Electronic Supplementary Material (ESI) for Chemical Communications

The cross-selective titanium(III)-catalysed acyloin reaction

Markus Feurer, Georg Frey, Hieu-Trinh Luu, Daniel Kratzert[b] and Jan Streuff*[a]

[a] *Institut für Organische Chemie, Albert-Ludwigs-Universität Freiburg, Albertstraße 21, 79104 Freiburg, Germany*

[b] *Institut für Anorganische und Analytische Chemie, Albert-Ludwigs-Universität Freiburg, Albertstraße 21, 79104 Freiburg, Germany*

Supporting Information

Table of Contents

Materials and Methods

All reactions have been carried out in flame-dried Schlenk–tubes under argon atmosphere (argon 5.0) using dry solvents unless noticed otherwise. Absolute THF was dried over potassium under argon atmosphere and freshly distilled prior to use. Ethyl Acetate for column chromatography was purchased in technical quality and purified by destillation with a rotary evaporator. Dichloromethane was purchased in p.a. quality from Aldrich. Zinc powder was purchased from Merck and used without further activation. Chlorotrimethylsilane was purchased from Acros and used as received. Triethylamine hydrochloride was purchased from Aldrich and purified by crystallization from chloroform. All other chemicals were purchased from Aldrich and used without further purification. An IKAmag temperature modulator in combination with an oil bath or stainless steel heating block were used to control the reaction temperatures. Thin-layer chromatography (TLC) was performed using E. Merck silica gel 60 F254 precoated plates (0.25 mm) and visualized by UV fluorescence quenching or *p*-Anisaldehyde staining. In general, Macherey-Nagel Silica gel 60 (particle size 0.04–0.063 mm) was used for flash chromatography. Florisil (60–100 mesh) by Roth was used as described. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DRX 500 (500 MHz and 125 MHz), a Bruker Avance II 400 (400 MHz and 100 MHz), a Bruker DRX 250 (250 MHz or 62.5 MHz) or a Varian Mercury 300 HFCP (300 MHz, ^{1}H only) spectrometer and reported to $CDCl_3$ (δ = 7.26 ppm and δ = 77.00 ppm, respectively) or C_6D_6 (δ = 7.16 ppm and δ = 128.00 ppm, respectively). The following abbreviations were used: s = singlet, d = doublet, t = triplet, q = quartet, quin = quintet, br = broad signal, ps = pseudo. IR spectra were recorded on a Perkin Elmer Spectrum 65 FT-IR-spectrometer and are reported in frequency of absorption. Low and high resolution mass analyses were performed by the service department at the Institute for Organic Chemistry and Biochemistry, Freiburg University using a Thermo Finnigan TSQ 700 for electron impact ionization (EI) at 70 eV, 200 ºC. High resolution mass analyses (HRMS) were carried out on a Thermo Exactive with Orbitrap-Analyzer using atmospheric pressure chemical ionization (APCI or ESI).

All ketones and nitriles were commercially available and purchased from Sigma-Aldrich.
Imine **5a** was synthesized according to a literature procedure.[1]
Imine **5b** was synthesized according to a literature procedure.[2]

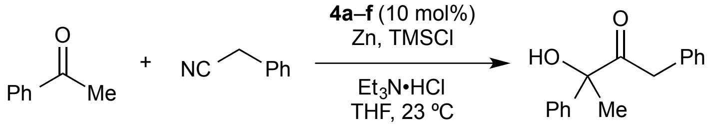
Titanocene catalyst **4a** was purchased from AlfaAesar.
Titanocene catalyst **4b** was purchased from AlfaAesar.
Titanocene catalyst **4c** was purchased from AlfaAesar.
Titanocene catalyst **4d** was purchased from mcat, Konstanz, Germany (www.mcat.de).
Titanocene catalyst **4e** was synthesized following a literature procedure.[3]
Titanocene catalyst **4f** was synthesized following the same literature procedure starting from 8-phenylmenthol.[3,4]

Full Reference 15

Gaussian 09, Revision B.01, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, Gaussian, Inc., Wallingford CT, **2010**.

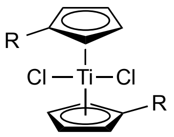
Extended Screening Results for the Cross-Coupling of 1a and 2a

Table S1. Selected screening results.[a]

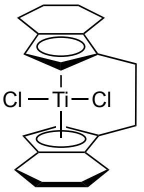


1a **2a** **3a**

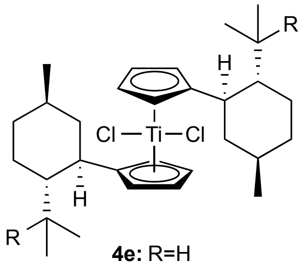
Entry	Catalyst	*c* (M)	*T* (°C)	*t* (h)	Yield (%)[b]
1	**4a**	1.0	23	24	80
2	**4b**	1.0	23	24	71
3	**4c**	1.0	23	66	70
4	**4d**	1.0	23	24	62
5	**4e**	1.0	23	24	45
6	**4f**	1.0	23	24	53
7[c]	**4a**	**1.0**	**35**	**24**	**81**
8[d]	**4a**	1.0	35	24	70
9[e]	**4a**	1.0	35	24	66
10	none	1.0	35	24	0
11[f]	**4b**	0.2	23	24	0



4a: R = Et
4b: R = H
4c: R = *t*-Bu



4d



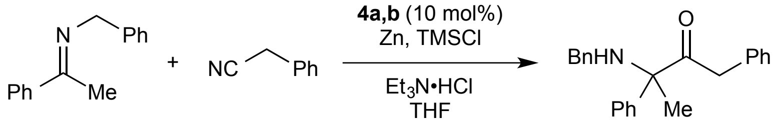
4e: R=H
4f: R=Ph

---

[a] Conditions: **1a** (0.5 mmol), **2a** (1.5–5 equiv), **4** (10 mol%), zinc (2 equiv), TMSCl (3.0 equiv), Et_3N•HCl (1.3–2.0 equiv), absolute THF (*c* = 0.2–1M); TBAF (1M in THF) then H_2O. [b] Isolated Yield. [c] Only 1.5 equiv of TMSCl were added. [d] With 1.5 equiv **2a**. [e] With 5 mol% **4b**. [f] With 1.5 equiv **2a**; imidazole (1 equiv) was added, see ref. 12 in the main manuscript.

Screening Results for the Cross-Coupling of 5a and 2a

Table S2. Selected screening results.[a]



5a **2a** **6a**

Entry	Catalyst	Equiv Et_3N•HCl	T (°C)	*c* (M)	Yield (%)[b]
1	**4b**	2	35	0.4	31
2	**4b**	2	35	1.0	34
3	**4a**	2	35	1.0	38
4	**4b**	2	23	1.0	28
5	**4a**	2	23	1.0	49
6	**4b**	1.1	35	1.0	49
7	**4b**	0.5	35	1.0	77
8	**4a**	0.5	35	1.0	76

[a] Conditions: **5a** (0.5 mmol), **2a** (5 equiv), **4** (10 mol%), zinc (2 equiv), TMSCl (3.0 equiv), Et_3N•HCl (0–2 equiv), THF (*c* = 0.2–2.0M), 24 h; workup: 1N HCl. [b] Isolated Yield.

General Procedure for the Catalytic Intermolecular Acyloin Reaction

A flame-dried and argon-filled 10 ml Schlenk-tube equipped with a magnetic stir bar was charged under argon atmosphere with Et_3N•HCl (137.7 mg, 1.0 mmol, 2 equiv), zinc dust (65.4 mg, 1.0 mmol, 2 equiv) and **4a** (15.3 mg, 0.05 mmol, 10 mol%). The tube was evacuated and back-filled with argon. Absolute, deoxygenated THF (0.5 ml) was added and the mixture was stirred for about one minute to allow for the color to change from red to lime green. At this point nitrile **2** was added (2.5 mmol, 5.0 equiv) and the color of the reaction mixture changed to blue. Ketone **1** (0.5 mmol) was added followed by slow addition of TMSCl (95.2 μl, 0.75 mmol, 1.5 equiv), which led again to a color change to green. The reaction vessel was sealed and stirred for 48 hours at 35 ºC. The reaction was cooled to room temperature. Then, TBAF (2.5 ml, 1M in THF, 5 equiv) was added and the mixture was stirred for 60 minutes. At this time, water (5 ml) was added and the mixture stirred for additional 5 minutes. The reaction mixture was transferred to a separation funnel with dichloromethane. Additional water (20 ml) was added and the aqueous phase extracted with dichloromethane (5 x 15 ml). The combined organic phase was dried (Na_2SO_4), filtered and concentrated under reduced pressure. The crude product was purified by column chromatography using dichloromethane as eluent (unless noted otherwise).

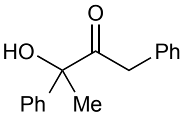
General Procedure for the Catalytic Intermolecular Imine-Nitrile Coupling

A flame-dried and argon-filled 10 ml Schlenk-tube equipped with a magnetic stir bar was charged under argon atmosphere with Et_3N•HCl (34.4 mg, 0.25 mmol, 0.5 equiv), zinc dust (65.4 mg, 1.0 mmol, 2 equiv) and **4b** (12.5 mg, 0.05 mmol, 10 mol%). The tube was evacuated and back-filled with argon. Absolute, deoxygenated THF (0.5 ml) was added and the mixture was stirred for about one minute to allow for the color to change from red to lime green. At this point nitrile **2** was added (2.5 mmol, 5.0 equiv) and the color of the reaction mixture changed to blue. Imine **5** (0.5 mmol) was added followed by slow addition of TMSCl (190.8 μl, 1.50 mmol, 3.0 equiv). The reaction vessel was sealed and stirred for 48 hours at 35 ºC. After the reaction was cooled to room temperature, the mixture was transferred with 3–5 ml CH_2Cl_2 to a separating funnel containing ice-cold aq. 1M HCl (20 ml) and ice-cold diethyl ether (50 ml). The ether phase was extracted six times briefly (only quick shaking) with ice-cold aq. 1M HCl (20 ml each) and the aqueous phases were collected and carefully neutralized (pH 8) with sat. aqueous $NaHCO_3$ solution. The aqueous phase (total volume about 300 ml) was extracted with CH_2Cl_2 (3 x 30 ml) and the CH_2Cl_2-phase was dried (Na_2SO_4), filtered and concentrated. The crude product was purified by column chromatography as described.

Representative Stoichiometric Procedure for Scheme 4

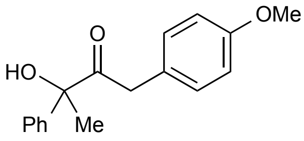
A flame-dried and argon-filled 10 ml Schlenk-tube equipped with a magnetic stir bar was charged under argon atmosphere with **4b** (50 mg, 1 equiv), zinc powder (65 mg, 5 equiv) and Et_3N•HCl (55 mg, 2 equiv). Absolute THF (1 mL) was added and the reaction stirred until the color had changed to green. Then benzyl cyanide and acetophenone were added in the way described in the manuscript text. The reactions were stirred overnight (14 h) and quenched by addition of sat. aq. NH_4Cl solution (5 ml). The mixture was transferred to a separation funnel, water (10 ml) was added and the aqueous layer extracted with dichloromethane (3 x 15 ml). The combined organic layers were dried (Na_2SO_4), filtered, and concentrated to give the crude product, which was analyzed by NMR. Flash chromatography gave the desired product and the pinacol products[5] (elute with 10:1 CH_2Cl_2:EtOAc) in the reported yields.

Purification and Analytical Data of New Compounds



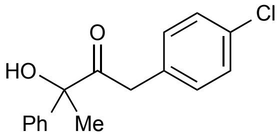
3a

3-hydroxy-1,3-diphenylbutane-2-one. This compound was previously isolated and characterized by ^{1}H and ^{13}C NMR.[6] Synthesized according to the general procedure with 10 mol% $(EtCp)_2TiCl_2$ and 24 h reaction time. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.18) and isolated in 81% yield. The analytical data matched the literature data. ^{1}H NMR (400.1 MHz, $CDCl_3$/TMS): δ = 1.72 (s, 3H), 3.58 (s, 2H), 4.30 (s, 1H, OH), 6.83-6.85 (m, 2H), 7.08-7.16 (m, 3H), 7.21-7.32 (m, 3H), 7.35-7.39 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$/TMS): δ = 24.42, 42.56, 80.52, 126.48, 128.20, 128.50, 128.71, 129.06, 129.62, 134.01, 141.33, 203.39. MS (EI, 70 eV): m/z (%) = 240.2 $[M]^+$ (1), 122.1 (8), 121.1 (100.00), 91.1 (8), 43.2 (23). HRMS (APCI, MeOH/NH_4) calcd for $C_{16}H_{20}NO_2{}^{+\cdot}$ $[M+NH_4]^+$: 258.14940, found: 258.14930. IR (NaCl): ν [cm^{-1}] = 3087, 3062, 3030, 2980, 2933, 1955, 1885, 1809, 1714, 1601, 1584, 1496, 1447, 1404, 1370, 1329, 1315, 1221, 1161, 1118, 1104, 1069, 1035, 1002, 940, 915, 825, 759, 724, 698.



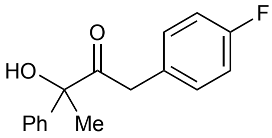
3b

3-hydroxy-1-(4-methoxyphenyl)-3-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.2) and isolated in 85% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 1.82 (s, 3H), 3.62 (s, 2H), 3.76 (s, 3H), 4.41 (br. s, 1H, OH), 6.75-6.87 (m, 4H), 7.32-7.42 (m, 3H), 7.44-7.48 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.12, 41.44, 55.29, 80.20, 113.99, 125.73, 126.31, 128.29, 128.85, 130.39, 141.16, 158.67, 209.59. MS (EI, 70 eV): m/z (%) = 270.1 $[M]^+$ (1), 150.0 (23), 122.1 (66), 121.0 (100), 105 (4), 91.1 (5), 77.1 (8), 43.6 (27). HRMS (APCI, MeOH): calcd for $C_{17}H_{17}O_3{}^-$ $[M-H]^-$: 269.11777, found: 269.11790. HRMS (APCI, MeOH): calcd for $C_{17}H_{18}O_3Cl^-$ $[M+Cl]^-$: 305.09445, found: 305.09450. IR (NaCl): ν [cm^{-1}] = 3464, 3060, 3032, 2997, 2935, 2909, 2836, 1713, 1612, 1585, 1513, 1493, 1447, 1422, 1403, 1370, 1325, 1301, 1248, 1178, 1106, 1068, 1035, 941, 915, 861, 821, 789, 758, 701.



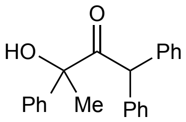
3c

1-(4-chlorophenyl)-3-hydroxy-3-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.4) and isolated in 79% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 1.82 (s, 3H), 3.65 (d, J = 2.3 Hz, 2H), 4.27 (br. s, 1H, OH), 6.82-6.87 (m, 2H), 7.17-7.22 (m, 2H), 7.32-7.47 (m, 5H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.18, 41.62, 80.31, 126.18, 128.38, 128.60, 128.89, 130.73, 132.23, 132.98, 140.90, 208.72. MS (EI, 70 eV): m/z (%) = 231.1 $[M-CH_3CO]^+$ (6), 169.1 (7), 139.0 (7), 121.1 (100), 105.1 (17), 43.2 (25). HRMS (APCI, MeOH): calcd for $C_{16}H_{14}O_2Cl^-$ $[M-H]^-$: 273.06823, found: 273.06840. HRMS (APCI, MeOH): calcd for $C_{16}H_{15}O_2Cl_2{}^-$ $[M+Cl]^-$: 309.04491, found: 309.04510. IR (NaCl): ν [cm^{-1}] = 3458, 3060, 2980, 2933, 1714, 1599, 1492, 1446, 1409, 1370, 1321, 1270, 1220, 1152, 1118, 1092, 1069, 1033, 1016, 938, 915, 830, 805, 776, 755, 701, 672.



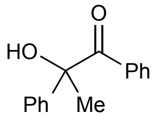
3d

1-(4-fluorophenyl)-3-hydroxy-3-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.26) and isolated in 79% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 1.82 (s, 3H), 3.66 (s, 2H), 4.29 (br. s, 1H, OH), 6.85-6.95 (m, 4H), 7.32-7.48 (m, 5H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.18, 41.44, 80.27, 115.35 (d, *J* = 23 Hz), 126.22, 128.37, 128.89, 129.45 (d, *J* = 4 Hz), 130.91 (d, *J* = 8 Hz), 140.98, 162.20 (d, *J* = 248 Hz), 209.04. ^{19}F NMR (235.3 MHz, $CDCl_3$): δ = –115.65- –115.85 (m, 1F). MS (EI, 70 eV): m/z (%) = 215.0 $[M-CH_3CO]^+$ (3), 122.1 (9), 121.1 (100), 109.0 (14), 105.0 (6), 43.2 (19). HRMS (APCI, MeOH): calcd for $C_{16}H_{14}O_2F^-$ $[M-H]^-$: 257.09778, found: 257.09810. IR (NaCl): ν [cm^{-1}] = 3463, 3060, 2981, 2933, 1714, 1601, 1510, 1494, 1447, 1418, 1322, 1222, 1158, 1118, 1095, 1069, 1033, 915, 864, 845, 825, 790, 759, 740, 701.



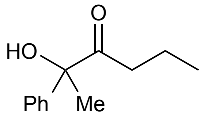
3e

3-hydroxy-1,1,3-triphenylbutan-2-one. Synthesized according to the general procedure. After the addition of TBAF, HCl (1 M, 4 mL) was added instead of water and the reactionmixture was stirred for 10 min. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.6) and isolated in 80% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$/TMS): δ = 1.61 (s, 3H), 4.23 (s, 1H), 5.29 (s, 1H, OH), 6.67-6.72 (m, 2H), 7.00-7.05 (m, 3H), 7.06-7.30 (m, 8H), 7.32-7.38 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$/TMS): δ = 24.65, 57.16, 81.35, 126.62, 126.98, 127.29, 127.66, 128.61, 128.65, 128.84, 128.96, 129.10, 138.44, 138.97, 140.73, 209.90. MS (EI, 70 eV): m/z (%) = 316.3 $[M]^+$ (1), 168.1 (15), 167.1 (21), 166.1 (7), 165.1 (20), 152.1 (7), 122.1 (9), 121.1 (100.00), 105.0 (10), 43.2 (18). HRMS (APCI, MeOH/NH_4) calcd for $C_{22}H_{19}O_2^-$ $[M-H]^-$: 315.13850, found: 315.13870. IR (NaCl): ν [cm^{-1}] = 3087, 3062, 3028, 3003, 2981, 2934, 1954, 1886, 1808, 1713, 1599, 1584, 1495, 1449, 1372, 1343, 1302, 1279, 1219, 1186, 1176, 1158, 1117, 1102, 1068, 1037, 1002, 934, 911, 877, 865, 768, 735, 698.



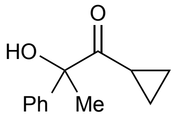
3f

2-Hydroxy-1,2-diphenylpropan-1-one. This compound is literature-known.[7] Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.38) and isolated in 46% yield as colorless oil. ^{1}H NMR (300.1 MHz, $CDCl_3$/TMS): δ = 1.90 (s, 3H), 4.71 (s, 1H, OH), 7.26-7.48 (m, 8H), 7.66-7.72 (m, 2H).



3g

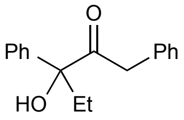
2-hydroxy-2-phenylhexan-3-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.43) and isolated in 66% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 0.75 (t, *J* = 7.4 Hz, 3H), 1.40-1.61 (m, 2H), 1.77 (s, 3H), 2.24-2.32 (dddd, *J* = 6.8, 6.8, 6.8, 6.4 Hz, 1H), 2.38-2.46 (dddd, *J* = 6.4, 6.4, 6.4, 6.4 Hz, 1H), 4.63 (s, 1H), 7.28-7.32 (m, 1H), 7.34-7.39 (m, 2H), 7.41-7.44 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 13.58, 17.53, 24.13, 37.55, 79.84, 126.21, 128.10, 128.74, 144.65, 212.00.MS (EI, 70 eV): m/z (%) = 121.1 $[M-C_4H_7O]^+$ (100), 105.0 (5), 91.1 (3), 77.1 (5), 43.6 (20). HRMS (APCI, MeOH/NH_4) calcd. for $C_{12}H_{20}NO_2^+$ $[M+NH_4]^+$: 210.14940, found: 210.14930. IR (NaCl): ν [cm^{-1}] = 3459, 3088, 3061, 3028, 2965, 2935, 2904, 2876, 1956, 1884, 1811, 1708, 1601, 1584, 1494, 1447, 1405, 1369. 1356, 1288, 1266, 1228, 1215, 1161, 1129, 1069, 1028, 931, 915, 896, 843, 761, 700.



3h

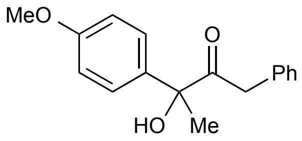
1-cyclopropyl-2-hydroxy-2-phenylpropan-1-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.23) and isolated in 67% yield as colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 0.75-0.82 (m, 1H), 0.94-1.09 (m, 3H), 1.85

(s, 3H), 1.89-1.96 (m, 1H), 4.68 (s, 1H), 7.28-7.33 (m, 1H), 7.35-7.40 (m, 2H), 7.44-7.47 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 12.15, 13.15, 16.25, 24.37, 79.95, 126.41, 128.07, 128.71, 141.79, 212.20. MS (EI, 70 eV): m/z (%) = 121.0 $[M-C_4H_5O]^+$ (100), 105.0 (5), 77.1 (5), 43.6 (31). HRMS (APCI, MeOH) calcd. for $C_{12}H_{15}O_2^+$ $[M–H]^+$: 191.10720, found: 191.10700. IR (NaCl): ν [cm^{-1}] = 3453, 3088, 3061, 3008, 2980, 2934, 2875, 1956, 1886, 1811, 1692, 1601, 1494, 1447, 1420, 1377, 1361, 1222, 1195, 1176, 1119, 1102, 1069, 1048, 1028, 1015, 935, 915, 871, 837, 818, 795, 773, 736, 715, 699.



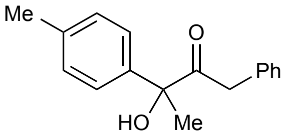
3i

3-hydroxy-1,3-diphenylpentan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.55) and isolated in 74% yield as yellow oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 0.93 (t, *J* = 7.4 Hz, 3H), 2.22-2.39 (m, 2H), 3.68 (d, *J* = 7.2 Hz, 2H), 4.37 (br. s, 1H, OH), 6.90-6.95 (m, 2H), 7.18-7.27 (m, 3H), 7.32-7.37 (m, 1H), 7.38-7.43 (m, 2H), 7.48-7.53 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 7.63, 29.20, 42.42, 83.21, 126.61, 127.05, 128.18, 128.49, 128.83, 129.49, 133.63, 140.47, 209.13. MS (EI, 70 eV): m/z (%) = 254.1 $[M]^+$ (1), 197.0 $[M-CH_3CH_2CO]^+$ (4), 136.1 (9), 135.1 (100), 105.0 (7), 91.1 (12), 77.3 (6), 57.3 (25). HRMS (APCI, MeOH): calcd for $C_{17}H_{24}O_2Cl^-$ $[M+Cl]^-$: 289.09953, found: 289.09940. IR (NaCl): ν [cm^{-1}] = 3468, 3087, 3062, 3029, 2970, 2937, 2879, 1711, 1601, 1496, 1454, 1448, 1382, 1313, 1270, 1154, 1120, 1051, 1031, 986, 915, 785, 757, 722, 697.



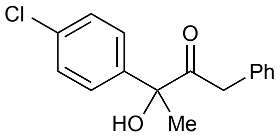
3j

3-hydroxy-3-(4-methoxyphenyl)-1-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.2) and isolated in 74% yield as colorless oil. ^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 1.81 (s, 3H), 3.67 (s, 2H), 3.83 (s, 3H), 4.38 (br. s, 1H, OH), 6.90-6.98 (m, 4H), 7.18-7.28 (m, 3H), 7.37 (m_c, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.16, 42.28, 55.44, 79.86, 114.22, 127.04, 127.62, 128.52, 129.41, 133.16, 133.87, 159.61, 209.40. MS (EI, 70 eV): m/z (%) = 270.3 $[M]^+$ (1), 151.1 $[M-C_8H_7O]^+$ (100), 135.0 (9), 133.1 (6), 91.1 (6), 43.6 (19). HRMS (APCI, MeOH): calcd for $C_{17}H_{17}O_3^-$ $[M-H]^-$: 269.11777, found: 269.11770. HRMS (APCI, MeOH): calcd for $C_{17}H_{18}O_3Cl^-$ $[M+Cl]^-$: 305.09445, found: 305.09440. IR (NaCl): ν [cm^{-1}] = 3463, 3063, 3029, 2934, 2837, 1713, 1609, 1583, 1511, 1497, 1454, 1413, 1369, 1302, 1252, 1180, 1125, 1093, 1077, 1033, 932, 837, 795, 723, 696.



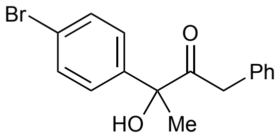
3k

3-hydroxy-1-phenyl-3-(*p*-tolyl)butan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.27) and isolated as a colorless oil in 61% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.83 (s, 3H), 2.40 (s, 3H), 3.70 (s, 2H), 4.39 (br s, 1H), 6.97-6.99 (m, 2H), 7.21-7.28 (m, 5H), 7.35-7.38 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 21.20, 24.20, 42.34, 80.16, 126.22, 1247.05, 128.53, 129.46, 129.58, 133.90, 138.14, 138.20, 209.39. MS (EI, 70 eV): m/z (%) = 254.3 $[M]^+$ (1), 211.0 (4), 135.1 (100), 119.0 (6), 91.1 (12), 43.6 (31). HRMS (APCI, MeOH) calcd. for $C_{17}H_{18}O_2C^-l$ $[M+Cl]^-$: 289.09953, found: 289.09860. IR (NaCl): ν [cm^{-1}] = 3466, 3088, 3063, 3029, 2979, 2924, 1911, 1714, 1603, 1511, 1497, 1454, 1406, 1369, 1329, 1314, 1211, 1187, 1154, 1109, 1096, 1077, 1066, 1035, 1019, 1002, 935, 834, 817, 750, 723, 696.



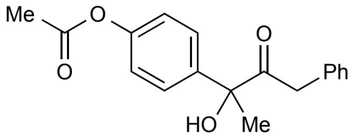
3l

3-(4-chlorophenyl)-3-hydroxy-1-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.28) and isolated as a pale yellow powder in 58% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.81 (s, 3H), 3.68 (d, J = 16.0 Hz, 2H), 4.33 (s, 1H), 6.95-6.97 (dd, J = 7.6, 2.0 Hz, 2H), 7.21-7.28 (m, 3H), 7.35-7.43 (m, 4 H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.43, 42.45, 80.01, 127.22, 127.82, 128.65, 129.03, 129.38, 133.51, 134.42, 139.78, 208.79. MS (EI, 70 eV): m/z (%) = 274.7 $[M]^+$ (1), 155.0 (100), 119.0 (5), 91.0 (10), 43.6 (24). HRMS (APCI, MeOH) calcd. for $C_{16}H_{15}O_2Cl_2^-$ $[M+Cl]^-$: 309.04491, found: 309.04380. IR (NaCl): ν [cm^{-1}] = 3461, 3088, 3064, 3030, 2981, 2934, 1949, 1908, 1716, 1600, 1586, 1495, 1454, 1400, 1371, 1329, 1220, 1155, 1121, 1094, 1034, 1013, 1003, 966, 936, 838, 817, 769, 734, 721, 700.



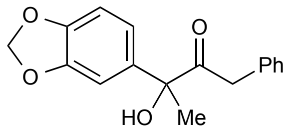
3m

3-(4-bromophenyl)-3-hydroxy-1-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.27) and isolated as a pale yellow powder in 68% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.80 (s, 3H), 3.68 (d, J = 16.0 Hz, 2H), 4.31 (s, 1H), 6.94-6.97 (dd, J = 7.6, 2.0 Hz, 2H), 7.22-7.28 (m, 3H), 7.32-7.36 (dt, J = 9.1, 2.2 Hz, 2H), 7.50-7.54 (dt, J = 8.7, 2.4 Hz, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.41, 42.48, 80.07, 122.63, 127.22, 128.14, 128.66, 129.39, 132.00, 133.48, 140.31, 208.72. MS (EI, 70 eV): m/z (%) = 318.0 [M, ^{79}Br]$^+$ (1), 200.9 [M-119.1, ^{81}Br] (94), 189.9 [M-119.1, ^{79}Br]$^+$ (100), 184.9 (7), 182.9 (8), 135.1 (5), 91.1 (16), 43.6 (39). HRMS (APCI, MeOH) calcd. for $C_{16}H_{15}O_2ClBr^-$ $[M+Cl]^-$: 352.99439, found: 352.99330. IR (NaCl): ν [cm^{-1}] = 3458, 3087, 3063, 3030, 2980, 2933, 1907, 1716, 1602, 1589, 1496, 1488, 1454, 1396, 1370, 1329, 1210, 1153, 1120, 1089, 1076, 1034, 1009, 936, 835, 764, 730, 698.



3n

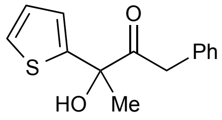
4-(2-hydroxy-3-oxo-4-phenylbutan-2-yl)phenyl acetate. Synthesized according to the general procedure. After quenching with TBAF, 5 mL aqueous HCl (1N) was added. After 1 h further workup (extraction/neutralization) was carried out as described in the general procedure. Purification of the crude mixture via flash chromatography (CH_2Cl_2/ ethyl acetate, 20:1, R_f = 0.17) gave **3n** in 74% yield as pale yellow powder. ^{1}H-NMR (400 MHz, $CDCl_3$) δ = 1.81 (s, 3H), 2.31 (s, 3H), 3.70 (s, 2H), 4.30 (s, 1H), 6.94-6.97 (m, 2H*),* 7.11-7.14 (m, 2H) 7.21-7.27 (m, 3H), 7.46-7.49 (m, 2H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ = 21.26, 24.56, 42.50, 80.11, 121.98, 127.14, 127.55, 128.63, 129.45, 133.69, 138.74, 150.75, 169.31, 209.00. MS (EI, 70 eV): m/z (%) = 298.0 $[M]^+$ (1), 179.0 (87), 137.0 (100), 121.0 (8), 91.0 (14), 65.0 (5), 43.1 (22). HRMS (APCI, MeOH) calcd. for $C_{18}H_{19}O_4^+$ $[M+H]^+$: 299.12833, found: 299.12810. IR (NaCl): ν [cm^{-1}] = 3062, 3029, 2979, 2932, 1756, 1716, 1602, 1504, 1454, 1410, 1370, 1329, 1203, 1169, 1121, 1092, 1077, 1066, 1034, 1016, 913, 825, 723, 697, 680.



3o

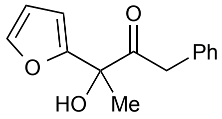
3-(benzo[*d*][1,3]dioxol-5-yl)-3-hydroxy-1-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.15) and isolated in 62% yield as colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ = 1.77 (s, 3H), 3.69 (s, 2H), 4.32 (s, 1H), 5.97-5.98 (d, J = 1.6 Hz, 2H), 6.82 (d, J = 8.4 Hz, 1H), 6.91-7.00 (m, 4H), 7.19-7.28 (m, 3H). ^{13}C-

NMR (100.6 MHz, $CDCl_3$): δ = 24.43, 42.33, 80.05, 101.44, 107.11, 108.44, 119.97, 127.13, 128.59, 129.45, 133.86, 135.24, 147.72, 148.34, 20914. MS (EI, 70 eV): m/z (%) = 284.1 $[M]^+$ (1), 165.0 (100), 148.9 (4), 147.0 (3), 117.0 (5), 91.0 (13). HRMS (APCI, MeOH) calcd. for $C_{17}H_{17}O_4^+$ $[M+H]^+$: 285.11268, found: 285.11260. IR (NaCl): ν [cm^{-1}] = 3063, 3029, 2981, 2900, 1714, 1605, 1504, 1487, 1454, 1436, 1403, 1341, 1244, 1156, 1096, 1076, 1038, 1003, 935, 866, 813, 756, 727, 715, 697, 670, 638, 572.



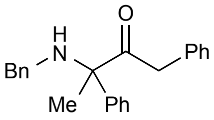
3p

3-hydroxy-1-phenyl-3-(thiophen-2-yl)butan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.39) and isolated in 61% yield as yellow oil. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 1.87 (s, 3H), 3.83 (d, *J* = 8.7 Hz, 2H), 4.63 (br. s, 1H, OH), 6.99-7.03 (m, 2H), 7.04 (dd, *J* = 5.1, 3.5 Hz, 1H), 7.11 (dd, *J* = 3.6, 1.2 Hz, 1H), 7.21-7.30 (m, 3H), 7.33 (dd, *J* = 5.1, 1.1 Hz, 1H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 25.65, 41.82, 78.76, 125.43, 126.37, 127.17, 127.43, 128.60, 129.40, 133.61, 146.31, 207.76. MS (EI, 70 eV): m/z (%) = 246.0 $[M]^+$ (2), 203.0 (13), 135.0 (15), 127.0 (100), 111.0 (12), 91.1 (13), 44.1 (18), 43.2 (25). HRMS (APCI, MeOH): calcd for $C_{14}H_{13}O_2S^-$ $[M-H]^-$: 245.06363, found: 245.06370. IR (NaCl): ν [cm^{-1}] = 3456, 3106, 3088, 3064, 3030, 2982, 2932, 1715, 1603, 1497, 1454, 1432, 1403, 1370, 1328, 1239, 1199, 1148, 1102, 1075, 1038, 1023, 1002, 933, 855, 838, 761, 709, 696.



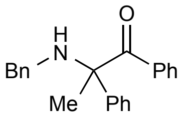
3q

3-(furan-2-yl)-3-hydroxy-1-phenylbutan-2-one. Synthesized according to the general procedure. After extraction, the product was purified by flash chromatography (CH_2Cl_2, R_f = 0.25) and isolated in 68% yield as yellow oil. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 1.78 (s, 3H), 3.67 (d, *J* = 3.4 Hz, 2H), 4.44 (br. s, 1H, OH), 6.44 (ddd, *J* = 19.6, 3.3, 1.3 Hz, 2H), 7.04-7.08 (m, 2H), 7.22-7.32 (m, 3H), 7.41 (dd, *J* = 1.8, 0.9 Hz, 1H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 23.06, 42.53, 76.70, 108.21, 110.90, 127.18, 128.59, 129.46, 133.38, 143.08, 153.94, 207.17. MS (EI, 70 eV): m/z (%) = 230.0 $[M]^+$ (2), 202.0 (6), 183.0 (14), 112.0 (13), 111.0 (100), 95.0 (6), 91.0 (16), 43.2 (26). HRMS (APCI, MeOH): calcd for $C_{14}H_{13}O_3^-$ $[M-H]^-$: 229.08647, found: 229.08650. IR (NaCl): ν [cm^{-1}] = 3465, 3063, 3030, 2986, 2935, 1720, 1603, 1498, 1455, 1331, 1240, 1158, 1107, 1070, 1035, 1014, 946, 922, 884, 822, 729, 697.



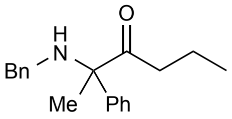
6a

3-(benzylamino)-1,3-diphenylbutan-2-one. Synthesized according to the general procedure for the imine-nitrile coupling. After extraction, the product was purified by flash chromatography (CH_2Cl_2,/ethyl acetate = 40:1, R_f = 0.26) and isolated as pale yellow oil in 77% yield. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 1.79 (s, 3H), 2.36 (br s, 1H), 3.56 (d, *J* = 12.8 Hz, 2H), 3.65 (d, *J* = 16.0 Hz, 2H), 6.94-6.97 (dd, *J* = 7.8, 1.8 Hz, 2H),7.17-7.27 (m, 4H), 7.30-7.37 (m, 5H), 7.39-7.44 (m, 2H), 7.48-7.51 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 21.67, 43.59, 47.44, 69.86, 126.77, 126.88, 127.12, 127.93, 128.25, 128.40, 128.50, 128.98, 129.54, 134.73, 140.16, 144.41, 208.11. MS (EI, 70 eV): m/z (%) = 210.1 $[M-C_8H_7O]^+$ (100), 105.0 (11), 91.1 (58), 77.1 (4), 65.1 (4). HRMS (APCI, MeOH) calcd. for $C_{23}H_{24}ON^+$ $[M+H]^+$: 330.18579, found: 330.18550. IR (NaCl): ν [cm^{-1}] = 3336, 3086, 3062, 3028, 2984, 2848, 1952, 1881, 1809, 1716, 1602, 1584. 1495, 1453, 1447, 1373, 1310, 1207, 1156, 1075, 1029, 1001, 916, 844, 761, 724, 698.



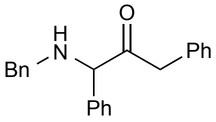
6b

2-(benzylamino)-1,2-diphenylpropan-1-one. Synthesized according to the general procedure for the imine-nitrile coupling. After extraction, the product was purified by flash chromatography (CH_2Cl_2,/ethyl acetate = 40:1, R_f = 0.29) and isolated as pale yellow powder in 66% yield. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 1.78 (s, 3H), 2.32 (br s, 1H), 3.56 (d, *J* = 12.0 Hz, 2H), 7.13-7.15 (m, 2H), 7.19-7.34 (m, 6H), 7.37-7.44 (m, 3H), 7.51-7.54 (m, 2H), 7.58-7.61 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 25.07, 47.70, 69.17, 126.01, 127.12, 127.73, 128.29, 128.42, 128.48, 129.08, 129.39, 132.08, 136.43, 140.46, 143.50, 202.93. MS (EI, 70 eV): m/z (%) = 210.1 $[M-C_8H_7O]^+$ (100), 105.0 (5), 91.1 (43), 77.1 (3), 65.1 (3). HRMS (APCI, MeOH) calcd. for $C_{22}H_{22}ON^+$ $[M+H]^+$: 316.17014, found: 316.17090. IR (NaCl): ν [cm^{-1}] = 3336, 3062, 3027, 2988, 2936, 2843, 1958, 1678, 1597, 1577, 1495, 1446, 1371, 1234, 1181, 1076, 1028, 1002, 985, 964, 848, 760, 714, 700.



6c

2-(benzylamino)-2-phenylhexan-3-one. Synthesized according to the general procedure for the imine-nitrile coupling. After extraction, the product was purified by flash chromatography (CH_2Cl_2,/ethyl acetate = 40:1, R_f = 0.21) and isolated as a colorless oil in 47% yield. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 0.75 (t, *J* = 7.6 Hz, 3H), 1.42-1.58 (m, 2H), 1.74 (s, 3H), 2.20-2.28 (dddd, *J* = 6.8, 6.8, 6.8, 6.4 Hz, 1H), 2.31-2.39 (dddd, *J* = 6.8, 6.8, 6.4, 6.4 Hz, 1H), 2.42 (br s, 1H), 3.45-3.56 (d, *J* = 12.6 Hz, 2H), 7.22-7.26 (m, 1H), 7.28-7.40 (m, 7H), 7.43-7.46 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 13.74, 17.70, 21.51, 38.95, 47.33, 69.30, 126.82, 127.04, 127.65, 128.27, 128.48, 128.80, 140.85, 141.75, 211.07. MS (EI, 70 eV): m/z (%) = 210.1 $[M-C_8H_7O]^+$ (100),104.1 (3), 91.1 (69), 65.2 (3). HRMS (APCI, MeOH) calcd. for $C_{19}H_{24}ON^+$ $[M+H]^+$: 282.18579, found: 282.18560. IR (NaCl): ν [cm^{-1}] = 3339, 3086, 3062, 3028, 2964, 2933, 2874, 1951, 1710, 1600, 1494, 1452, 1447, 1373, 1264, 1117, 1073, 1028, 896, 761, 735, 700.



6d

1-(benzylamino)-1,3-diphenylpropan-2-one. Synthesized according to the general procedure for the imine-nitrile coupling. After extraction, the product was purified by flash chromatography (CH_2Cl_2,/ethyl acetate = 40:1, R_f = 0.21) and isolated as yellow powder in 61% yield. ^1H NMR (400.1 MHz, $CDCl_3$): δ = 2.61 (br s, 1H), 3.56-3.66 (m, 4H), 4.49 (s 1H), 6.99-7.01 (m, 2H), 7.21-7.32 (m, 10H), 7.35-7.41 (m 3H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 46.80, 51.03, 70.67, 127.05, 127.15, 127.15, 128.36, 128.46, 128.50, 128.67, 129.19, 129.57, 133.88, 137.70, 139.80, 206.27. MS (EI, 70 eV): m/z (%) = 196.1 $[M-C_8H_7O]^+$ (100), 165.1 (2), 120.0 (3), 105.0 (4), 91.0 (75). HRMS (APCI, MeOH) calcd. for $C_{22}H_{22}ON^+$ $[M+H]^+$: 316.17014, found: 316.16980. IR (NaCl): ν [cm^{-1}] = 3086, 3062, 3029, 2920, 1953, 1718, 1645, 1602, 1539, 1495, 1453, 1311, 1074, 1029, 1002, 754, 732, 698.

X-ray Analysis of Compound 3a

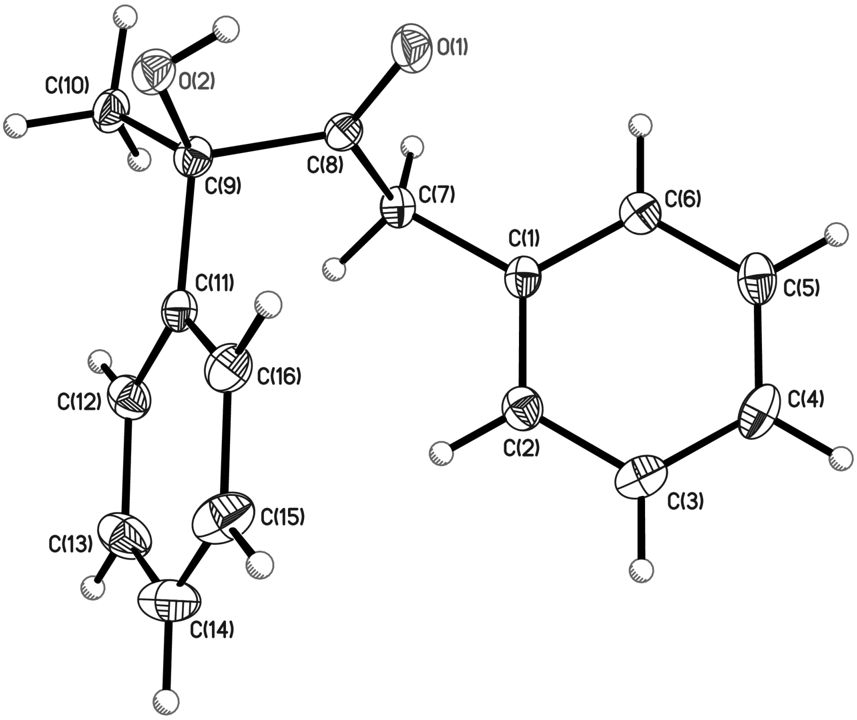


Figure S1. Molecular structure of compound **3a**. Anisotropic displacement parameters are depicted at the 50 % probability level.

Crystallographic data for the structure reported in this paper has been deposited with the Cambridge Crystallographic Data Centre (**CCDC 948380**). Copies of the data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

The data for **3a** was collected from shock-cooled crystals at 100 K on a Bruker smart APEX II with INCOATEC mirror optics as radiation monochromator. The diffractometer was equipped with a low-temperature device and used MoK$_\alpha$ radiation, λ = 0.71073 Å. The data of **3a** was integrated with SAINT,[8] and an empirical absorption correction (SADABS) was applied.[9] The structure was solved by direct methods (SHELXT-2013) [10] and refined by full-matrix least-squares methods against F^2 (SHELXL-2013).[10] All non-hydrogen atoms were refined with anisotropic displacement parameters. The hydrogen atoms were refined isotropically on calculated positions using a riding model with their U_{iso} values constrained to 1.5 times the U_{eq} of their pivot atoms for terminal sp^3 carbon atoms and 1.2 times for all other carbon atoms. The hydrogen atom H1 at O2 was found via difference Fourier analysis and was allowed to refine only with a distance restraint set to 0.84 Å. The U_{iso} value of H1 was also constrained to 1.5 times of its adjacent carbon atom.

Table S3. Crystal data and structure refinement for JS_III_132, **3a**.

CCDC number	948380	
Empirical formula	$C_{16}H_{16}O_2$	
Formula weight	240.29	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	*Pc*	
Unit cell dimensions	a = 6.4499(11) Å	α= 90°.
	b = 13.834(2) Å	β= 90.240(3)°.
	c = 7.0464(12) Å	γ = 90°.
Volume	628.74(18) $Å^3$	
Z	2	
Density (calculated)	1.269 Mg/m^3	
Absorption coefficient	0.082 mm^{-1}	
F(000)	256	
Crystal size	0.556 x 0.328 x 0.173 mm^3	
Theta range for data collection	2.945 to 27.150°.	
Index ranges	-8<=h<=8, -17<=k<=17, -9<=l<=9	
Reflections collected	19964	
Independent reflections	2806 [R(int) = 0.0354]	
Completeness to theta = 25.242°	99.9 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.7455 and 0.6820	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2806 / 3 / 167	
Goodness-of-fit on F^2	1.058	
Final R indices [$I > 2$sigma(I)]	$R1$ = 0.0308, w$R2$ = 0.0810	
R indices (all data)	$R1$ = 0.0318, w$R2$ = 0.0817	
Absolute structure parameter	-0.1(3)	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.254 and -0.173 eÅ^{-3}	

Computational Details

All structures were fully optimized by using Density Functional Theory (DFT) with the BP86 functional.[11] Open-shell systems were treated with the unrestricted formalism (UBP86). Structure optimizations were carried out with the def2-SV(P) basis set.[12] Thermodynamic corrections were calculated at the same level of theory from a harmonic vibrational analysis. Transition states and minimum structures were identified by the presence or absence of one imaginary frequency. In order to obtain accurate energies, single point energy calculations were calculated using the PBE0 (PBE1PBE) functional[13] and the larger triple-ζ def2-TZVPP basis set.[14] Before, we tested the BP86, B3LYP,[15] PBE0 and M06[16] functionals in benchmark calculations against CCSD(T)/aug-cc-pVTZ and found the PBE0 functional to give the best results. Solvation effects were estimated using the SMD model[17] with the default settings for tetrahydrofuran (Σ = 7.4257) as solvent and using the def2-SV(P) basis set for H, C, N, O, Cl and a Stuttgart-Dresden core potential (SDD) for Ti and Zn.[18] The combination of the BP86 functional with the def2-SVP basis set was previously found to give reliable results for the structure optimization of titanium complexes.[19] We tested the def2-SV(P), def2-SVP,[12] and def2-TZVP[20] basis sets and found that the def2-SV(P) basis set provided sufficient results (Table S4). The Gibbs free Energy for the sublimation of metallic zinc was calculated for T = 298.15K to be ΔG = +22.66 kcal/mol using literature values for the sublimation enthalpy and entropy.[21] This value was used to calculate the reduction step with zinc in Scheme 5.[22] All electronic structure calculations were carried out using the Gaussian 09 suite of programs with the grid=ultrafine option.[23] Avogadro 1.1.0 was used for visualization of the results.[24]

Table S4. Geometrical parameters of titanium complexes in the gas phase. Literature values were taken from reference 19.

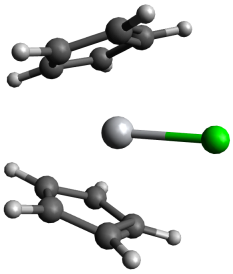
Compd.	**Symm.**	**Parameter**	**Exp. Value**[a]	**def2-SV(P)**	**def2-SVP**	**def2-TZVP**
$TiCl_4$	T_d	Ti-Cl bond length	216.9 pm	218.6 pm	217.7 pm	218.4 pm
$TiMeCl_3$	C_{3V}	Ti-C bond length	204.7 pm	204.2 pm	204.0 pm	205.0 pm
		Ti-Cl bond length	218.5 pm	219.7 pm	218.7 pm	219.4 pm
		Cl-Ti-C angle	105.6 deg	105.1 deg	105.1 deg	105.5 deg
$TiMe_2Cl_2$	C_{2V}	Ti-C bond length	205.8 pm	205.2 pm	205.0 pm	205.9 pm
		Ti-Cl bond length	219.6 pm	220.9 pm	219.8 pm	220.6 pm
		C-Ti-C angle	102.8 deg	104.9 deg	104.9 deg	105.4 deg
		Cl-Ti-Cl angle	117.3 deg	117.7 deg	117.7 deg	117.1 deg

[a] Determined by gas phase electron diffraction. See ref. 19.

Optimized Structures and Data of the Catalytic Cycle in Scheme 5

All energy values are given in Hartree if not specified otherwise.

A:

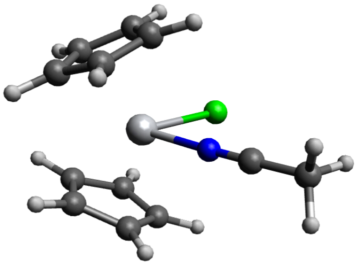


Cartesian Coordinates:

C	-2.28580	0.29307	-0.71541
C	-1.78294	-0.96768	-1.15965
C	-1.49238	-1.74906	0.00556
C	-1.78203	-0.95816	1.16456
H	-1.67808	-1.29446	-2.20429
C	-2.28542	0.29884	0.71035
H	-2.56313	1.14160	-1.35624
H	-2.56234	1.15254	1.34440
Ti	0.00005	0.09294	-0.00206
C	1.78930	-0.94445	-1.16807
C	2.28933	0.30772	-0.69658
C	1.49331	-1.74836	-0.01971
C	1.77681	-0.97994	1.15583
C	2.28155	0.28587	0.72901
H	1.14107	-2.78749	-0.03787
H	1.69124	-1.25137	-2.21936
H	2.56954	1.16859	-1.31932
H	1.66528	-1.31831	2.19609
H	2.55477	1.12725	1.38101
Cl	-0.00076	2.41498	0.00022
H	-1.13963	-2.78817	0.01007
H	-1.67708	-1.27666	2.21173

```
Thermal correction to Gibbs Free Energy=          0.124705
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(UB-P86) =  -905.377407577
SCF Done:  E(UB-P86) =  -905.396255053 (SMD, THF)

Single-point Calculation:
SCF Done:  E(UPBE1PBE) =  -1696.20503225
```

B:

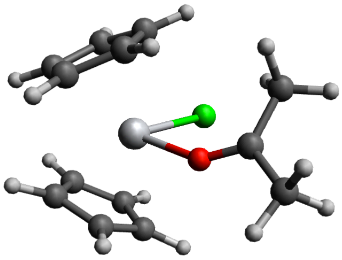


Cartesian Coordinates:

C	-1.00393	-2.24987	0.70434
C	-2.10752	-1.64025	0.04748
C	-1.73030	-1.39613	-1.31591
C	-0.38370	-1.82601	-1.49002
H	-3.08194	-1.41226	0.50292
C	0.06615	-2.35054	-0.22882
H	-0.95266	-2.51488	1.76744
H	1.06611	-2.74782	-0.00815
Ti	-0.32649	0.00152	0.02634
C	-1.42595	1.97796	0.78313
C	-0.10625	2.34758	0.36999
C	-2.13594	1.54479	-0.37291
C	-1.26189	1.64974	-1.50358
C	-0.01553	2.15794	-1.04458
H	-3.17626	1.19007	-0.39494
H	-1.79848	1.98397	1.81572
H	0.69952	2.67962	1.03700
H	-1.50868	1.39115	-2.54292
H	0.86812	2.35001	-1.66924
Cl	0.43352	-0.07611	2.32653
N	1.76311	-0.00361	-0.38640
H	-2.37373	-0.96013	-2.09211
H	0.19685	-1.78212	-2.42260
C	2.92867	-0.00758	-0.52330
C	4.37998	-0.01478	-0.65207
H	4.86187	-0.10245	0.34873
H	4.73444	0.92561	-1.13085
H	4.71332	-0.87215	-1.27905

```
Thermal correction to Gibbs Free Energy=          0.162329
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(UB-P86) =  -1038.03870107
SCF Done:  E(UB-P86) =  -1038.06462057 (SMD, THF)

Single-point Calculation:
SCF Done:  E(UPBE1PBE) =  -1828.85634335
```

C:

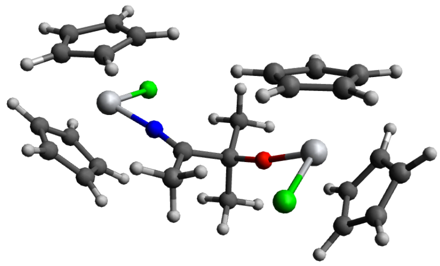


Cartesian Coordinates:

C	0.99926	-1.98009	-1.20431
C	2.20220	-1.22151	-1.14689
C	2.61429	-1.14022	0.22379
C	1.67804	-1.87073	1.00695
H	2.72480	-0.77709	-2.00516
C	0.67089	-2.37482	0.13400
H	0.41592	-2.20492	-2.10794
H	-0.21971	-2.93682	0.44491
Ti	0.48507	0.01382	0.02079
C	-0.26673	1.99900	-1.18881
C	-0.06922	2.36075	0.17353
C	0.99076	1.60920	-1.73480
C	1.97618	1.76605	-0.70764
C	1.32349	2.21343	0.47583
H	1.17082	1.27220	-2.76550
H	-1.22346	1.99140	-1.73019
H	-0.84166	2.67243	0.88681
H	3.05211	1.57080	-0.81397
H	1.79058	2.40011	1.45215
O	-1.43648	-0.59900	-0.50145
Cl	-0.30167	0.08600	2.31271
H	3.50114	-0.61508	0.60657
H	1.68758	-1.96866	2.09951
C	-2.66776	-0.37152	-0.38155
C	-3.19980	0.77136	0.44512
C	-3.64868	-1.27502	-1.09206
H	-4.34745	-0.68168	-1.72924
H	-4.28544	-1.81419	-0.34977
H	-3.11543	-2.01862	-1.71987
H	-2.54851	0.89787	1.34003
H	-4.25507	0.59911	0.75011
H	-3.17476	1.72380	-0.13947

```
Thermal correction to Gibbs Free Energy=         0.200507
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(UB-P86)  =  -1098.38947603
SCF Done:  E(UB-P86)  =  -1098.41026215 (SMD, THF)

Single-point Calculation:
SCF Done:  E(UPBE1PBE) =  -1889.21488502
```

E:



Cartesian Coordinates:

Ti	-3.53006	0.08897	-0.03024
Ti	3.43232	0.09878	0.05799
N	-1.70166	-0.27224	0.27771
O	1.79960	-0.67517	-0.12462
C	0.49691	-1.09666	-0.46773
C	-0.51751	-0.57727	0.61678
C	-0.04109	-0.57559	2.05797
H	0.93828	-0.05990	2.17476
H	0.13536	-1.62260	2.40114
H	-0.80619	-0.11405	2.71689
Cl	-3.54869	-0.47993	-2.37880
C	0.44640	-2.64518	-0.44062
H	1.12603	-3.06299	-1.21633
H	-0.58542	-3.00053	-0.65497
H	0.76792	-3.03804	0.54845
C	0.12225	-0.57223	-1.86402
H	0.16621	0.53742	-1.89283
H	-0.91526	-0.86624	-2.13683
H	0.83607	-0.97378	-2.61771
C	-2.84899	2.19876	0.92595
C	-2.61937	2.29078	-0.48683
C	-4.24998	2.07535	1.13155
C	-4.88972	2.08652	-0.15345
C	-3.87997	2.24329	-1.14374
H	-5.96954	2.01273	-0.34408
H	-4.03865	2.25385	-2.22844
H	-1.64302	2.36815	-0.98249
H	-2.08001	2.21460	1.70995
H	-4.75553	2.00213	2.10377
C	-5.58734	-0.74260	0.98249
C	-4.53480	-0.87276	1.94826
C	-3.61153	-1.84150	1.45709
C	-4.05651	-2.26802	0.17445
C	-5.28616	-1.59282	-0.11354
H	-3.53980	-2.96558	-0.49725
H	-5.86501	-1.68799	-1.04093
H	-6.46922	-0.09335	1.07292
H	-4.46944	-0.35646	2.91601
H	-2.69908	-2.17257	1.96989
C	4.43702	-2.14391	-0.02872
C	4.06062	-1.80968	-1.35710
C	4.83316	-0.68478	-1.76736
C	5.74085	-0.36212	-0.70128
C	5.48763	-1.25468	0.36869
H	6.49254	0.43889	-0.70518
H	5.98200	-1.24585	1.34821
H	3.98179	-2.91919	0.60191
H	3.26850	-2.28930	-1.94697
H	4.77892	-0.19304	-2.74888
C	4.17654	2.16246	-1.05258
C	4.26908	2.39304	0.34587

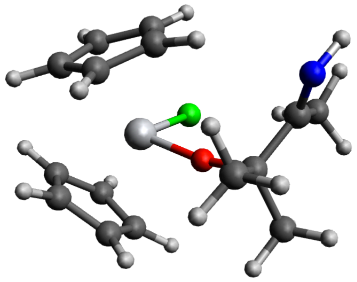
C	2.93676	2.38776	0.87818
C	2.03730	2.13400	-0.18361
C	2.80110	1.94661	-1.37883
H	0.94868	2.02341	-0.08910
H	2.39988	1.72142	-2.37711
H	5.01385	2.14174	-1.76227
H	5.18940	2.55198	0.92523
H	2.67289	2.51934	1.93459
Cl	3.57617	-0.12126	2.42427

Thermal correction to Gibbs Free Energy= 0.393562
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done: E(RB-P86) = -2136.47898684
SCF Done: E(RB-P86) = -2136.51211231 (SMD, THF)

Single-point Calculation:
SCF Done: E(RPBE1PBE) = -3718.10279406

F:



Cartesian Coordinates:

Ti	0.83630	0.05164	0.03399
N	-3.66085	1.17126	-0.46675
O	-0.84845	-0.58910	-0.17822
C	-2.21923	-0.79477	-0.48726
C	-3.02832	0.31011	0.25046
C	-2.96500	0.30323	1.76344
H	-1.90585	0.27716	2.11516
H	-3.47168	-0.59562	2.18411
H	-3.46332	1.20640	2.18032
C	-2.61777	-2.19596	0.03402
H	-2.08116	-2.98036	-0.54445
H	-3.71255	-2.36547	-0.08076
H	-2.34644	-2.31421	1.10470
C	-2.41764	-0.72403	-2.01111
H	-2.15340	0.27763	-2.40541
H	-3.48027	-0.91241	-2.27478
H	-1.78069	-1.49282	-2.50224
C	1.50134	-2.27994	0.51049
C	1.35614	-2.16770	-0.89812
C	2.33633	-1.24773	-1.37284
C	3.13061	-0.83249	-0.25020
C	2.60740	-1.46211	0.90650
H	3.98758	-0.14581	-0.27427
H	2.96272	-1.32057	1.93485
H	0.85461	-2.85321	1.18806
H	0.58020	-2.64788	-1.50929
H	2.48812	-0.95474	-2.42134
C	2.02932	1.75687	-1.26512
C	1.84556	2.28003	0.04092

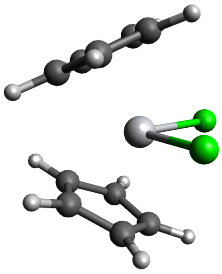
C	0.43642	2.47543	0.23949
C	-0.23897	2.06011	-0.93234
C	0.73784	1.56198	-1.85139
H	-1.32847	2.05307	-1.07810
H	0.53439	1.15435	-2.85216
H	2.99132	1.52482	-1.74036
H	2.63266	2.49673	0.77655
H	-0.03080	2.84605	1.16028
Cl	0.70083	0.35334	2.39850
H	-4.14011	1.85985	0.14826

Thermal correction to Gibbs Free Energy= 0.257898
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done: E(RB-P86) = -1231.66484783
SCF Done: E(RB-P86) = -1231.68388923 (SMD, THF)

Single-point Calculation:
SCF Done: E(RPBE1PBE) = -2022.48420136

G:



Cartesian Coordinates:

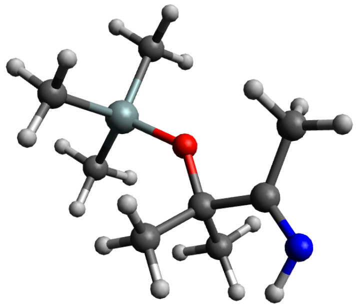
C	-2.18394	0.22719	1.06919
C	-1.54994	1.49974	0.95655
C	-1.44947	1.81635	-0.43980
C	-1.97480	0.72125	-1.17596
H	-1.23822	2.13772	1.79529
C	-2.42175	-0.26723	-0.24063
H	-2.38861	-0.30673	2.00495
H	-2.83009	-1.25411	-0.49451
Ti	0.00000	-0.06263	-0.00000
C	1.97456	0.72188	1.17590
C	2.42173	-0.26709	0.24118
C	1.44940	1.81659	0.43904
C	1.55011	1.49922	-0.95712
C	2.18416	0.22661	-1.06895
H	1.04403	2.74483	0.86371
H	1.99876	0.62801	2.26964
H	2.83004	-1.25382	0.49567
H	1.23851	2.13672	-1.79625
H	2.38901	-0.30782	-2.00437
Cl	0.06101	-1.60236	1.75320
Cl	-0.06103	-1.60264	-1.75295
H	-1.04416	2.74434	-0.86506
H	-1.99921	0.62679	-2.26965

Thermal correction to Gibbs Free Energy= 0.126614
Number of imaginary frequencies = 0

Solvation Energy Calculation:

```
SCF Done:  E(RB-P86) =  -1365.53428575
SCF Done:  E(RB-P86) =  -1365.55404693 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -2156.31240222
```

H:

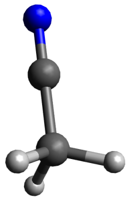


Cartesian Coordinates:

Si	-1.71617	0.12539	-0.00275
C	-2.17144	0.21936	1.83824
H	-1.74813	1.13721	2.30660
H	-1.80412	-0.65790	2.41664
H	-3.27922	0.26002	1.95970
C	-2.47072	1.59537	-0.91999
H	-3.58100	1.60087	-0.82523
H	-2.21896	1.56389	-2.00424
H	-2.08886	2.55875	-0.51233
C	-2.36472	-1.50145	-0.73958
H	-3.47519	-1.54240	-0.64371
H	-1.95733	-2.40042	-0.22337
H	-2.11861	-1.58633	-1.82240
O	-0.04717	0.33233	-0.23784
C	1.11567	-0.47532	-0.05163
C	1.27215	-1.41745	-1.26711
H	2.21330	-2.00800	-1.20704
H	1.29224	-0.82489	-2.20783
H	0.42026	-2.13115	-1.31814
C	1.03377	-1.27623	1.26655
H	0.89020	-0.59237	2.13160
H	1.96490	-1.85967	1.44033
H	0.18504	-1.99672	1.23703
C	2.35102	0.47867	0.01362
N	3.56518	0.07213	0.14223
C	2.08725	1.96212	-0.08266
H	1.41714	2.30142	0.73900
H	1.56008	2.21088	-1.03057
H	3.05411	2.50435	-0.02984
H	3.60372	-0.96695	0.19471

```
Thermal correction to Gibbs Free Energy=         0.206887
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -735.367696658
SCF Done:  E(RB-P86) =  -735.375998849 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -735.347360685
```

Acetonitrile, MeCN:

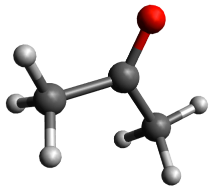


Cartesian Coordinates:

N	0.00000	0.00000	1.45045
C	0.00000	0.00000	0.27897
C	0.00000	0.00000	-1.18387
H	0.00000	1.04159	-1.57459
H	-0.90204	-0.52079	-1.57459
H	0.90204	-0.52079	-1.57459

```
Thermal correction to Gibbs Free Energy=         0.020755
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -132.645052836
SCF Done:  E(RB-P86) =  -132.652324207 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -132.640211298
```

Acetone, $OCMe_2$:



Cartesian Coordinates:

C	-1.29695	-0.61852	0.00200
C	-0.00001	0.18879	0.00000
H	-1.30611	-1.36343	0.83105
H	-1.39072	-1.19590	-0.94773
H	-2.16539	0.06518	0.10020
C	1.29698	-0.61852	-0.00201
H	1.39102	-1.19527	0.94807
H	2.16536	0.06515	-0.10094
H	1.30579	-1.36394	-0.83060
O	-0.00001	1.40972	0.00000

```
Thermal correction to Gibbs Free Energy=         0.052002
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -192.995498719
SCF Done:  E(RB-P86) =  -193.000144374 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -193.002201334
```

Zn:

CODATA Key Values for Thermodynamics (298.15 K):

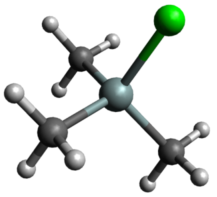
State	**D_fH^o [kJ•mol^{-1}]**	**S^o [J•K^{-1}•mol^{-1}]**	**calcd $\Delta G_f^{298.15}$ [kJ•mol^{-1}]**
cr	0	41.63±15	–12.41
g	130.40±0.40	160.990±0.004	82.42

$\Delta G_{sublim} = \Delta G_g - \Delta G_{cr}$ = 22.66 kcal/mol

```
Thermal correction to Gibbs Free Energy=        -0.015877
```

```
Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -1779.14416957
```

TMSCl:



Cartesian Coordinates:

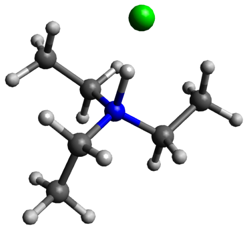
```
Si          0.00000        0.00000       -0.33760
C           0.00000        1.80362       -0.90358
H           0.89978        2.34108       -0.52824
H          -0.89978        2.34108       -0.52824
H           0.00000        1.86692       -2.01683
C           1.56198       -0.90181       -0.90358
H           1.61680       -0.93346       -2.01683
H           1.57754       -1.94977       -0.52824
H           2.47732       -0.39131       -0.52824
C          -1.56198       -0.90181       -0.90358
H          -1.61680       -0.93346       -2.01683
H          -2.47732       -0.39131       -0.52824
H          -1.57754       -1.94977       -0.52824
Cl          0.00000        0.00000        1.77711
```

```
Thermal correction to Gibbs Free Energy=         0.077262
Number of imaginary frequencies = 0
```

```
Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -869.237860696
SCF Done:  E(RB-P86) =  -869.242224501 (SMD, THF)
```

```
Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -869.169476304
```

Et$_3$N•HCl:

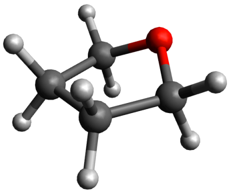


Cartesian Coordinates:

C	-1.18287	-0.35962	-1.08394
C	-0.59963	-0.29627	1.36479
N	-0.32649	0.22152	-0.00859
H	0.17440	0.15577	2.01945
C	-0.50501	-1.82021	1.47091
H	-1.59004	0.08381	1.71523
C	-0.24438	1.71214	-0.06918
H	-0.13124	1.96534	-1.14620
C	0.94143	2.29235	0.70942
H	-1.20952	2.15442	0.27719
H	-0.98038	-1.45146	-1.09522
H	-0.77161	0.03052	-2.04073
C	-2.68412	-0.07981	-0.97782
H	1.87611	1.75428	0.43439
H	0.80418	2.23642	1.81157
H	1.05765	3.36693	0.44668
H	0.45401	-2.16665	1.02445
H	-1.34954	-2.34272	0.96993
H	-0.52224	-2.11346	2.54361
H	-3.12929	-0.50756	-0.05189
H	-3.20550	-0.54949	-1.84123
H	-2.91582	1.00821	-1.00376
H	0.84545	-0.21285	-0.31583
Cl	2.26625	-0.80316	-0.71604

```
Thermal correction to Gibbs Free Energy=         0.172107
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86)  =  -752.874405029
SCF Done:  E(RB-P86)  =  -752.893275272 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE)  =  -752.843106109
```

THF:



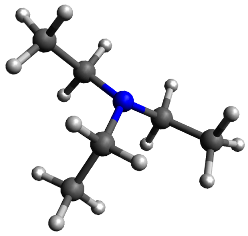
Cartesian Coordinates:

C	0.09262	1.01805	0.77934
C	0.09262	-0.49353	1.12910
O	-0.47101	-1.14935	0.00000
C	0.09262	-0.49353	-1.12910
C	0.09262	1.01805	-0.77934
H	0.97133	1.54452	1.21124

H	-0.82027	1.51372	1.17442
H	-0.51996	-0.75528	2.01851
H	1.14149	-0.85271	1.30813
H	-0.51996	-0.75528	-2.01851
H	1.14149	-0.85271	-1.30813
H	-0.82027	1.51372	-1.17442
H	0.97133	1.54452	-1.21124

```
Thermal correction to Gibbs Free Energy=         0.084589
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -232.256734788
SCF Done:  E(RB-P86) =  -232.262345022 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -232.265041681
```

Et_3N:

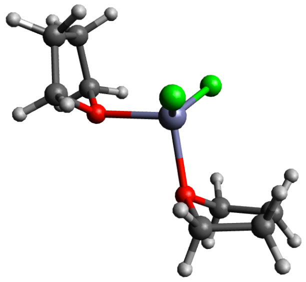


Cartesian Coordinates:

C	0.70530	0.20520	2.50068
C	0.70530	-0.62992	1.21372
H	1.10854	-0.39900	3.34407
H	-0.31354	0.54047	2.79772
H	1.34513	1.10826	2.37896
N	0.40822	0.13359	0.00000
H	0.02108	-1.51709	1.35009
H	1.72425	-1.06144	1.07680
C	0.70530	-0.62992	-1.21372
C	0.70530	0.20520	-2.50068
H	0.02108	-1.51709	-1.35009
H	1.72425	-1.06144	-1.07680
H	-0.31354	0.54047	-2.79772
H	1.10854	-0.39900	-3.34407
H	1.34513	1.10826	-2.37896
C	-0.88515	0.82565	0.00000
C	-2.15616	-0.05240	0.00000
H	-0.90923	1.50245	-0.88353
H	-0.90923	1.50245	0.88353
H	-2.21166	-0.70779	-0.89866
H	-3.06601	0.59021	0.00000
H	-2.21166	-0.70779	0.89866

```
Thermal correction to Gibbs Free Energy=         0.164826
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -292.154208860
SCF Done:  E(RB-P86) =  -292.159691352 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -292.152791023
```

$ZnCl_2$•2THF:



Cartesian Coordinates:

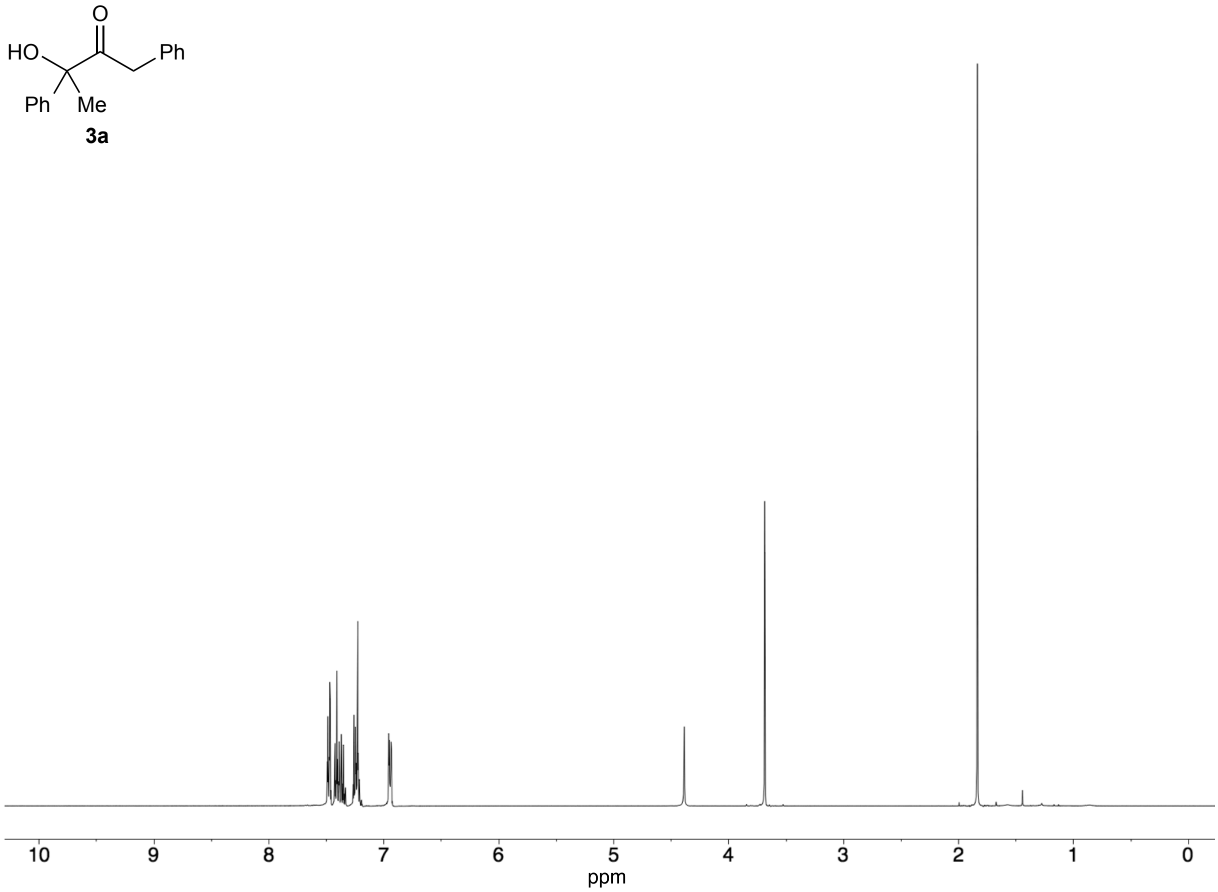
Zn	0.00000	0.00000	0.31509
Cl	0.00000	2.03489	1.19013
Cl	0.00000	-2.03489	1.19013
O	-1.62155	0.00000	-1.05343
O	1.62155	0.00000	-1.05343
C	2.50203	-1.15486	-1.02094
C	3.60383	-0.78071	-0.01049
H	2.90565	-1.30407	-2.05036
H	1.88145	-2.02385	-0.72213
C	3.60383	0.78071	-0.01049
H	4.58598	-1.21301	-0.29827
H	3.33849	-1.17371	0.99385
C	2.50203	1.15486	-1.02094
H	4.58598	1.21301	-0.29827
H	3.33849	1.17371	0.99385
H	2.90565	1.30407	-2.05036
H	1.88145	2.02385	-0.72213
C	-2.50203	1.15486	-1.02094
C	-3.60383	0.78071	-0.01049
H	-2.90565	1.30407	-2.05036
H	-1.88145	2.02385	-0.72213
C	-3.60383	-0.78071	-0.01049
H	-4.58598	1.21301	-0.29827
H	-3.33849	1.17371	0.99385
C	-2.50203	-1.15486	-1.02094
H	-4.58598	-1.21301	-0.29827
H	-3.33849	-1.17371	0.99385
H	-2.90565	-1.30407	-2.05036
H	-1.88145	-2.02385	-0.72213

```
Thermal correction to Gibbs Free Energy=         0.185518
Number of imaginary frequencies = 0

Solvation Energy Calculation:
SCF Done:  E(RB-P86) =  -1612.10986864
SCF Done:  E(RB-P86) =  -1612.12857015 (SMD, THF)

Single-point Calculation:
SCF Done:  E(RPBE1PBE) =  -3163.96488343
```

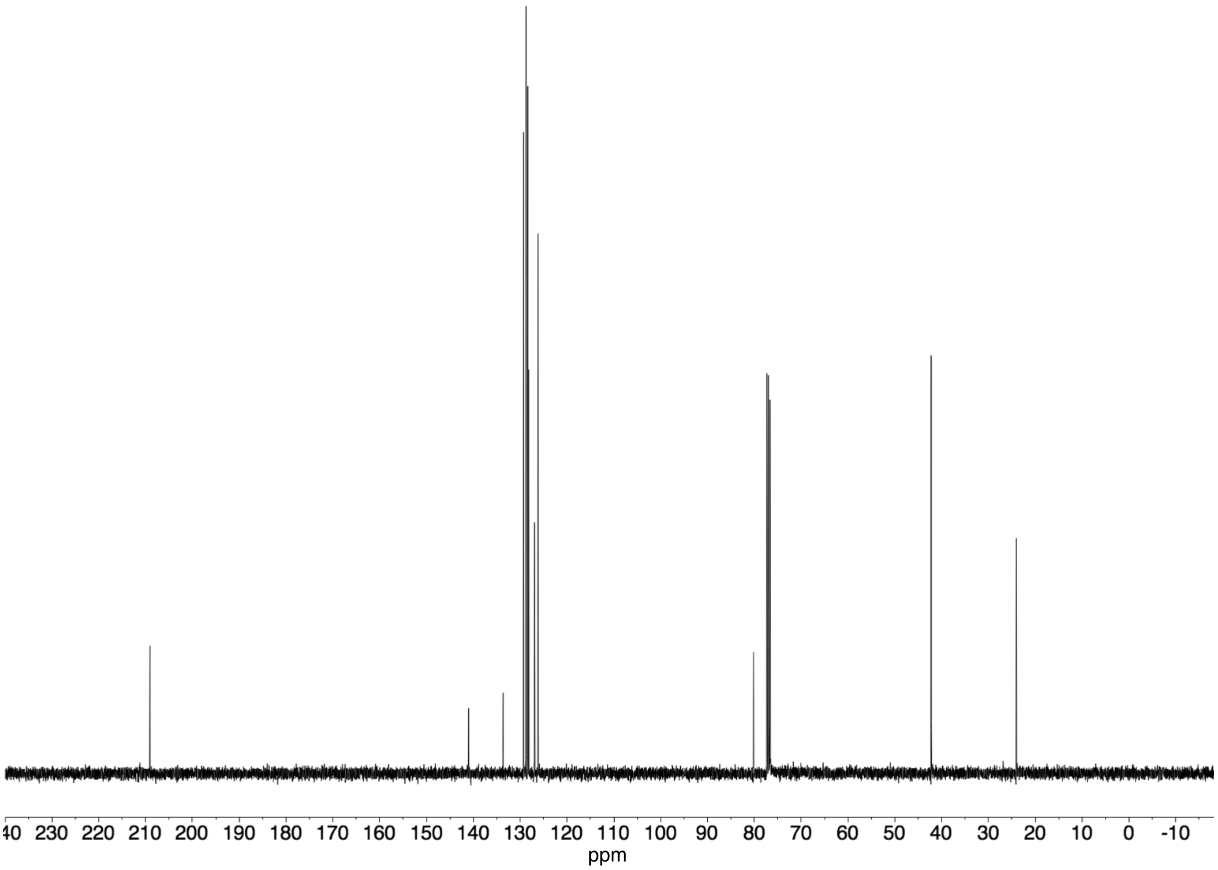
References

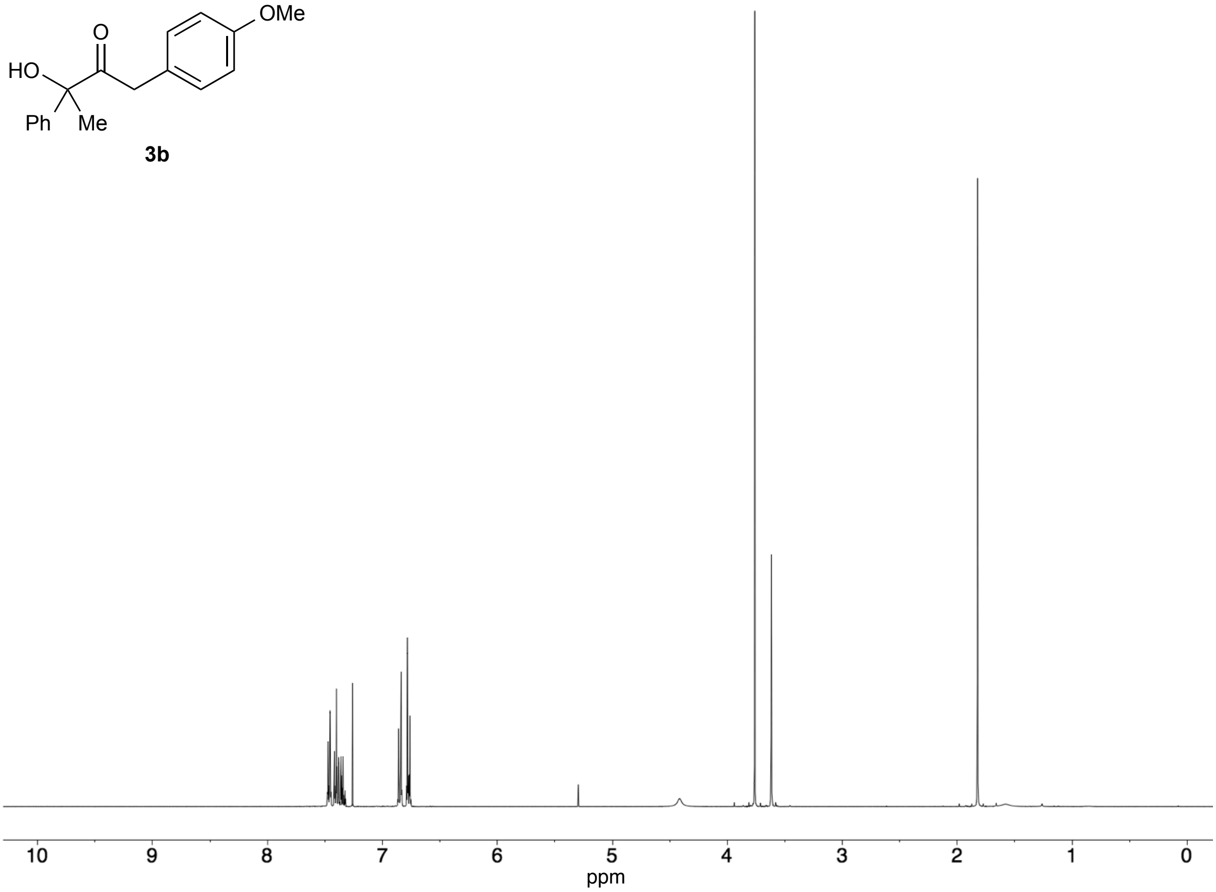
1. P. Schnider, G. Koch, R. Prétôt, G. Wang, F. M. Bohnen, C. Krüger, A. Pfaltz, *Chem. Eur. J.* **1997**, *3*, 887–892.
2. D. J. Vyas, R. Fröhlich, M. Oestreich, *Org. Lett.* **2011**, *13*, 2094–2097.
3. A. Gansäuer, S. Narayan, N. Schiffer-Ndene, H. Bluhm, J. E. Oltra, J. M. Cuerva, A. Rosales, M. Nieger, *J. Organomet. Chem.* **2006**, *691*, 2327–2331.
4. O. Ort, *Org. Synth.* **1993**, *65*, 203–210.
5. M. Paradas, A. G. Campaña, R. E. Estévez, L. Á. de Cienfuegos, T. Jiménez, R. Robles, J. M. Cuerva, J. E. Oltra, *J. Org. Chem.* **2009**, *74*, 3616–3619.
6. F. Cadoret, Y. Six, *Tetrahedron Lett.* **2007**, *48*, 5491-5495.
7. G. J. Chuang, W. Wang, E. Lee, T. Ritter, *J. Am. Chem. Soc.* **2011**, *133*, 1760-1762.
8. Bruker, SAINT V8.30C, Bruker AXS Inc., Madison (WI, USA), **2013**.
9. G. M. Sheldrick, SADABS-2012/1, Göttingen, **2012**.
10. G. M. Sheldrick, Acta Crystallogr. **2008**, *A64*, 112–122.
11. a) A. D. Becke, *J. Chem. Phys.* **1993,** *98,* 5648. b) J. P. Perdew, *Phys. Rev. B.* **1986**, *33*, 8822–8824.
12. A. Schäfer, H. Horn, R. Ahlrichs, *J. Chem. Phys.* **1992**, *97*, 2571–2577.
13. C. Adamo and V. Barone, *J. Chem. Phys.* **1999**, *110*, 6158–6169.
14. F. Weigend, R. Ahlrichs, *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297–3305.
15. a) P.J. Stephens, F.J. Devlin, C.F. Chabalowski, M.J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623-11627. b) A. D. Becke, J.Chem.Phys. **1993** *98*, 5648-5652. c) C. Lee, W. Yang, R. G. Parr, *Phys. Rev. B* **1988**, *37*, 785-789. d) S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* **1980**, *58*, 1200-1211.
16. Y. Zhao, D. G. Truhlar, *Theor. Chem. Acc.* **2008**, *120*, 215-241.
17. A. V. Marenich, C. J. Cramer, D. G. Truhlar, *J. Phys. Chem. B* **2009**, *113*, 6378–6396.
18. M. Dolg, U. Wedig, H. Stoll, H. Preuss, *J. Chem. Phys.* **1987**, *86*, 866.
19. M. Bühl, H. Kabrede, *J. Chem. Theory Comput.* **2006**, *2*, 1282–1290.
20. A. Schäfer, C. Huber, R. Ahlrichs, *J. Chem. Phys.* **1994**, *100*, 5829–5835.
21. http://www.codata.org/resources/databases/key1.html
22. Y. Zhang, J. R. G. Evans, S. Yang, *J. Chem. Eng. Data.* **2011**, *56*, 328–337.
23. Gaussian 09, Revision B.01, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, Gaussian, Inc., Wallingford CT, **2010**.
24. a) Avogadro: an open-source molecular builder and visualization tool. Version 1.1.0. http://avogadro.openmolecules.net/. b) M. D. Hanwell, D. E. Curtis, D. C. Lonie, T. Vandermeersch, E. Zurek, G. R. Hutchison, *J. Cheminform.* **2012**, *4*, 17.

NMR Spectra of New Compounds


O
HO
Ph
Ph
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

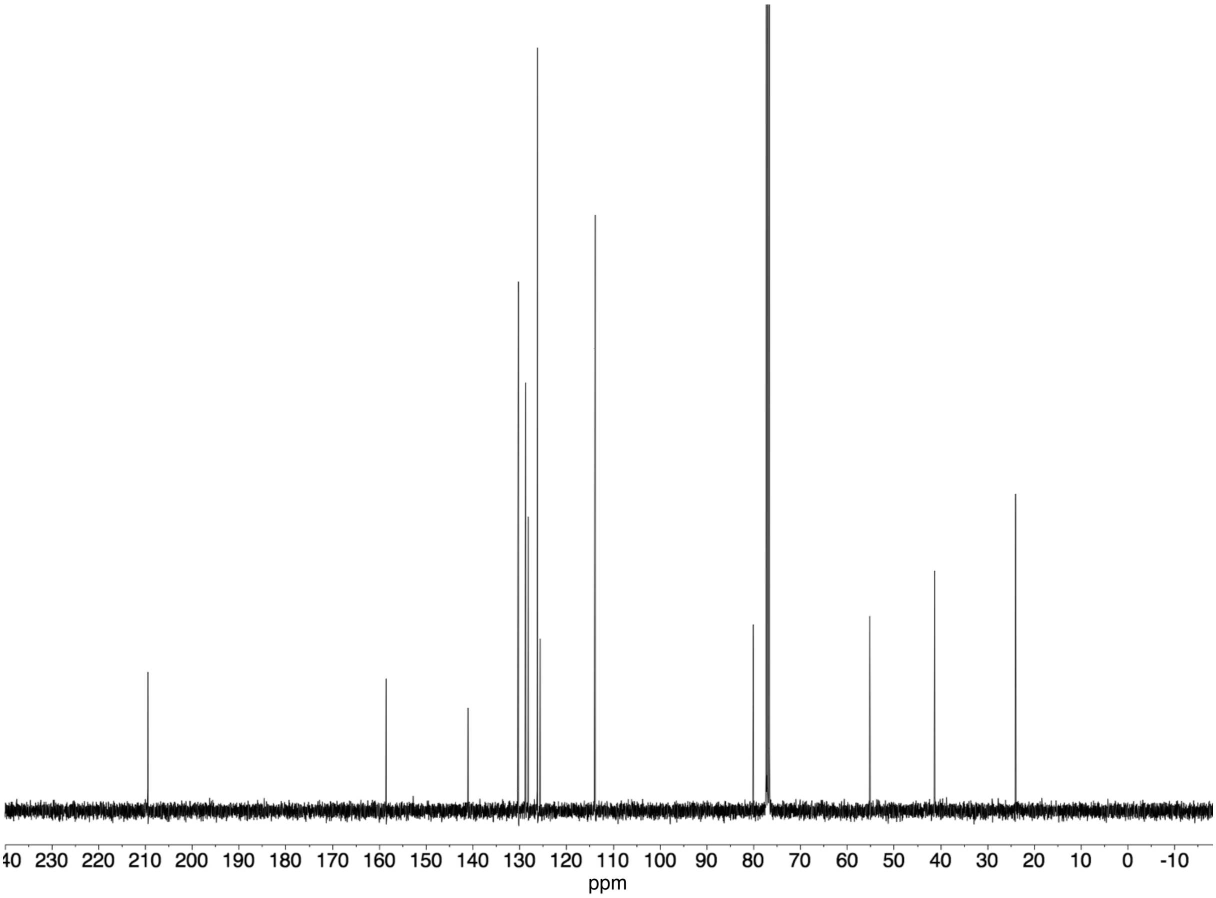
3a


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

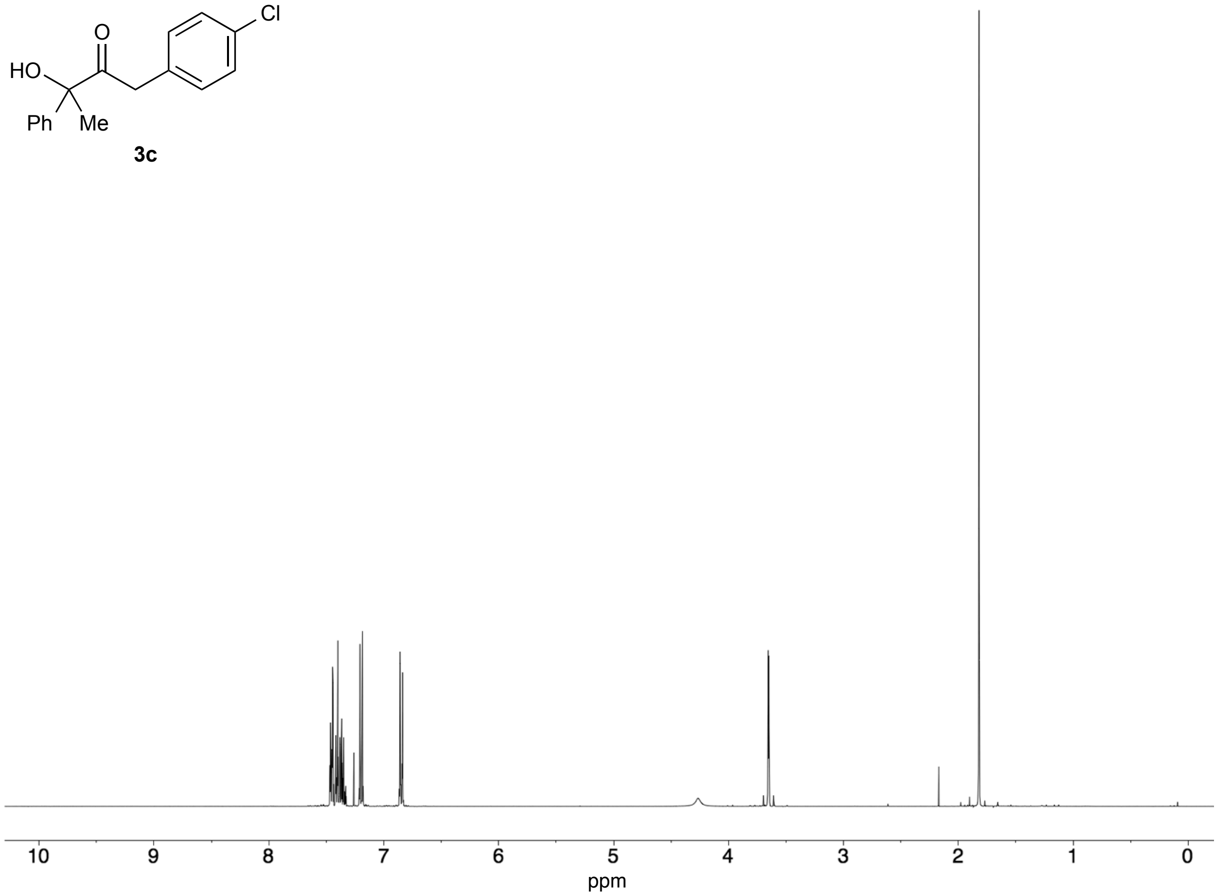


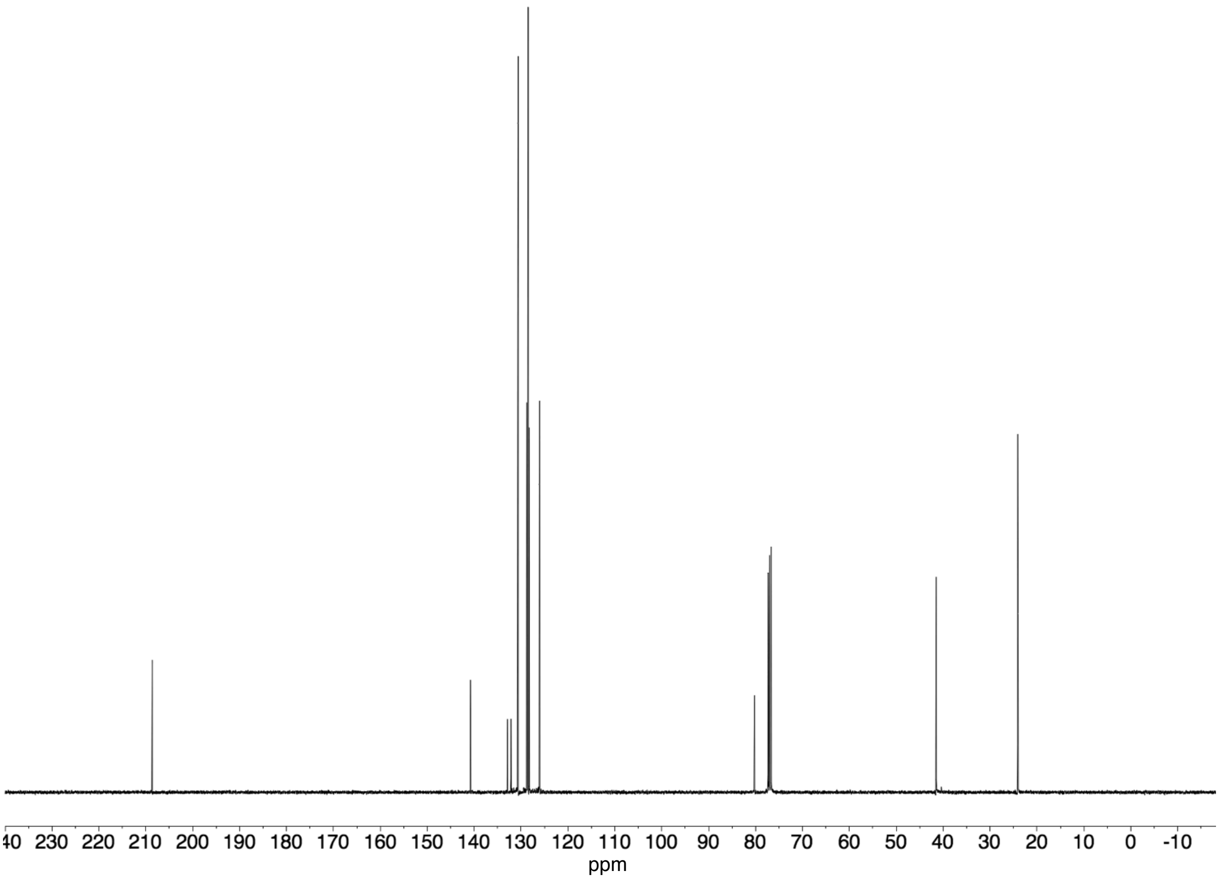
3b

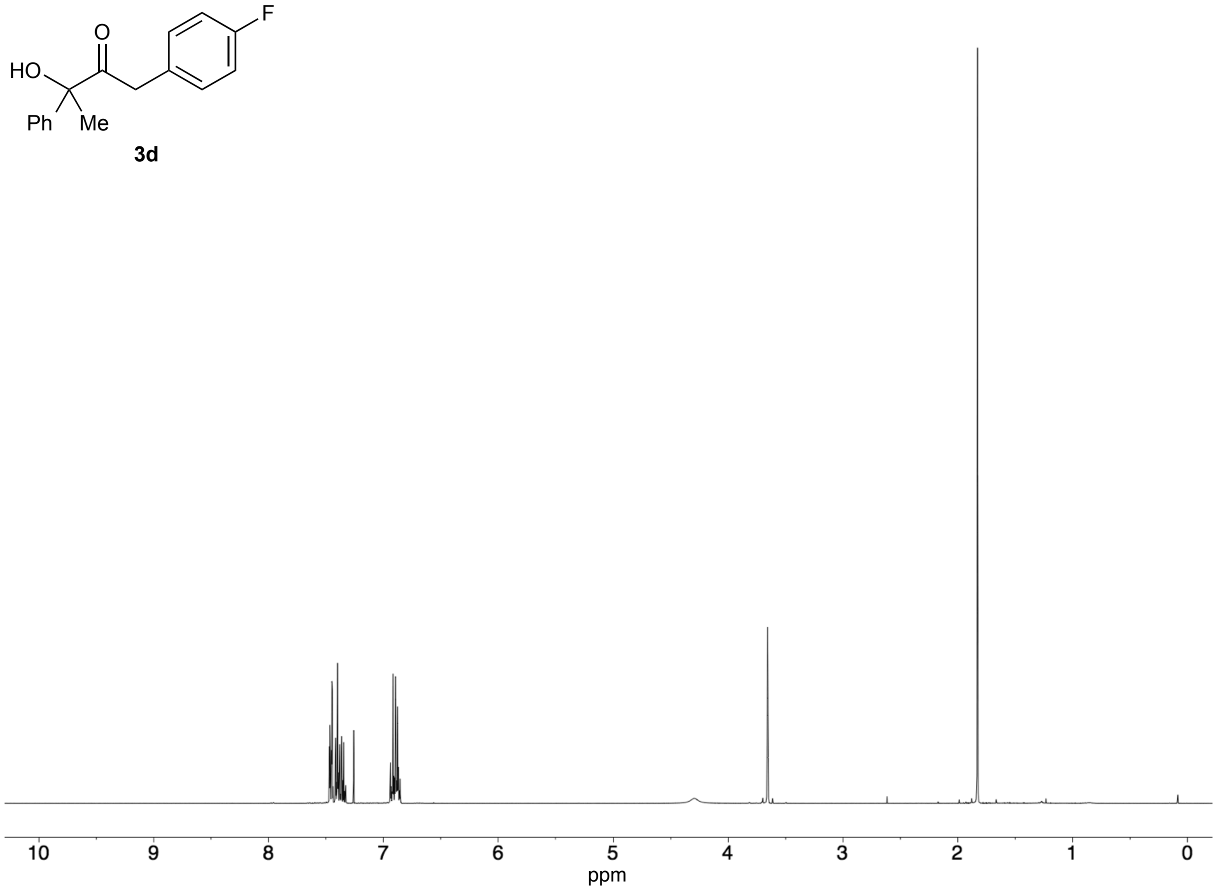
OMe
O
HO
Ph
Me
10
9
8
7
6
5
4
3
2
1
0
ppm



40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

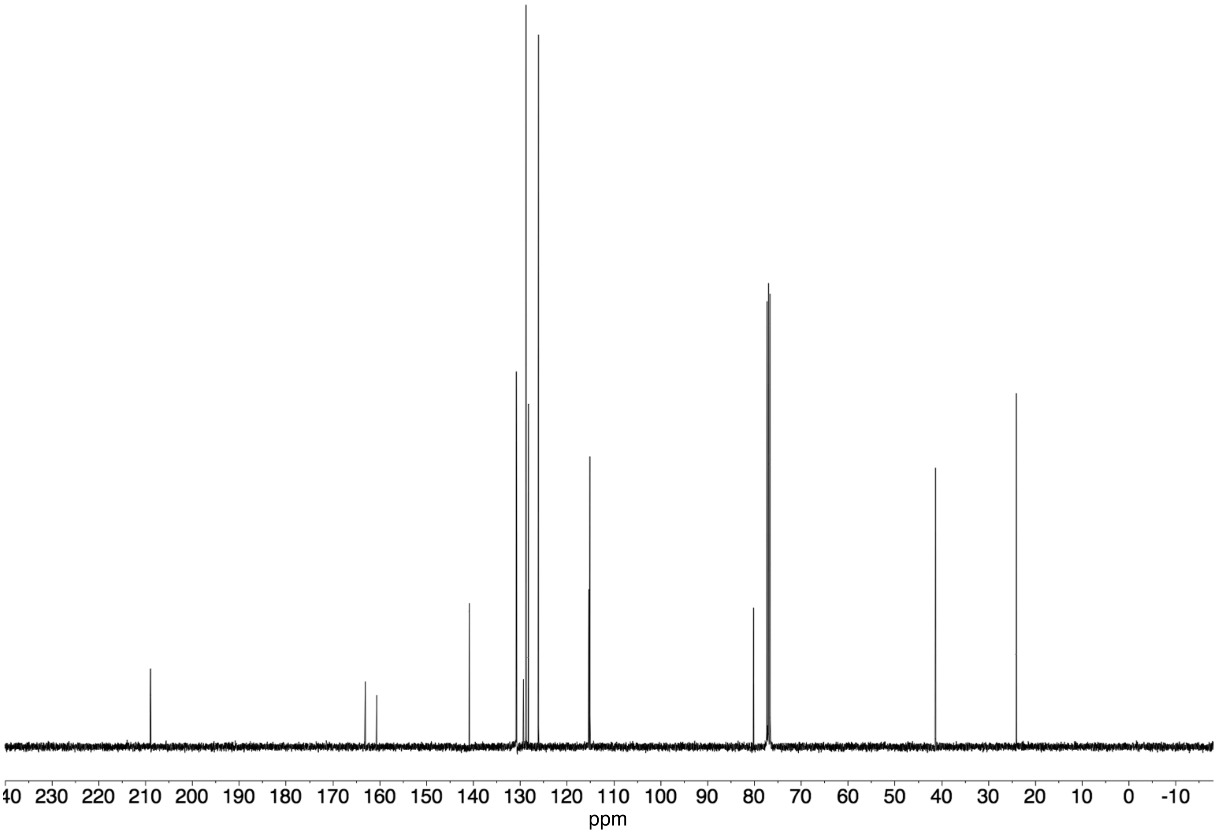

Cl
O
HO
Ph
Me
3c
10
9
8
7
6
5
4
3
2
1
0
ppm


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


O
F
HO
Ph
Me

3d

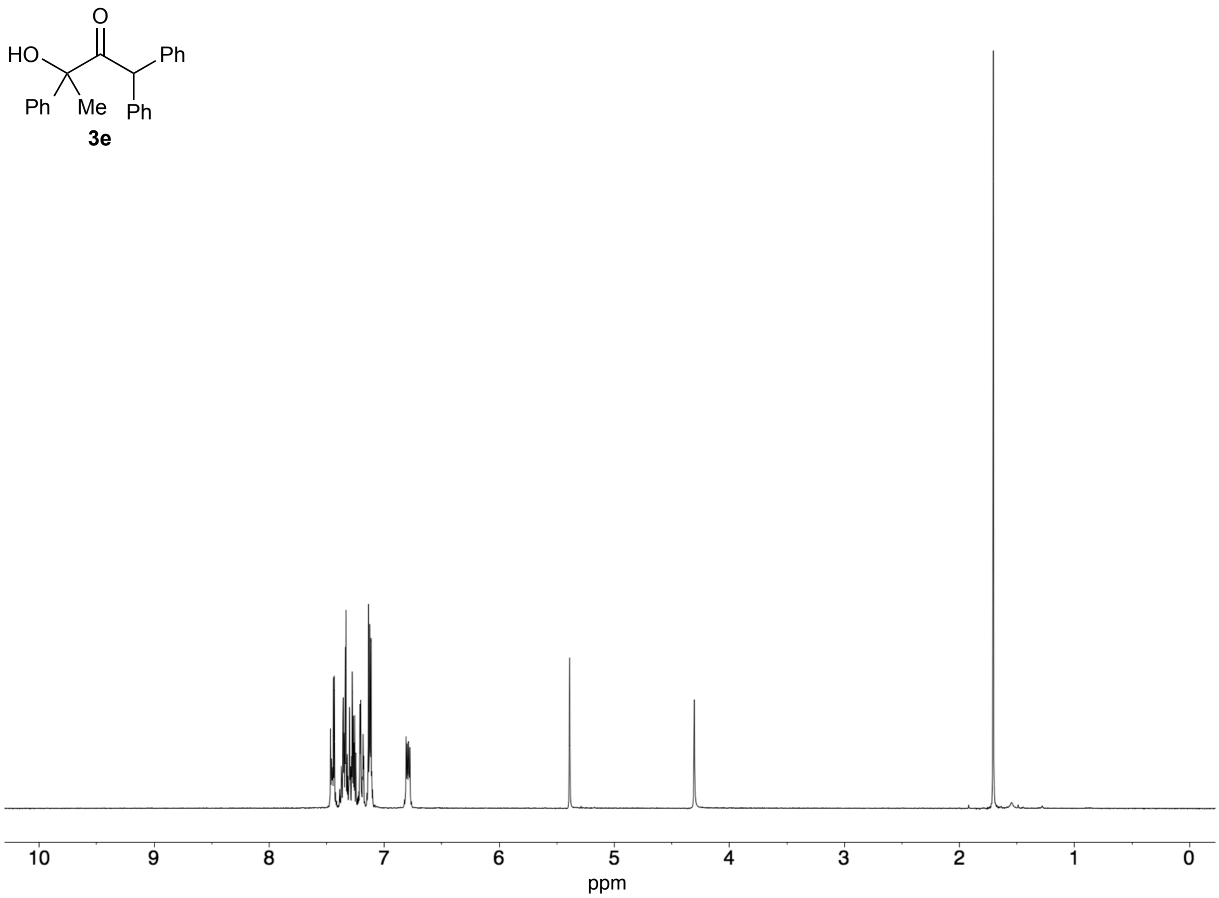
10
9
8
7
6
5
4
3
2
1
0
ppm

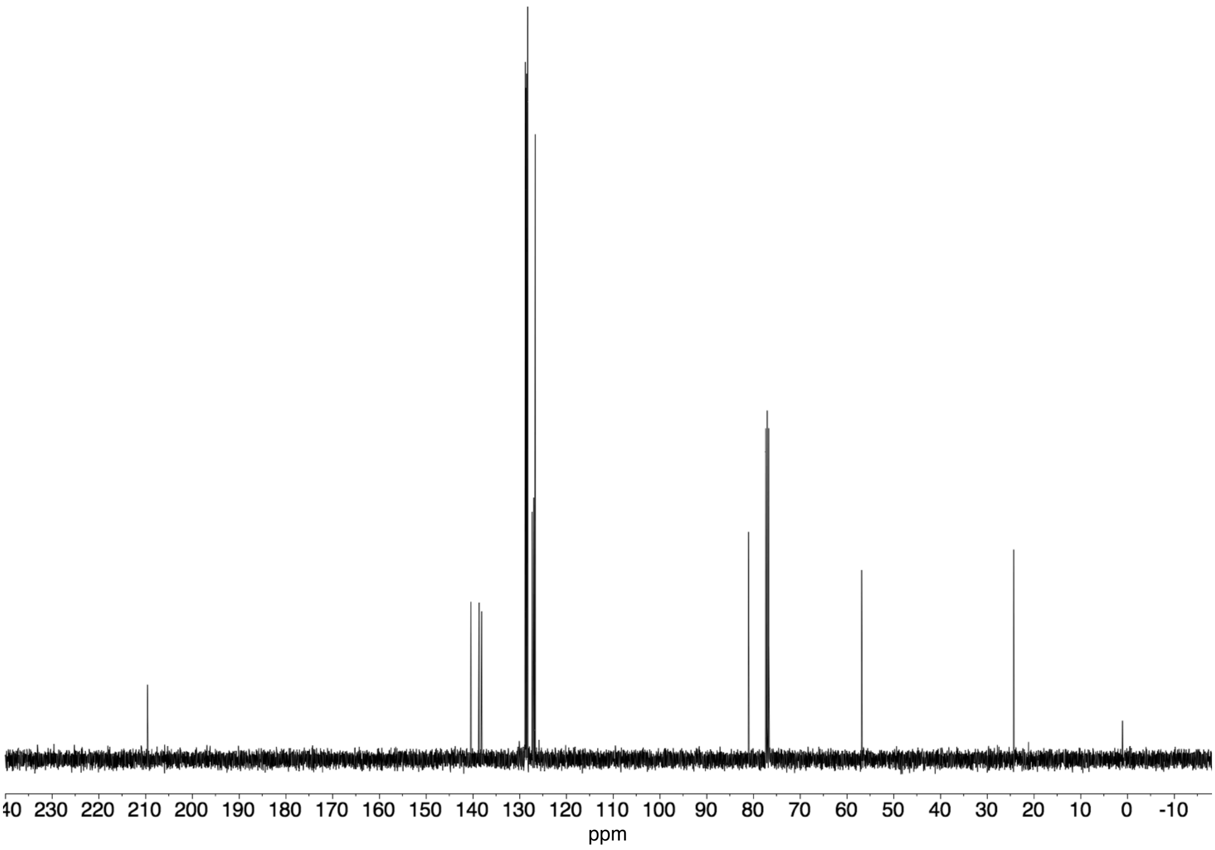

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

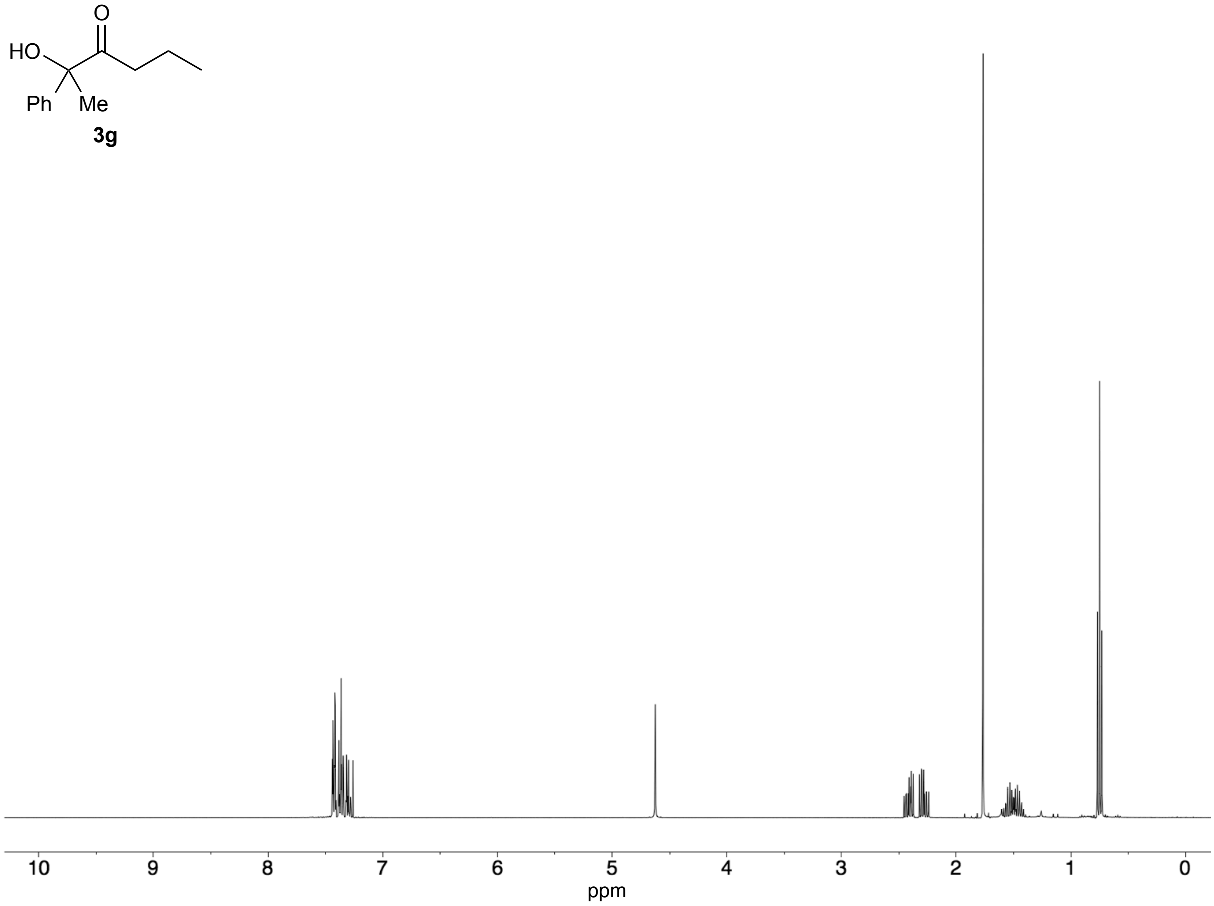

O
F
HO
Ph
Me

3d

0
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
-210
ppm

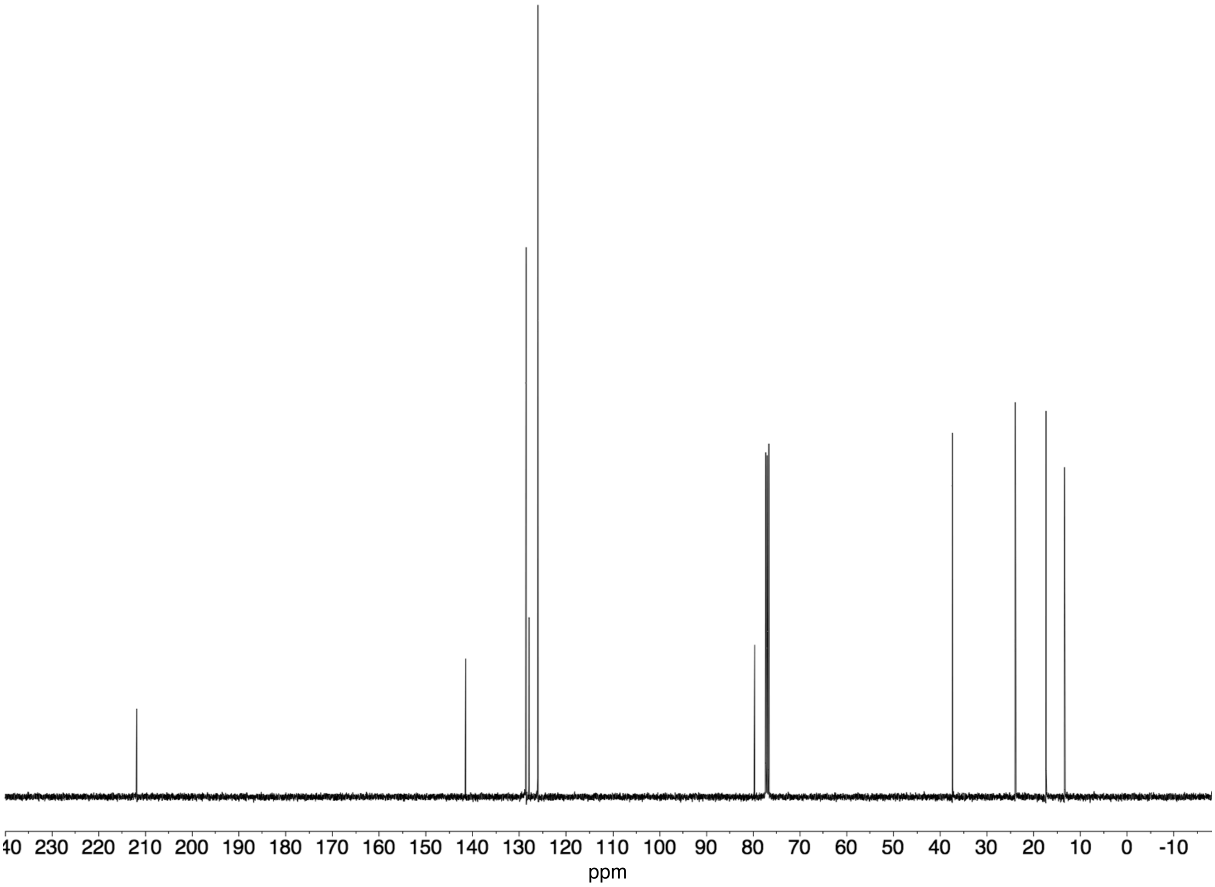

O
HO
Ph
Ph
Me
Ph
3e
10
9
8
7
6
5
4
3
2
1
0
ppm

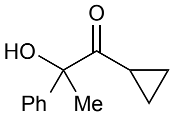

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


O
HO
Ph
Me

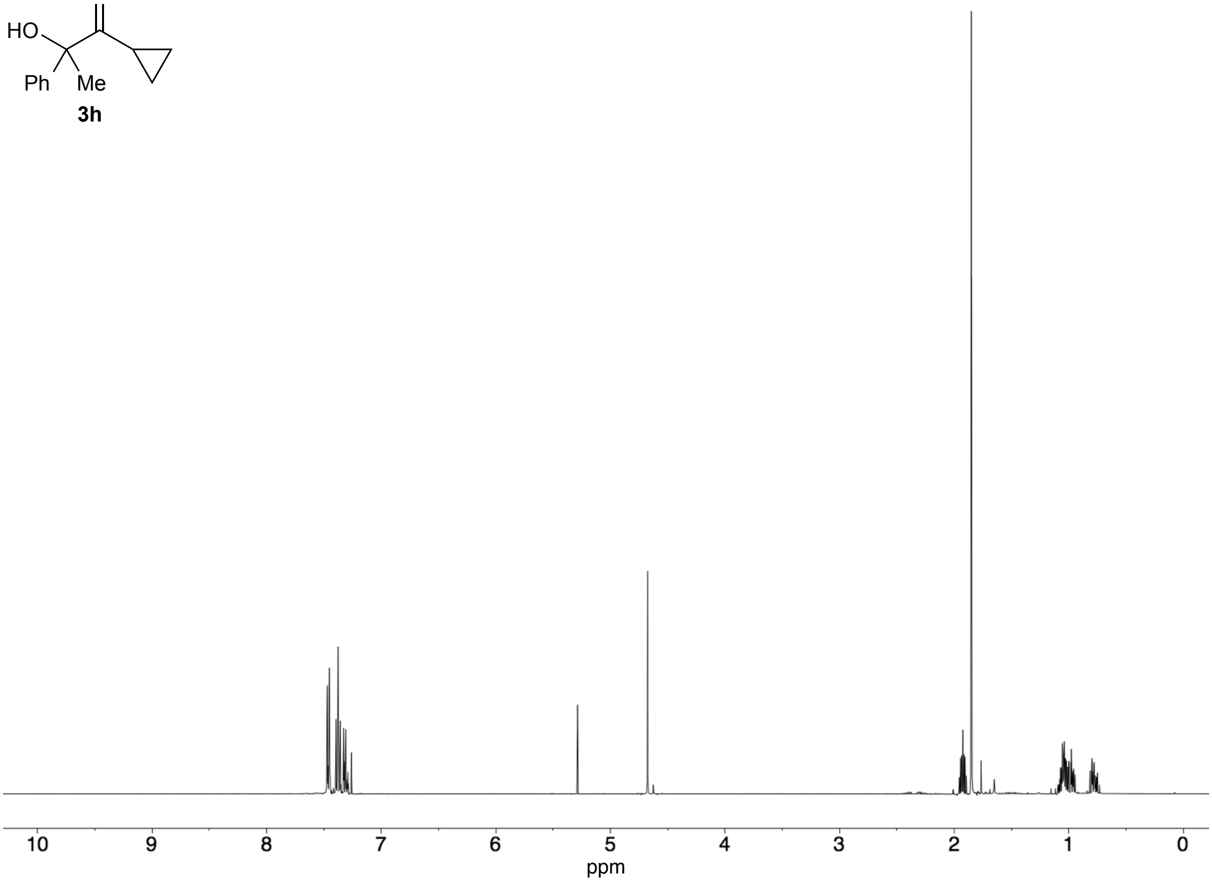
3g

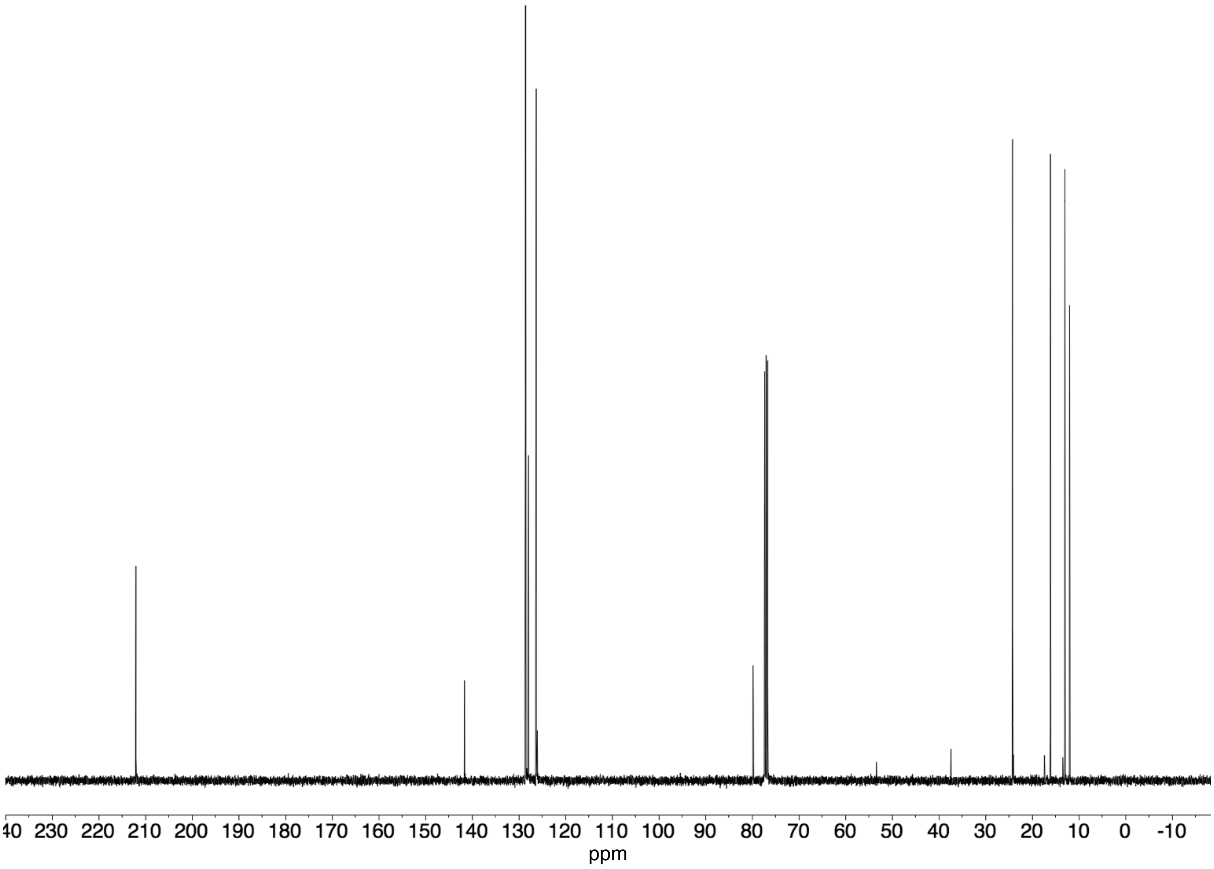
10
9
8
7
6
5
4
3
2
1
0
ppm

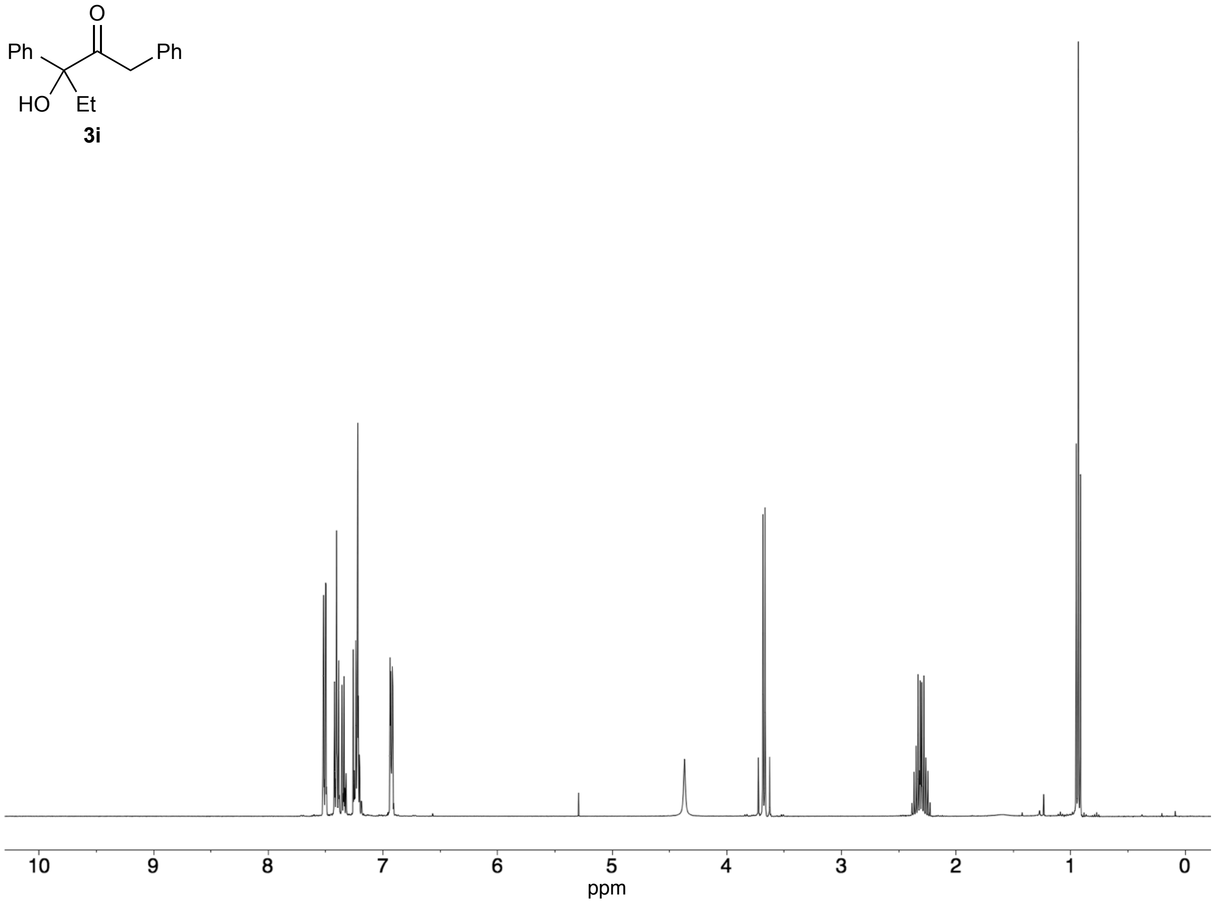

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


O
HO
Ph
Me

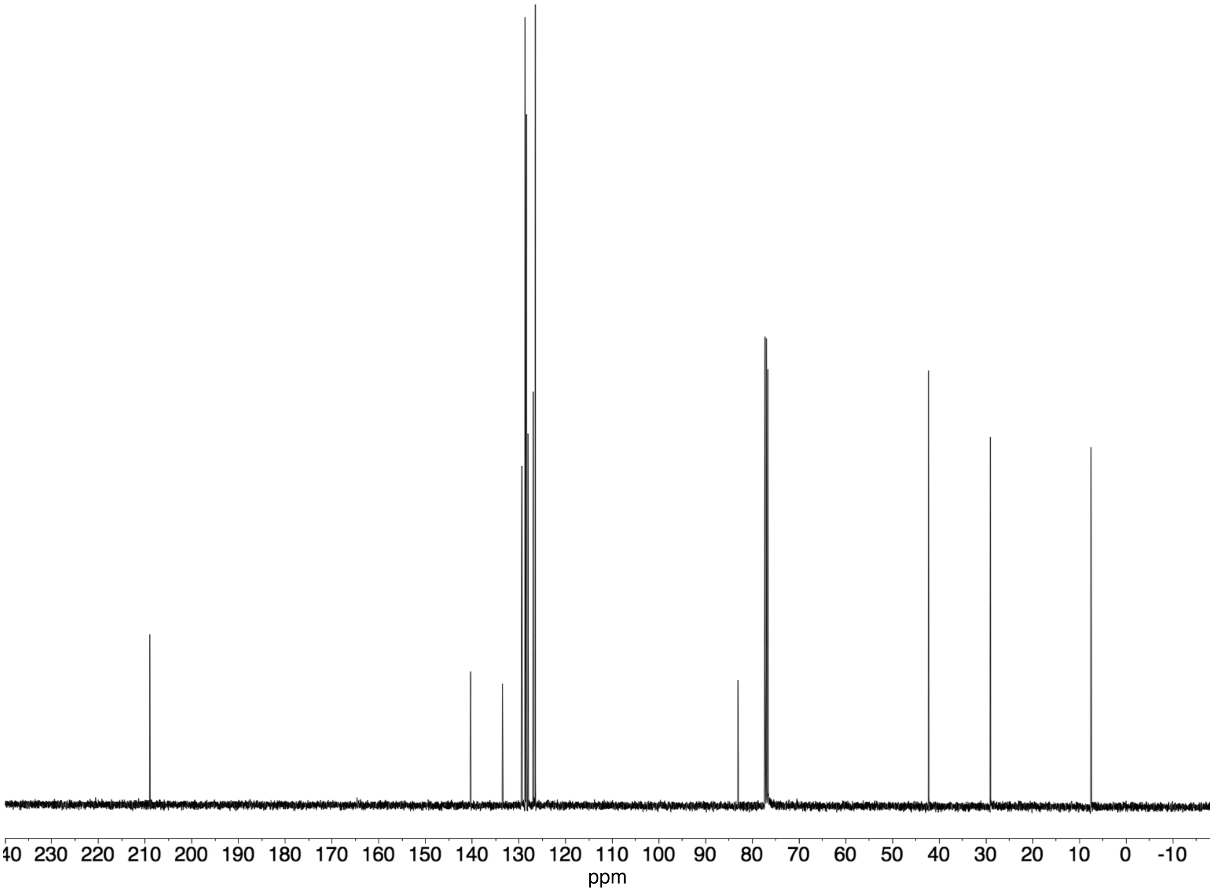
3h

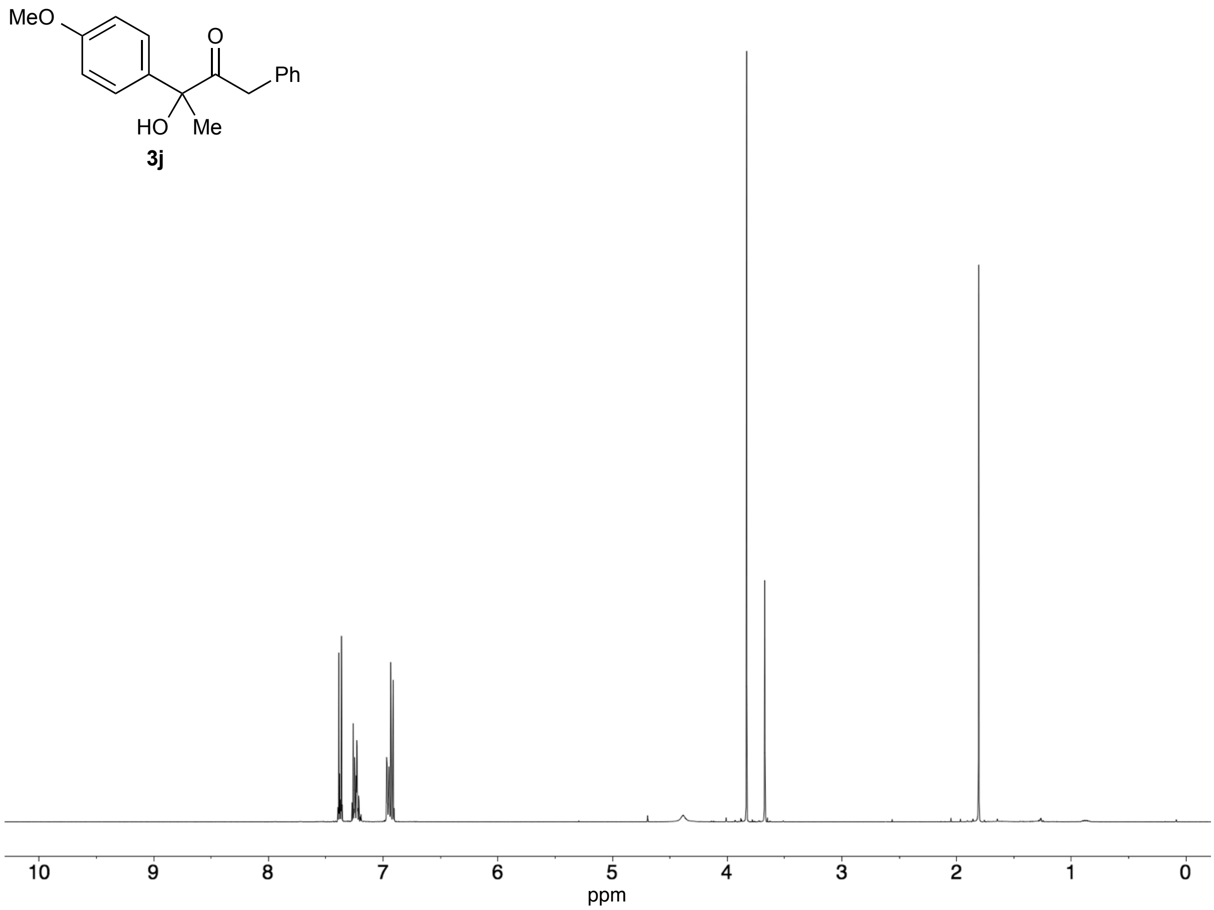

10
9
8
7
6
5
4
3
2
1
0
ppm


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

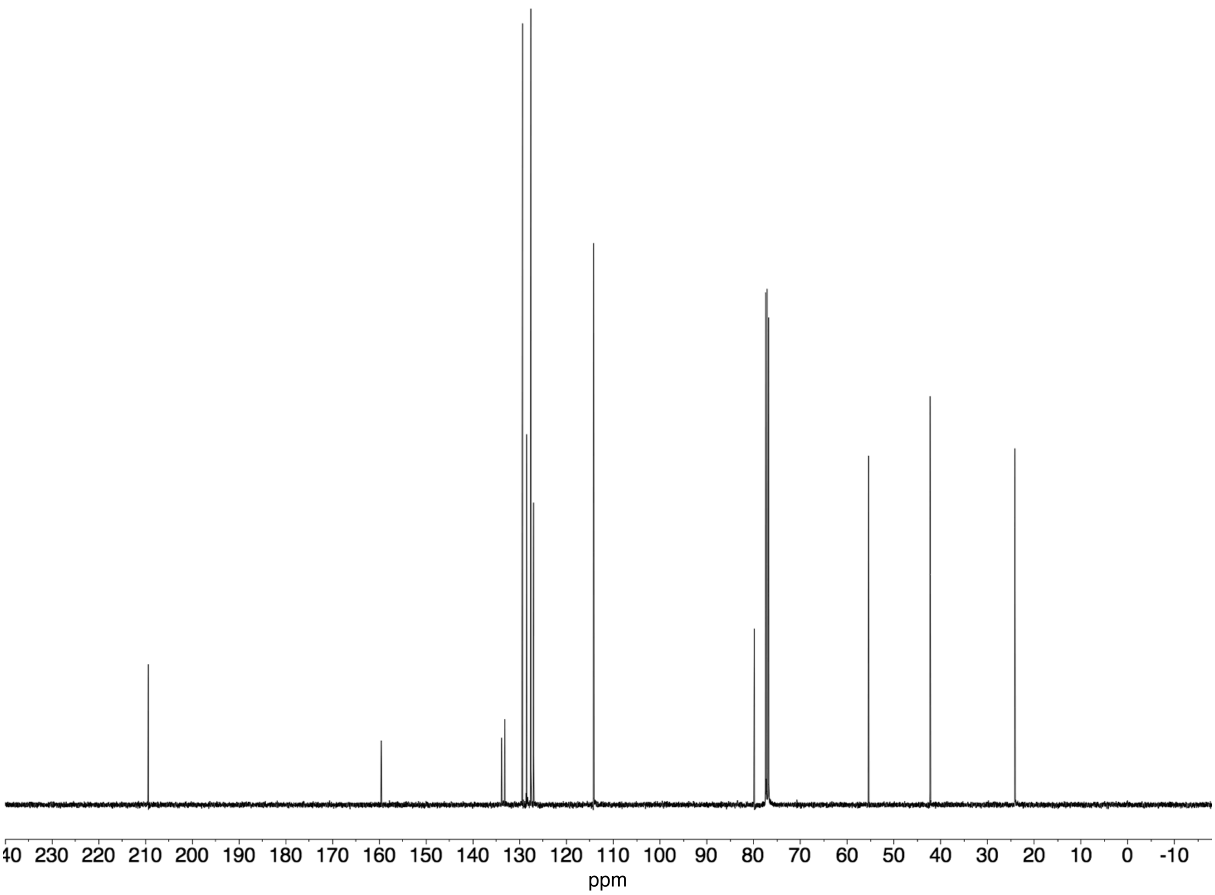

O
Ph
Ph
HO
Et
10
9
8
7
6
5
4
3
2
1
0
ppm

3i


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

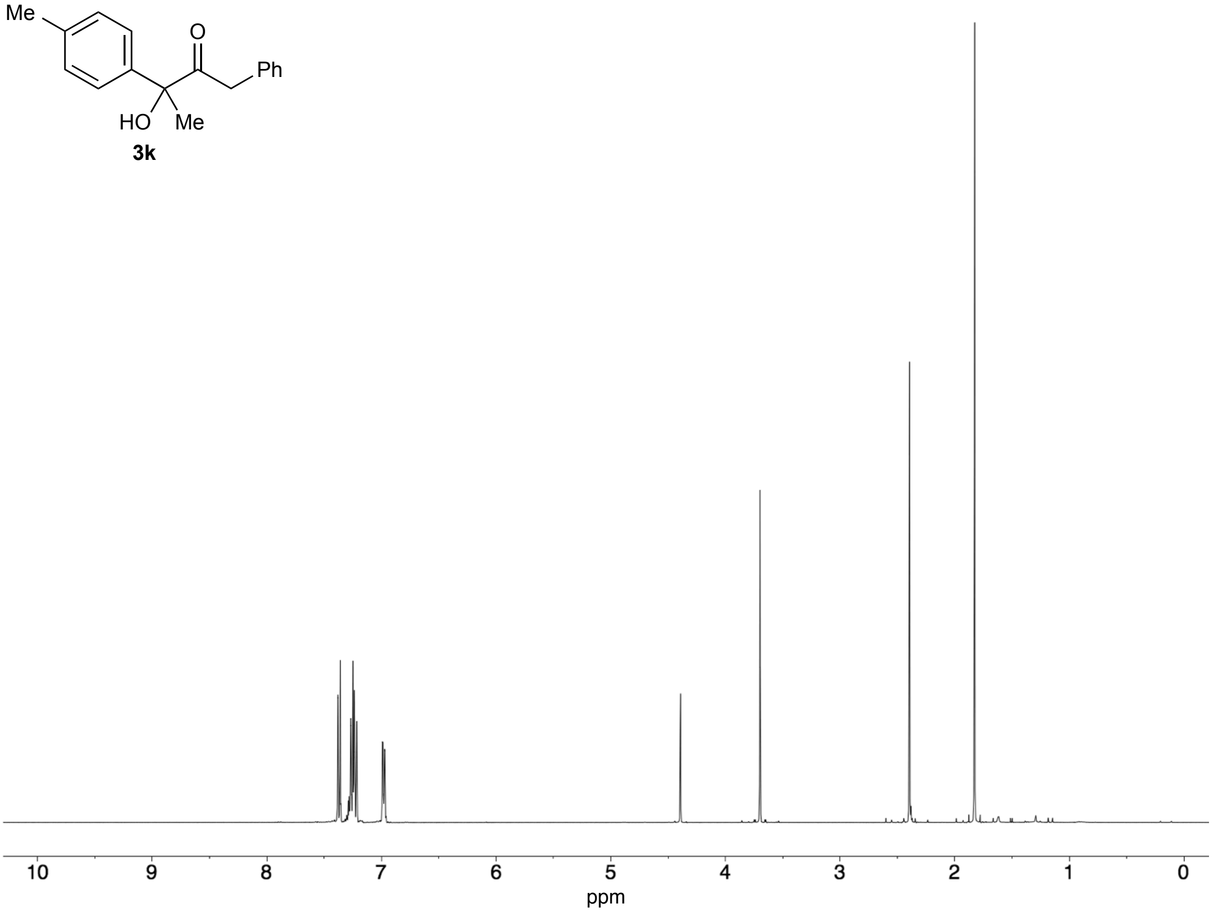

MeO
O
Ph
HO
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

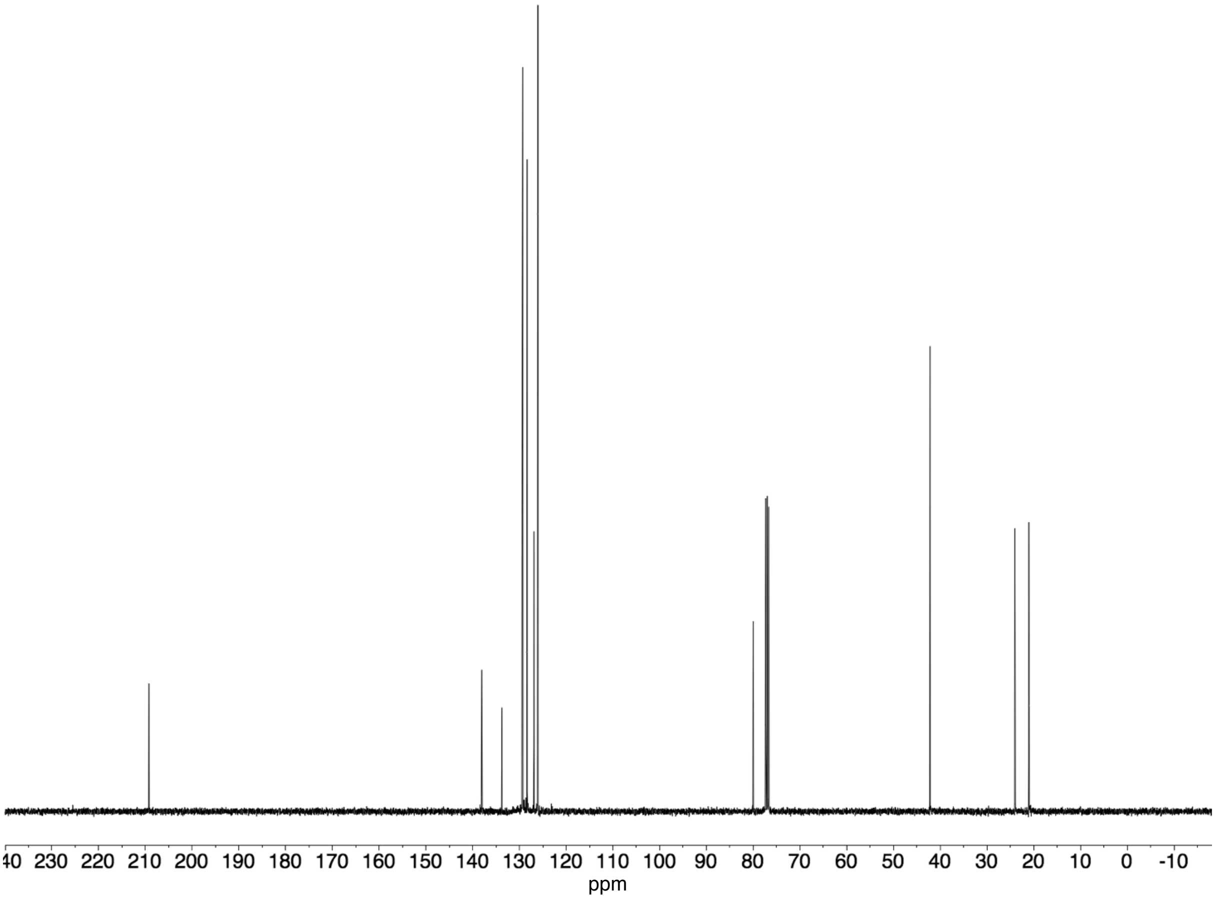
3j

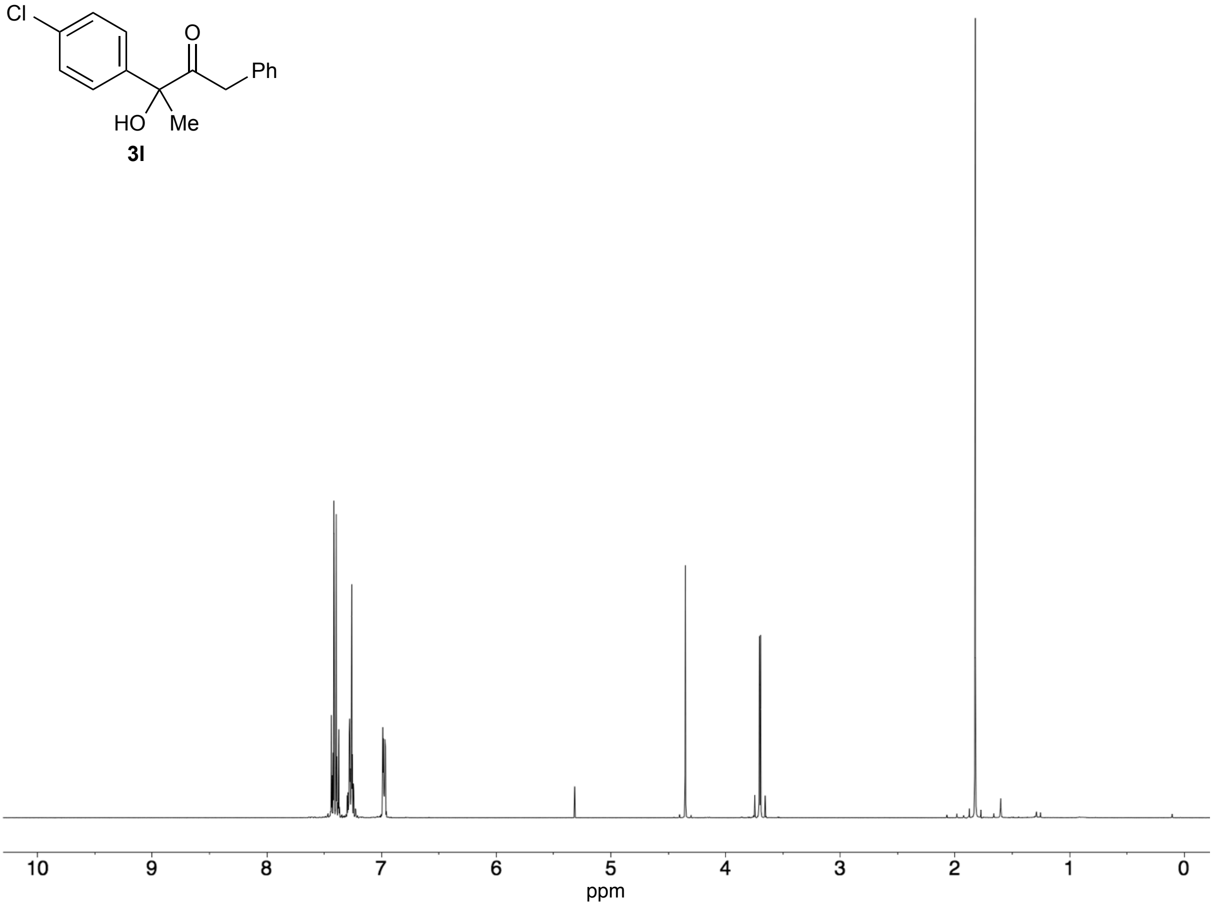

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

Me
O
Ph
HO
Me

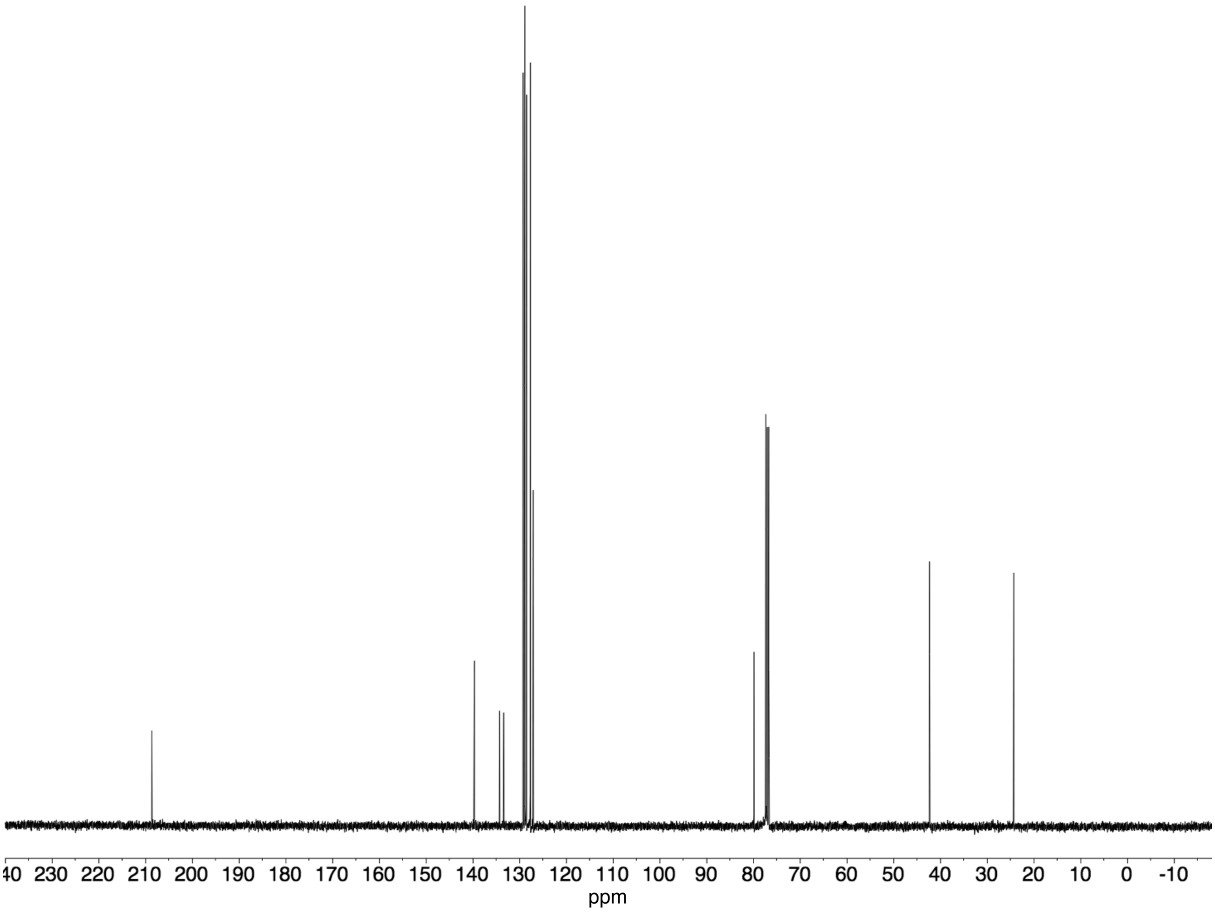
3k

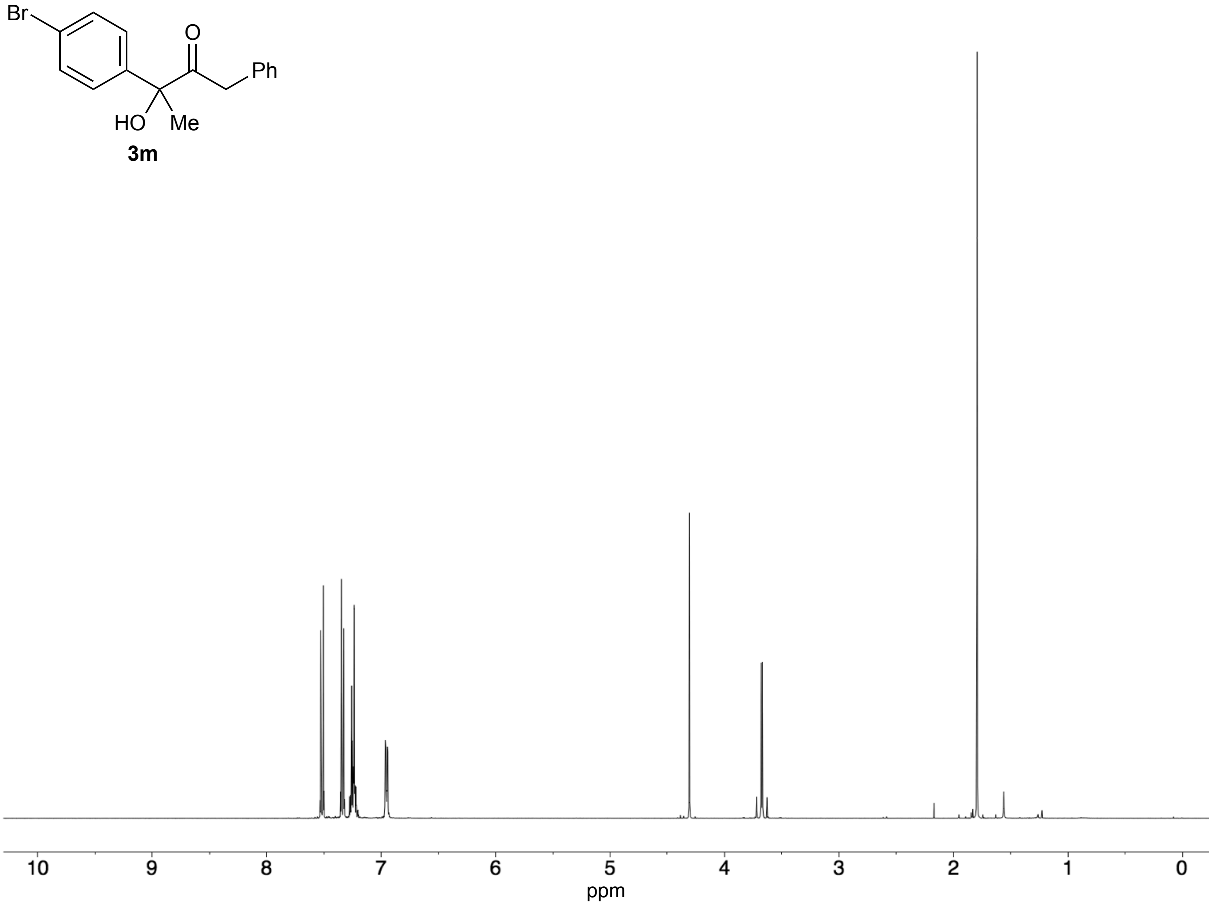

10
9
8
7
6
5
4
3
2
1
0
ppm


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


Cl
O
Ph
HO
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

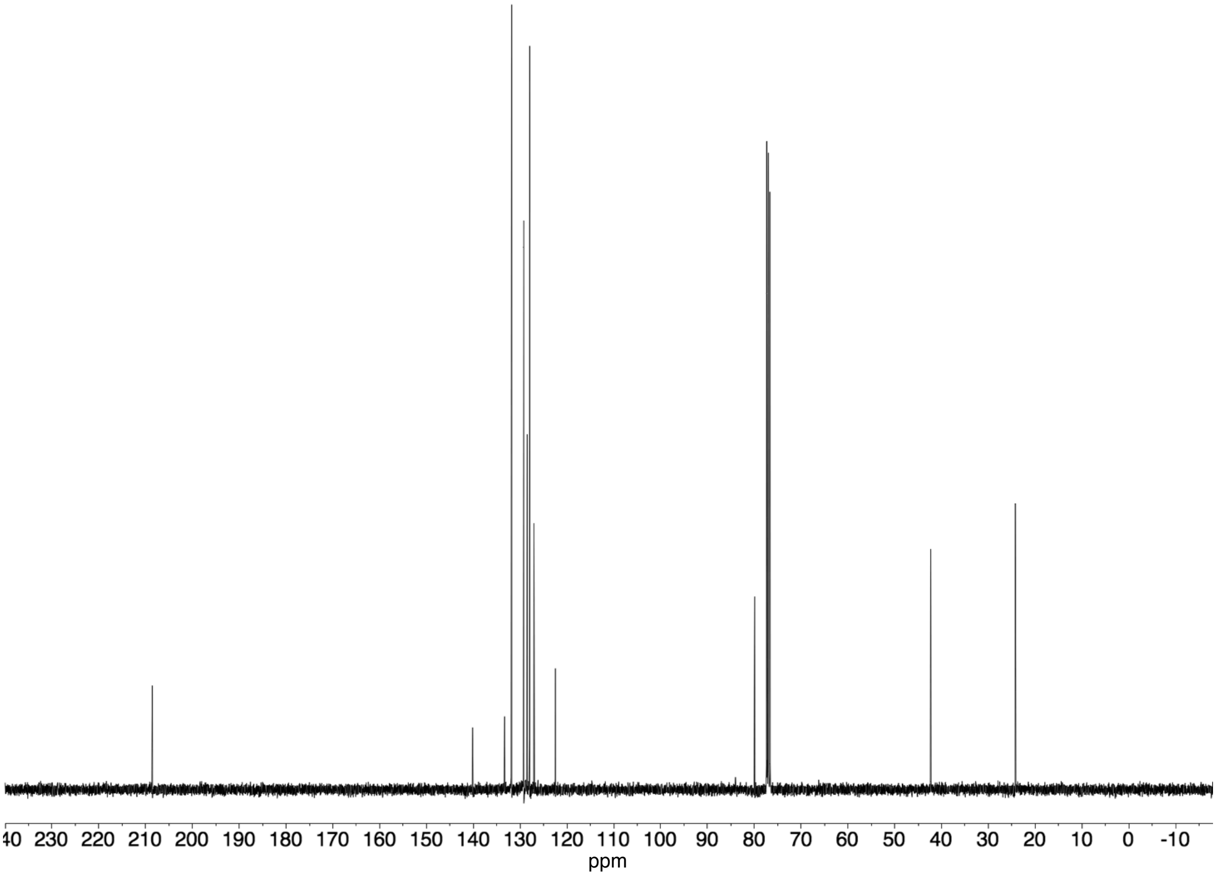
3l

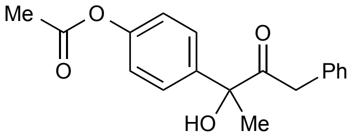

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


Br
O
Ph
HO
Me

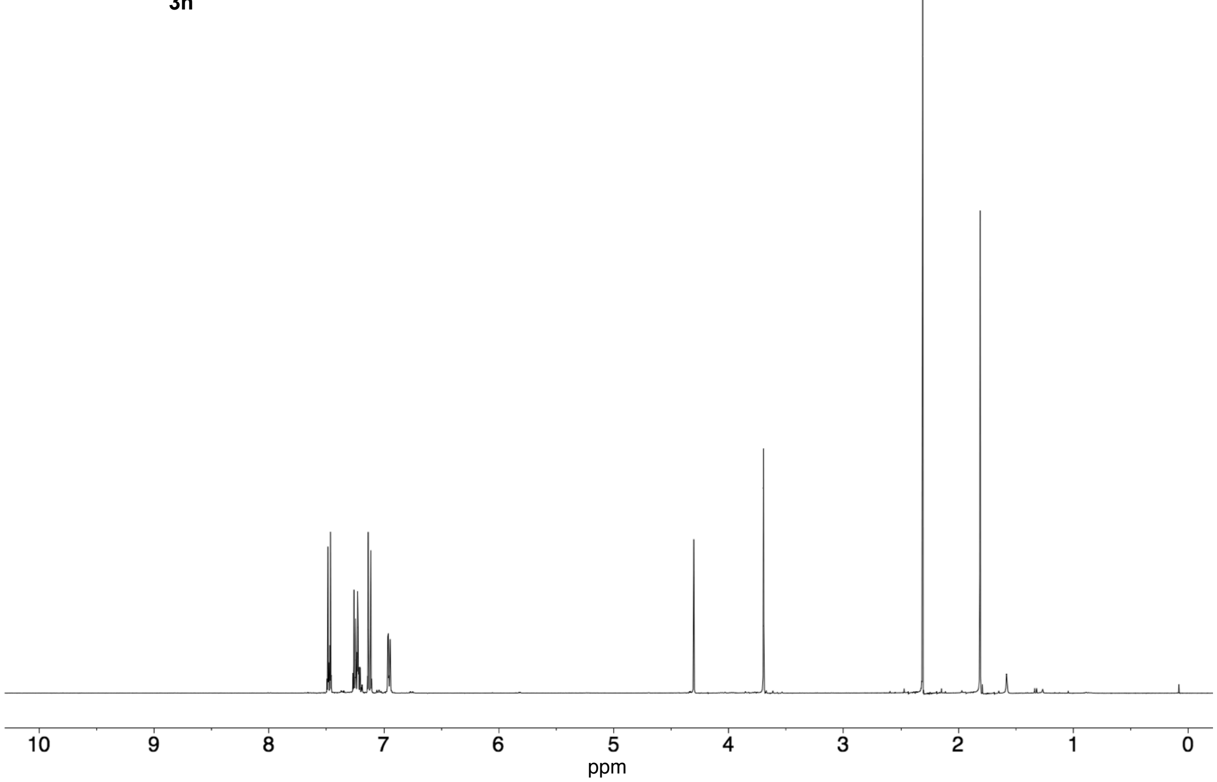
3m

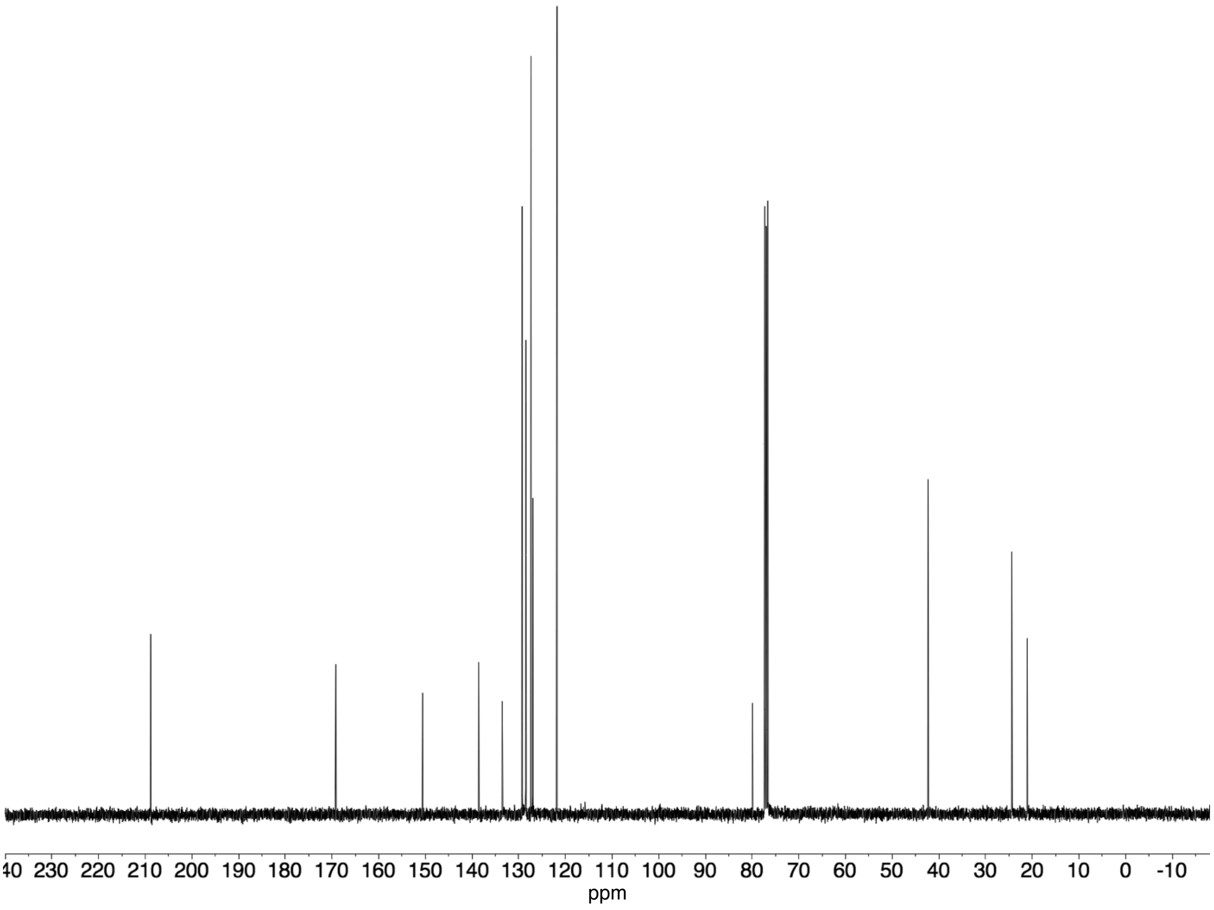
10
9
8
7
6
5
4
3
2
1
0
ppm

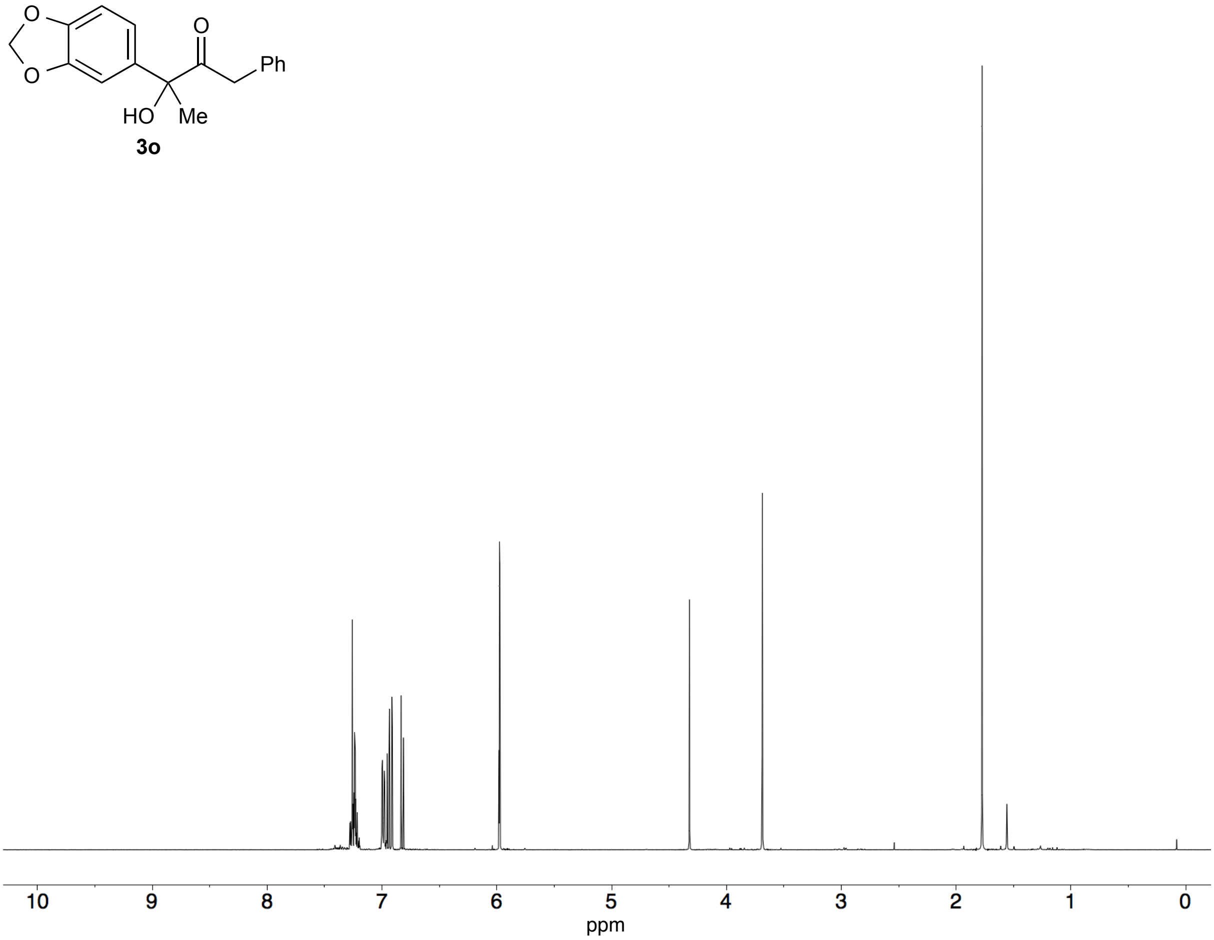

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


Me
O
O
O
Ph
HO
Me

3n

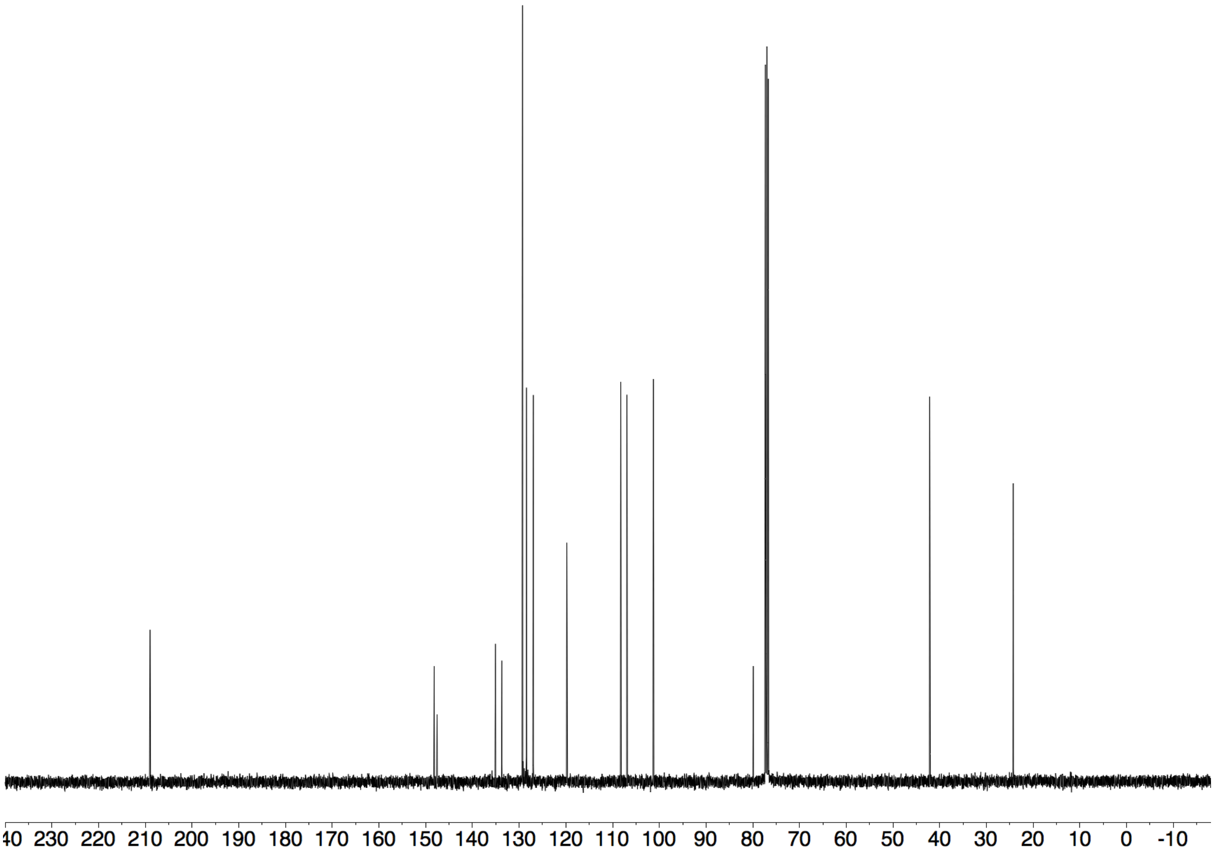

10
9
8
7
6
5
4
3
2
1
0
ppm


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

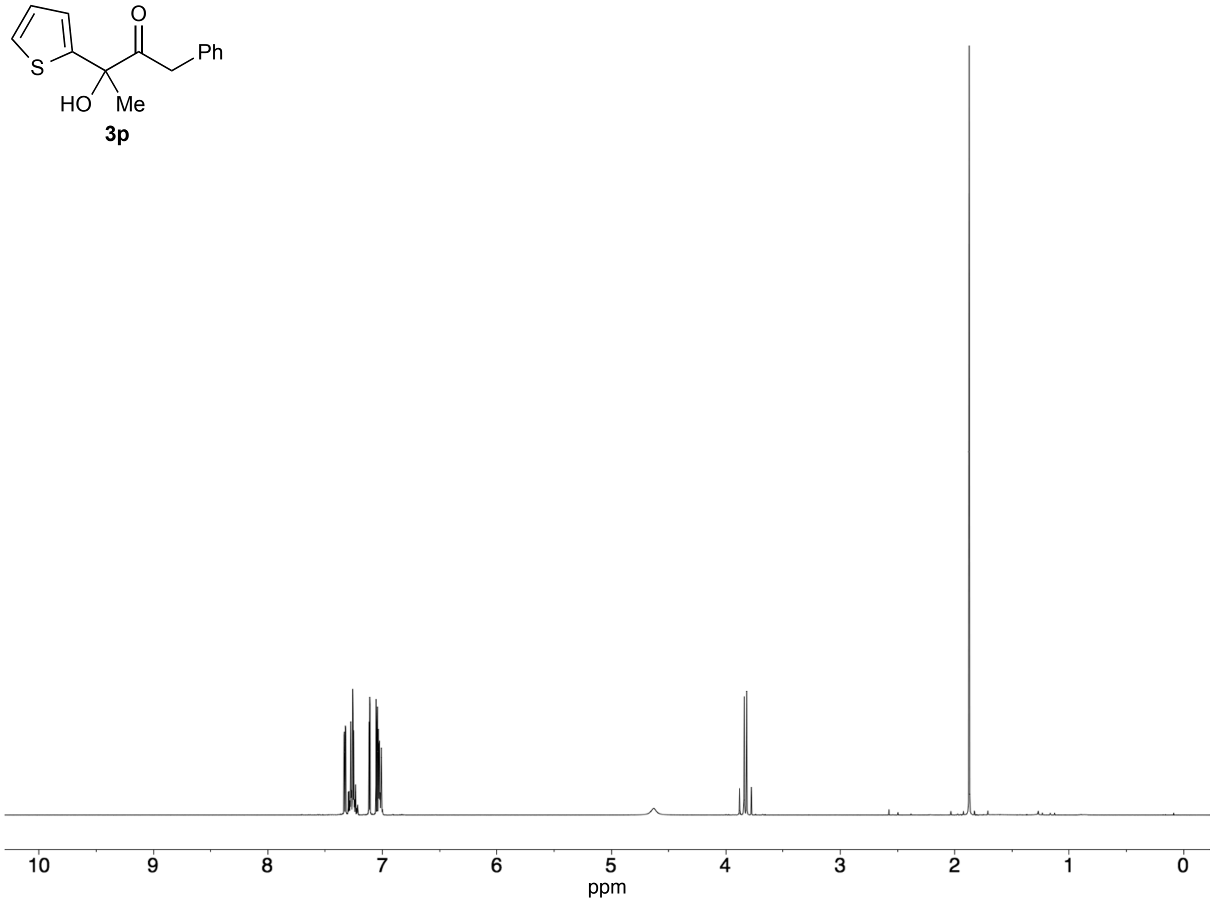


3o

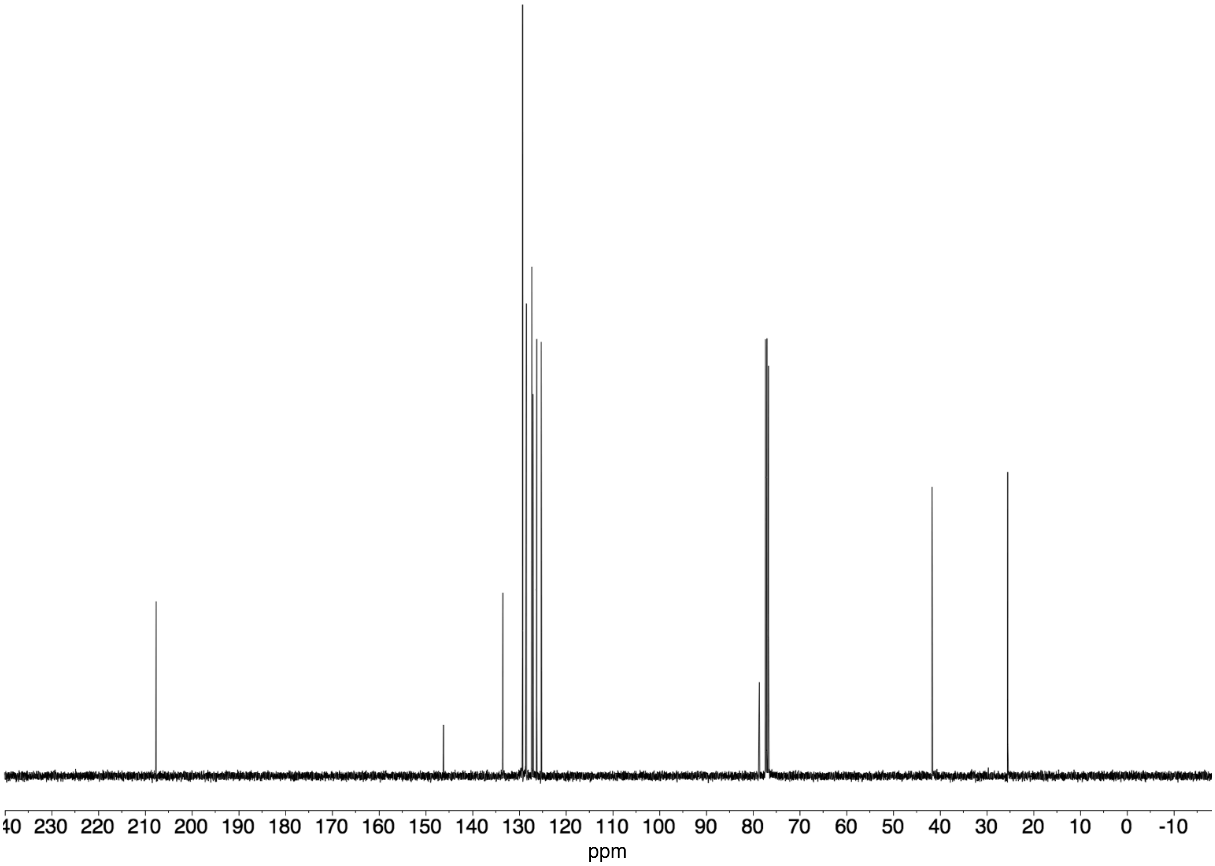
O
O
O
Ph
HO
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

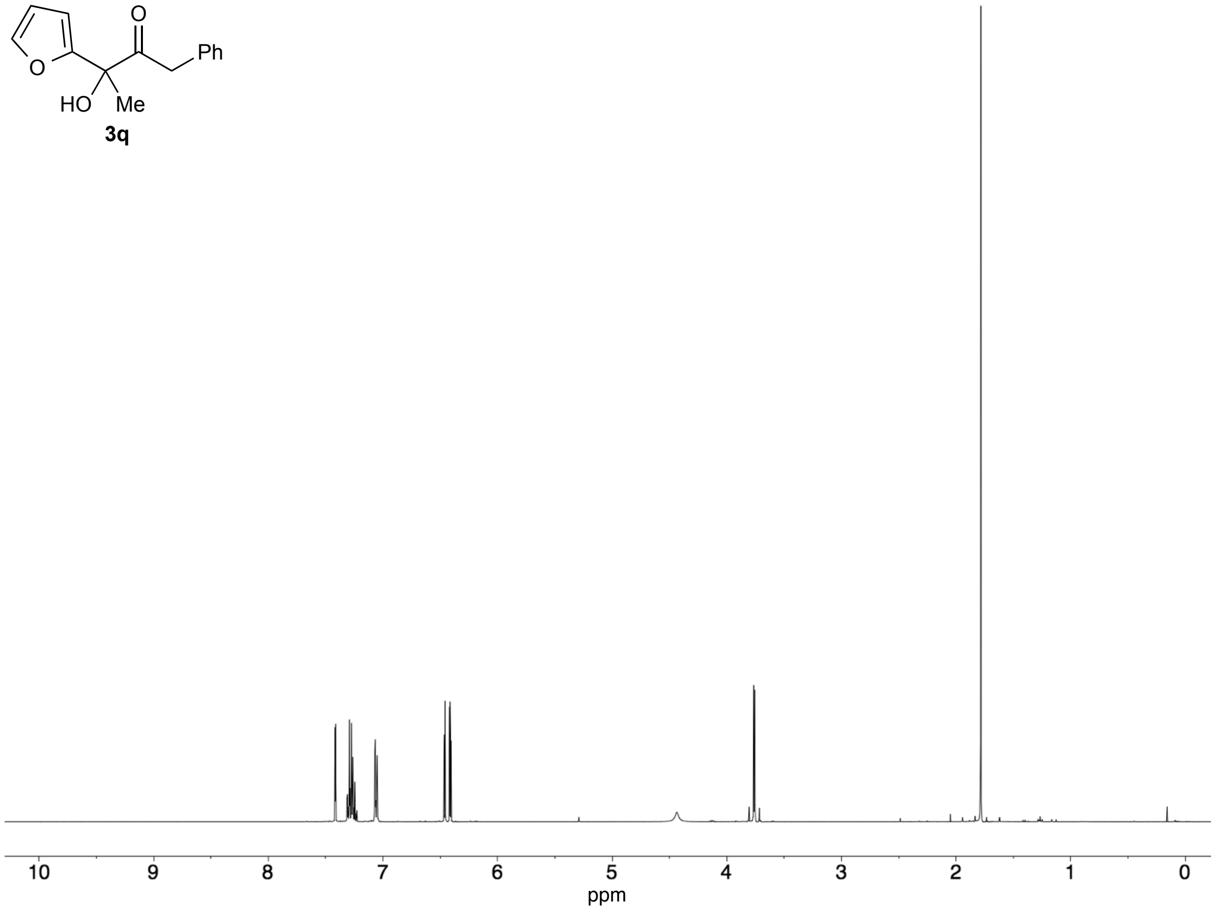


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

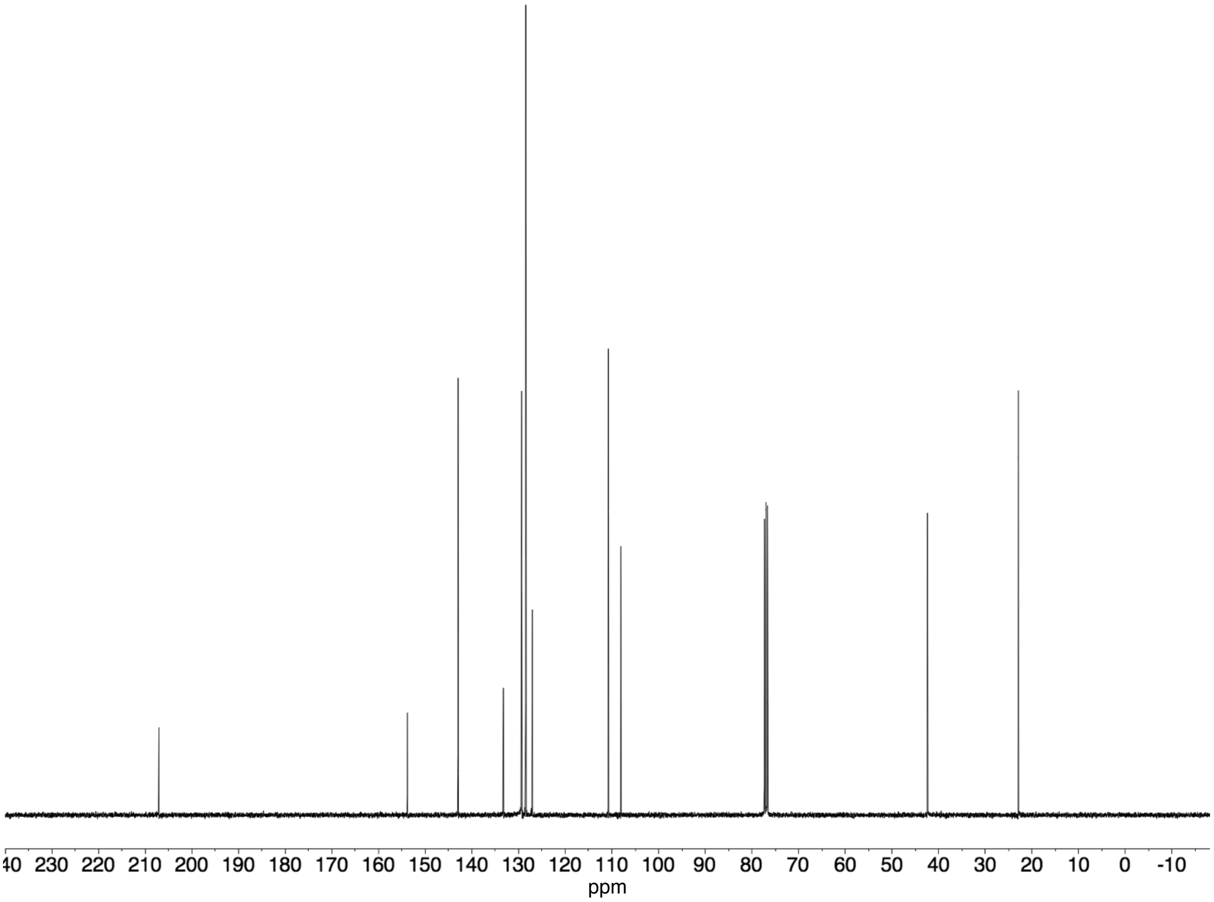

O
Ph
S
HO
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

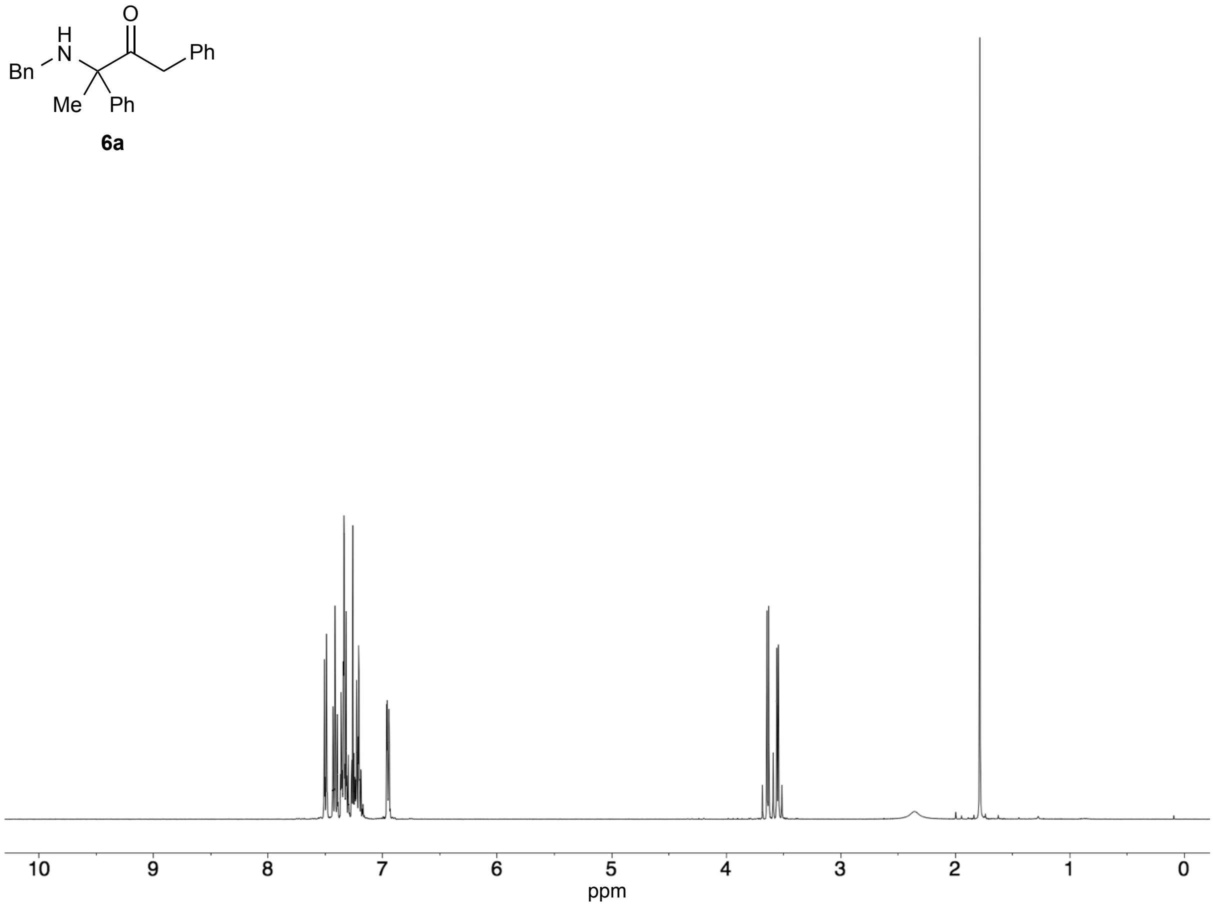
3p


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

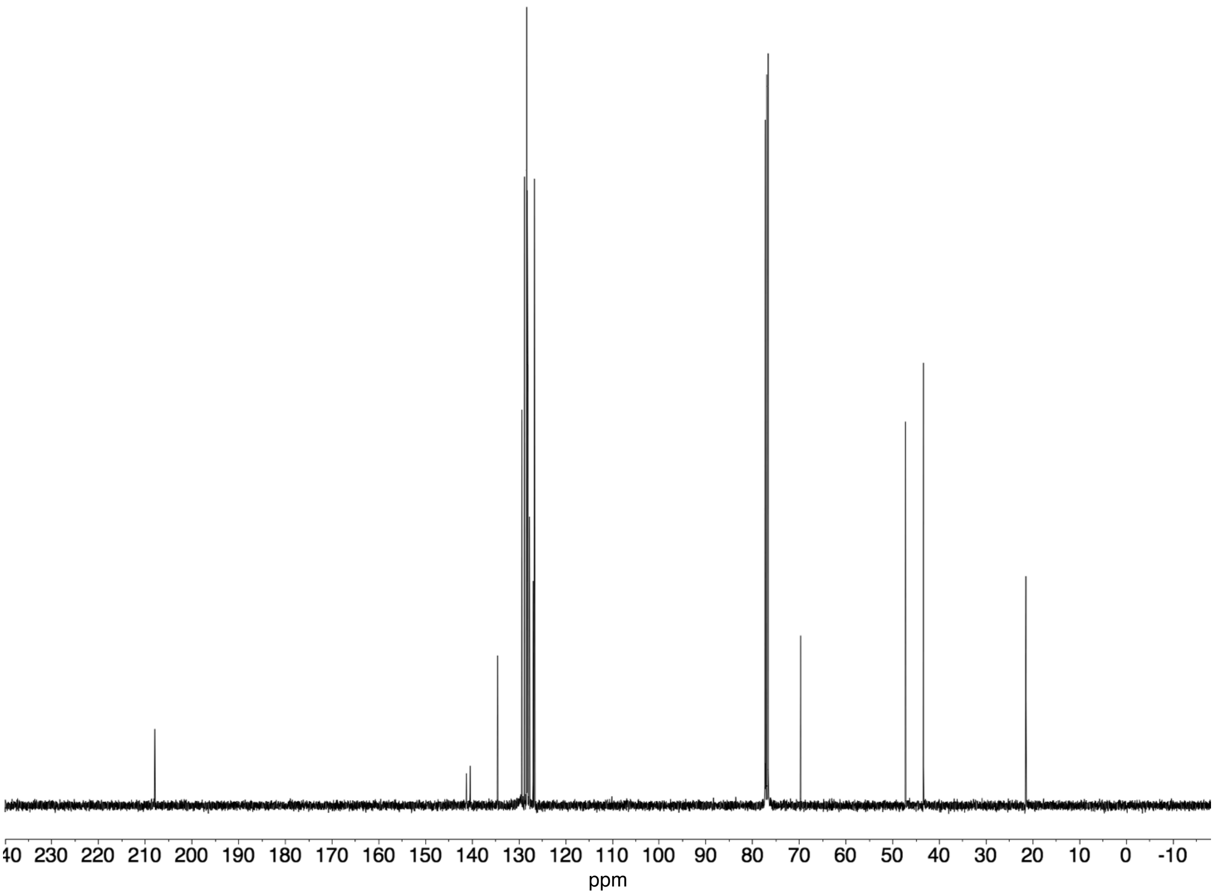

O
Ph
O
HO
Me
10
9
8
7
6
5
4
3
2
1
0
ppm

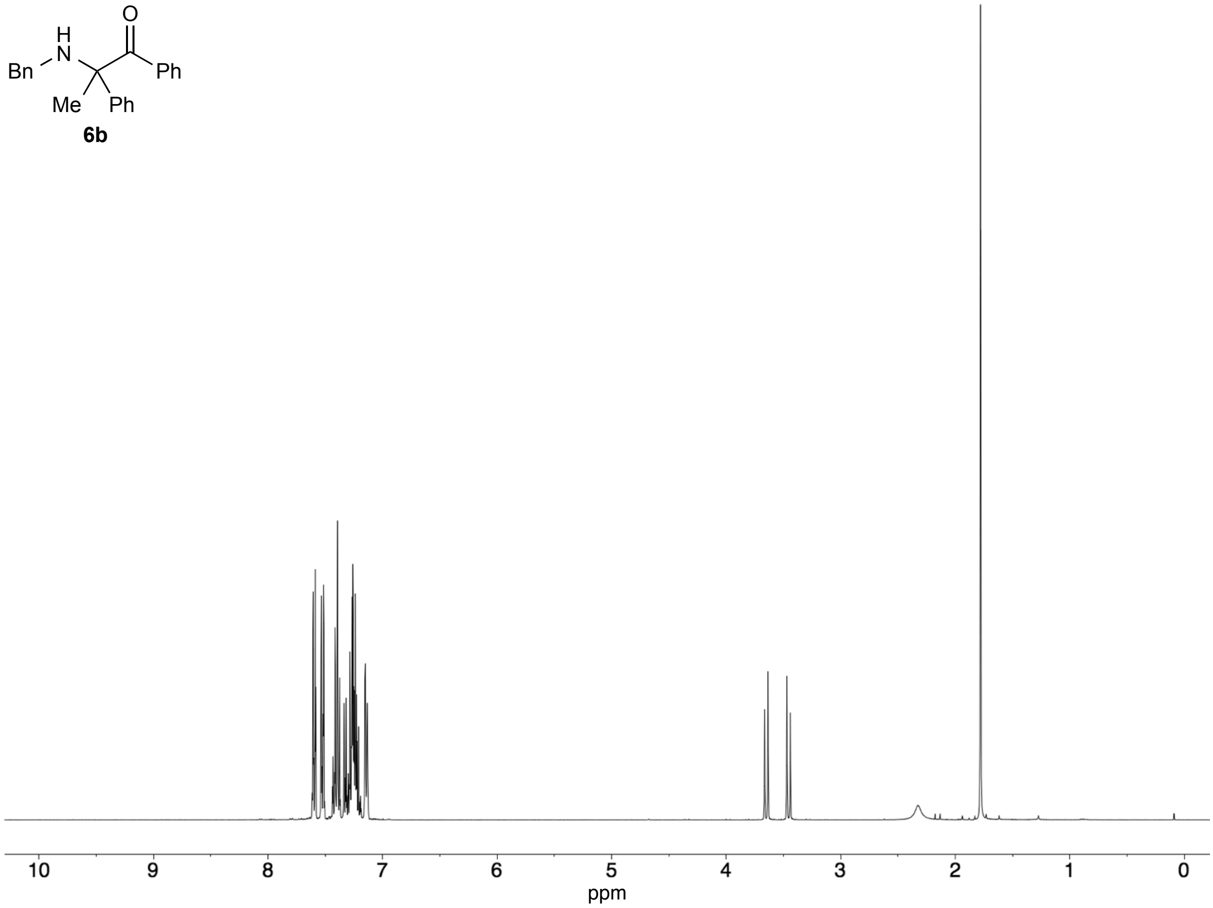
3q

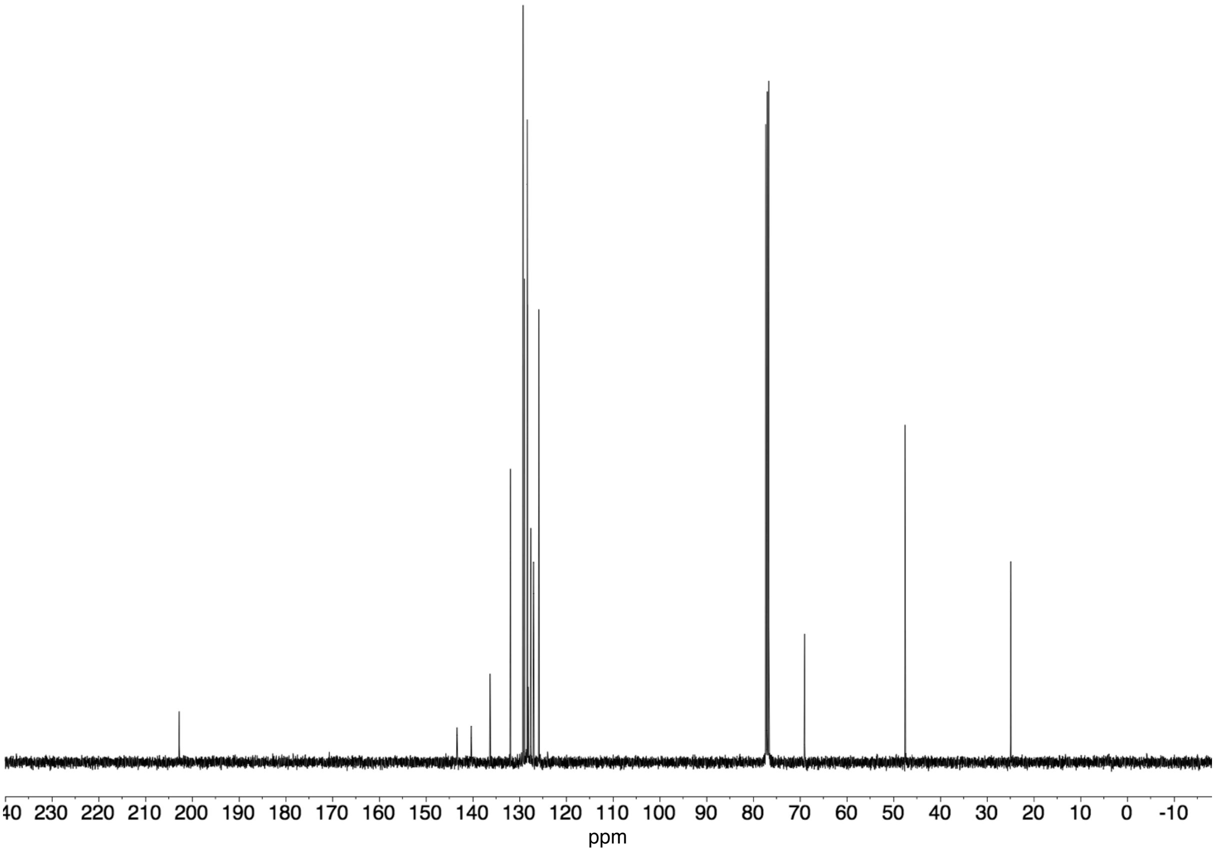

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

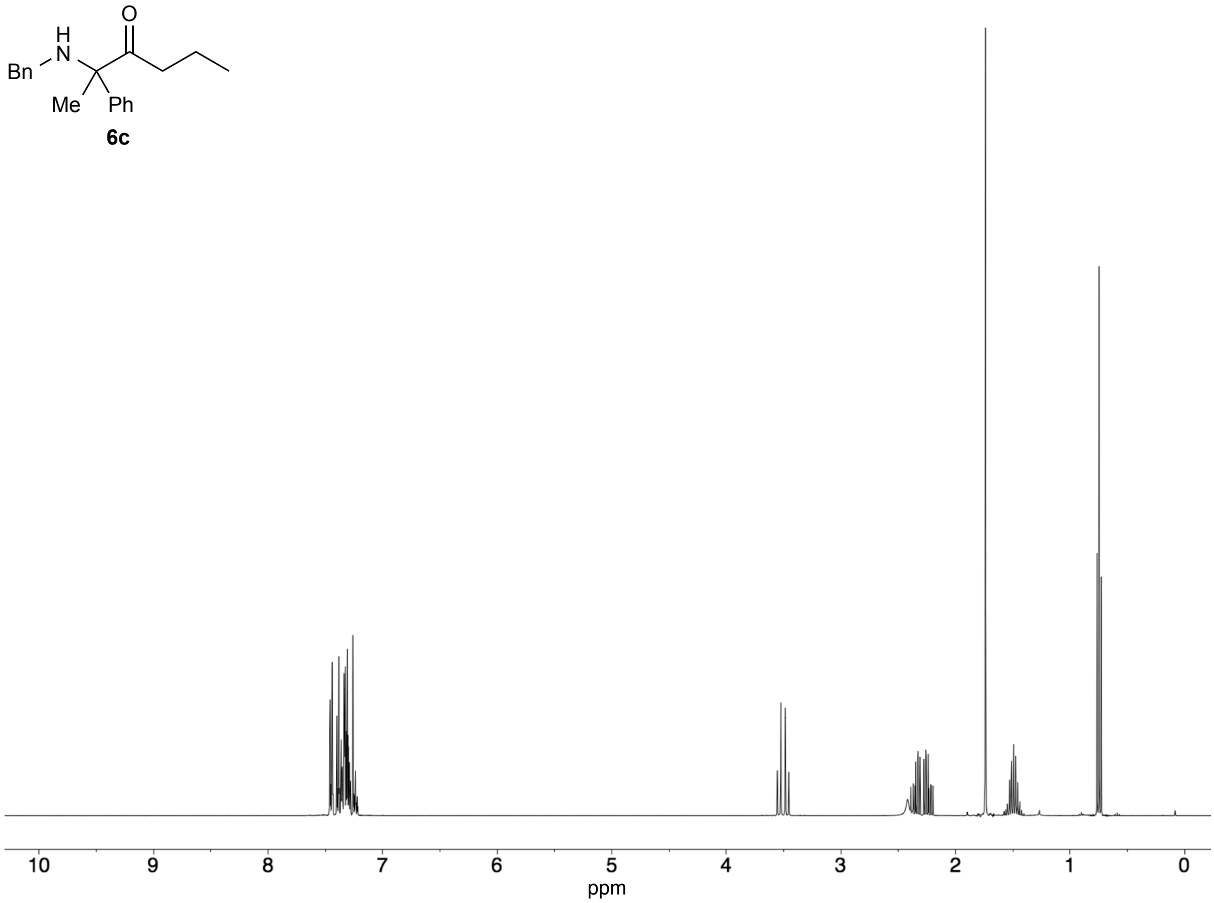

O
H
N
Bn
Ph
Me
Ph
10
9
8
7
6
5
4
3
2
1
0
ppm

6a

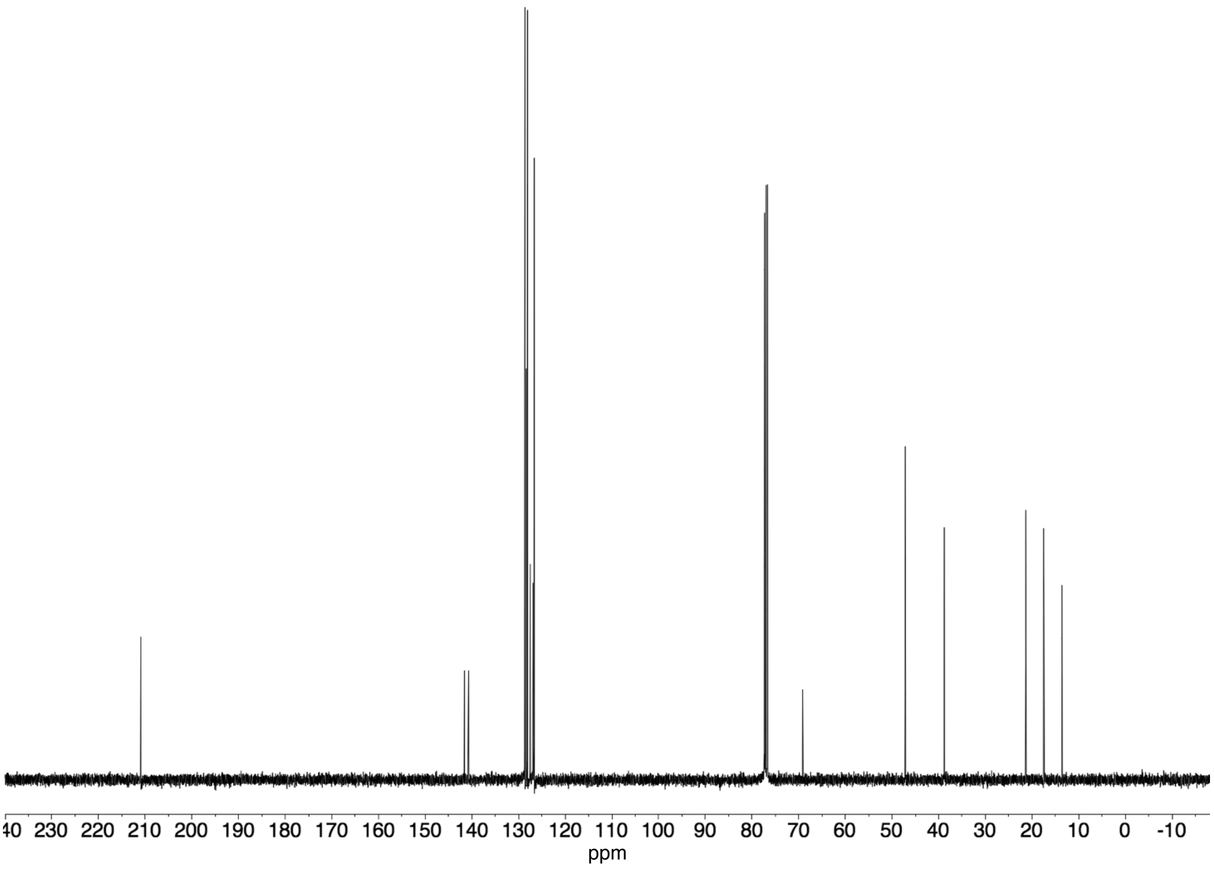

40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

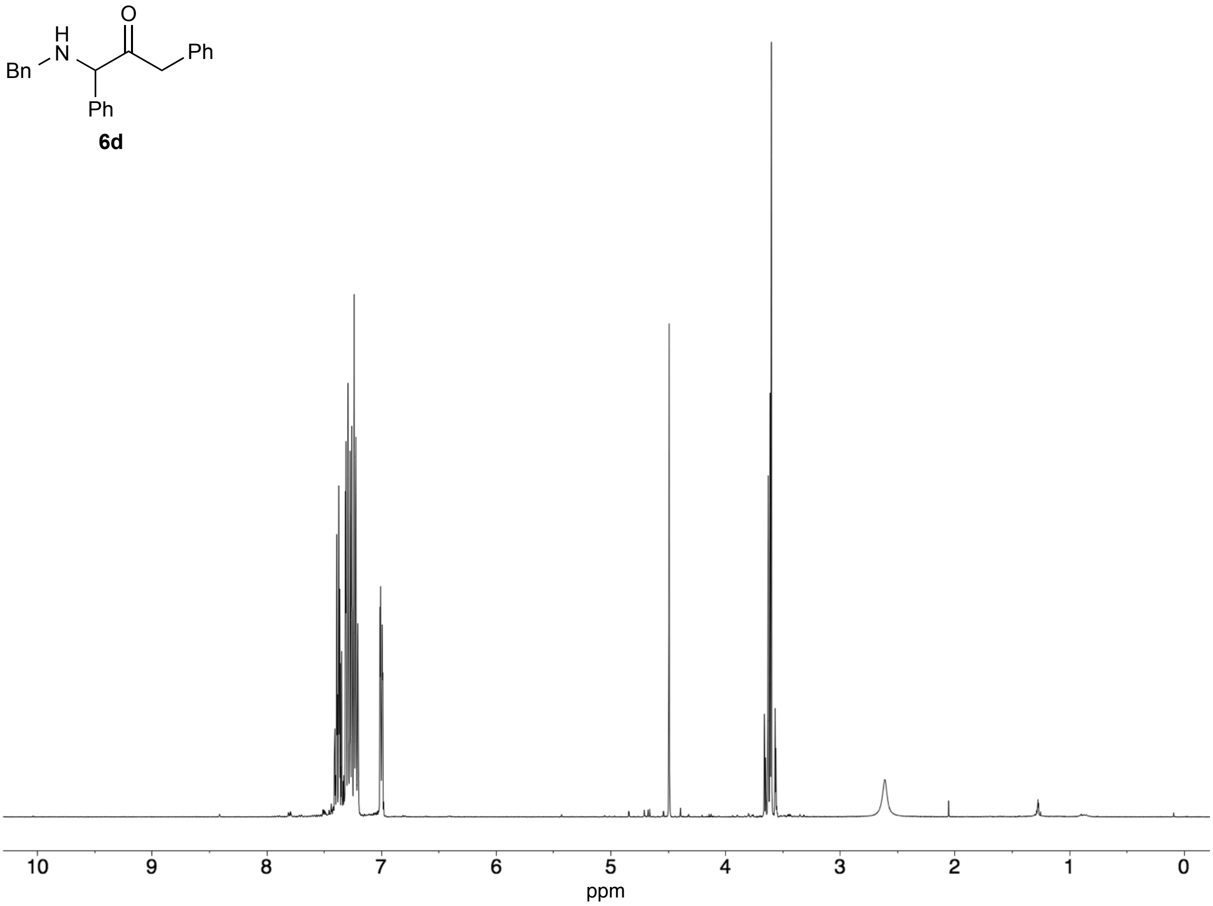

O
H
N
Bn
Ph
Me
Ph
6b
10
9
8
7
6
5
4
3
2
1
0
ppm


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm

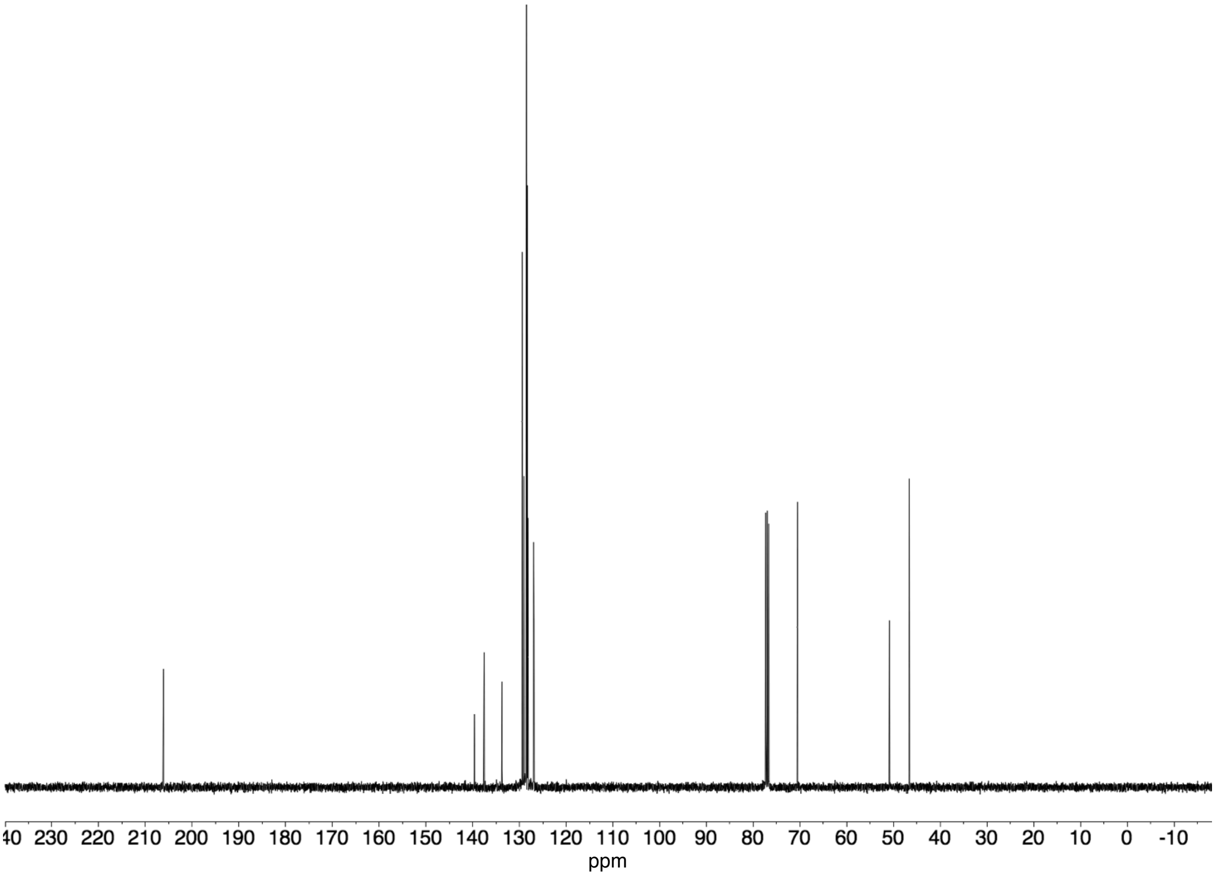

O
H
N
Bn
Me
Ph
10
9
8
7
6
5
4
3
2
1
0
ppm

6c


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm


O
H
N
Bn
Ph
Ph
10
9
8
7
6
5
4
3
2
1
0
ppm

6d


40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
ppm