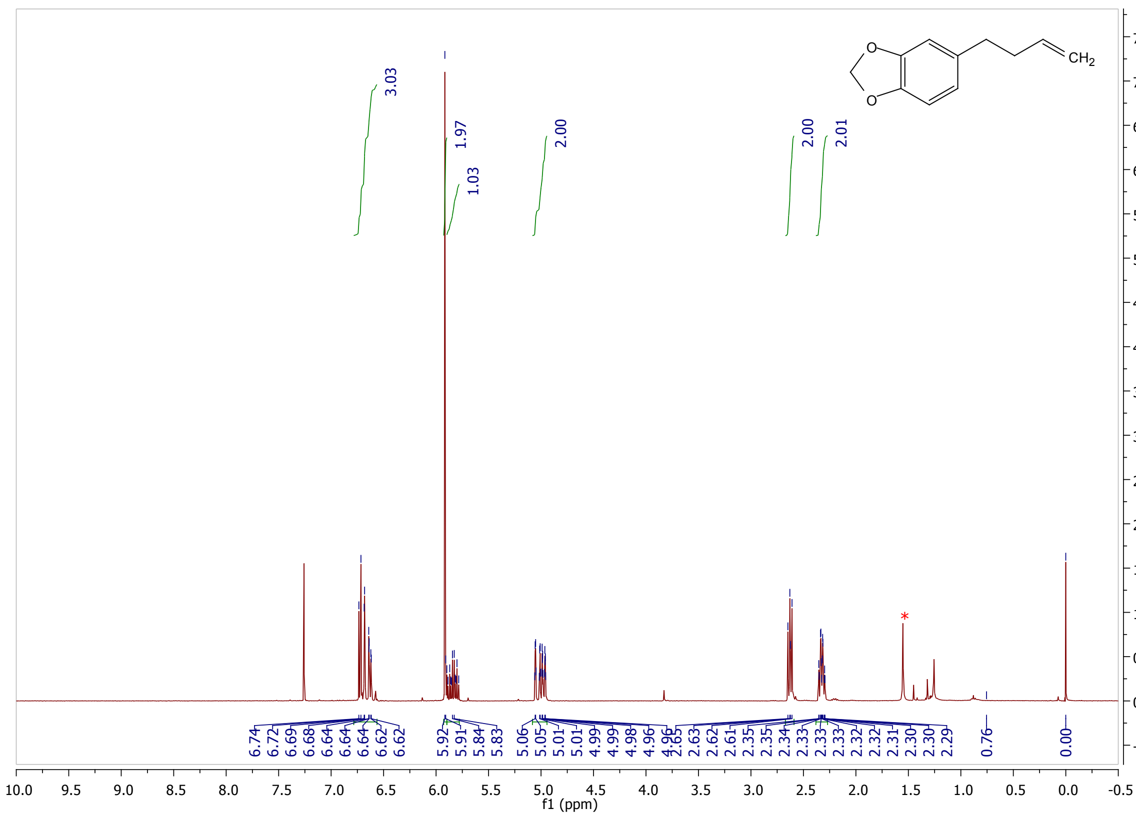


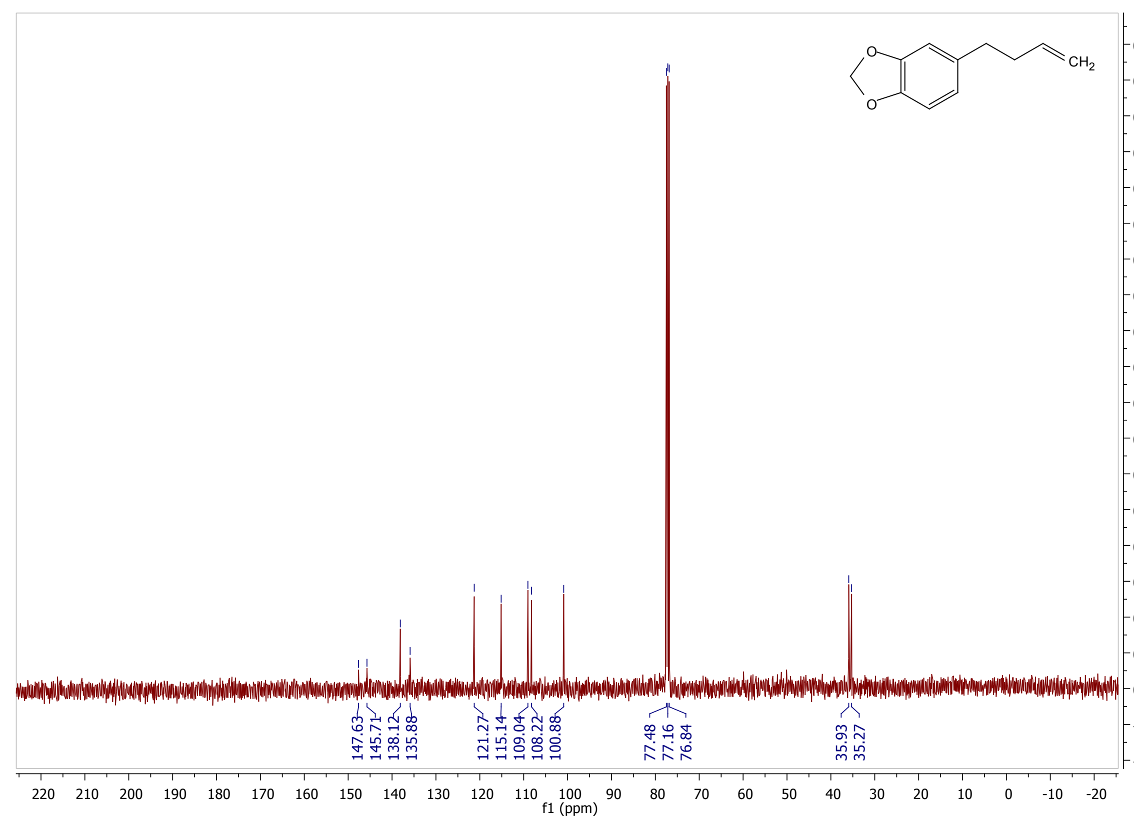
^{1}H and ^{13}C spectra of **2f**.



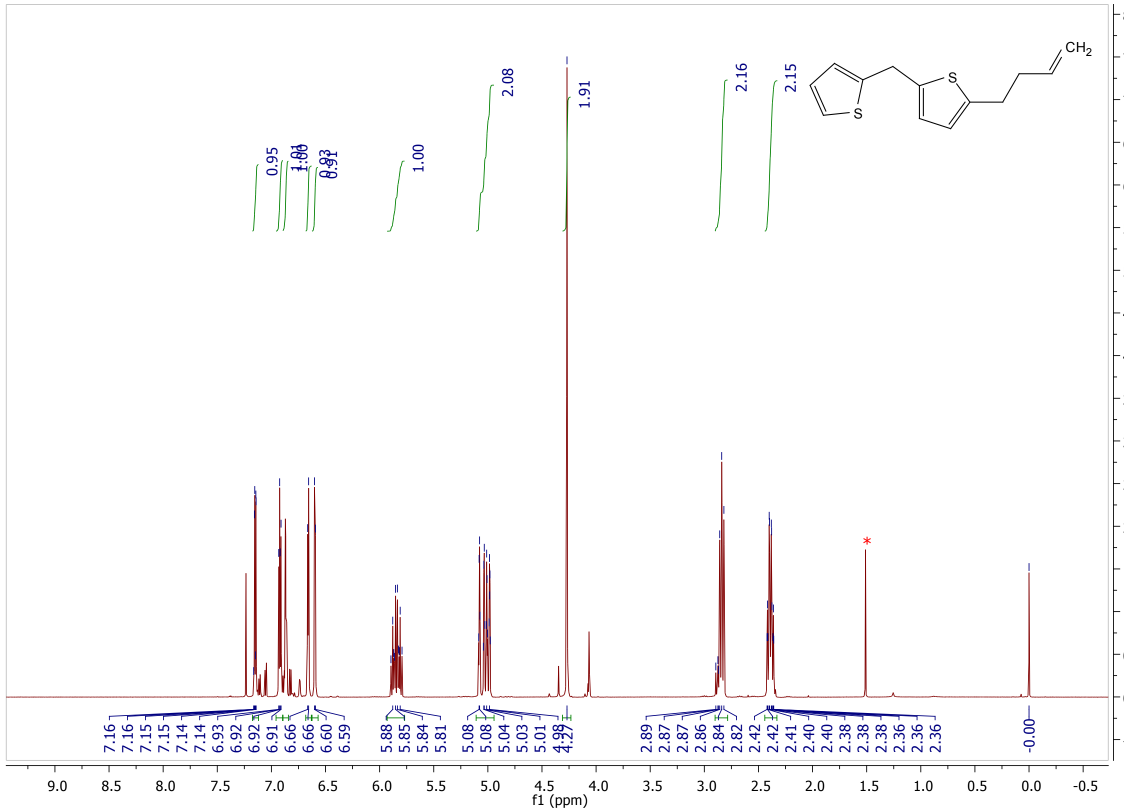


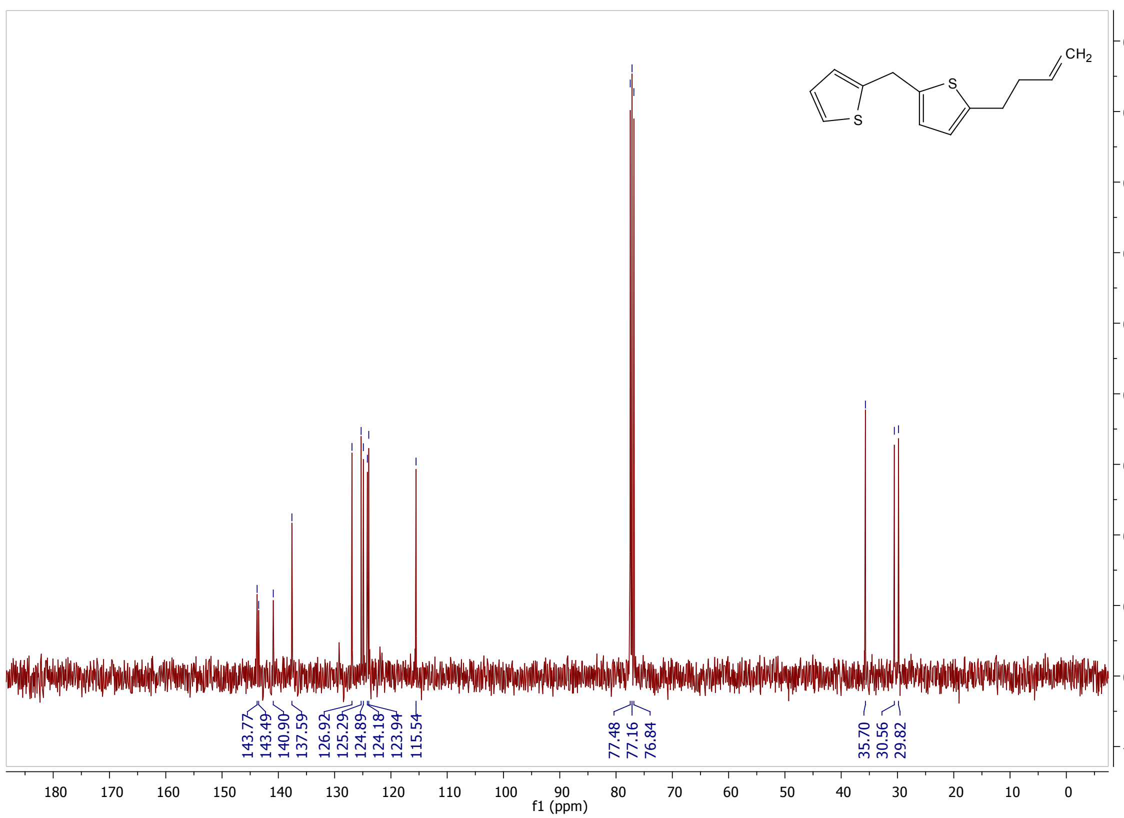
[1]H and [13]C spectra of **2h**.



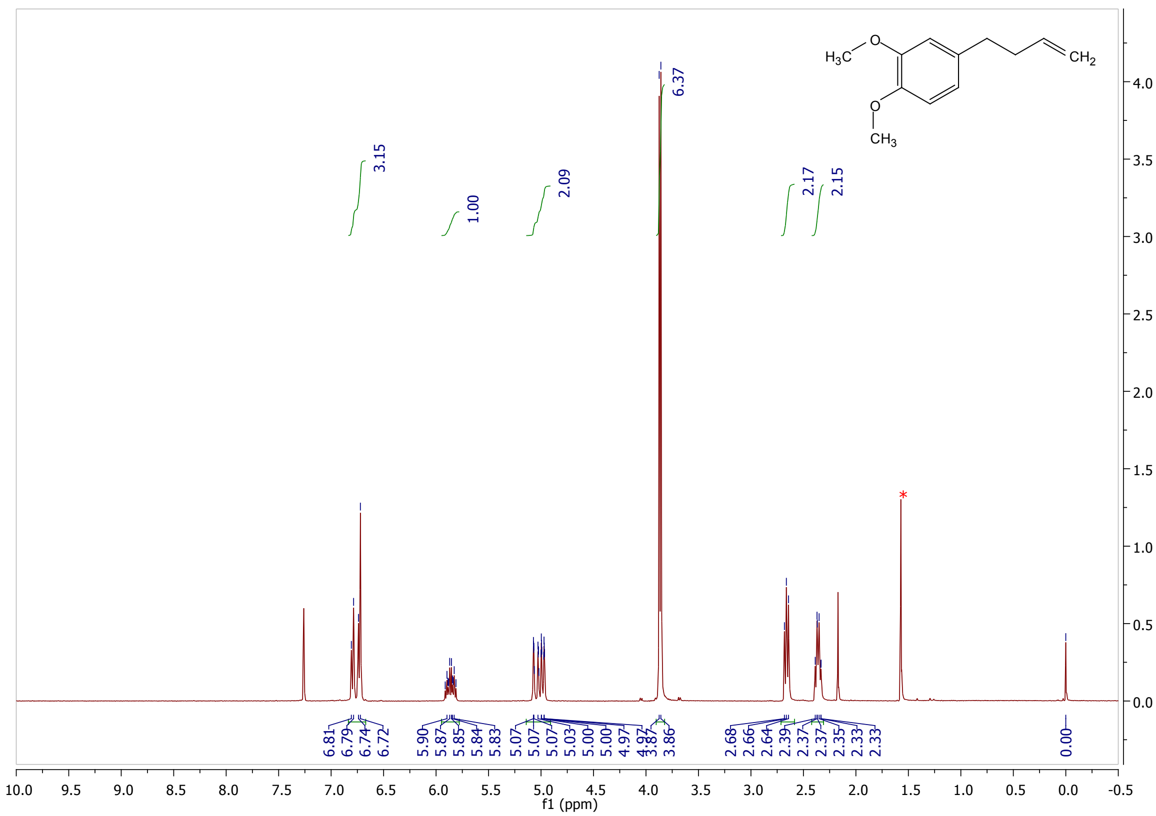


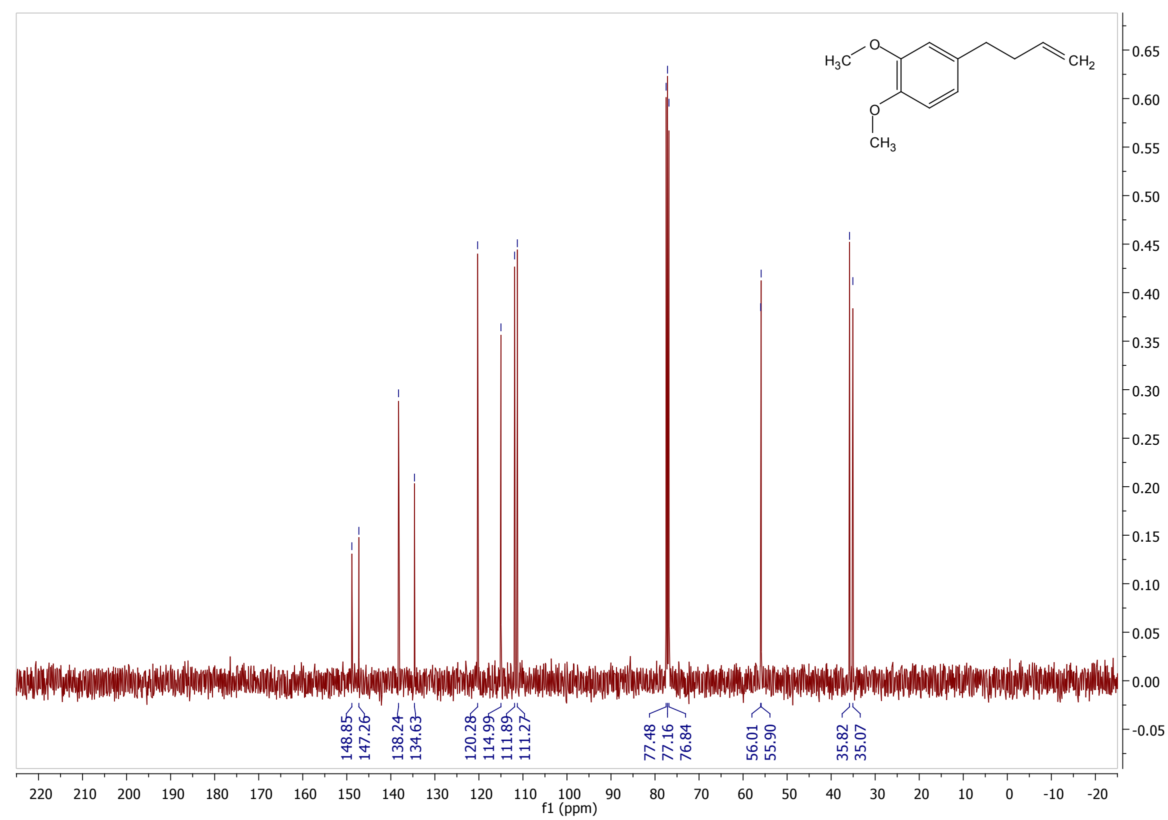
[1]H and [13]C spectra of **2j**.



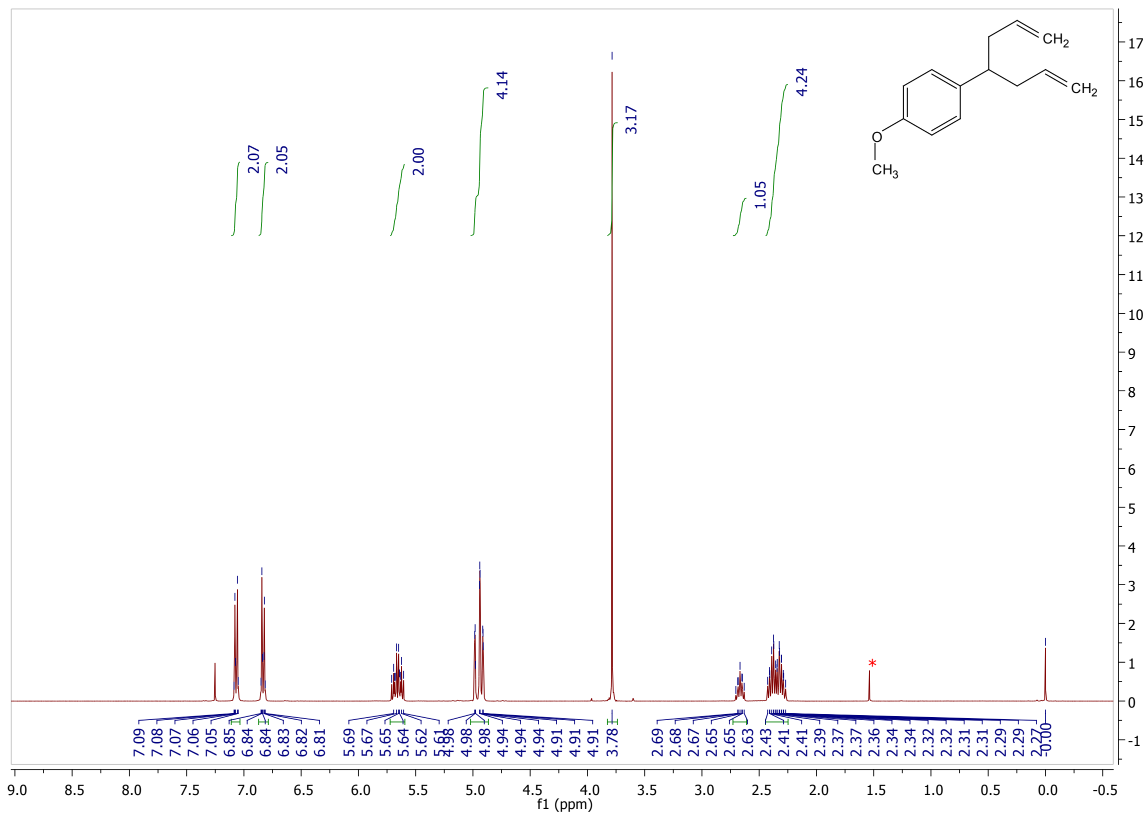


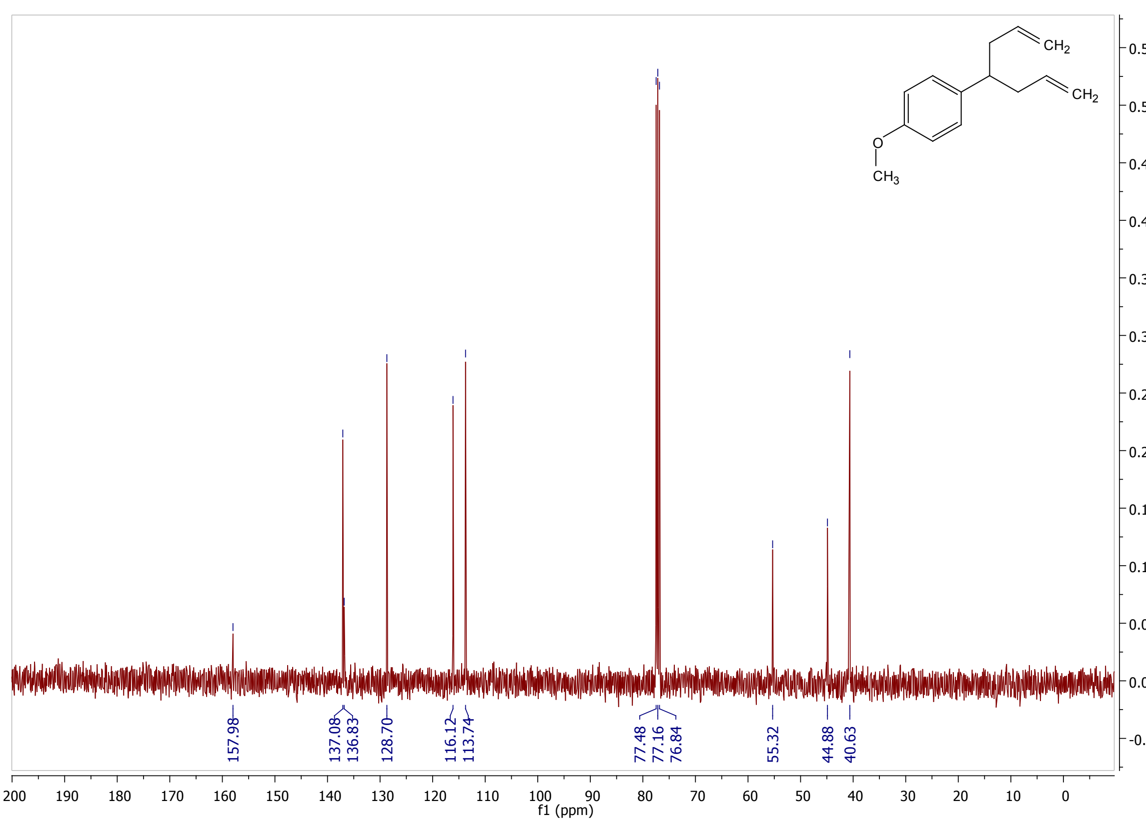
[1]H and [13]C spectra of **2l’**.



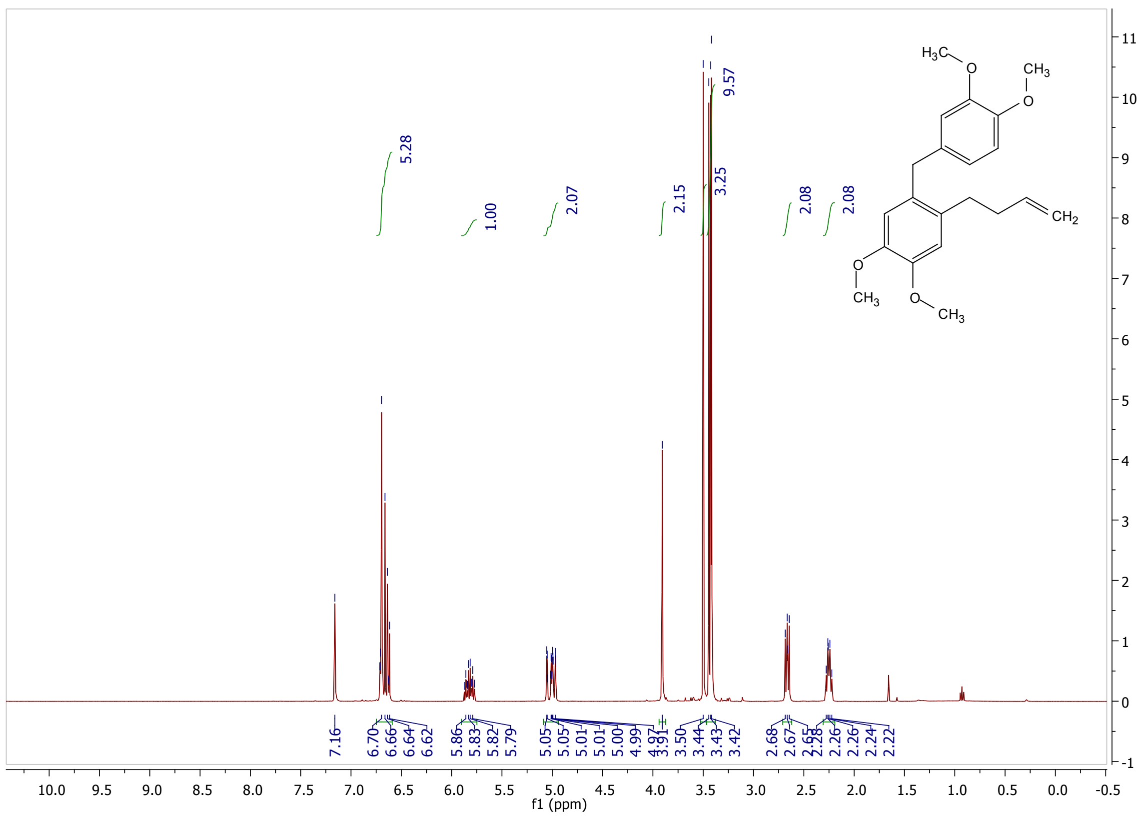


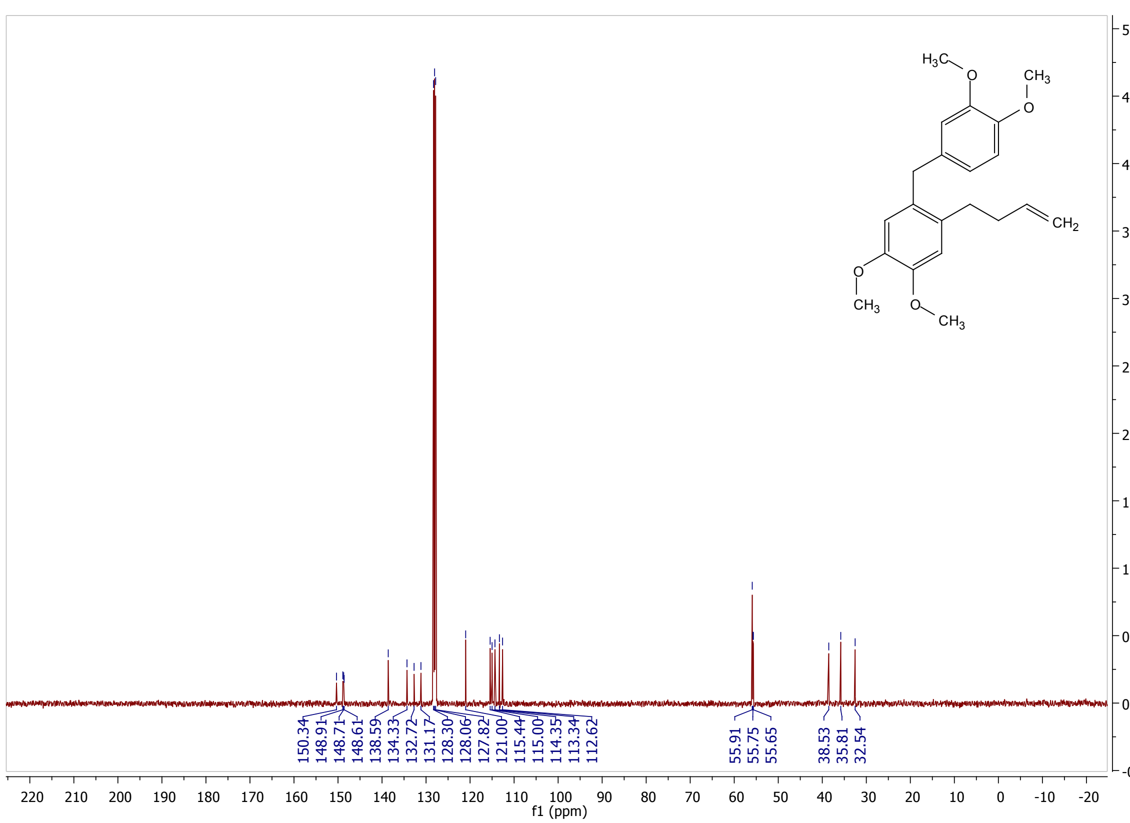
^1H and ^{13}C spectra of **2m**.



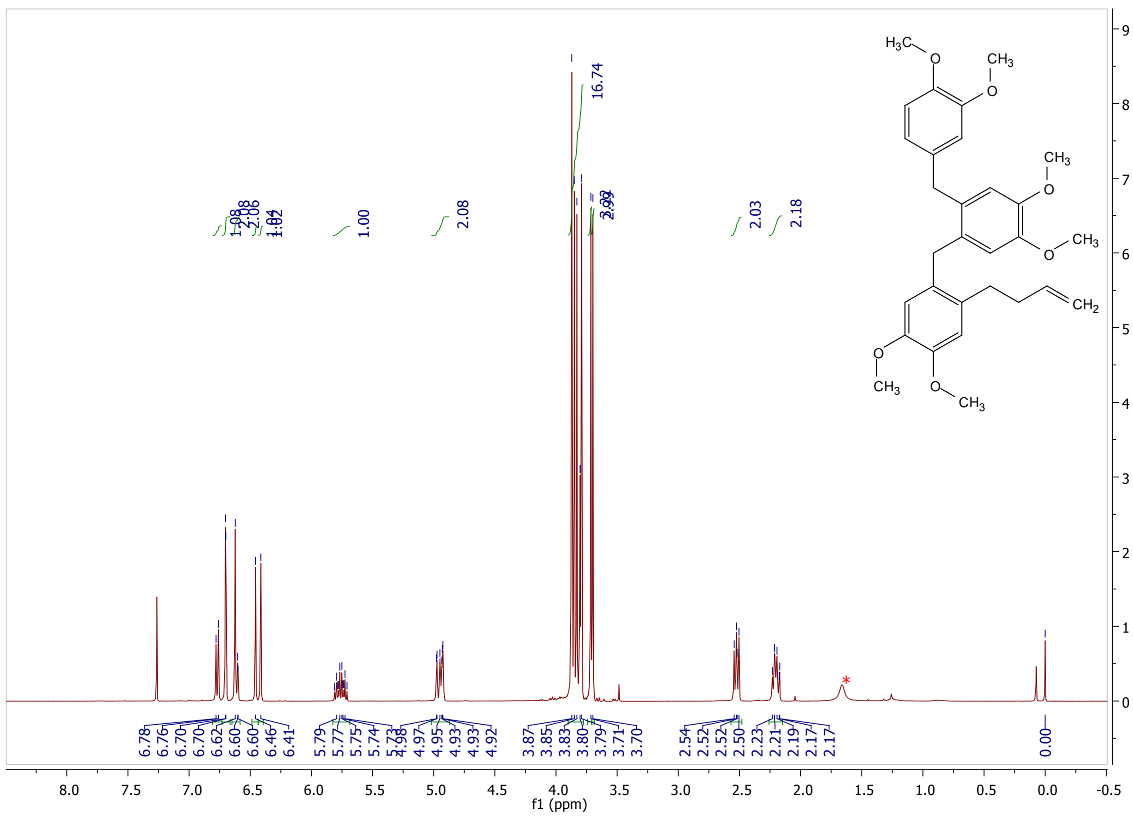


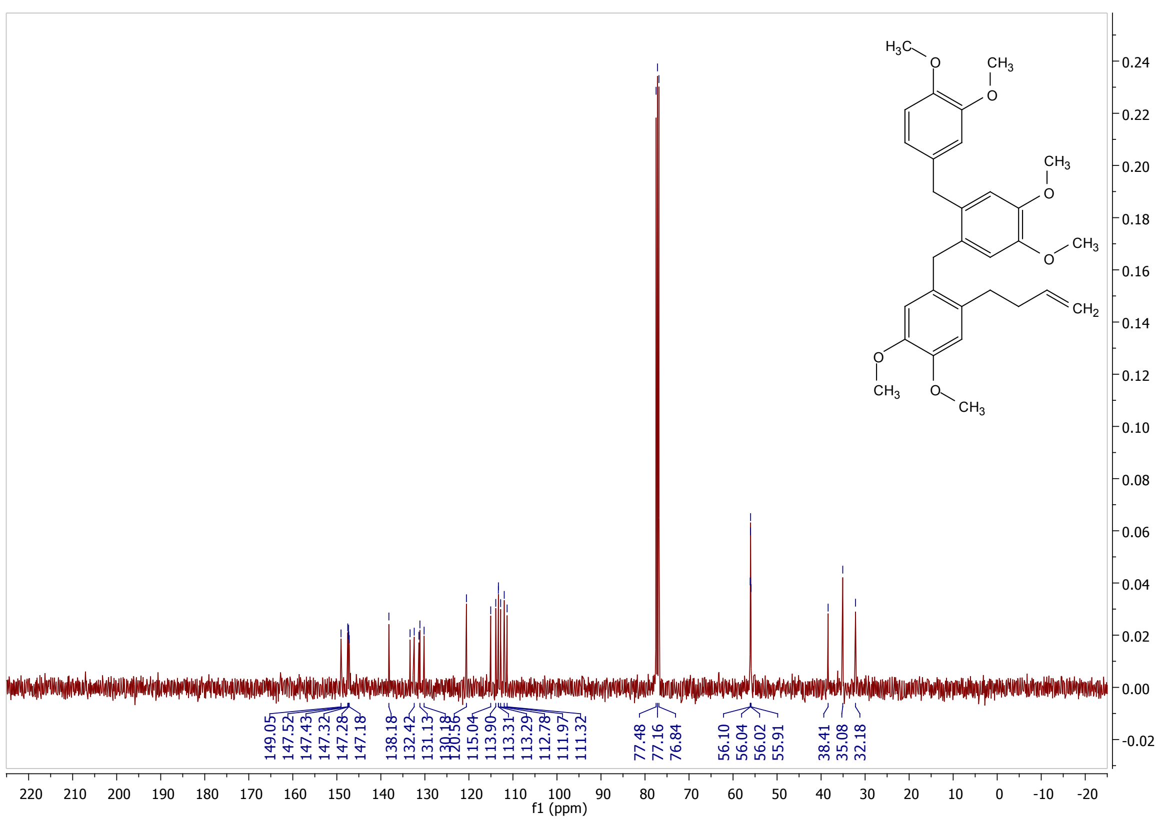
[1]H and [13]C spectra of **4**.



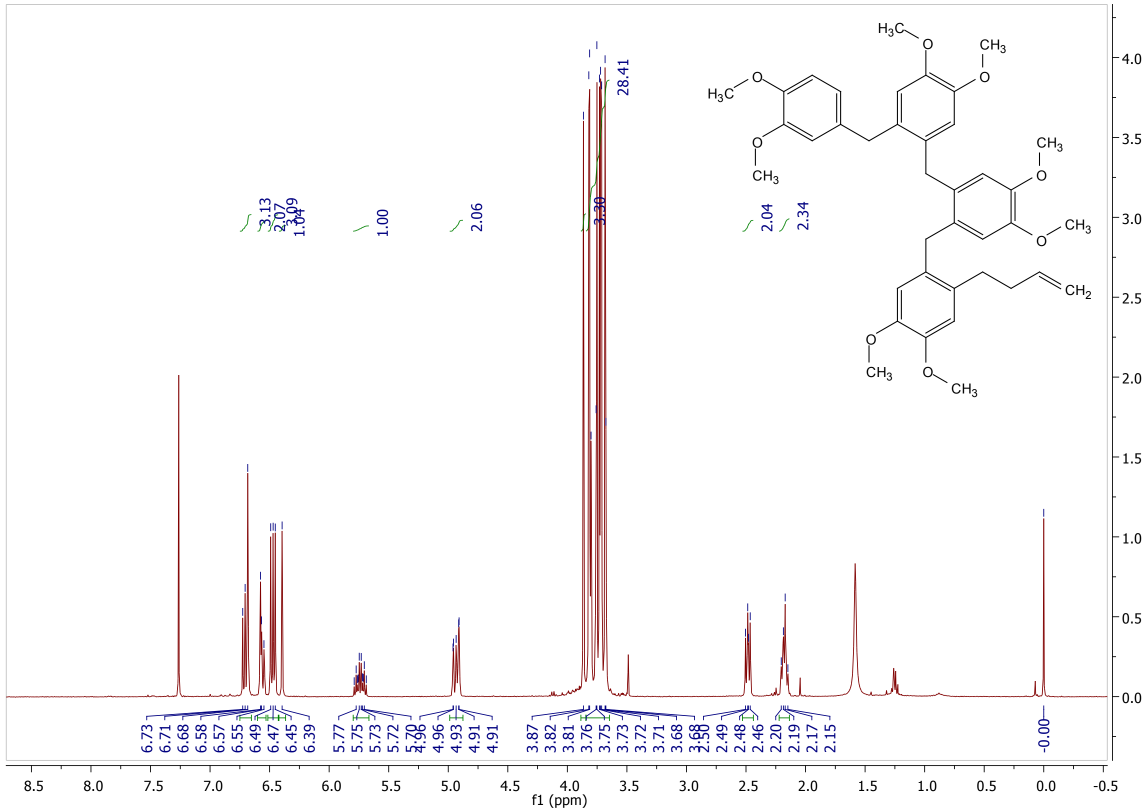


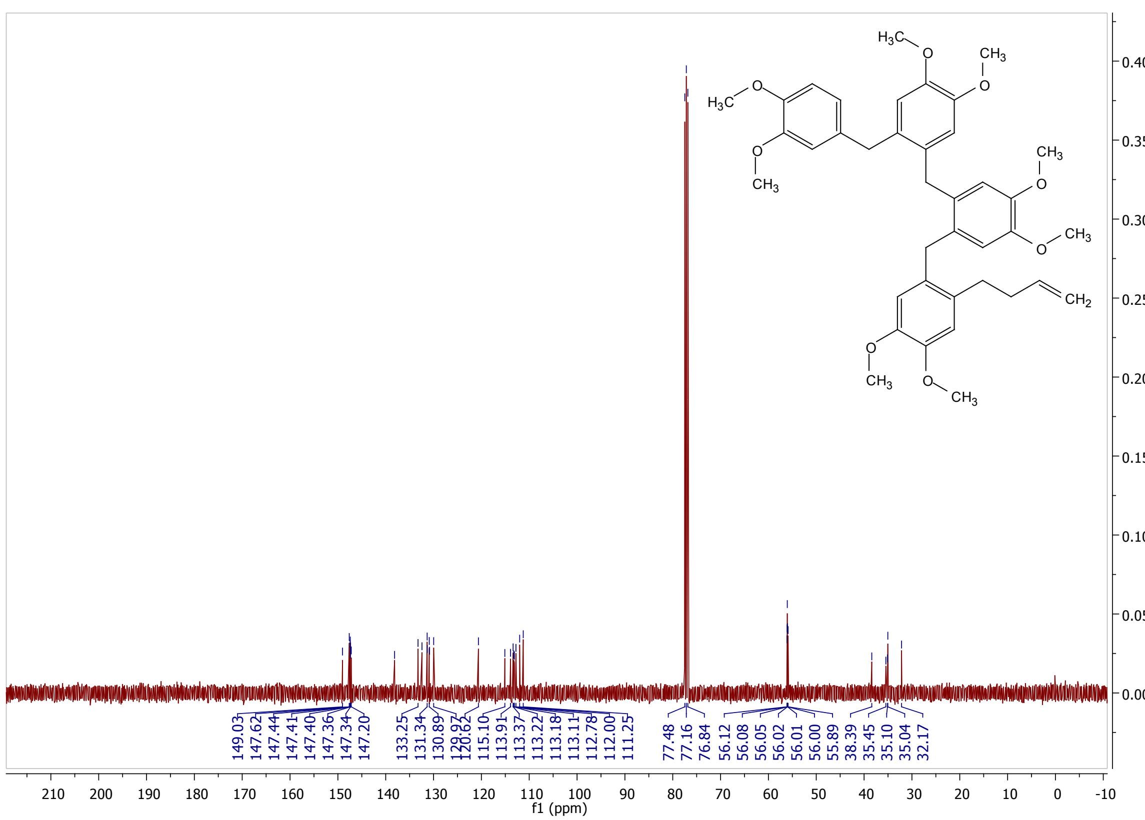
^{1}H and ^{13}C spectra of **5**.



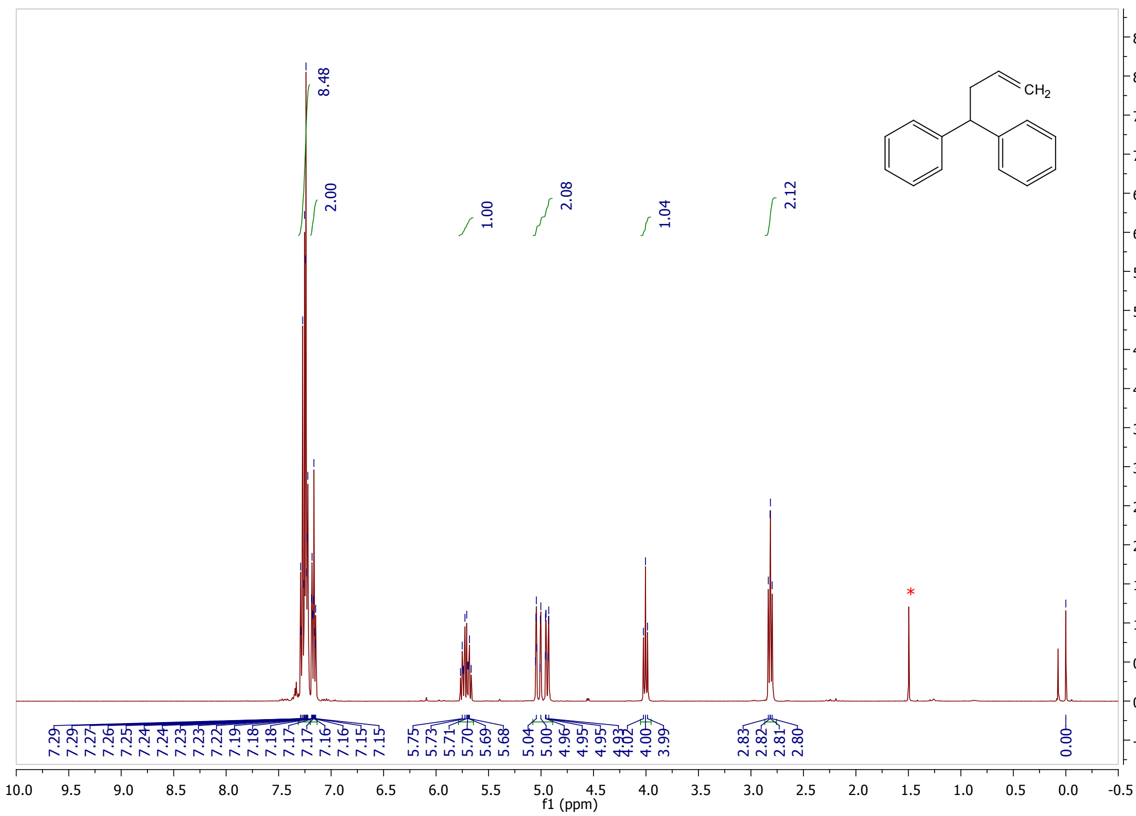


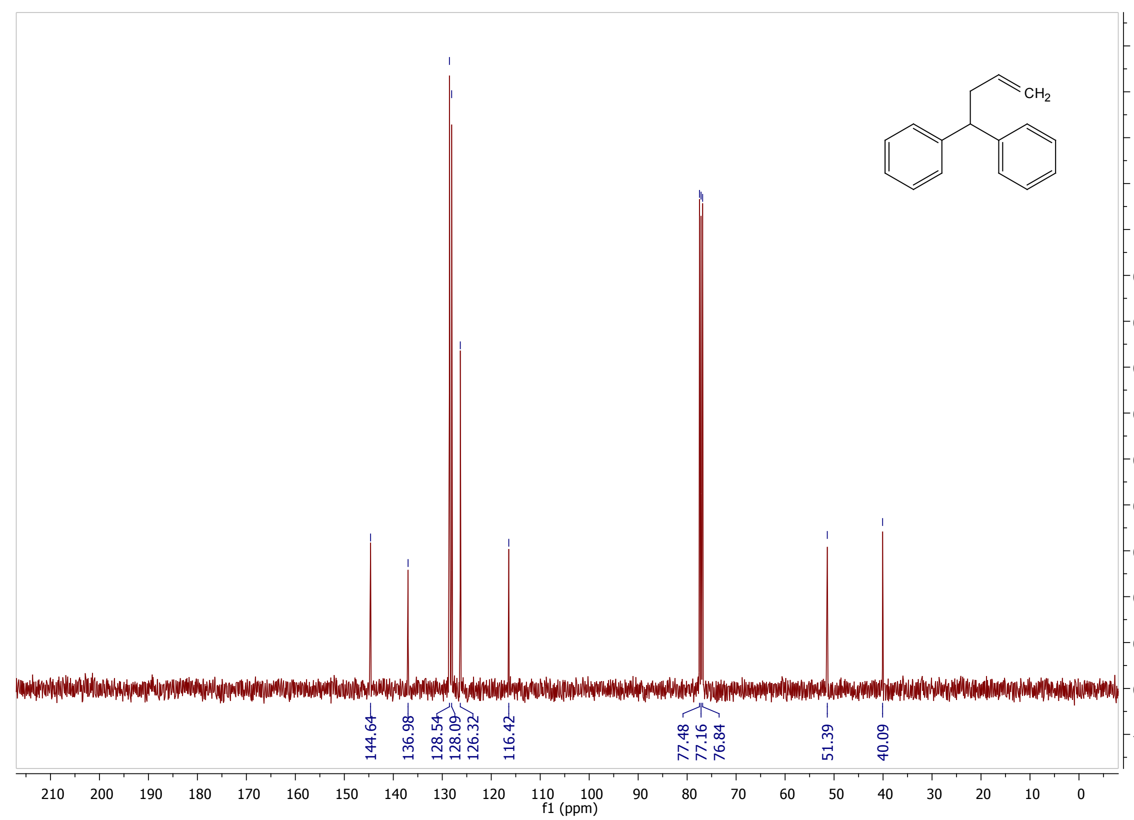
^{1}H and ^{13}C spectra of **6**.



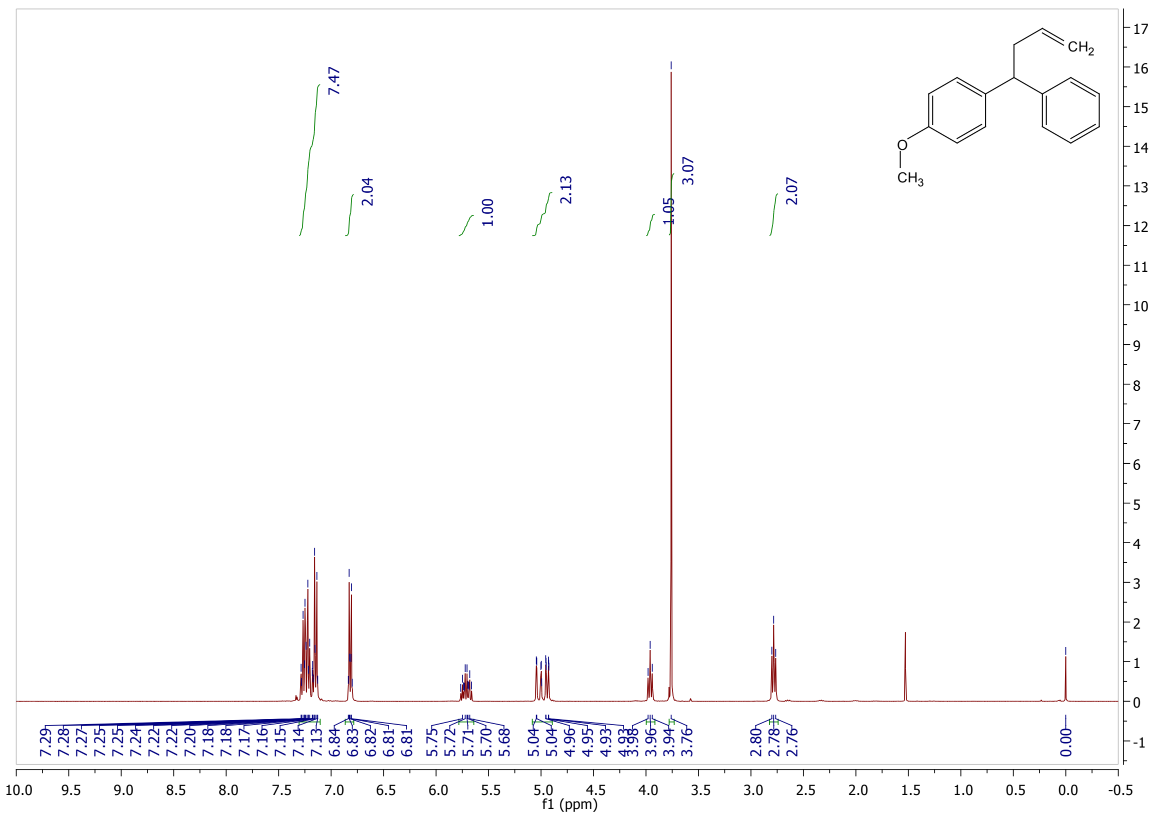


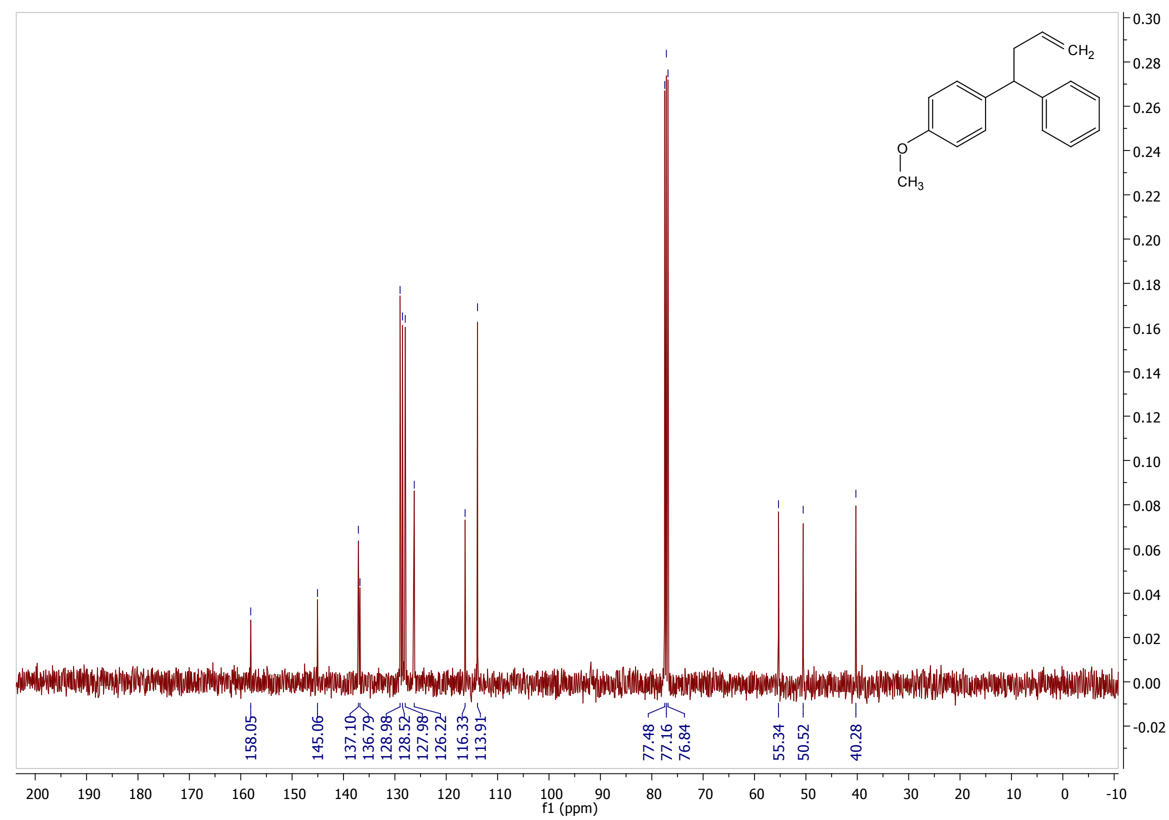
[1]H and [13]C spectra of **7**.



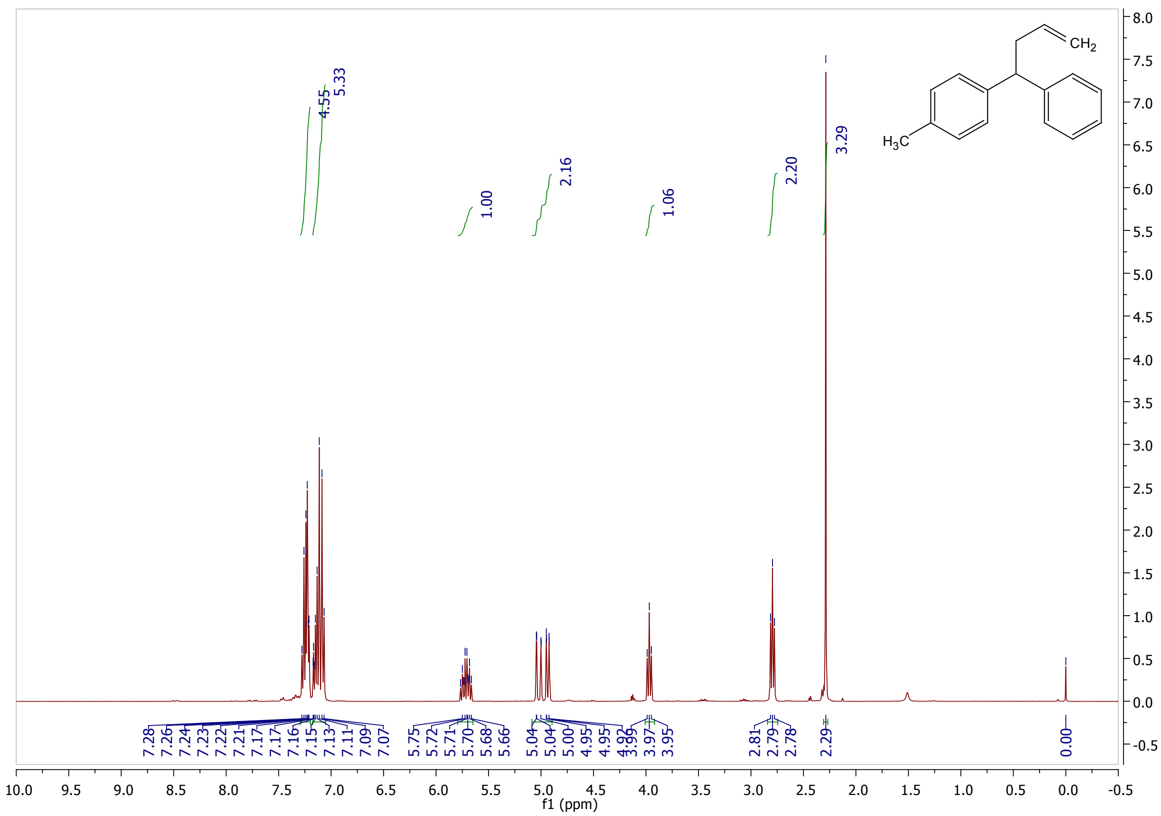


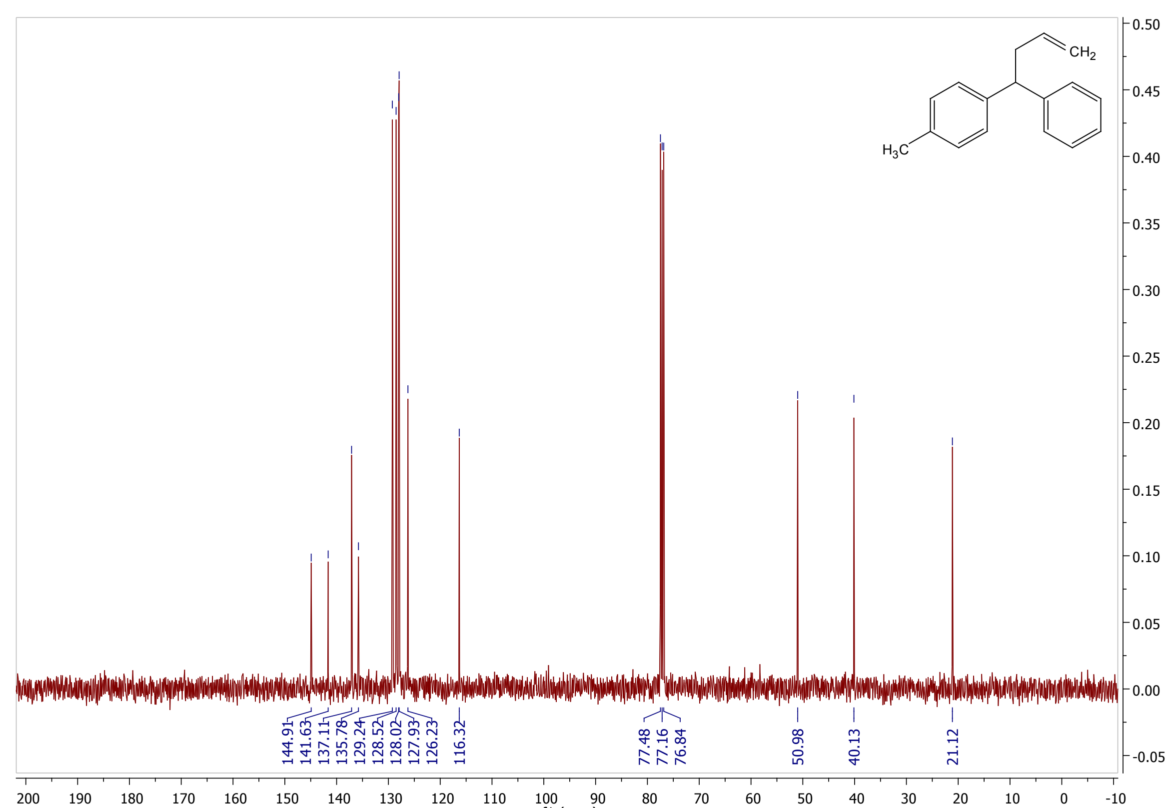
^{1}H and ^{13}C spectra of **9a**.



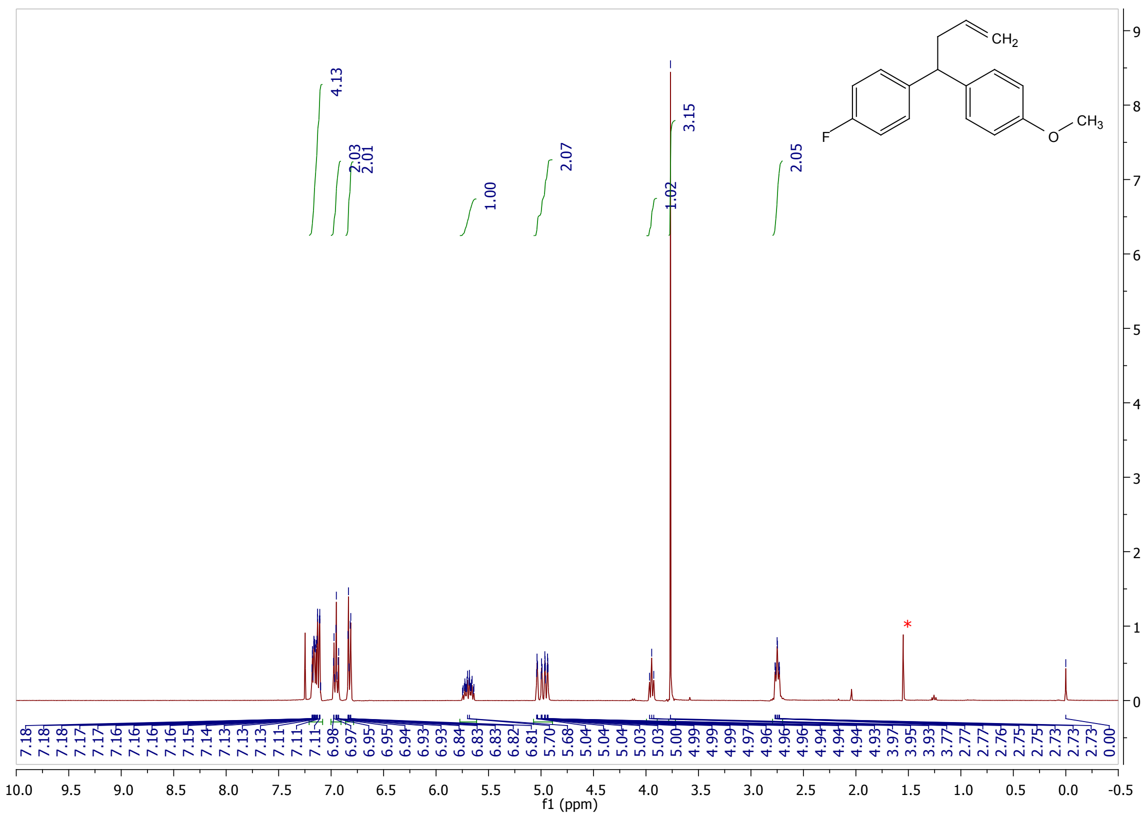


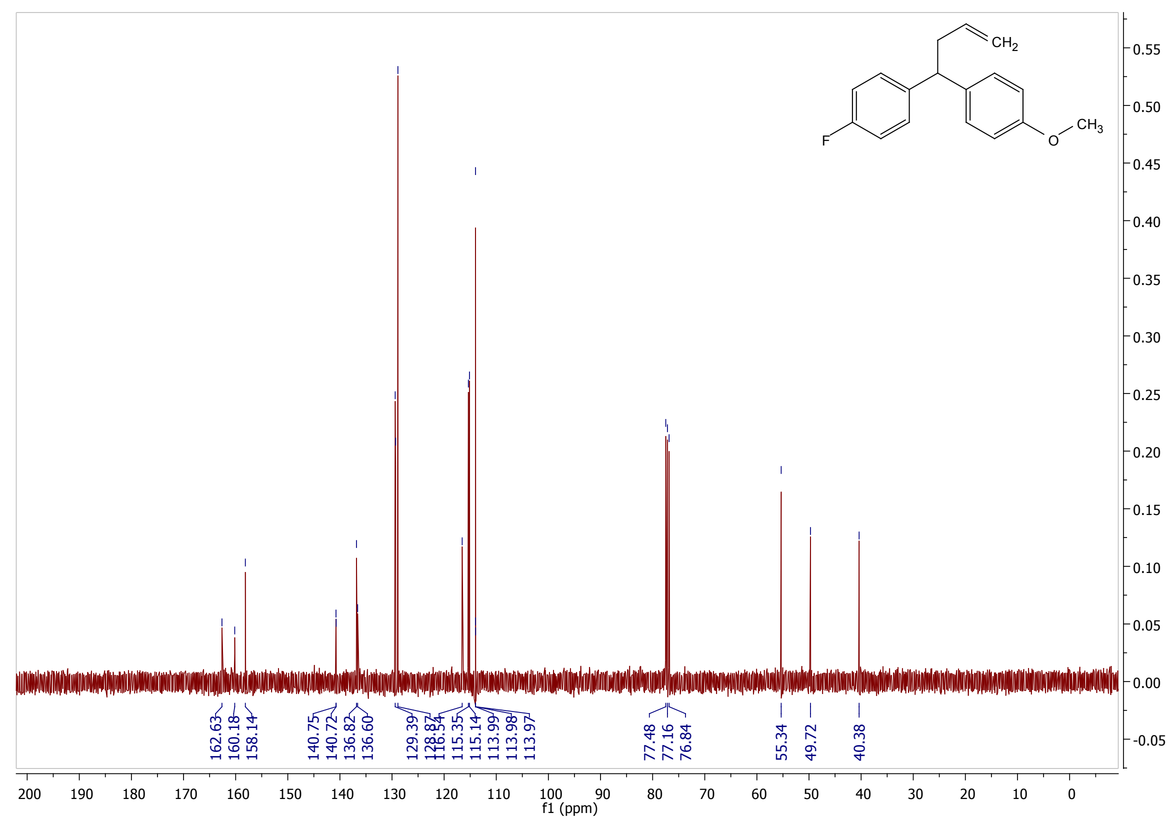
^{1}H and ^{13}C spectra of **9b**.



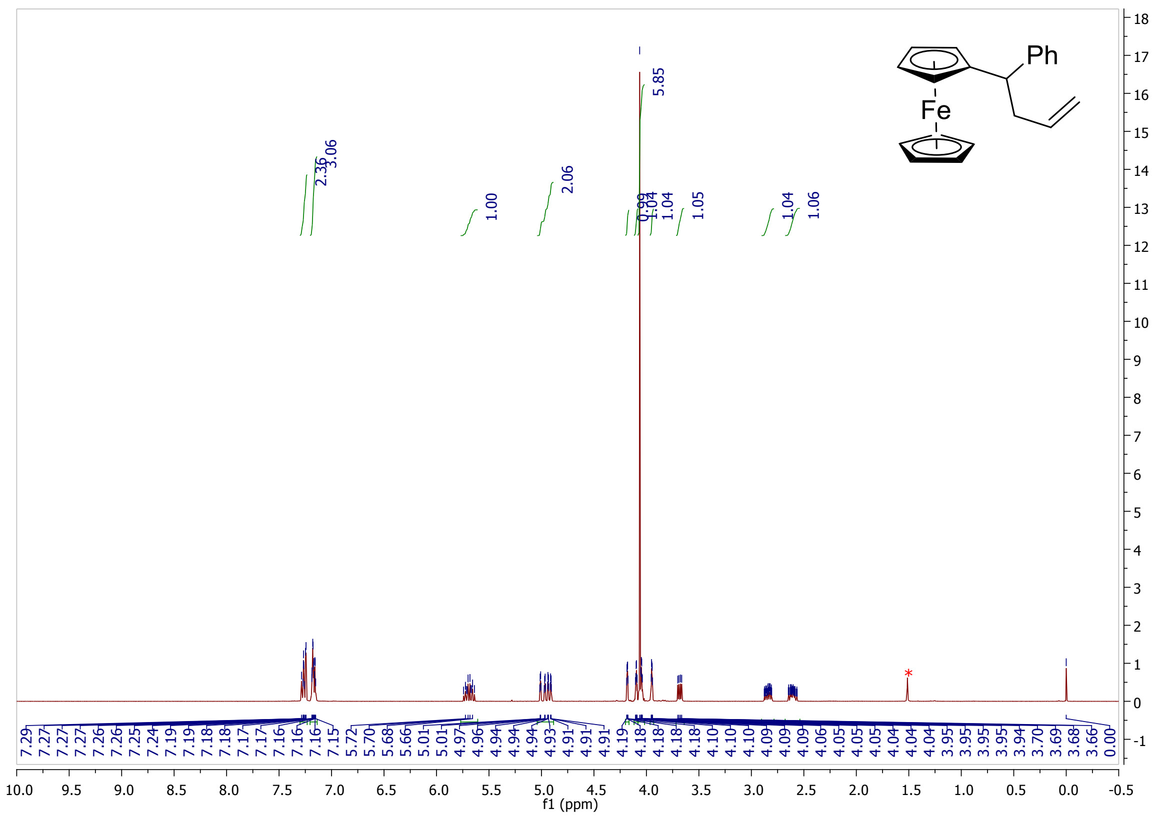


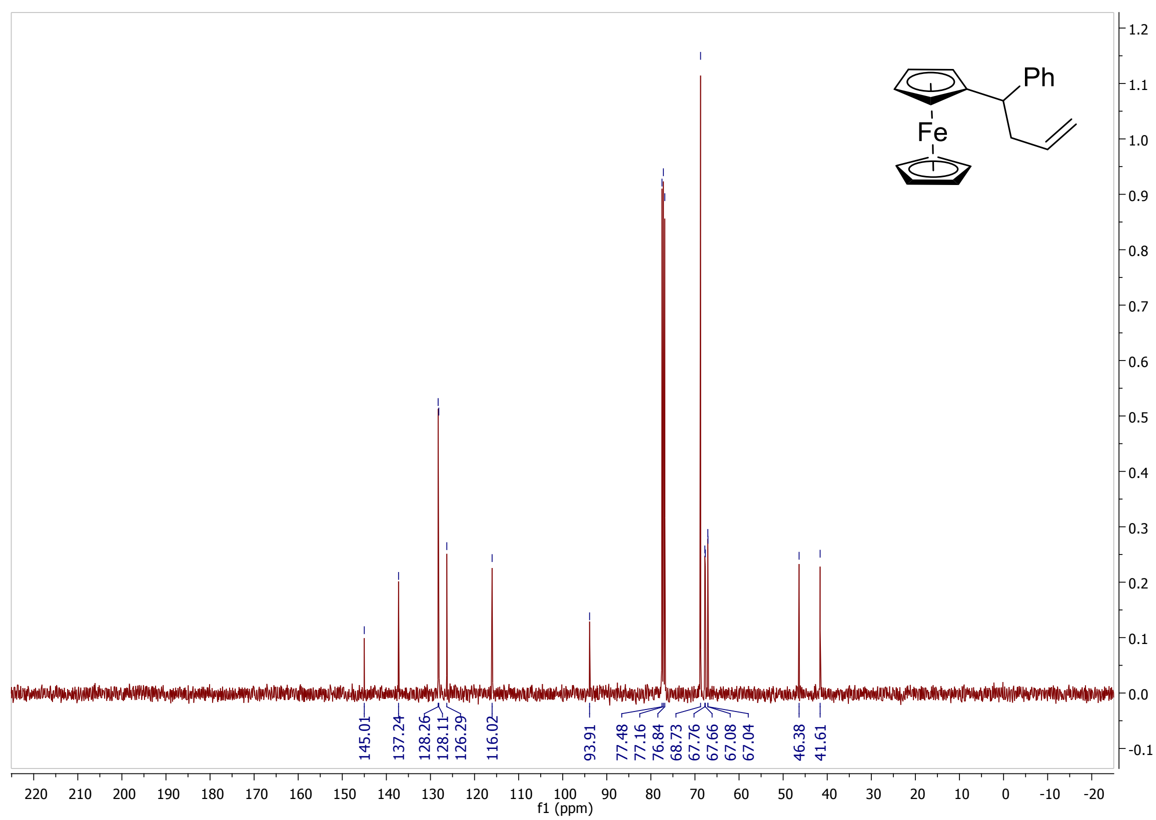
[1]H and [13]C spectra of **9c**.



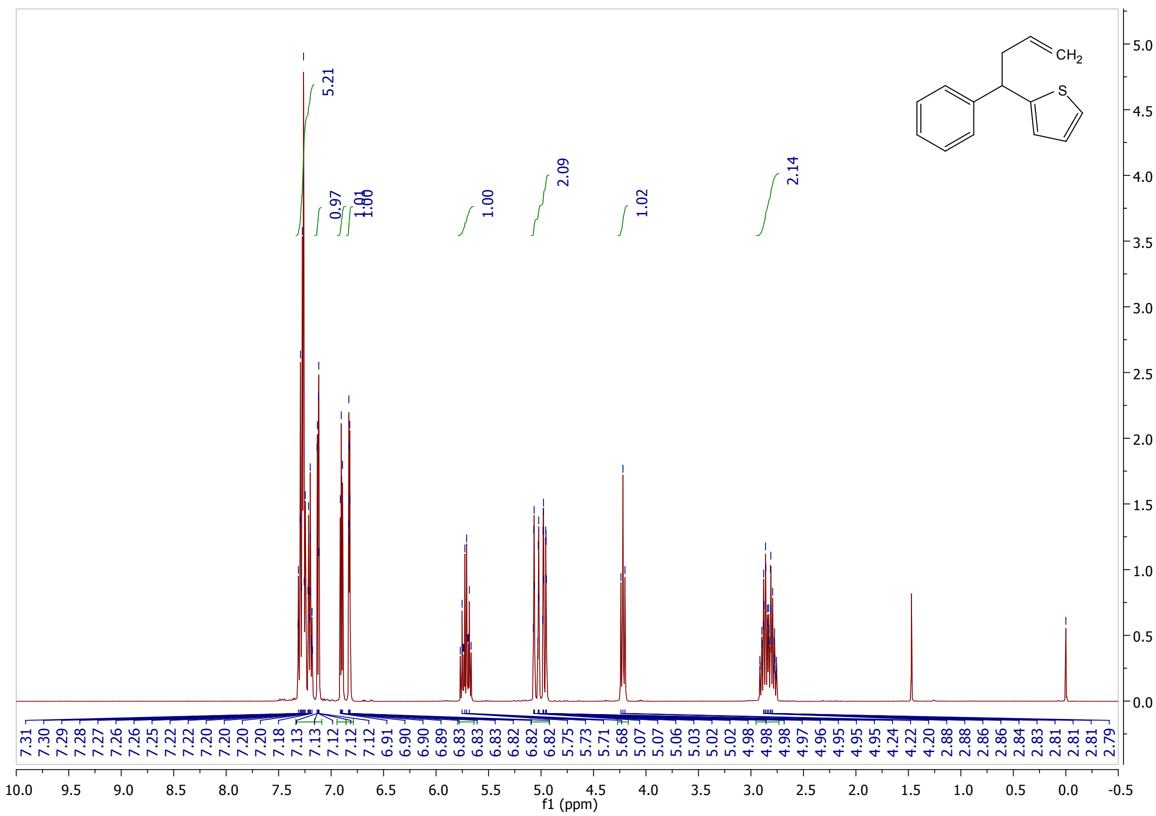


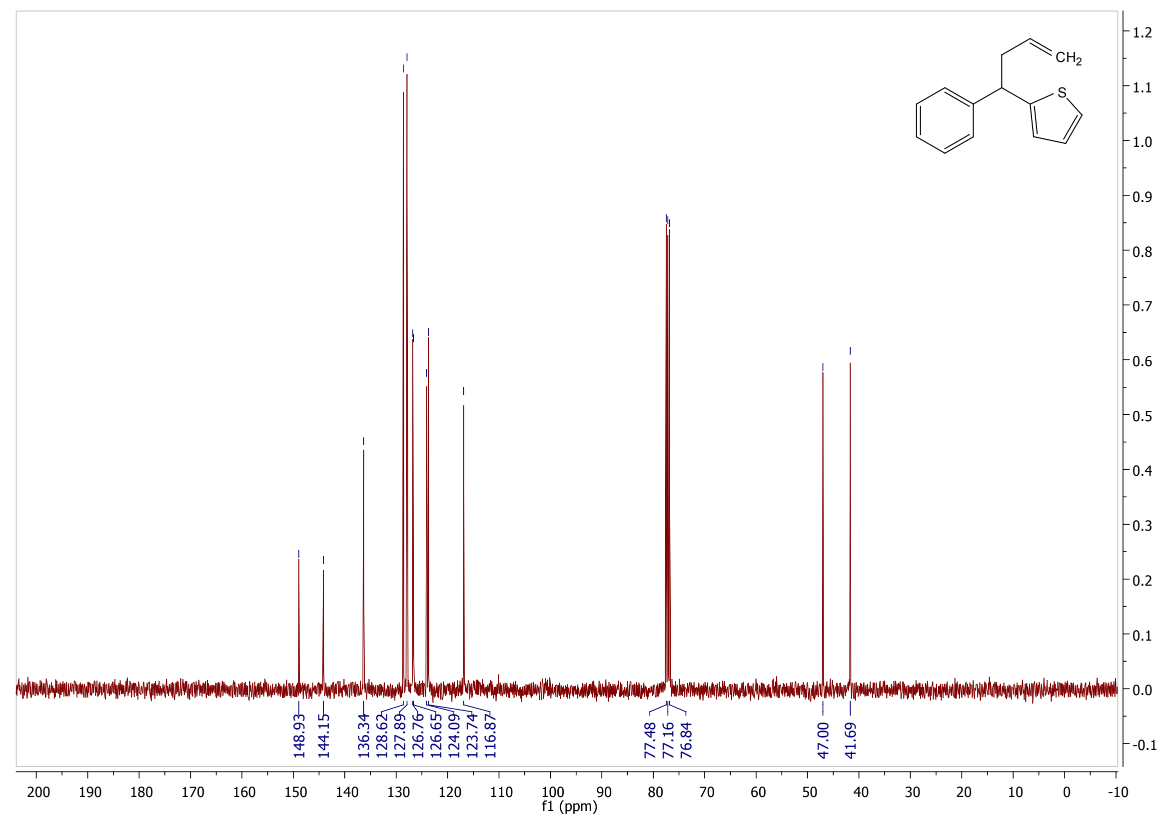
^{1}H and ^{13}C spectra of **9d**.



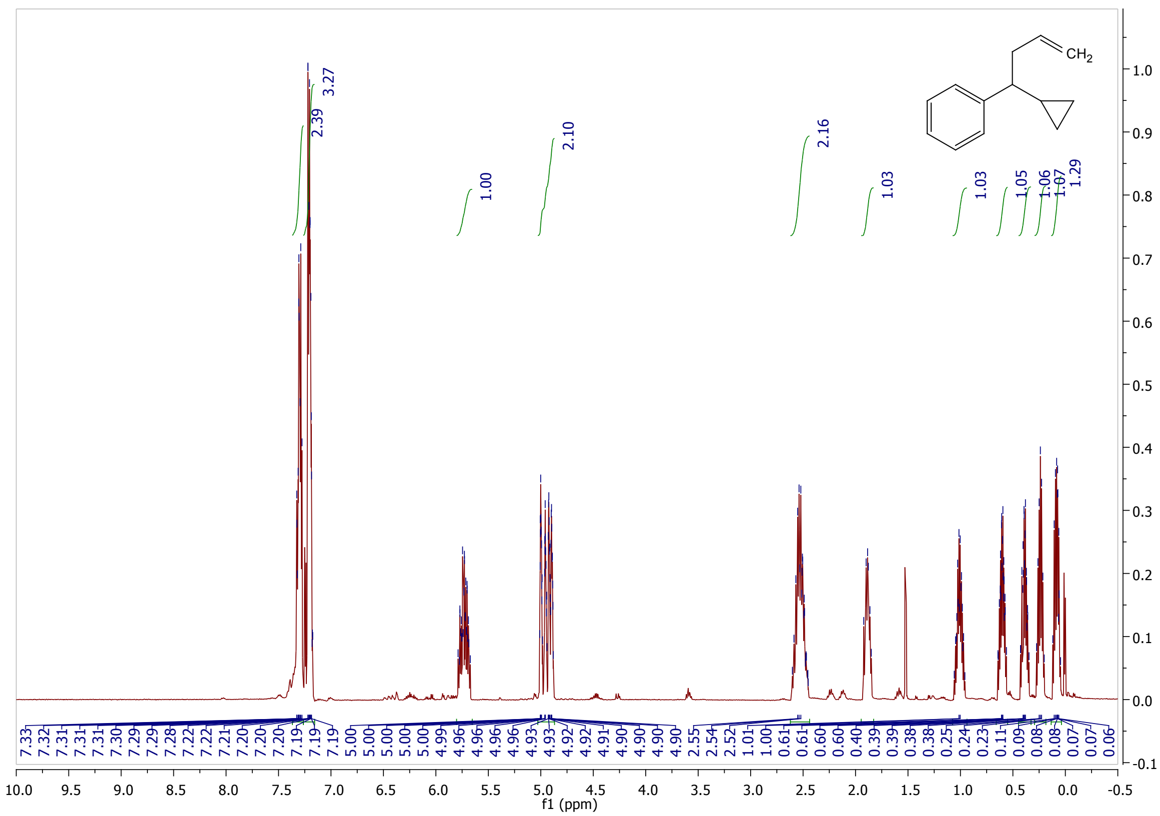


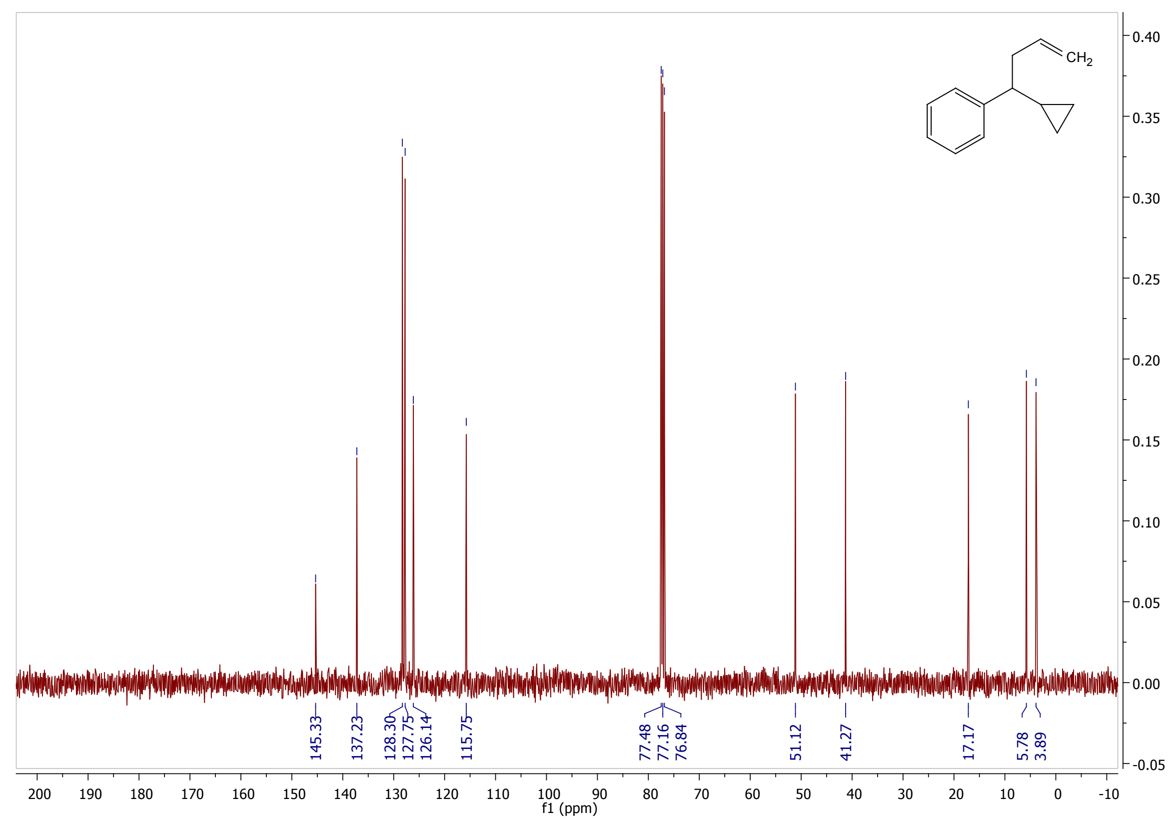
^{1}H and ^{13}C spectra of **9e**.



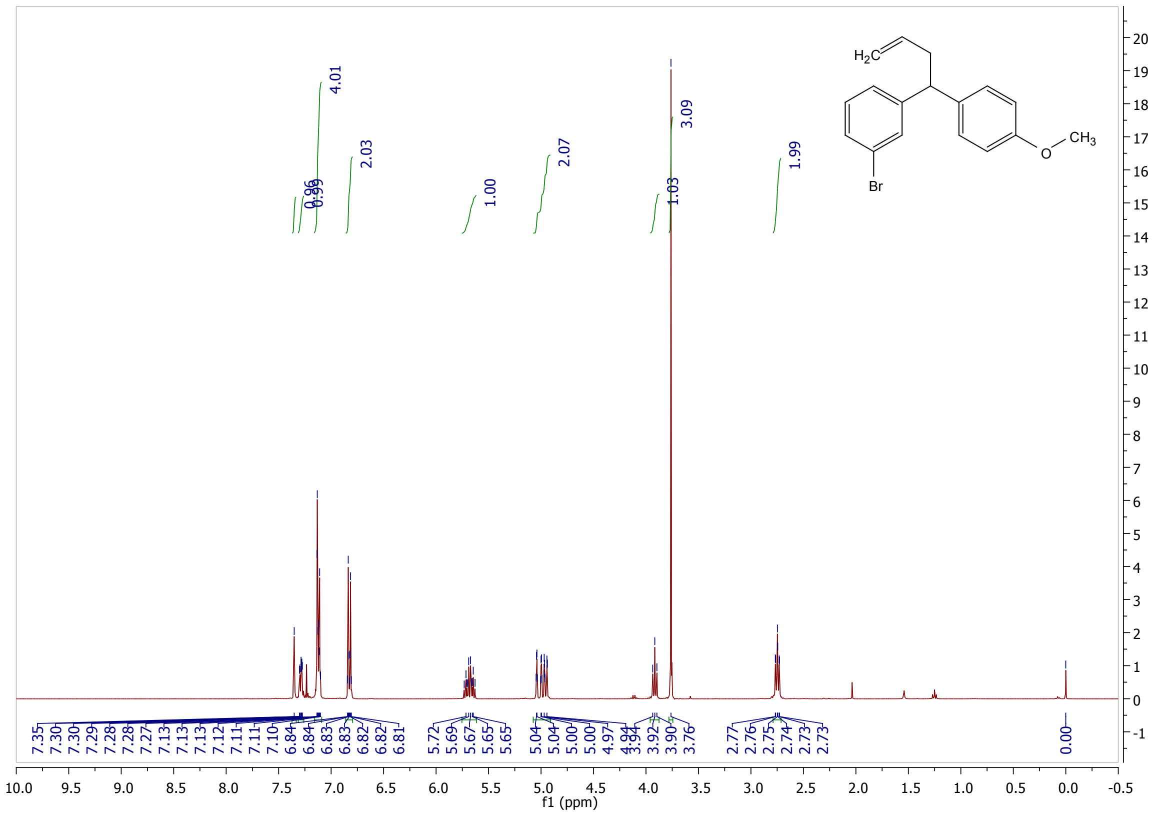


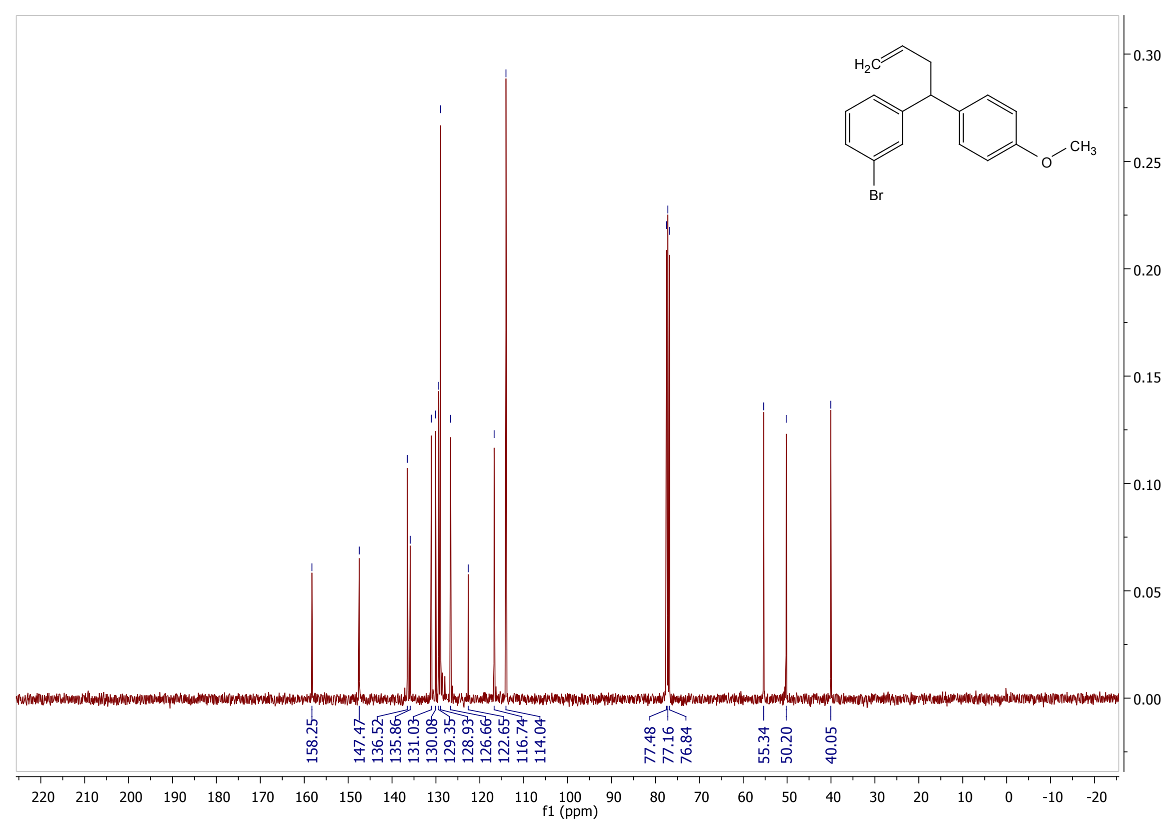
^{1}H and ^{13}C spectra of **9f**.



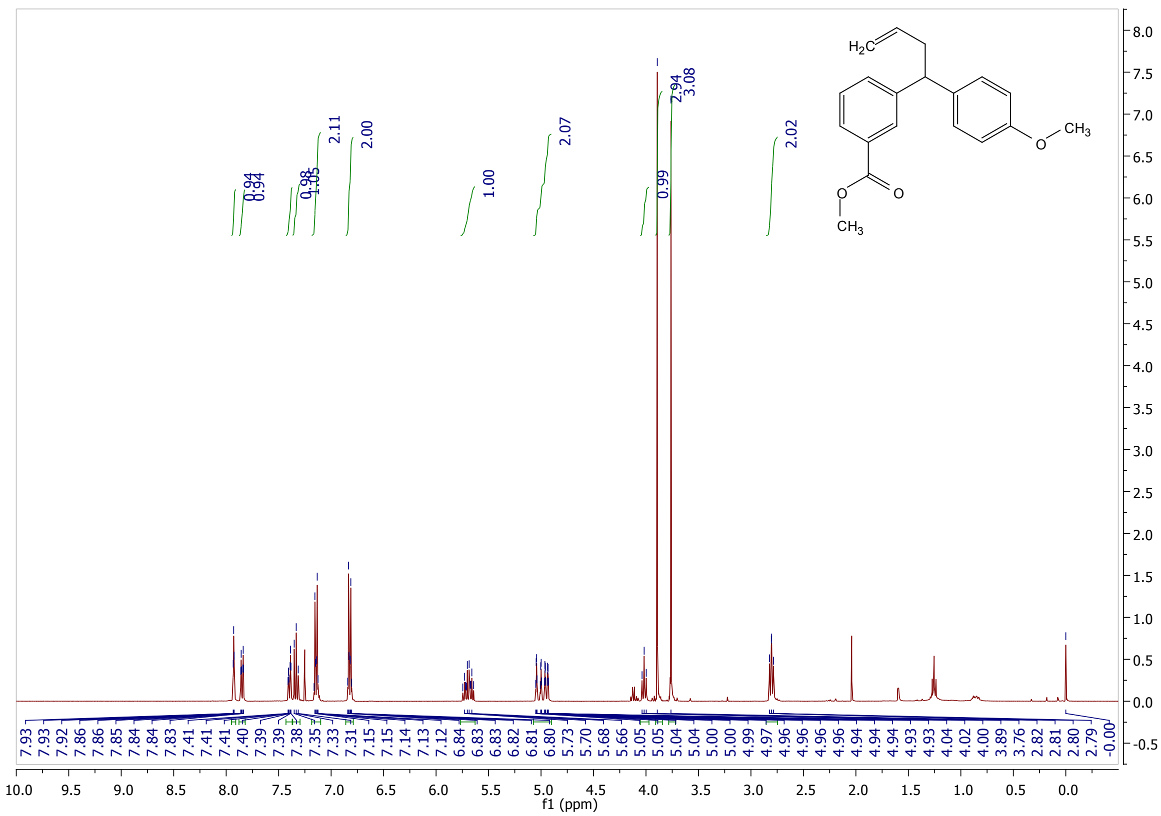


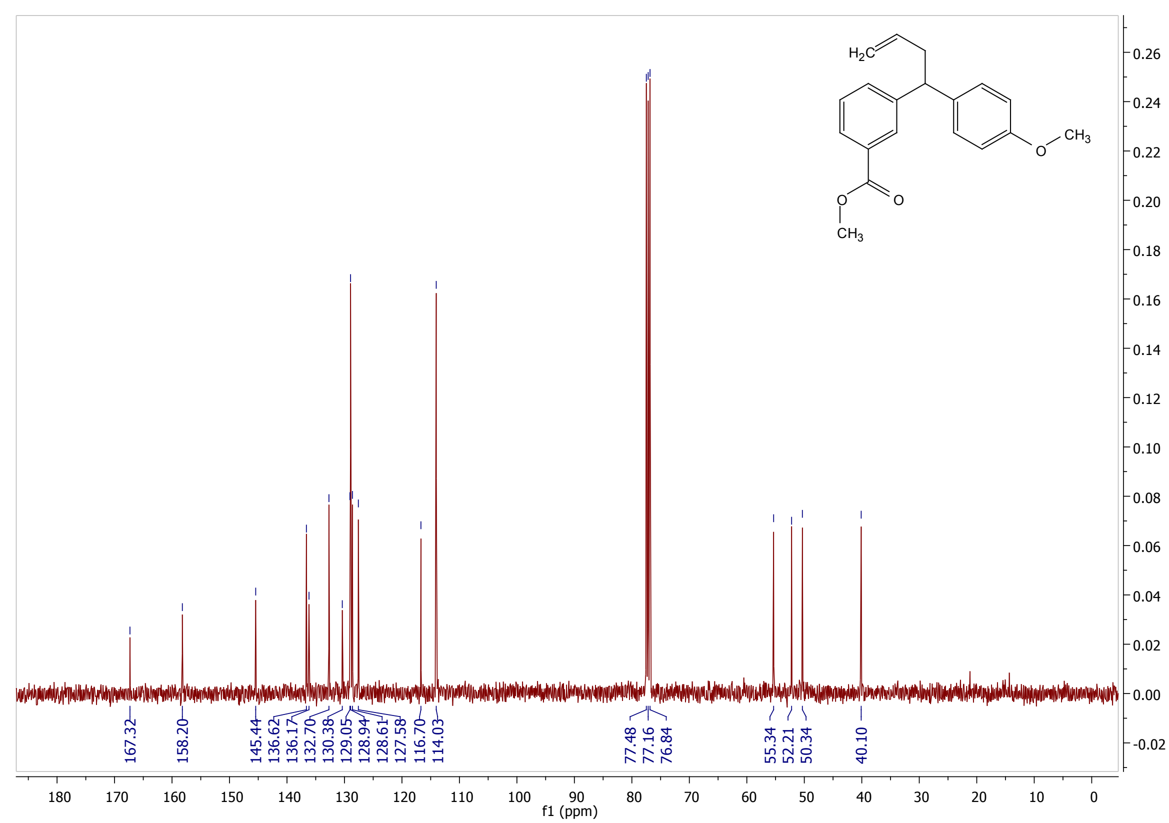
[1]H and [13]C spectra of **9h**.





^{1}H and ^{13}C spectra of **9i**.





[1]H and [13]C spectra of **9j**.

References

(1) Kurosawa, W.; Kan, T.; Fukuyama, T. *J. Am. Chem. Soc.* **2003**, *125*, 8112.
(2) Skrypai, V.; Hurley, J. J. M.; Adler, M. J. *Eur. J. Org. Chem.* **2016**, *2016*, 2207.
(3) Srivastava, P.; Ali, R.; Razi, S. S.; Shahid, M.; Patnaik, S.; Misra, A. *Tetrahedron Lett.* **2013**, *54*, 3688.
(4) Ueda, M.; Miyaura, N. *J. Org. Chem.* **2000**, *65*, 4450.
(5) Zhao, H.; Cheng, M.; Zhang, T.; Cai, M. *J. Organomet. Chem.* **2015**, *777*, 50.
(6) Carroll, M. A.; White, A. J. P.; Widdowson, D. A.; Williams, D. J. *J. Chem. Soc., Perkin Trans. 1* **2000**, 1551.
(7) Bariak, V.; Malastová, A.; Almássy, A.; Šebesta, R. *Chemistry – A European Journal* **2015**, *21*, 13445.
(8) Yamamoto, T.; Furusawa, T.; Zhumagazin, A.; Yamakawa, T.; Oe, Y.; Ohta, T. *Tetrahedron* **2015**, *71*, 19.
(9) Das, M.; O'Shea, D. F. *J. Org. Chem.* **2014**, *79*, 5595.
(10) Schabel, T.; Belger, C.; Plietker, B. *Org. Lett.* **2013**, *15*, 2858.
(11) Ohtake, Y.; Sato, T.; Matsuoka, H.; Kobayashi, T.; Nishimoto, M.; Taka, N.; Takano, K.; Yamamoto, K.; Ohmori, M.; Higuchi, T.; Murakata, M.; Morikawa, K.; Shimma, N.; Suzuki, M.; Hagita, H.; Ozawa, K.; Yamaguchi, K.; Kato, M.; Ikeda, S. *Biorg. Med. Chem.* **2012**, *20*, 4117.
(12) Mochalov, S.; Fedotov, A.; Trofimova, E.; Zefirov, N. *Russ. J. Org. Chem.* **2015**, *51*, 1217.
(13) Li, Y.; Hu, Y.-Y.; Zhang, S.-L. *Chem. Commun.* **2013**, *49*, 10635.
(14) Kashanna, J.; Jangili, P.; Kumar, R. A.; Das, B. *Helv. Chim. Acta* **2012**, *95*, 1666.
(15) Ranu, B. C.; Banerjee, S.; Adak, L. *Tetrahedron Lett.* **2007**, *48*, 7374.
(16) Yates, P.; Macas, T. S. *Can. J. Chem.* **1988**, *66*, 1.
(17) Lai, Y.-L.; Huang, J.-M. *Org. Lett.* **2017**, *19*, 2022.
(18) Orizu, I.; Bolshan, Y. *Tetrahedron Lett.* **2016**, *57*, 5798.
(19) Podder, S.; Choudhury, J.; Roy, S. *J. Org. Chem.* **2007**, *72*, 3129.
(20) Narayana Kumar, G. G. K. S.; Laali, K. K. *Organic & Biomolecular Chemistry* **2012**, *10*, 7347.