Supporting Information

Maleimides-assisted *Anti*-Markovnikov Wacker-type Oxidation of Vinylarenes Using Molecular Oxygen as a Terminal Oxidant

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General Information

Unless otherwise indicated, all reactions were performed under an oxygen atmosphere (1 atm). $PdCl_2(MeCN)_2$,[1] $Pd_2(dba)_3 \cdot CHCl_3$,[2] and $Pd(\eta^2\text{-mah})_2(\eta^2\text{-cyclopentene})$[3] were prepared as described in the literature. *t*-AmylOH was purchased from Wako Pure Chemical Industries and Tokyo Chemical Industry Co. Ltd. and was degassed by carrying out three freeze-pump-thaw cycles. Other chemicals including styrene derivatives were also commercially available and were used without further purification. Flash column chromatography was performed using silica gel SILICYCLE SiliaFlash F60 (40–63μm, 230–400 mesh). NMR spectra were recorded on either a JEOL AL-400 (400 MHz (^{1}H), 376 MHz (^{19}F), 100 MHz (^{13}C)) or a Bruker AV-300N (300 MHz (^{1}H), 282 MHz (^{19}F)) spectrometer. Chemical shift values (δ) were expressed relative to $SiMe_4$. GC analyses were performed on a Shimadzu GC-14B gas chromatograph with a capillary column (Shinwa Chemical Industries, ULBON HR-1701, 0.25 mm i.d. × 25 m). HPLC was performed on a Japan Analytical Industry Co., Ltd. LC-908 with columns (Japan Analytical Industry Co., Ltd., JAIGEL-1H and JAIGEL-2H, 20 mm i.d. × 6 m). Infrared spectra were measured on a JASCO FT/IR-6100 spectrophotometer. Mass spectra were recorded on a SHIMADZU GCMS-QP5050 spectrometer.

General Procedure for the Synthesis of Arylacetaldehydes 2a-2o from Vinylarenes 1a-1o

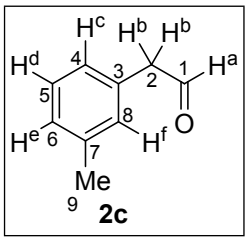
To a reaction vessel, $PdCl_2(MeCN)_2$ (13.0 mg, 0.050 mmol), maleimide (4.9 mg, 0.050 mmol), and CuCl (9.9 mg, 0.10 mmol) were added. Vinylarene (0.50 mmol), H_2O (45.1 μL, 2.5 mmol), *t*-AmylOH (5.0 mL) were then added, and the reaction mixture was stirred at 40 °C for 0.8–72 h under 1 atm of O_2 (an O_2 balloon was equipped). The reaction mixture was cooled to room temperature and was quenched by the addition of hexane (1.5 mL). After filtration of the precipitates, the solution was passed through a short silica gel column (eluent: hexane to hexane/ethyl acetate) to remove *t*-AmylOH. The solvents were removed and the residue was purified by flash column chromatography (eluent: hexane/ethyl acetate) (for **2e**–**2o**) or by HPLC (for **2c** and **2d**). Compounds **2a** and **2b** were derivatized to 2,4-dinitrophenylhydrazones using literature procedures.[4]

Determination of the GC yields: Mesitylene (69.8 μL, 0.50 mmol) was added to the reaction mixture as an internal standard. A portion of the reaction mixture was sampled and diluted with Et_2O. The sample solution was passed through a short silica gel column to remove metal complexes, and was analyzed by GC.

Determination of the NMR yields: After the reaction, the mixture was cooled to room temperature and was quenched by the addition of hexane (1.5 mL). 1,1,2,2-Tetrachloroethene (52.9 μL, 0.50 mmol) was added as an internal standard. The mixture was sampled and mixed with $CDCl_3$, and the sample was analyzed by ^{1}H NMR. Integrations of the characteristic triplet peaks which appear at around 9.7 ppm for arylacetaldehydes **2a**–**2o**, those of the singlet peaks which appear at around 2.6 ppm for acetophenone derivatives **3a**–**3o**, and those of the singlet peaks which appear at around 9.9

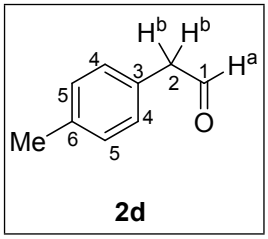
ppm for benzaldehyde derivatives were compared to those of the peaks for the internal standard to calculate the NMR yields of the products.

The spectral data for **2a** (2,4-dinitrophenylhydrazone derivative),[5] **2b** (2,4-dinitrophenylhydrazone derivative),[4] **2g**,[6] **2k**,[7] and **2l**[8] were in accordance with those reported in the literature. The ^{1}H and ^{13}C NMR data for **2c**–**2f**, **2h–2j**, and **2m–2o** are listed below.



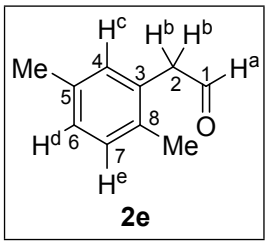
2c

(3-Methylphenyl)acetaldehyde (2c). Compound **2c** was purified by HPLC (solvent: $CHCl_3$) and was obtained as a mixture with 3-methylacetophenone (**3c**). ^{1}H NMR for **2c** (400 MHz, $CDCl_3$): d 9.71 (t, J = 2.4 Hz, 2H, H^a), 7.25 (t, J = 7.6 Hz, 1H, H^d), 7.10 (d, J = 8.0 Hz, 1H, H^c or H^e), 7.02 (s, 1H, H^f), 7.00 (d, J = 8.4 Hz, 1H, H^c or H^e), 3.62 (d, J = 2.4 Hz, 2H, H^b), 2.34 (s, 3H, Me). ^{13}C NMR for **2c** (100 MHz, $CDCl_3$): δ 199.4 (C^1), 138.6 (C^3 or C^7), 131.6(C^3or C^7), 130.3 (arom.), 128.8 (arom.), 128.3 (arom.), 126.5 (arom.), 50.4 (C^2), 26.5 (Me). IR spectrum (CH_2Cl_2 solution): 3061, 3022, 2924, 2826, 2731, 1723, 1683, 1608, 1589, 1489, 1274, 1259, 1042, 784 cm^{-1}. MS (EI) *m/z* 134 (M^+), 105 ([M-CHO]$^+$).



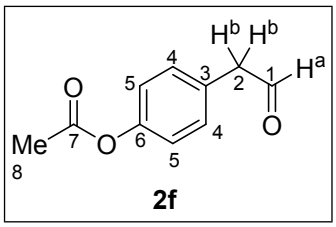
2d

(4-Methylphenyl)acetaldehyde (2d). Compound **2d** was purified by HPLC (solvent: $CHCl_3$) and was obtained as a mixture with 2-methylacetophenone (**3d**). The ^{1}H NMR spectral data for **2d** were in accordance with that reported in the literature.[9] ^{13}C NMR for **2d** (100 MHz, $CDCl_3$): δ199.6 (C^1), 137.0 (C^3 or C^6), 129.6 (C^4 or C^5), 129.4 (C^4 or C^5), 128.7 (C^3 or C^6), 50.1 (C^2), 21.6 (Me). IR spectrum (CH_2Cl_2 solution): 3054, 3026, 2925, 2826, 2730, 1724, 1605, 1515, 1414, 1386, 1269, 1210, 1170, 1113, 1041, 810 cm^{-1}. MS (EI) *m/z* 134 (M^+), 105 ([M-CHO]$^+$).



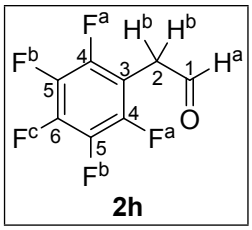
2e

(2,5-Dimethylphenyl)acetaldehyde (2e). Compound **2e** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.67 (t, J =2.4 Hz, 1H, H^a), 7.08 (d, J = 7.8 Hz, 1H, H^d or H^e), 7.02 (d, J = 7.8 Hz, 1H, H^d or H^e), 6.96 (s, 1H, H^c), 3.63 (d, J = 2.4 Hz, 2H, H^b), 2.30 (s, 3H, Me), 2.21 (s, 3H, Me). ^{13}C NMR (100 MHz, $CDCl_3$): δ 199.2 (C1), 135.9 (arom.), 133.8 (arom.), 131.2 (arom.), 130.4 (arom.), 130.3 (arom.), 48.6 (C^2), 20.7 (Me), 19.1 (Me). IR spectrum (CH_2Cl_2 solution): 3062, 3003, 2925, 2824, 2729, 1724, 1616, 1505, 1456, 1383, 1315, 1261, 1182, 1156, 1117, 1042, 881, 816 cm^{-1}. MS (EI) *m/z* 148 (M^+), 119 ([M-CHO]$^+$).



2f

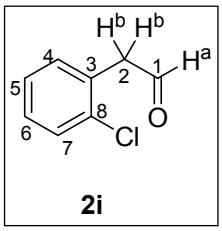
(4-Acetoxyphenyl)acetaldehyde (2f). *N*-methylmaleimide was used in place of maleimide as an additive for better separation. Compound **2f** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.74 (t, J = 2.1 Hz, 1H, H^a), 7.21 (d, J = 8.4 Hz, 2H, arom.), 7.10 (d, J = 8.4 Hz, arom.), 3.68 (d, J =2.1 Hz, 2H, H^b), 2.30 (s, 3H, Me). ^{13}C NMR (100 MHz, $CDCl_3$): δ 199.0 (C^1), 169.3 (C^7), 149.9 (C^3 or C^6), 130.5 (C^4 or C^5), 129.3 (C^3 or C^6), 122.1 (C^4 or C^5), 49.7 (C^2), 21.0 (Me). IR spectrum (KBr disk): 2923, 2895, 2824, 2728, 1749, 1726, 1509, 1378, 1371, 1222, 1207, 1195, 1167, 1019, 1012, 915, 858 cm^{-1}. MS (EI) *m/z* 178 (M^+), 136 ([M-$COCH_3$+H]$^+$), 107 ([M-$COCH_3$+H-CHO]$^+$).



2h

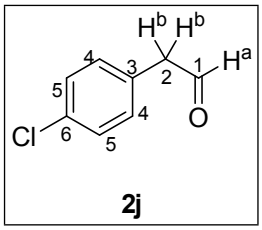
(2,3,4,5,6-Pentafluorophenyl)acetaldehyde (2h). Compound **2h** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 1:20). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.76 (s, 1H, H^a), 3.88 (s, 2H, H^b). ^{13}C NMR (100 MHz, $CDCl_3$): δ 194.1 (C^1), 145.2 (m, C^4, J^1_{CF} = 243.3 Hz) ,

140.7 (m, C^6, J^1_{CF} = 252.6 Hz), 137.6 (m, C^5, J^1_{CF} = 253.9 Hz), 37.0 (C^2). ^{19}F NMR (282 MHz, $CDCl_3$): δ -150.8 (dd, J = 8.5, 22.6 Hz, 2F, F^a), -163.4 (t, J = 19.7 Hz, 1F, F^c), -171.0 – -170.7 (m, 2F, F^b). IR spectrum (CH_2Cl_2 solution): 2837, 2736, 1726, 1658, 1523, 1508, 1384, 1323, 1269, 1258, 1126, 1052, 990, 956, 909 cm^{-1}. MS (EI) *m/z* 210 (M^+), 181 ([M-CHO]$^+$).



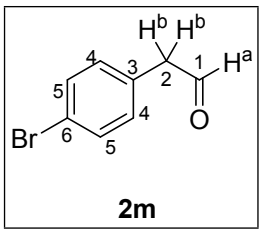
2i

(2-Chlorophenyl)acetaldehyde (2i). Compound **2i** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 10:1 to 7:1). The ^1H NMR spectral data was in accordance with that reported in the literature.[9] ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.1 (C^1), 134.5 (C^7), 149.9 (C^3 or C^6), 130.5 (C^4 or C^5), 129.3 (C^3 or C^6), 122.1 (C^4 or C^5), 49.7 (C^2), 21.0 (Me). IR spectrum (CH_2Cl_2 solution): 3064, 3024, 2907, 2829, 2732, 1724, 1595, 1574, 1475, 1444, 1407, 1387, 1318, 1266, 1187, 1129, 1055, 1039, 933, 808 cm^{-1}. MS (EI) *m/z* 154 (M^+), 125 ([M-CHO]$^+$).



2j

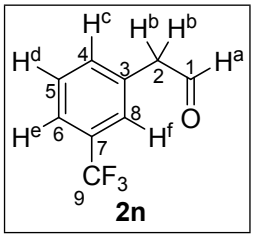
(4-Chlorophenyl)acetaldehyde (2j). Compound **2j** was purified by flash column chromatography (eluent: hexane/ethyl acetate =11:1 to 7:1). The ^1H NMR spectral data were in accordance with that reported in the literature.[9] ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.6 (C^1), 133.3 (C^3 or C^6), 130.9 (C^4 or C^6), 130.2 (C^3 or C^6), 129.0 (C^4 or C^5), 49.7 (C^2). IR spectrum (KBr disk): 2899, 2847, 2472, 1703, 1494, 1405, 1385, 1319, 1089, 1017, 935, 793, 752 cm^{-1}. MS (EI) *m/z* 154 (M^+), 125 ([M-CHO]$^+$).



2m

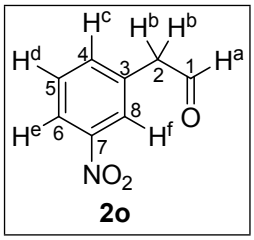
(4-Bromophenyl)acetaldehyde (2m). Compound **2m** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 14:1 to 9:1). ^1H NMR (400 MHz, $CDCl_3$): δ 9.73 (t, J =2.4 Hz, 1H, H^a), 7.48 (d, J =8.4 Hz, 2H arom.), 7.09 (t, J = 8.4 Hz, 2H, arom.), 3.65 (d, J = 2.4 Hz, 2H, H^b). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.4 (C^1), 132.0 (C^4 or C^5), 131.2 (C^4 or C^5), 130.7 (C^3 or C^6), 121.4

(C^3 or C^6), 49.7 (C^2). IR spectrum (KBr disk): 2898, 2844, 2741, 1702, 1488, 1404, 1382, 1318, 1070, 1013, 935, 789, 741 cm^{-1}. MS (EI) *m/z* 198 (M^+), 169 ([M-CHO]$^+$).



2n

(3-Trifluoromethylphenyl)acetaldehyde (2n). Compound **2n** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 10:1 to 7:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.78 (t, J = 2.0 Hz, 1H, H^a), 7.57 (d, J = 7.6 Hz, 1H, H^c or H^e), 7.50 (t, J = 7.6 Hz, 1H, H^d), 7.48 (s, 1H. H^f), 7.40 (d, J = 7.6 Hz, 1H, H^c or H^e), 3.78 (d, J = 2.0 Hz, 2H, H^b). ^{13}C NMR (100 MHz, $CDCl_3$): δ 198.2 (C^1), 133.0 (q, J^4_{CF} = 4 Hz, C^5), 132.8 (C^3), 131.3 (q, J^2_{CF} = 128.8 Hz, C^7), 129.4 (C^4), 126.3 (q, J^3_{CF} = 15.2 Hz, C^6 or C^8), 124.3 (q, J^3_{CF} = 15.2 Hz, C^6 or C^8), 123.9 (q, J^1_{CF} = 270.9 Hz, C^9), 50.1 (C^2). ^{19}F NMR (376 MHz, $CDCl_3$): δ -71.8. IR spectrum (CH_2Cl_2 solution): 3064, 2962, 2926, 2831, 2733, 1728, 1493, 1451, 1335, 1268, 1247, 1168, 1127, 1098, 1075, 1041, 946, 902, 802 cm^{-1}. MS (EI) *m/z* 188 (M^+), 159 ([M-CHO]$^+$).



2o

(3-Nitrophenyl)acetaldehyde (2o). Compound **2o** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 3:1). ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.85 (t, J = 2.0 Hz, 1H, H^a), 8.17 (td, J = 4.9, 2.2 Hz, 1H, H^d), 8.11 (br s, 1H, H^f), 7.57 (d, J = 4.9 Hz, 2H, H^c and H^e), 3.91 (d, J = 2.0 Hz, 2H, H^b). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.5 (C^1), 135.8 (arom.), 135.0 (arom.), 133.8 (arom.), 129.7 (arom.), 124.5 (arom.), 122.4 (arom.), 49.6 (C^2). IR spectrum (KBr disk): 2841, 2738, 1725, 1527, 1351, 1086, 1033, 804, 736 cm^{-1}. MS (EI) *m/z* 165 (M^+), 136 ([M-CHO]$^+$).

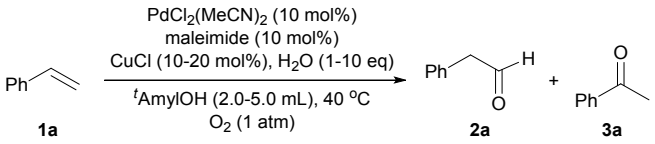
Synthesis of Pd(η^2-mah)$_2$(η^2-cyclopentene)

Pd(η^2-mah)$_2$(η^2-cyclopentene) was prepared as described in the literature.[3] IR spectrum (KBr disk): 1820, 1765 cm^{-1} [ν(CO)]. Anal. Calcd for $C_{13}H_{12}O_6Pd$: C, 42.13; H, 3.26. Found: C, 41.78; H, 3.32. Because of the instability in solution, satisfactory NMR data were not obtained as reported previously.

Pd(0) Complex-catalyzed *Anti*-Markovnikov Wacker-type Oxidation

To a reaction vessel, Pd(η^2-mah)$_2$(η^2-cyclopentene) (0.05 mmol) or $Pd_2(dba)_3 \cdot CHCl_3$ (0.025 mmol), $CuCl_2$ (0.10 mmol), and *t*-AmylOH (5.0 mL) were added under argon, and the reaction mixture was stirred at room temperature for 30 min. Oxygen was then introduced to the reaction mixture. Styrene (0.50 mmol) and H_2O (2.5 mmol) were added to the mixture, and the reaction mixture was stirred at 60 °C. After 1 h, mesitylene (0.50 mmol) was added as an internal standard. A portion of the reaction mixture was sampled and diluted with Et_2O. The sample solution was passed through a short silica gel column to remove metal complexes, and was analyzed by GC.

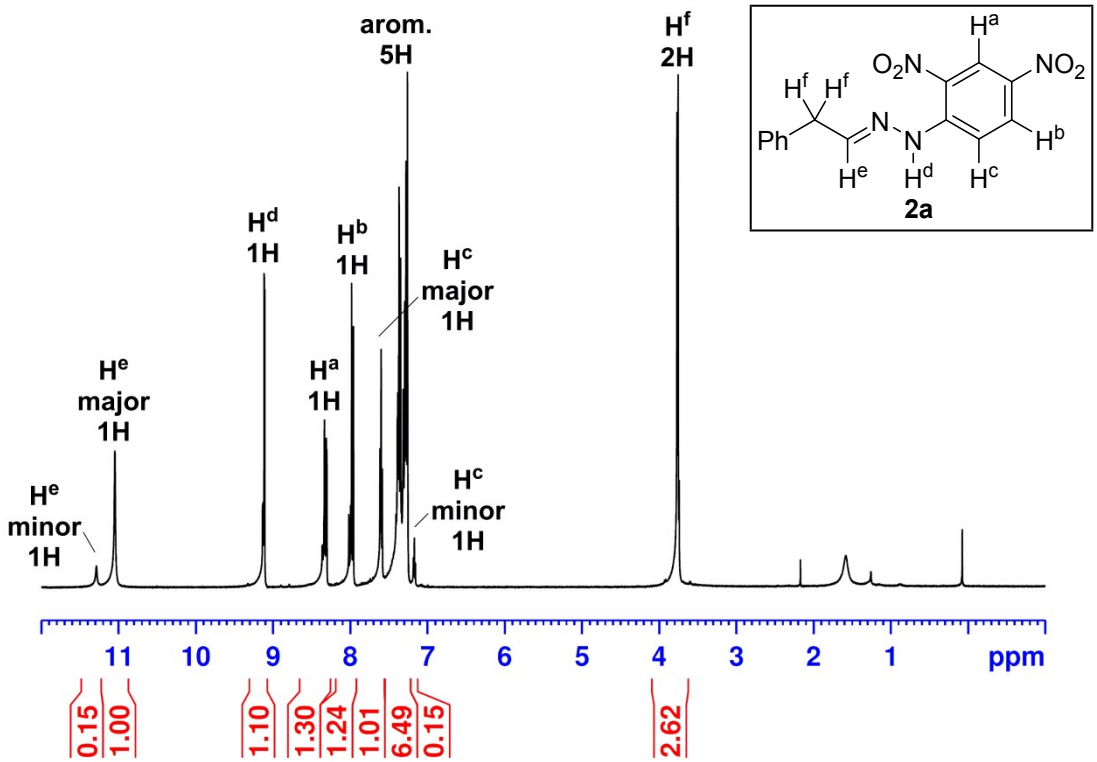
Table S1 Effect of amounts of CuCl, H_2O, and ^{t}AmylOH on the maleimide-assisted *anti*-Markovnikov Wacker-type oxidation [a]



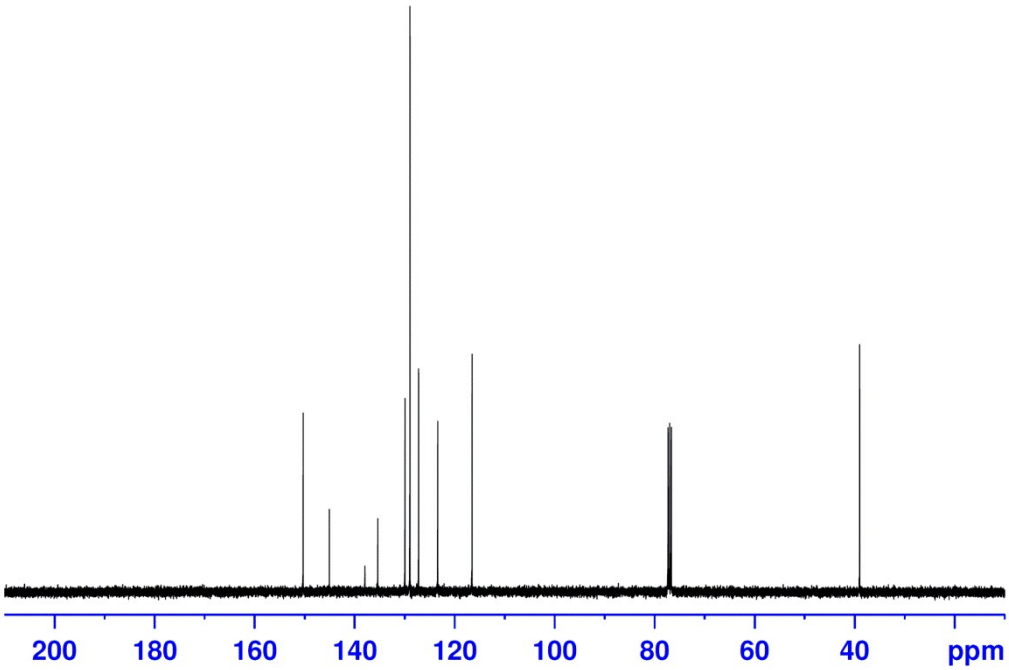
Entry	CuCl (mol%)	H_2O (eq)	^{t}AmylOH (mL)	Time (h)	Yield (%)[b]	
					2a	**3a**
1	10	5.0	2.0	1	60	7
2	20	5.0	2.0	1	63	8
3	20	1.0	2.0	4	61	9
4	20	3.0	2.0	2	63	10
5	20	10.0	2.0	3	45	7
6	20	5.0	3.0	2	66	10
7	20	5.0	5.0	3	74[c]	10[c]

[a] Reaction conditions: **1a** (0.50 mmol), $PdCl_2(MeCN)_2$ (0.05 mmol), maleimide (0.05 mmol), CuCl (0.05–0.10 mmol), H_2O (0.50–5.0 mmol), *t*-AmylOH (2.0–5.0 mL), 40 °C, O_2 (1 atm), 1–4 h. [b] GC yields. [c] NMR yields.

Phenylacetaldehyde (2a). Compound **2a** was isolated as a 2,4-dinitrophenylhydrazone derivative.

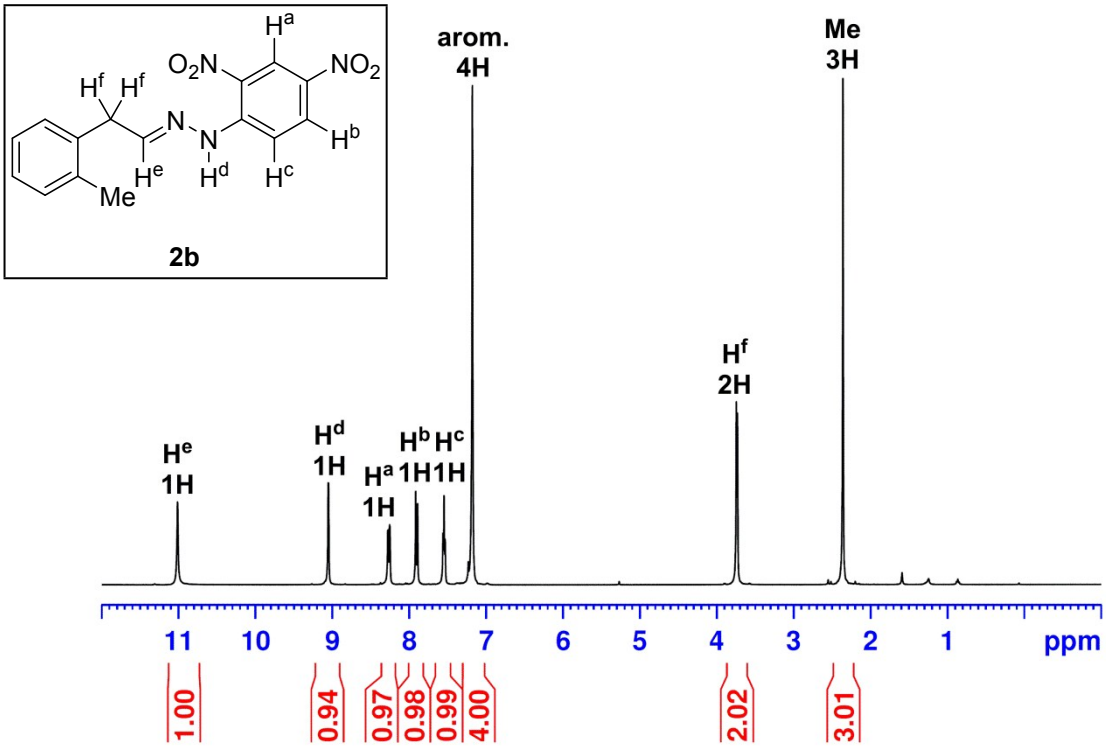


^{1}H NMR (400 MHz, $CDCl_3$)

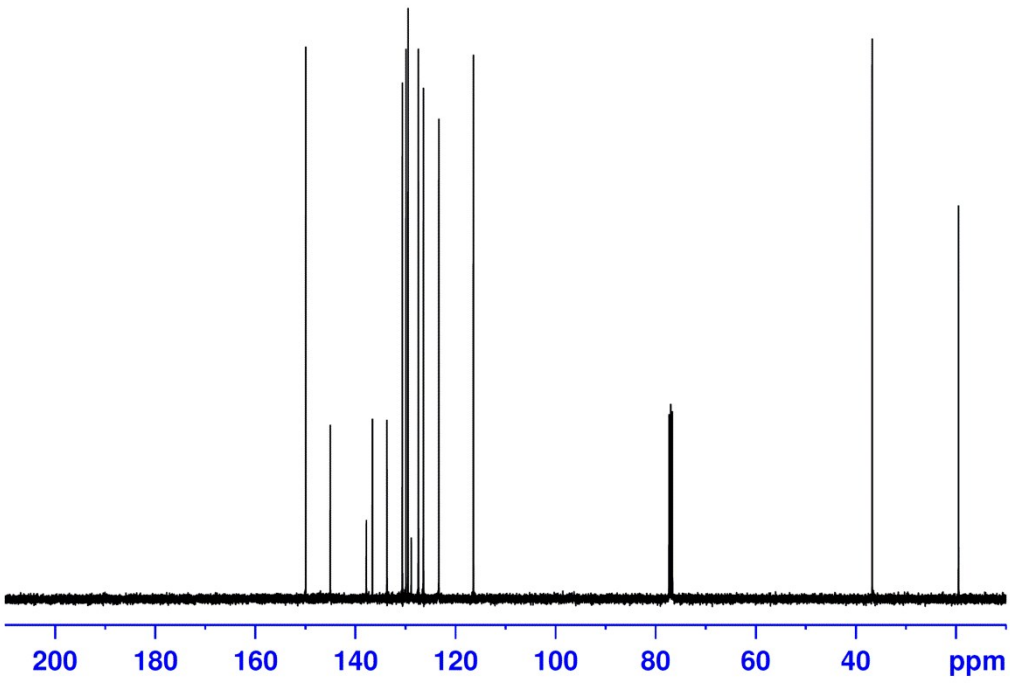


^{13}C NMR (100 MHz, $CDCl_3$)

(2-Methylphenyl)acetaldehyde (2b). Compound **2b** was isolated as a 2,4-dinitrophenylhydrazone derivative.

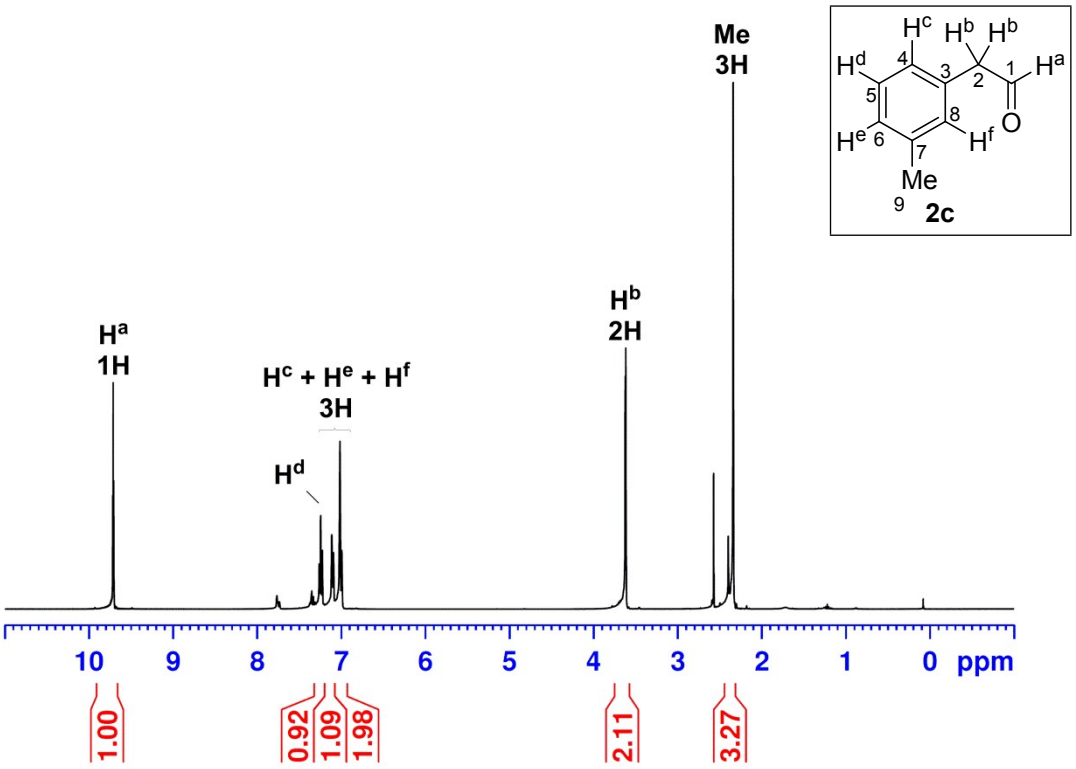


^{1}H NMR (400 MHz, $CDCl_3$)

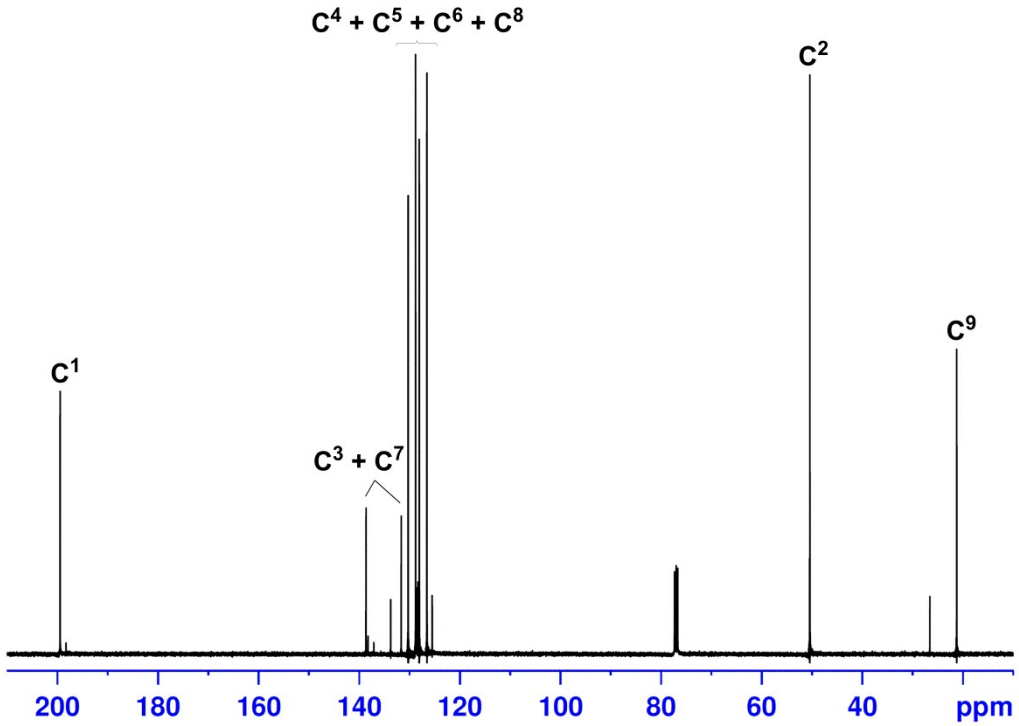


^{13}C NMR (100 MHz, $CDCl_3$)

(3-Methylphenyl)acetaldehyde (2c). Compound **2c** was obtained as a mixture with **3c**.

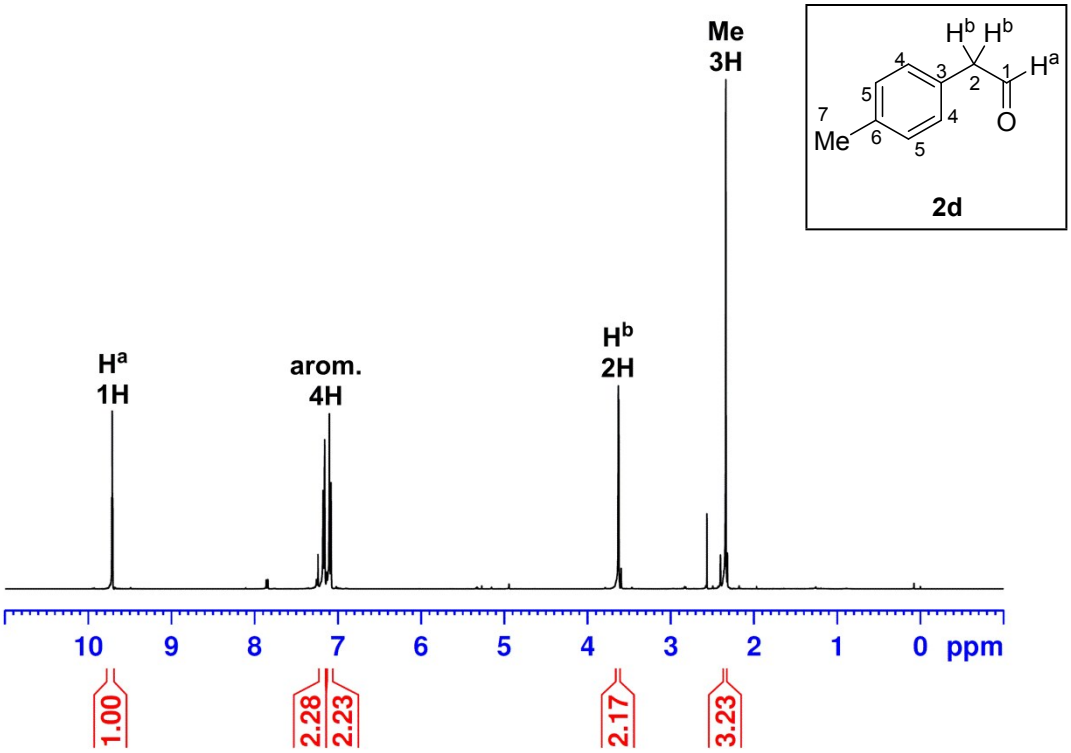


^{1}H NMR (400 MHz, $CDCl_3$)

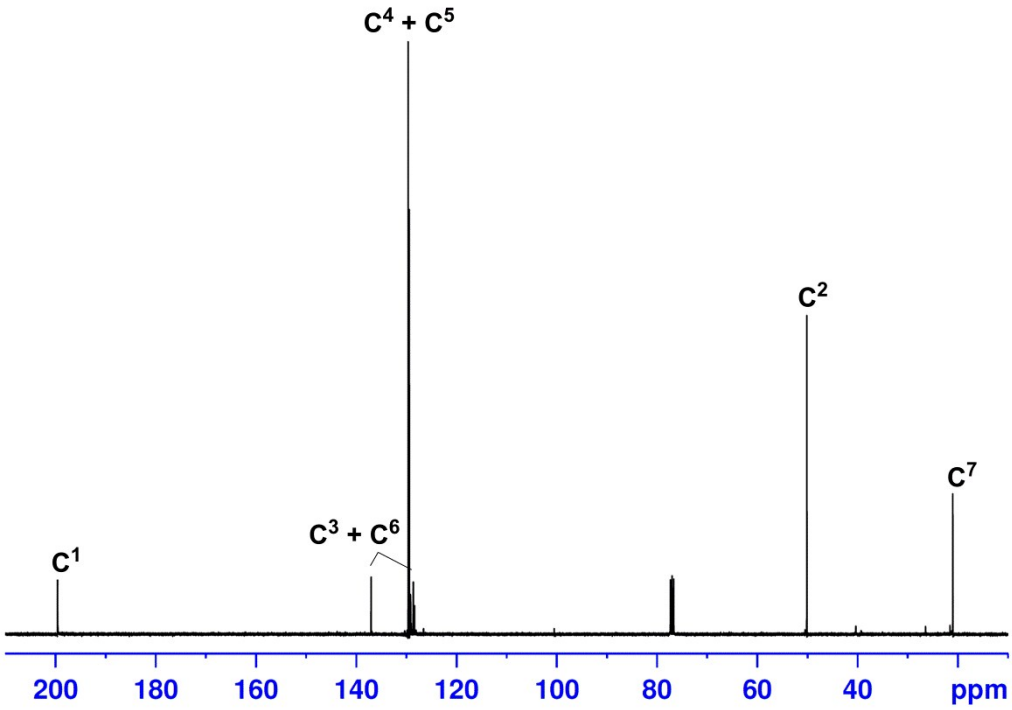


^{13}C NMR (100 MHz, $CDCl_3$)

(4-Methylphenyl)acetaldehyde (2d). Compound **2d** was obtained as a mixture with **3d**.

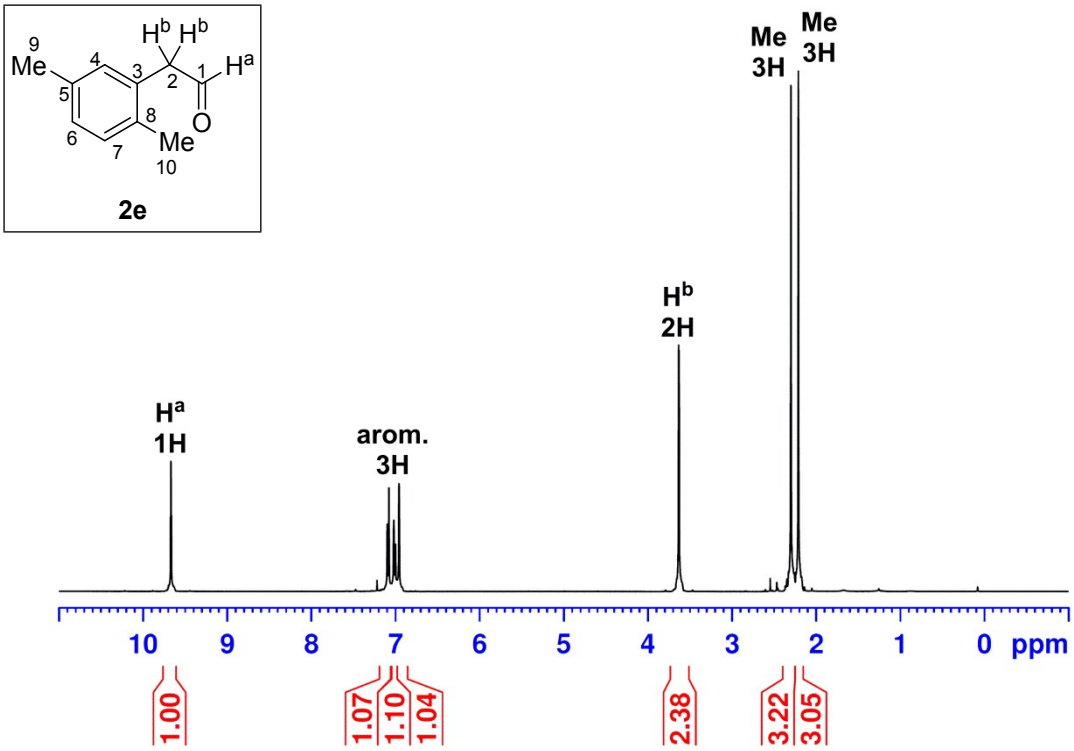


^{1}H NMR (400 MHz, $CDCl_3$)

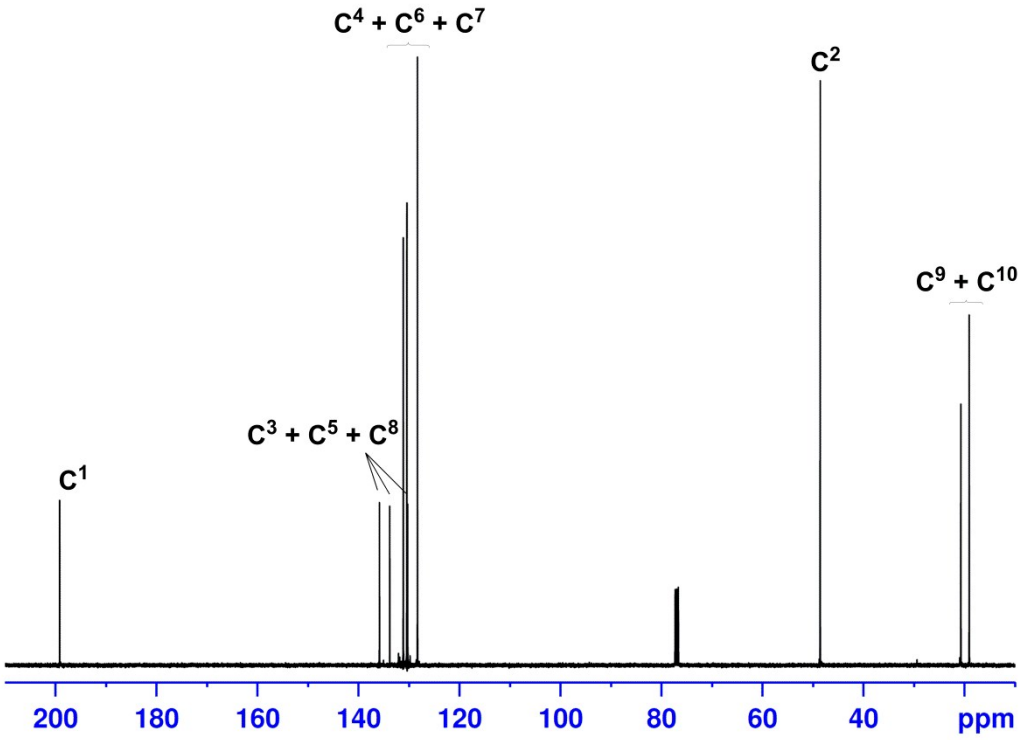


^{13}C NMR (100 MHz, $CDCl_3$)

(2,5-Dimethylphenyl)acetaldehyde (2e).

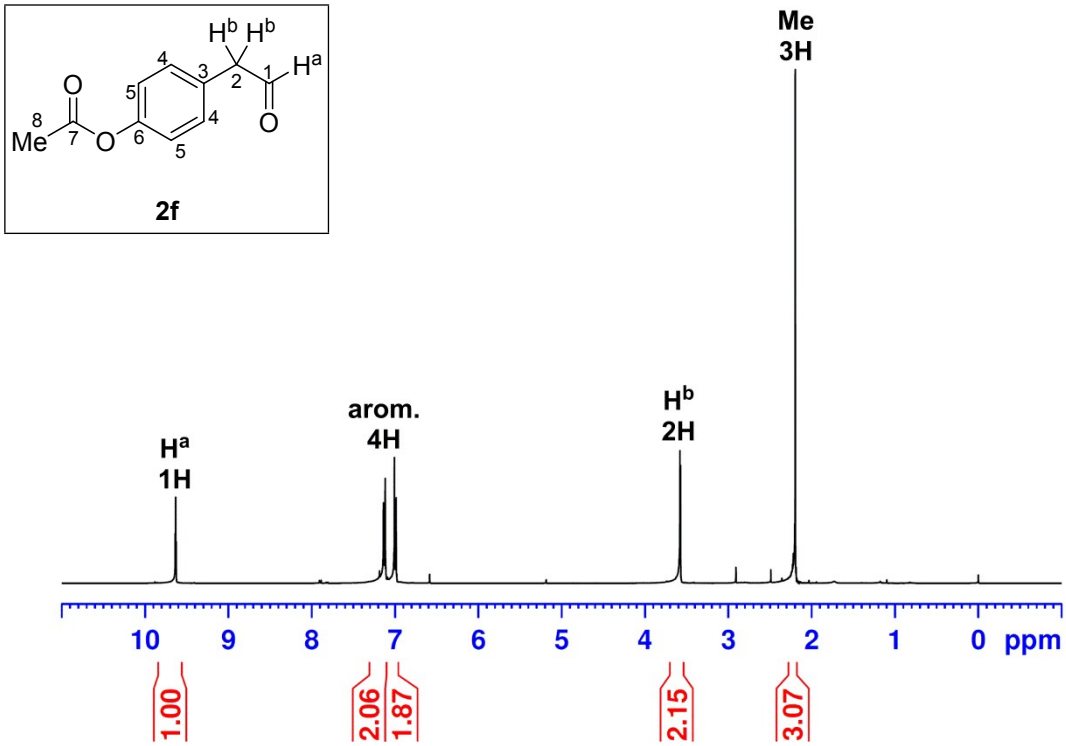


^{1}H NMR (400 MHz, $CDCl_3$)

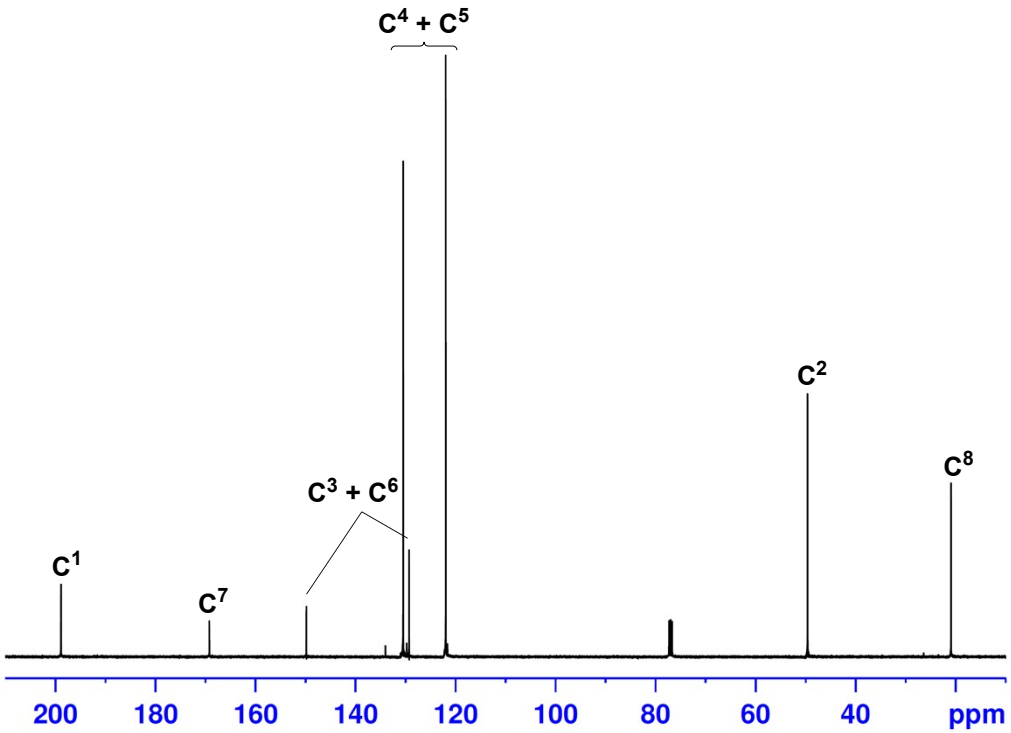


^{13}C NMR (100 MHz, $CDCl_3$)

(4-Acetoxyphenyl)acetaldehyde (2f).

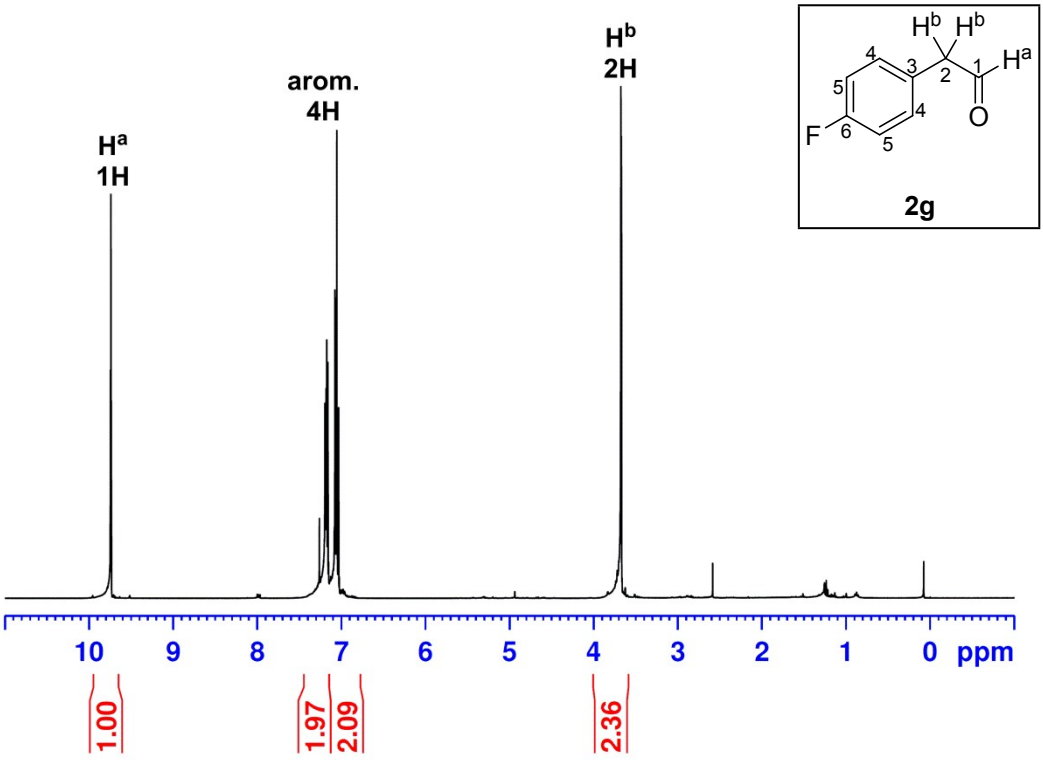


^{1}H NMR (400 MHz, $CDCl_3$)

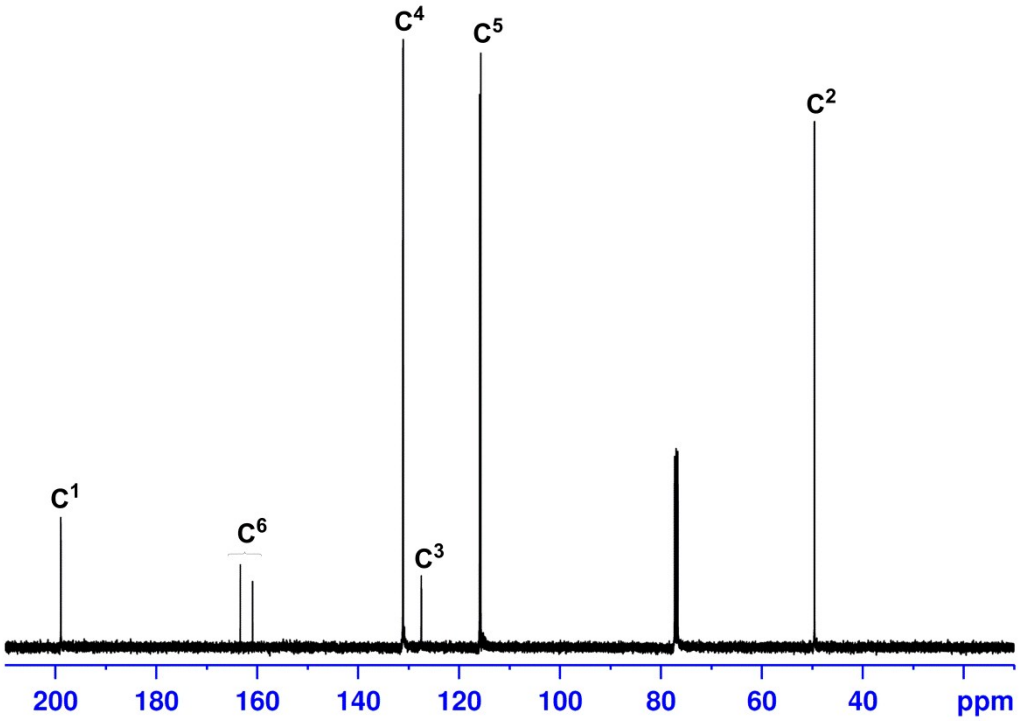


^{13}C NMR (100 MHz, $CDCl_3$)

(4-Fluorophenyl)acetaldehyde (2g). Compound **2g** was purified by flash column chromatography (eluent: hexane/ethyl acetate =10:1 to 7:1).

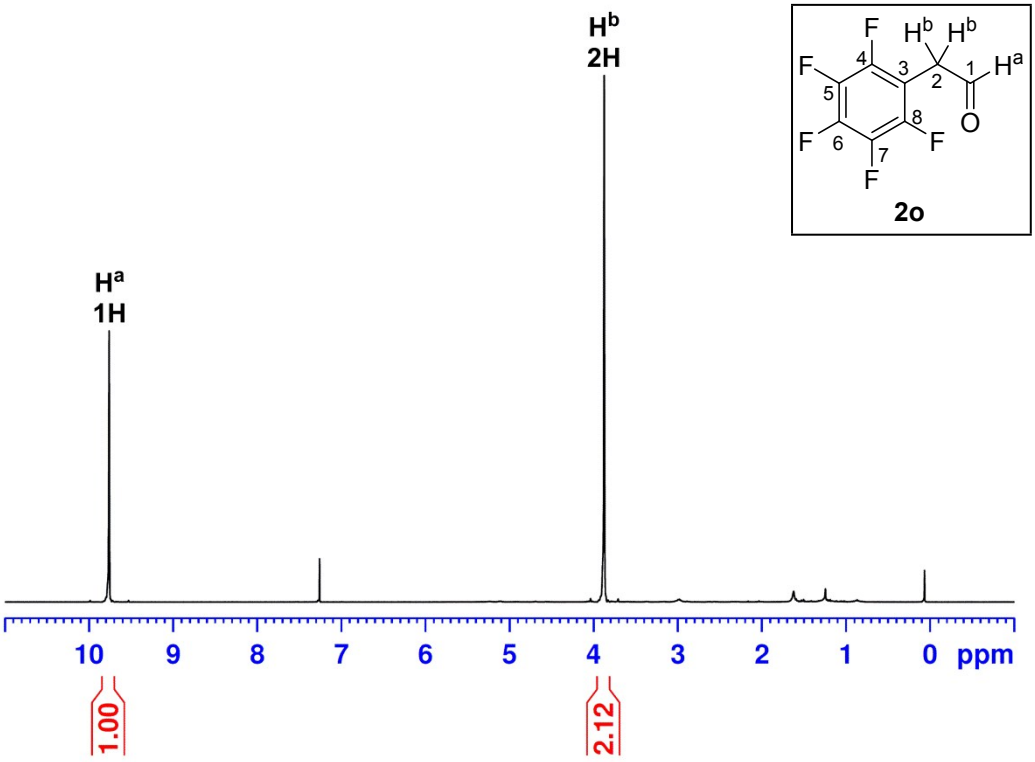


^{1}H NMR (400 MHz, $CDCl_3$)

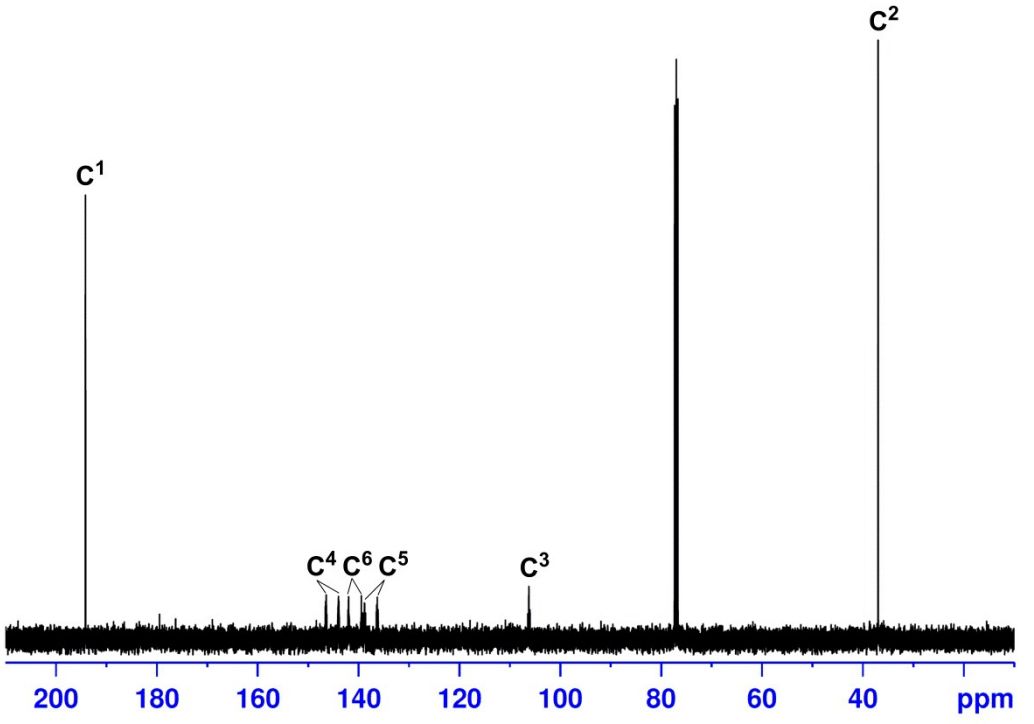


^{13}C NMR (100 MHz, $CDCl_3$)

(2,3,4,5,6-Pentafluorophenyl)acetaldehyde (2h).

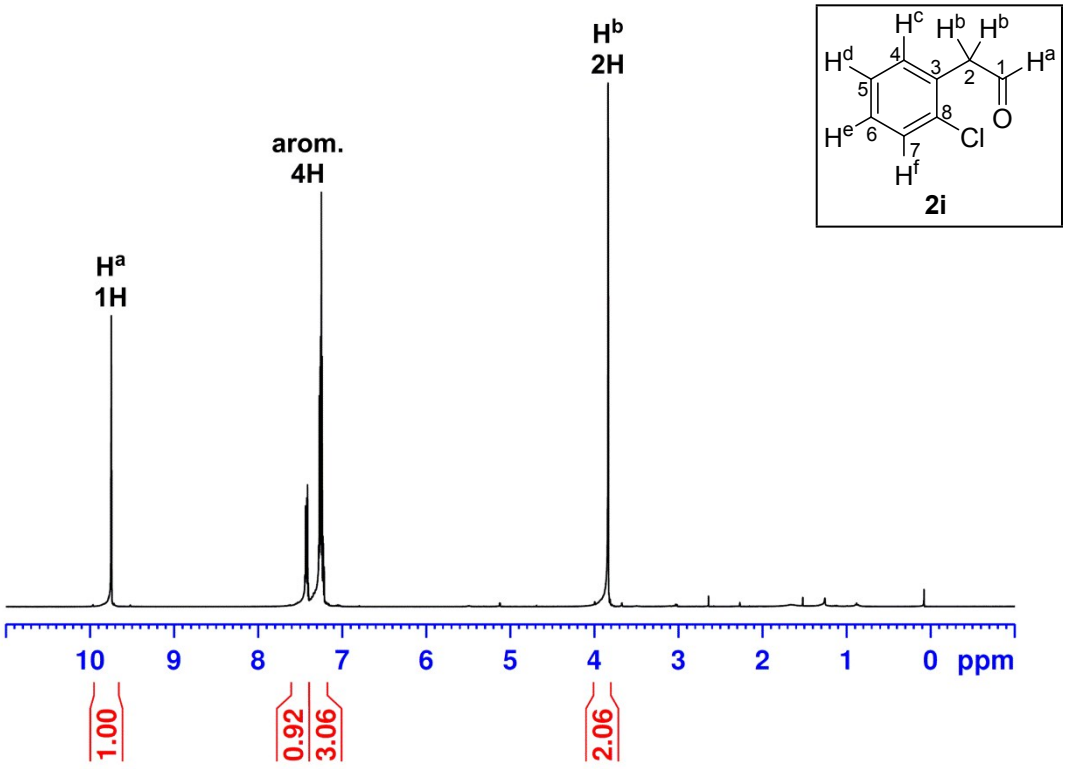


^{1}H NMR (400 MHz, $CDCl_3$)

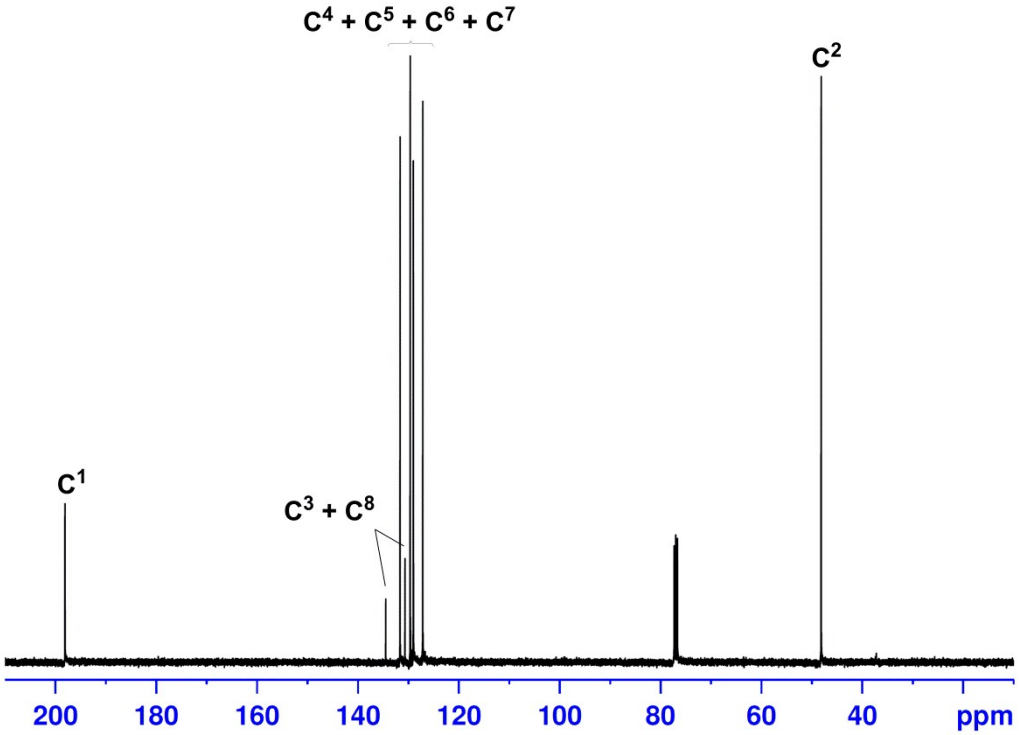


^{13}C NMR (100 MHz, $CDCl_3$)

(2-Chlorophenyl)acetaldehyde (2i).

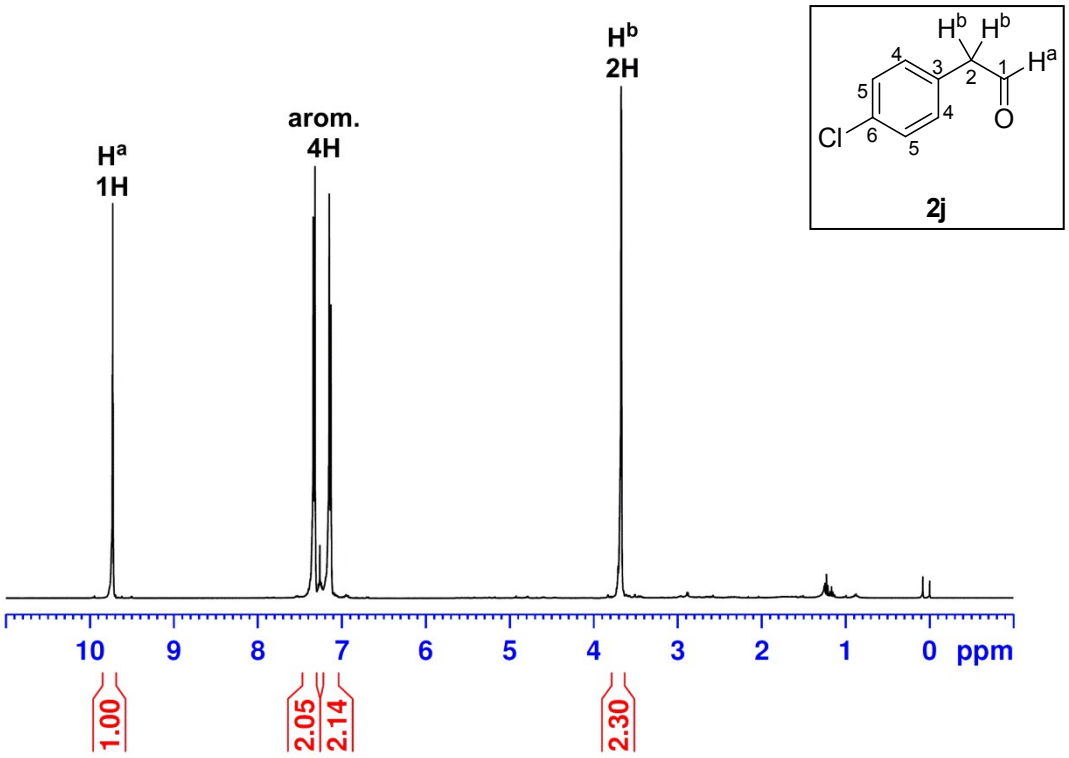


^{1}H NMR (400 MHz, $CDCl_3$)

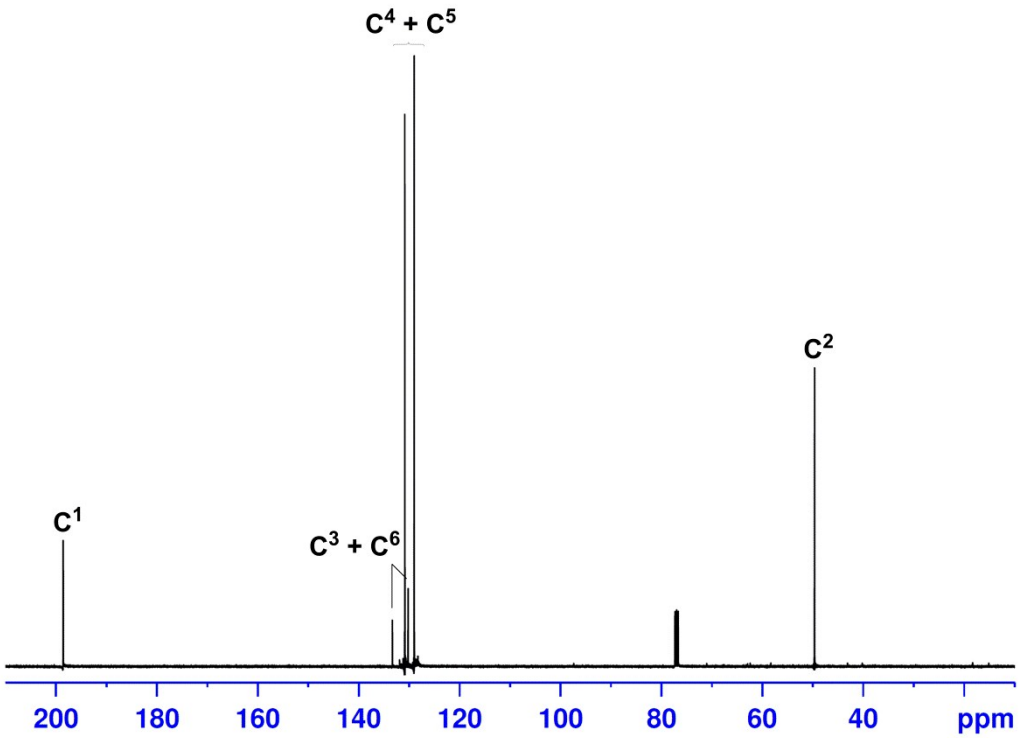


^{13}C NMR (100 MHz, $CDCl_3$)

(4-Chlorophenyl)acetaldehyde (2j).

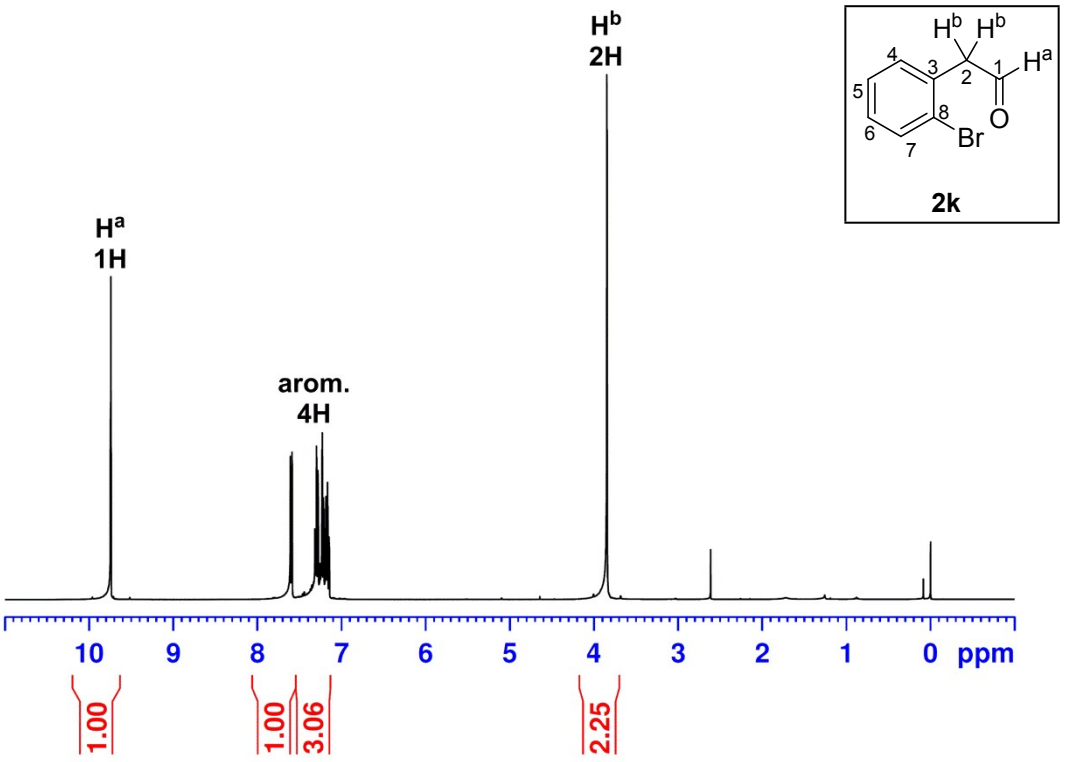


^{1}H NMR (400 MHz, $CDCl_3$)

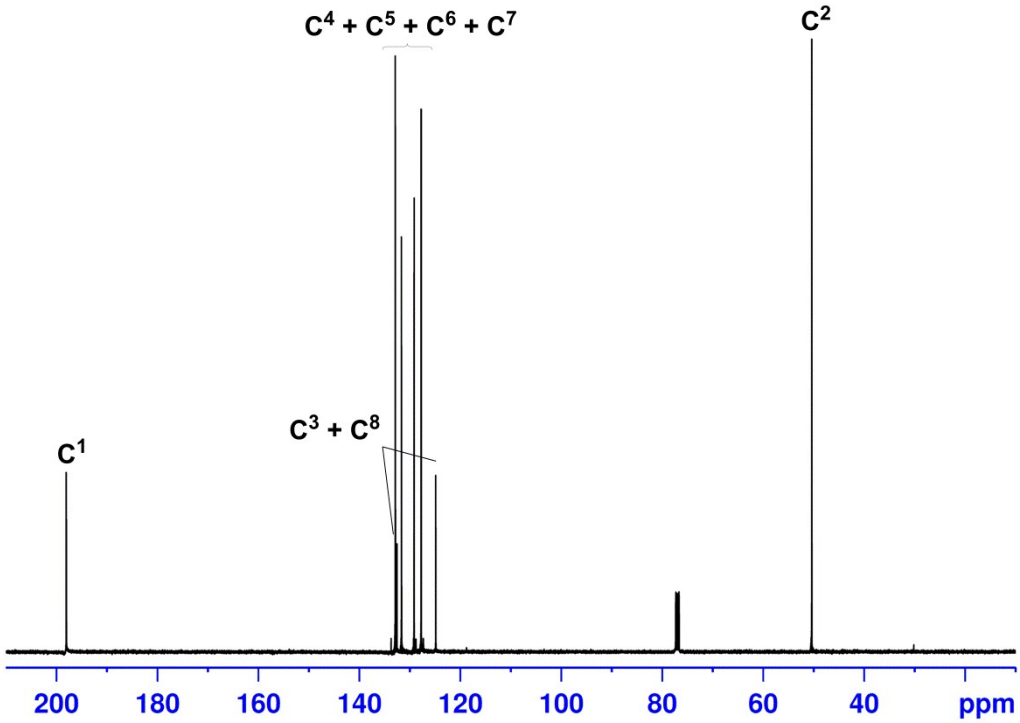


^{13}C NMR (100 MHz, $CDCl_3$)

(2-Bromophenyl)acetaldehyde (2k). Compound **2k** was purified by flash column chromatography (eluent: hexane/ethyl acetate = 20:1).

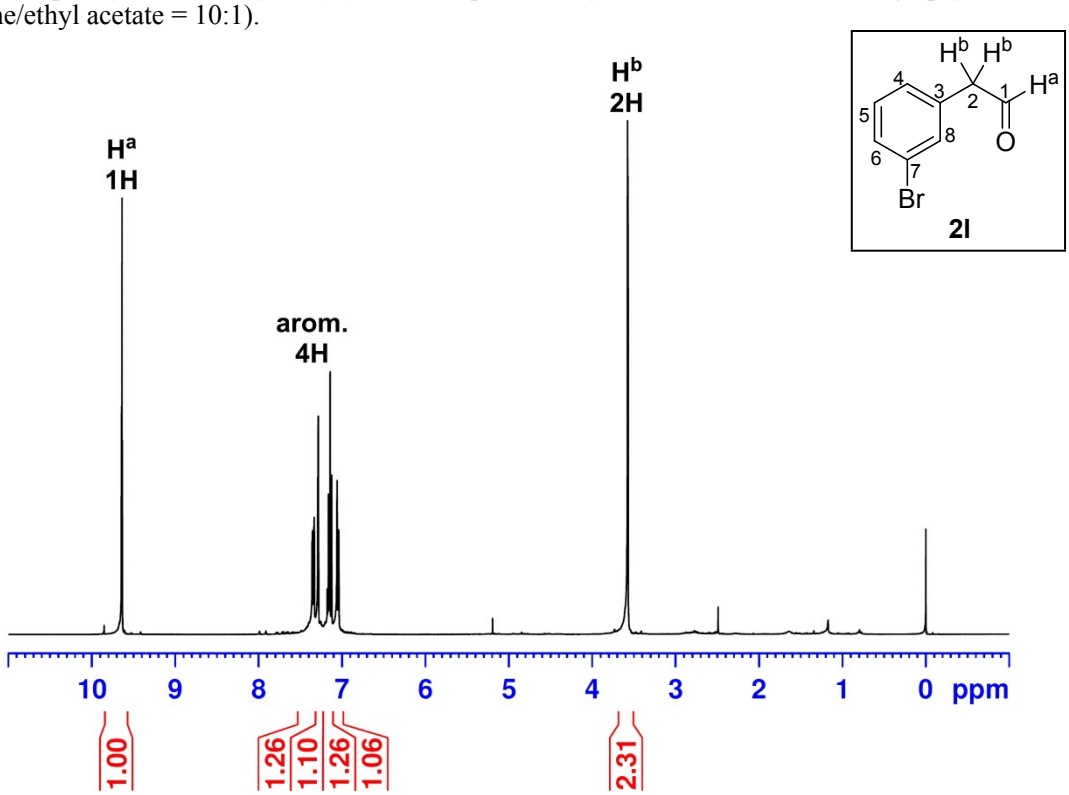


^{1}H NMR (400 MHz, $CDCl_3$)

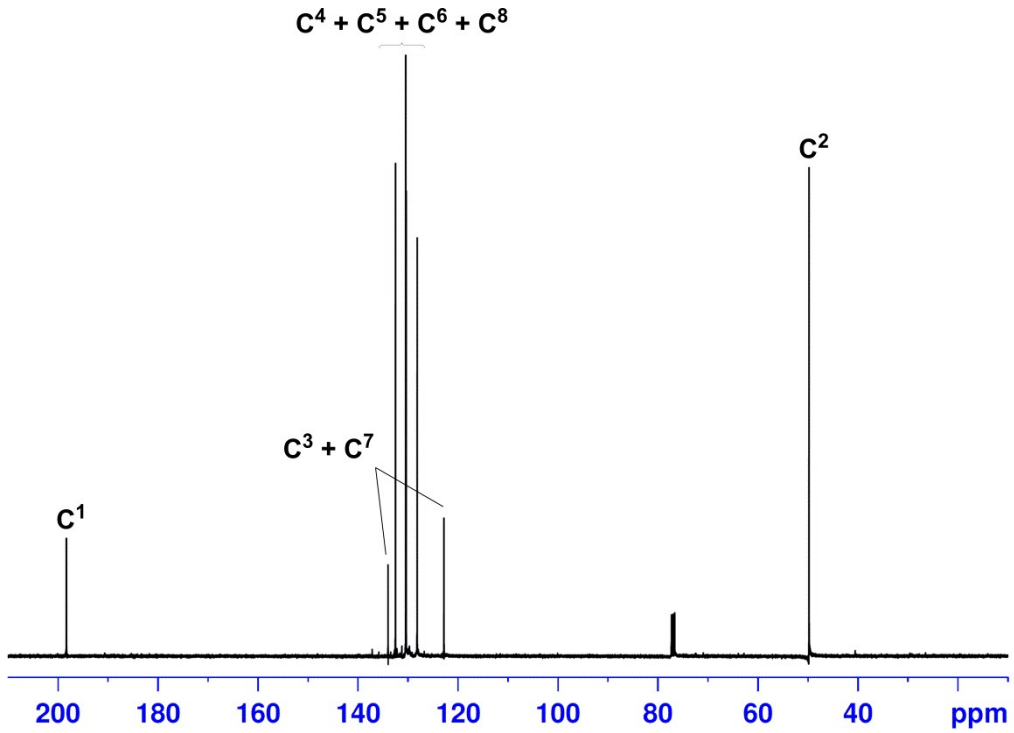


^{13}C NMR (100 MHz, $CDCl_3$)

(3-Bromophenyl)acetaldehyde (2l). 2l was purified by flash column chromatography (eluent: hexane/ethyl acetate = 10:1).

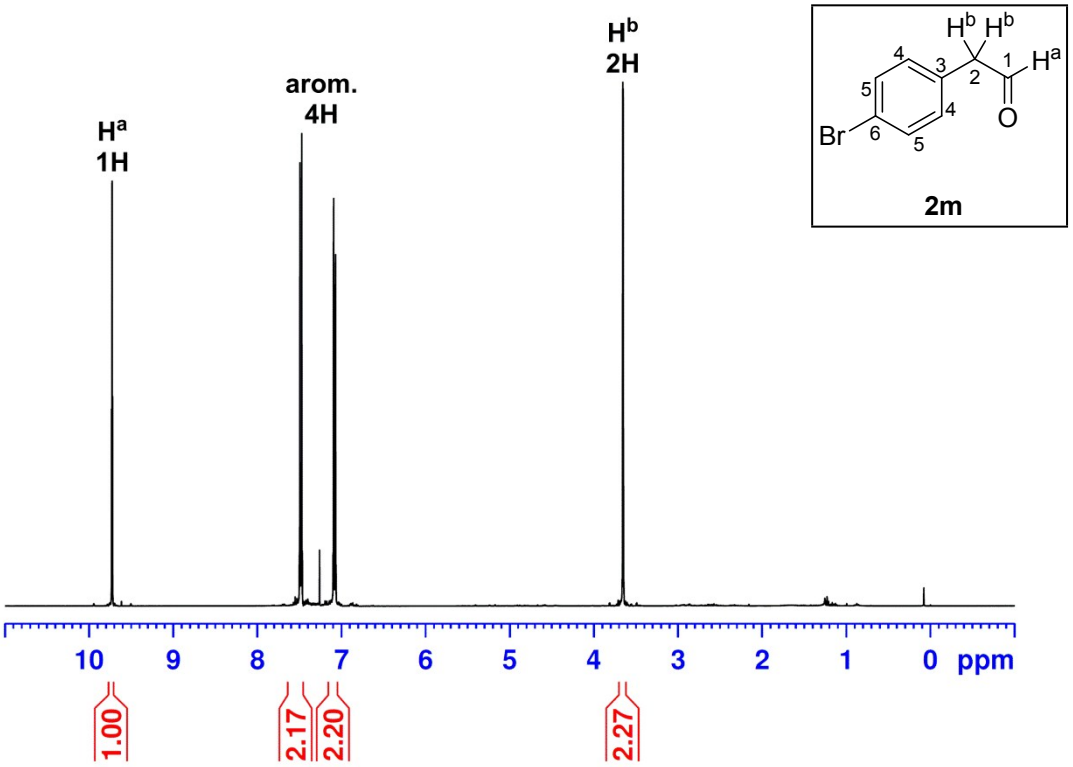


^{1}H NMR (400 MHz, $CDCl_3$)

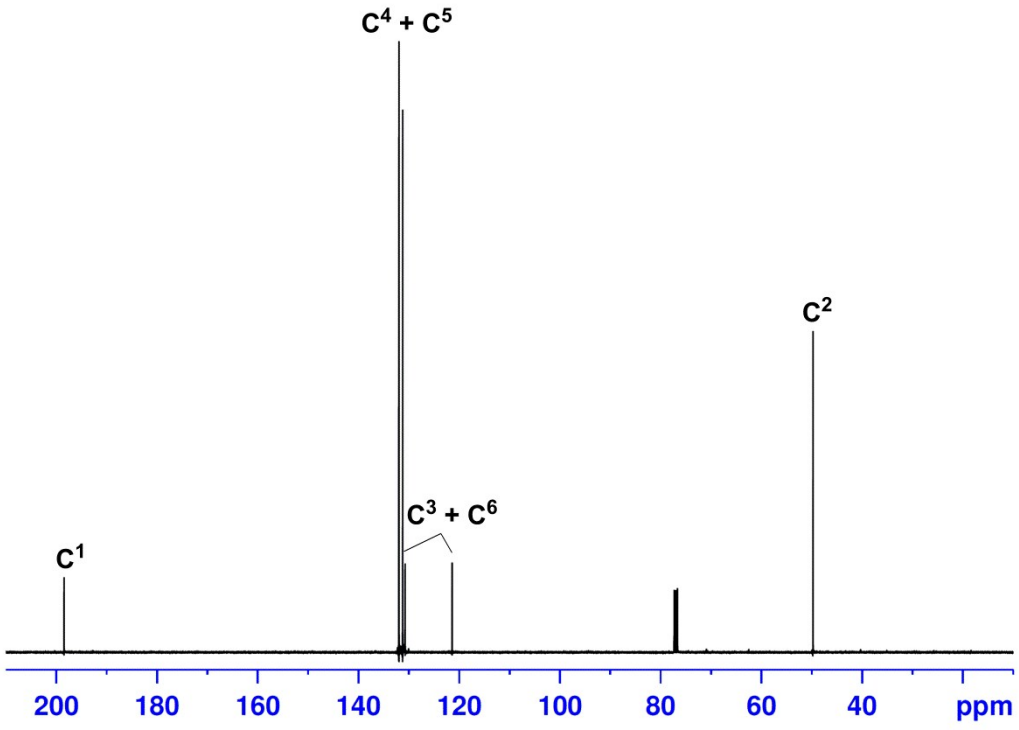


^{13}C NMR (100 MHz, $CDCl_3$)

(4-Bromophenyl)acetaldehyde (2m).

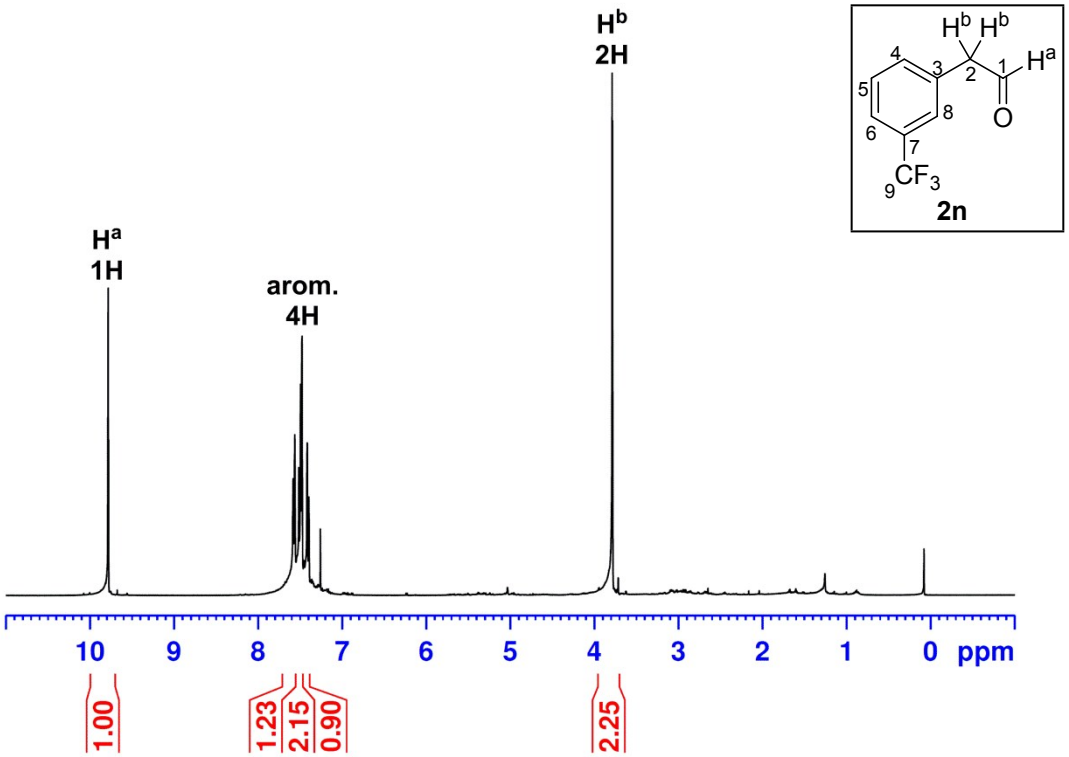


^{1}H NMR (400 MHz, $CDCl_3$)

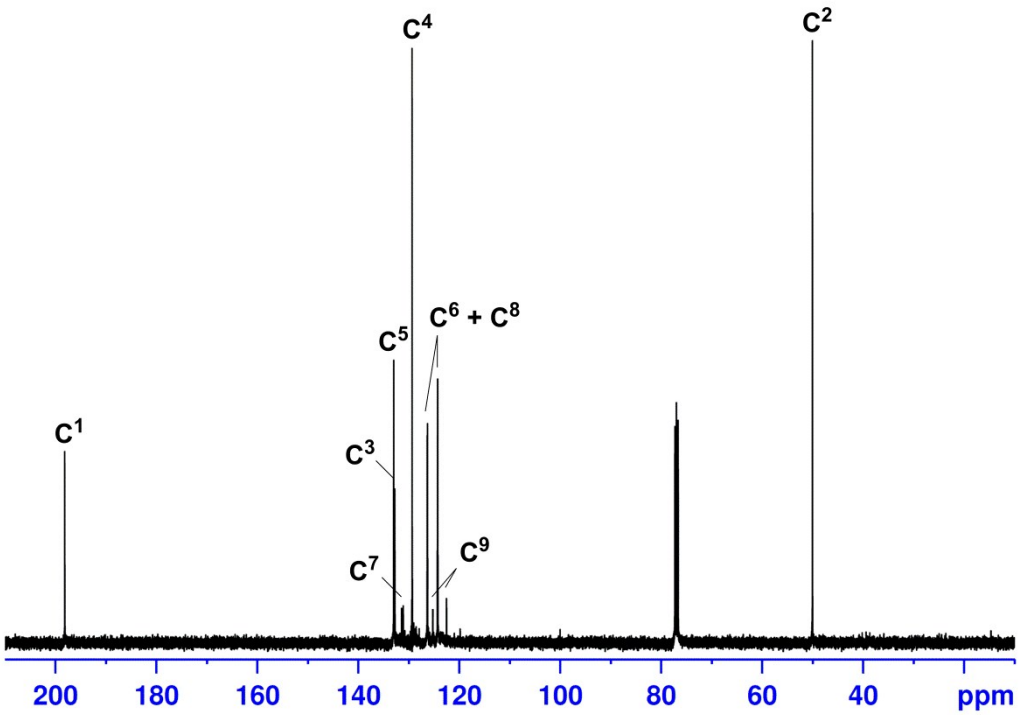


^{13}C NMR (100 MHz, $CDCl_3$)

(3-Trifluoromethylphenyl)acetaldehyde (2n).

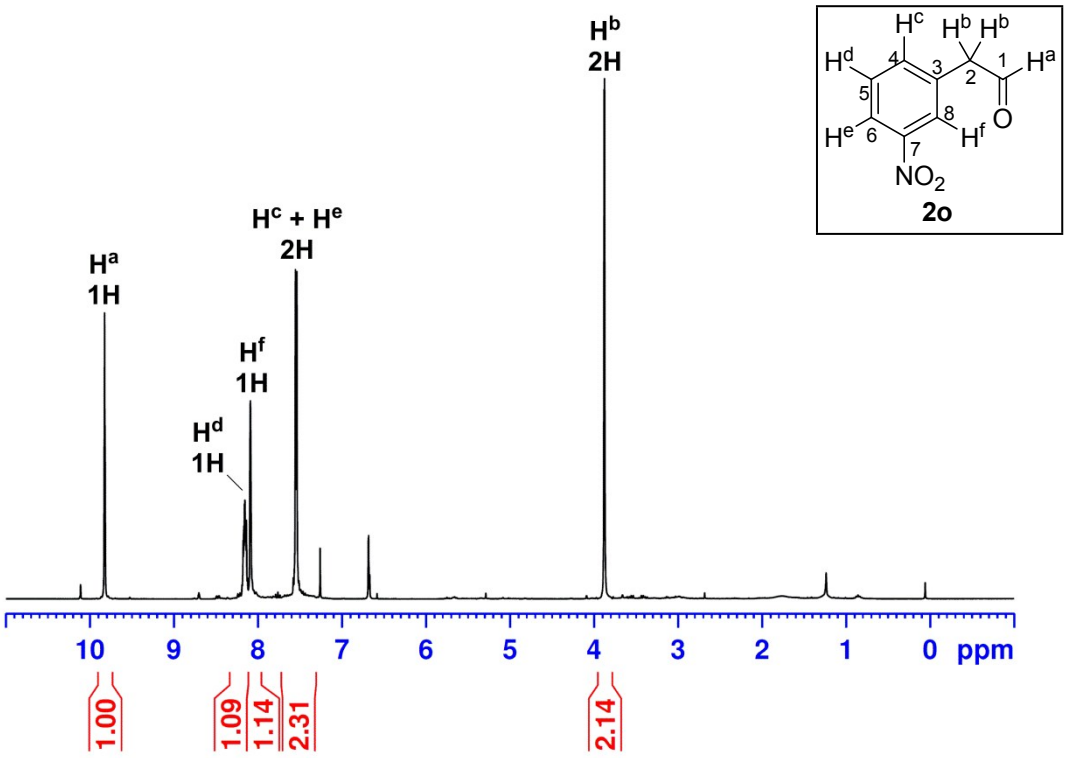


^{1}H NMR (400 MHz, $CDCl_3$)

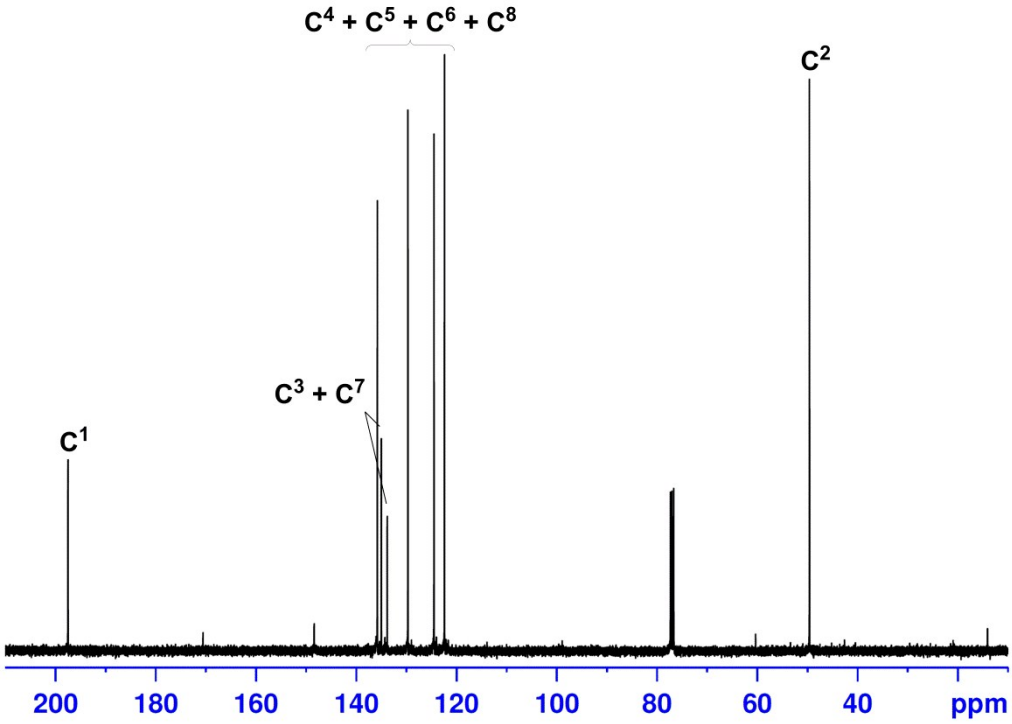


^{13}C NMR (100 MHz, $CDCl_3$)

(3-Nitrophenyl)acetaldehyde (2o).



^{1}H NMR (400 MHz, $CDCl_3$)



^{13}C NMR (100 MHz, $CDCl_3$)

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