Catalytic Asymmetric Synthesis with Rh-Diene Complexes: 1,4-Addition of Arylboronic Acids to Unsaturated Esters

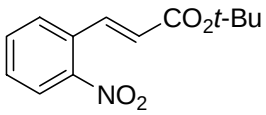
*Jean-François Paquin, Corey R. J. Stephenson, Christian Defieber and Erick M. Carreira**

The following includes general experimental procedures, specific details for representative reactions, and isolation and spectroscopic information for the new compounds prepared. All reactions were performed in oven dried glassware under argon. ^{1}H and ^{13}C NMR spectra were recorded on a VARIAN Mercury 300 MHz or a Gemini 300 MHz. Infrared spectra were recorded on a Perkin-Elmer RX-I FT-IR or a Perkin Elmer spectrometer. High resolution mass spectra were obtained on a VG-TRIBRID for electron impact ionization (EI). Enantiomeric excesses were determined by chiral HPLC analysis with a Merck-Hitachi D-7000 system. Optical rotation $[\alpha]_D$ were measured on a Jasco DIP-1000 Polarimeter. The absolute stereochemistry was assigned based on the established stereochemical outcome of the reaction of aryl boronic acids with enones[1] and enals.[2] The ligands were prepared as previously reported.[1,2] Ethyl cinnamate (**1**) and benzyl cinnamate (**2**) were purchased and used as received. *t*-Butylcinnamates were prepared from the reaction of the corresponding acid with Boc_2O and DMAP in THF using conditions previously reported.[3] The spectral data for *t*-butylcinnamate (**3**),[4] *t*-butyl

[1] Defieber, C.; Paquin, J.-F.; Serna, S.; Carreira, E. M. *Org. Lett.* **2004**, *6*, 3873.
[2] Paquin, J.-F.; Defieber, C.; Stephenson, C. R. J.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, In Press.
[3] Takeda, K.; Akiyama, A.; Nakamura, H.; Takizawa, S.-i.; Mizuno, Y.; Takayanagi, H.; Harigaya, Y. *Synthesis* **1994**, 1063.

4-methoxycinnamate,[5] *t*-butyl 3-fluorocinnamate,[6] *t*-butyl 3-(furan-2-yl)acrylate,[7] and *t*-butyl 3-(pyridin-3-yl)acrylate[8] were identical as those reported previously.

Preparation of t-Butyl Esters



***tert*-Butyl 3-(2-nitrophenyl)acrylate**

To a solution of 2-nitrocinnamic acid (1.00 g, 5.18 mmol) in dry THF (25.0 mL) was added Boc_2O (2.26 g, 10.4 mmol) and DMAP (190 mg, 1.55 mmol). The reaction mixture was stirred for 72 h and concentrated. The residue was purified by chromatography on SiO_2 (85:15, pentane/Et_2O) to give 1.29 g, 100% of a light yellow solid. IR (neat) ν = 2979, 2933, 1711, 1638, 1572, 1526, 1368, 1345, 1326, 1295, 1208, 1153 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.03-7.98 (m, 2 H), 7.64-7.63 (m, 2 H), 7.56-7.48 (m, 1 H), 6.30 (d, 1 H, J = 15.6 Hz), 1.54 (s, 9 H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 164.8, 148.1, 138.5, 133.2, 130.6, 129.9, 128.9, 125.1, 124.7, 81.1, 28.2; HRMS-EI calcd for $C_9H_6NO_3$ $[M\text{-}OC_4H_9]^+$ 176.0343, found 176.0343.

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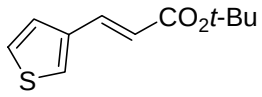
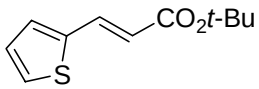
[4] Yang, D.; Chen, Y.-C.; Zhu, N.-Y. *Org. Lett.* **2004**, *6*, 1577.
[5] Imashiro, R.; Seki, M. *J. Org. Chem.* **2004**, *69*, 4216.
[6] Liu, J.; Zhao, Y.; Zhou, Y.; Li, L.; Zhang, T. Y.; Zhang, H. *Org. Biomol. Chem.* **2003**, *1*, 3227.
[7] Huang, Z.-Z.; Ye, S.; Xia, W.; Yu, Y.-H.; Tang, Y. *J. Org. Chem.* **2002**, *67*, 3096.
[8] Bull, S. D.; Davies, S. G.; Fox, D. J.; Gianotti, M.; Kelly, P. M.; Pierres, C.; Savory, E. D.; Smith, A. D. *J. Chem. Soc. Perkin Trans. 1* **2002**, *16*, 1858.



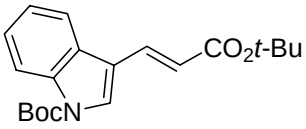
***tert*-Butyl 3-(thiophen-3-yl)acrylate**

Yellow oil; IR (neat) ν = 3099, 2976, 2932, 1699, 1632, 1366, 1309, 1279, 1141, 976, 854, 782 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.57 (d, 1H, *J* = 15.9 Hz), 7.46 (m, 1H), 7.35-7.26 (m, 2H), 6.19 (d, 1H, *J* = 15.9 Hz), 1.53 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 166.4, 137.6, 137.0, 127.4, 126.7, 125.1, 119.8, 80.4, 28.3; HRMS-EI calcd for $C_{11}H_{14}O_2S$ $[M]^+$ 210.0715, found 210.0710.



***tert*-Butyl-3-(thiophen-2-yl)acrylate**

Yellow oil; IR (neat) ν = 3106, 2977, 2931, 1703, 1626, 1427, 1391, 1367, 1310, 1283, 1230, 1208, 971, 852 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68 (d, 1H, *J* = 15.6 Hz), 7.33 (m, 1H), 7.22 (m, 2H), 7.05-7.02 (m, 1H), 6.17 (d, 1H, *J* = 15.6 Hz), 1.52 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 166.0, 139.7, 135.9, 130.3, 127.8, 118.9, 80.4, 28.1; HRMS-EI calcd for $C_{11}H_{14}O_2S$ $[M]^+$ 210.0715, found 210.0712.

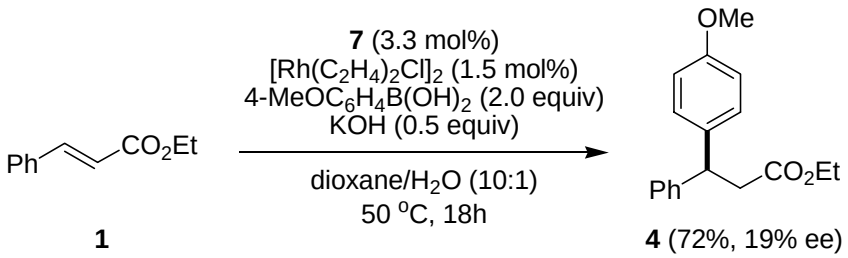


***tert*-Butyl 3-(3-tert-butoxy-3-oxoprop-1-enyl)-1*H*-indole-1-carboxylate**

Colorless solid; mp = 111-112 ºC; IR (neat) ν = 3140, 2978, 2932, 1740, 1704, 1636, 1452, 1367, 1258, 1256, 1146, 1094, 913, 743 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.19 (d, 1H, *J* = 7.8 Hz), 7.86-7.83 (m, 2H), 7.73 (dd, 1H, *J* = 16.2, 0.6 Hz), 7.41-7.29 (m, 2H), 6.47 (d, 1H, *J* = 16.2 Hz), 1.68 (s, 9H), 1.53 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ

166.6, 149.0, 136.1, 135.1, 128.1, 127.9, 125.1, 123.4, 120.2, 119.4, 116.8, 115.4, 84.5, 80.4, 28.4, 28.3; HRMS-MALDI calcd for $[C_{20}H_{25}NO_4Na]^+$ 366.1676, found 366.1669.

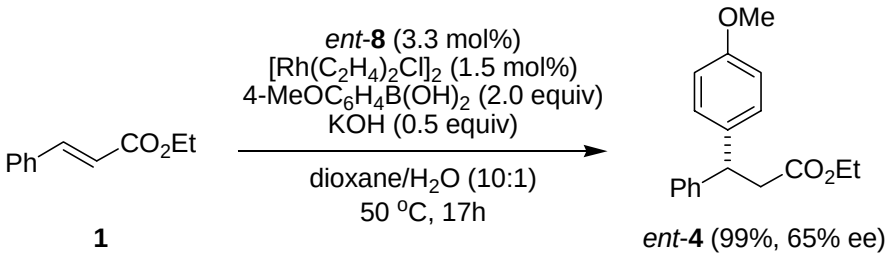
1,4-Addition to Cinnamates Derivatives - Ligand Screening and Reaction Optimization



(*S*)-Ethyl 3-(4-methoxyphenyl)-3-phenylpropanoate (4). General Procedure in dioxane.

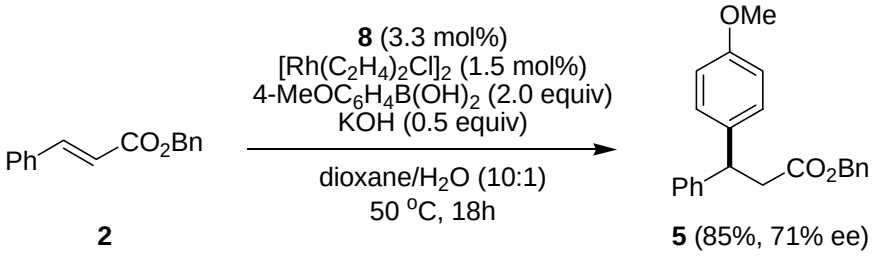
To $[Rh(C_2H_4)Cl]_2$ (1.7 mg, 4.4 μmol) in a Schlenk flask (10 mL) was added a solution of **7** (2.7 mg, 9.6 μmol) in dioxane (1 mL). The resulting solution was stirred for 15 min, and KOH (1.5 M/H_2O, 100 μL, 0.15 mmol) was added. After stirring 15 min, 4-$MeOC_6H_4B(OH)_2$ (88 mg, 0.58 mmol) was added followed by ethyl cinnamate (49 μL, 0.29 mmol) and the reaction was stirred at 50 ºC for 18 h. Saturated NH_4Cl was added, and the aqueous layer was extracted with Et_2O (3×). The combined organic layers were washed with brine, dried over $MgSO_4$, and the solvent was evaporated to give the crude. The desired product (59 mg, 72%) was isolated by flash chromatography using 15% Et_2O/hexane as a colorless liquid. The enantioselectivity was 19% ee (OD-H, 254 nm, hexane:2-propanol = 95:5, flow rate = 1.0 mL/min, $t_{r\ (minor)}$ = 7.13 min, $t_{r\ (major)}$ = 8.34 min). IR (neat) ν = 3030, 2980, 2835, 1730, 1510, 1246, 1031, 699, 667 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.31-7.15 (m, 7H), 6.83 (m, 2H), 4.53 (t, 1H, *J* = 8.1 Hz), 4.05 (q, 2H, *J* = 7.2 Hz), 3.77 (s, 3H), 3.04 (d, 2H, *J* = 8.1 Hz), 1.13 (t, 3H, *J* = 7.2 Hz); ^{13}C NMR

(75.5 MHz, $CDCl_3$) δ 172.1, 158.3, 144.1, 135.8, 128.8, 128.7, 127.8, 126.6, 114.1, 60.6, 55.4, 46.5, 41.2, 14.3; HRMS-EI calcd for $C_{18}H_{20}O_3$ $[M]^+$ 284.1412, found 284.1409.



(*R*)-Ethyl 3-(4-methoxyphenyl)-3-phenylpropanoate (*ent*-4).

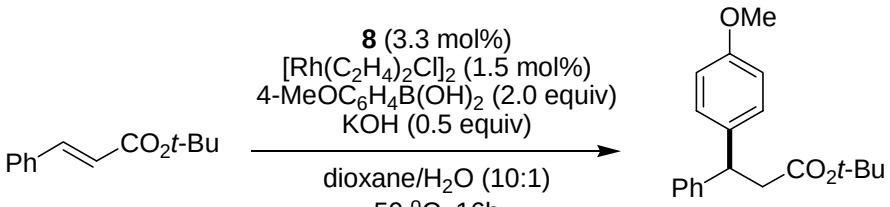
Following the general procedure in dioxane on 0.33 mmol scale using ethyl cinnamate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand *ent*-**8** with a reaction time of 17 h, the desired product (93 mg, 99%) was isolated by flash chromatography using 15% Et_2O/hexane as a colorless liquid. The enantioselectivity was -65% ee (OD-H, 254 nm, hexane:2-propanol = 95:5, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 7.15 min, $t_{r\ (minor)}$ = 8.47 min).



(*S*)-Benzyl 3-(4-methoxyphenyl)-3-phenylpropanoate (5)

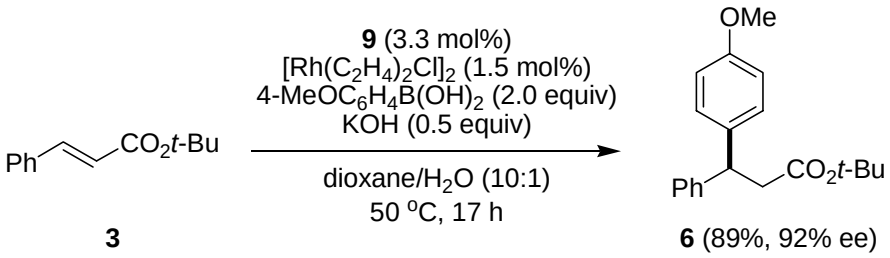
Following the general procedure in dioxane on 0.31 mmol scale using benzyl cinnamate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand **8** with a reaction time of 18 h, the desired product (91 mg, 85%) was isolated by flash chromatography using 15% Et_2O/hexane as a colorless solid. The enantioselectivity was 71% ee (OD-H, 254 nm, hexane:2-propanol = 90:10, flow rate = 1.0 mL/min, $t_{r\ (minor)}$ = 9.18 min, $t_{r\ (major)}$ = 10.49

min). mp = 79-80 ºC; IR (neat) ν = 3031, 2960, 2909, 2837, 1727, 1246, 1147, 732, 693, 667 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.32-7.14 (m, 12H), 6.82 (m, 2H), 5.03 (s, 2H), 4.54 (t, 1H, *J* = 8.1 Hz), 3.78 (s, 3H), 3.09 (d, 2H, *J* = 8.1 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 171.9, 158.4, 143.9, 136.0, 135.7, 128.8, 128.7, 128.6, 128.3, 127.8, 126.7, 114.1, 66.5, 55.4, 46.5, 41.2; HRMS-EI calcd for $C_{23}H_{22}O_3$ $[M]^+$ 346.1569, found 346.1564.



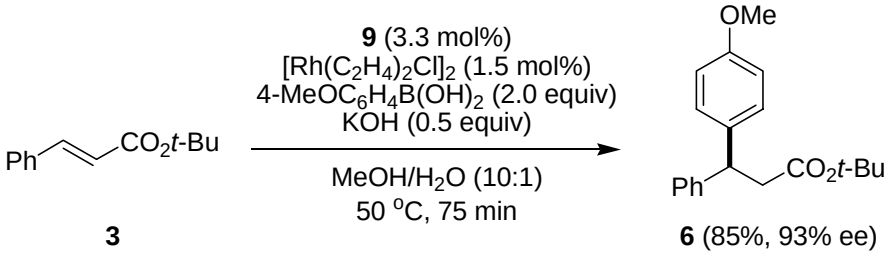
(*S*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-phenylpropanoate (6)

Following the general procedure in dioxane on 0.29 mmol scale using *t*-butyl cinnamate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand **8** with a reaction time of 16 h, the desired product (65 mg, 72%) was isolated by flash chromatography using 10% Et_2O/hexane as a colorless solid. The enantioselectivity was 89% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 0.35 mL/min, $t_{r\ (major)}$ = 23.55 min, $t_{r\ (minor)}$ = 25.73 min). mp = 70-71 ºC; IR (neat) ν = 3030, 3005, 2969, 2932, 2838, 1714, 1512, 1139, 1029, 667 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.30-7.15 (m, 7H), 6.82 (m, 2H), 4.44 (t, 1H, *J* = 8.4 Hz), 3.77 (s, 3H), 2.94 (d, 2H, *J* = 8.4 Hz), 1.29 (s, 3H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 171.4, 158.3, 144.1, 136.0, 128.9, 128.6, 127.9, 126.5, 114.0, 80.6, 55.4, 46.8, 42.5, 28.1; HRMS-EI calcd for $C_{20}H_{24}O_3$ $[M]^+$ 312.1725, found 312.1722.



(*S*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-phenylpropanoate (6)

Following the general procedure in dioxane on 0.31 mmol scale using *t*-butyl cinnamate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 17 h, the desired product (86 mg, 89%) was isolated by flash chromatography using 10% Et_2O/hexane as a colorless solid. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 0.35 mL/min, $t_{r\ (major)}$ = 24.29 min, $t_{r\ (minor)}$ = 26.56 min).

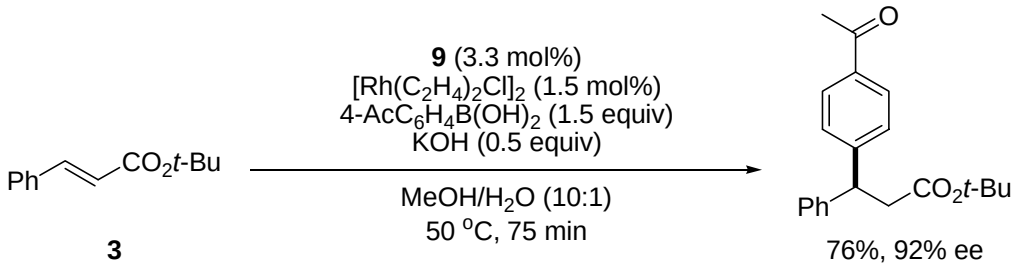


(*S*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-phenylpropanoate (6). General Procedure in MeOH.

To $[Rh(C_2H_4)Cl]_2$ (2.0 mg, 5.1 μmol) in a Schlenk flask (10 mL) was added a solution of **9** (3.5 mg, 11.3 μmol) in MeOH (1 mL). The resulting solution was stirred for 15 min, and KOH (1.5 M/H_2O, 113 μL, 0.17 mmol) was added. After stirring 15 min, 4-$MeOC_6H_4B(OH)_2$ (103 mg, 0.68 mmol) was added followed by *t*-butyl cinnamate (69 μL, 0.34 mmol) and the reaction was stirred at 50 ºC for 75 min. Saturated NH_4Cl was added, and the aqueous layer was extracted with Et_2O (3×). The combined organic layers

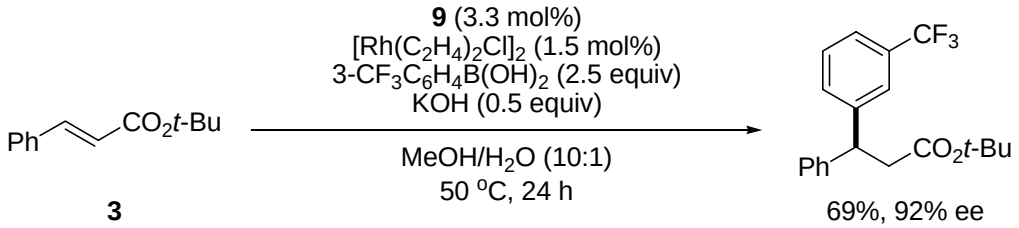
were washed with brine, dried over $MgSO_4$, and the solvent was evaporated to give the crude. The desired product (90 mg, 85%) was isolated by flash chromatography using 15% Et_2O/hexane as a colorless liquid. The enantioselectivity was 93% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 0.35 mL/min, $t_{r\ (major)}$ = 24.25 min, $t_{r\ (minor)}$ = 26.63 min). $[\alpha]_D^{26}$ +1.6 (*c* 0.96, MeOH).

1,4-Addition to t-Butyl Cinnamates Derivatives



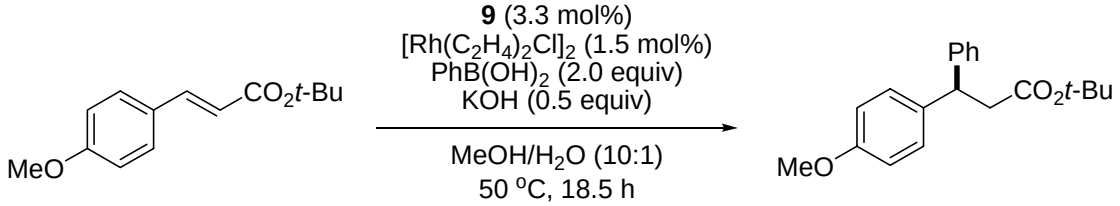
(*S*)-*tert*-Butyl 3-(4-acetylphenyl)-3-phenylpropanoate

Following the general procedure in MeOH on 0.3 mmol scale using *t*-butyl cinnamate, 4-acetylphenylboronic acid (1.5 equiv), and ligand **9** with a reaction time of 75 min, the desired product (74 mg, 76%) was isolated by flash chromatography using hexanes/EtOAc 7:1 as a colorless solid. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 19.7 min, $t_{r\ (minor)}$ = 21.5 min). $[\alpha]_D^{34}$ +7.5 (*c* 1.03, $CHCl_3$). IR (neat) ν = 3028, 3005, 2979, 2931, 1720, 1680, 1597, 1495, 1365, 1261, 1145, 1116, 957, 850 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.88 (d, 2H, *J* = 8.4 Hz), 7.35 (d, 2H, *J* = 8.4 Hz), 7.32-7.17 (m, 5H), 4.54 (t, 1H, *J* = 8.1 Hz), 2.98 (d, 2H, *J* = 8.1 Hz), 2.56 (s, 3H), 1.28 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 197.5, 170.5, 149.0, 142.6, 135.4, 128.6, 127.9, 127.6, 126.7, 80.8, 47.4, 41.7, 28.0, 26.7; HRMS-EI calcd for $C_{21}H_{24}O_3$ $[M]^+$ 324.1725, found 324.1759.



(*S*)-*tert*-Butyl 3-(3-trifluoromethylphenyl)-3-phenylpropanoate

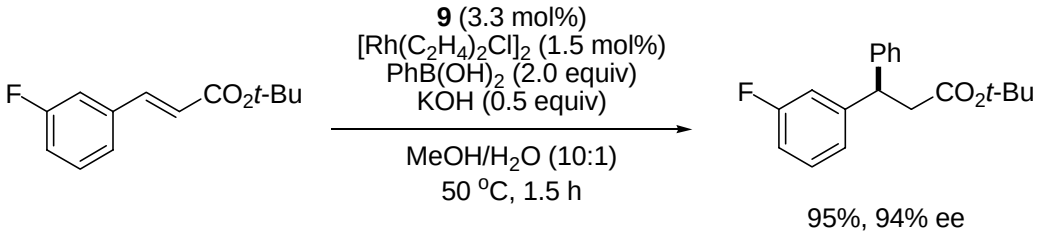
Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl cinnamate, 3-trifluoromethylphenylboronic acid (2.5 equiv), and ligand **9** with a reaction time of 24 h, the desired product (94 mg, 69%) was isolated by flash chromatography using 5% EtOAc/hexane as a colorless oil. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 4.44 min, $t_{r\ (minor)}$ = 5.69 min). $[\alpha]_D^{29}$ –5.4 (*c* 0.8, MeOH). IR (neat) ν = 3066, 3030, 2979, 2933, 1706, 1444, 1366, 1327, 1160, 1119, 1075 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.53 (bs, 1 H). 7.47-7.35 (m, 3 H), 7.32-7.18 (m, 5 H), 4.55 (t, 1 H, *J* = 8.1 Hz), 2.98 (d, 2 H, *J* = 8.4 Hz), 1.28 (s, 9 H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.6, 144.6, 142.7, 131.4 (q, $^4J_{CF}$ = 1.1 Hz), 130.8 (q, $^2J_{CF}$ = 31.9 Hz), 128.9, 128.7, 127.7, 126.8, 124.4 (q, $^3J_{CF}$ = 3.8 Hz), 124.1 (q, $^1J_{CF}$ = 272 Hz), 123.4 (q, $^3J_{CF}$ = 4.0 Hz), ; HRMS-EI calcd for $C_{20}H_{21}F_3O_2$ $[M]^+$ 350.1489, found 350.1483.



(*R*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-phenylpropanoate (*ent*-6)

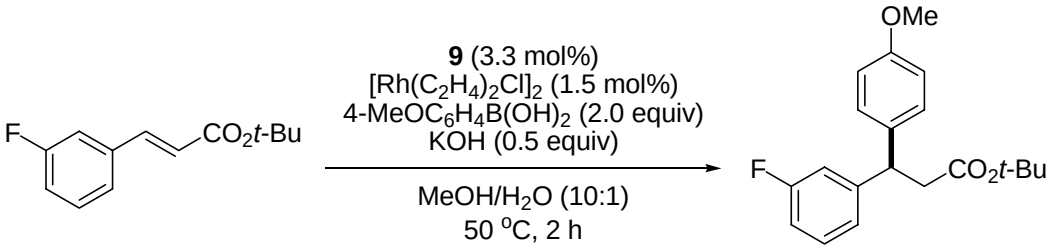
Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl 4-methoxycinnamate, phenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of

18.5 h, the desired product (115 mg, 95%) was isolated by flash chromatography using 10% EtOAc/hexane as a light yellow oil. The enantioselectivity was 91% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 0.35 mL/min, $t_{r\ (minor)}$ = 24.16 min, $t_{r\ (major)}$ = 26.14 min). $[\alpha]_D^{31}$ –0.92 (*c* 0.86, MeOH). The spectral data were identical to **6**.



(*R*)-*tert*-Butyl 3-(3-fluorophenyl)-3-phenylpropanoate

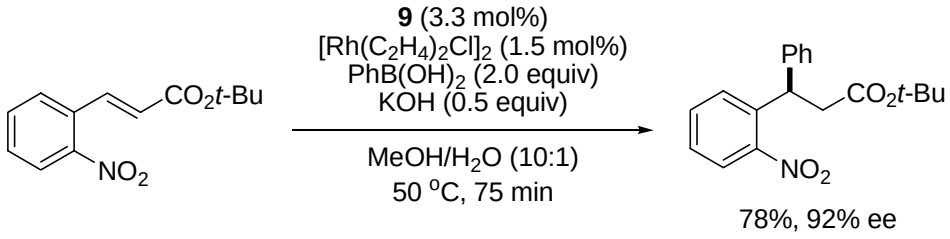
Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl 3-fluorocinnamate, phenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 1.5 h, the desired product (111 mg, 95%) was isolated by flash chromatography using 5% EtOAc/hexane as a colorless oil. The enantioselectivity was 94% ee (OJ-H, 254 nm, hexane:2-propanol = 99:1, flow rate = 0.50 mL/min, $t_{r\ (minor)}$ = 32.37 min, $t_{r\ (major)}$ = 34.37 min). $[\alpha]_D^{25}$ –7.1 (*c* 1.2, C_6H_6); IR (neat) ν = 3066, 3030, 2977, 2929, 1725, 1366, 1247, 1141, 699 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.33-7.18 (m, 6H), 7.04 (br d, 1H, *J* = 7.5 Hz), 6.96 (dt, 1H, *J* = 10.2, 2.4 Hz), 6.88 (tdd, 1H, *J* = 8.7, 2.4, 0.9 Hz), 4.49 (t, 1H, *J* = 8.4 Hz), 2.96 (d, 2H, *J* = 8.4 Hz), 1.30 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.6, 162.7 (d, $^1J_{C\text{-}F}$ = 244.8 Hz), 146.1 (d, $^3J_{C\text{-}F}$ = 6.7 Hz), 142.8, 129.8 (d, $^3J_{C\text{-}F}$ = 8.5 Hz), 128.5, 127.6, 126.6, 123.3 (d, $^4J_{C\text{-}F}$ = 2.4 Hz), 114.6 (d, $^2J_{C\text{-}F}$ = 21.4 Hz), 113.3 (d, $^2J_{C\text{-}F}$ = 21.4 Hz), 80.7, 47.2, 41.9, 27.9; HRMS-EI calcd for $C_{19}H_{21}FO_2$ $[M]^+$ 300.1526, found 300.1522.



93%, 93% ee

(*R*)-*tert*-Butyl 3-(3-fluorophenyl)-3-(4-methoxyphenyl)propanoate

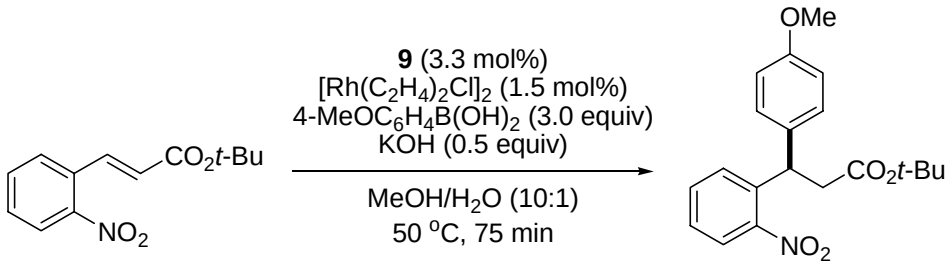
Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl 3-fluorocinnamate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 2 h, the desired product (120 mg, 93%) was isolated by flash chromatography using 5% EtOAc/hexane as a colorless oil. The enantioselectivity was 93% ee (OJ-H, 254 nm, hexane:2-propanol = 99:1, flow rate = 0.50 mL/min, $t_{r\ (minor)}$ = 28.57 min, $t_{r\ (major)}$ = 33.79 min). $[\alpha]_D^{28}$ –2.4 (*c* 0.84, C_6H_6); mp = 67-68 ºC; IR (neat) ν = 3064, 2982, 2934, 2838, 1711, 1512, 1247, 1139, 1026, 687 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.27-7.12 (m, 3H), 7.03-6.80 (m, 5H), 4.43 (t, 1H, *J* = 8.1 Hz), 3.77 (S, 3H), 2.91 (d, 2H, *J* = 8.1 Hz), 1.30 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.7, 162.7 (d, $^1J_{C\text{-}F}$ = 245.4 Hz), 158.1, 146.5 (d, $^3J_{C\text{-}F}$ = 6.7 Hz), 134.9, 129.7 (d, $^3J_{C\text{-}F}$ = 7.9 Hz), 128.5, 123.2 (d, $^4J_{C\text{-}F}$ = 2.5 Hz), 114.5 (d, $^2J_{C\text{-}F}$ = 21.4 Hz), 113.8, 113.1 (d, $^2J_{C\text{-}F}$ = 21.4 Hz), 80.6, 55.2, 46.4, 42.1, 27.9; HRMS-EI calcd for $C_{20}H_{23}FO_3$ $[M]^+$ 330.1631, found 330.1627.



78%, 92% ee

(*R*)-*tert*-Butyl 3-(2-nitrophenyl)-3-phenylpropanoate

Following the general procedure in MeOH on 0.40 mmol scale using *t*-butyl 2-nitrocinnamate, phenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 75 min, the desired product (102 mg, 78%) was isolated by flash chromatography using 10% EtOAc/hexane as a colorless oil. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 99:1, flow rate = 0.50 mL/min, $t_{r\ (minor)}$ = 29.43 min, $t_{r\ (major)}$ = 39.13 min). $[\alpha]_D^{27}$ +13.3 (*c* 0.42, $CHCl_3$). IR (neat) ν = 33066, 3026, 2971, 1725, 1524, 1354, 1256, 1148 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.77 (dd, 1 H, *J* = 8.1, 1.2 Hz), 7.56-7.44 (m, 2 H), 7.36-7.17 (m, 6 H), 5.15 (t, 1 H, *J* = 8.4 Hz), 3.07-2.93 (m, 2 H), 1.26 (s, 9 H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.0, 149.8, 141.6, 137.5, 132.5, 129.3, 128.6, 127.8, 127.3, 126.9, 124.4, 80.9, 42.0, 41.1, 27.7; HRMS-EI calcd for $C_{15}H_{12}NO_3$ $[M\text{-}OC_4H_9]^+$ 254.0817, found 254.0813.

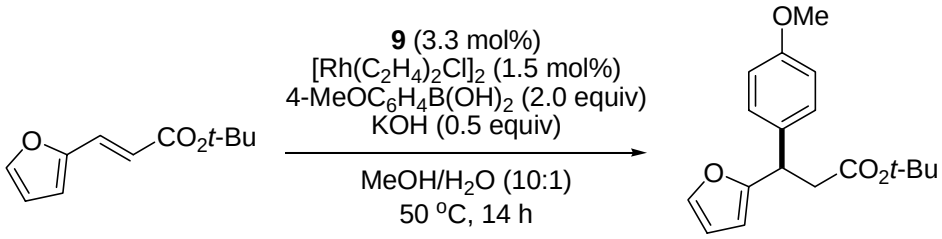


84%, 92% ee

(*R*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-(2-nitrophenyl)propanoate

Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl 2-nitrocinnamate, 4-methoxyphenylboronic acid (3.0 equiv), and ligand **9** with a reaction

time of 75 min, the desired product (117 mg, 84%) was isolated by flash chromatography using 10% EtOAc/hexane as a light yellow oil. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 0.5 mL/min, $t_{r\ (minor)}$ = 39.29 min, $t_{r\ (major)}$ = 53.89 min). $[\alpha]_D^{29}$ +35.1 (*c* 0.94, MeOH). IR (neat) ν = 2977, 1728, 1610, 1527, 1512, 1355, 1252, 1151, 1034 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.79-7.76 (m, 1 H), 7.56-7.44 (m, 2 H), 7.37-7.31 (m, 1 H), 7.21-7.17 (m, 2 H), 6.86-6.81 (m, 2 H), 5.10 (t, 1 H, *J* = 8.1 Hz), 3.77 (s, 3 H), 3.05-2.90 (m, 2 H), 1.28 (s, 9 H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.1, 158.4, 149.8, 137.9, 133.7, 132.5, 129.2, 128.8, 127.2, 124.4, 113.9, 80.9, 55.2, 42.2, 40.4, 27.7; HRMS-EI calcd for $C_{16}H_{15}NO_5$ $[M-C_4H_8]^+$ 301.0945, found 301.0946.

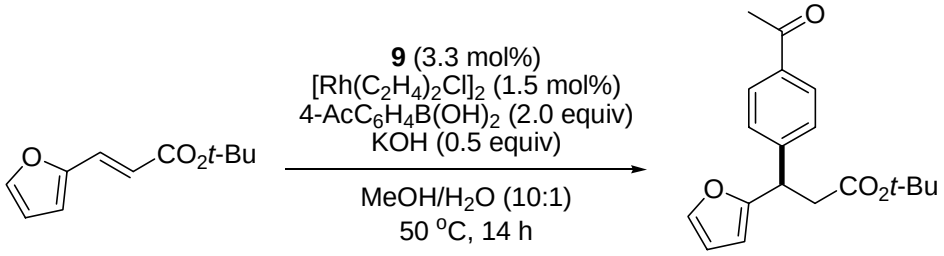


62%, 92% ee

(*R*)-*tert*-Butyl 3-(furan-2-yl)-3-(4-methoxyphenyl)propanoate

Following the general procedure in MeOH on 0.37 mmol scale using *t*-butyl 3-(furan-2-yl)acrylate, 4-methoxyphenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 14 h, the desired product (68 mg, 62%) was isolated by flash chromatography using 10% EtOAc/hexane as a colorless oil. The enantioselectivity was 92% ee (AD-H, 254 nm, hexane:2-propanol = 99:1, flow rate = 0.50 mL/min, $t_{r\ (major)}$ = 18.17 min, $t_{r\ (minor)}$ = 23.64 min). $[\alpha]_D^{27}$ –38.2 (*c* 0.66, $CHCl_3$). IR (neat) ν = 2976, 2932, 2836, 1727, 1511, 1246, 1145, 730 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.30 (dd, 1H, *J* = 1.8, 0.6 Hz), 7.18

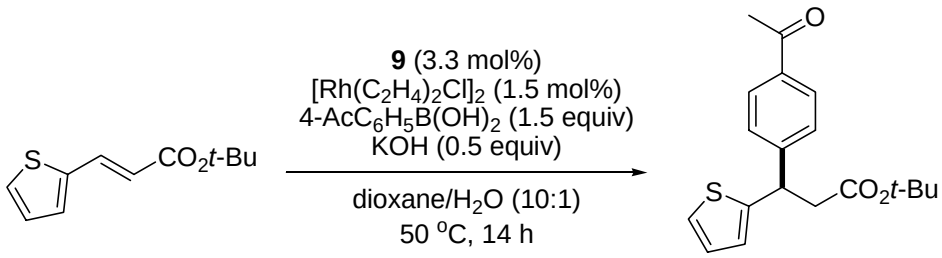
(m, 2H), 6.84 (m, 2H), 6.27 (dd, 1H, *J* = 3.3, 1.8 Hz), 6.02 (dt, 1H, *J* = 3.3, 0.6 Hz), 4.44 (t, 1H, *J* = 8.1 Hz), 3.78 (s, 3H), 2.98 (dd, 1H, *J* = 15.0, 8.1 Hz), 2.77 (dd, 1H, *J* = 15.0, 8.1 Hz), 1.33 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.9. 158.7. 157.0. 141.7. 133.5. 129.0. 114.0. 110.2. 105.6. 80.8. 55.4. 41.3. 41.1. 28.1; HRMS-EI calcd for $C_{18}H_{22}O_4$ $[M]^+$ 302.1518, found 302.1514.



68%, 91% ee

(*R*)-*tert*-Butyl 3-(4-acetylphenyl)-3-(furan-2-yl)propanoate

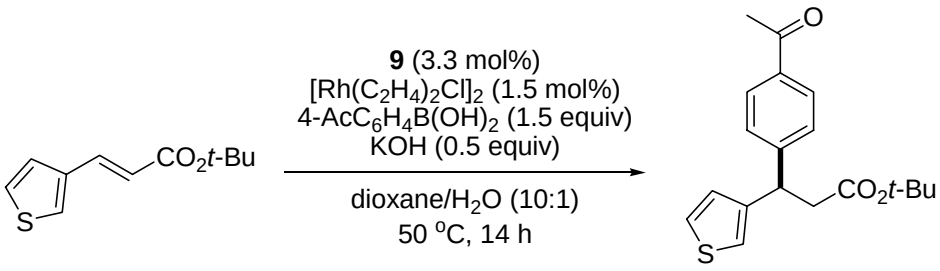
Following the general procedure in MeOH on 0.39 mmol scale using *t*-butyl 3-(furan-2-yl)acrylate, 4-acetylphenylboronic acid (2.0 equiv), and ligand **9** with a reaction time of 14 h, the desired product (82 mg, 68%) was isolated by flash chromatography using 10% then 20% EtOAc/hexane as a colorless oil. The enantioselectivity was 91% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 15.58 min, $t_{r\ (minor)}$ = 20.35 min). $[\alpha]_D^{30}$ –41.3 (*c* 0.8, $CHCl_3$). IR (neat) ν = 3006, 2977, 2933, 1726, 1682, 1265, 1146, 734 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.92 (m, 2H), 7.35 (m, 2H), 7.31 (dd, 1H, *J* = 1.8, 0.9 Hz), 6.28 (dd, 1H, *J* = 3.3, 1.8 Hz), 6.06 (dt, 1H, *J* = 3.3, 0.9 Hz), 4.55 (br t, 1H, *J* = 8.1 Hz), 3.01 (dd, 1H, *J* = 15.3, 7.5 Hz), 2.83 (dd, 1H, *J* = 15.3, 8.3 Hz), 2.57 (s, 3H), 1.32 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 197.5, 170.0, 155.3, 146.5, 141.7, 135.8, 128.5, 128.0, 110.1, 105.9, 80.9, 41.6, 40.5, 28.0, 26.7; HRMS-EI calcd for $C_{19}H_{22}O_4$ $[M\text{-}C_4H_9]^+$ 257.0814, found 257.0806.



65%, 91% ee

(*R*)-*tert*-Butyl 3-(4-acetylphenyl)-3-(thiophen-2-yl)propanoate

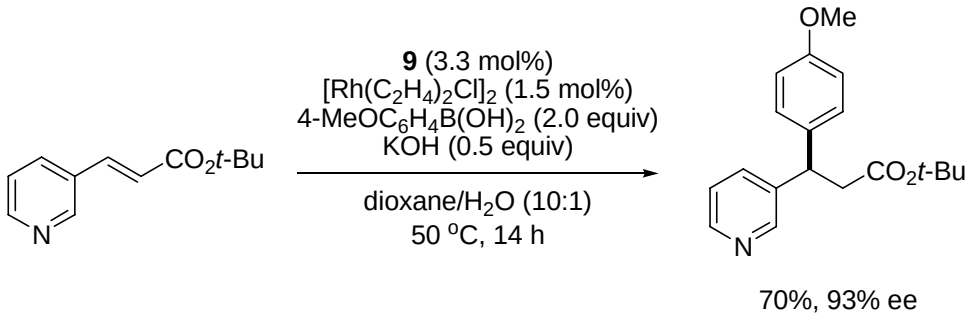
Following the general procedure in dioxane on 0.39 mmol scale using *tert*-butyl-3-(thiophen-2-yl)acrylate, 4-acetylphenylboronic acid (1.5 equiv), and ligand **9** with a reaction time of 14 h, the desired product (64 mg, 65%) was isolated by flash chromatography using hexanes/EtOAc 10:1 as a colorless oil. The enantioselectivity was 91% ee (OD-H, 254 nm, hexane:2-propanol = 96:4, flow rate = 0.5 mL/min, $t_{r\ (minor)}$ = 18.9 min, $t_{r\ (major)}$ = 20.1 min). $[\alpha]_D^{29}$ –14.5 (*c* 0.95, $CHCl_3$). IR (neat) ν = 2976, 1727, 1686, 1606, 1366, 1267, 1147, 956, 843 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.1 Hz), 7.38 (d, 2H, *J* = 8.1 Hz), 7.17-7.14 (m, 1H), 6.91 (m, 1H), 6.83 (m, 1H), 4.76 (t, 1H, *J* = 8.1 Hz), 3.01 (dd, 1H, *J* = 15.3, 7.5 Hz), 2.83 (dd, 1H, *J* = 15.3, 8.3 Hz), 2.57 (s, 3H), 1.30 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 197.5, 169.9, 148.4, 146.4, 135.7, 128.6, 127.8, 126.6, 124.2, 124.1, 81.6, 43.0, 42.9, 28.0, 26.7; HRMS-EI calcd for $C_{19}H_{22}O_3S$ $[M\text{-}C_4H_8]^+$ 274.0659, found 274.0659.



68%, 89% ee

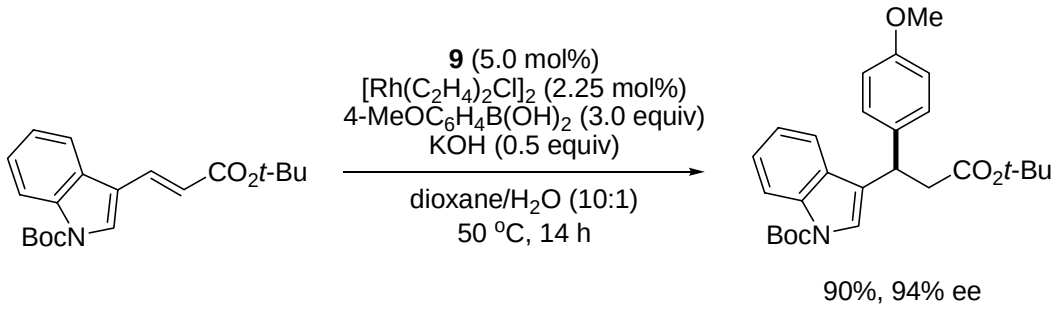
(*R*)-*tert*-Butyl 3-(4-acetylphenyl)-3-(thiophen-3-yl)propanoate

Following the general procedure in dioxane on 0.30 mmol scale using *tert*-butyl 3-(thiophen-3-yl)acrylate, 4-acetylphenylboronic acid (1.5 equiv), and ligand **9** with a reaction time of 14 h, the desired product (67 mg, 68%) was isolated by flash chromatography using hexane/EtOAc (3:1) as a colorless oil. The enantioselectivity was 89% ee (AD-H, 254 nm, hexane:2-propanol = 98:2, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 22.4 min, $t_{r\ (minor)}$ = 25.4 min). $[\alpha]_D^{34}$ –37.2 (*c* 1.0, $CHCl_3$). IR (neat) ν = 3103, 2976, 2929, 1723, 1681, 1606, 1366, 1357, 1265, 1141, 956, 830, 779 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89 (d, 2H, *J* = 8.4 Hz), 7.33 (d, 2H, *J* = 8.4 Hz), 7.27 (m, 1H), 7.01 (m, 1H), 6.88 (m, 1H), 4.59 (t, 1H, *J* = 8.1 Hz), 3.04-2.86 (m, 2H), 2.58 (s, 3H), 1.30 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 197.5, 170.4, 148.7, 143.3, 135.5, 128.6, 127.9, 127.3, 125.9, 120.6, 80.9, 43.2, 42.2, 28.0, 26.7; HRMS-EI calcd for $C_{19}H_{22}SO_3$ $[M]^+$ 330.1290, found 330.1292.



(*R*)-*tert*-Butyl 3-(4-methoxyphenyl)-3-(pyridin-3-yl)propanoate

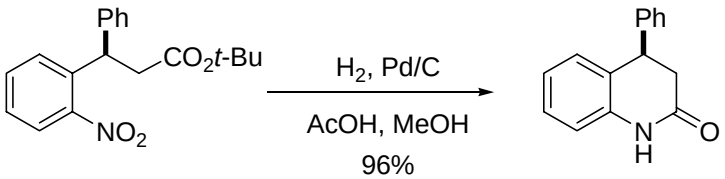
Following the general procedure in dioxane on 0.30 mmol scale using *t*-butyl 3-(pyridin-3-yl)acrylate, 4-methoxyphenylboronic acid (1.5 equiv), and ligand **9** with a reaction time of 14 h, the desired product (66 mg, 70%) was isolated by flash chromatography using hexane/EtOAc (2:1) as a colorless powder. The enantioselectivity was 93% ee (OD-H, 254 nm, hexane:2-propanol = 92:8, flow rate = 0.5 mL/min, $t_{r\ (major)}$ = 19.4 min, $t_{r\ (minor)}$ = 21.2 min). $[\alpha]_D^{34}$ +6.8 (*c* 1.095, $CHCl_3$). mp = 57-58 ºC; IR (neat) ν = 2977, 2932, 2835, 1725, 1610, 1512, 1367, 1250, 1178, 1146, 1030, 833, 713 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.54 (d, 1H, *J* = 2.2 Hz), 8.45 (m, 1H), 7.51 (m, 1H), 7.20 (m, 1H), 7.15 (d, 2H, *J* = 8.7 Hz), 6.84 (d, 2H, *J* = 8.7 Hz), 4.45 (t, 1H, *J* = 8.1 Hz), 3.77 (s, 3H), 2.94 (d, 2H, *J* = 8.1 Hz), 1.29 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.4, 158.2, 149.3, 147.8, 135.0, 134.4, 128.5, 123.3, 114.0, 80.9, 55.3, 44.3, 41.9, 28.0; HRMS-EI calcd for $C_{19}H_{23}NO_3$ $[M]^+$ 313.1678, found 313.1677.



90%, 94% ee

(*R*)-*tert*-Butyl 3-(3-tert-butoxy-1-(4-methoxyphenyl)-3-oxopropyl)-1*H*-indole-1-carboxylate

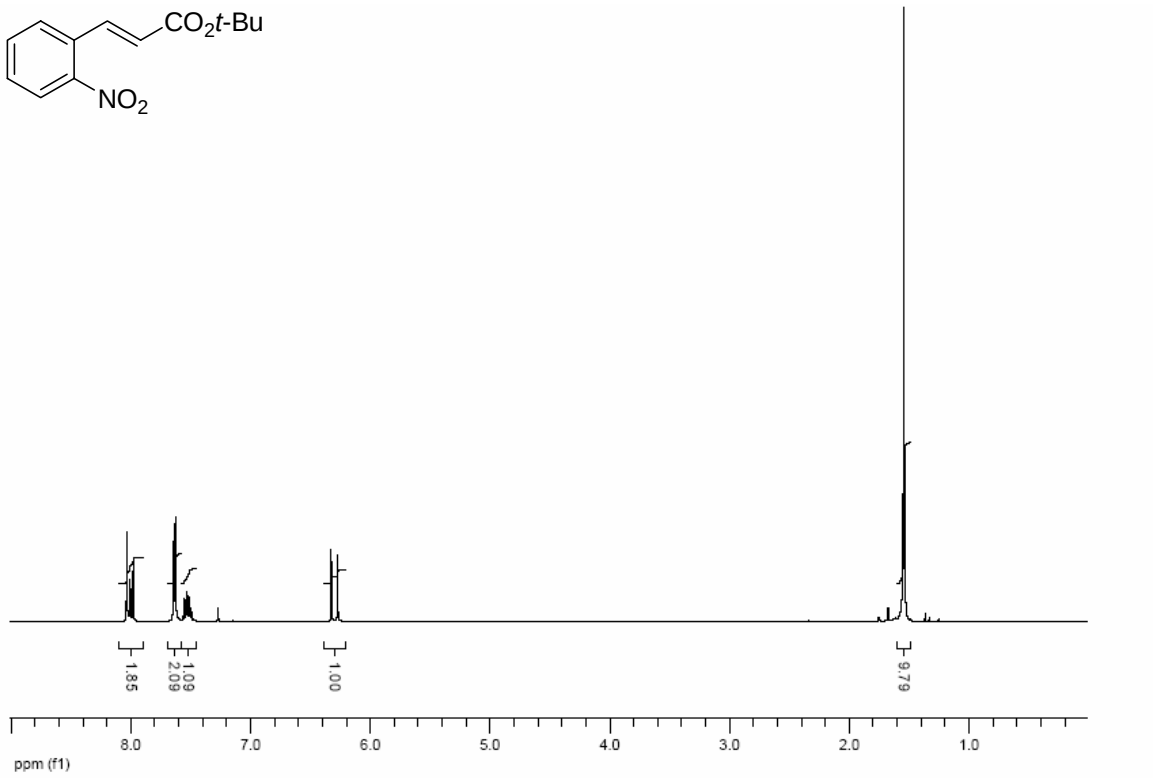
Following the general procedure in dioxane on 0.20 mmol scale using *tert*-butyl 3-(3-tert-butoxy-3-oxoprop-1-enyl)-1*H*-indole-1-carboxylate, 4-methoxyphenyl- boronic acid (3.0 equiv), $[Rh(C_2H_4)_2Cl]_2$ (2.25 mol%), and **9** (5.0 mol%) with a reaction time of 14 h, the desired product (81 mg, 90%) was isolated by flash chromatography using hexane/EtOAc (15:1) as a colorless oil. The enantioselectivity was 94% ee (AD-H, 254 nm, hexane:2-propanol = 99:1, flow rate = 1.0 mL/min, $t_{r\ (major)}$ = 9.9 min, $t_{r\ (minor)}$ = 16.6 min): $[\alpha]_D^{34}$ –81.5 (*c* 0.435, $CHCl_3$). IR (neat) ν = 2977, 2932, 2835, 1731, 1610, 1511, 1453, 1369, 1253, 1157, 1092, 1036, 912, 746 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.08 (d, 1H, *J* = 8.0 Hz), 7.47 (s, 1H), 7.31-7.19 (m, 2H), 7.22 (d, 2H, *J* = 8.8 Hz), 7.10 (m, 1H), 6.80 (d, 2H, *J* = 8.8 Hz), 4.60 (t, 1H, *J* = 7.7 Hz), 3.76 (s, 3H), 3.02 (dd, 1H, *J* = 15.3, 7.7 Hz), 2.85 (dd, 1H, *J* = 15.3, 7.7 Hz), 1.67 (s, 9H), 1.33 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.9, 158.1, 149.7, 135.6, 134.5, 129.7, 128.7, 124.3, 123.4, 122.3, 122.0, 119.8, 115.1, 113.8, 83.5, 80.6, 55.3, 42.4, 38.5, 28.4, 28.1; HRMS-MALDI calcd for $C_{27}H_{33}NO_5Na$ $[M]^+$ 474.2251, found 474.2244.



10 **11**

(*R*)-4-Phenyl-3,4-dihydroquinolin-2(1*H*)-one (**11**)

A mixture of **10** (75 mg, 0.23 mmol) and Pd/C (24 mg, 0.023 mmol, 10 wt% Pd on C) under Ar was suspended in MeOH (2.0 mL) and treated with AcOH (13 μL, 0.23 mmol). The flask was evacuated and purged with H_2 (1 atm) and the reaction was vigorously stirred for 1.5 h. The H_2 balloon was removed and the reaction was stirred under Ar for 14 h, filtered through Celite and concentrated. The residue was purified by chromatography on SiO_2 (1:1, hexanes/EtOAc) to give **11** (49 mg, 96%) as a colorless solid: $[\alpha]_D^{27}$ –48.8 (*c* 0.79, $CHCl_3$). IR (neat) ν = 3208, 3059, 2914, 1679, 1593, 1486, 1374, 1260 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.11 (bs, 1 H), 7.37-7.19 (m, 6 H), 6.99-6.89 (m, 3 H), 4.31 (t, 1 H, *J* = 7.5 Hz), 3.02-2.88 (m, 2 H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.8, 141.3, 136.9, 128.8, 128.2, 127.9, 127.7, 127.1, 126.5, 123.2, 115.6, 42.0, 38.5; HRMS-EI calcd for $C_{15}H_{13}NO$ $[M]^+$ 223.0992, found 223.0992.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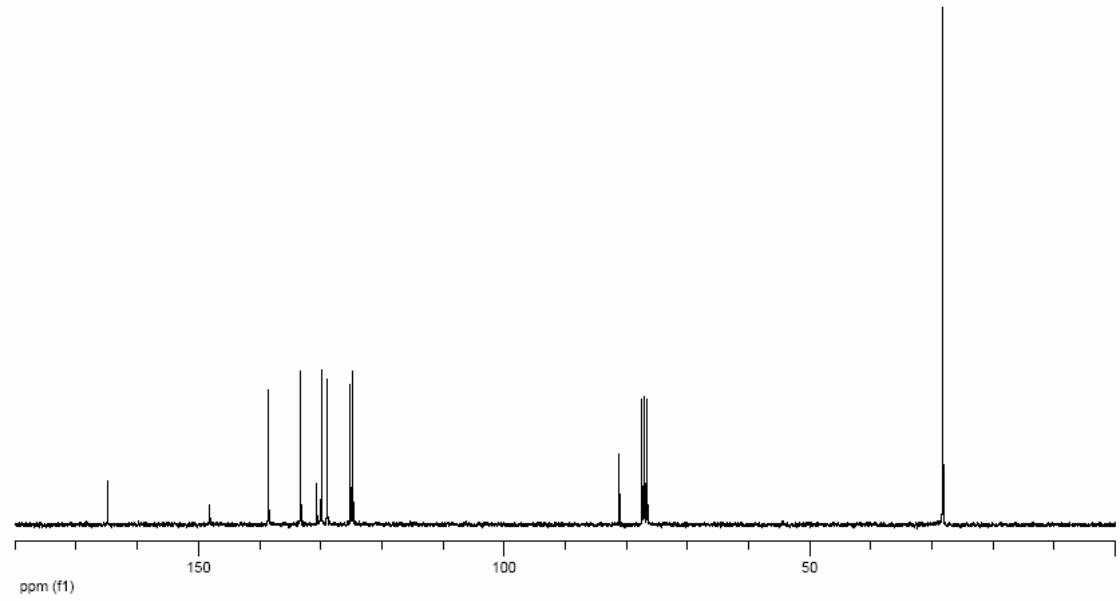
2.0
1.0
ppm (f1)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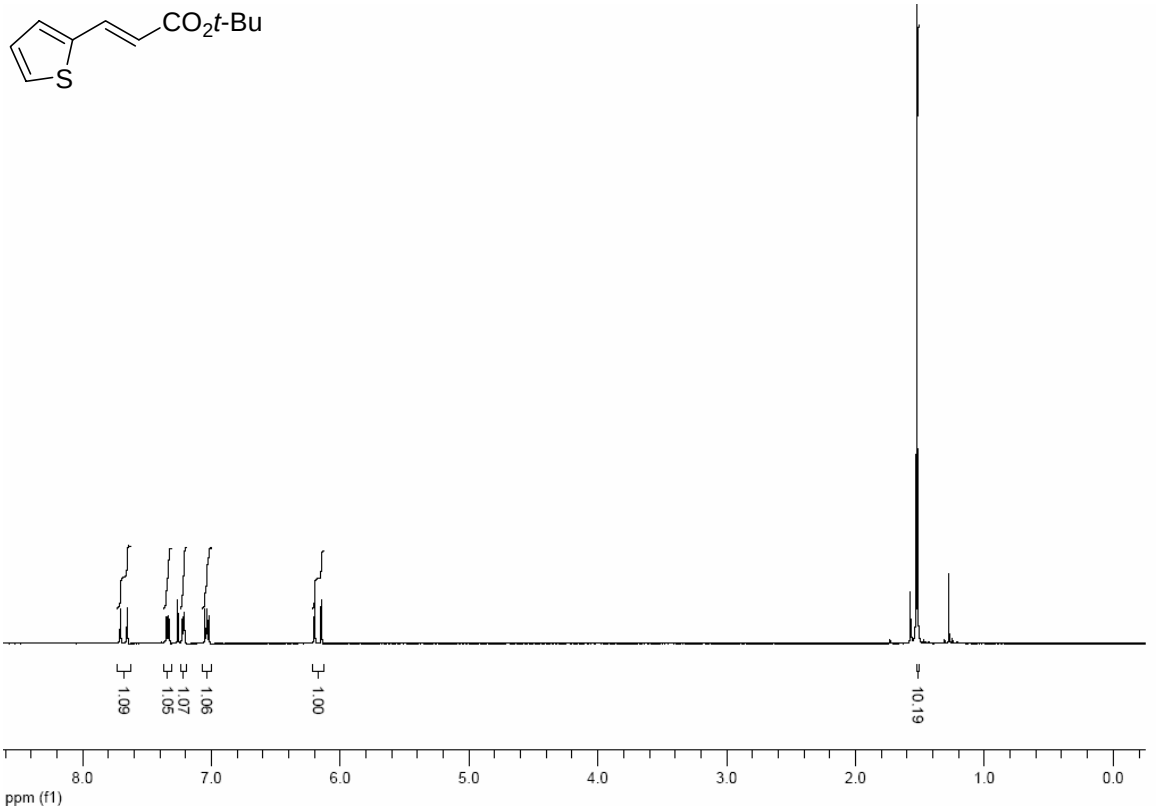
100
50
ppm (f1)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1.07
1.06
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10.19
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7.0
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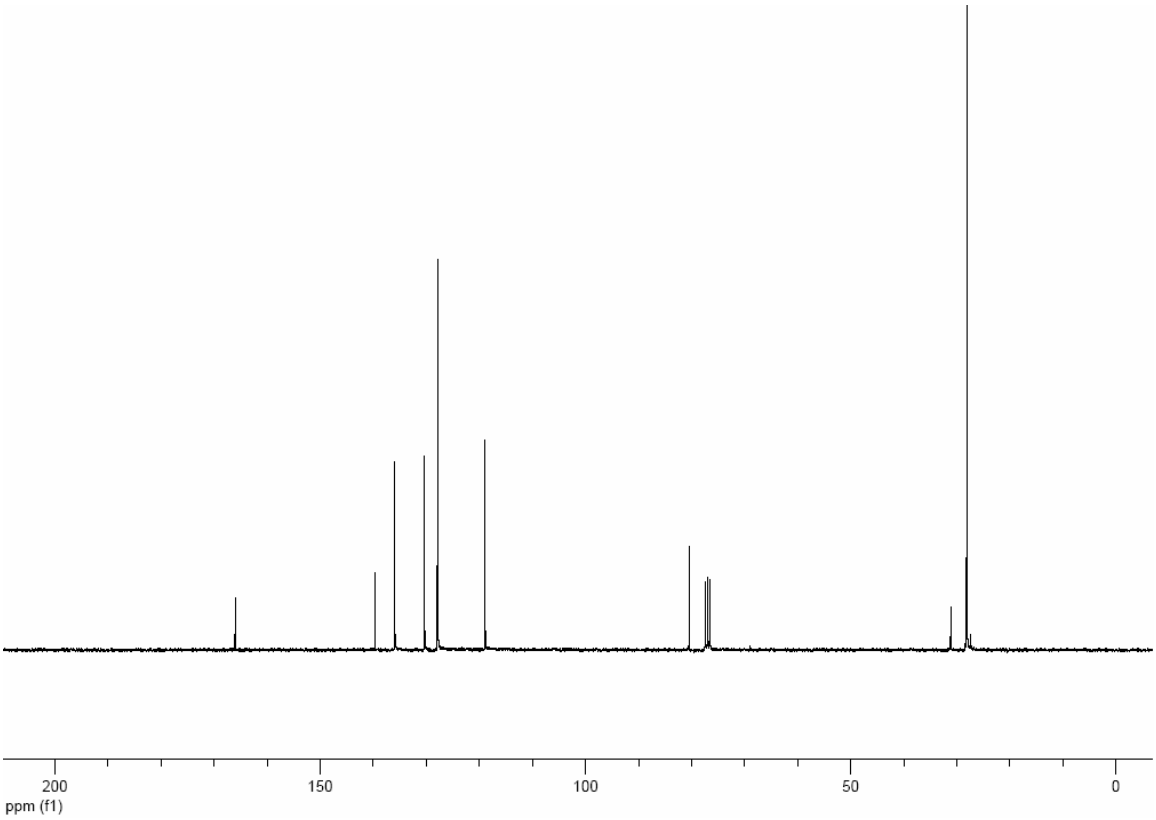
3.0
2.0
1.0
0.0
ppm (f1)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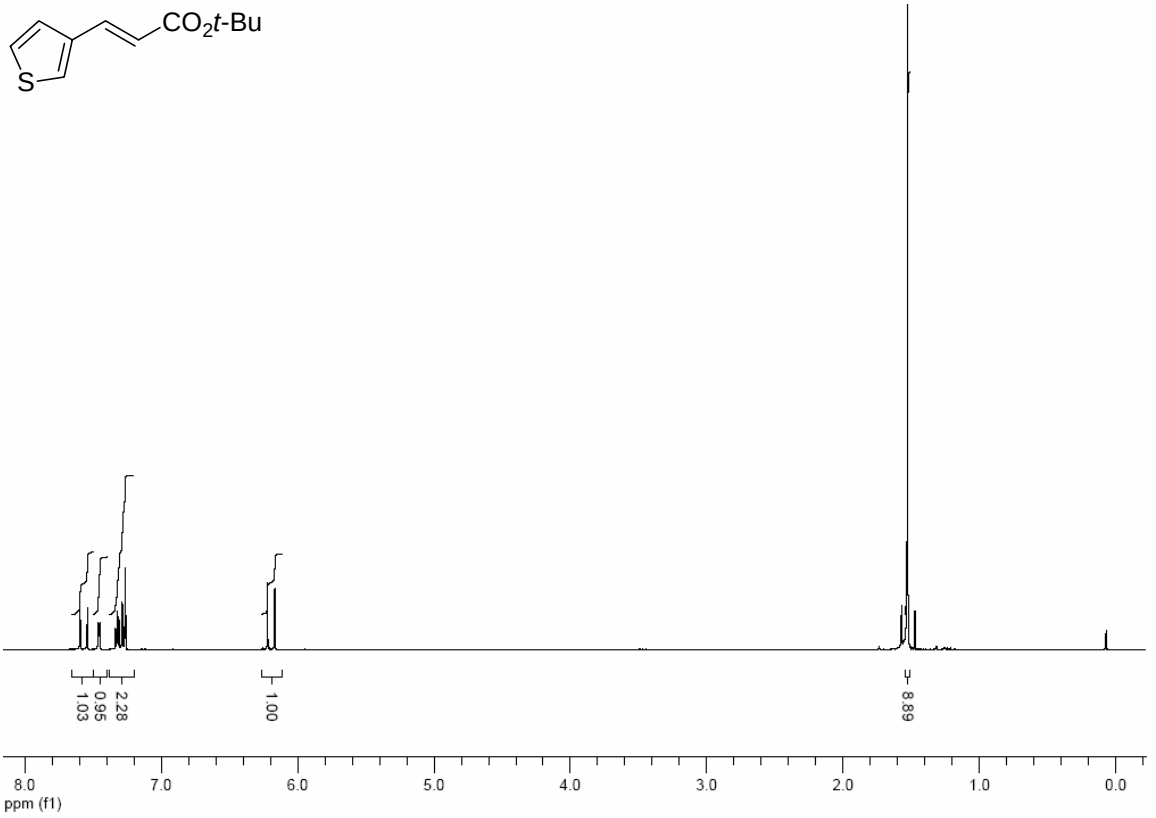
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6.0
5.0
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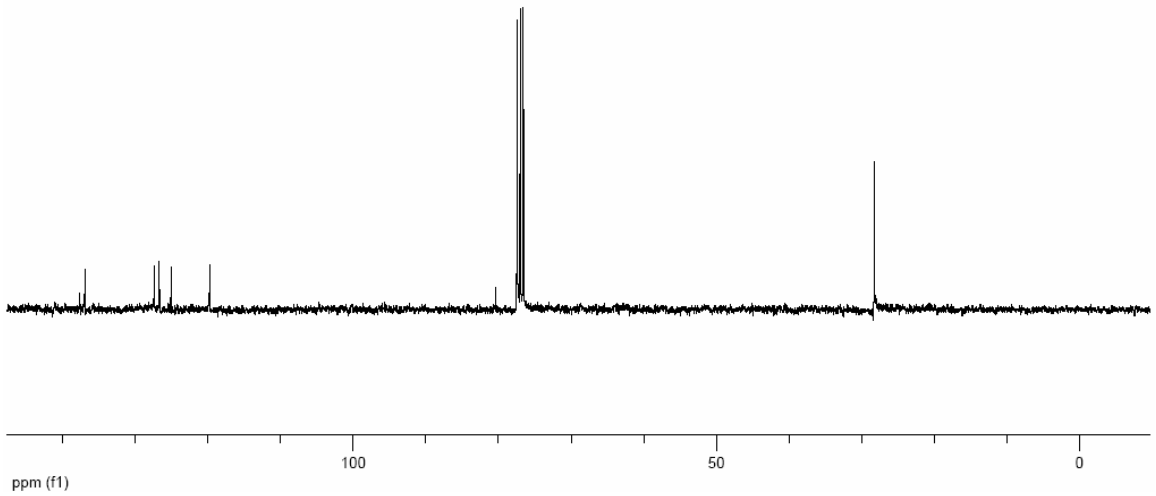
2.0
1.0
0.0
ppm (f1)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50
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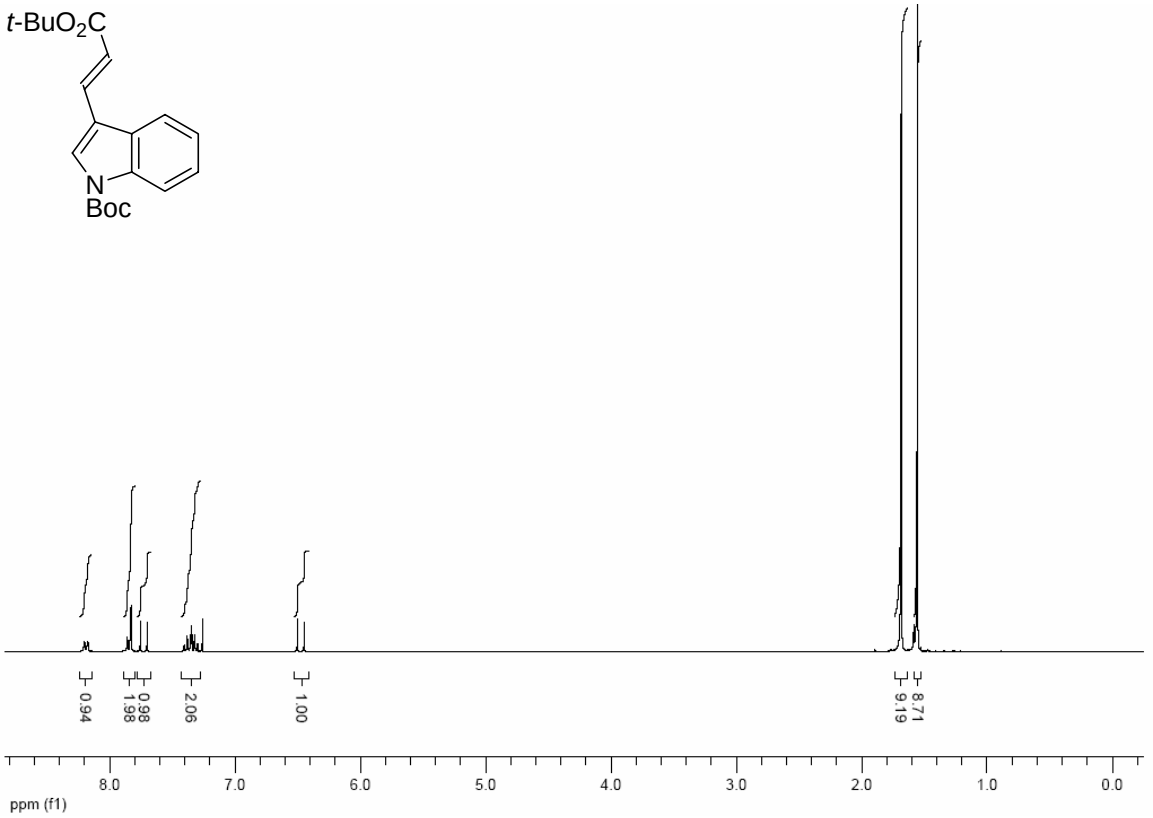
ppm (f1)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Boc
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0.98
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1.00
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5.0
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2.0
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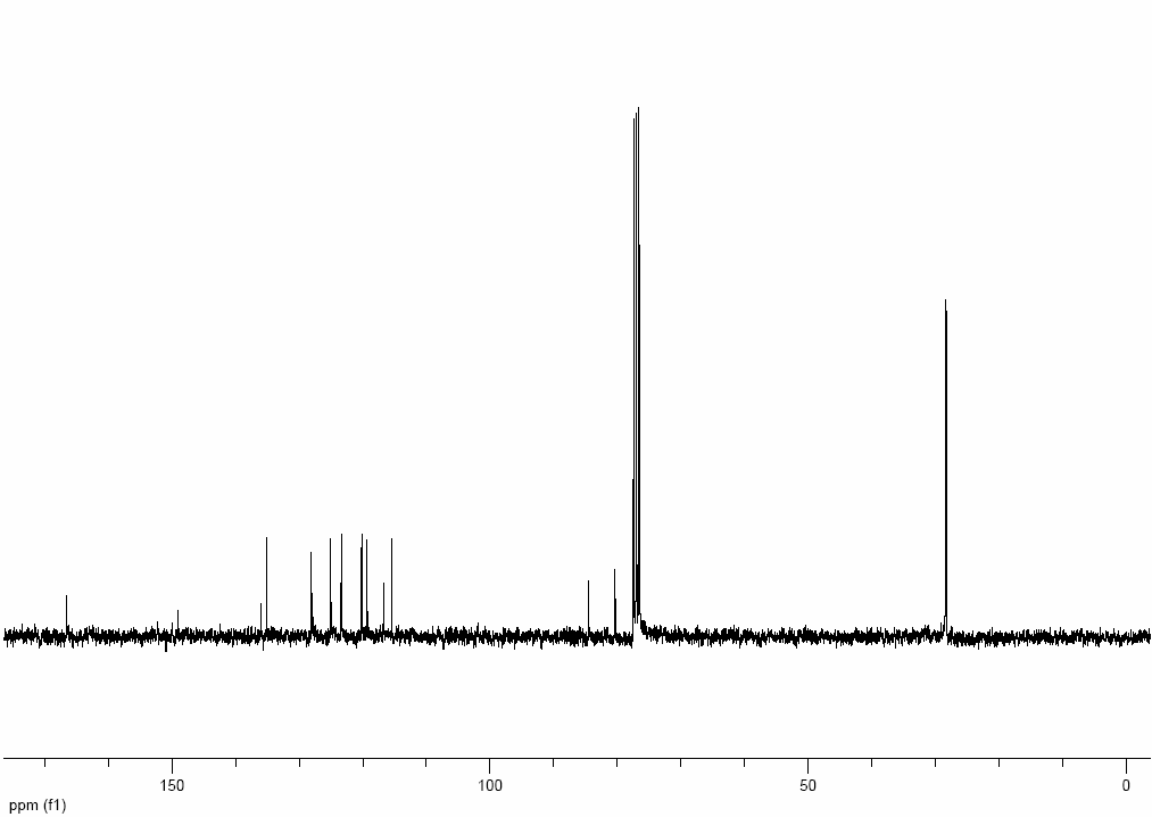
ppm (f1)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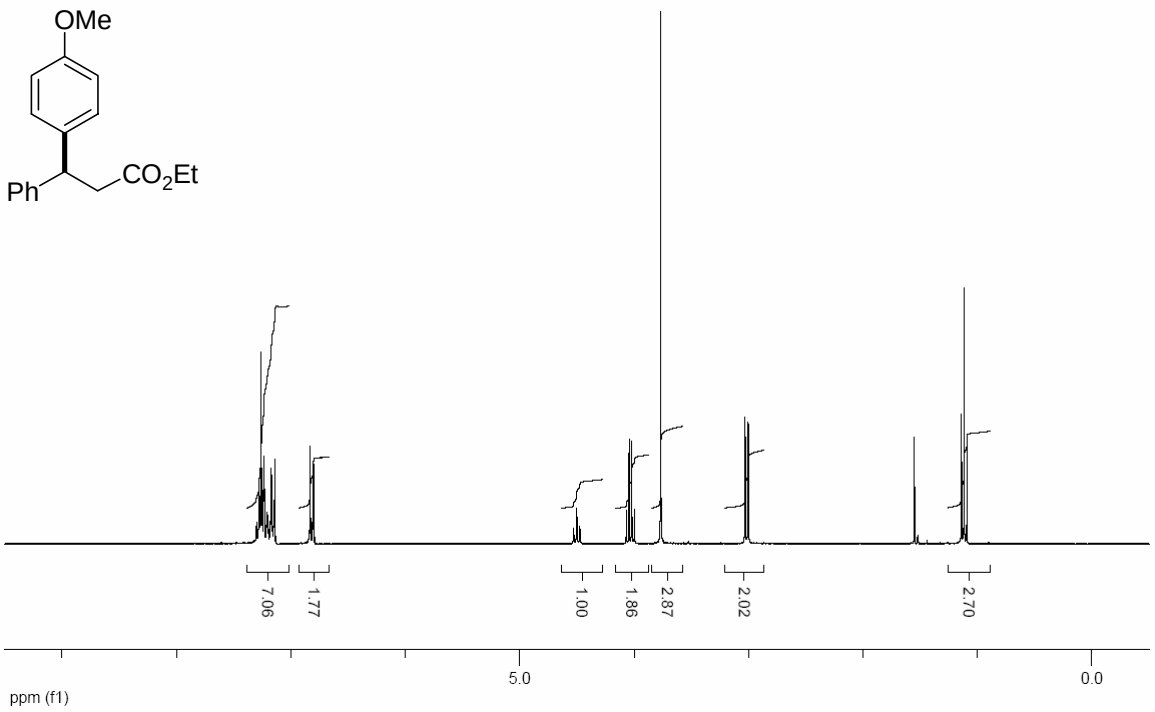
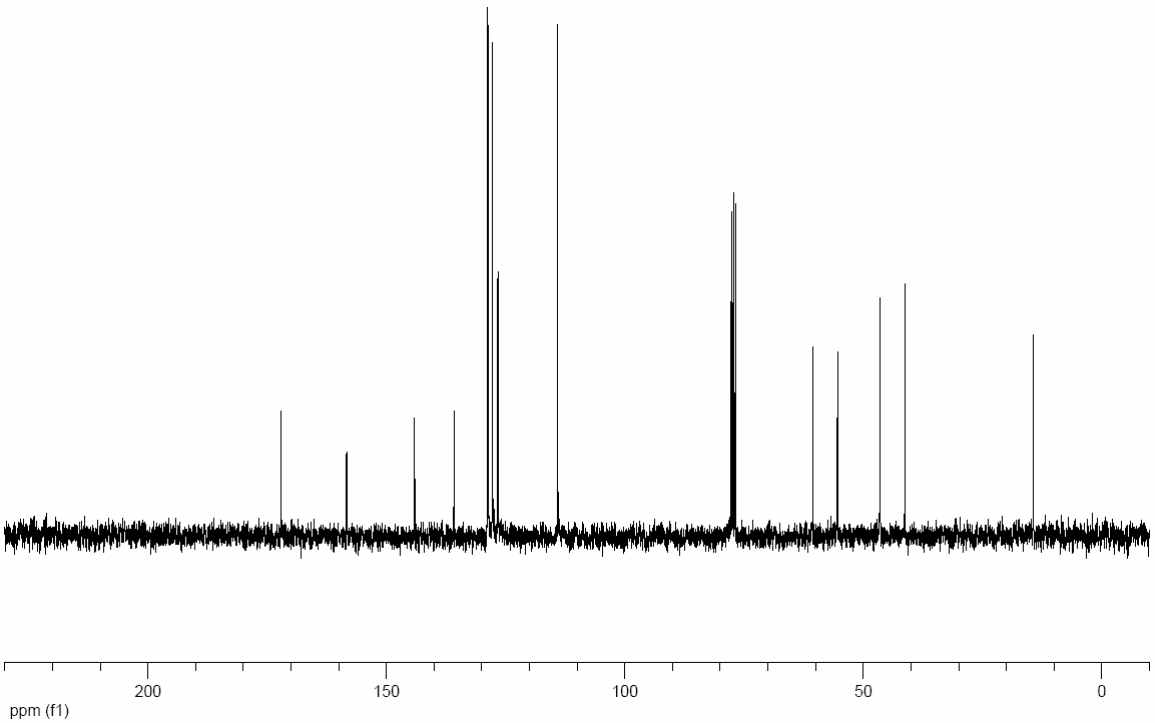
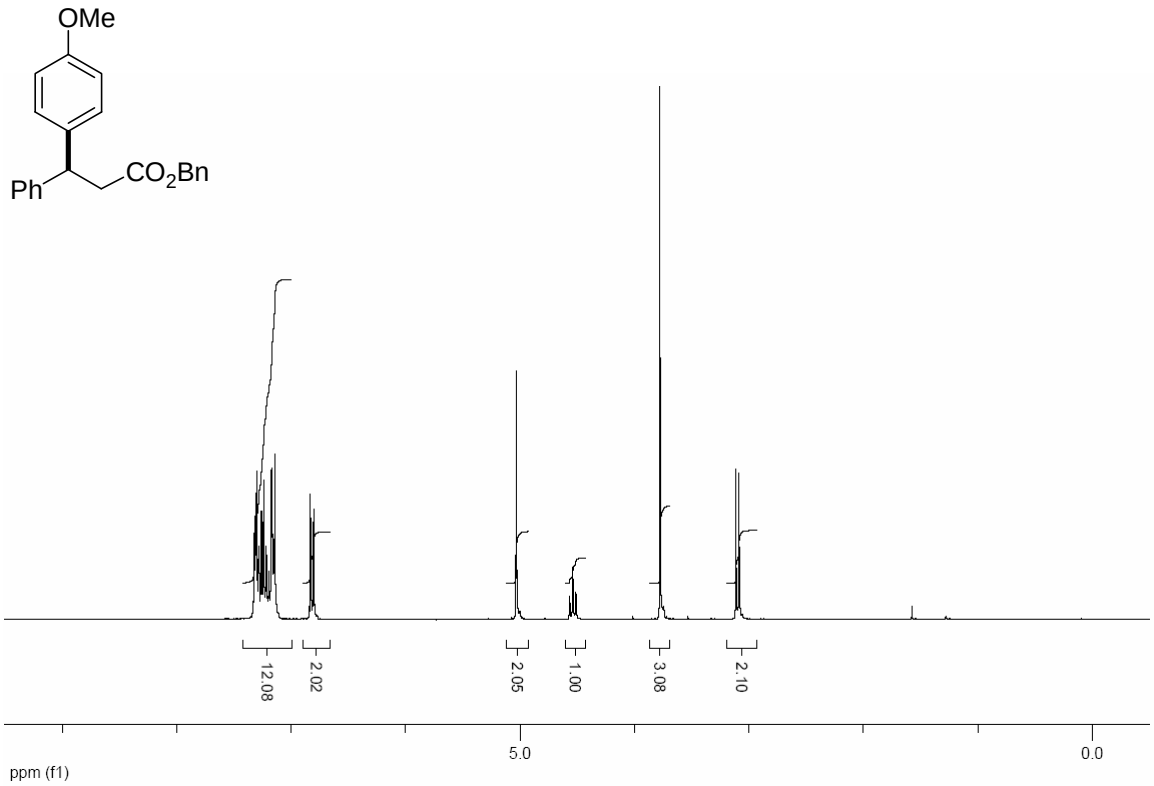
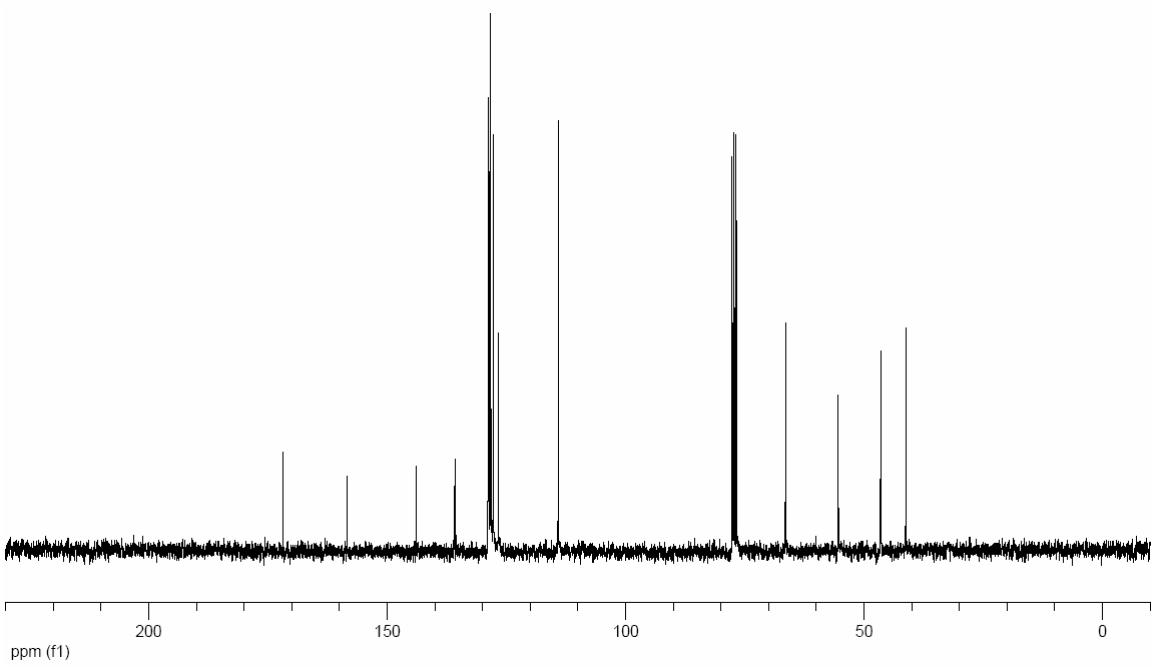
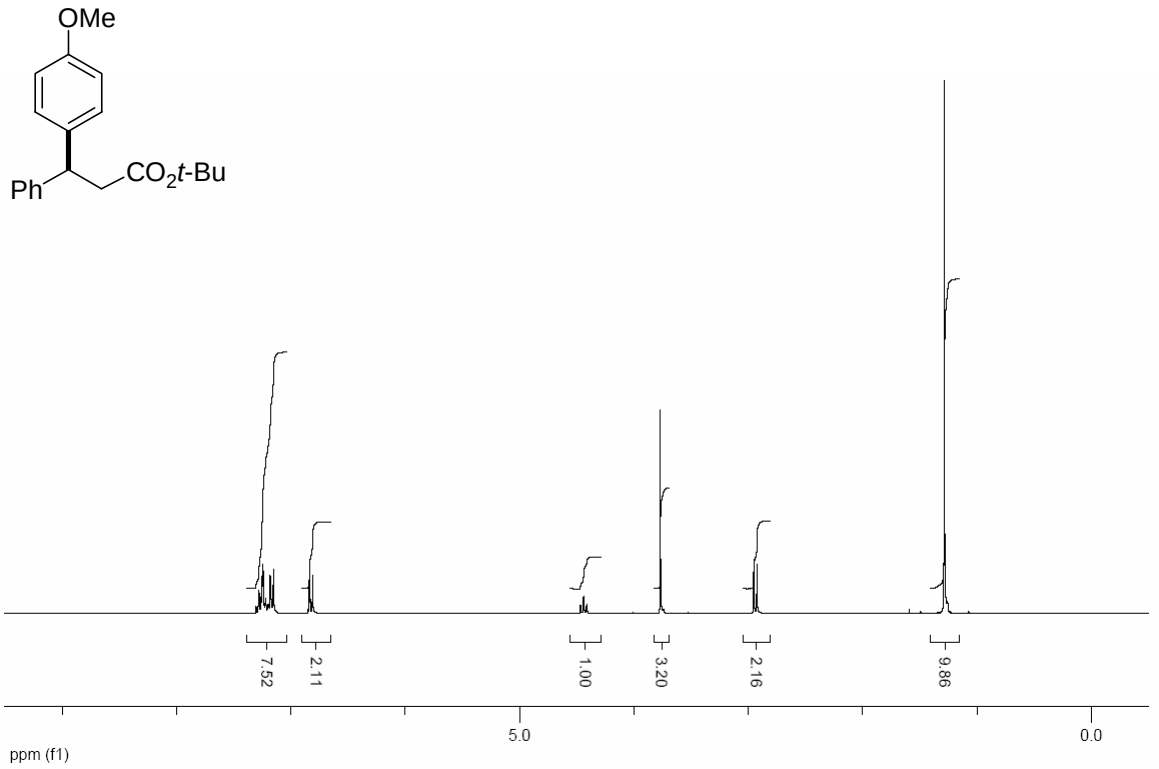
0
ppm (f1)

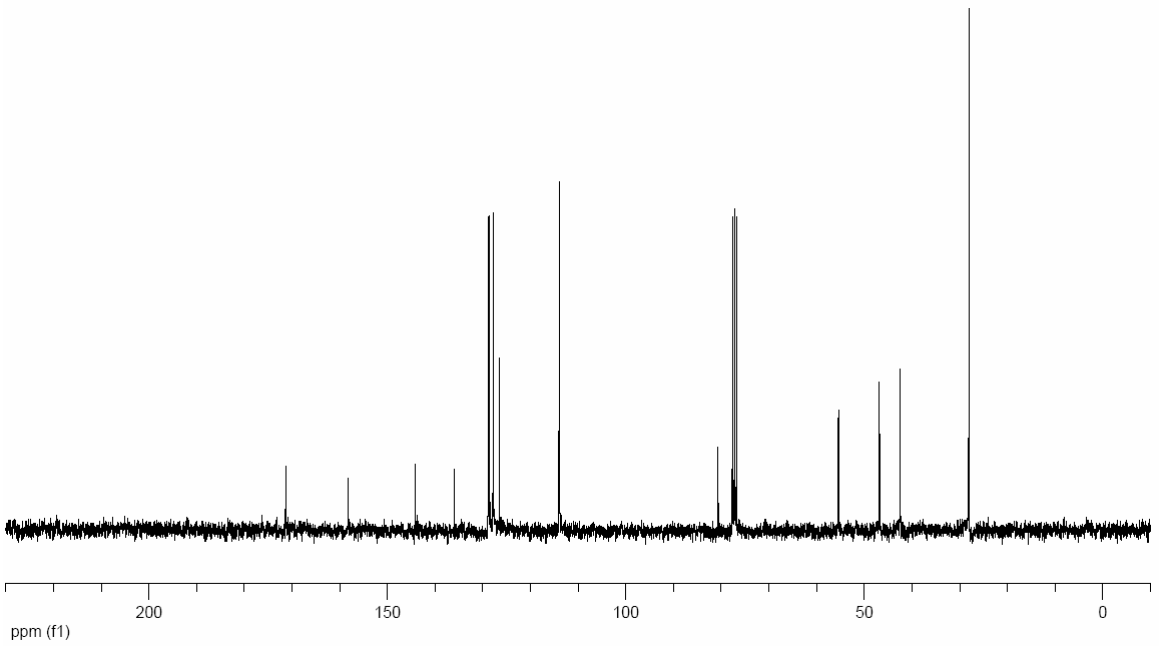

OMe
Ph
CO2Et
7.06
1.77
1.00
1.86
2.87
2.02
2.70
5.0
0.0
ppm (f1)

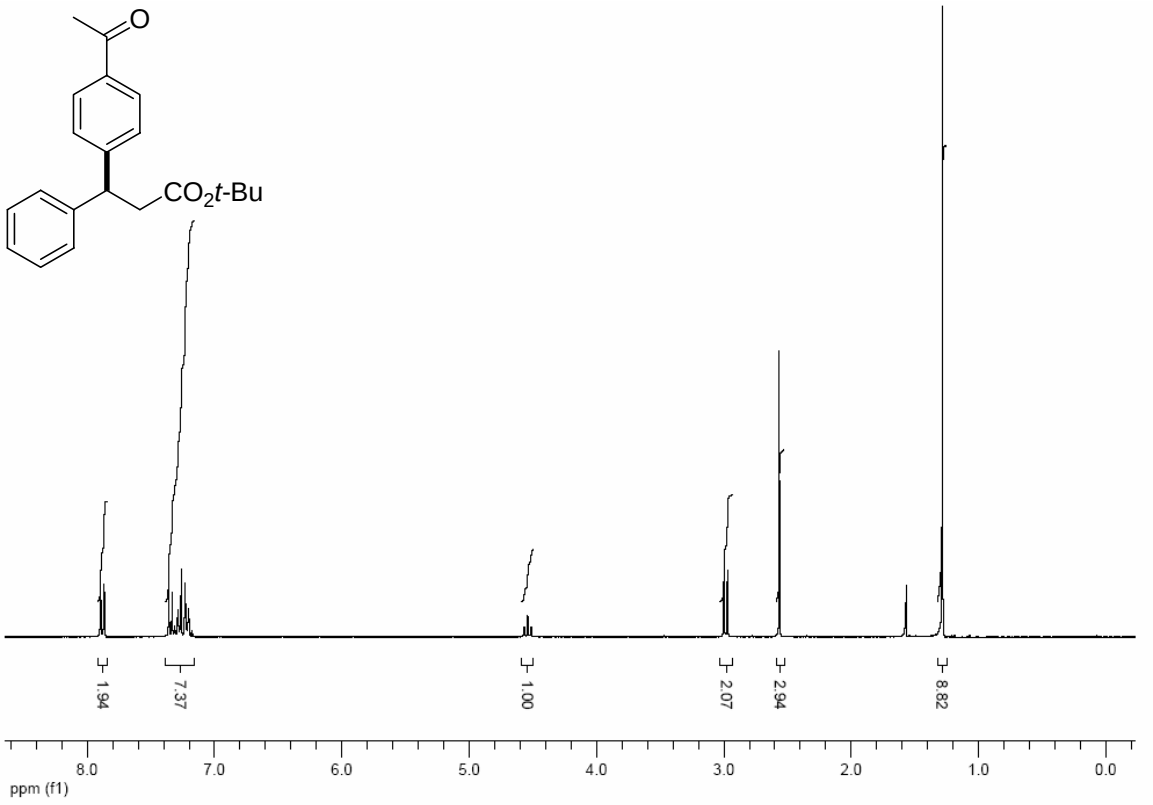

200
150
100
50
0
ppm (f1)

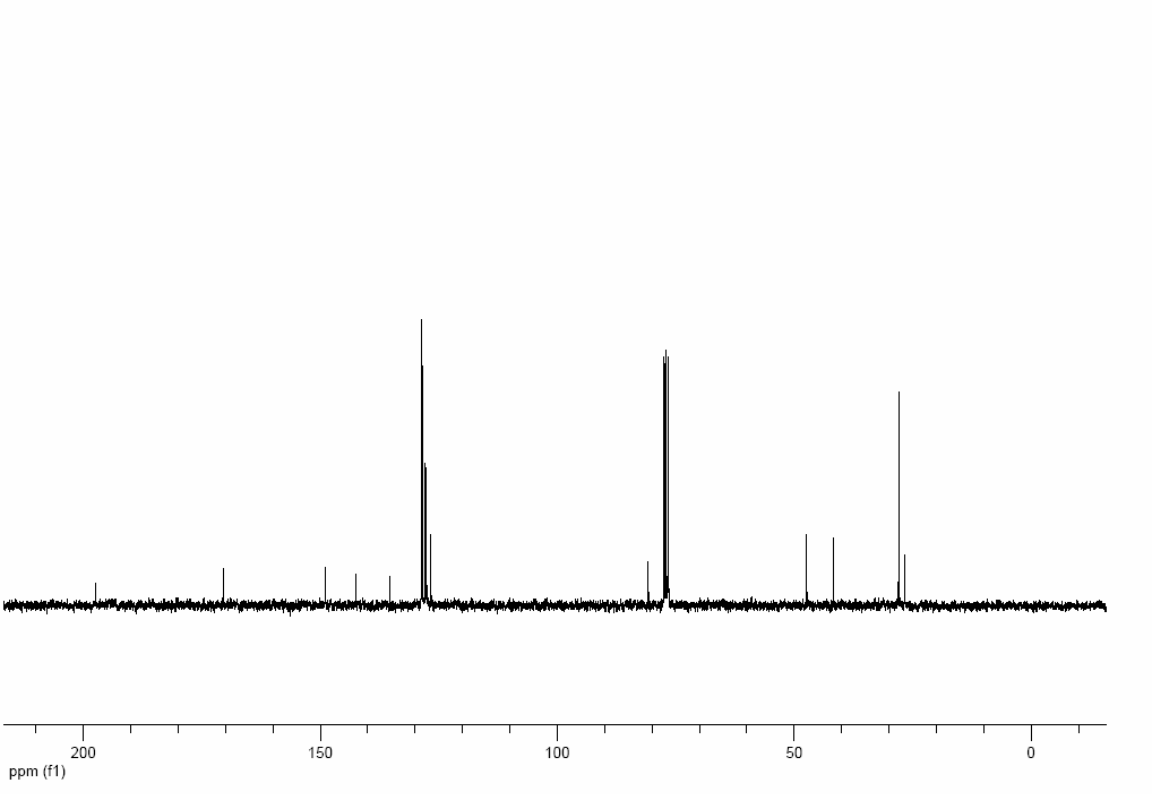

OMe
Ph
CO2Bn
12.08
2.02
2.05
1.00
3.08
2.10
5.0
0.0
ppm (f1)

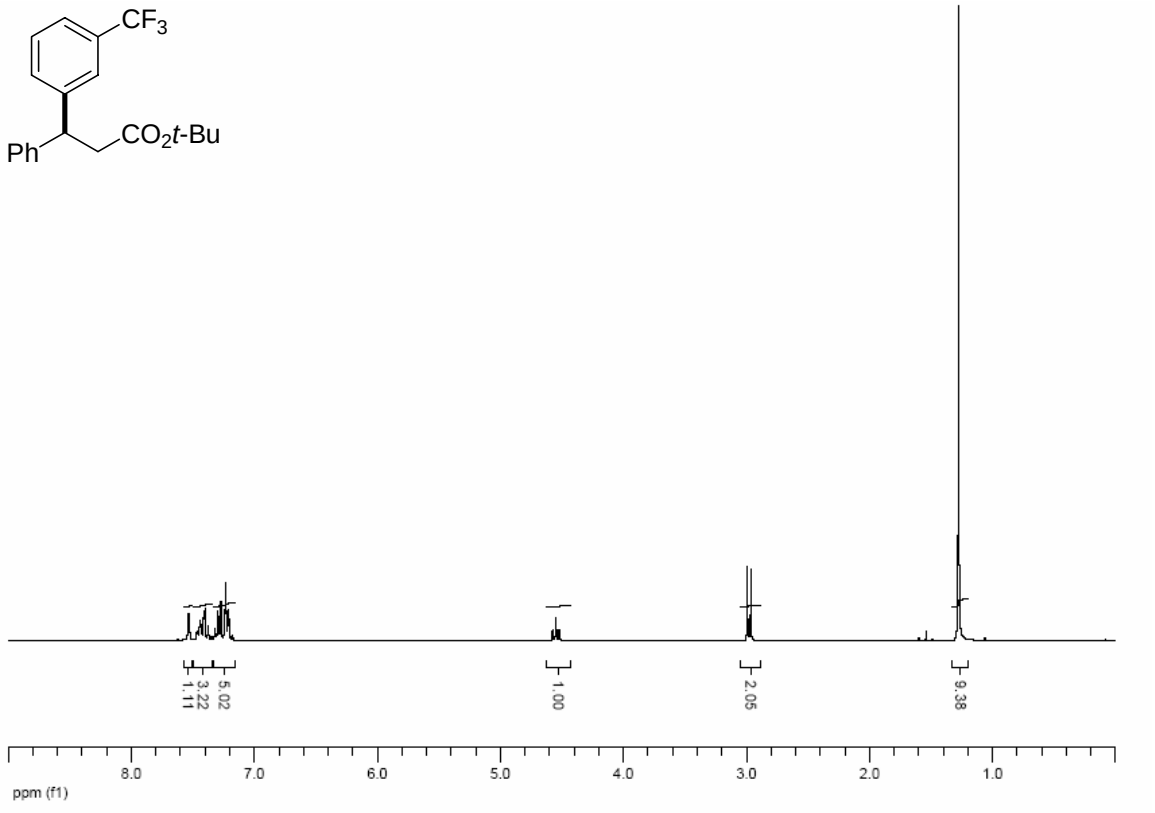

200
150
100
50
0
ppm (f1)

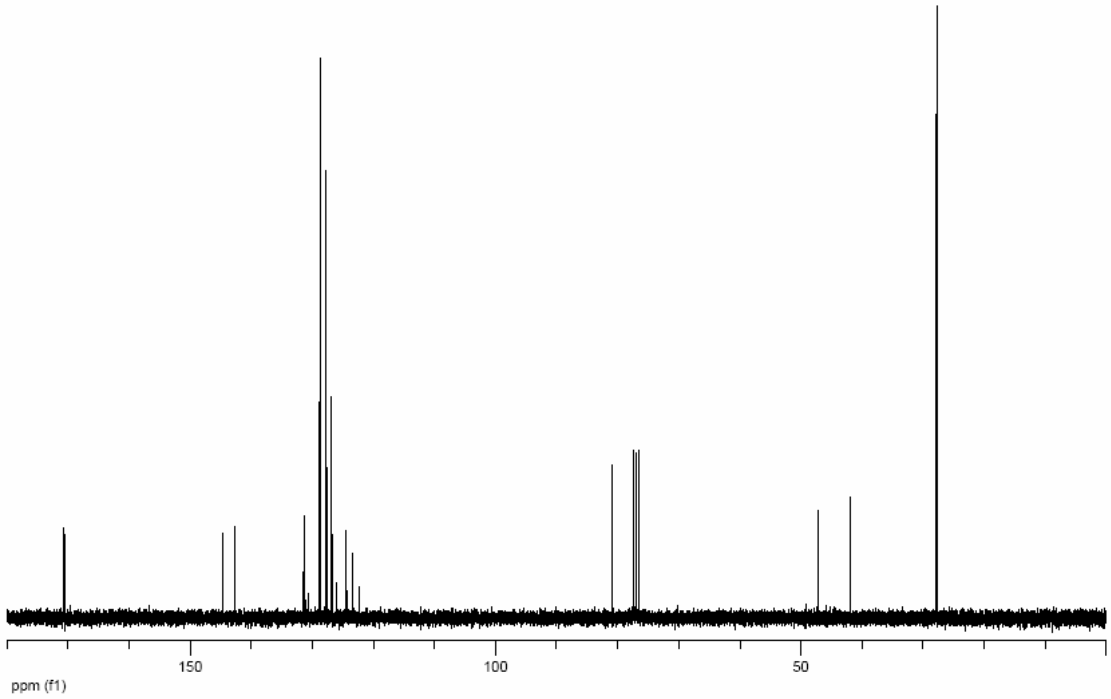

OMe
Ph
CO2t-Bu
7.52
2.11
1.00
3.20
2.16
9.86
5.0
0.0
ppm (f1)

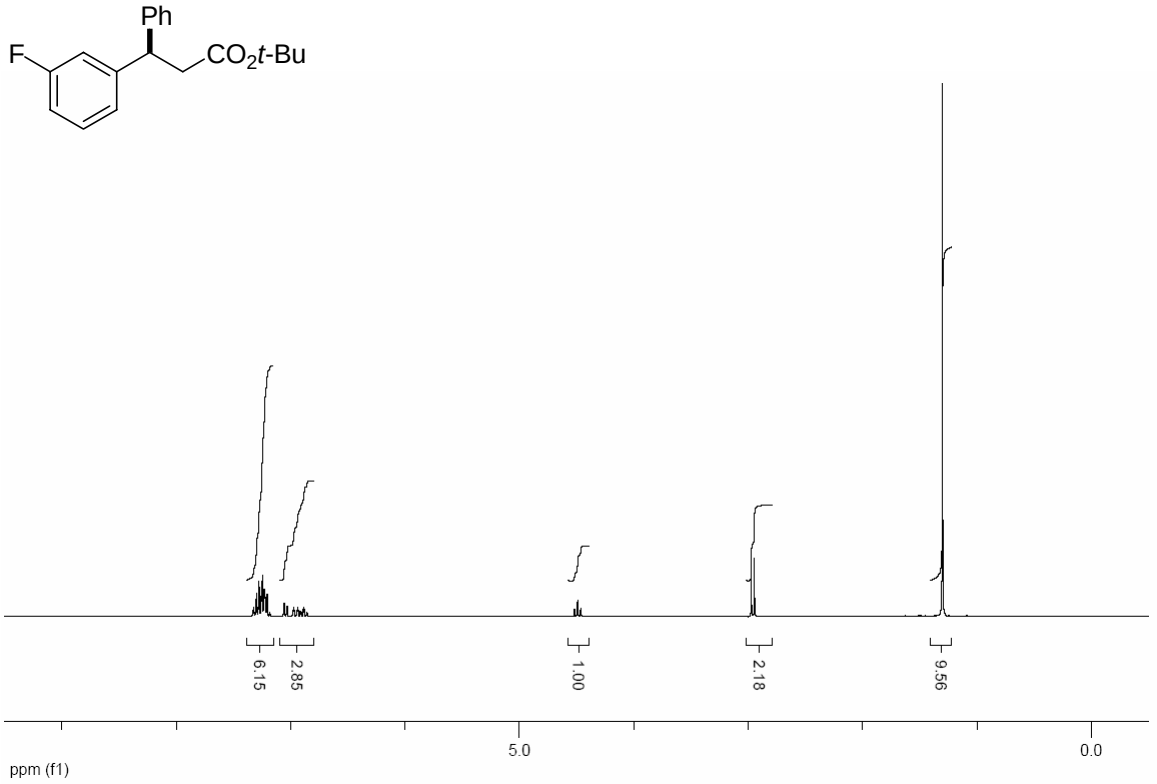

200
150
100
50
0
ppm (f1)

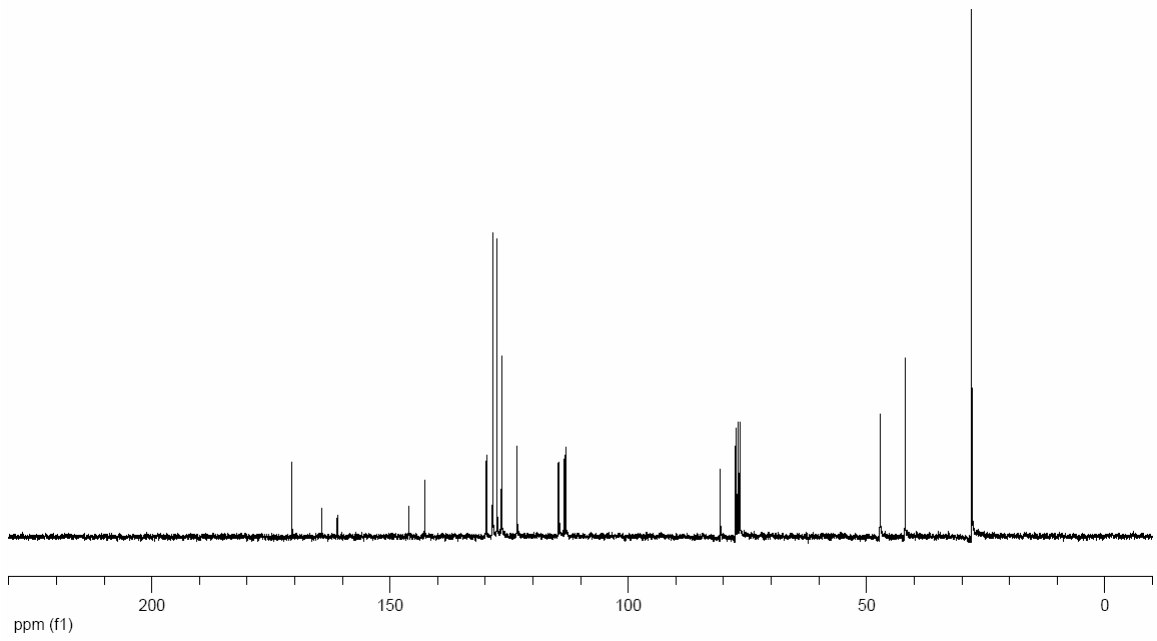

O
CO2t-Bu
1.94
7.37
1.00
2.07
2.94
8.82
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppm (f1)

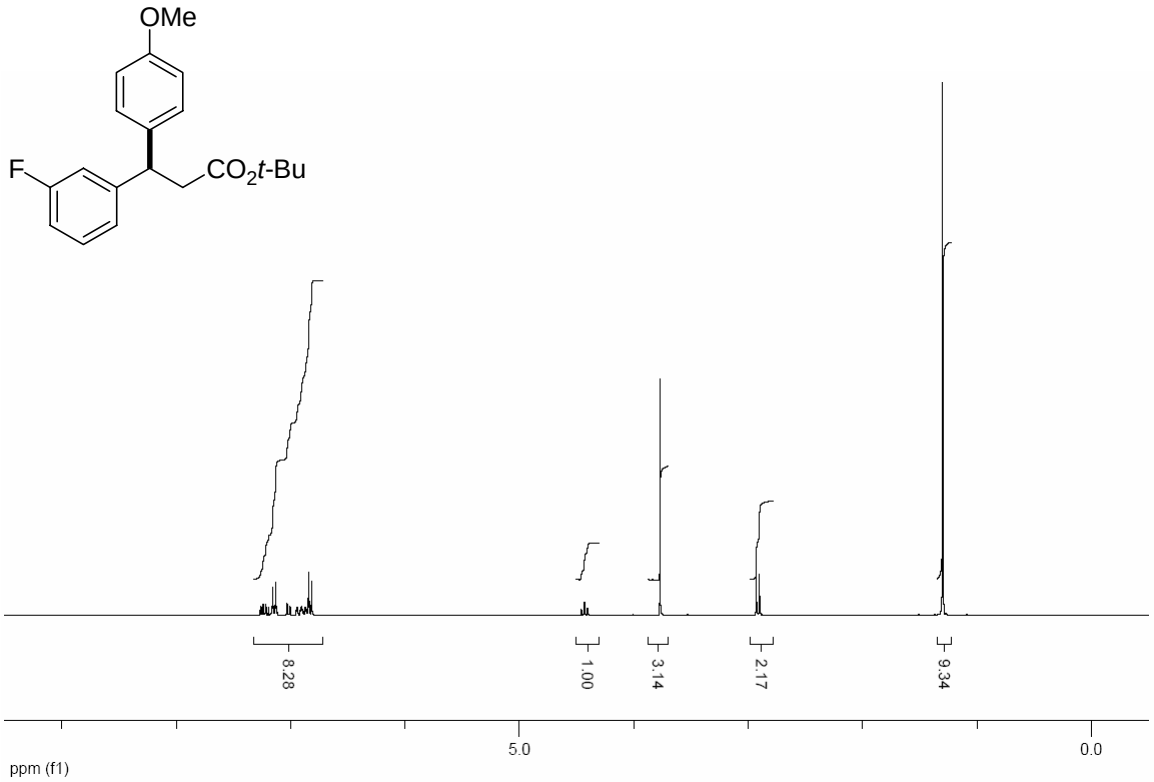

200
150
100
50
0
ppm (f1)

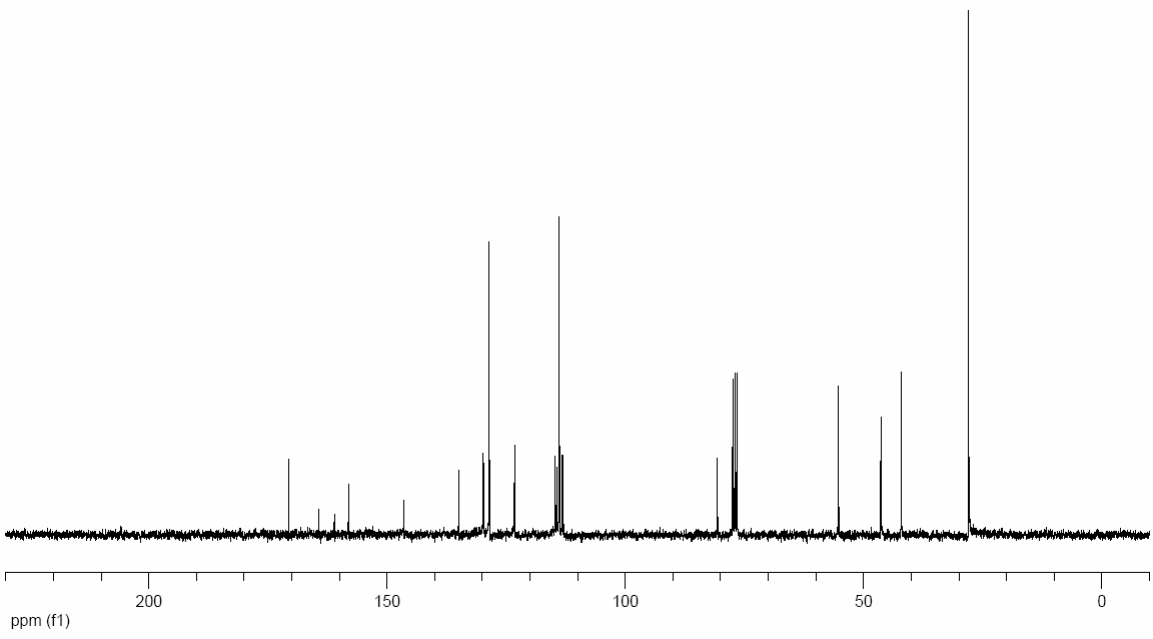

CF3
CO2t-Bu
Ph
1.11
3.22
5.02
1.00
2.05
9.38
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
ppm (f1)

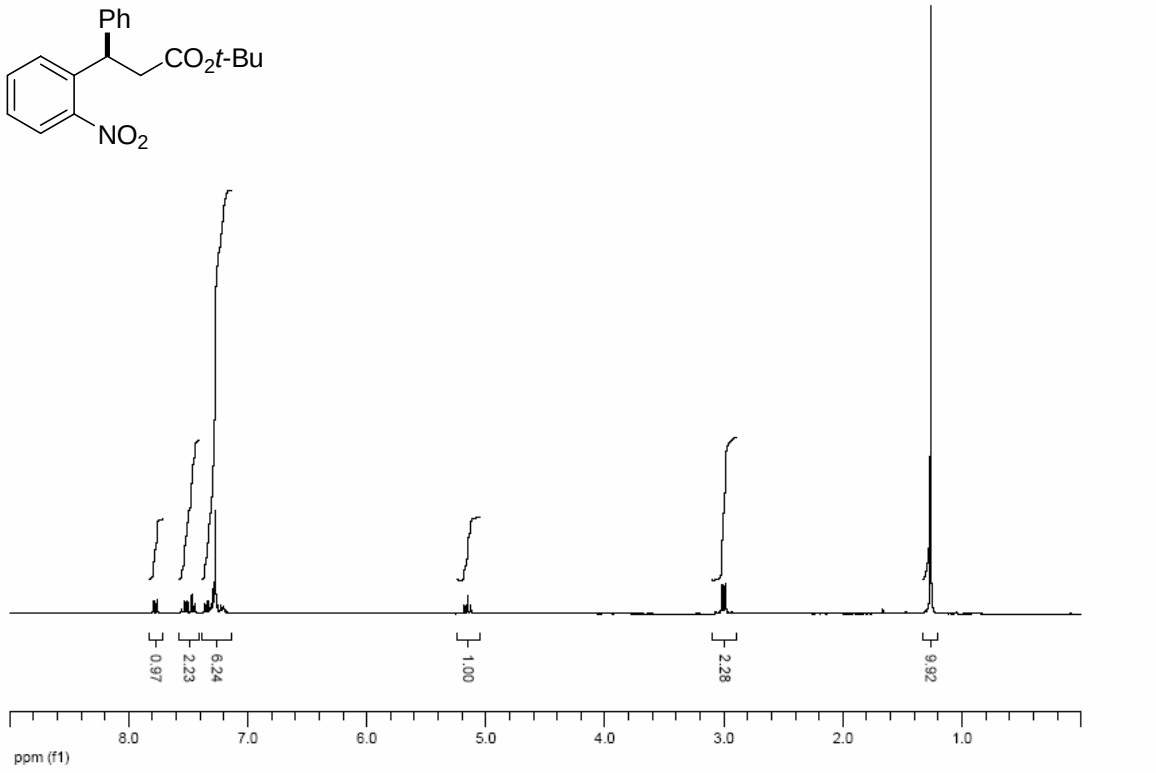

150
100
50
ppm (f1)

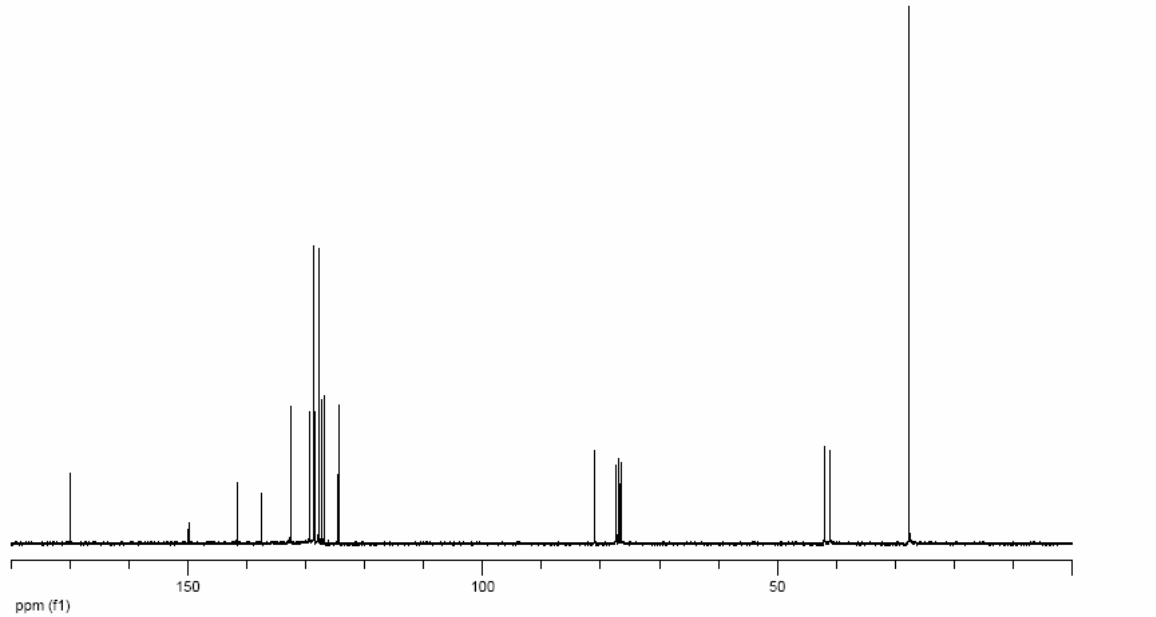

Ph
F
CO2t-Bu
6.15
2.85
1.00
2.18
9.56
5.0
0.0
ppm (f1)

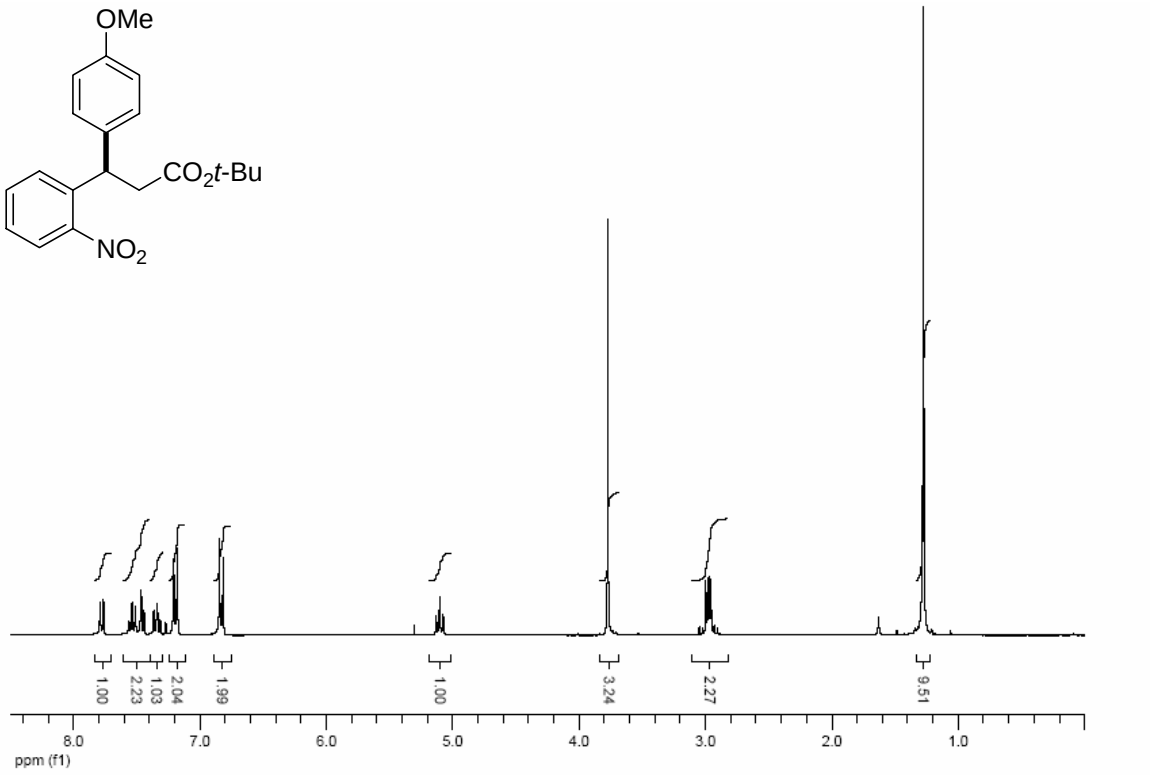

200
150
100
50
0
ppm (f1)

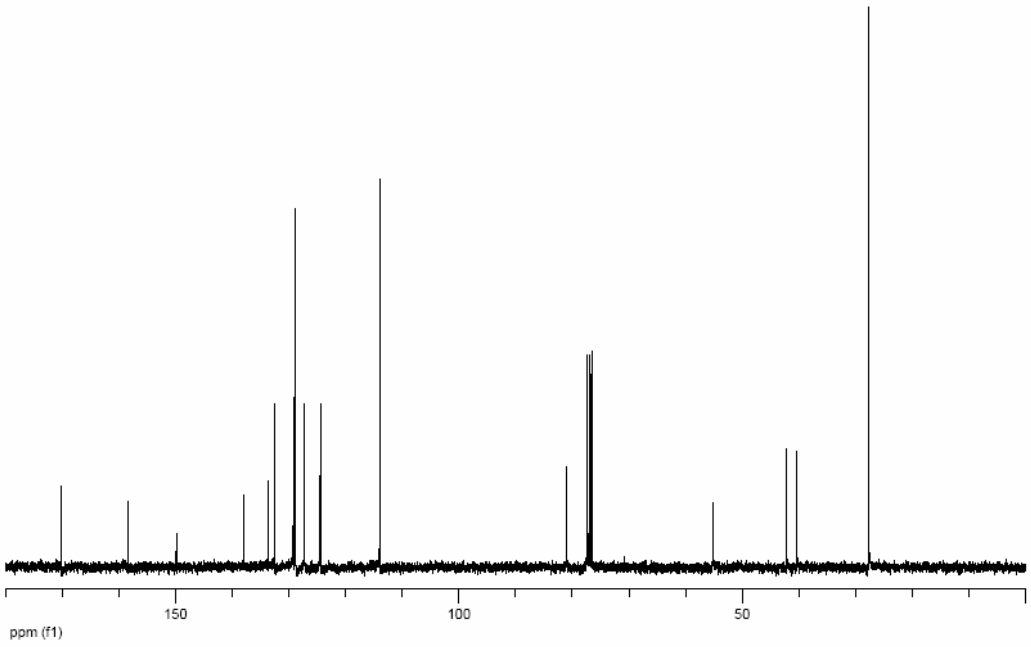

OMe
F
CO2t-Bu
8.28
1.00
3.14
2.17
9.34
5.0
0.0
ppm (f1)

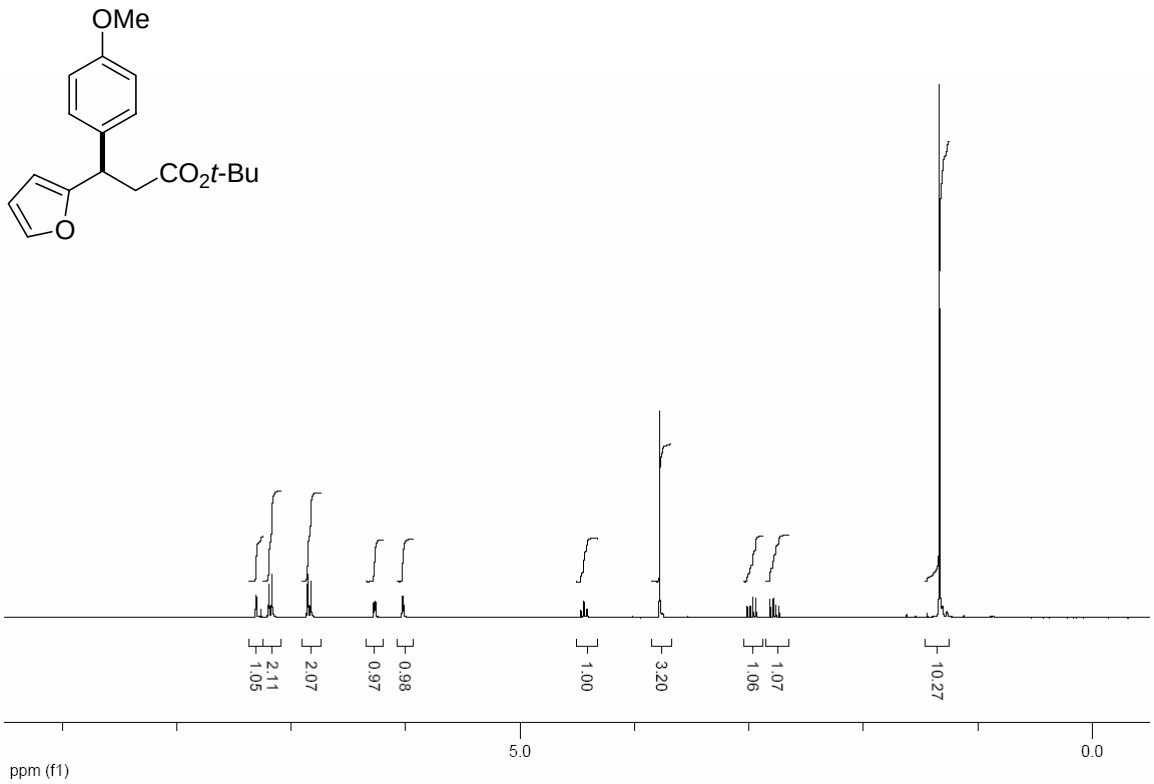

200
150
100
50
0
ppm (f1)

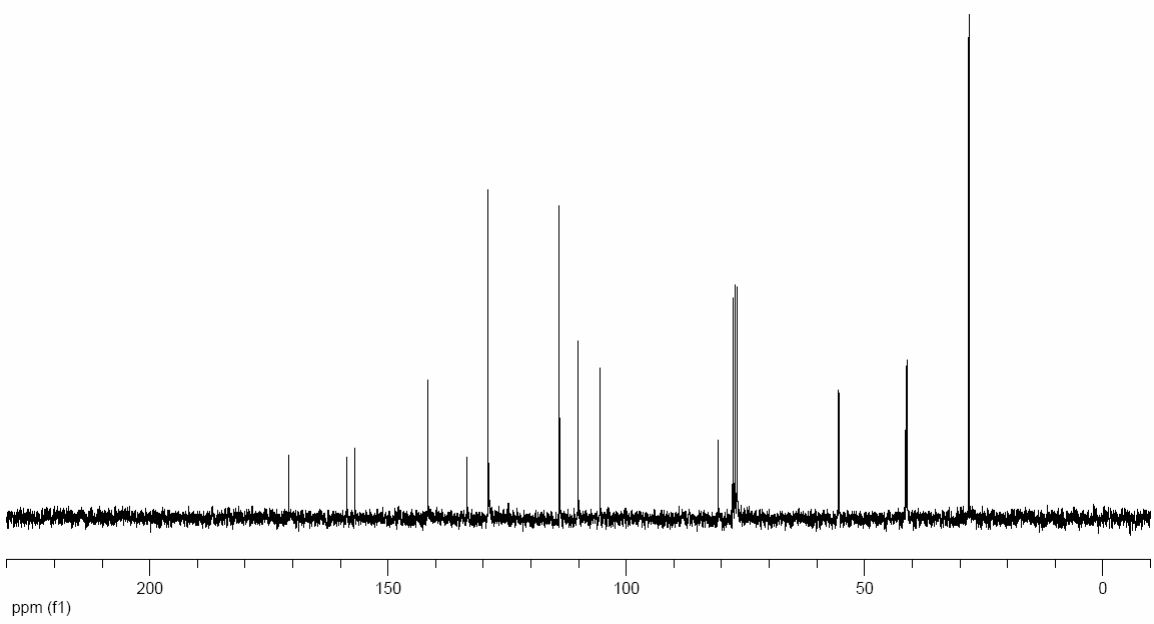

Ph
CO2t-Bu
NO2
0.97
2.23
6.24
1.00
2.28
9.92
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
ppm (f1)

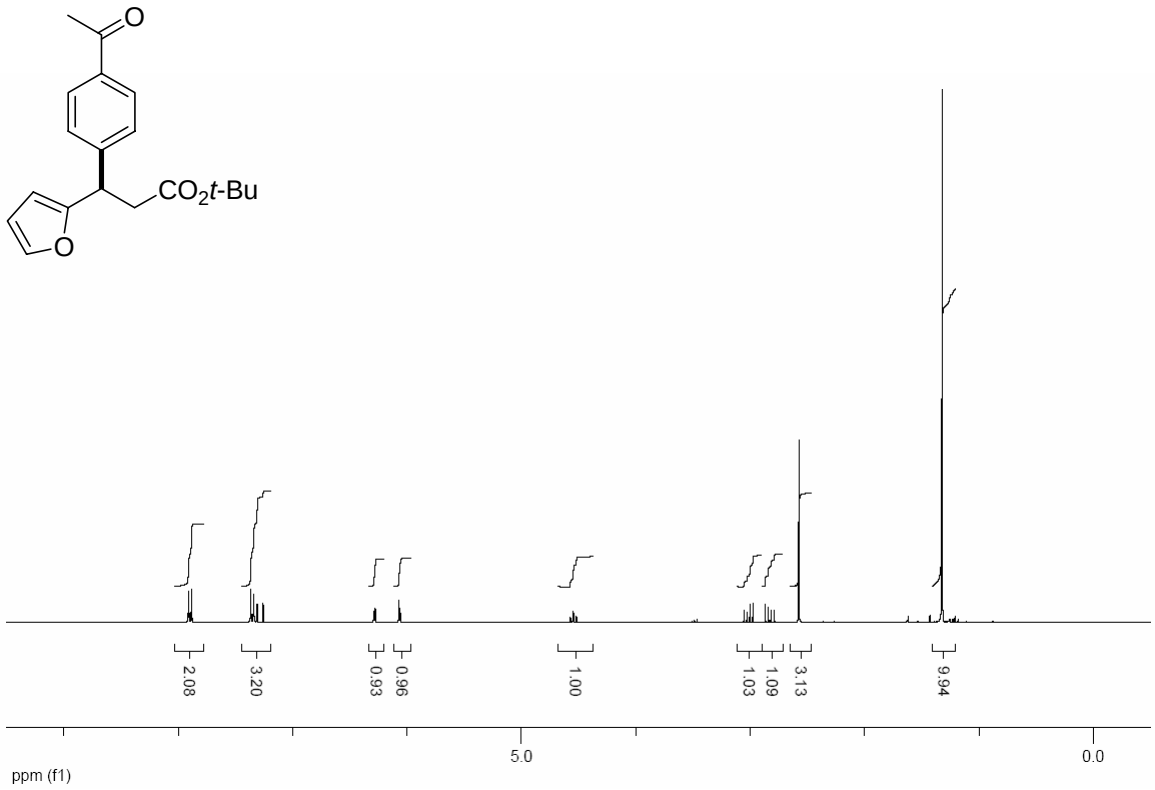

150
100
50
ppm (f1)

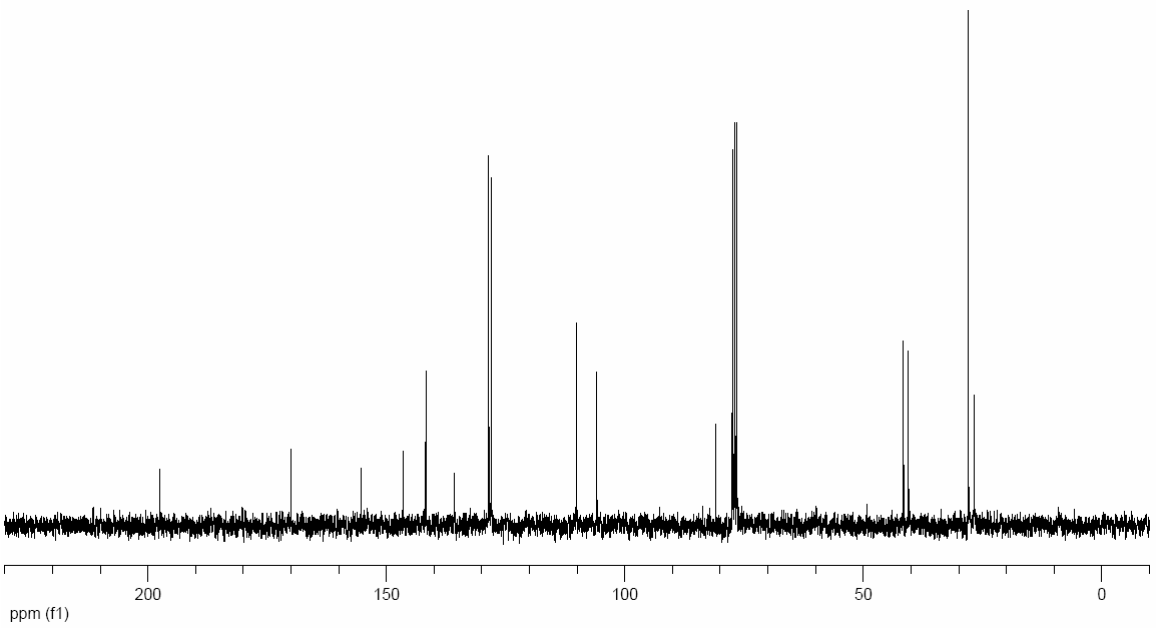

OMe
CO2t-Bu
NO2
1.00
2.23
1.03
2.04
1.99
1.00
3.24
2.27
9.51
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
ppm (f1)

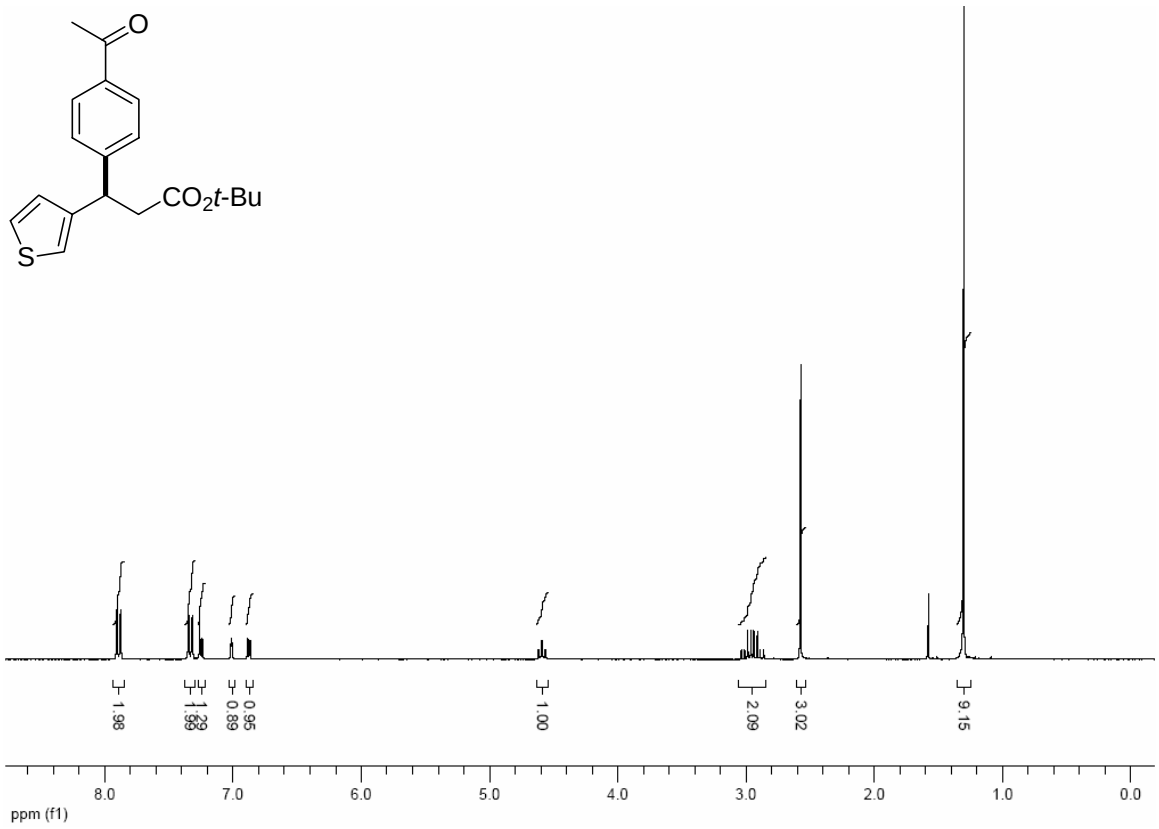

150
100
50
ppm (f1)

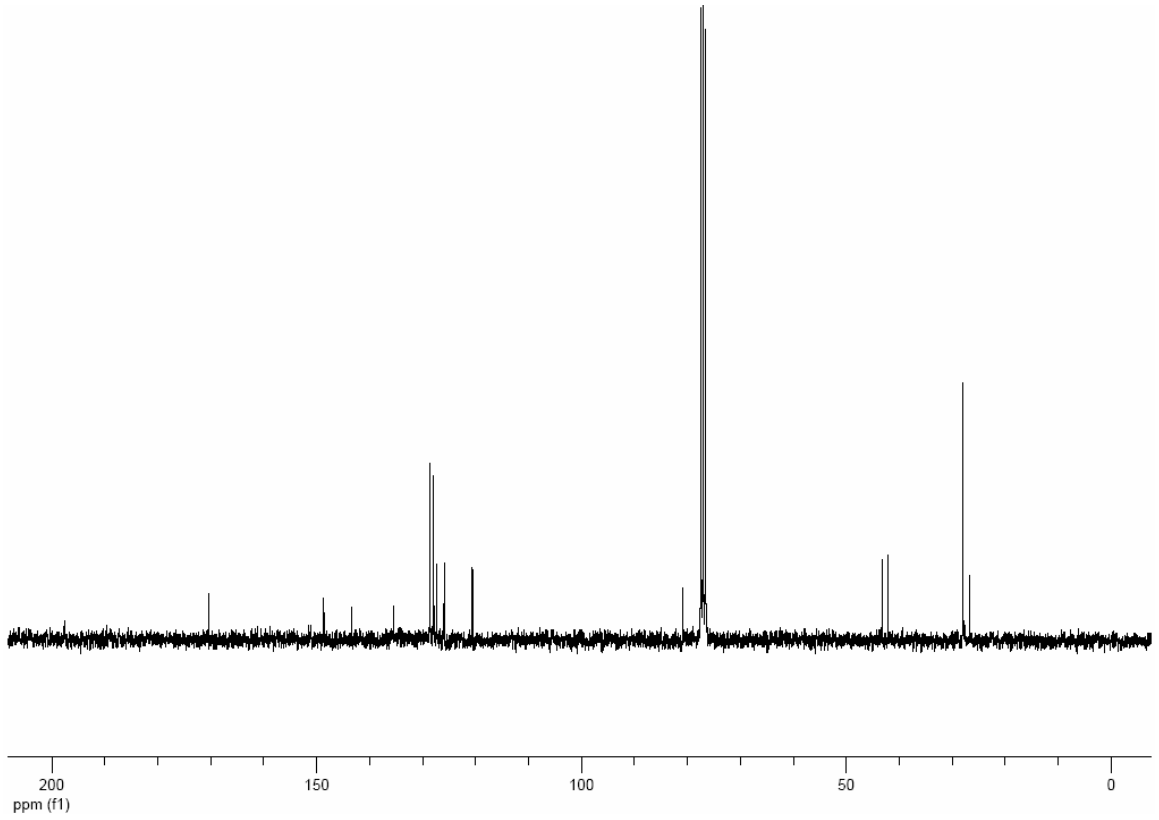

OMe
CO2t-Bu
O
1.05
2.11
2.07
0.97
0.98
1.00
3.20
1.06
1.07
10.27
5.0
0.0
ppm (f1)

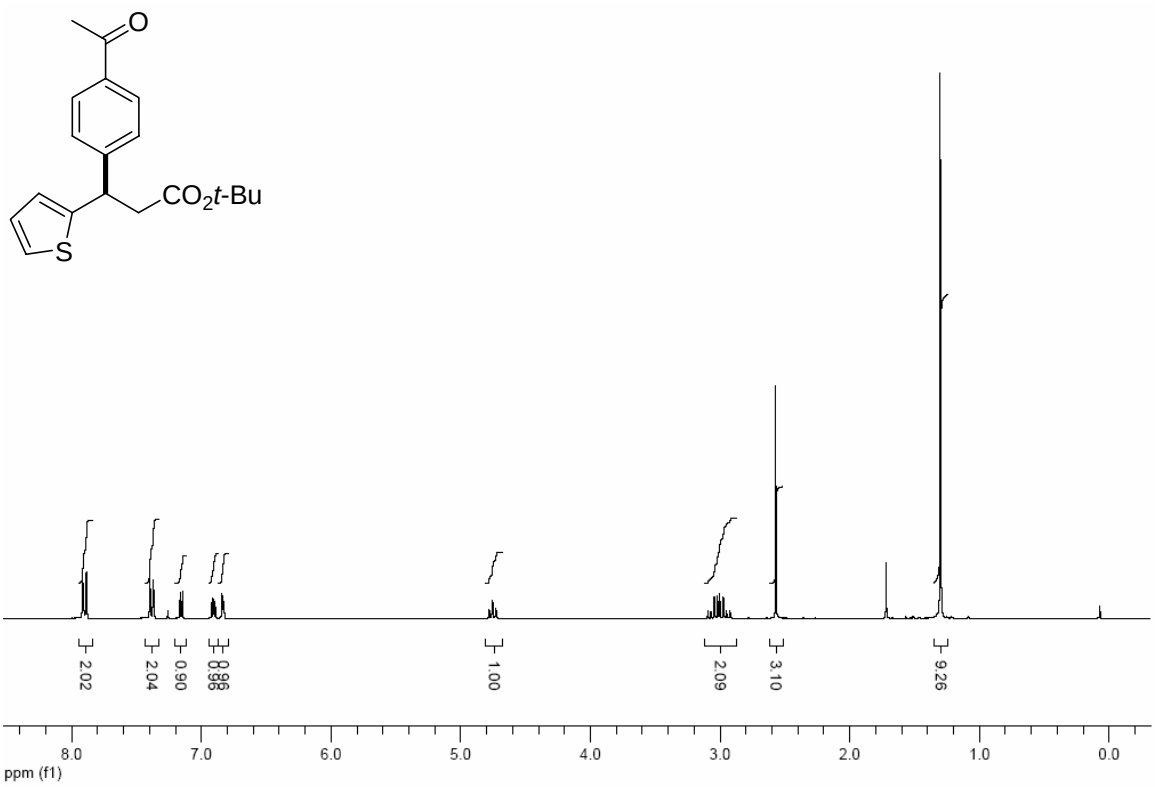

200
150
100
50
0
ppm (f1)

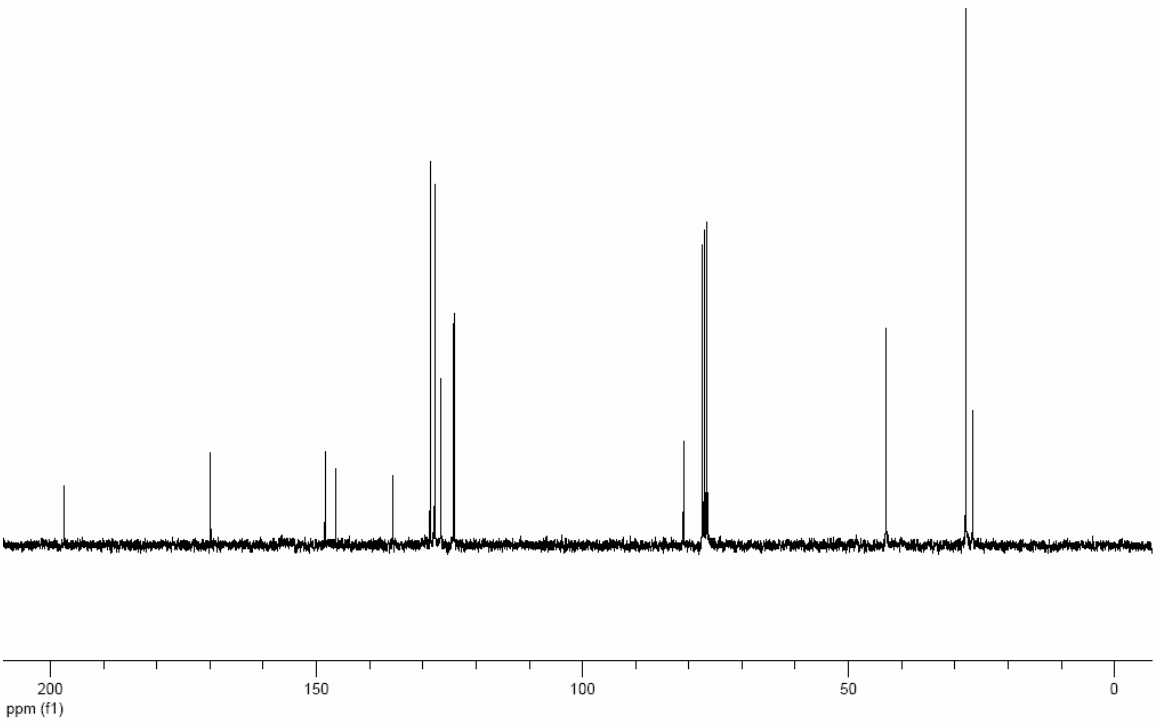

O
CO2t-Bu
O
2.08
3.20
0.93
0.96
1.00
1.03
1.09
3.13
9.94
5.0
0.0
ppm (f1)

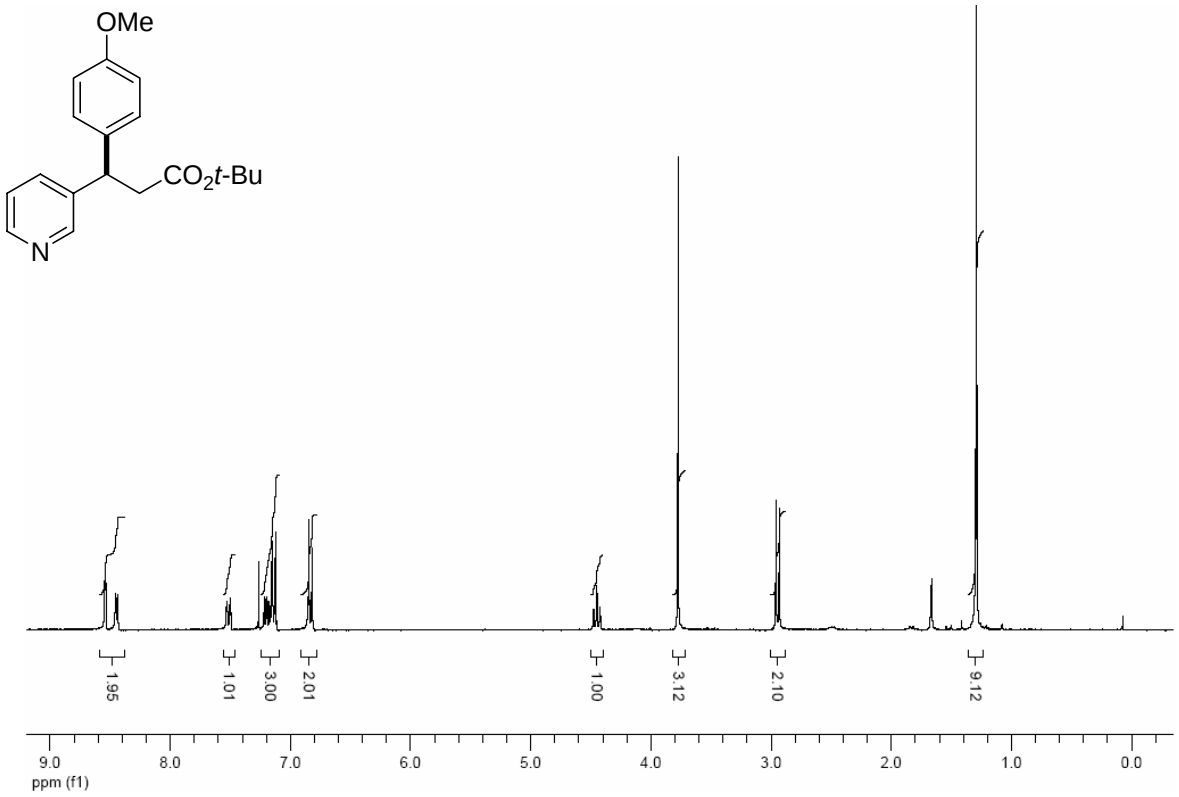

200
150
100
50
0
ppm (f1)

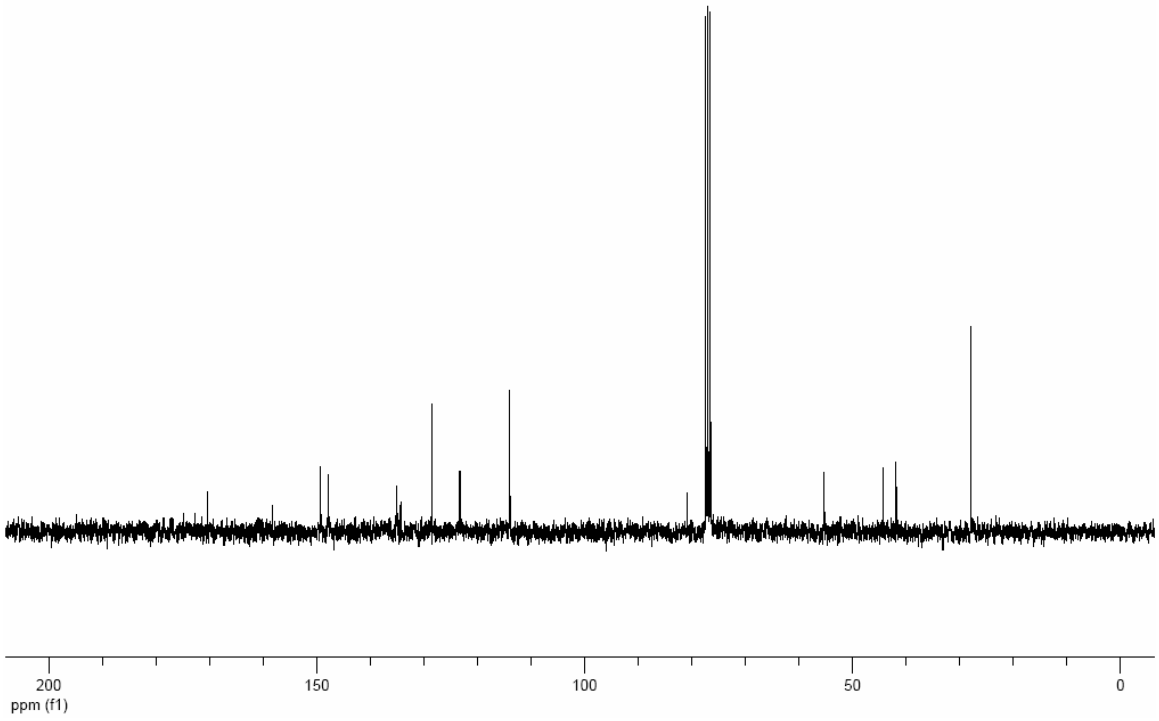

O
CO2t-Bu
S
1.98
1.29
1.99
0.89
0.95
1.00
2.09
3.02
9.15
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppm (f1)

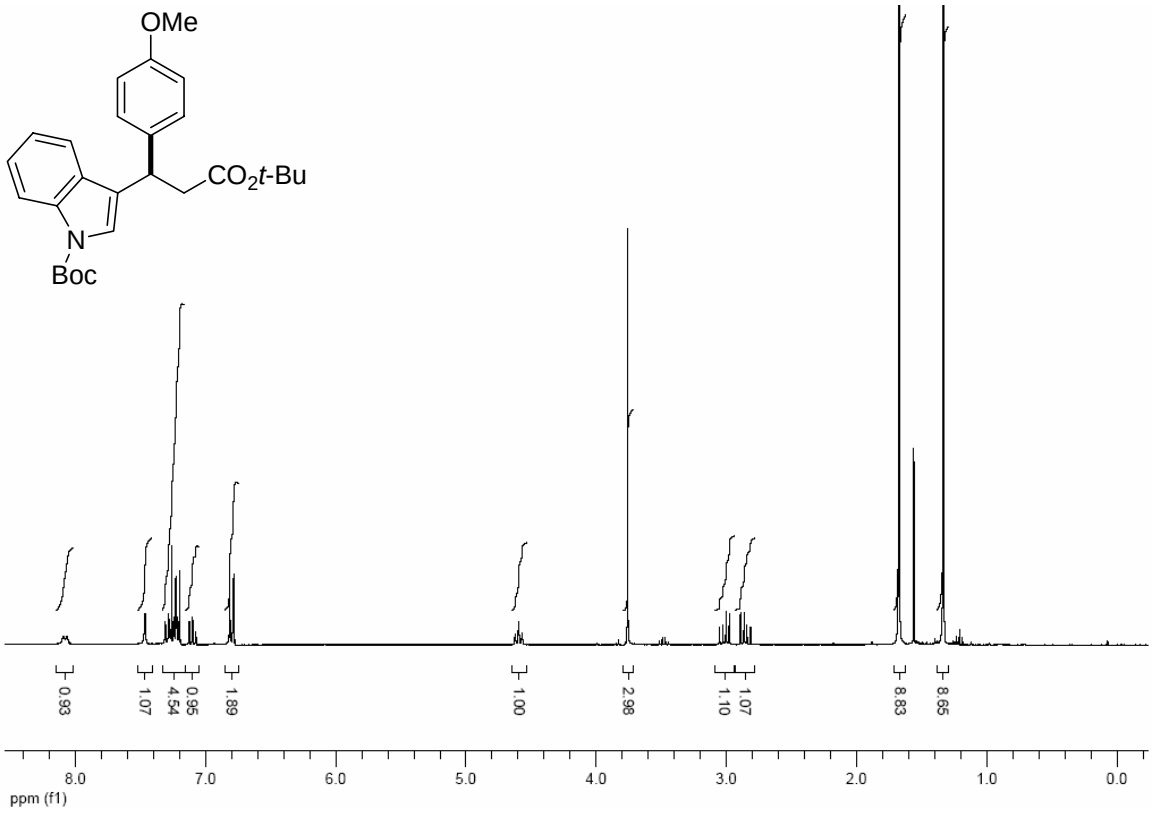

200
150
100
50
0
ppm (f1)

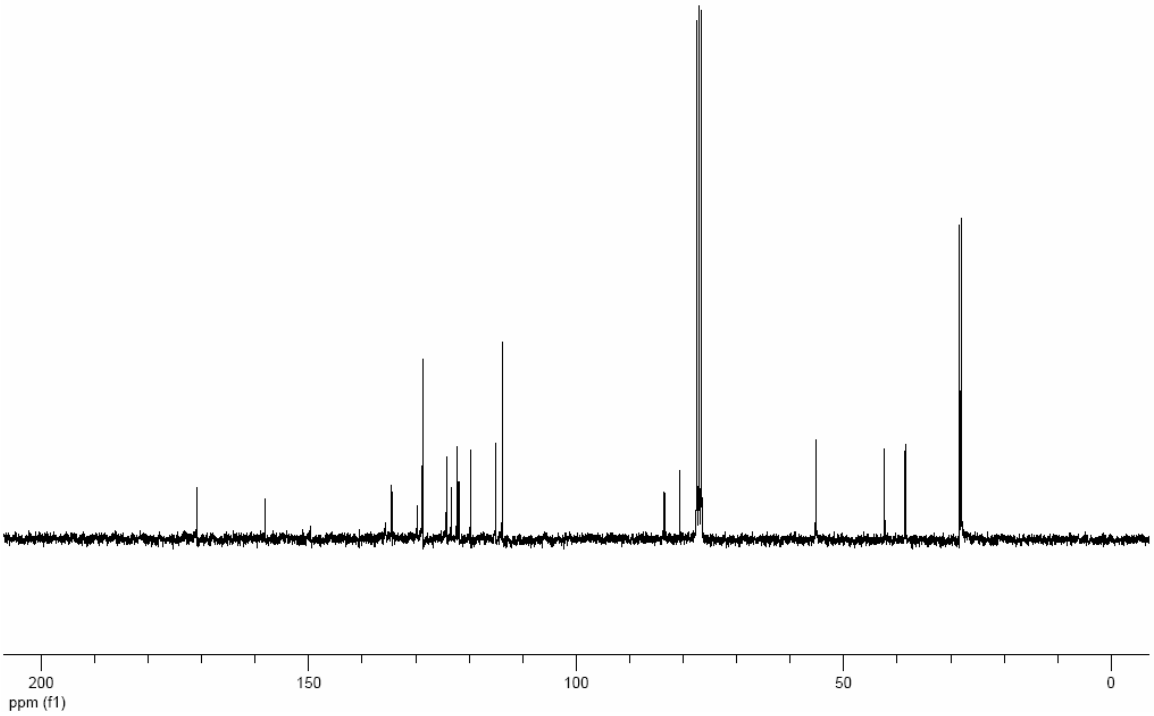

O
CO2t-Bu
S
2.02
2.04
0.90
1.00
2.09
3.10
9.26
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppm (f1)

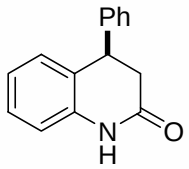

200
150
100
50
0
ppm (f1)


OMe
CO2t-Bu
N
1.95
1.01
3.00
2.01
1.00
3.12
2.10
9.12
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppm (f1)

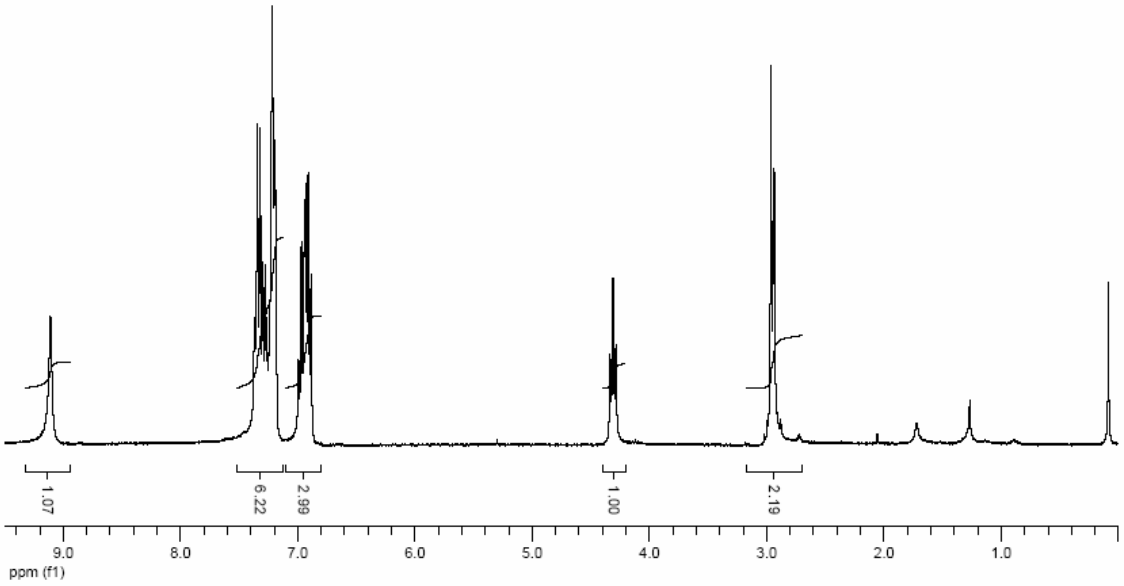

200
150
100
50
0
ppm (f1)

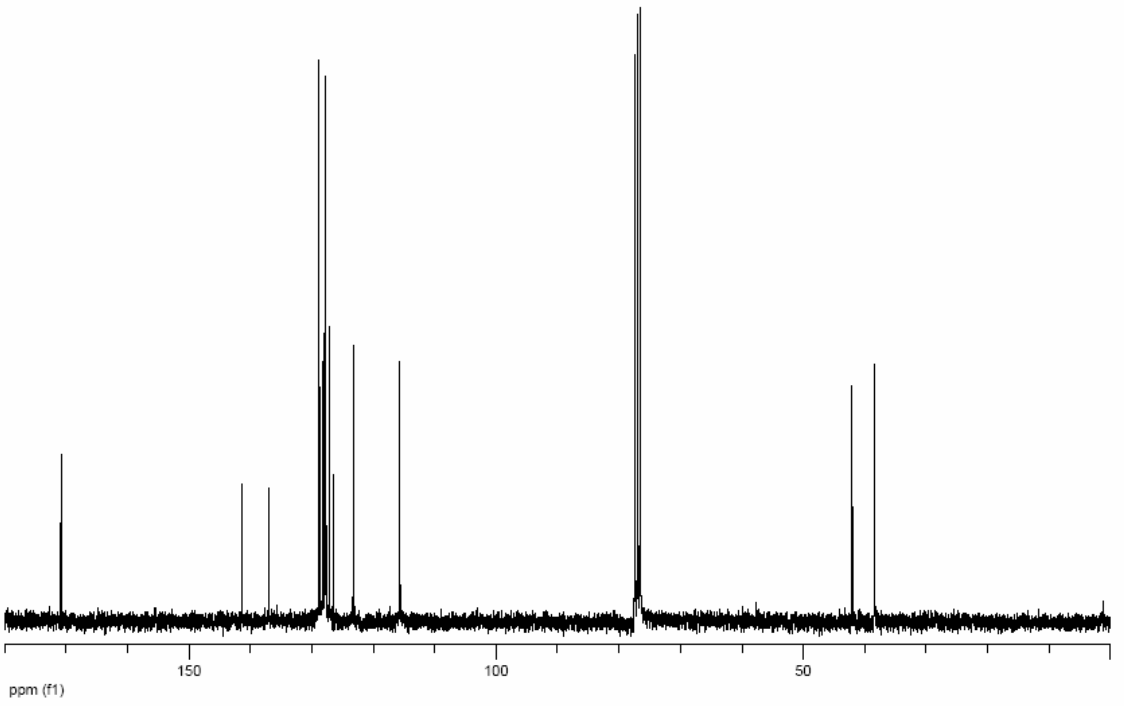

OMe
CO2t-Bu
N
Boc
0.93
1.07
4.54
0.95
1.89
1.00
2.98
1.10
1.07
8.83
8.65
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppm (f1)


200
150
100
50
0
ppm (f1)


Ph
N
H
O

11


1.07
6.22
2.99
1.00
2.19
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
ppm (f1)


150
100
50
ppm (f1)