

Electronic Supplementary Information

Iridium-catalyzed efficient reduction of ketones in water with formic acid as hydride donor at low catalyst loading

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1. General information

Except formic acid, all the chemicals were used directly as commercially received. ^1H and ^{13}C NMR spectra were recorded on a Bruker (400 MHz) NMR spectrometer, unless otherwise indicated, with CDCl_3 as the solvent and tetramethylsilane as internal standard. TLC analyses were performed on silica gel plates, and the plates were visualized with UV light. PE and EA are the abbreviations for petroleum ether (60-90 °C) and ethyl acetate, respectively.

All the synthesized alcohols are known products. Their spectra are identical with those reported.

2. Preparation of the catalysts

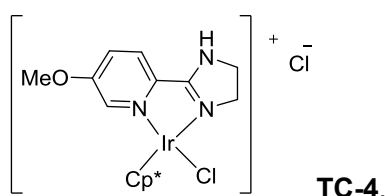
Catalysts **TC-1**, **TC-3**, **TC-5**, and **TC-7** were prepared according to our previous publications.¹ The procedures for preparations of catalysts **TC-2**, **TC-4**, **TC-6**, and **TC-8** are described as following.

2.1. General procedure for the preparation of the ligand.

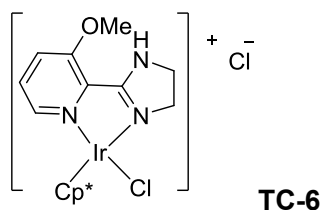
To the solution of substituted pyridine-2-carboxaldehyde (2.1 mmol) in dichloromethane (20 mL) was dropwise added ethylenediamine (0.16 mL, 2.3 mmol). The mixture was stirred for 1 h, and then was cooled to 0 °C. *N*-Bromosuccinimide (410 mg, 2.3 mmol) was added and the mixture was stirred overnight. Washing the reaction mixture with 5% NaOH solution (20 mL) and then saturated $\text{Na}_2\text{S}_2\text{O}_3$ solution (20 mL), drying with Na_2SO_4 and removal of the dichloromethane under vacuum directly gave the desired substituted 2-(4,5-dihydro-1*H*-imidazol-2-yl)pyridine crude products in quantitative yield. This product was directly used in next step without further purification.

2.2. General procedure for the synthesis of catalysts.

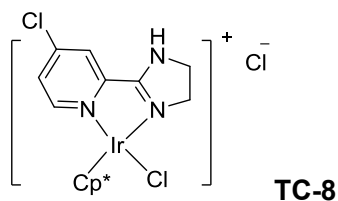
To a solution of ligand (1.13 mmol) in 10 ml of DCM was added the powder of $[\text{Cp}^*\text{IrCl}_2]_2$ (0.5 mmol, 400 mg). The resultant orange solution was stirred overnight. DCM was removed under reduced pressure, and the resultant yellow solid was dissolved in minimum amount of DCM. Then a large amount of EtOAc slowly was added to precipitate an orange solid as desired product, which was isolated by reduced-pressure filtration and further dried under vacuum at room temperature.



Yellow powder. M.p. > 300 °C. Yield: 547 mg, 95%. ¹H NMR (400 MHz, CDCl₃, TMS): δ 1.75 (s, 15H), 3.90-3.99 (m, 4H), 4.08-4.16 (m, 3H), 7.57 (dd, *J* = 2.4, 8.8 Hz, 1H), 8.32 (s, 1H), 9.24-9.31 (m, 1H); ¹³C NMR (100 MHz, CDCl₃): δ 9.1, 46.2, 51.8, 56.7, 87.5, 121.6, 128.9, 139.5, 140.5, 159.1, 168.9; HRMS (ESI) for C₁₉H₂₆N₃OClIr (M⁺), (Calc.) 540.1394, found 540.1372.

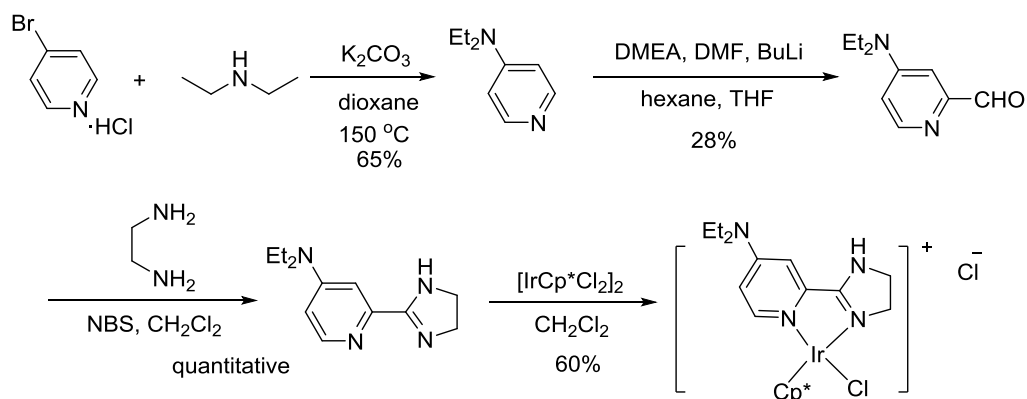


Yellow powder. M.p. > 300 °C. Yield: 559 mg, 97%. ¹H NMR (400 MHz, CDCl₃, TMS): δ 1.76 (s, 15H), 3.84-3.93 (m, 1H), 4.13-4.24 (m, 6H), 7.73-7.78 (m, 2H), 8.44 (dd, *J* = 0.6, 3.8 Hz, 1H), 8.96 (s, 1H); ¹³C NMR (100 MHz, CDCl₃): δ 9.2, 46.7, 51.2, 57.6, 87.8, 123.0, 130.9, 136.3, 143.6, 157.6, 167.9; HRMS (ESI) for C₁₉H₂₆N₃OClIr (M⁺), (Calc.) 540.1394, found 540.1383.



Yellow powder. M.p. > 300 °C. Yield: 522 mg, 90%. ¹H NMR (400 MHz, D₂O, TMS): δ 1.62 (s, 15H), 3.73-4.05 (m, 4H), 7.78 (dd, *J* = 2.0, 6.0 Hz, 1H), 8.00 (d, *J* = 2.0 Hz, 1H), 8.74 (d, *J* = 6.0 Hz, 1H); ¹³C NMR (100 MHz, D₂O): δ 8.2, 46.0, 52.3, 88.8, 125.8, 130.0, 147.3, 148.2, 152.6, 168.5; HRMS (ESI) for C₁₈H₂₃N₃Cl₂Ir (M⁺), (Calc.) 544.0898, found 544.0899.

2.3. Preparation of catalyst TC-2



(1) To a mixture of 4-bromopyridine hydrochloride (1.5 g, 7.7 mmol), K₂CO₃ (2.7 g, 20 mmol) and dioxane (10 mL) in a 50-mL flask was slowly added diethylamine (6 mL, 60 mmol). The flask was placed in an oil bath and heated at 150 °C for 10 h. Water was added and the mixture was extracted with ethyl acetate. The organic phase was collected, concentrated and purified on flash column to give 4-(*N,N*-diethyl)pyridine as a brown solid

(750 mg) in 65% yield.

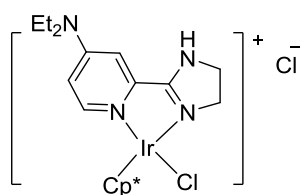
Brown solid. Yield: 750 mg, 65%. ^1H NMR (400 MHz, CDCl_3 , TMS): δ 1.08 (t, $J = 7.2$ Hz, 6H), 3.36 (q, $J = 7.2$ Hz, 4H), 6.46 (d, $J = 6.0$ Hz, 2H), 8.17 (d, $J = 6.0$ Hz, 2H); ^{13}C NMR (100 MHz, CDCl_3): δ 12.3, 43.8, 106.2, 149.8, 152.1;

(2) To a flask charged with DMEA (0.8 mL, 8 mmol) and hexane (10 mL) at -5 °C was dropwise added *n*-BuLi (1.6 mol/L in hexane, 7 mL, 11.2 mmol), then the mixture was stirred at -5 °C for 30 min, followed by addition of 4-(*N,N*-diethylamino)pyridine (600 mg, 4 mmol). The mixture was stirred at 0 °C for 1 h. The flask was placed at -78 °C and a solution of DMF (0.64 mL, 8 mmol) in 5 mL of THF was added dropwise. The mixture was stirred at 0 °C for another 1.5 h. The reaction was quenched by adding 20 mL of water, and extracted with ethyl acetate. The organic phase was concentrated and the residue was purified on flash column to give 4-aldehyde as yellow oil (200 mg, 28%).

Yellow oil. Yield: 200 mg, 28%. ^1H NMR (400 MHz, CDCl_3 , TMS): δ 1.20 (t, $J = 7.2$ Hz, 6H), 3.42 (q, $J = 7.2$ Hz, 4H), 6.63 (dd, $J = 2.8, 6.0$ Hz, 1H), 7.14 (d, $J = 2.8$ Hz, 1H), 8.33 (d, $J = 6.0$ Hz, 1H), 9.97 (s, 1H); ^{13}C NMR (100 MHz, CDCl_3): δ 12.1, 43.9, 104.0, 109.5, 150.2, 152.6, 153.2, 194.5;

(3) To the solution of 4-(*N,N*-diethylamino)pyridine-2-carboxaldehyde (200 mg, 1.12 mmol) in dichloromethane (10 mL) was dropwise added ethylenediamine (0.08 mL, 1.15 mmol). The mixture was stirred for 1 h, and then was cooled to 0 °C. *N*-Bromosuccinimide (205 mg, 1.15 mmol) was added and the mixture was stirred overnight. Following the general workup procedure in Section 2.1, crude product 2-(4,5-dihydro-1*H*-imidazol-2-yl)-4-(*N,N*-diethylamino)-pyridine was obtained in quantitative yield. This product was directly used in next step without further purification.

(4) To a solution of ligand (ca. 1.12 mmol) in 10 ml of DCM was added the powder of $[\text{Cp}^*\text{IrCl}_2]_2$ (0.5 mmol, 400 mg). The resultant orange solution was stirred overnight. Following the general workup procedure in Section 2.2, desired product **TC-2** was obtained in 82% yield.



TC-2

Yellow powder. M.p. > 300 °C. Yield: 370 mg, 60%. ^1H NMR (400 MHz, CDCl_3 , TMS): δ 1.61 (s, 6H), 1.73 (s, 15H), 3.43-3.63 (m, 4H), 4.03-4.16 (m, 4H), 6.52 (dd, $J = 2.6, 6.6$ Hz, 1H), 8.02 (d, $J = 6.8$ Hz, 1H), 8.38 (s, 1H), 10.23 (brs, 1H); ^{13}C NMR (100 MHz, CDCl_3): δ 9.2, 12.4, 14.2, 21.1, 46.2, 51.7, 60.4, 86.4, 108.9, 111.2, 146.3, 148.9, 153.4, 170.4; HRMS (ESI) for $\text{C}_{22}\text{H}_{33}\text{N}_4\text{ClIr}$ (M^+), (Calc.) 581.2023, found 581.2010.

3. Optimization of reaction conditions

3.1. Procedure for preparation of catalyst solutions

- (1) Iridium catalysts (0.0025 mmol, 1.4 mg for **TC-3, TC-4, TC-5, TC-6, TC-7**; 1.5 mg for **TC-1, TC-2, TC-8**) was dissolved to 5.0 mL of deionized water in a 5-mL volumetric flask to obtain the desired catalyst solution at **0.0005 mol/L**.
- (2) Iridium catalyst **TC-3** (1.4 mg, **0.0025 mmol**) was diluted to 2.5 ml with deionized water, to obtain a **0.001 mol/L** catalyst solution.
- (3) Iridium catalyst **TC-3** (1.4 mg, **0.0025 mmol**) was diluted to 2.5 ml with absolute ethanol to obtain a **0.001 mol/L** catalyst solution.
- (4) 1.0 mL of **0.0005 mol/L** solution of **TC-7** was diluted to 5.0 mL with deionized water to obtain a **0.0001 mol/L** solution.
- (5) 1.0 mL of **0.0005 mol/L** solution of **TC-7** was diluted to 10.0 mL with deionized water to obtain a **0.00005 mol/L** solution.
- (6) 1.0 mL of **0.0001 mol/L** solution of **TC-7** was diluted to 10.0 mL with deionized water to obtain a **0.00001 mol/L** solution.
- (7) 1.0 mL of **0.00005 mol/L** solution of **TC-7** was diluted to 10.0 mL with deionized water to obtain a **0.000005 mol/L** solution.
- (8) 1.0 mL of **0.000005 mol/L** solution of **TC-7** was diluted to 10.0 mL with deionized water to obtain a **0.0000005 mol/L** solution.

3.2. General procedure for initial optimization of reaction conditions in open air (Table S1 in ESI)

(1) Procedures for the reactions in entries 1-8, Table S1 (catalyst loading 0.1 mol%).

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the solution of catalyst (**Cat. TC-1, TC-2, TC-3, TC-4, TC-5, TC-6, TC-7, TC-8**) in deionized water (0.5 mL, **0.0005 mol/L**), and ethanol (0.5 ml). The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (38 µL, **1.0 mmol**) in one portion. The resultant reaction mixture was stirred for 1h in open air. After cooling to room temperature, diluting with water (1.5 mL), extracting with ethyl acetate (2 mL x 3), and concentration under reduced pressure, the crude residue was submitted to ¹H NMR to determine the conversion of substrates.

(2) Procedures for the reactions in entries 9-13, Table S1.

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the solution of catalyst **TC-3** in deionized water (0.5 mL, **0.0005 mol/L**), and the indicated alcohols or deionized H₂O (0.5 ml) as indicated in entries 9-13, Table S1. The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (38 µL, **1.0 mmol**) in one portion. Similar workup as above gave the conversion values.

(3) Procedures for the reactions in entries 14-18, Table S1.

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the catalyst solution and ethanol (for detailed amount, see below). The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (38 µL, **1.0 mmol**) in one

portion. Similar workup as above gave the conversion values.

Entry 14, Table S1, H₂O: EtOH = 1:2. Catalyst solution of **TC-3** in water (0.25 mL, **0.001** mol/L), H₂O (0.08 ml), and EtOH (0.66 ml).

Entry 15, Table S1, H₂O: EtOH = 1:3. Catalyst solution of **TC-3** in water (0.25 mL, **0.001** mol/L), and EtOH (0.75 ml).

Entry 16, Table S1, H₂O: EtOH = 0:1. Catalyst solution of **TC-3** in ethanol (0.25 mL, **0.001** mol/L), and EtOH (0.75 ml).

Entry 17, Table S1, H₂O: EtOH = 2:1. Catalyst solution of **TC-3** in water (0.50 mL, **0.0005** mol/L), H₂O (0.16 mL), and EtOH (0.33 ml).

Entry 18, Table S1, H₂O: EtOH = 4:1. Catalyst solution of **TC-3** in water (0.50 mL, **0.0005** mol/L), H₂O (0.30 mL), and EtOH (0.20 ml).

(4) Procedures for the reactions in entries 19-22, Table S1.

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the catalyst solution of **TC-3** in water (0.50 mL, **0.0005** mol/L), deionized H₂O (0.16 mL), EtOH (0.33 ml), and 0.25 mmol of acid as indicated in entries 19-22, Table S1. The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (38 μL, **1.0** mmol) in one portion. Similar workup as above gave the conversion values.

(5) Procedures for the reactions in entries 23-25, Table S1.

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the catalyst solution of **TC-3** in water (0.50 mL, **0.0005** mol/L), deionized H₂O (0.16 mL), and EtOH (0.33 ml). The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (76 μL, 2 mmol, 8 equiv; 152 μL, 3 mmol, 12 equiv; 190 μL, 4 mmol, 16equiv) in one portion. Similar workup as above gave the conversion values.

(6) Procedures for the reactions in entries 26-29, Table S1.

To a 5-mL reaction tube was sequentially added acetophenone (30 mg, 0.25 mmol), the catalyst solution of **TC-3** in water (0.50 mL, **0.0005** mol/L), deionized H₂O (0.16 mL), and EtOH (0.33 ml). The tube was immersed in a preheated 80 °C oil-bath, followed by addition of formic acid (152 μL, 3 mmol, 12 equiv.) in one portion. The resultant reaction mixture was stirred for indicated time entries 26-29, Table S1 (1.5 h, 2 h, 3 h, 8 h). Similar workup as above gave the conversion values.

Table S1 Initial optimization of reaction conditions in open air. ^a

Tang's catalysts (TCs)

Entry	Catalyst (mol%)	HCOOH (equiv.)	Solvent (v:v)	Additive	Time (h)	Conversion (%) ^b
1	TC-1 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	25
2	TC-2 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	30

3	TC-3 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	42
4	TC-4 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	26
5	TC-5 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	39
6	TC-6 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	28
7	TC-7 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	38
8	TC-8 (0.1)	4	H ₂ O-EtOH (1:1)	-	1	10
9	TC-3 (0.1)	4	H ₂ O- ⁱ PrOH (1:1)	-	1	18
10	TC-3 (0.1)	4	H ₂ O- ^t BuOH (1:1)	-	1	16
11	TC-3 (0.1)	4	H ₂ O-CF ₃ CH ₂ OH (1:1)	-	1	40
12	TC-3 (0.1)	4	H ₂ O-MeOH (1:1)	-	1	52
13	TC-3 (0.1)	4	H ₂ O	-	1	36
14	TC-3 (0.1)	4	H ₂ O-EtOH (1:2)	-	1	9
15	TC-3 (0.1)	4	H ₂ O-EtOH (1:3)	-	1	7
16	TC-3 (0.1)	4	H ₂ O-EtOH (0:1)	-	1	trace
17	TC-3 (0.1)	4	H ₂ O-EtOH (2:1)	-	1	48
18	TC-3 (0.1)	4	H ₂ O-EtOH (4:1)	-	1	46
19	TC-3 (0.1)	4	H ₂ O-EtOH (2:1)	HCl	1	0
20	TC-3 (0.1)	4	H ₂ O-EtOH (2:1)	H ₂ SO ₄	1	29
21	TC-3 (0.1)	4	H ₂ O-EtOH (2:1)	AcOH	1	43
22	TC-3 (0.1)	4	H ₂ O-EtOH (2:1)	TsOH	1	21
23	TC-3 (0.1)	8	H ₂ O-EtOH (2:1)	-	1	62
24	TC-3 (0.1)	12	H ₂ O-EtOH (2:1)	-	1	79
25	TC-3 (0.1)	16	H ₂ O-EtOH (2:1)	-	1	76
26	TC-3 (0.1)	12	H ₂ O-EtOH (2:1)	-	1.5	83
27	TC-3 (0.1)	12	H ₂ O-EtOH (2:1)	-	2	80
28	TC-3 (0.1)	12	H ₂ O-EtOH (2:1)	-	3	86
29	TC-3 (0.1)	12	H ₂ O-EtOH (2:1)	-	8	95

^aReactions were conducted on 0.25-mmol scale in open air. All the chemicals were used directly as commercially received.

^bYields based on the ¹H NMR spectra of the crude reaction mixtures.

3.3. Procedure for degassing formic acid.

Formic acid (50 mL) was added to a 100-ml Schlenk flask, and was freeze-dried with liquid nitrogen. The air inside was then removed, and the solid formic acid was allowed to stand at reduced pressure for 10 min. Then the flask was back filled with nitrogen, and warmed to room temperature. This procedure sequence was repeated three times. The degassed formic acid was protected under nitrogen atmosphere, and used in the transfer hydrogenation of ketones.

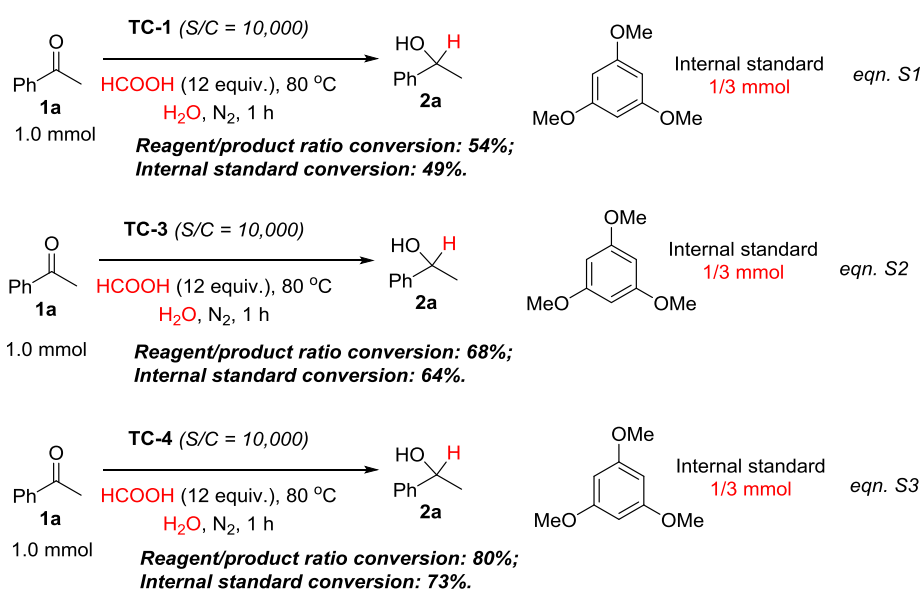
3.4. Procedure for optimization of reaction conditions under nitrogen atmosphere.

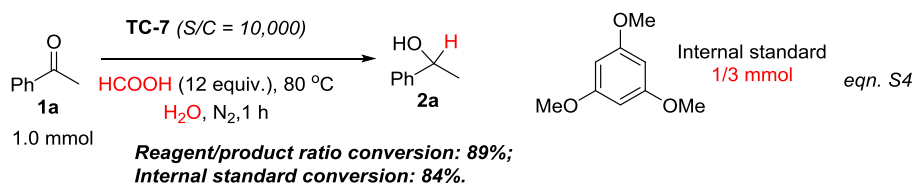
To a 10-mL Schlenk tube was sequentially added acetophenone (120 mg, 1 mmol), 2 mL of the **TC** catalyst solution in deionized water (0.00005 mol/L for $S/C = 10000$; 0.00001 mol/L for $S/C = 50000$; 0.000005 mol/L for $S/C = 100000$). The mixture was degassed three times according to the procedure described in Section 3.3, and protected under nitrogen atmosphere. The tube was immersed in a preheated 80 °C oil-bath for 5 min, followed by slow addition of formic acid (0.46 mL, 12 mmol) in 1 min. The resultant reaction mixture was stirred for indicated time shown in Table 1 in the full text under nitrogen atmosphere. After cooling to room temperature, diluting with water (3 mL), extracting with ethyl acetate (5 mL x 3), and concentration under reduced pressure, the crude residue was submitted to ^1H NMR to determine the conversion of substrates.

4. Two methods to determine the yields of 1-phenylethanol during reaction optimization (yield-confirming studies).

The reactions in Table 1, entries 1, 3, 4, and 7 were repeated according to the procedures described in Section 3.4. After cooling to room temperature, internal standard 1,3,5-trimethoxybenzene (1/3 mmol, 56.06 mg) was added to the mixtures. After diluting with water (3 mL), extracting with ethyl acetate (5 mL x 3), and concentration under reduced pressure, the crude residue was submitted to ^1H NMR to determine the conversion of substrates. The results are listed in Scheme S1.

As shown in Scheme S1, very similar conversions are obtained from reagent/product ratio method and internal standard method. More importantly, the conversions from these two different methods do not change the conclusions.





Scheme S1. Two methods to determine the yields of 1-phenylethanol (**2a**) during reaction optimization.

5. pH-Dependent transfer hydrogenation of acetophenone

HCOONa (6.80g, 100 mmol) was diluted to 10.00 ml in a volumetric flask to afford a 10.0 mol/L solution, which was degassed according to the procedures .

To a 10-mL Schlenk tube was sequentially added acetophenone (120 mg, 1 mmol) and 2.0 mL of the **TC-7** catalyst solution in deionized water (0.00005 mol/L for $S/C = 10000$). The mixture was degassed three times according to the procedure described in Section 3.3, and protected under nitrogen atmosphere. The tube was immersed in a preheated 80 °C oil-bath for 5 min, followed by slow addition of degassed formic acid and the above degassed HCOONa solution. The detailed added amount was shown in Table S2. The resultant reaction mixture was stirred for 1 h under nitrogen atmosphere. After cooling to room temperature, diluting with water (3 mL), extracting with ethyl acetate (5 mL x 3), and concentration under reduced pressure, the crude residue was submitted to ^1H NMR to determine the yields.

Table S2. The HCOOH-HCOONa solutions with different pH values prepared by varying the molar ratios of HCOOH and HCOONa.

pH of reaction media ^a		1.46	2.48	2.99	3.37	3.76	4.18	5.58	8.88
HCOOH	mL	0.46	0.38,	0.30	0.23	0.15	0.076	0.038	0
	mmol	12.0	10.0	8.0	6.0	4.0	2.0	1.0	0
HCOONa solution	mL	0	0.20	0.40	0.60	0.8	1.0	1.1	1.2
	mmol	0	2.0	4.0	6.0	8.0	10.0	11.0	12.0
Yield (%)		88	68	32	25	13	8	3	0

^aThe pH values of the reaction media were monitored by diluting the HCOOH and HCOONa solution (10 mol/L) with 2.0 mL of deionized water.

6. General procedure for transfer hydrogenation of ketones

To a 10-mL Schlenk tube was sequentially added ketone (1 mmol), 2 mL of the **TC-7** catalyst solution in deionized water (0.00005 mol/L for $S/C = 10000$; 0.00001 mol/L for $S/C = 50000$; 0.000005 mol/L for $S/C = 100000$). The mixture was degassed three times

according to the procedure described in Section 3.3, and protected under nitrogen atmosphere. The tube was immersed in a preheated 80 °C oil-bath for 5 min, followed by slow addition of formic acid (0.46 mL, 12 mmol) in 1 min. The resultant reaction mixture was stirred for indicated time shown in Table 1 in the full text under nitrogen atmosphere. After cooling to room temperature, diluting with water (3 mL), extracting with ethyl acetate (5 mL x 3), the reaction was first evaluated by TLC analysis. For volatile products, dichloromethane was used to extract. In cases where reactions are complete, direct concentration of the organic phase under reduced pressure afforded desired products in quantitative yields. For the incomplete reactions, the crude residues obtained by concentration of the organic phase under reduced pressure was purified by column chromatography on silica gel with PE and EA as eluent.

7. Gram-scale reduction of ninhydrin

To a 250-ml flask was sequentially added ninhydrin (**3o**, 8.9 g, 50 mmol), **TC-7** catalyst (2.8 mg, 0.005 mmol) and deionized water (100 ml). The mixture was degassed only once according to the procedure described in Section 3.3, and protected under nitrogen atmosphere. The flask was immersed in a preheated 80 °C oil-bath for 10 min, followed by slow addition of formic acid (not degassed, 34.2 mL, 0.9 mol) in 1 min. The resultant reaction mixture was stirred for 3 h under nitrogen atmosphere. TLC indicated the full conversion of substrate. After cooling to room temperature, the product (**4o**) was precipitated from the solution, separated by filtration, and dried under vacuum.

White solid; yield: 8.3 g, 99%.

8. Procedure for identification of iridium hydride in HCOONa solution

TC-7 (8.0 mg, 14 μ mol) was added to an NMR tube, followed by addition of sodium formate (3.8 mg, 56 μ mol, 4 equiv.) in D₂O (0.5 mL) under nitrogen atmosphere. Then the yellow solution was submitted to ¹H NMR test immediately and after 12 h. The obtained spectra are presented as following in Fig. S1.

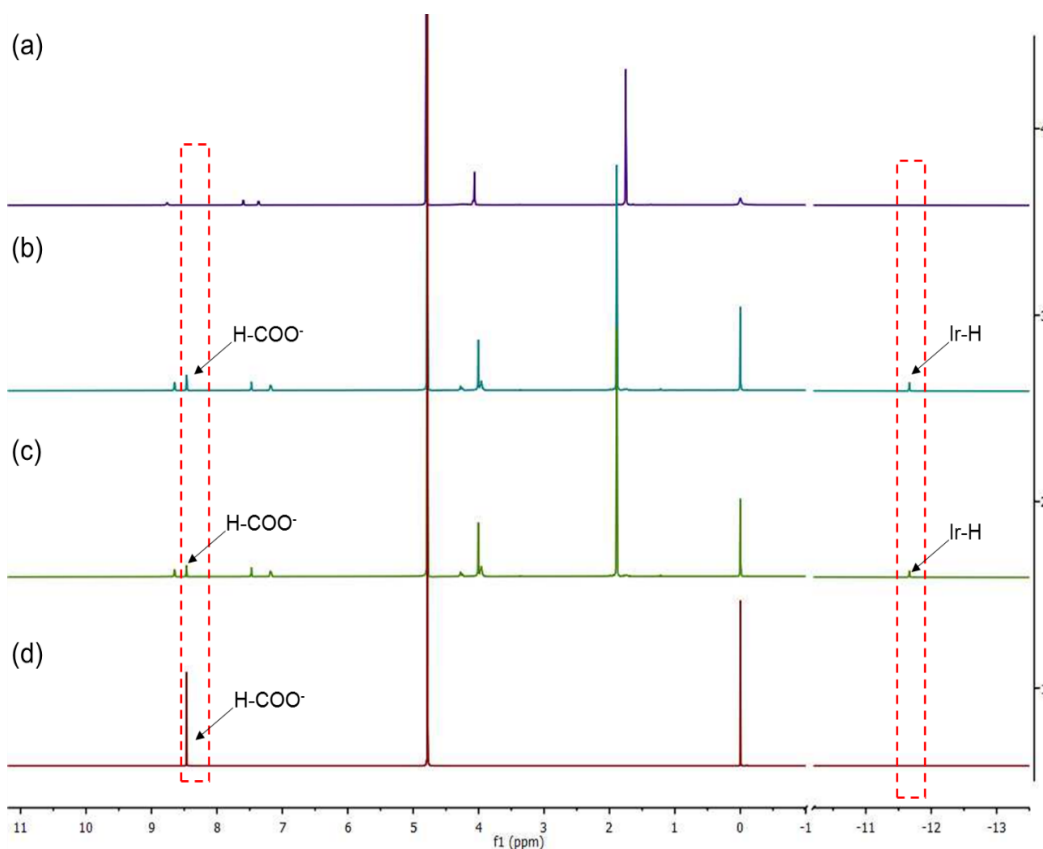


Figure S1. ^1H NMR spectra of different systems in D_2O . (a) **TC-3** only. (b) Solution of **TC-3** with sodium formate (1:4). (c). The same solution as b after 12h, (d). Sodium formate only.

9. Kinetic isotope effect studies.

(1) The procedures at $S/C = 10,000$ with **TC-7** was identical with those described above in Section 5, only with the variation of the reaction scale, reducing reagents and reaction time. The experimental results are summarized in **Scheme S1**.

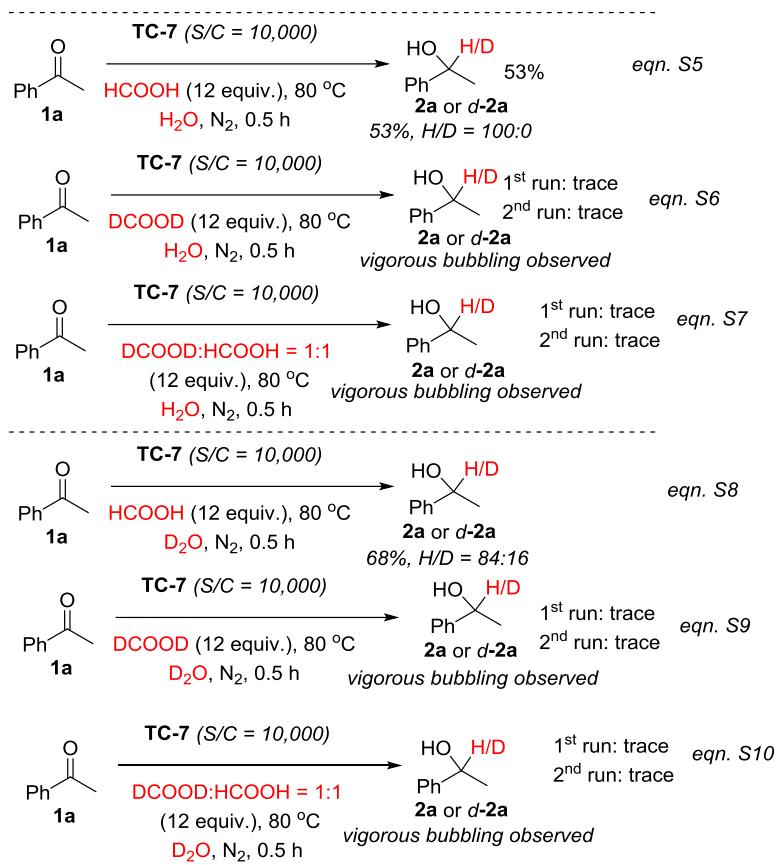
(2) General Procedure at $S/C = 100$ with **TC-7**.

To a 5 mL reaction tube was sequentially added acetophenone (30 μL , 0.25 mmol), **TC-7** catalyst (1.4 mg, $S/C=100$) and deuterated water (0.5 mL, 99.9% D). The mixture was degassed only once according to the procedure described above and protected under nitrogen atmosphere. The tube was immersed in a pre-heated 80 $^\circ\text{C}$ oil-bath for 5 min, followed by slow addition of HCOOH (commercial, 114 μL , 3 mmol, 12 equiv.) or DCOOD (99% D, 95% in D_2O , 120 μL , 3 mmol, 12 equiv.) or the mixture of HCOOH and DCOOD (1:1, molar ratio; HCOOH, 57 μL , 6 equiv.; DCOOD, 60 μL , 6 equiv.) dropwise. The resultant reaction mixture was stirred for 0.5 h under nitrogen atmosphere. After dilution with 1.0 mL of water, 1.5 mL of EtOAc was added. The mixture extracted with EtOAc (1.5 mL x 3), concentrated in vacuum, and submitted to ^1H NMR directly.

1-Phenylethan-1-*d*-1-ol (**d-2a**):

Reported data from Peters's group: ^1H NMR (300 MHz, CDCl_3): δ = 1.49 (t, J = 0.90 Hz, 3H, CH_3), 1.84 (s, 1H, OH), 7.24-7.39 (m, 5H, Ar-H).¹⁹

Our data: ^1H NMR (400 MHz, CDCl_3) δ 7.48 – 7.15 (m, 5H, ArH), 2.00 (brs. 1H, OH), 1.47 (t, J = 1.0 Hz, 3H, CH_3).



Scheme S2. The kinetic isotope studies with TC-7 at $S/C = 10,000$.

10. NMR studies of proton-activated ketones.

Acetophenone (30 μL , 0.25 mmol) was dissolved in the mixture of D_2O (0.5 mL) and formic acid (114 μL , 3 mmol) at room temperature. The solution was directly submitted to ^{13}C NMR. The obtained spectrum is given as following in **Figure S2**.

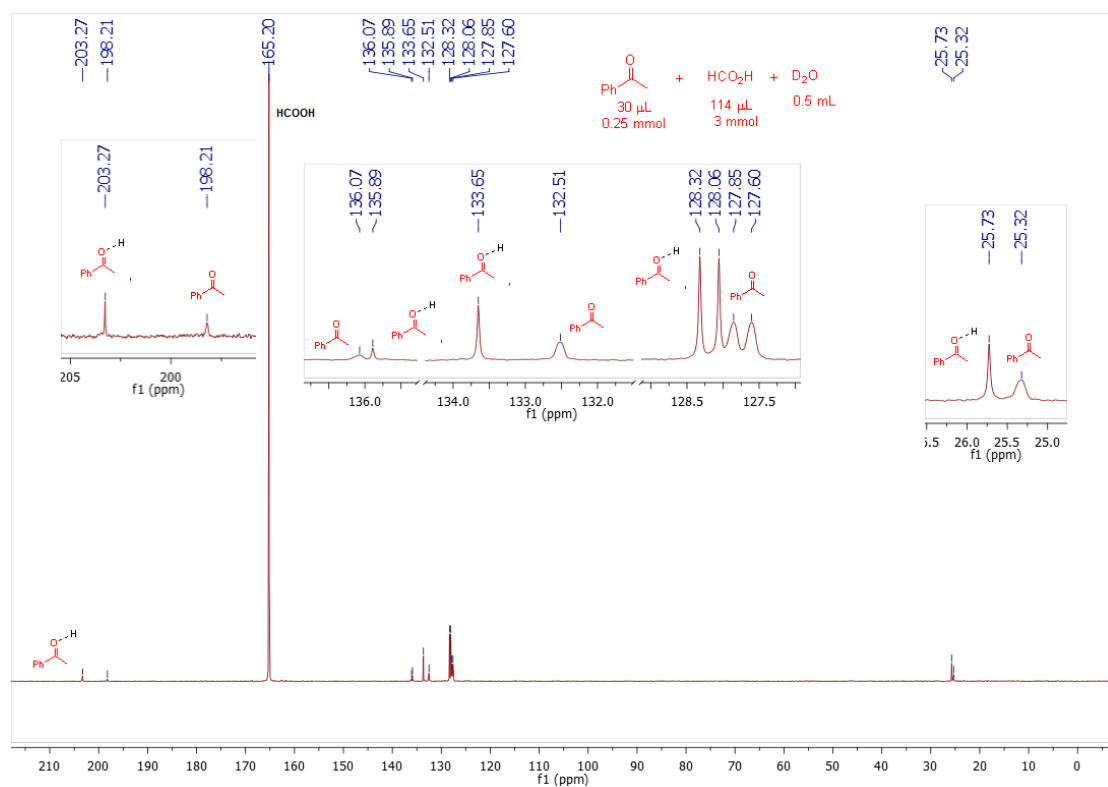
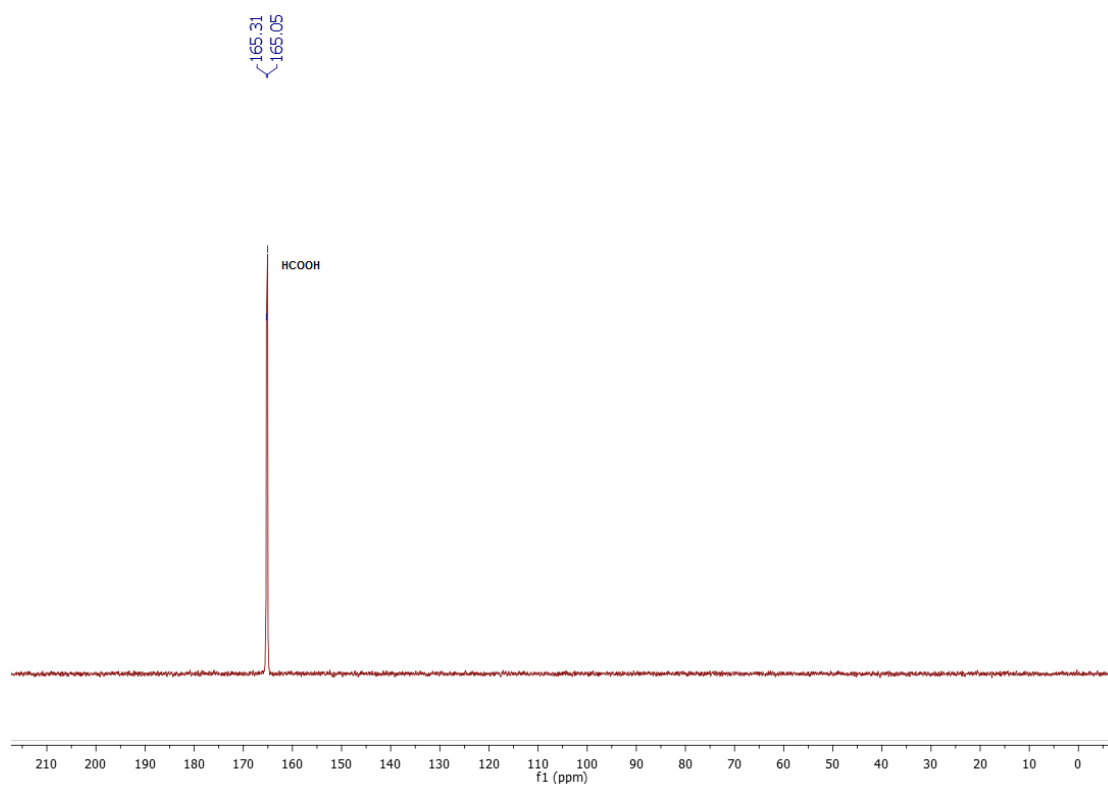


Figure S2. ¹³C NMR spectrum of acetophenone and HCO₂H in D₂O.

11. HCOOH dehydrogenation rates of Tang's catalysts.

To a 10-mL Schlenk tube was sequentially added 2 mL of the Tang's catalysts (TC-1 to TC-8) solution in deionized water (0.00005 mol/L, $S/C = 120,000$, $S = HCOOH$). The solution was degassed three times according to the procedure described in Section 3.3, and protected under nitrogen atmosphere. The tube was immersed in a preheated 80 °C oil-bath for 5 min, followed by addition of formic acid (0.46 mL, 12 mmol) in one portion. The time that it took to completely consume the formic acid (starting from addition to no bubbling) was recorded. The results are summarized in Table S3.

(Note: *This is only a crude evaluation*).

Table S3. Time needed for different catalysts to completely consume 0.46 mL of formic acid.

entry	1	2	3	4	5	6	7	8
R	4-NMe ₂	4-NEt ₂	4-OMe	5-OMe	6-OMe	3-OMe	H	Cl
Catalyst	TC-1	TC-2	TC-3	TC-4	TC-5	TC-6	TC-7	TC-8
Time (h)	3.3	4	3.6	6.5	6	8	9	12

12. Characterization data of products

1-Phenylethanol (2a)²: Yield: 121 mg, 99%; colorless liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.31-7.28 (m, 5H), 4.81 (q, $J = 6.4$ Hz, 1H), 2.00 (brs, 1H), 1.42 (d, $J = 6.4$ Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 145.9, 128.6, 127.6, 125.5, 70.5, 25.3.

1-(3-Methoxyphenyl)ethanol (2b)³: Yield: 151 mg, 99%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.28-7.24 (m, 1H), 6.95-6.94 (m, 2H), 6.81 (dd, $J = 8.0$ Hz, 2.2 Hz, 1H), 4.87 (q, $J = 6.0$ Hz, 1H), 3.81 (s, 3H), 1.90 (brs, 1H), 1.49 (d, $J = 6.4$ Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 159.8, 147.6, 129.5, 117.7, 112.9, 110.9, 70.3, 55.2, 25.1.

1-(2-Methoxyphenyl)ethanol (2c)⁴: Yield: 147 mg, 97%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.25 (dd, $J = 7.3$ Hz, 1.0 Hz, 1H), 7.15 (dt, $J = 8.0$ Hz, 1.6 Hz, 1H), 6.87 (dt, $J = 7.4$ Hz, 0.8 Hz, 1H), 6.78 (dd, $J = 8.0$ Hz, 1.0 Hz, 1H), 5.00 (q, $J = 6.4$ Hz, 1H), 3.76 (s, 3H), 2.65 (brs, 1H), 1.41 (d, $J = 6.4$ Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 156.6, 133.6, 128.3, 126.1, 120.9, 110.5, 66.5, 55.3, 23.0.

1-(4-Tolyl)ethanol (2d)²: Yield: 135 mg, 99%; colorless liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.27 (d, $J = 8.0$ Hz, 2H), 7.10 (d, $J = 7.6$ Hz, 2H), 4.87 (q, $J = 6.0$ Hz, 1H), 2.34 (s, 3H), 1.77 (brs, 1H), 1.48 (d, $J = 6.4$ Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 143.0, 137.3, 129.3, 125.5, 70.4, 25.2, 21.2.

1-(4-Fluorophenyl)ethanol (2e)²: Yield: 132 mg, 94%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.36-7.33 (m, 2H), 7.03 (t, *J* = 8.6 Hz, 2H), 4.92-4.87 (m, 1H), 1.78 (d, *J* = 3.2 Hz, 1H), 1.48 (d, *J* = 6.8 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm) 162.0 (d, *J*_{C-F} = 245.0 Hz), 141.5 (d, *J*_{C-F} = 2.7 Hz), 127.0 (d, *J*_{C-F} = 8.0 Hz), 115.09 (d, *J*_{C-F} = 21.3 Hz), 69.5, 25.1.

1-(2-Fluorophenyl)ethanol (2f)²: Yield: 134 mg, 95%; colorless liquid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.46 (td, *J* = 1.6, 7.6 Hz, 1H), 7.22 (qd, *J* = 1.2, 7.2 Hz, 1H), 7.12 (td, *J* = 1.0, 7.4 Hz, 1H), 6.99 (qd, *J* = 1.0, 8.2 Hz, 1H), 5.16 (d, *J* = 6.4 Hz, 1H), 2.39 (brs, 1H), 1.48 (d, *J* = 6.4 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 159.7 (d, *J*_{C-F} = 243.8 Hz), 132.6 (d, *J*_{C-F} = 13.2 Hz), 128.7 (d, *J*_{C-F} = 8.2 Hz), 126.6 (d, *J*_{C-F} = 4.58 Hz), 124.3 (d, *J*_{C-F} = 3.5 Hz), 115.2 (d, *J*_{C-F} = 21.8 Hz), 64.4 (d, *J*_{C-F} = 3.0 Hz), 24.0.

1-(2-Chlorophenyl)ethanol (2g)⁵: Yield: 125 mg, 80%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.56 (d, *J* = 7.6 Hz, 1H), 7.28 (dd, *J* = 16.4 Hz, 8.4 Hz, 2H), 7.18 (t, *J* = 7.6 Hz, 1H), 5.26 (q, *J* = 6.4 Hz, 1H), 2.37 (brs, 1H), 1.46 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 143.0, 131.5, 129.3, 128.3, 127.1, 126.4, 66.9, 23.5.

1-(4-Chlorophenyl)ethanol (2h)²: Yield: 148 mg, 95%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.33-7.28 (m, 4H), 4.90-4.85 (m, 1H), 1.91 (brs, 1H), 1.47 (d, *J* = 6.8 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 144.2, 133.1, 128.6, 126.8, 69.7, 25.3.

1-(4-Bromophenyl)ethanol (2i)²: Yield: 134 mg, 67%; pale yellow solid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.35 (d, *J* = 8.4 Hz, 2H), 7.10 (d, *J* = 8.0 Hz, 2H), 4.71 (q, *J* = 6.4 Hz, 1H), 3.23 (brs, 1H), 1.34 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 144.7, 131.6, 127.2, 121.2, 69.8, 25.2.

1-(3-Bromophenyl)ethanol (2j)²: Yield: 178 mg, 89%; pale yellow liquid. ¹H NMR (400 MHz, CDCl₃): δ 7.49 (t, *J* = 1.6 Hz, 1H), 7.36 (dt, *J* = 1.4, 7.6 Hz, 1H), 7.24 (d, *J* = 3.8 Hz, 1H), 7.18 (q, *J* = 7.6 Hz, 1H), 4.78 (q, *J* = 6.4 Hz, 1H), 2.63 (brs, 1H), 1.42 (d, *J* = 6.4 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ 148.1, 130.4, 130.1, 128.6, 124.1, 122.6, 69.7, 25.2.

1-(4-(Trifluoromethyl)phenyl)ethanol (2k)²: Yield: 182 mg, 96%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.60 (d, *J* = 8.0 Hz, 2H), 7.48 (d, *J* = 8.0 Hz, 2H), 4.96 (q, *J* = 6.4 Hz, 1H), 1.98 (brs, 1H), 1.50 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm) 149.7, 129.6 (q, *J*_{C-F} = 32.4 Hz), 125.6, 125.37 (q, *J* = 3.6 Hz), 124.1 (q, *J* = 271.8 Hz), 69.7, 25.3.

1-(3-(Trifluoromethyl)phenyl)ethanol (2l)²: Yield: 159 mg, 84%; colorless liquid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.64 (s, 1H), 7.54 (t, *J* = 7.6 Hz, 2H), 7.46 (t, *J* = 7.6 Hz, 1H), 4.95 (q, *J* = 6.4 Hz, 1H), 2.06 (brs, 1H), 1.50 (d, *J* = 6.4 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 146.7, 130.9 (q, *J*_{C-F} = 31.8 Hz), 128.8 (q, *J*_{C-F} = 16.3 Hz), 125.5, 124.2 (q, *J*_{C-F} = 3.8 Hz), 122.8, 122.2 (q, *J*_{C-F} = 3.8 Hz), 69.8, 25.4.

1-(4-Nitrophenyl)ethanol (2m)²: Yield: 166 mg, 99%; yellow solid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 8.17 (d, *J* = 8.8 Hz, 2H), 7.53 (d, *J* = 8.4 Hz, 2H), 5.01 (q, *J* = 6.4 Hz, 1H), 2.28 (brs, 1H), 1.50 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 153.1, 147.1, 126.1, 123.7, 69.5, 25.5.

1-(3-Nitrophenyl)ethanol (2n)²: Yield: 153 mg, 99%; pale yellow liquid. ¹H NMR (400 MHz, CDCl₃): δ (ppm) 8.20 (s, 1H), 8.07 (d, *J* = 8.0 Hz, 1H), 7.69 (d, *J* = 7.6 Hz, 1H), 7.50 (t, *J* = 8.0 Hz, 1H), 4.98 (q, *J* = 6.4 Hz, 1H), 3.24 (brs, 1H), 1.50 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 148.2, 148.0, 131.7, 129.4, 122.2, 120.3, 69.2, 25.3.

4-(1-Hydroxyethyl)benzotrile (2o)²: Yield: 147 mg, 99%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.53 (d, *J* = 8.4 Hz, 2H), 7.42 (d, *J* = 8.4 Hz, 2H), 4.87 (d, *J* = 6.4 Hz, 1H), 3.34 (brs, 1H), 1.41 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 151.4, 132.2, 126.1, 118.9, 110.5, 69.3, 25.2.

1-(Naphthalen-2-yl)ethan-1-ol (2p)²: Yield: 146 mg, 85%; White solid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.71-7.78 (m, 3H), 7.68 (s, 1H), 7.37-7.45 (m, 3H), 4.91 (q, *J* = 6.4 Hz, 1H), 2.62 (brs, 1H), 1.48 (d, *J* = 6.4 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 143.3, 133.4, 132.9, 128.3, 128.0, 127.8, 126.2, 125.8, 124.0, 123.9, 70.4, 25.2.

1-(Furan-2-yl)ethan-1-ol (2q)²: Yield: 96 mg, 86%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.34 (dd, *J* = 1.8 Hz, 0.6 Hz, 1H), 6.30 (dd, *J* = 2.4 Hz, 2.0 Hz, 1H), 6.20-6.18 (m, 1H), 4.32 (q, *J* = 6.6 Hz, 1H), 2.58 (brs, 1H), 1.50 (d, *J* = 6.8 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 157.7, 141.89, 110.2, 105.1, 63.6, 21.3.

1-(Pyridin-2-yl)ethan-1-ol (2r)¹⁶: Yield: 121 mg, 98%; colorless liquid. ¹H NMR (400 MHz, CDCl₃): δ (ppm) 8.50 (d, *J* = 4.8 Hz, 1H), 7.68 (td, *J* = 1.6, 7.8 Hz, 1H), 7.33 (d, *J* = 8.0 Hz, 1H), 7.18 (dd, *J* = 5.4, 7.2 Hz, 1H), 4.90 (q, *J* = 6.6 Hz, 1H), 4.86 (brs, 1H), 1.50 (d, *J* = 6.6 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 163.4, 148.1, 136.9, 122.2, 119.8, 69.1, 24.2.

1-(1-Phenyl)propanol (2s)³: Yield: 78 mg, 57%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.40-7.29 (m, 5H), 4.59 (t, *J* = 6.6 Hz, 1H), 2.24 (s, 1H), 1.90-1.72 (m, 2H), 0.94 (t, *J* = 7.6 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 144.7, 128.4, 127.5, 126.1, 76.0, 31.9, 10.2.

4-Phenylbutan-2-ol (2t)¹⁷: Yield: 119 mg, 81%; Colorless liquid. ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.24-7.29 (m, 2H), 7.16-7.21 (m, 3H), 3.82 (sxt, *J* = 6.2 Hz, 1H), 2.63-2.79 (m, 2H), 1.73-1.80 (m, 2H), 1.56 (brs, 1H), 1.22 (d, *J* = 6.2 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 142.1, 128.4 (two carbons), 125.8, 67.5, 40.9, 32.3, 23.6.

2-Heptanol (2u)⁶: Yield: 65 mg, 58%; colorless liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 3.83-3.75 (m, 1H), 1.48-1.25 (m, 9H), 1.18 (d, *J* = 6.0 Hz, 3H), 0.89 (t, *J* = 7.0 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 68.2, 39.3, 31.9, 25.5, 23.5, 22.6, 14.0.

1-Cyclohexylethanol (2w)³: Yield: 83 mg, 65%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 3.52 (qui, *J* = 6.2 Hz, 1H), 1.85-1.63 (m, 6H), 1.29-1.09 (m, 4H), 1.13 (d, *J* = 6.0 Hz, 3H), 1.03-0.88 (m, 2H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 72.2, 45.1, 28.7, 28.4, 26.5, 26.2, 26.1, 20.3.

1-Cyclohexanol (2x)²: Yield: 100 mg, 99%; colorless liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 3.60-3.54 (m, 1H), 1.91 (s, 1H), 1.88-1.84 (m, 2H), 1.73-1.66 (m, 2H), 1.54-1.48 (m, 1H), 1.31-1.08 (m, 5H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 70.4, 35.6, 25.6, 24.3.

1-Cycloheptanol (2y)⁷: Yield: 73 mg, 65%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 3.81 (hept, *J* = 4.2 Hz, 1H), 1.92-1.85 (m, 2H), 1.84 (s, 1H), 1.66-1.48 (m, 8H), 1.41-1.33 (m, 2H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 72.7, 37.5, 28.0, 22.6.

1-(1,2,3,4-Tetrahydro)naphthalenol (2z)⁸: Yield: 102 mg, 69%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.44 (dd, *J* = 5.2 Hz, 4.0 Hz, 1H), 7.23-7.20 (m, 2H), 7.13-7.10 (m, 1H), 4.78 (t, *J* = 4.6 Hz, 1H), 2.88-2.70 (m, 2H), 2.05-1.73 (m, 5H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 138.9, 137.2, 129.1, 128.8, 127.6, 126.3, 68.2, 32.4, 29.3, 18.9.

3-(1-Hydroxyethyl)phenol (2aa)⁹: Yield: 138 mg, 99%; white solid; ¹H NMR (400 MHz, DMSO-*d*₆) δ (ppm): 9.26 (s, 1H), 7.11 (t, *J* = 7.4 Hz, 1H), 6.83 (t, *J* = 2.0 Hz, 1H), 6.77 (d, *J* = 7.6 Hz, 1H), 6.65 (dd, *J* = 8.0 Hz, 2.0 Hz, 1H), 5.11 (brs, 1H), 6.70 (q, *J* = 6.4 Hz, 1H), 1.30 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ (ppm): 157.2, 149.0, 129.0, 116.1, 113.5, 112.3, 68.2, 26.0

4-(1-Hydroxyethyl)benzoic acid (2ab)¹⁰: Yield: 108 mg, 65%; white solid; ¹H NMR (400 MHz, acetone-*d*₆) δ (ppm): 8.01 (d, *J* = 8.4 Hz, 2H), 7.52 (d, *J* = 8.4 Hz, 2H), 4.96 (q, *J* = 6.4 Hz, 1H), 1.43 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CD₃COCD₃-*d*₆) δ (ppm): 167.7, 153.4, 130.4, 129.8, 126.2, 69.6, 26.1.

1-Phenoxypropan-2-ol (4a)¹¹: Yield: 146 mg, 96% (S/C=10000), 138 mg, 96% (S/C=50000), colorless liquid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.25 (td, *J* = 1.2, 7.4 Hz, 2H), 6.93 (t, *J* = 7.4 Hz, 1H), 6.88 (d, *J* = 8.0 Hz, 2H), 4.12-4.18 (m, 1H), 3.86 (dd, *J* = 3.4, 9.2 Hz, 1H), 3.76 (dd, *J* = 7.6, 9.2 Hz, 1H), 2.93 (brs, 1H), 1.24 (d, *J* = 6.4 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 158.6, 129.6, 121.1, 114.6, 73.3, 66.2, 18.9.

1-Phenylethane-1,2-diol (4b)¹⁸: Yield: 124 mg, 90%, white solid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.23-7.33 (m, 5H), 4.73 (dd, *J* = 3.2, 8.4 Hz, 1H), 3.85 (brs, 2H), 3.65 (dd, *J* = 3.2, 11.6 Hz, 1H), 3.57 (dd, *J* = 8.4, 11.6 Hz, 1H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 140.5, 128.5, 127.9, 126.1, 74.7, 68.0.

2-Hydroxy-2-phenylethyl acetate (4c)¹⁹. Yield: 163 mg, 85%, colorless liquid. ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.29-7.38 (m, 5H), 4.93 (dd, *J* = 3.4, 8.4 Hz, 1H), 4.25 (dd, *J* = 3.4, 11.6 Hz, 1H), 4.13 (dd, *J* = 8.4, 11.6 Hz), 2.78 (brs, 1H), 2.08 (s, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 171.3, 139.8, 128.6, 128.2, 126.2, 72.4, 69.3, 20.9.

3-Hydroxy-3-phenylpropanenitrile (4d)¹¹: Yield: 147 mg, 99%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.30-7.20 (m, 5H), 4.85 (t, *J* = 6.2 Hz, 1H), 3.28 (br, 1H), 2.58 (d, *J* = 6.0 Hz, 2H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 144.1, 128.8, 128.6, 125.6, 117.6, 69.7, 27.8.

3-Hydroxy-3-(4-(trifluoromethyl)phenyl)propanenitrile (4e)¹²: Yield: 214 mg, 99%, (S/C=10000); 161mg, 75%, (S/C=50000); pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.63 (d, *J* = 8.0 Hz, 2H), 7.49 (d, *J* = 8.0 Hz, 2H), 5.07 (t, *J* = 6.0 Hz, 1H), 3.42 (brs, 1H), 2.78-2.70 (m, 2H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 145.0, 130.9 (q, *J*_{C-F} = 32.6 Hz), 126.1, 125.9 (q, *J*_{C-F} = 3.5 Hz), 124.0 (q, *J*_{C-F} = 272.2), 117.2, 69.2, 28.0.

3-(4-Fluorophenyl)-3-hydroxypropanenitrile (4f)¹¹: Yield: 159 mg, 97%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.37 (dd, *J* = 8.4 Hz, 5.2Hz, 2H), 7.07 (t, *J* = 8.6 Hz, 2H), 5.01 (t, *J* = 6.0 Hz, 1H), 2.96 (brs, 1H), 2.73 (d, *J* = 6.0 Hz, 2H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 162.9 (d, *J*_{C-F} = 247.4 Hz), 137.0 (d, *J*_{C-F} = 1.2 Hz), 127.5 (d, *J*_{C-F} = 8.3 Hz), 117.4, 115.9 (d, *J*_{C-F} = 21.7 Hz), 69.5, 28.2.

3-Hydroxy-butyric acid ethyl ester (4g)¹³: Yield: 117 mg, 89%; colorless liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 4.17 (q, *J* = 7.2 Hz, 2H), 2.79 (brs, 1H), 2.50-2.37 (m, 2H), 1.27 (t, *J* = 7.2 Hz, 3H), 1.22 (d, *J* = 6.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 173.1, 64.34, 60.8, 42.9, 22.6, 14.3.

Ethyl 4,4,4-trifluoro-3-hydroxybutanoate (4h)¹¹: Yield: 186 mg, 99%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 4.47-4.39 (m, 1H), 4.19 (q, *J* = 7.2 Hz, 2H), 3.90 (brs, 1H), 2.73-2.62 (m, 2H), 1.27 (t, *J* = 7.2 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃) δ (ppm): 171.0, 124.6 (q, ²*J*_{C-F} = 281.8 Hz), 67.3 (q, ³*J*_{C-F} = 33.3 Hz), 61.7, 39.9, 14.1.

Ethyl 2-hydroxy-2-phenylacetate (4i)¹¹: Yield: 167 mg, 93%, Colorless liquid; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 7.39-7.43 (m, 2H), 7.28-7.37 (m, 3H), 5.15 (brs, 1H), 4.13-4.26 (m, 2H), 1.20 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 173.7, 138.6, 128.6, 128.4, 126.6, 72.9, 62.2, 14.0.

2-Fluoro-1-phenylethan-1-ol (4j)¹¹: Yield: 140 mg, 99%; pale yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.39-7.32 (m, 5H), 5.02-4.94 (m, 1H), 4.56-4.33 (m, 2H), 3.16 (brs, 1H). ¹H NMR (400 MHz, CDCl₃) δ (ppm): 138.4, 128.6, 128.4, 126.4, 87.1 (d, *J* = 174.7 Hz), 72.9 (d, *J* = 19.8 Hz).

2,2,2-Trifluoro-1-phenylethan-1-ol (4k)¹¹: Yield: 176 mg, 99%; yellow liquid; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 7.49-39 (m, 5H), 5.00 (q, *J* = 6.8 Hz, 1H), 2.72 (brs, 1H). ¹H NMR (400 MHz, CDCl₃) δ (ppm): 134.1, 129.7, 128.8, 127.6, 124.4 (q, ²*J*_{C-F} = 282.1 Hz), 73.0 (q, ³*J*_{C-F} = 32.3 Hz).

2-Hydroxy-3-phenylpropanoic acid (4l)¹⁴: Yield: 166 mg, 99%; white solid; ¹H NMR (400

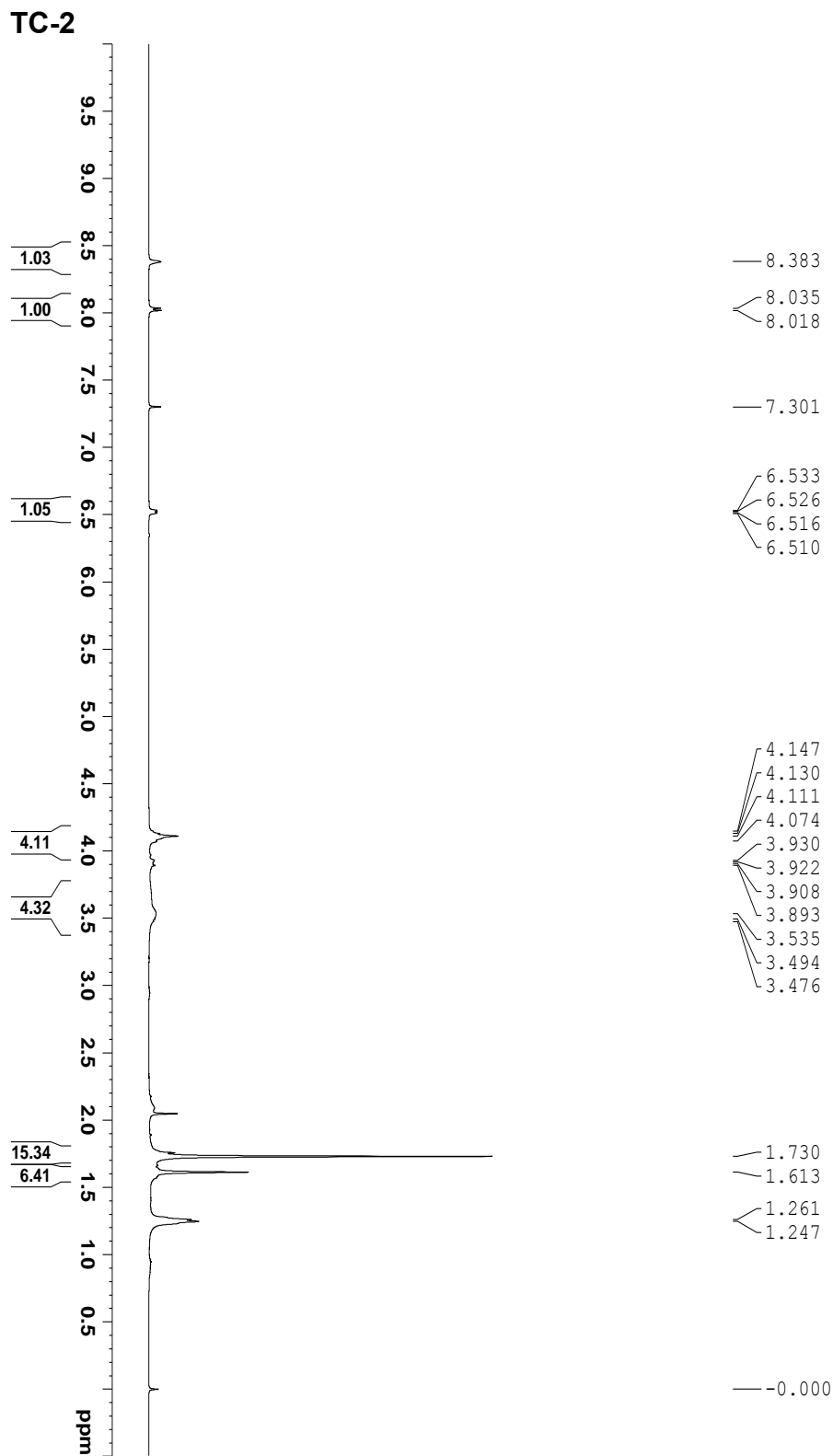
MHz, acetone-*d*₆) δ (ppm): 7.33-7.19 (m, 5H), 4.60 (dd, *J* = 7.8 Hz, 4.2Hz, 1H), 3.15 (dd, *J* = 14.0 Hz, 3.6Hz, 1H), 2.96 (dd, *J* = 14.0 Hz, 3.6 Hz, 1H). ¹H NMR (400 MHz, CD₃COCD₃-*d*₆) δ (ppm): 175.6, 138.4, 130.3, 128.8, 127.1, 71.9, 40.9.

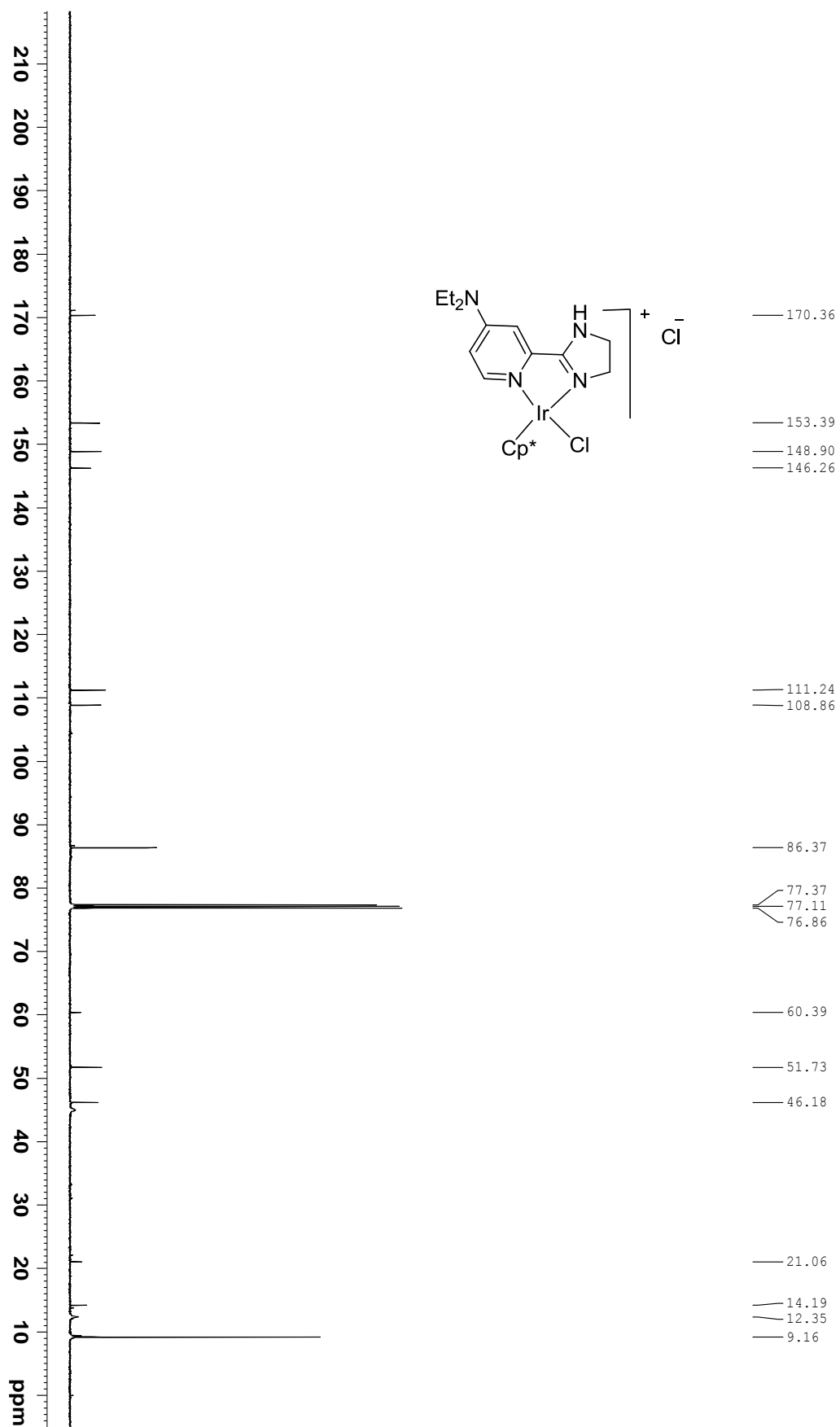
2,3-Dihydro-1H-indene-1,2,3-triol (4o): Yield: 8.3 g, 99%; white solid; ¹H NMR (400 MHz, DMSO-*d*₆) δ (ppm): 7.26 (br, 4H), 5.44 (d, *J* = 6.8 Hz, 2H), 5.39 (d, *J* = 5.6 Hz, 1H), 4.54 (t, *J* = 6.4 Hz, 2H), 3.73 (q, *J* = 6.4 Hz, 1H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ (ppm): 141.7, 127.5, 123.3, 89.0, 76.0.

13. Reference

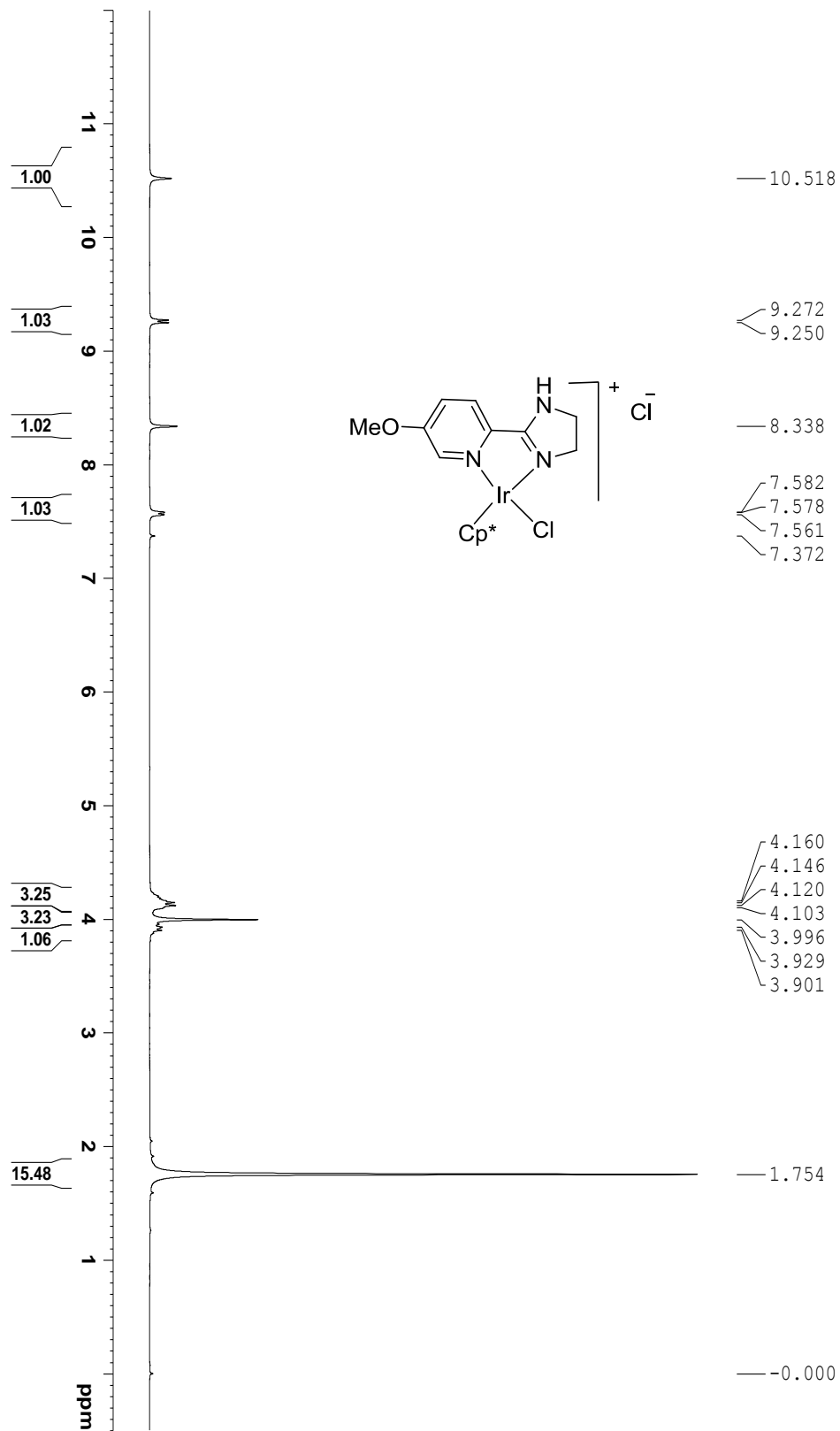
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14. Copies of ^1H NMR and ^{13}C NMR spectra of catalysts and products



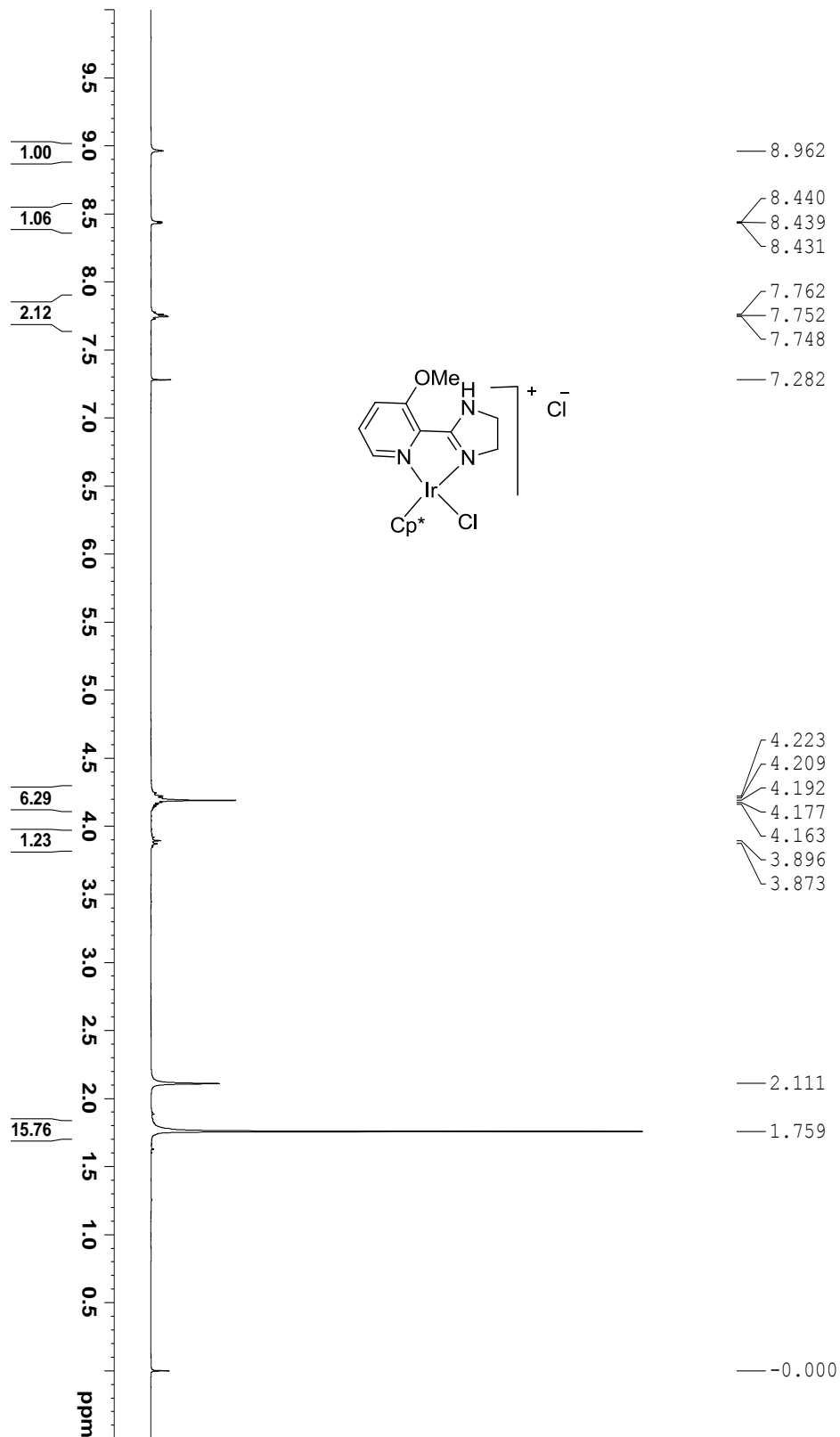


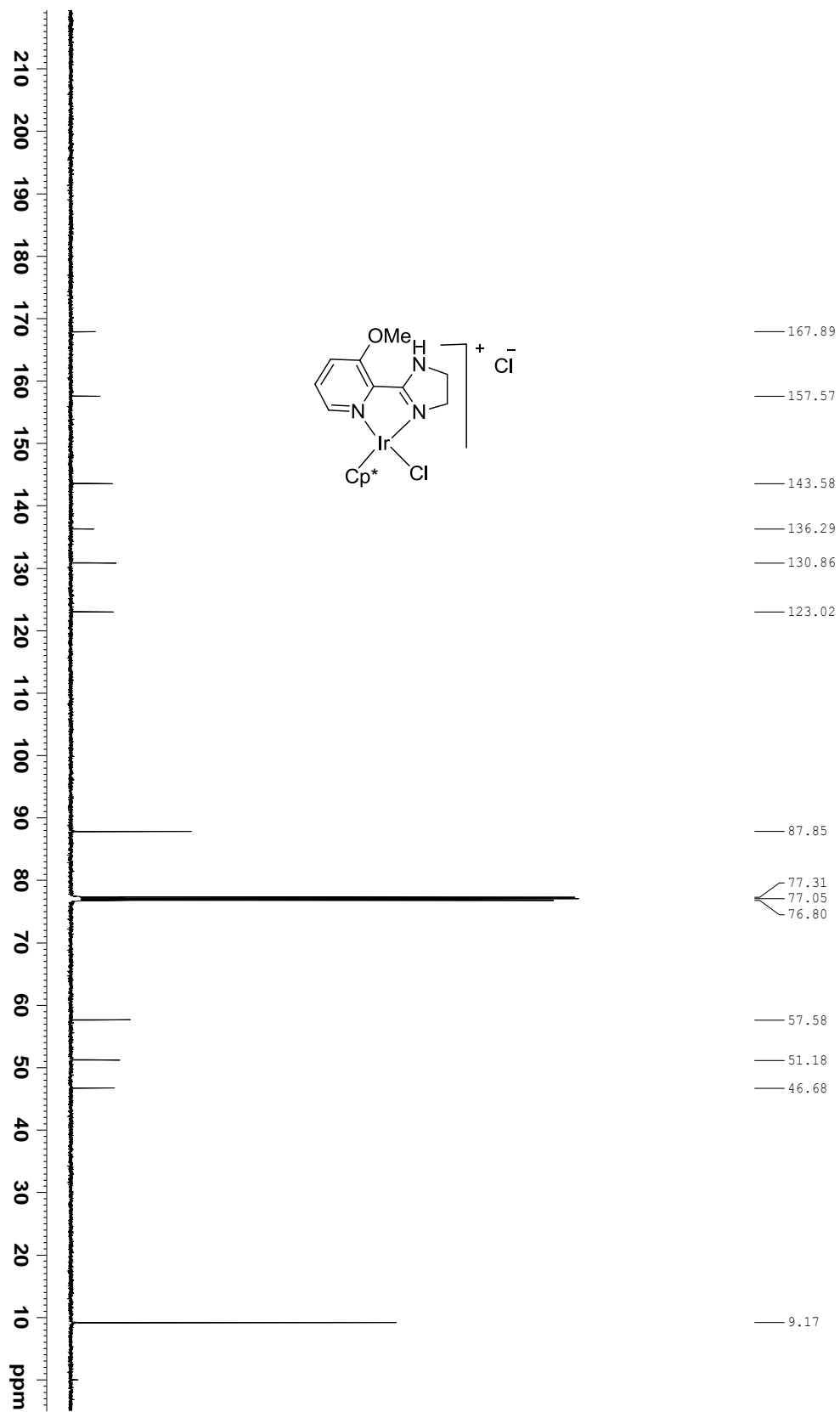
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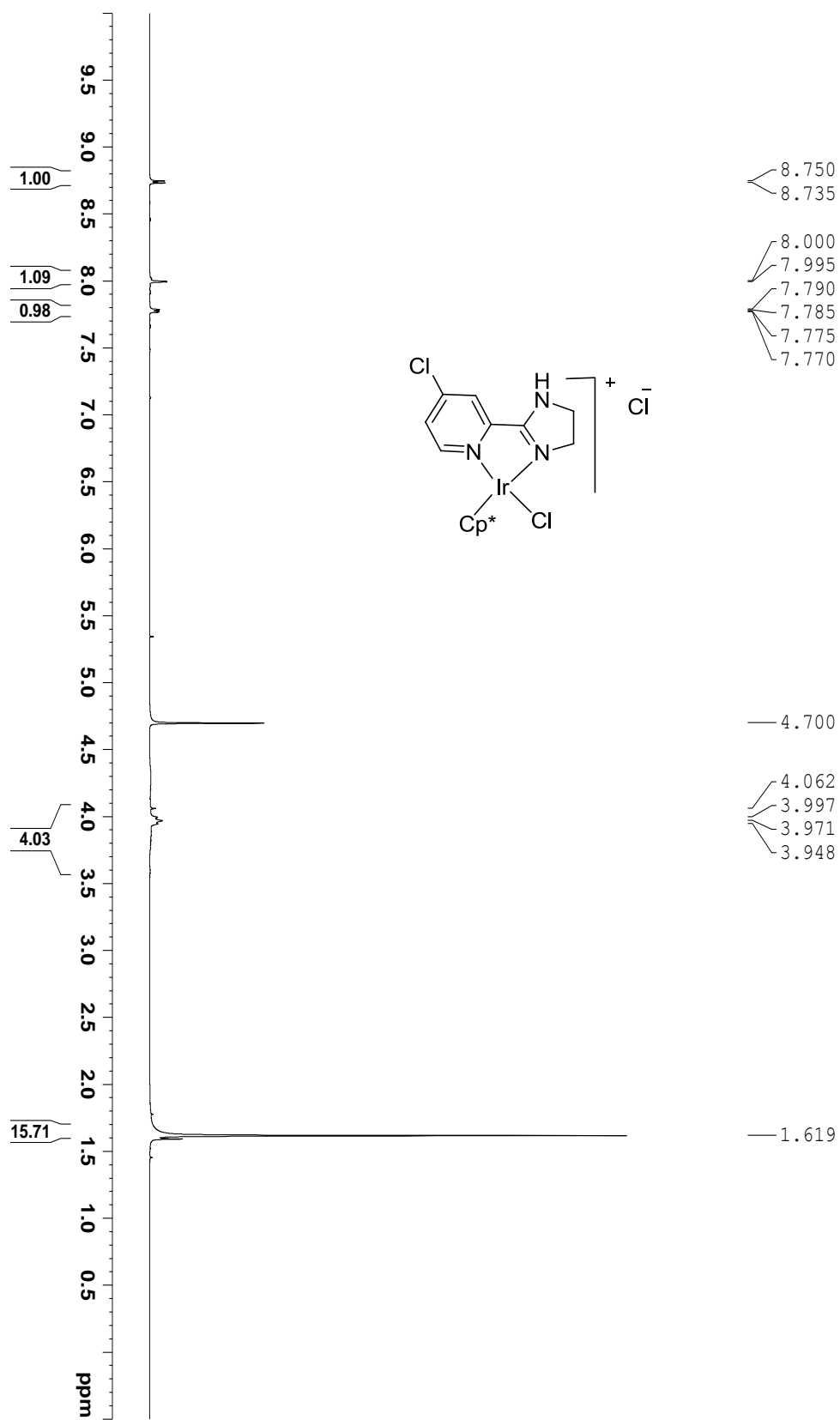


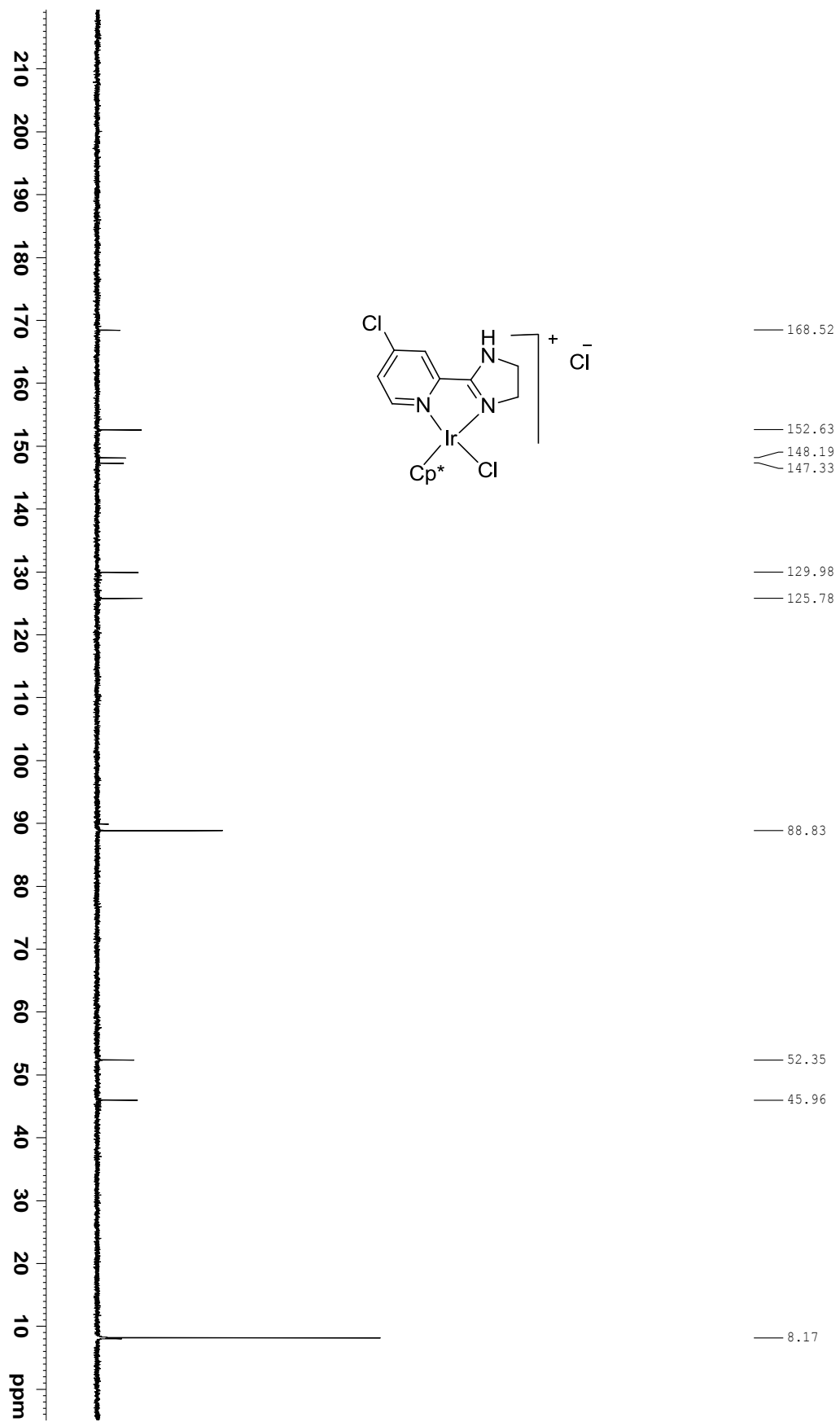
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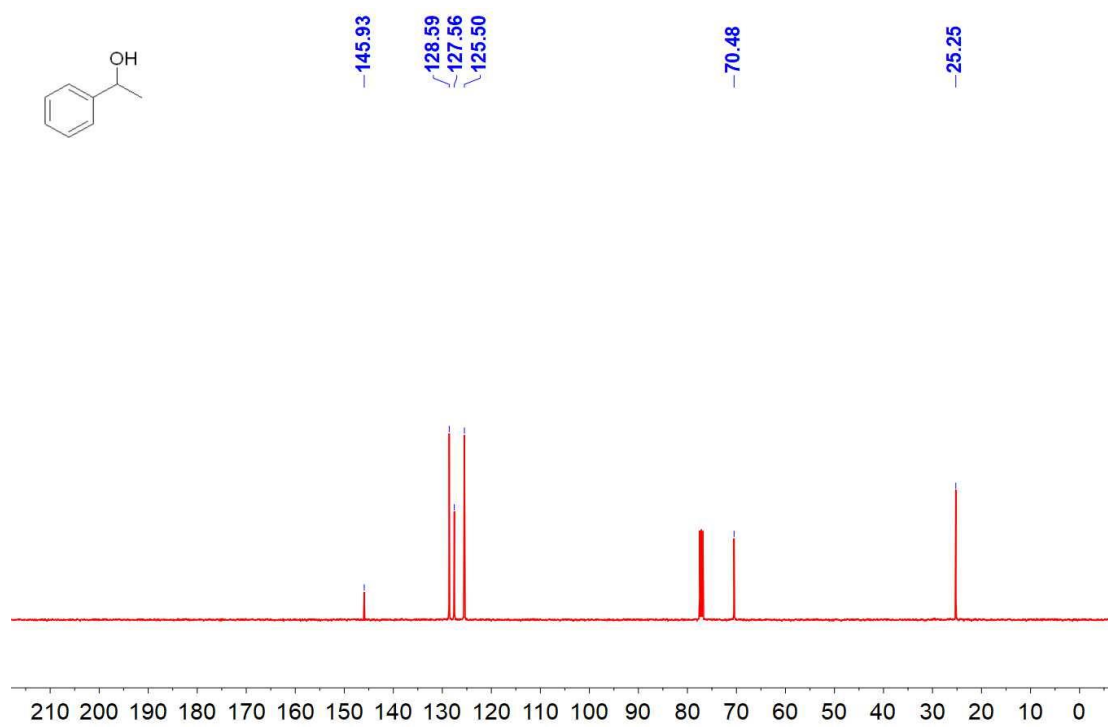
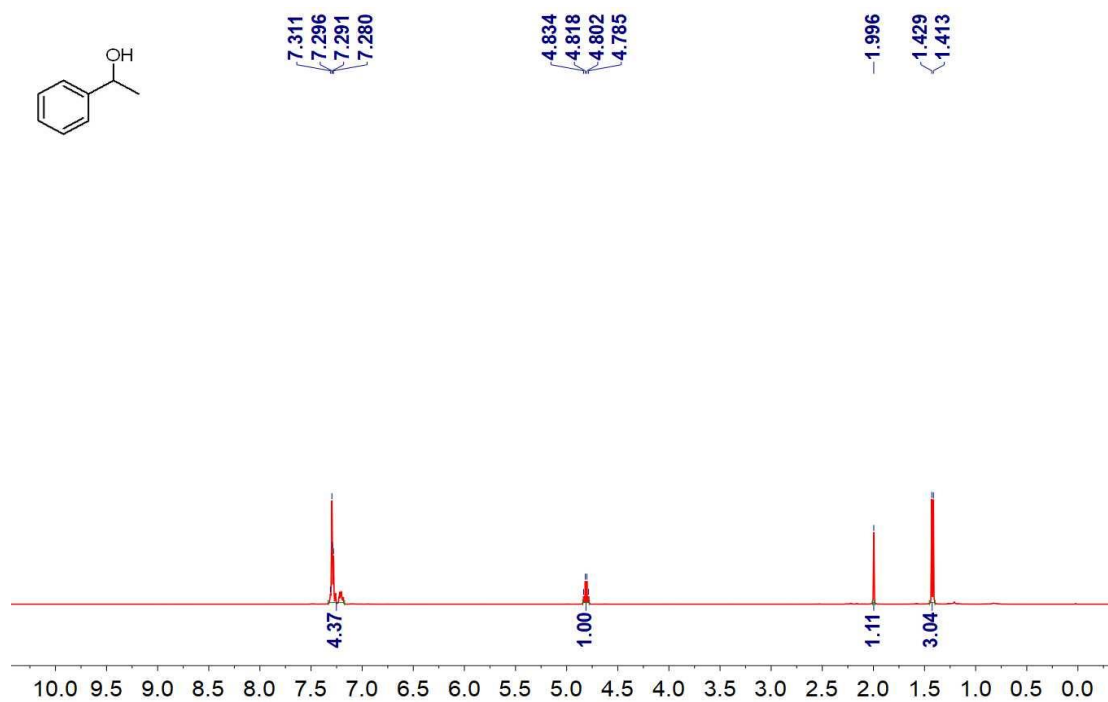


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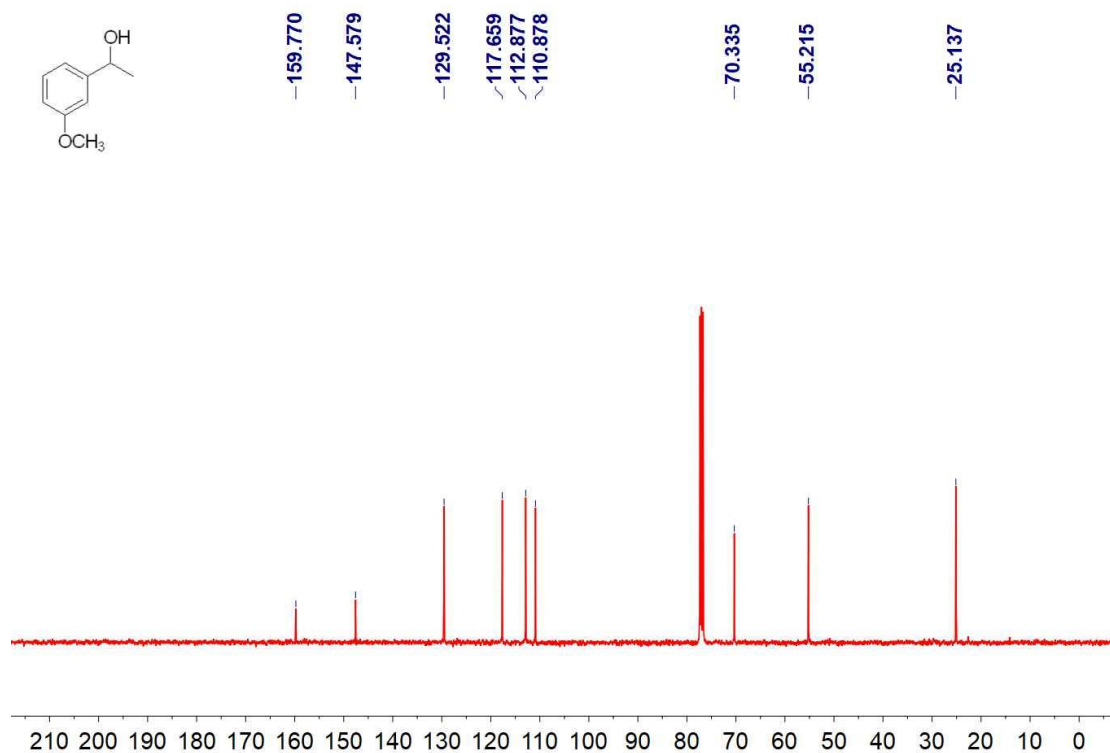
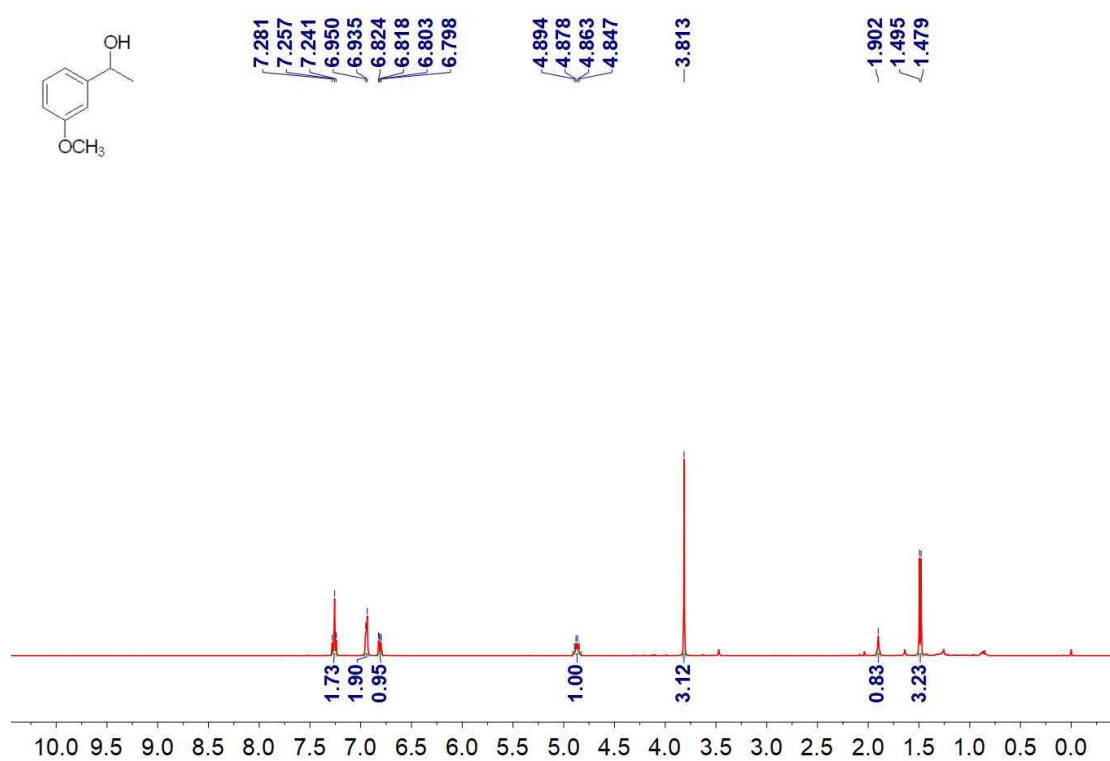




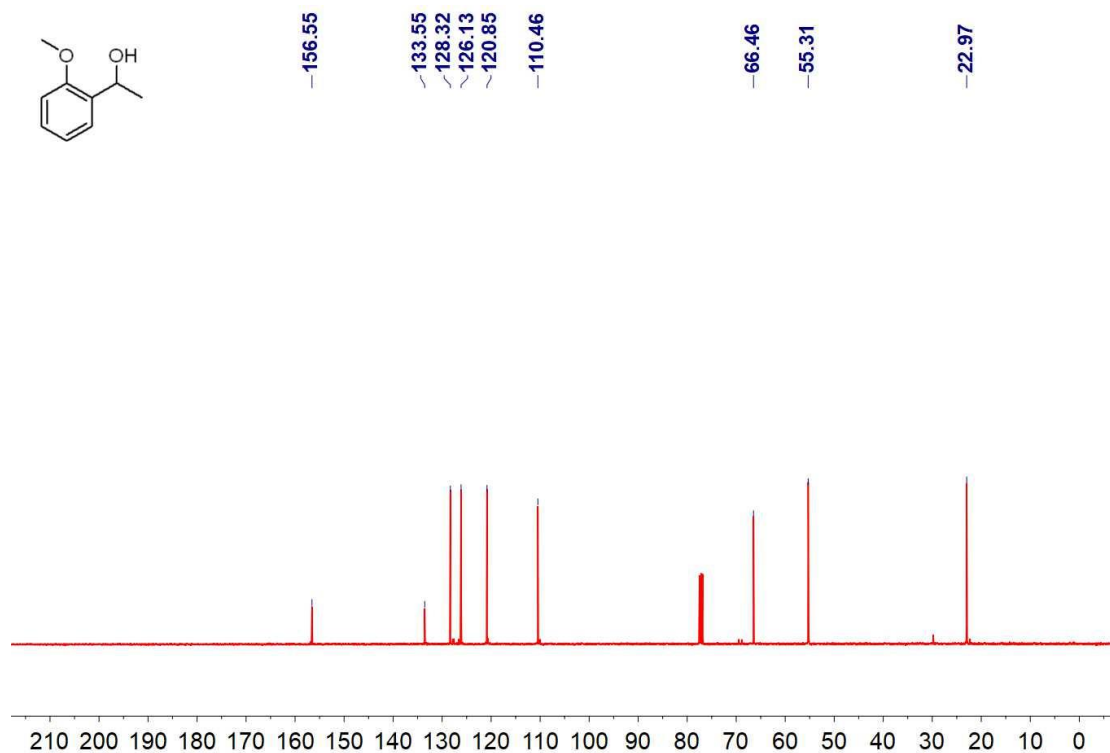
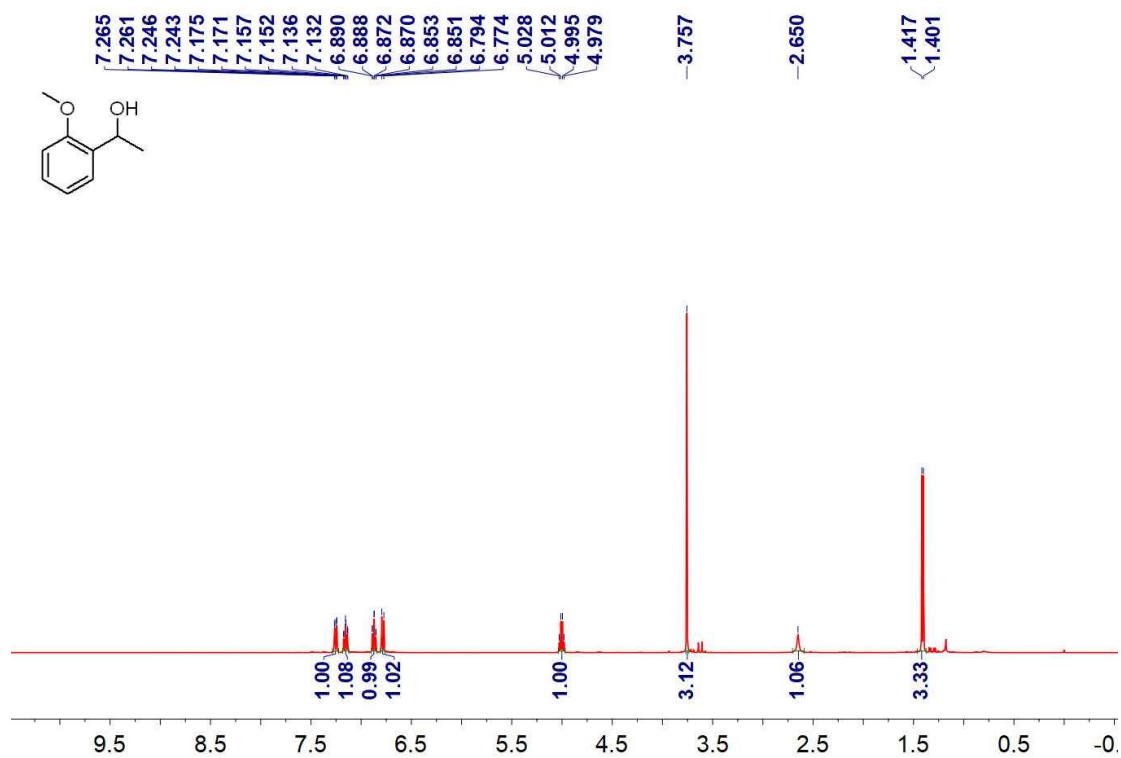
1-Phenylethanol (2a)



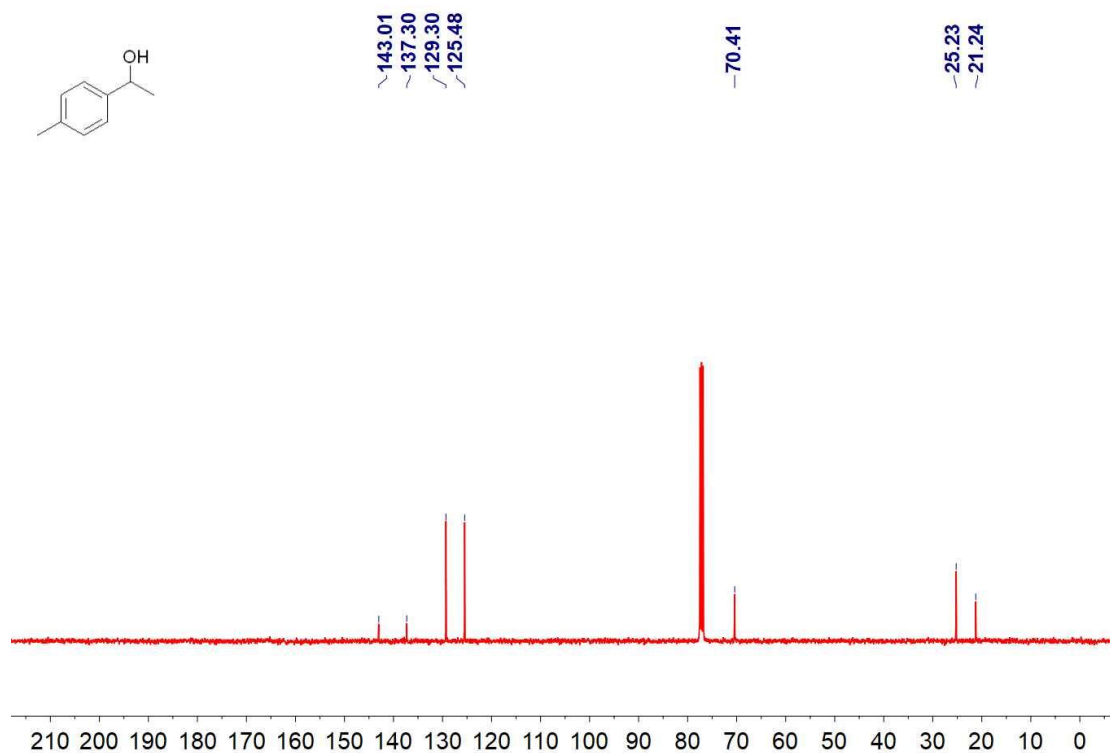
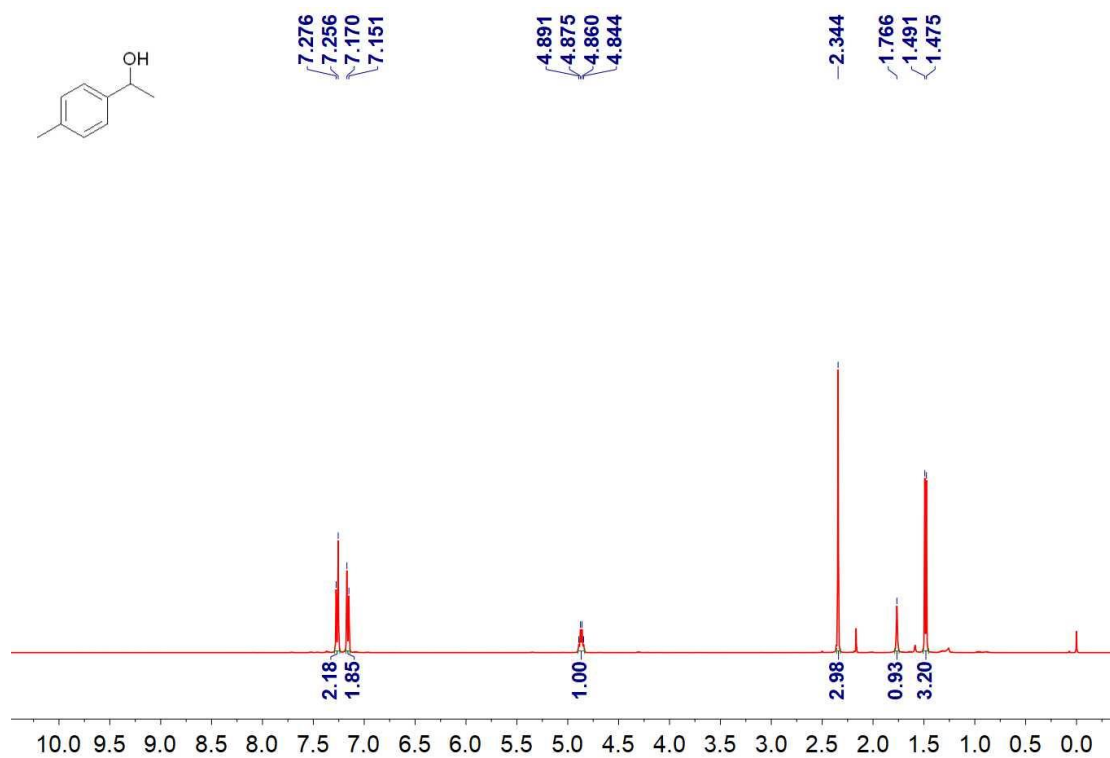
1-(3-Methoxyphenyl)ethanol (2b)



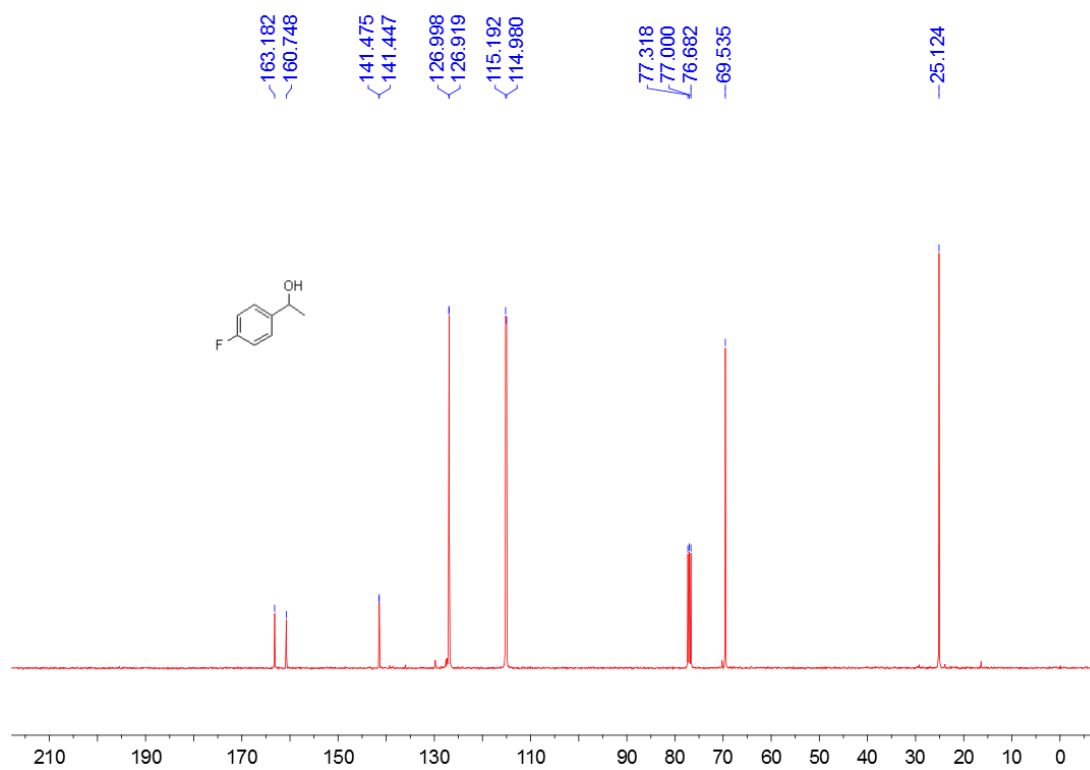
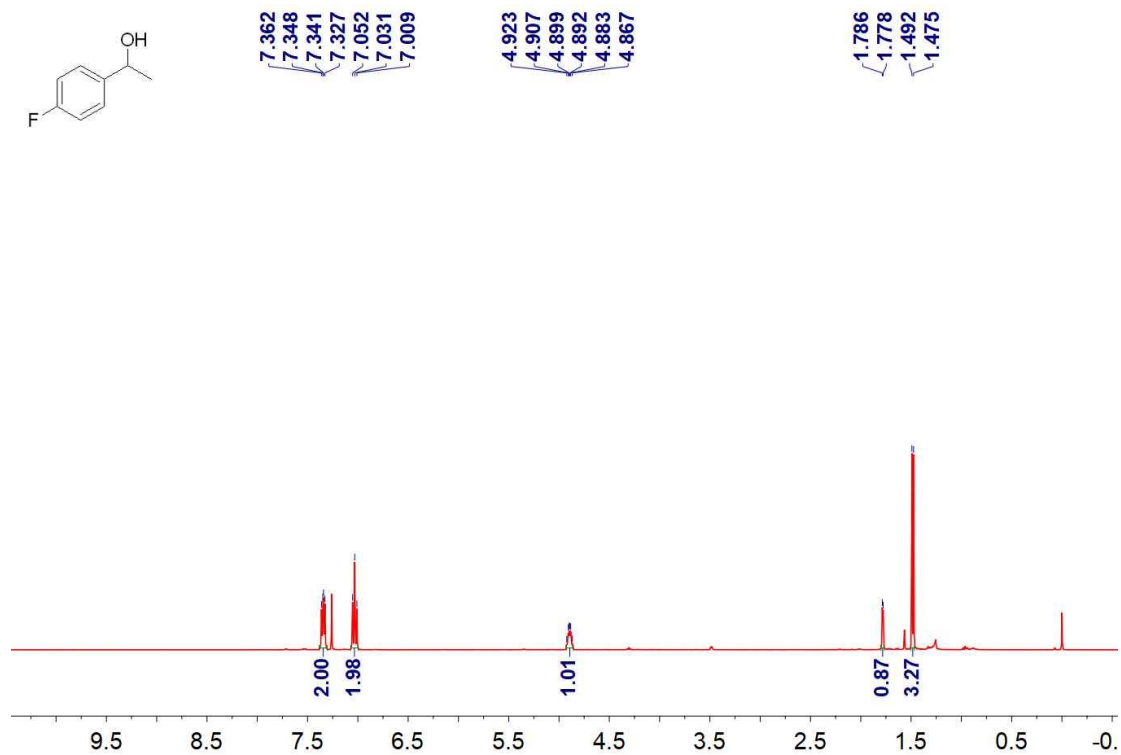
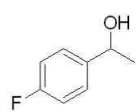
1-(2-Methoxyphenyl)ethanol (2c)



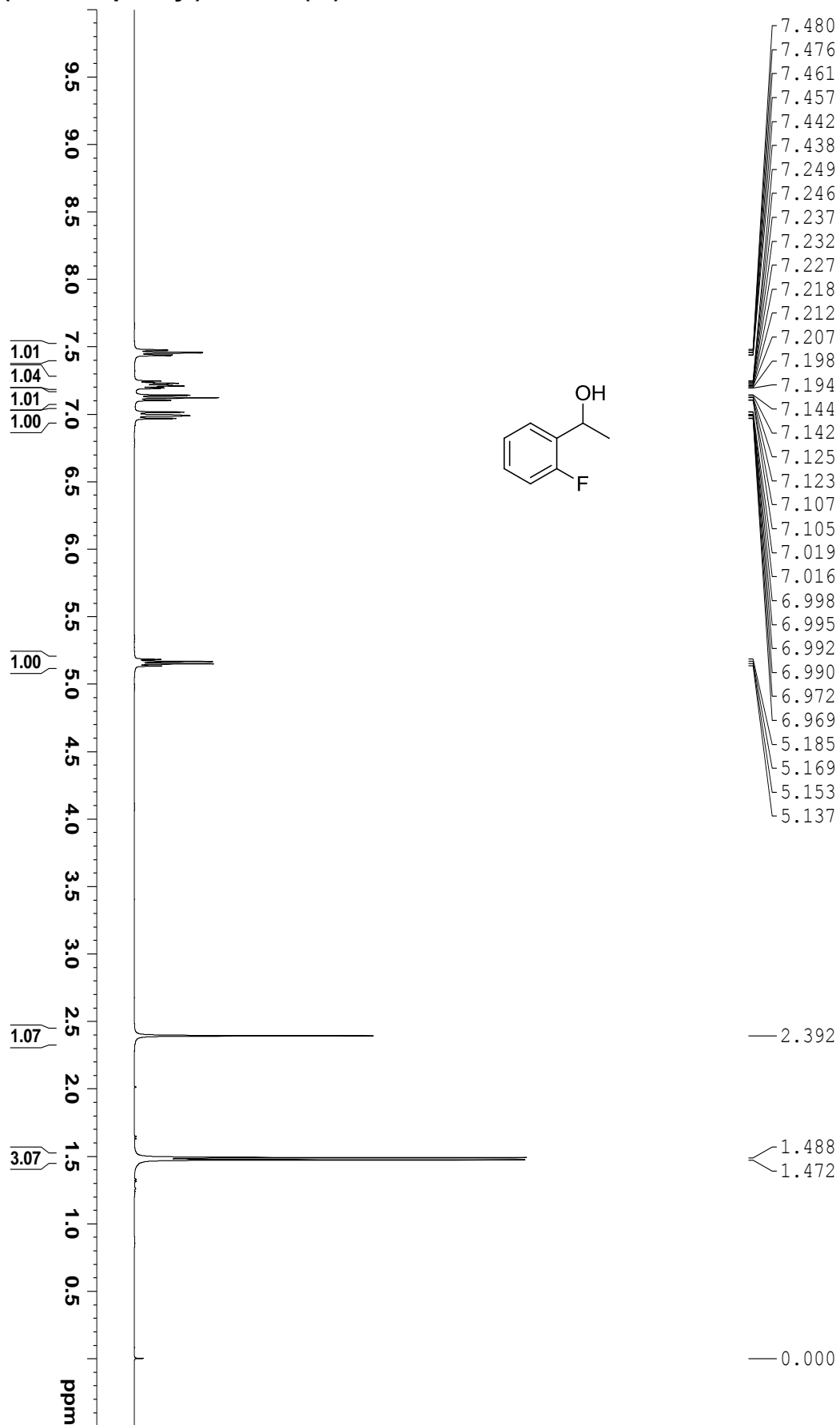
1-(4-Tolyl)ethanol (2d)

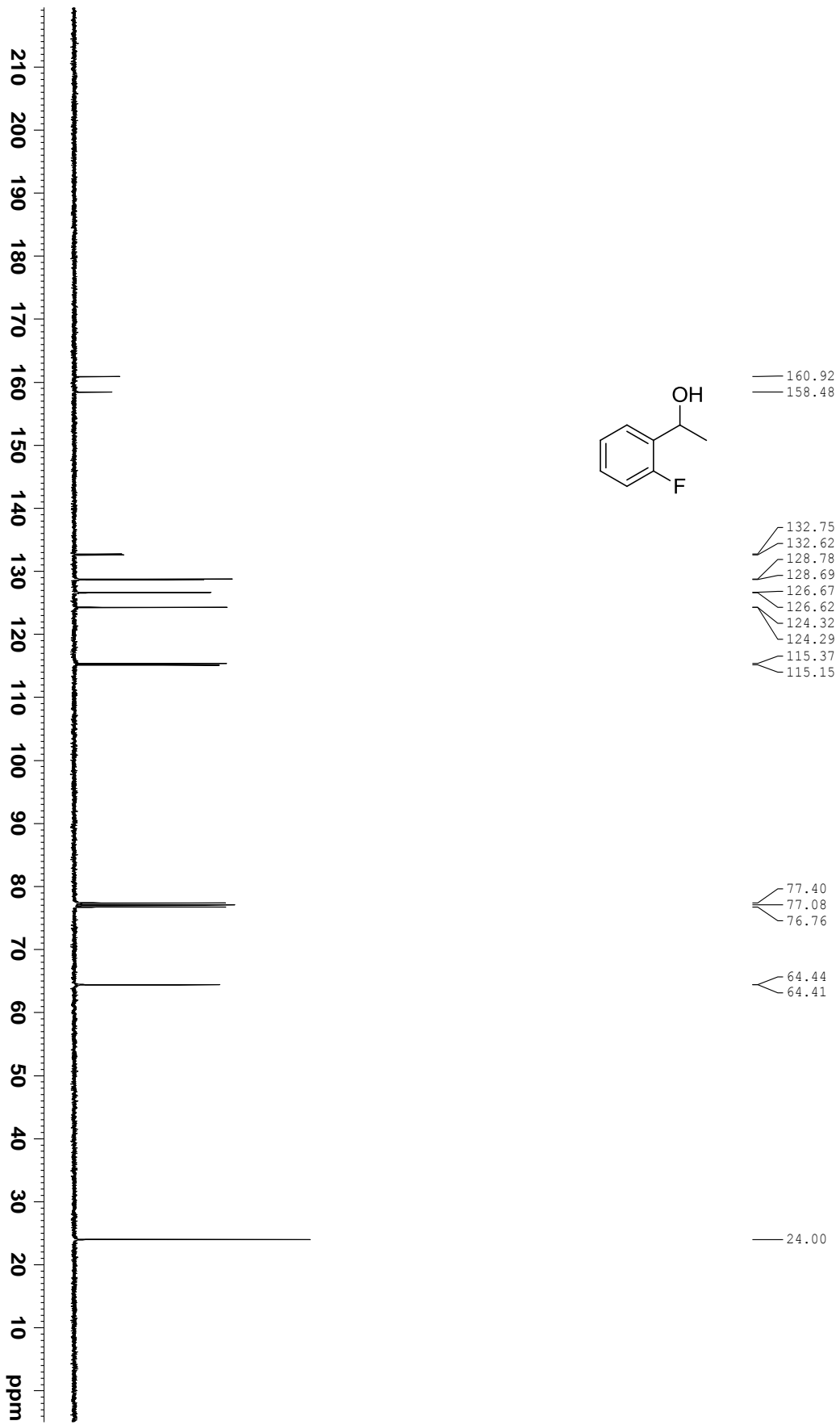


1-(4-Fluorophenyl)ethanol (2e)

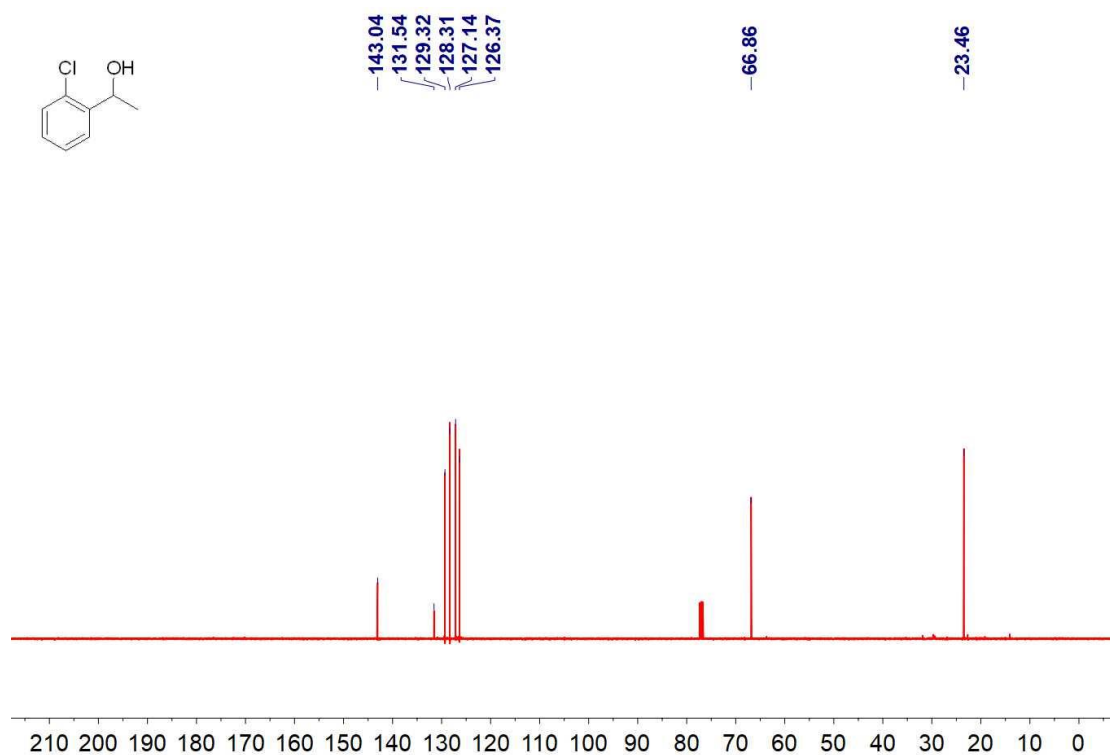
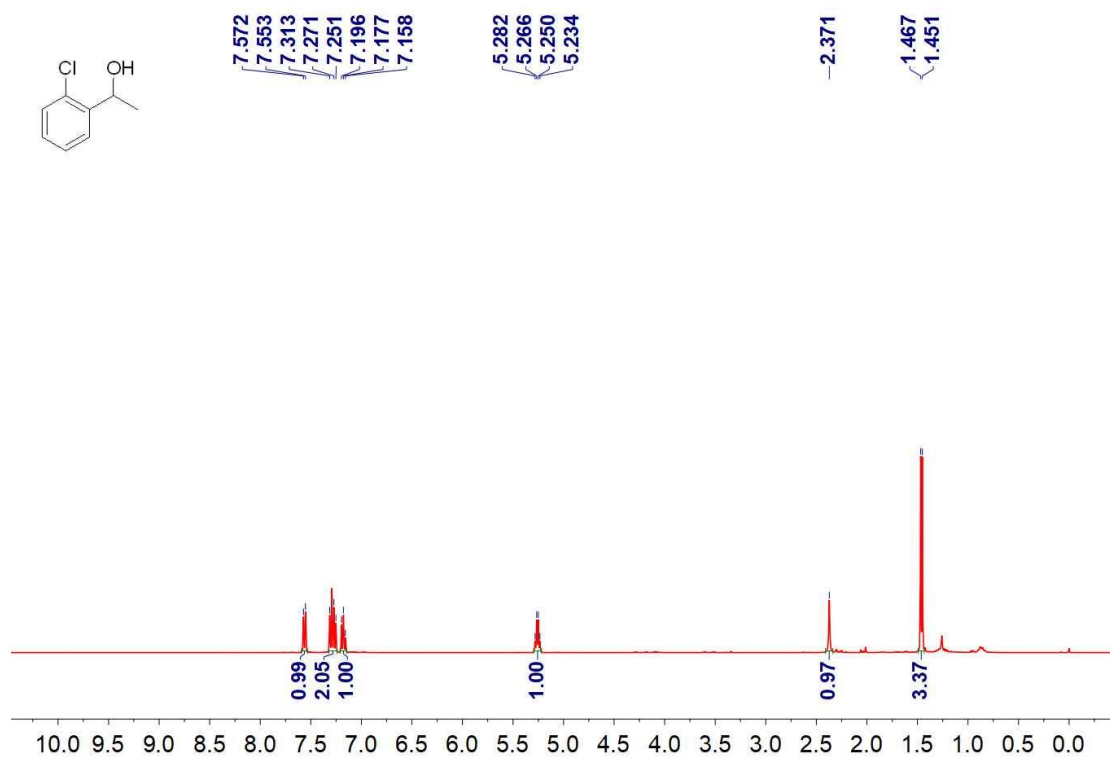


1-(2-Fluorophenyl)ethanol (2f)

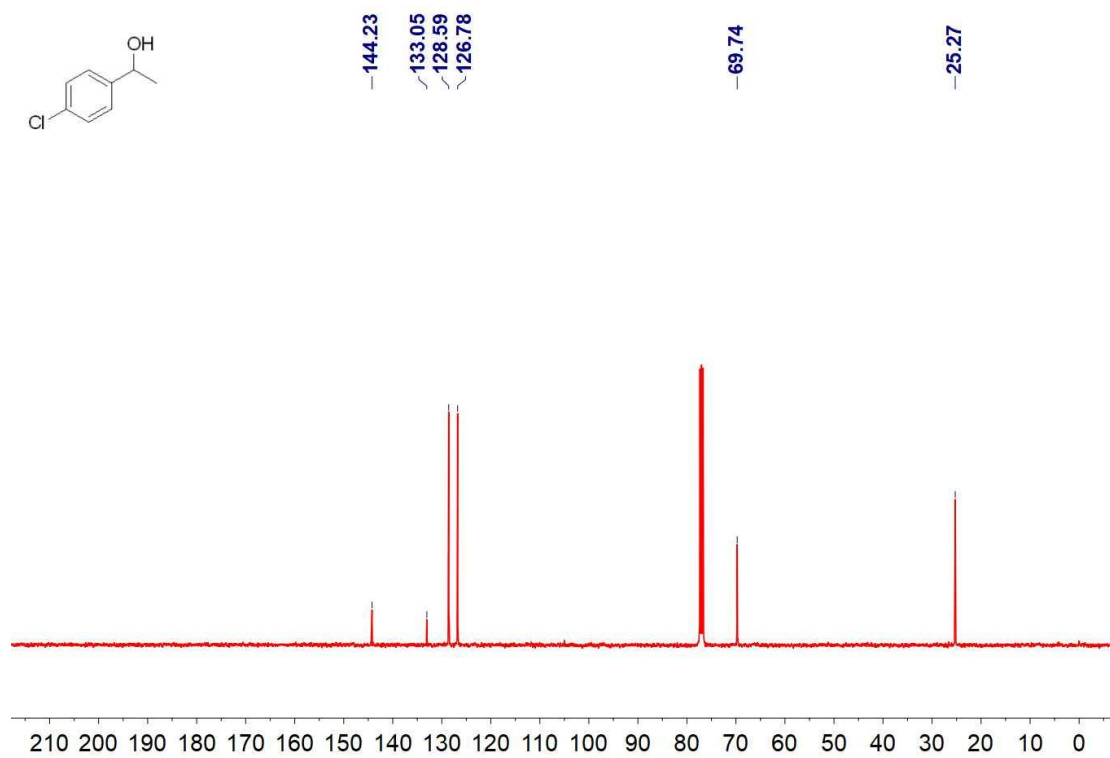
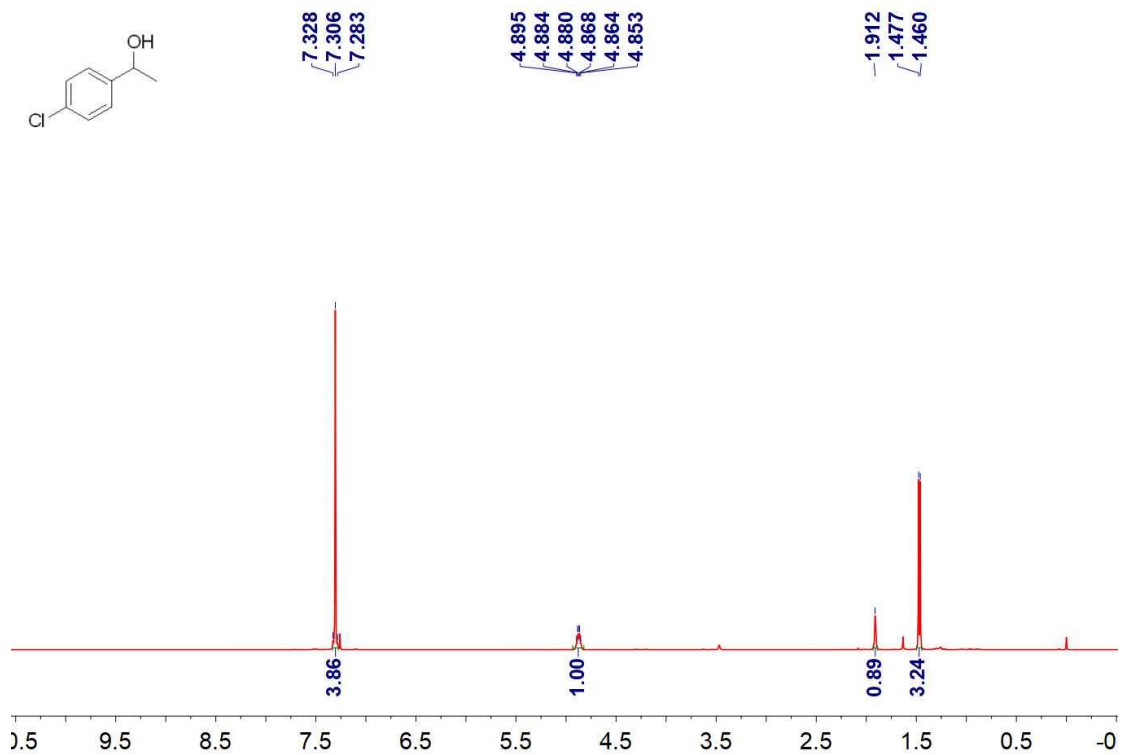




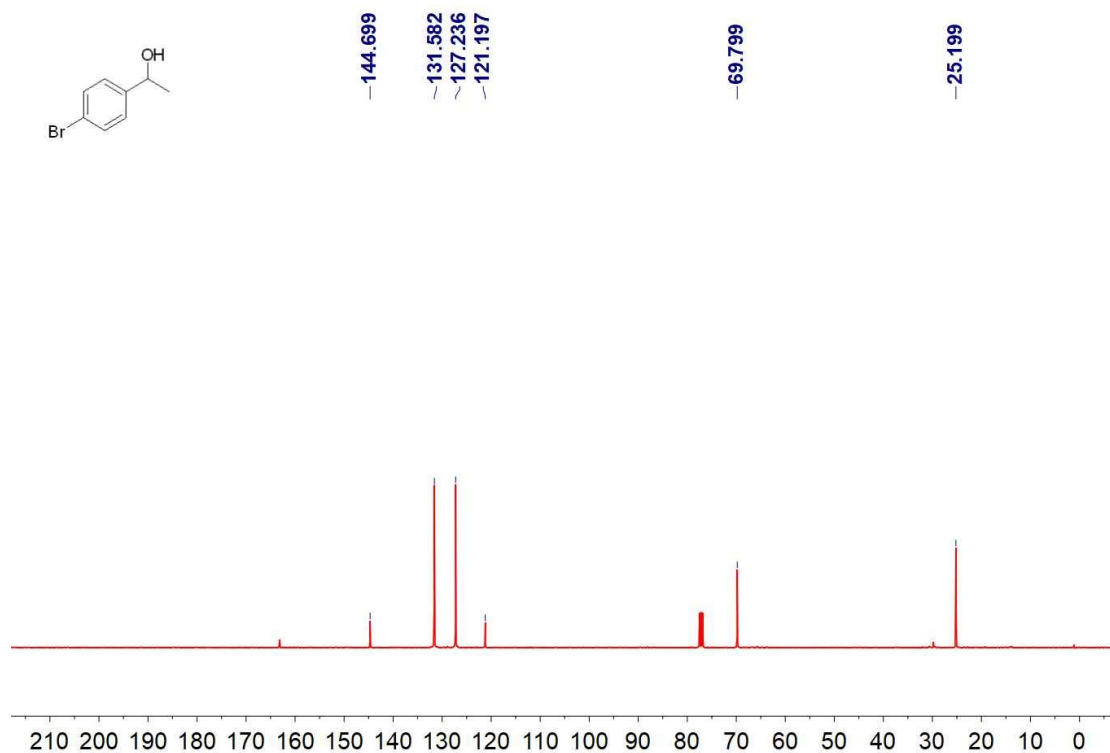
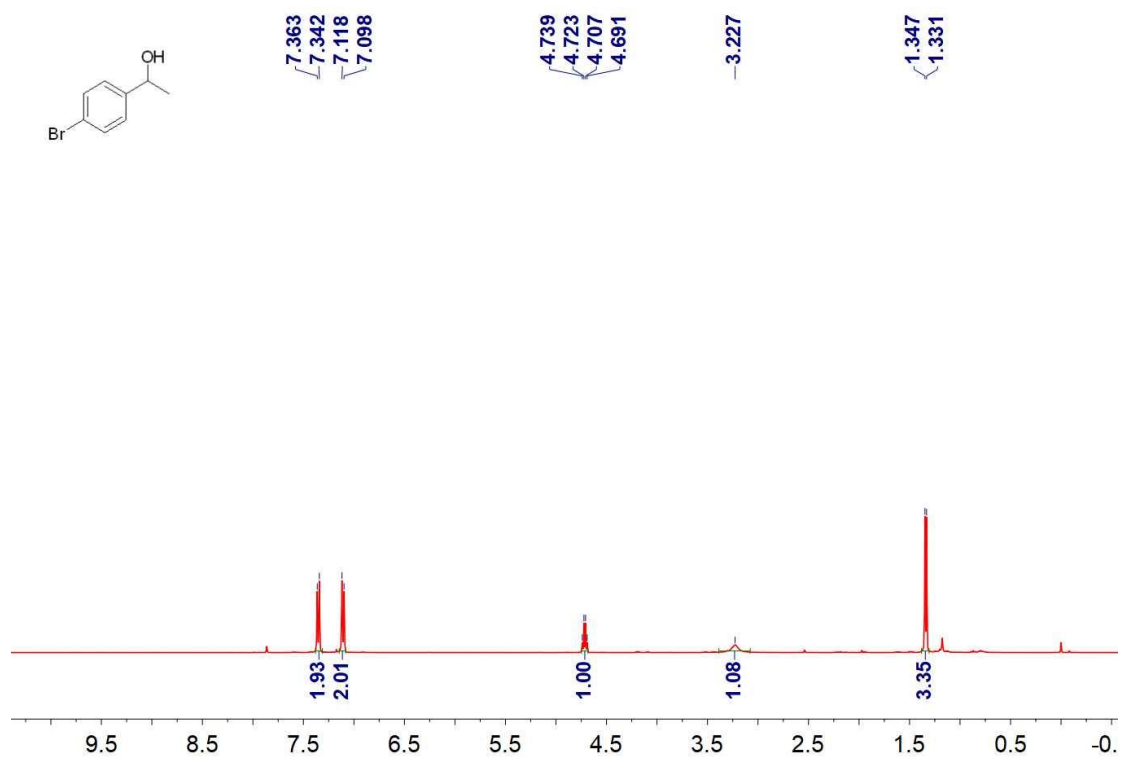
1-(2-Chlorophenyl)ethanol (2g)



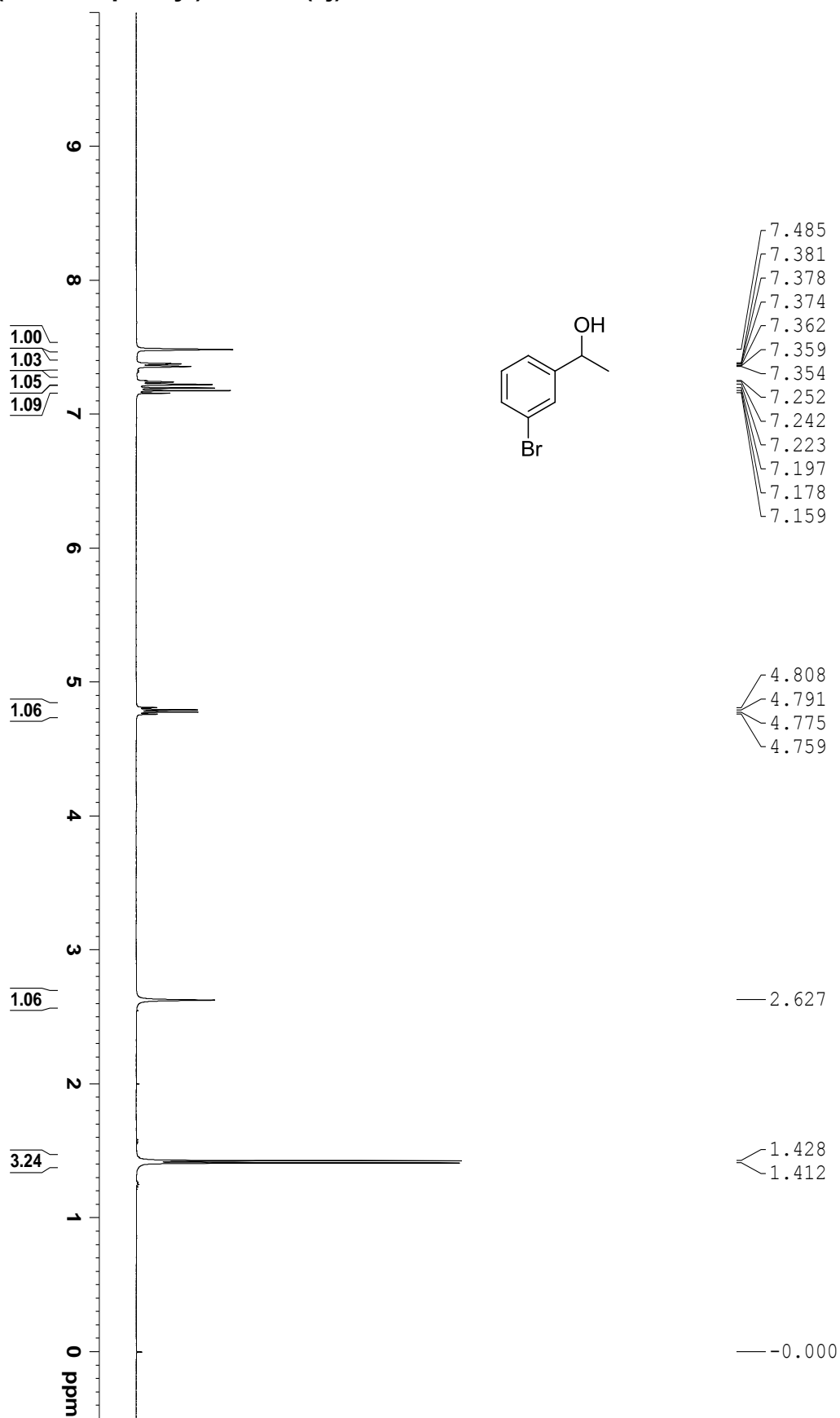
1-(4-Chlorophenyl)ethanol (2h)

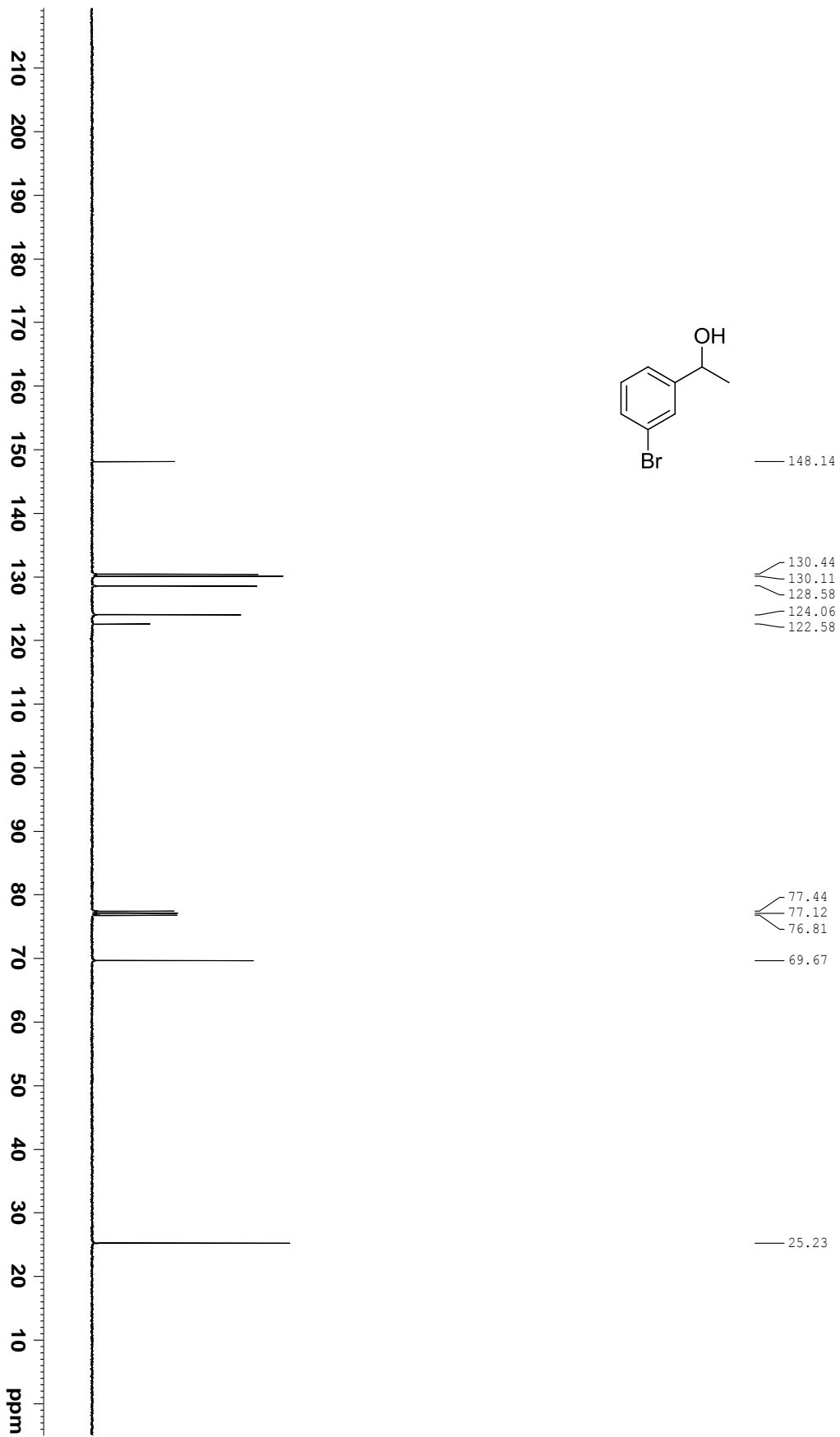


1-(4-Bromophenyl)ethanol (2i)

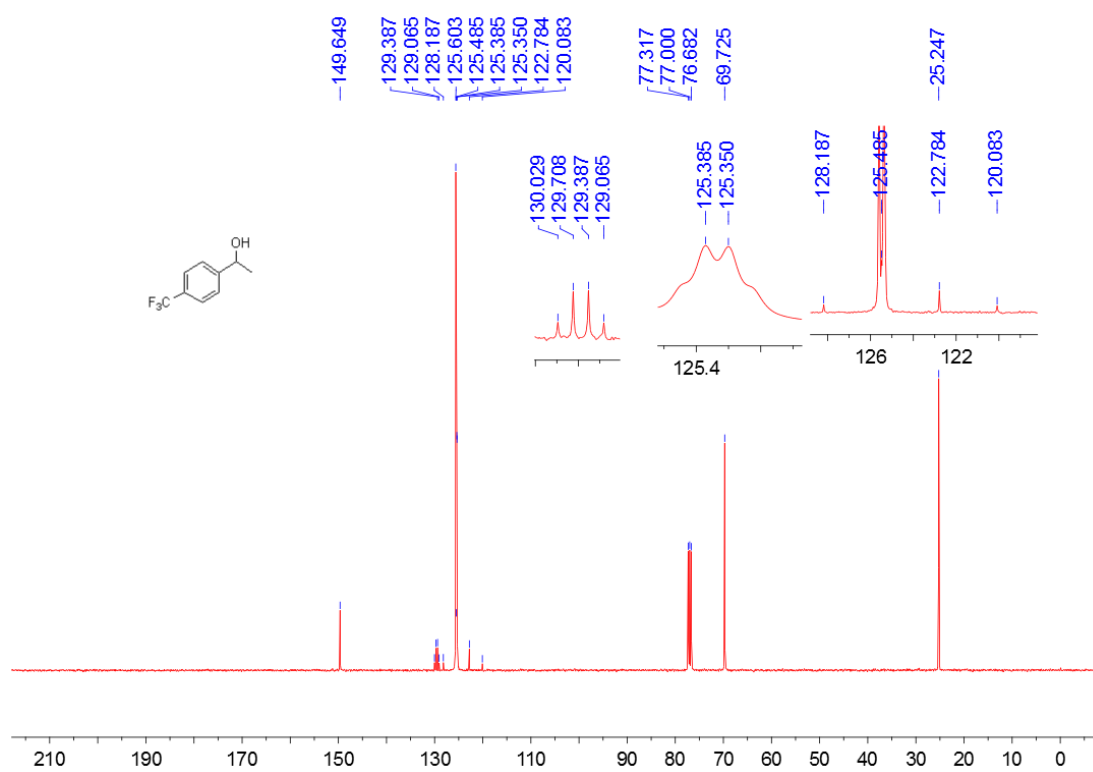
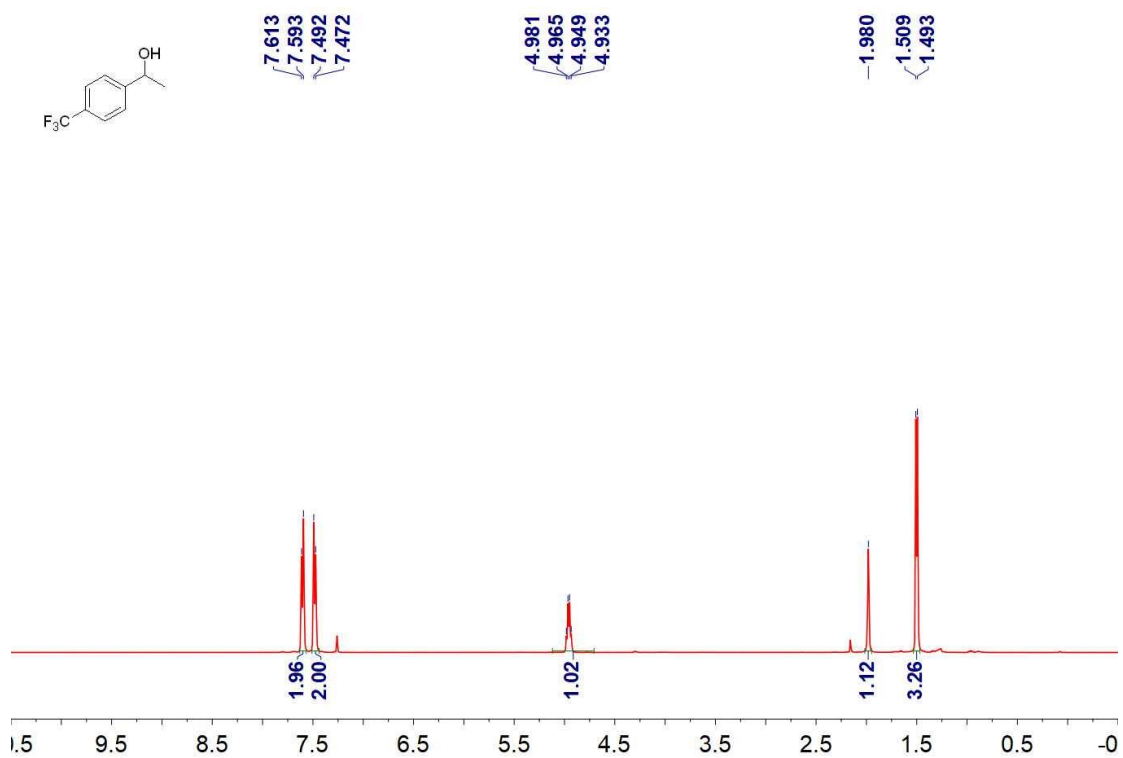


1-(3-Bromophenyl)ethanol (2j)

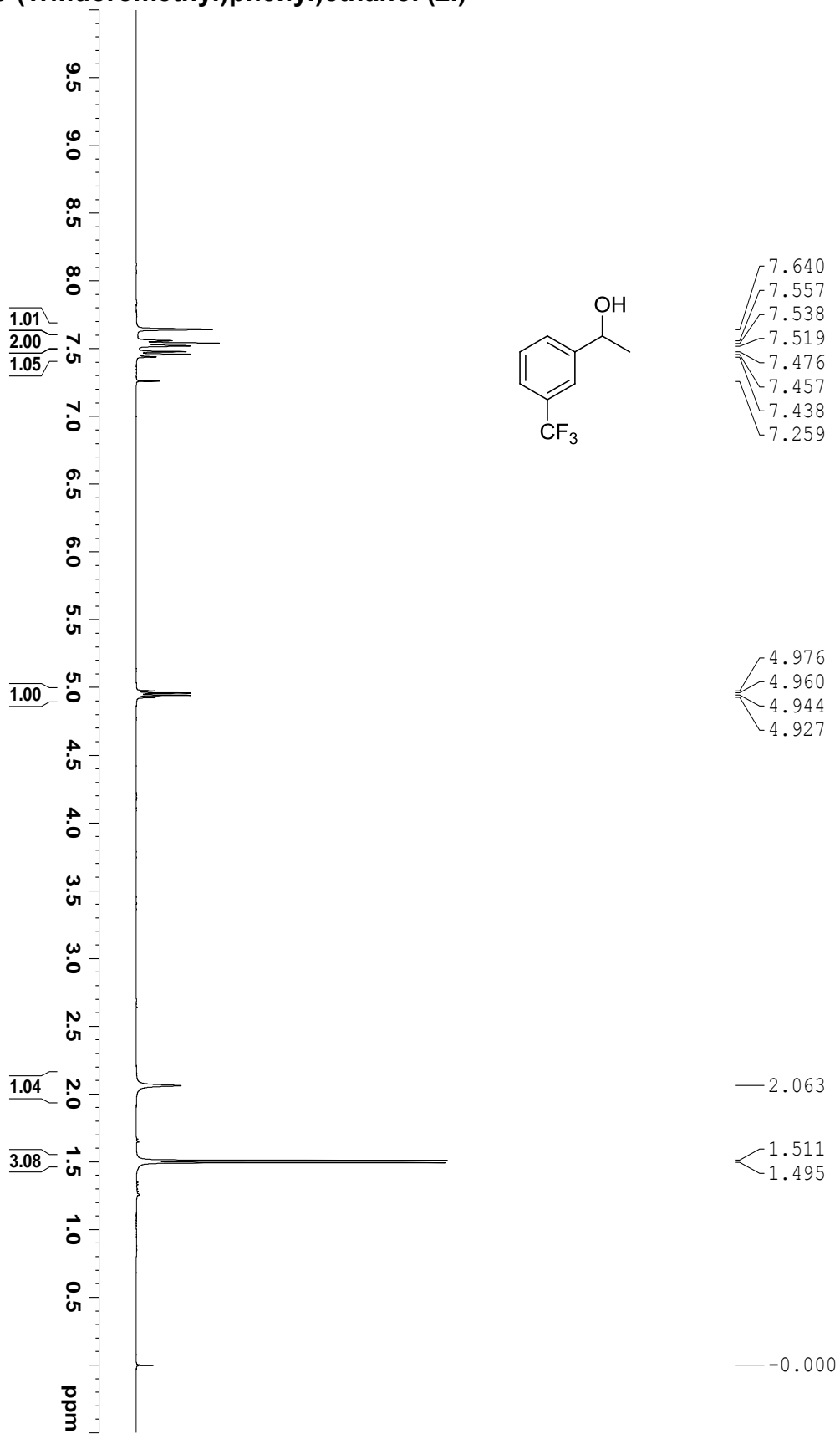


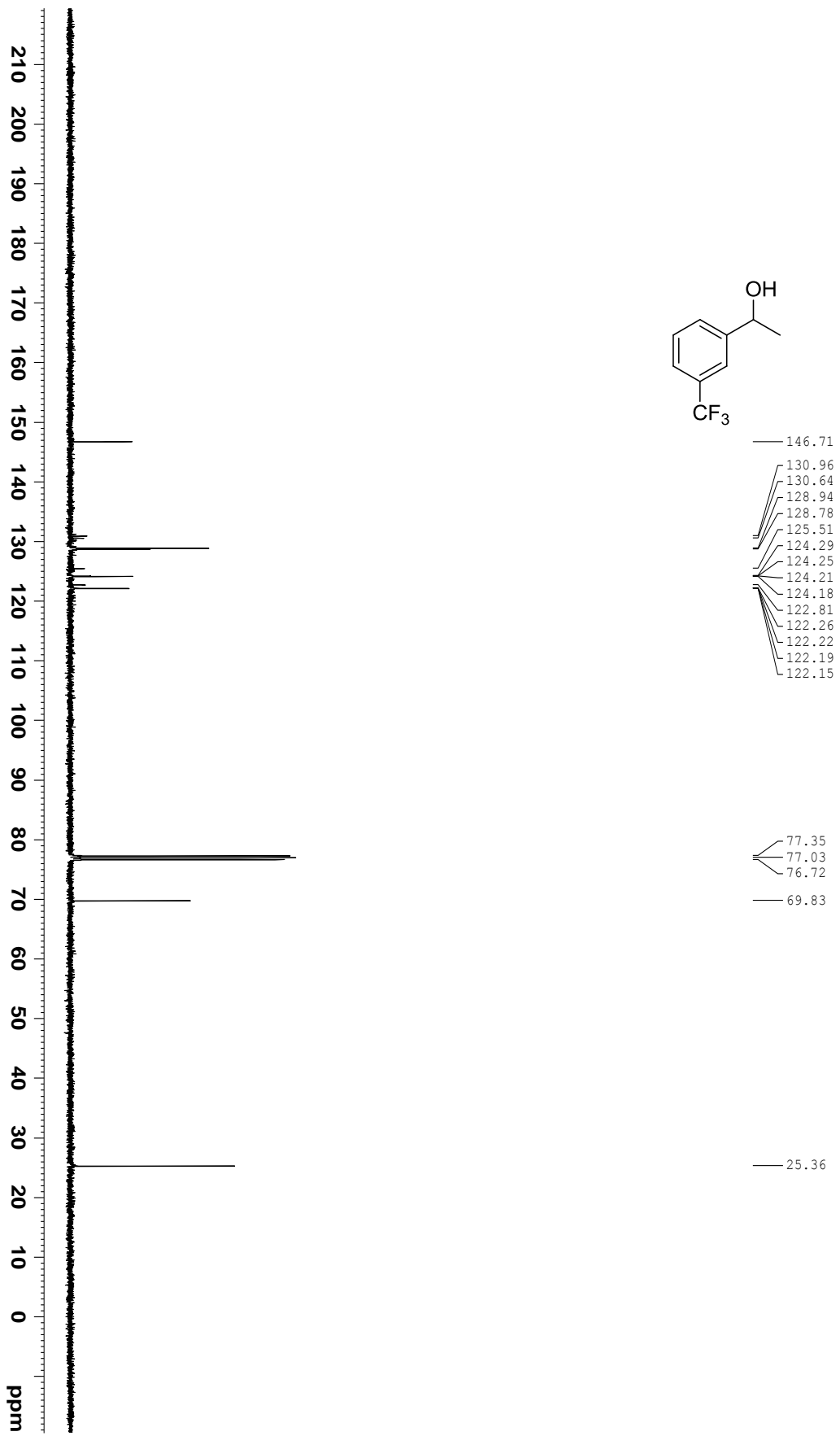


1-(4-(Trifluoromethyl)phenyl)ethanol (2k)

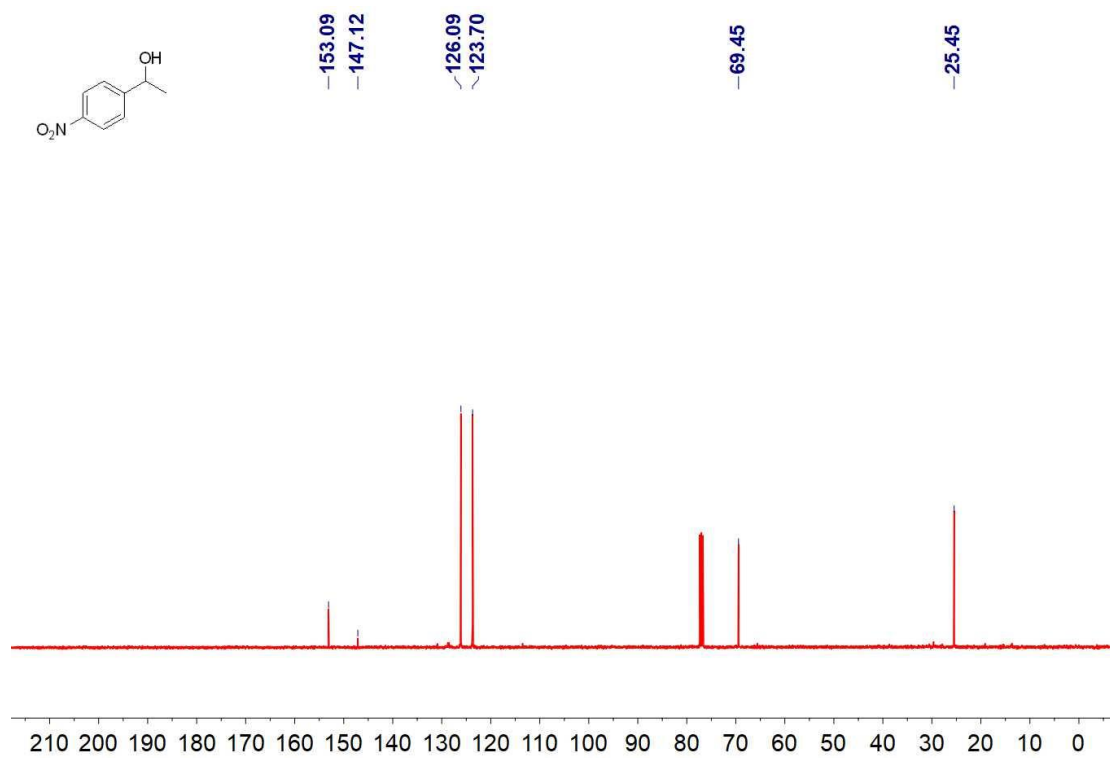
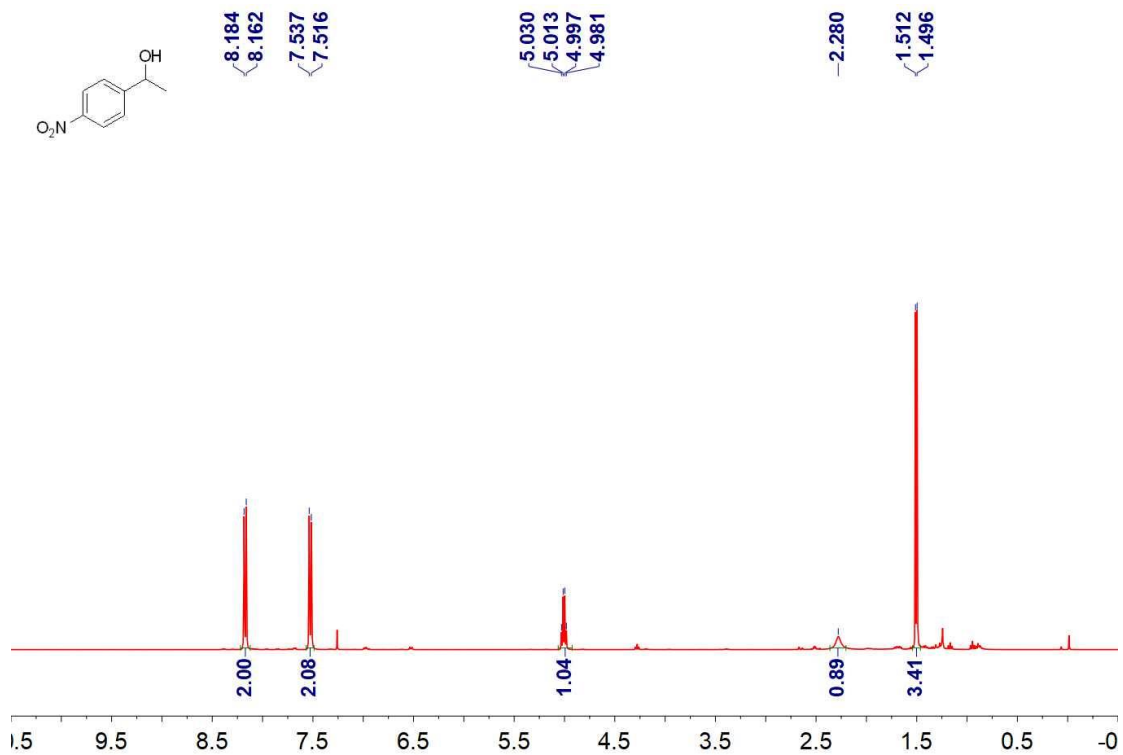


1-(3-(Trifluoromethyl)phenyl)ethanol (2I)

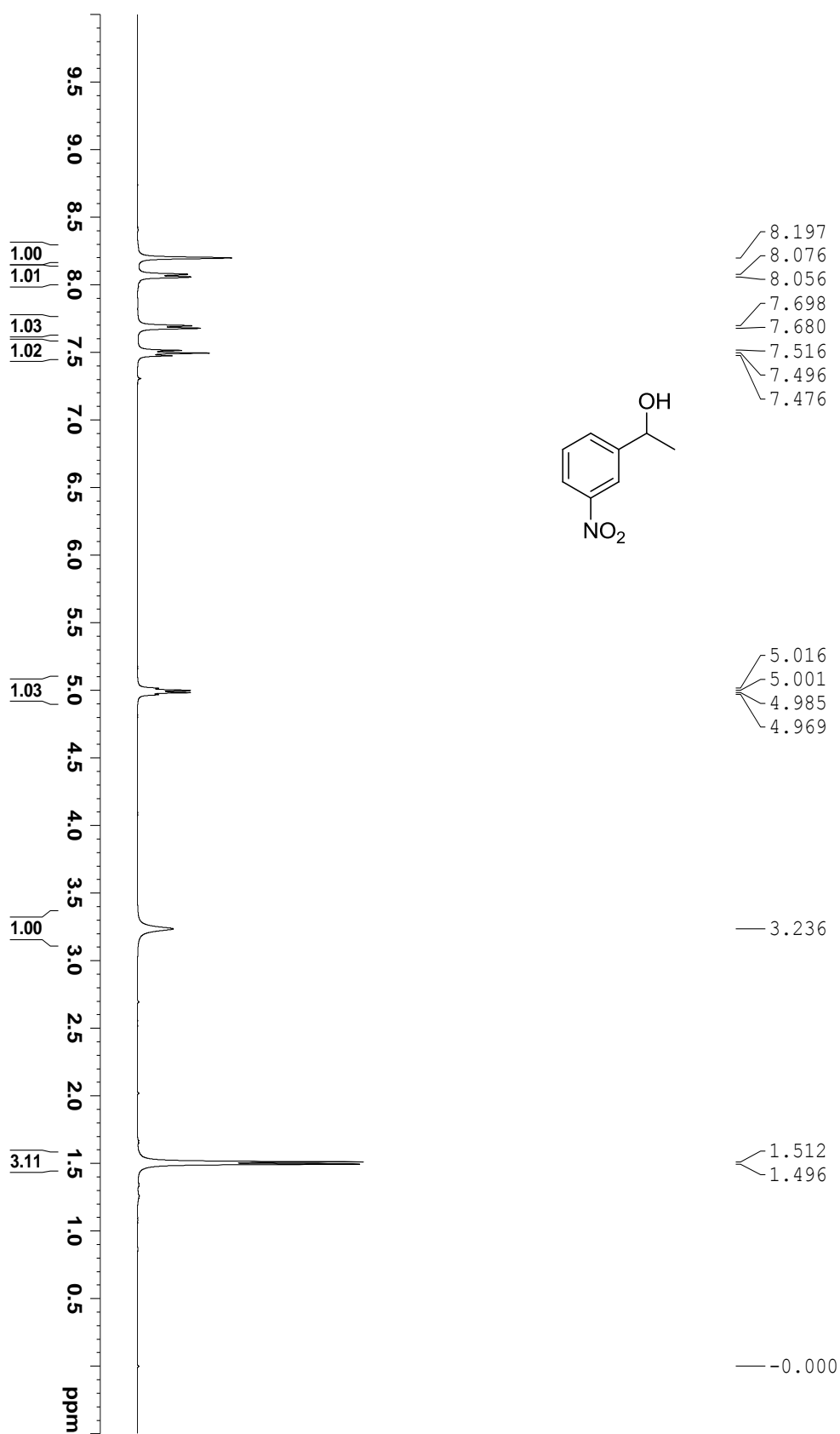


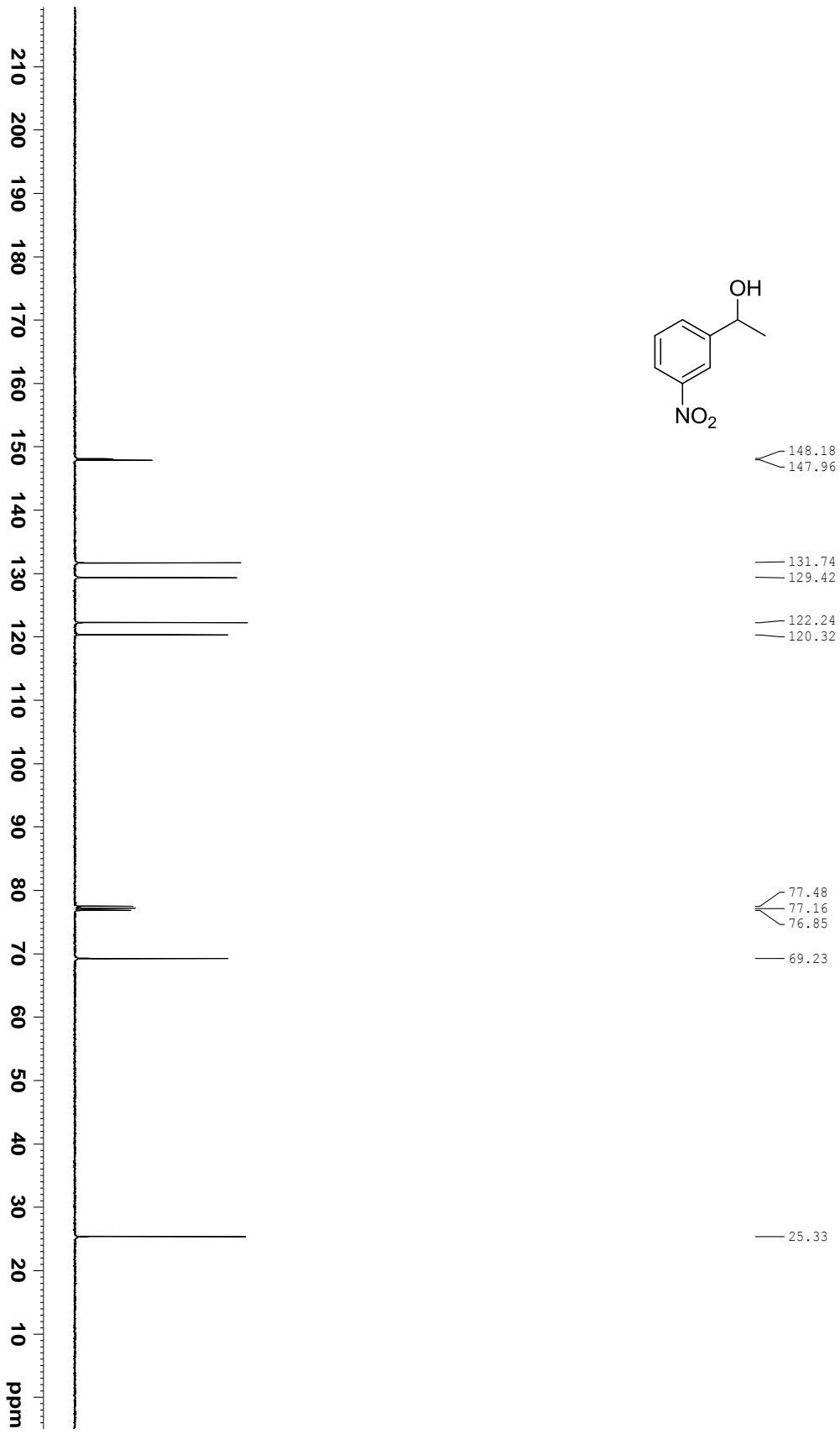


1-(4-Nitrophenyl)ethanol (2m)

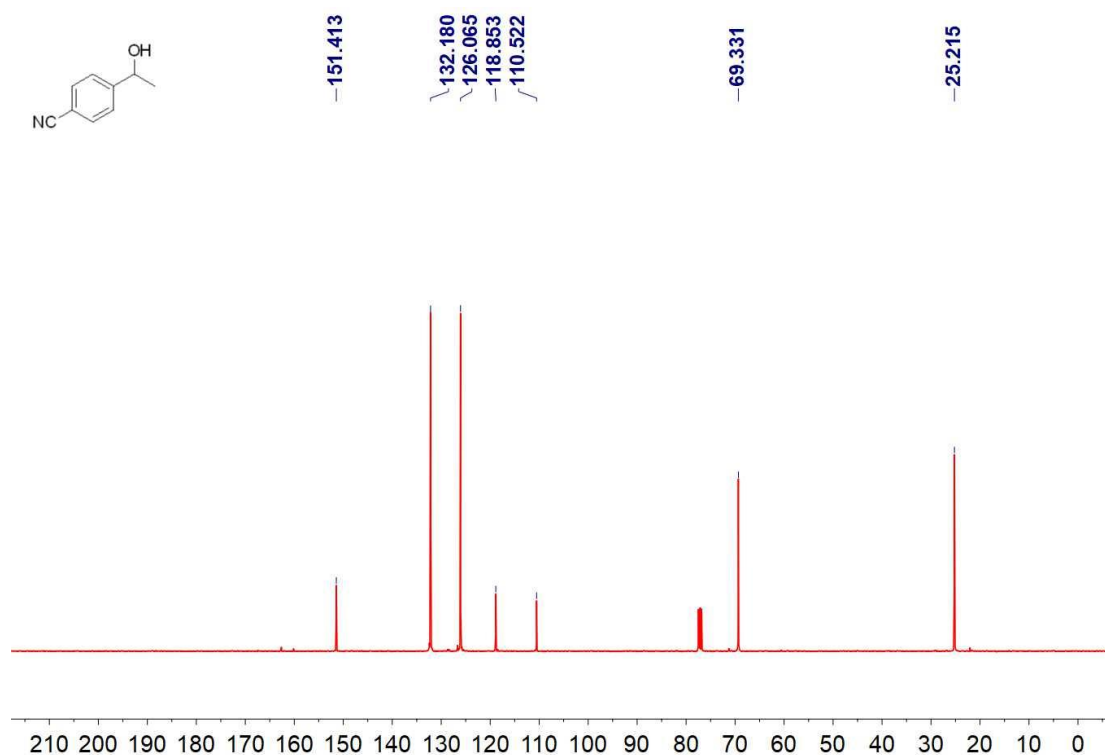
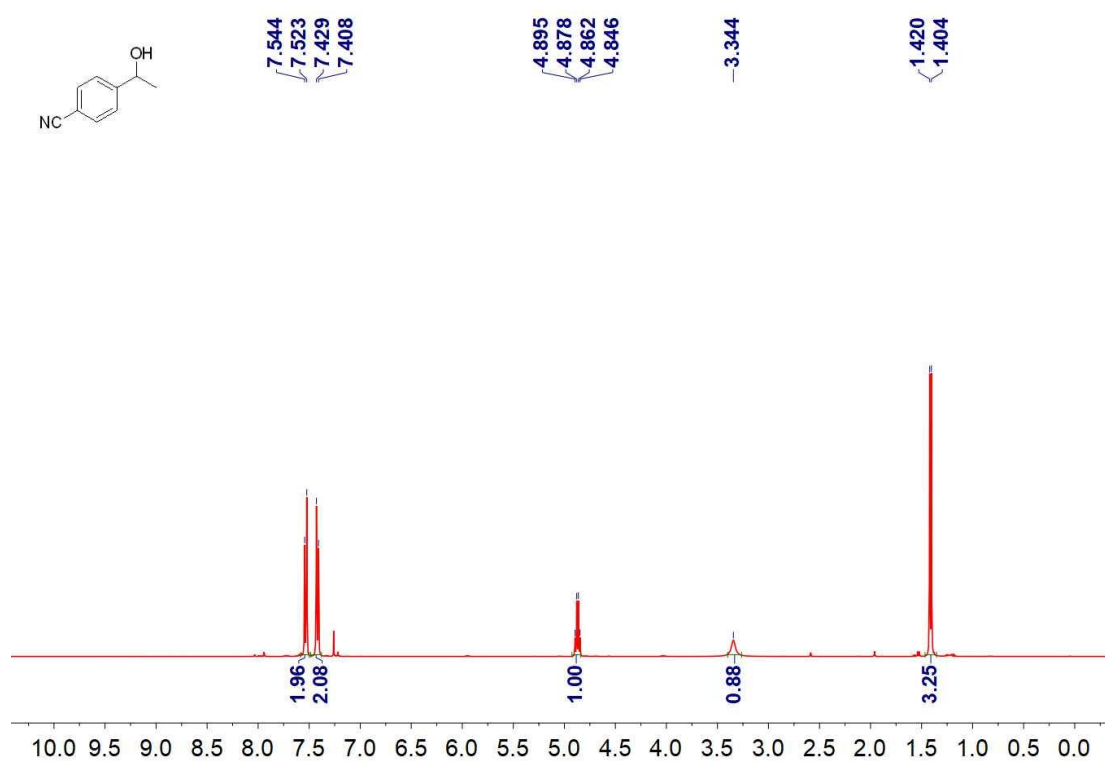


1-(3-Nitrophenyl)ethanol (2n)

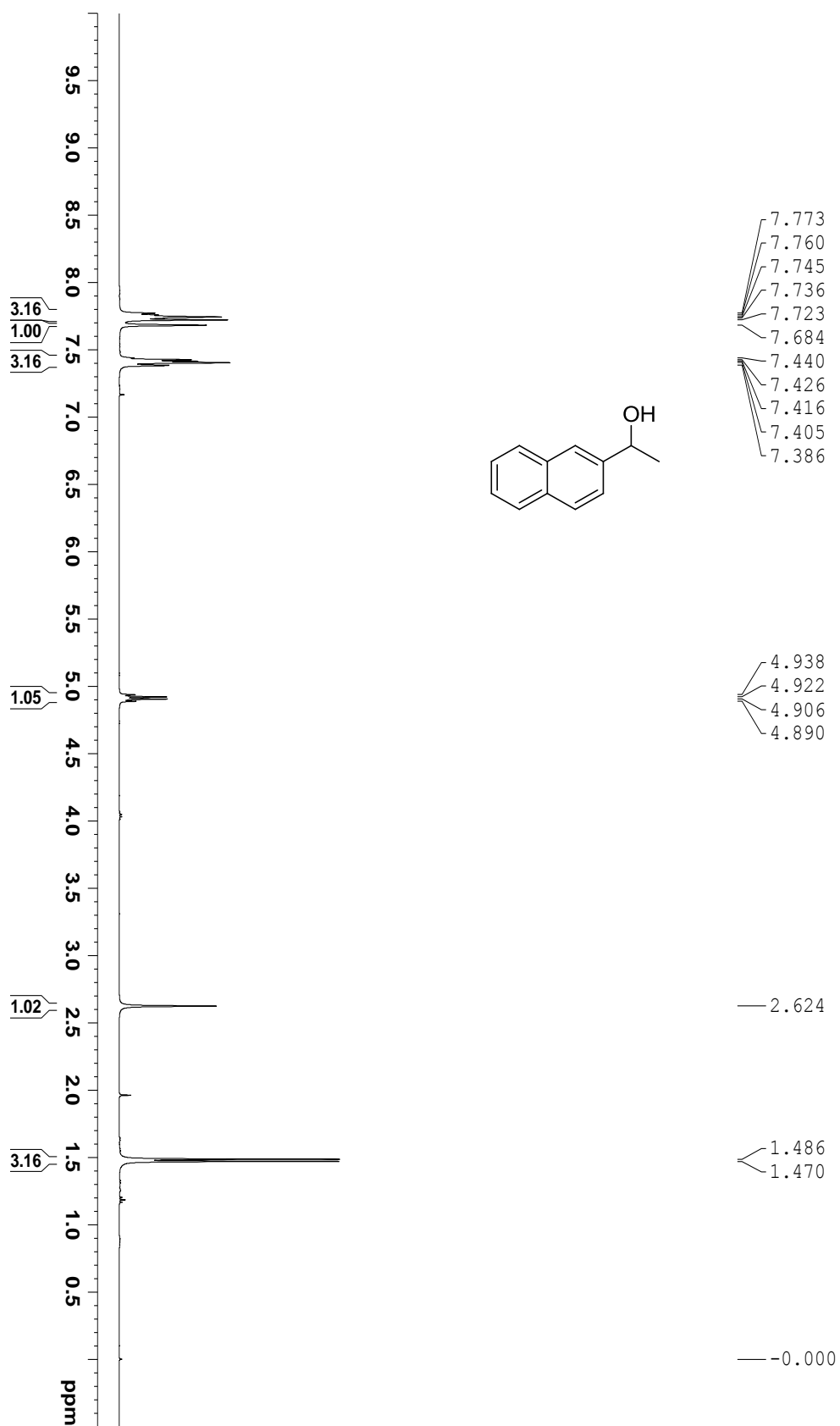


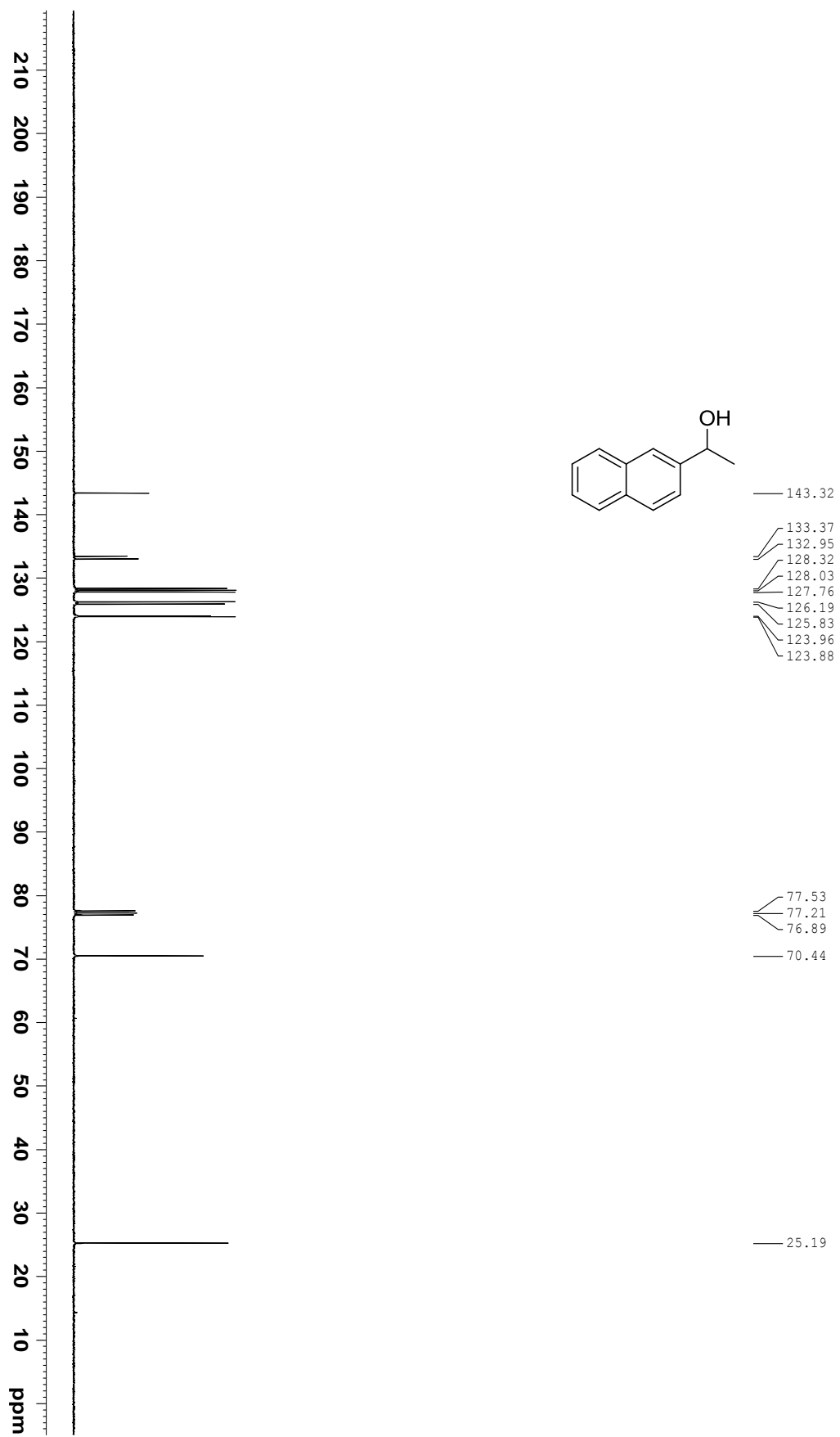


4-(1-Hydroxyethyl)benzonitrile (2o)

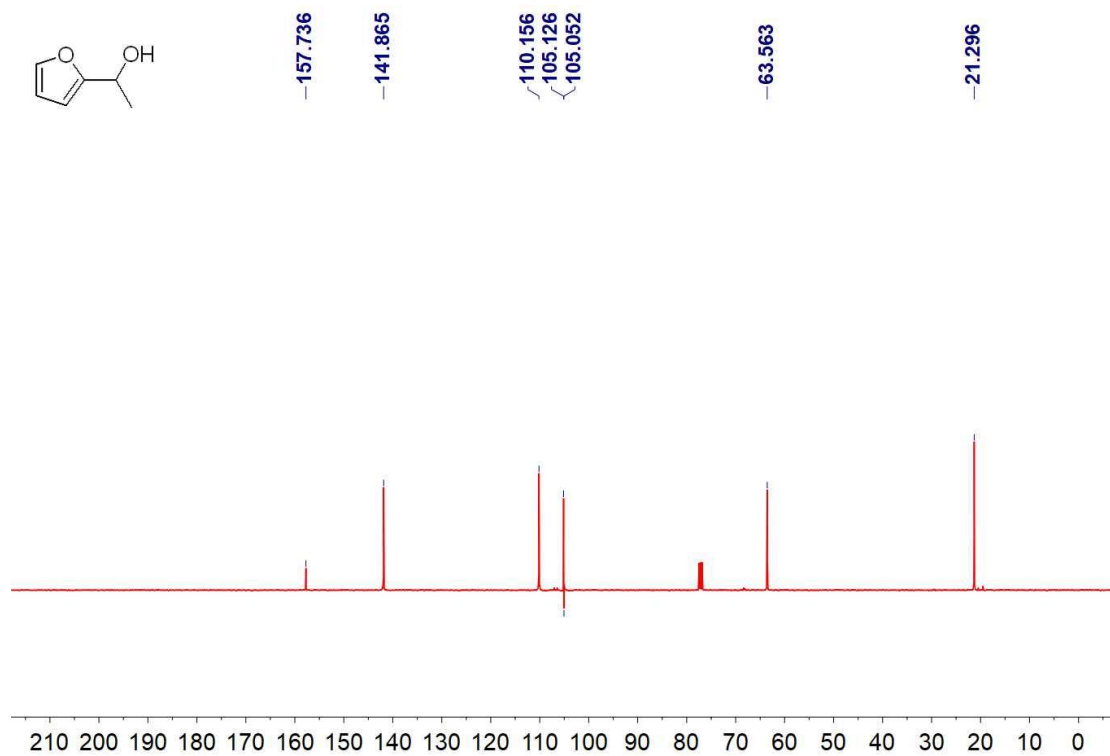
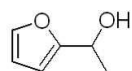
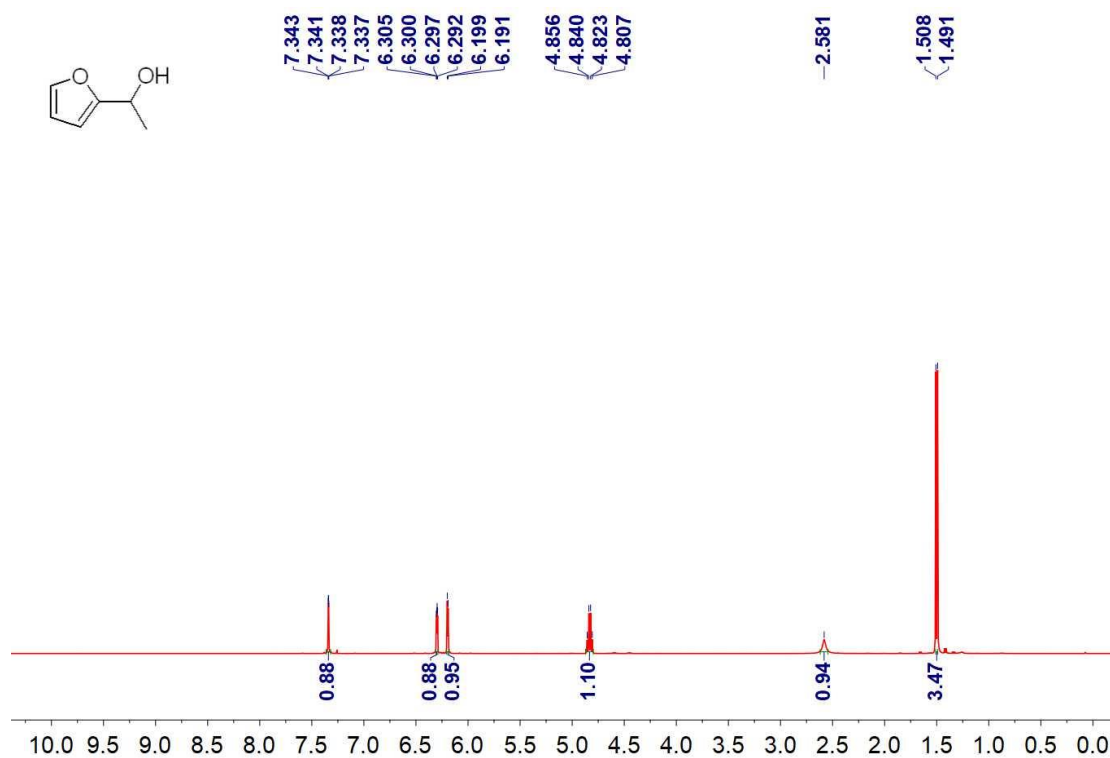
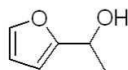


1-(Naphthalen-2-yl)ethan-1-ol (2p)

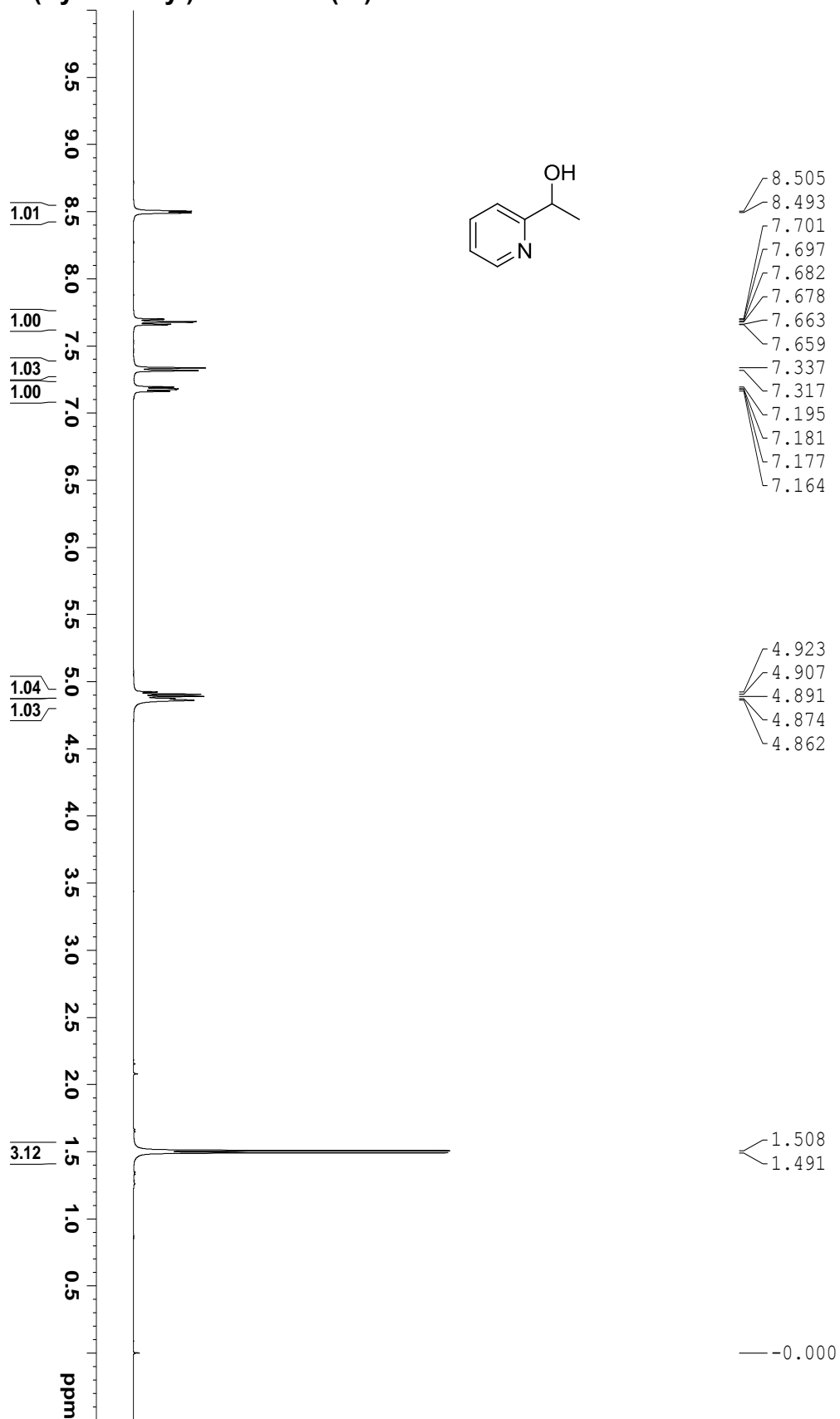


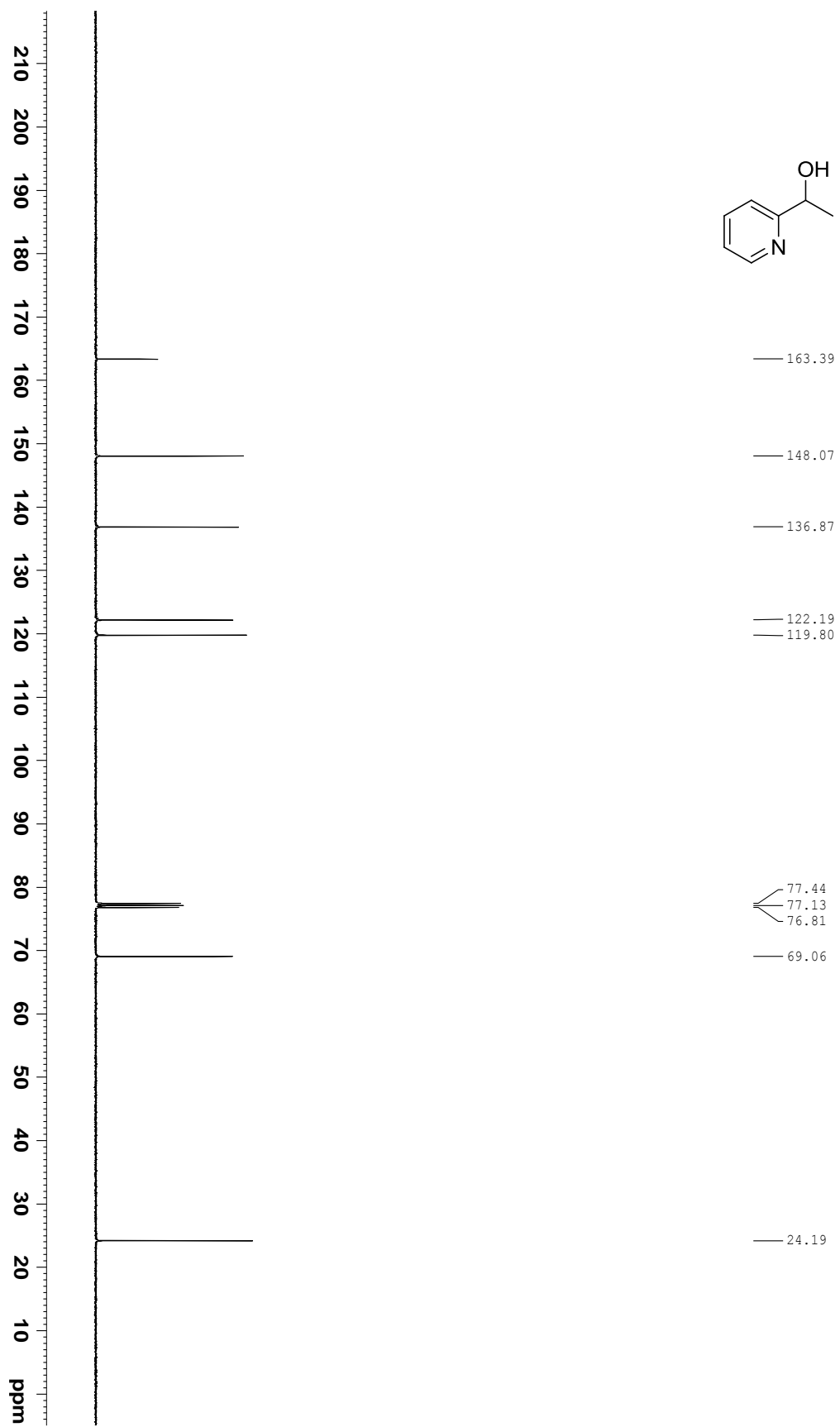


1-(Furan-2-yl)ethan-1-ol (2q)

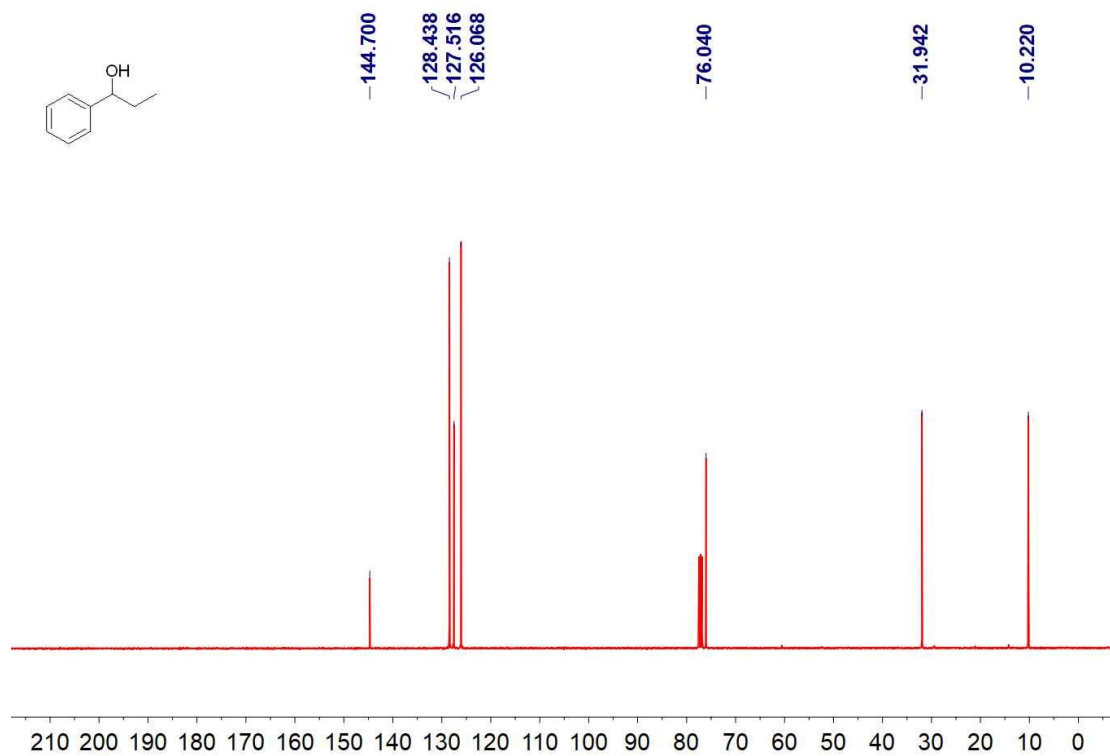
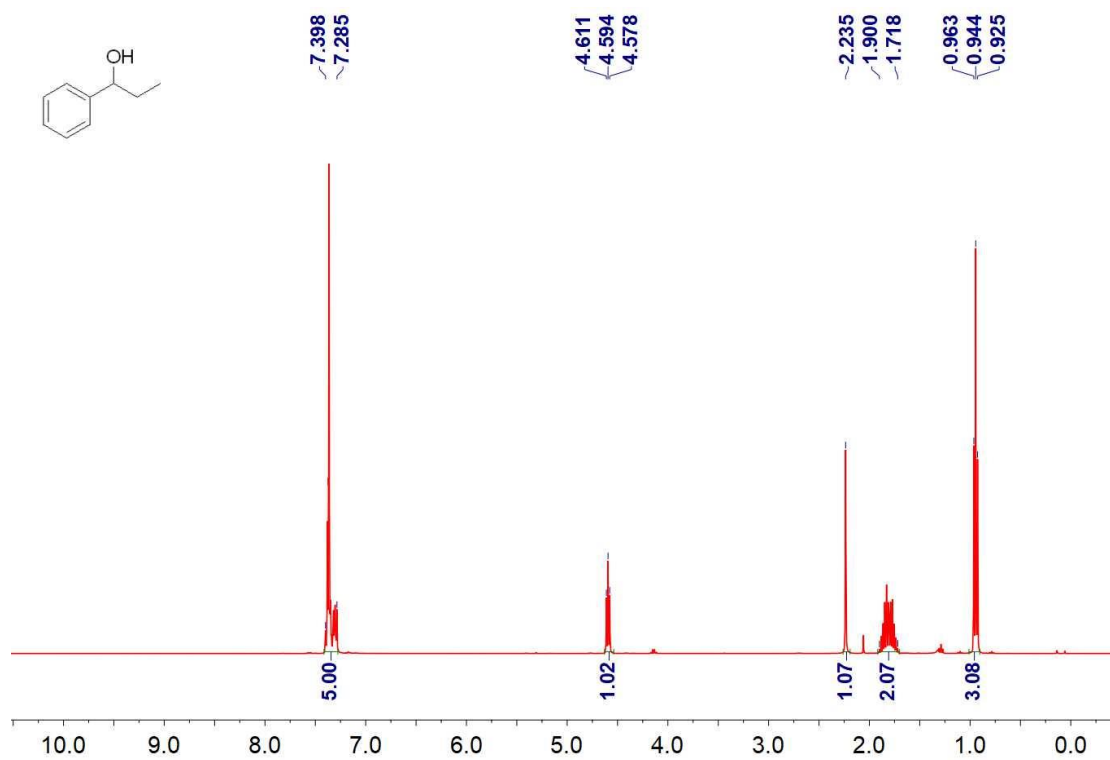


1-(Pyridin-2-yl)ethan-1-ol (2r)

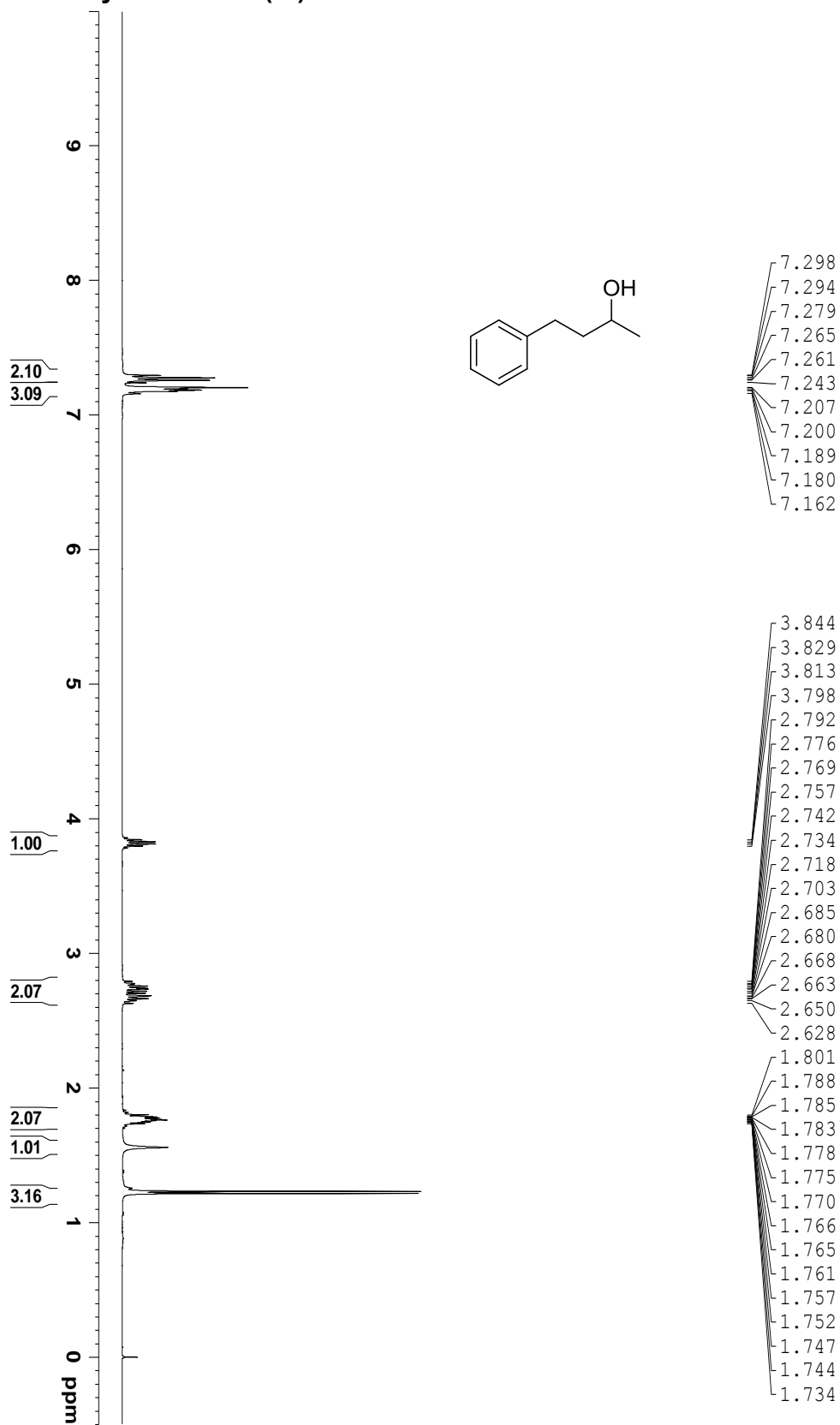


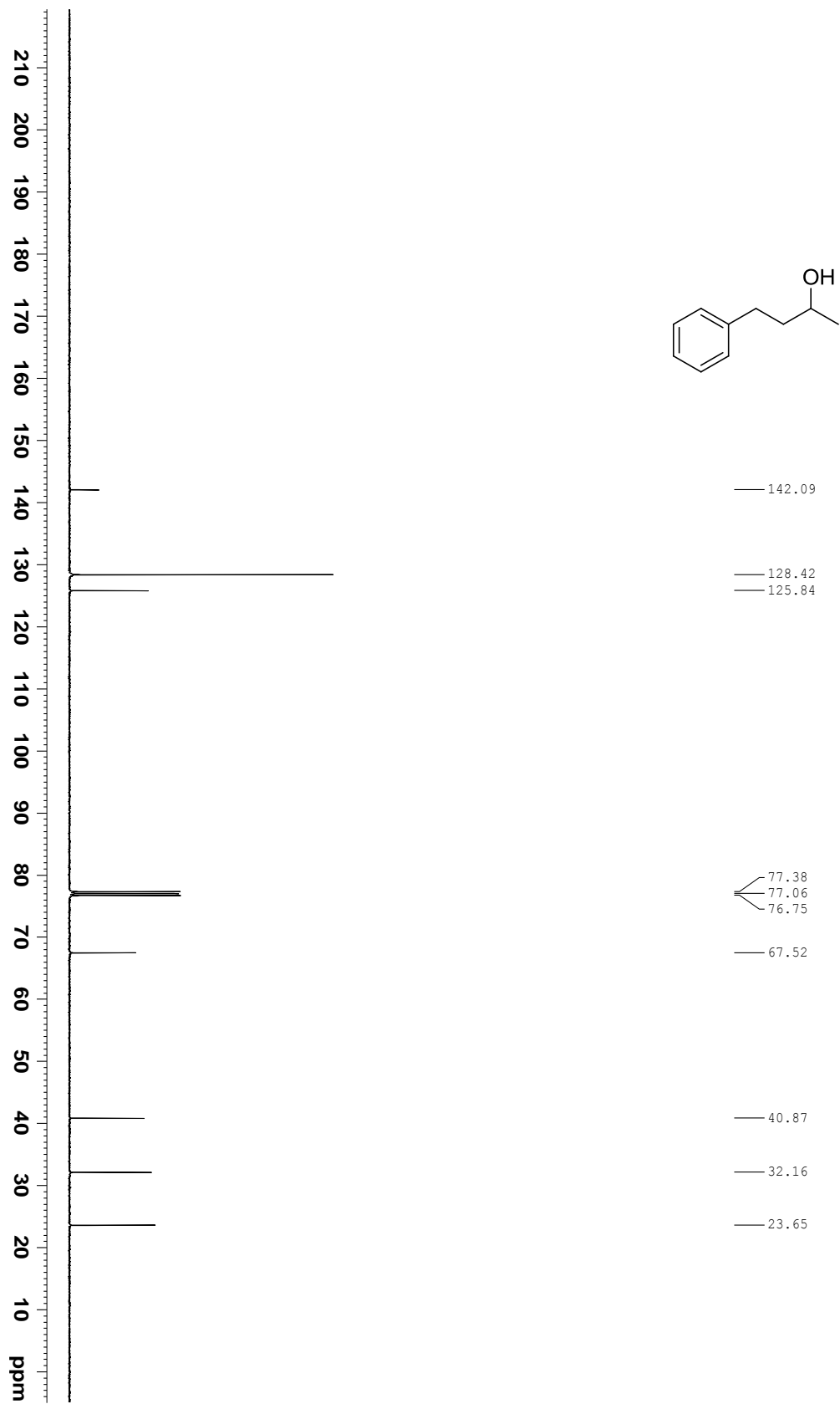


1-(1-Phenyl)propanol (2s)

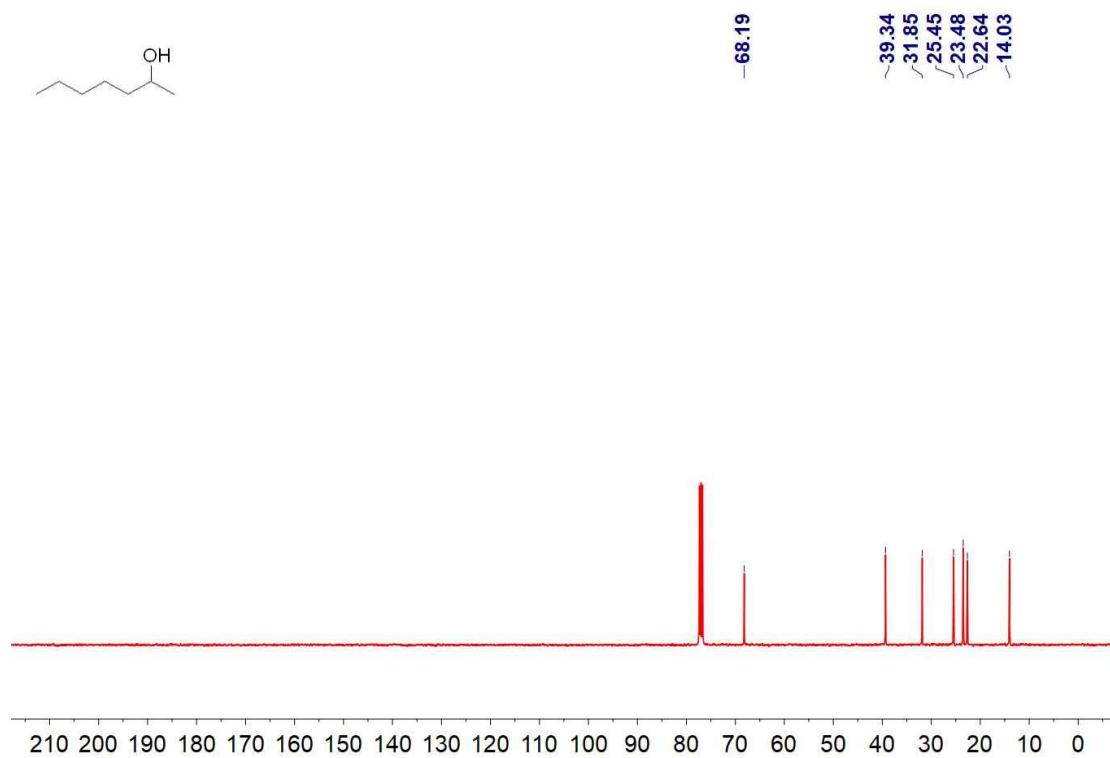
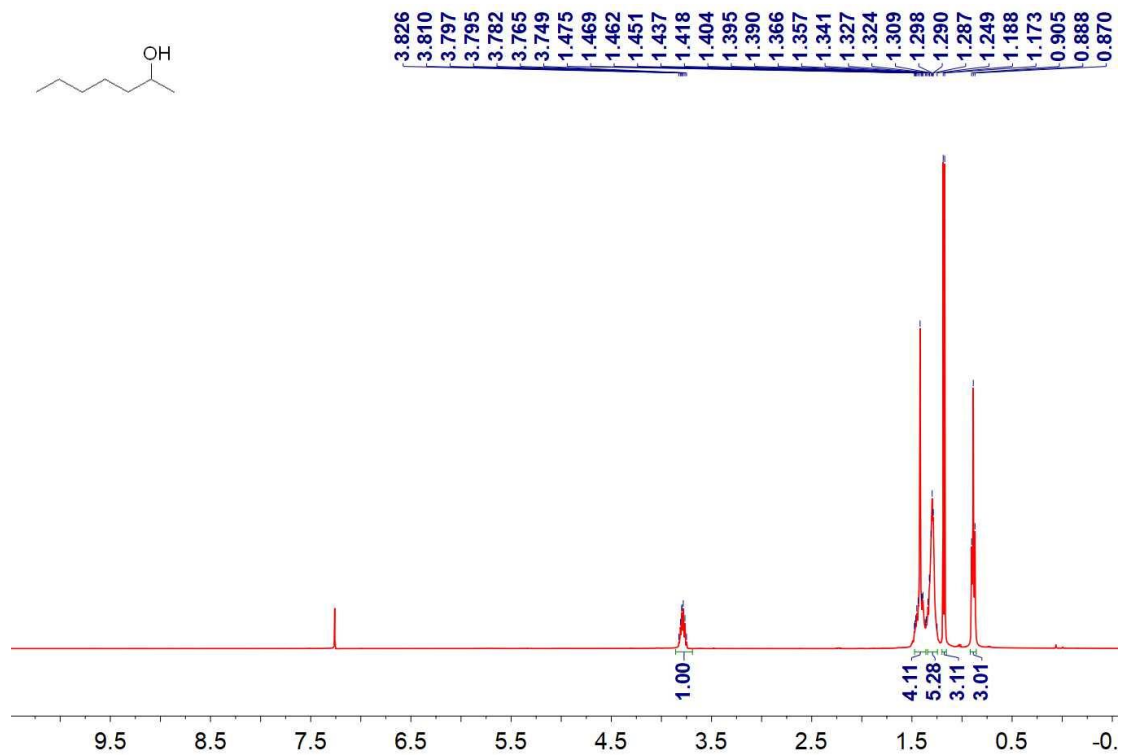


4-Phenylbutan-2-ol (2t)

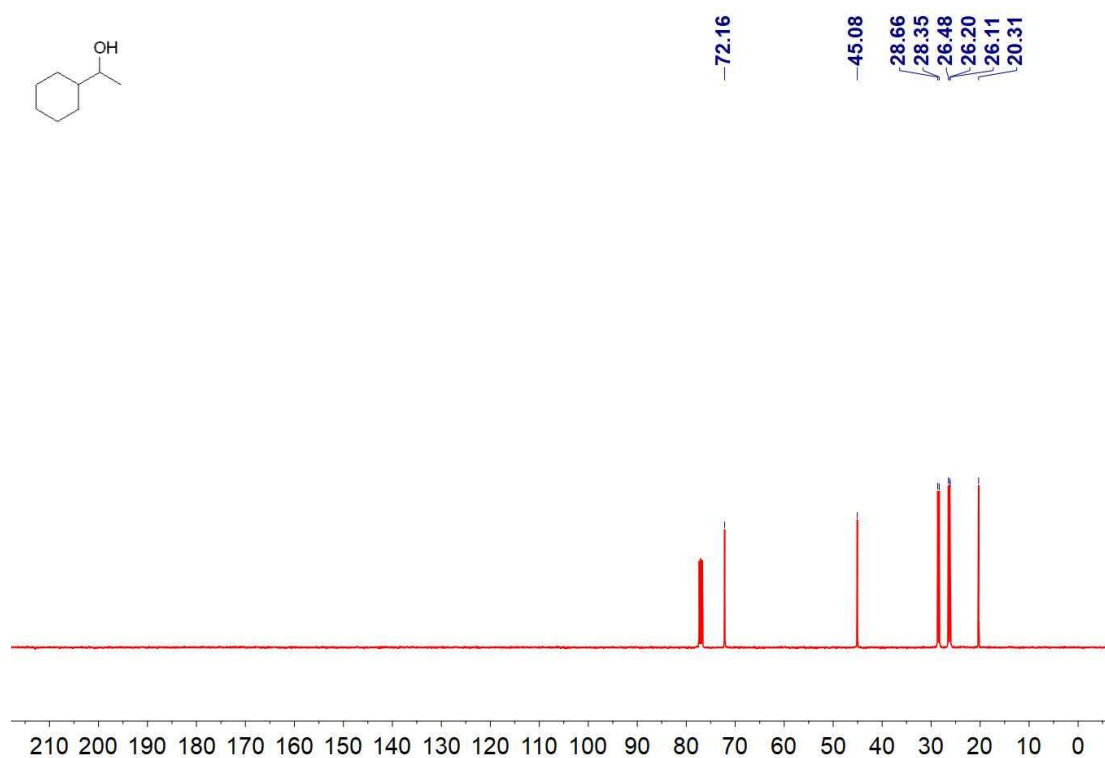
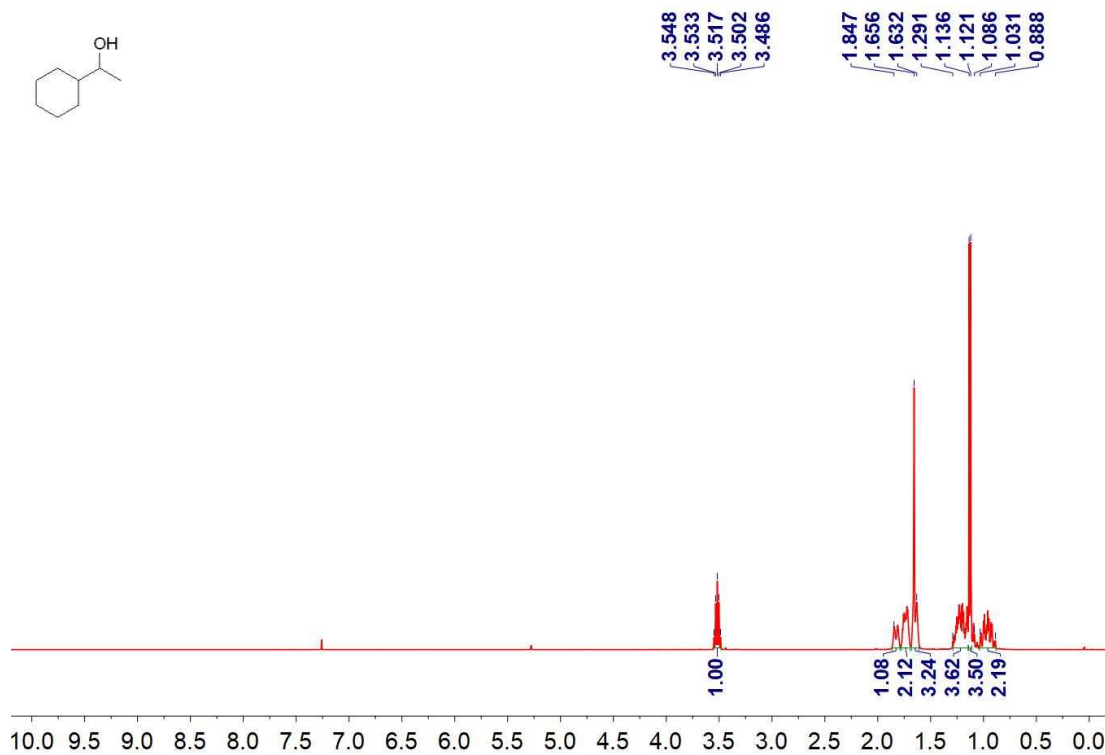




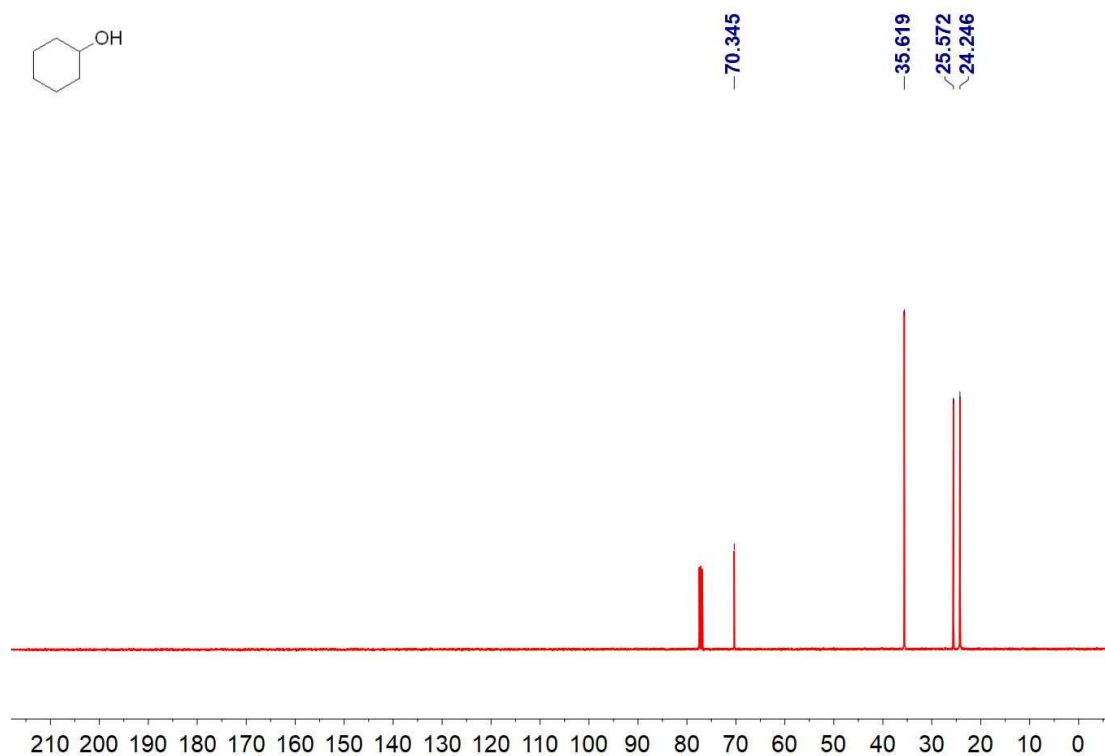
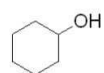
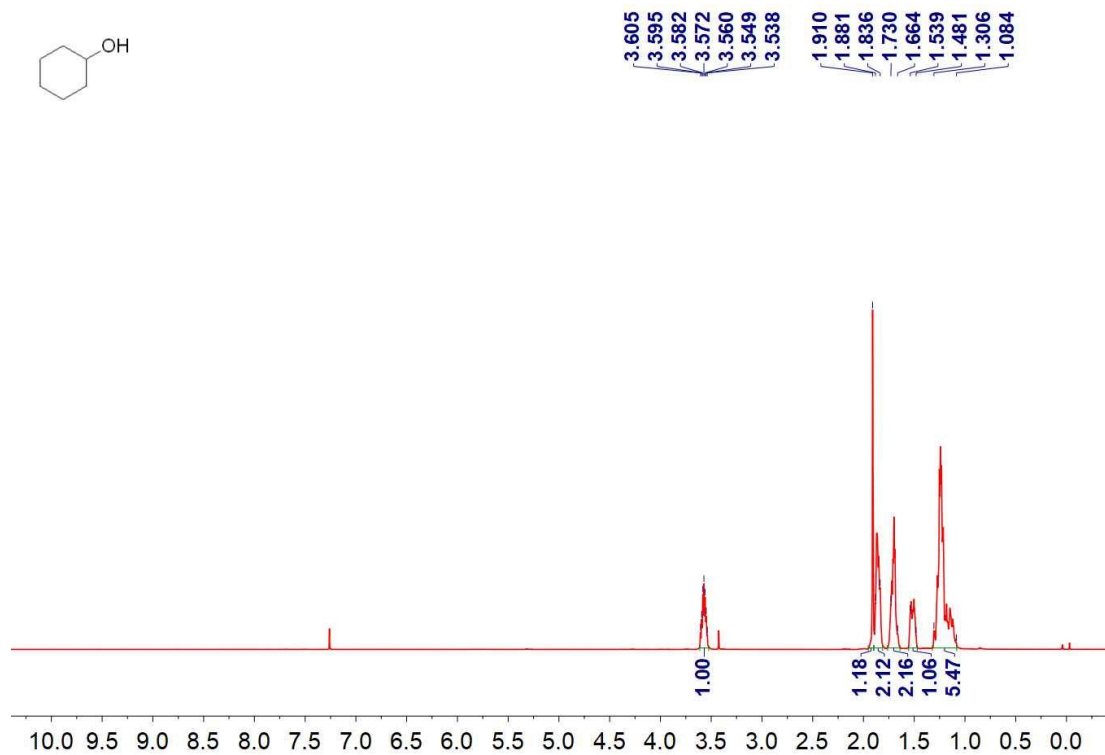
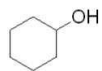
2-Heptanol (2u)



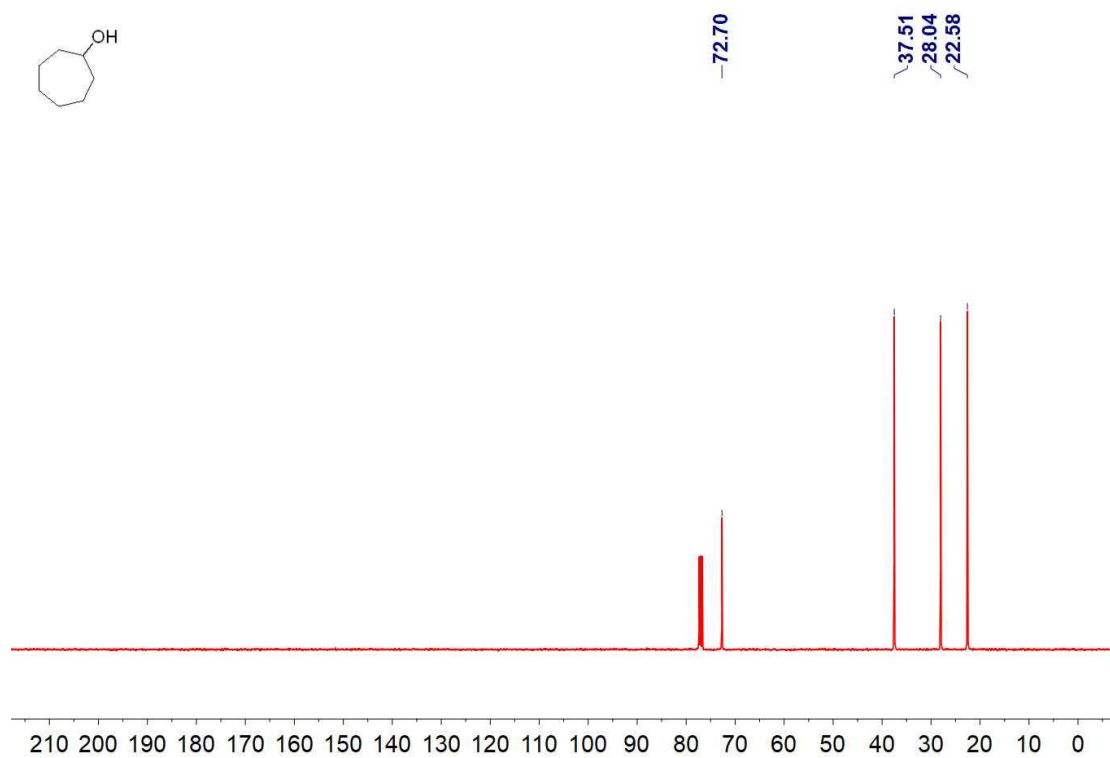
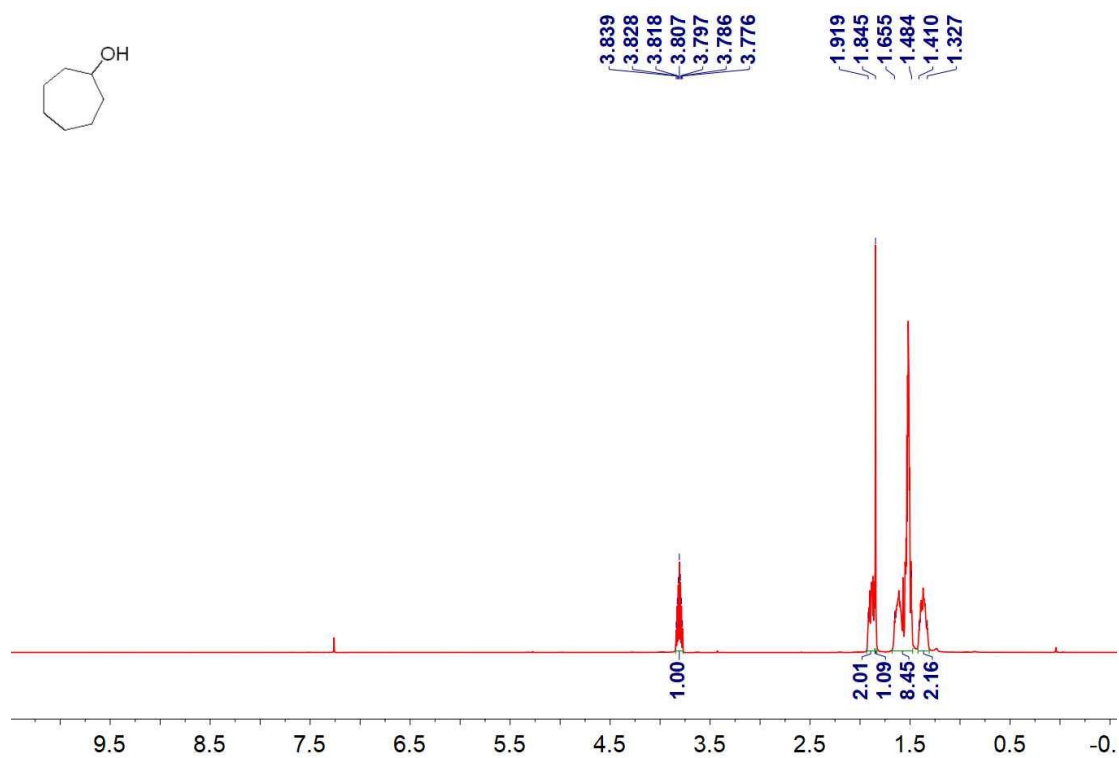
1-Cyclohexylethanol (2w)



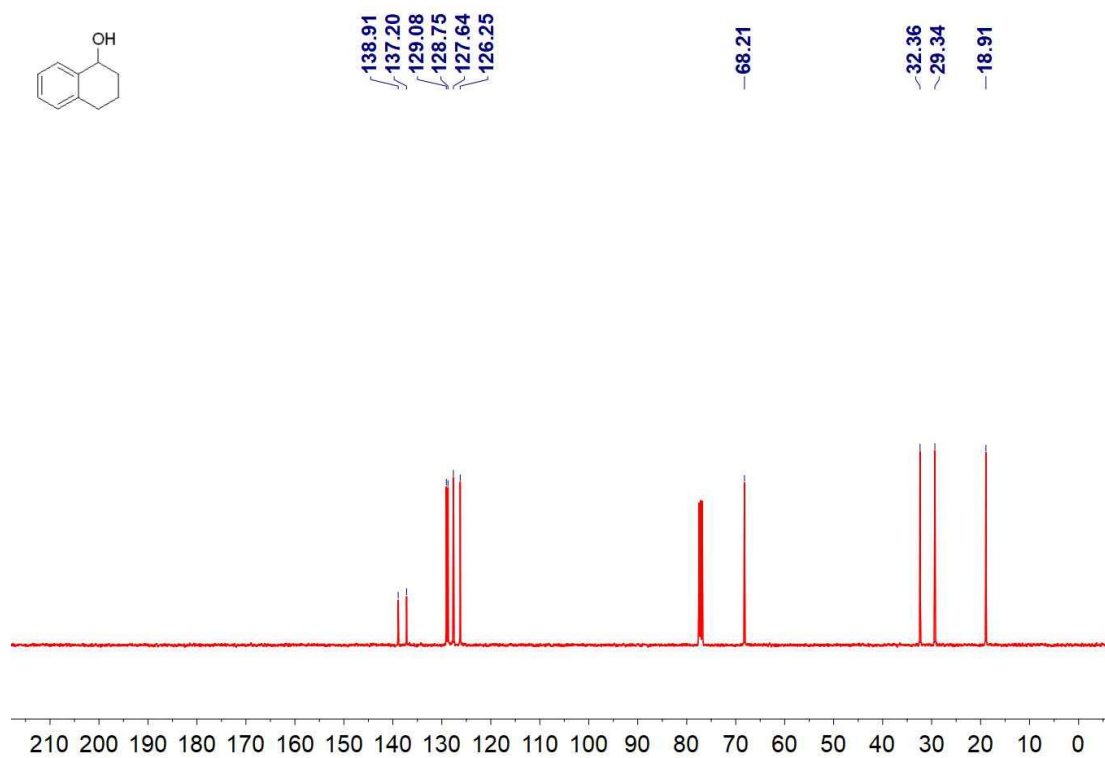
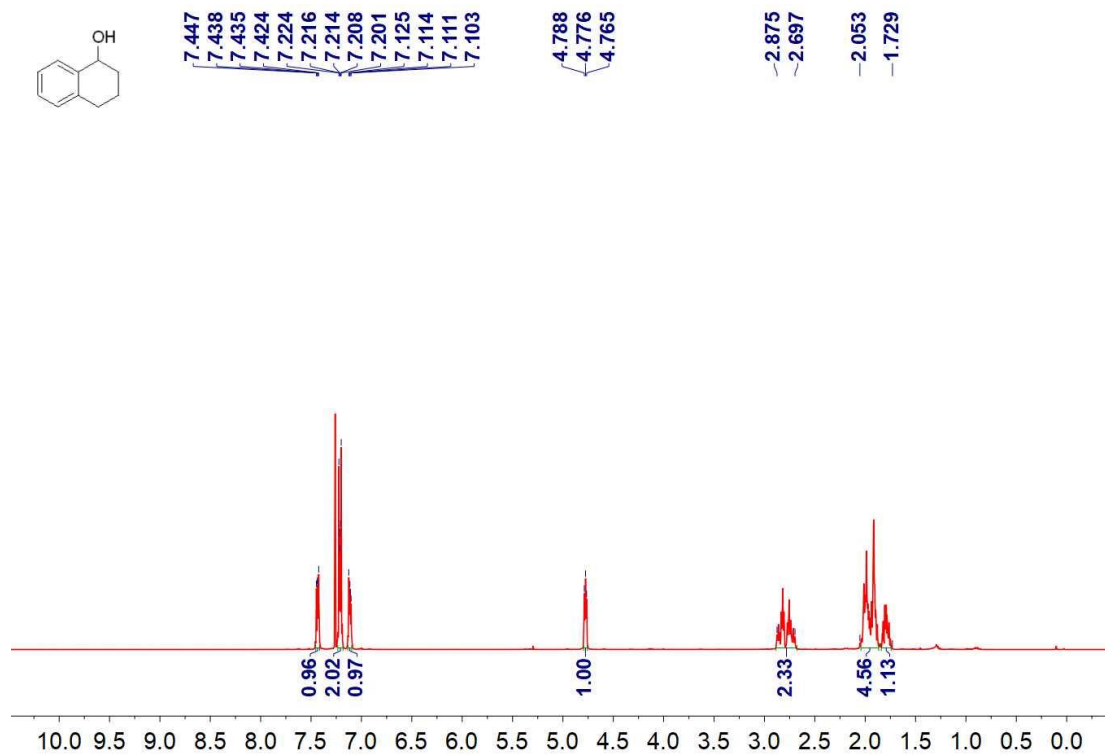
1-Cyclohexanol (2x)



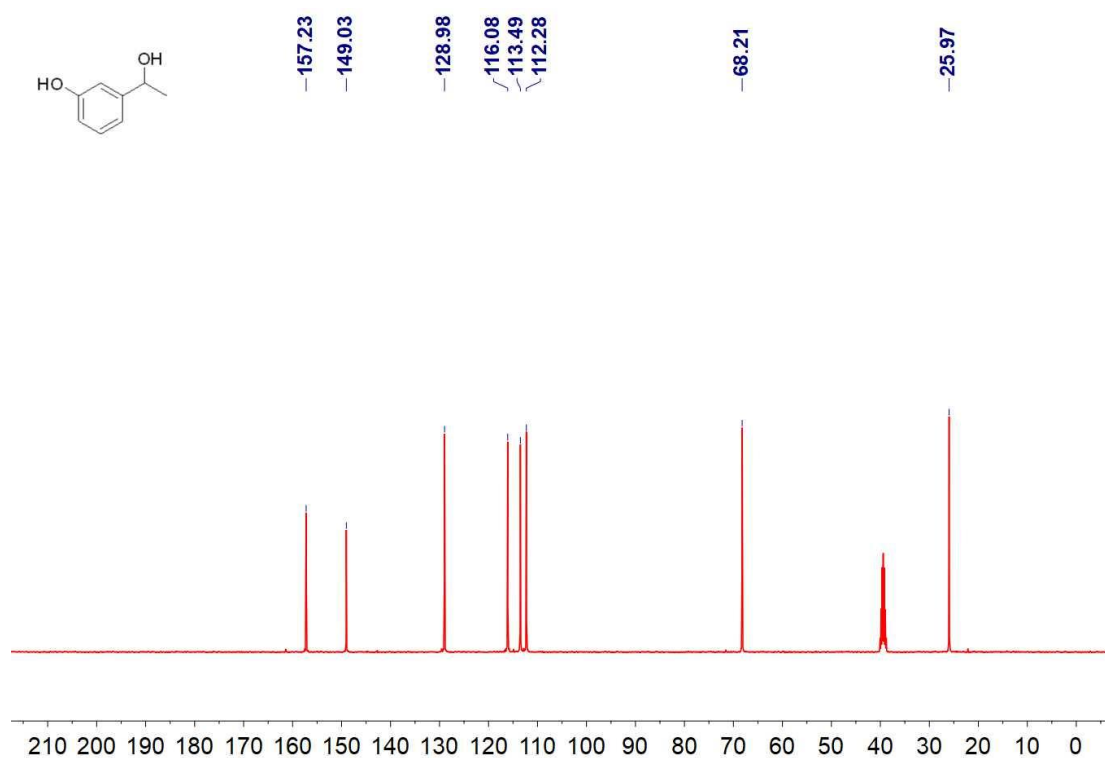
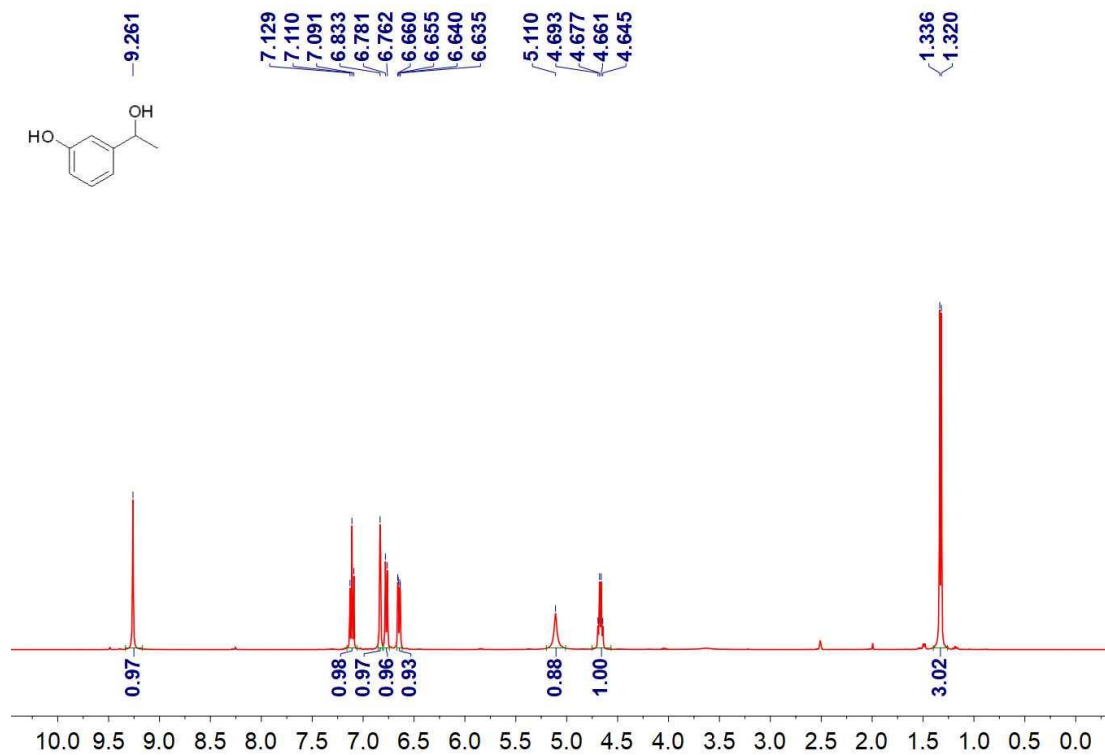
1-Cycloheptanol (2y)



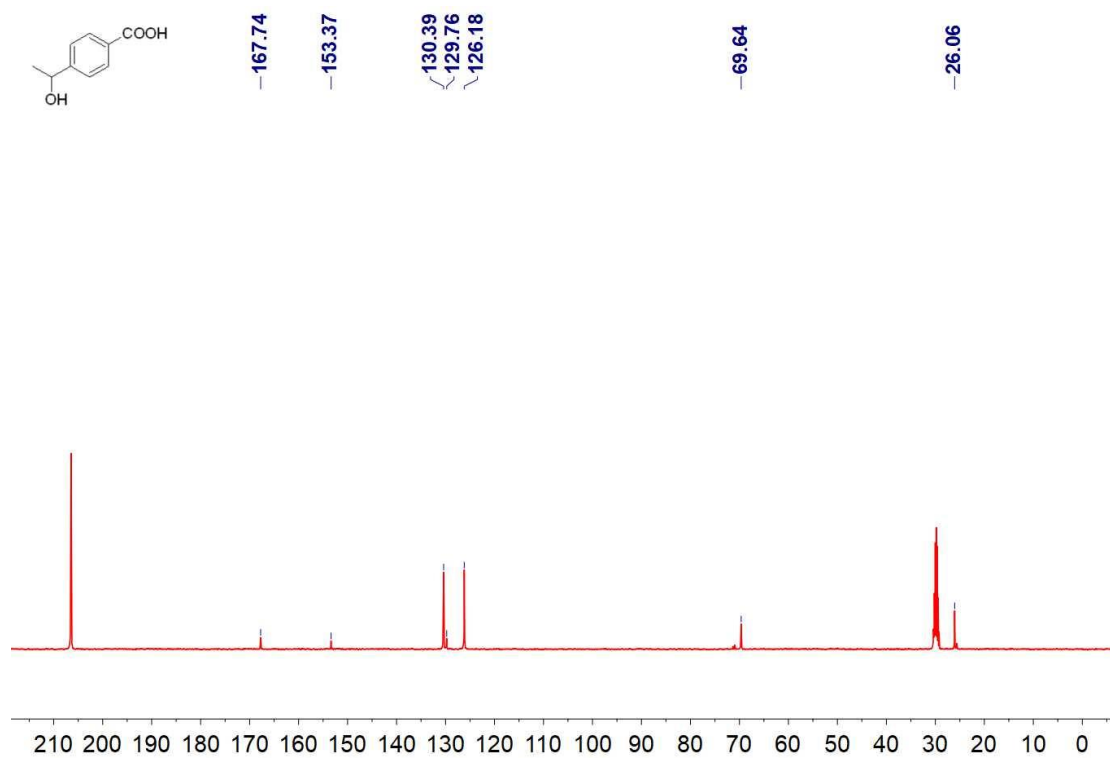
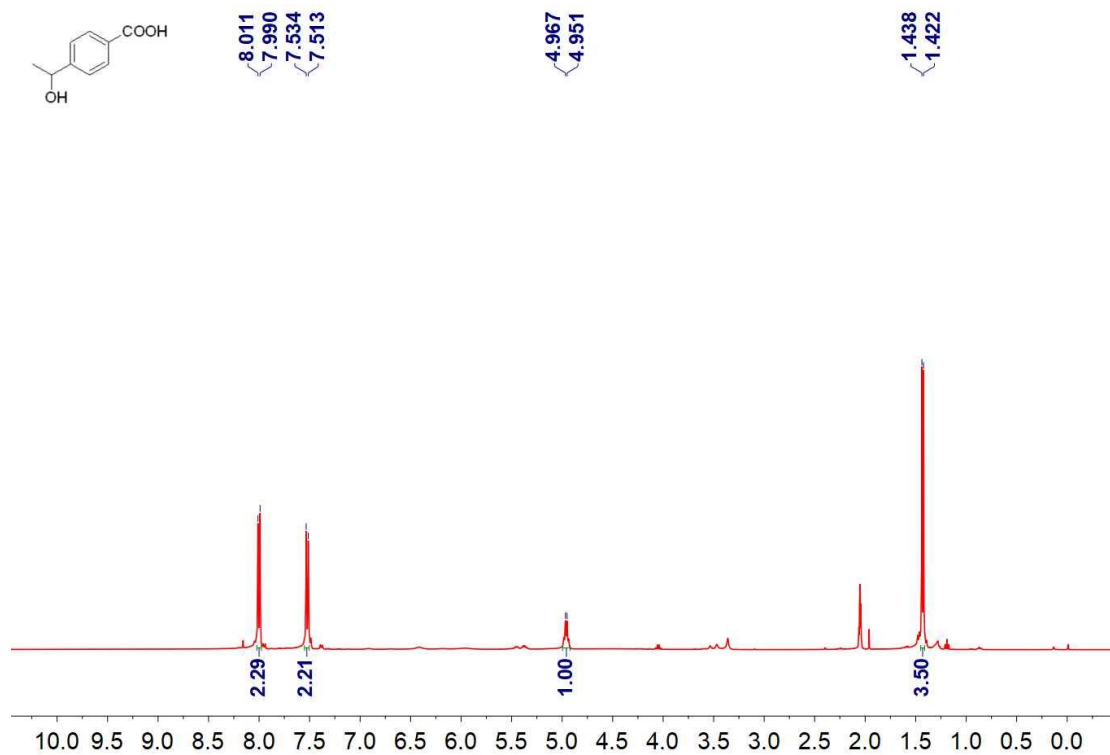
1-(1,2,3,4-Tetrahydro)naphthalenol (2z)



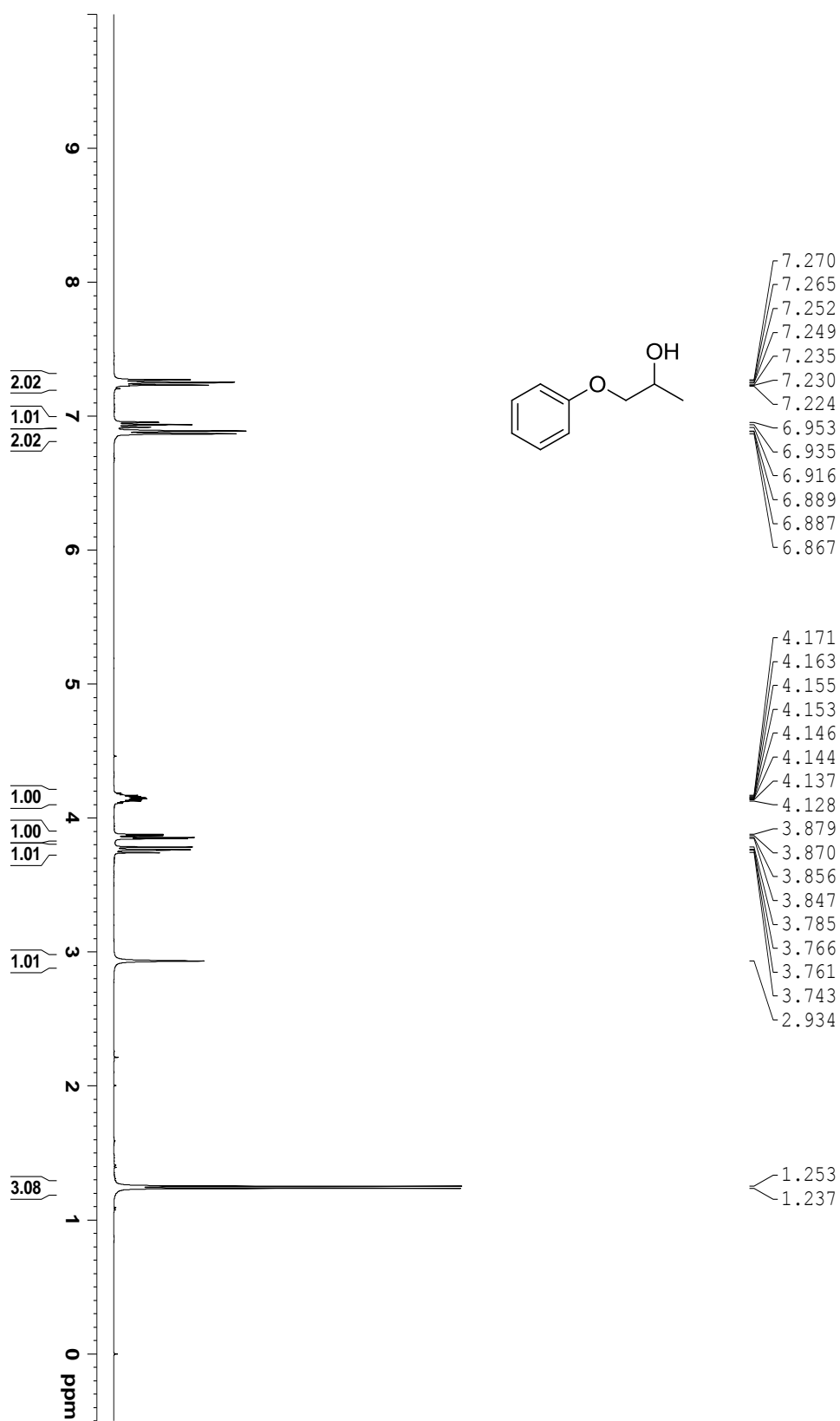
3-(1-Hydroxyethyl)phenol (2aa)

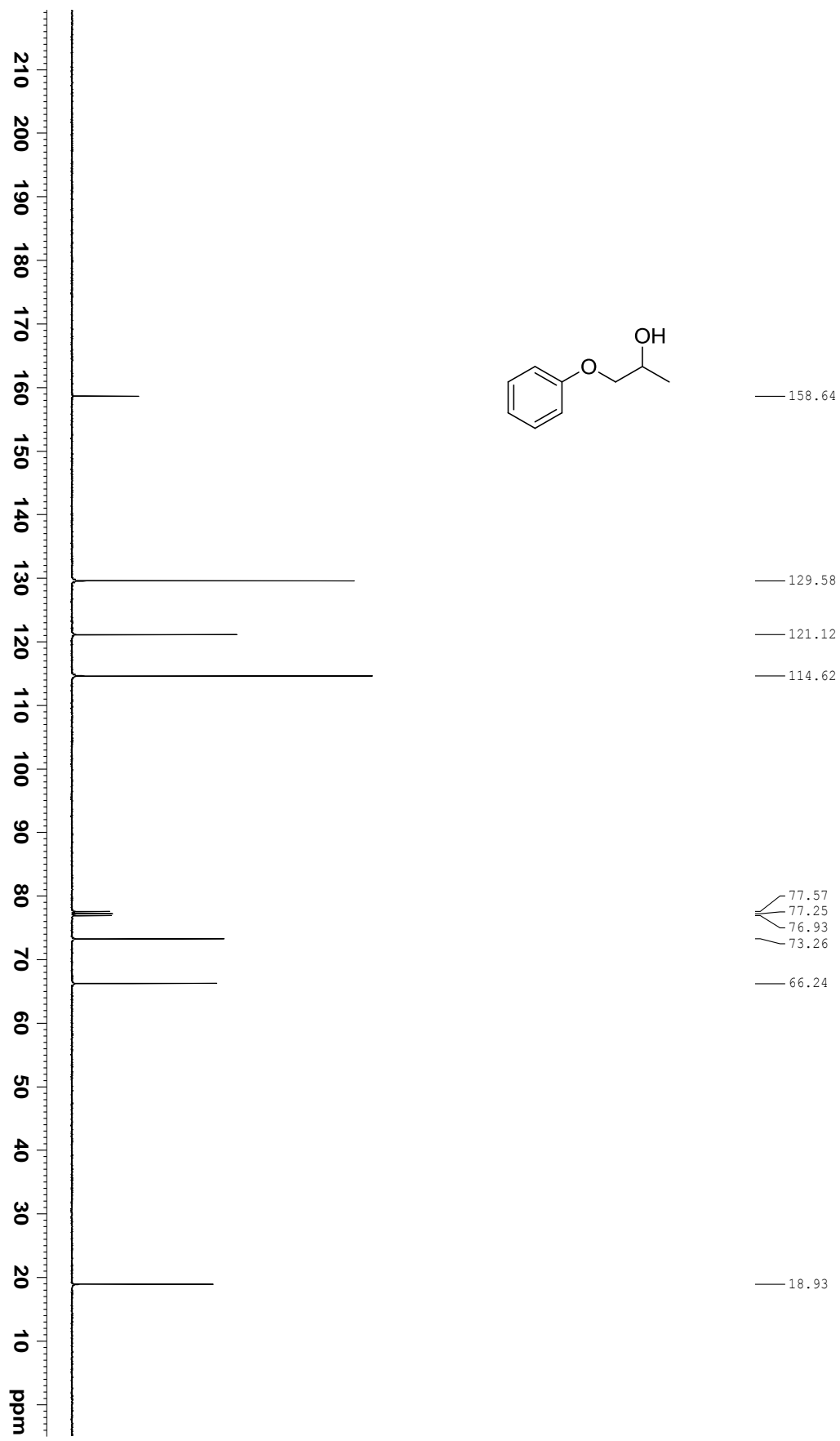


4-(1-Hydroxyethyl)benzoic acid (2ab)

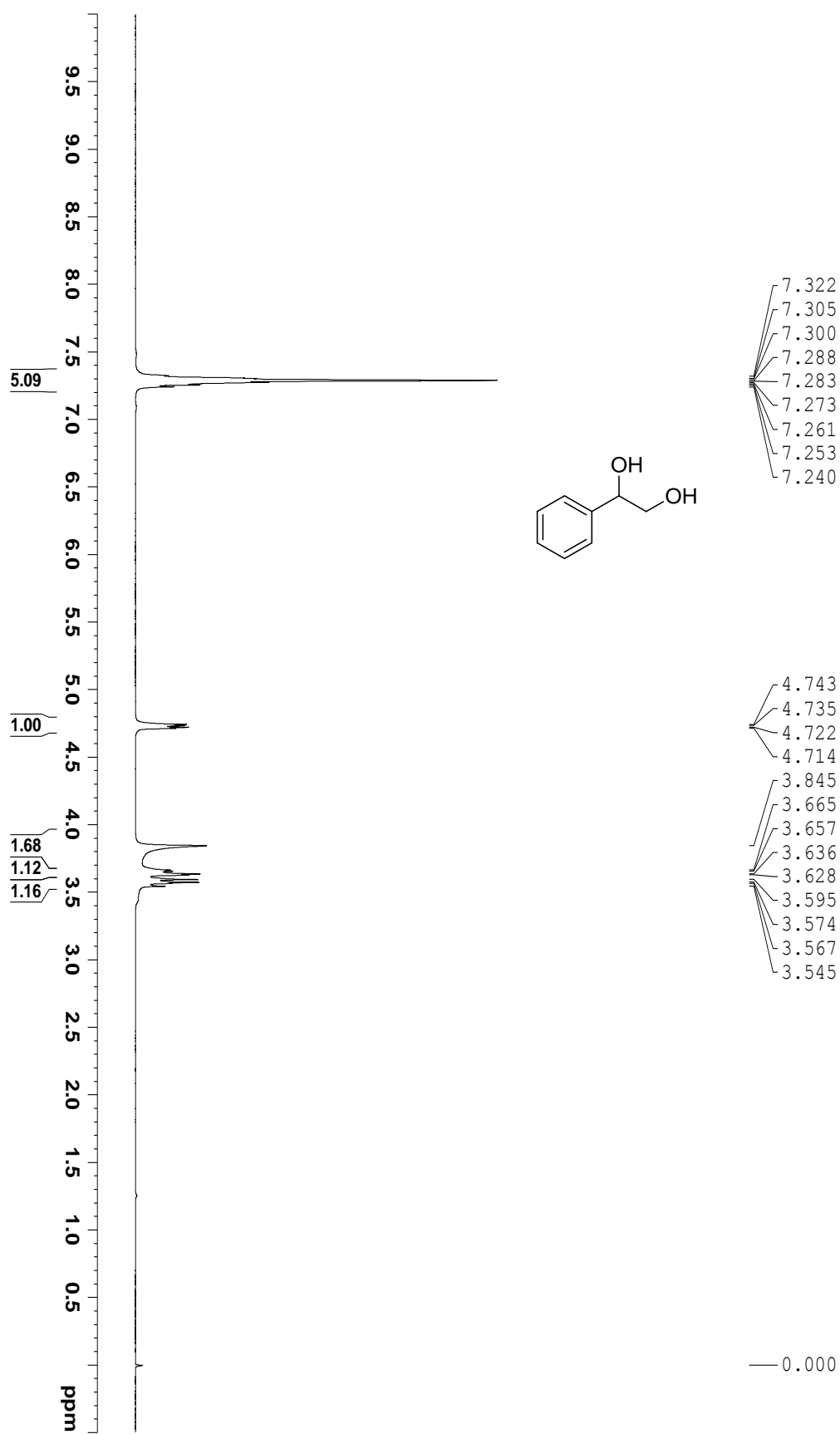


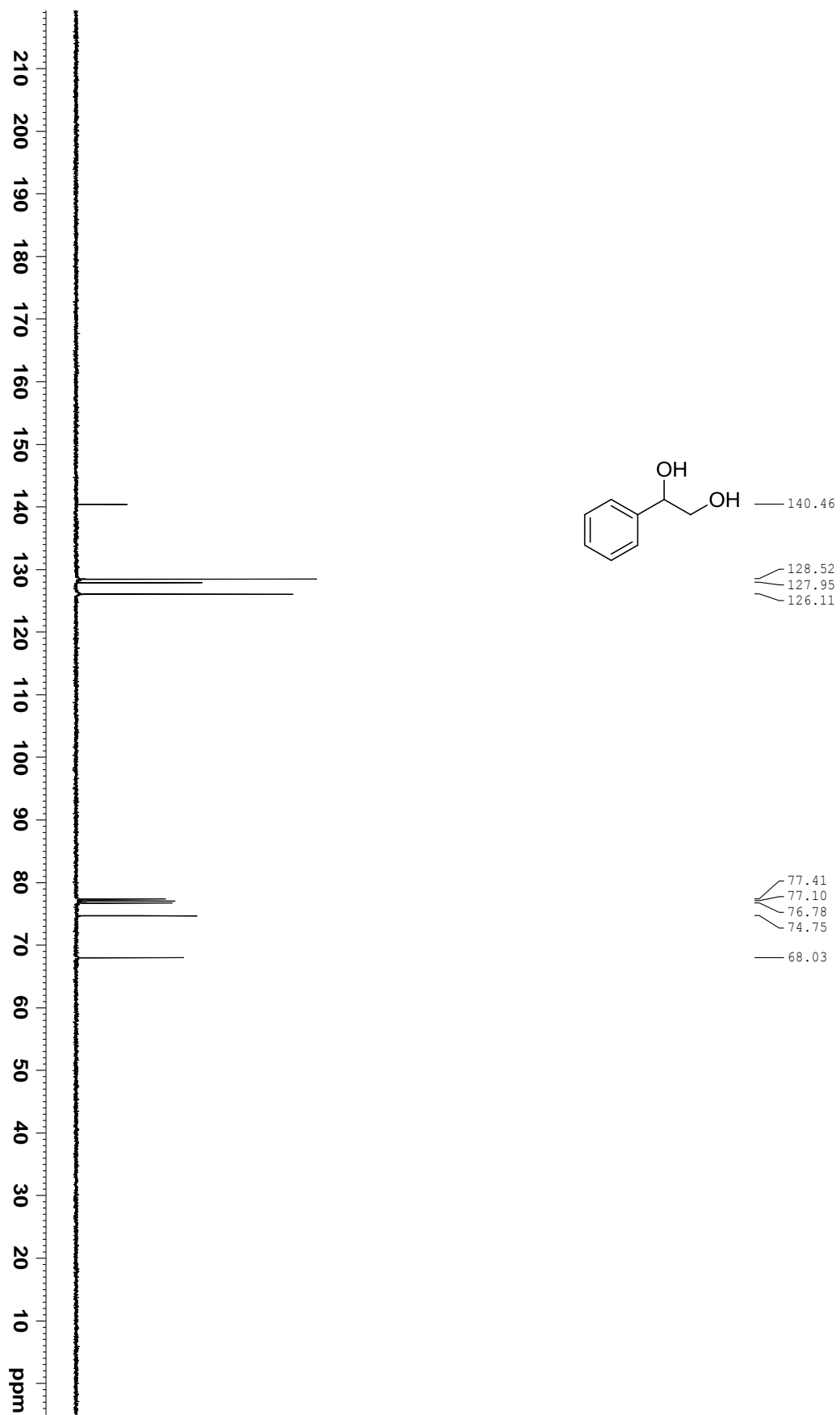
1-Phenoxypropan-2-ol (4a)



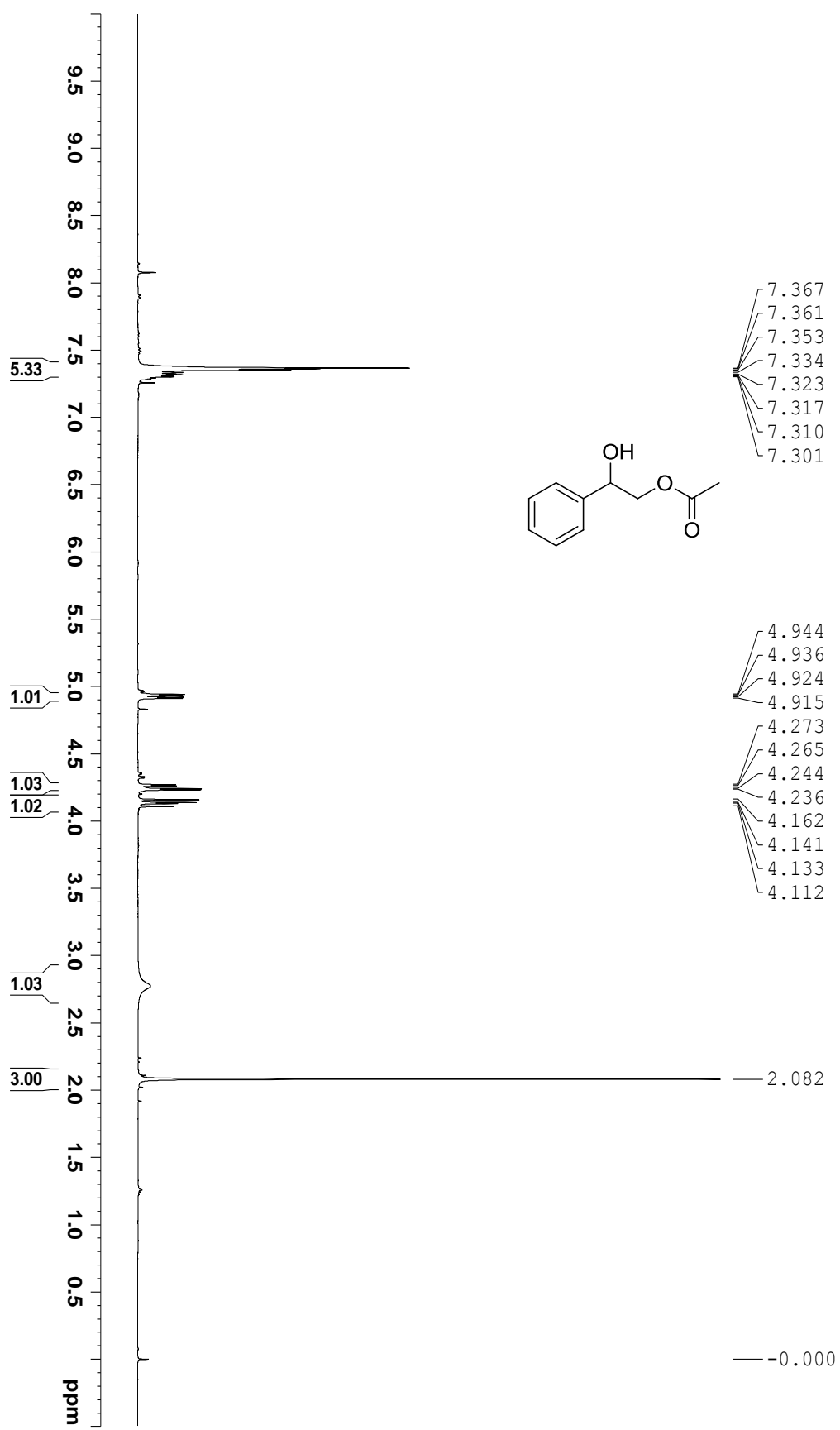


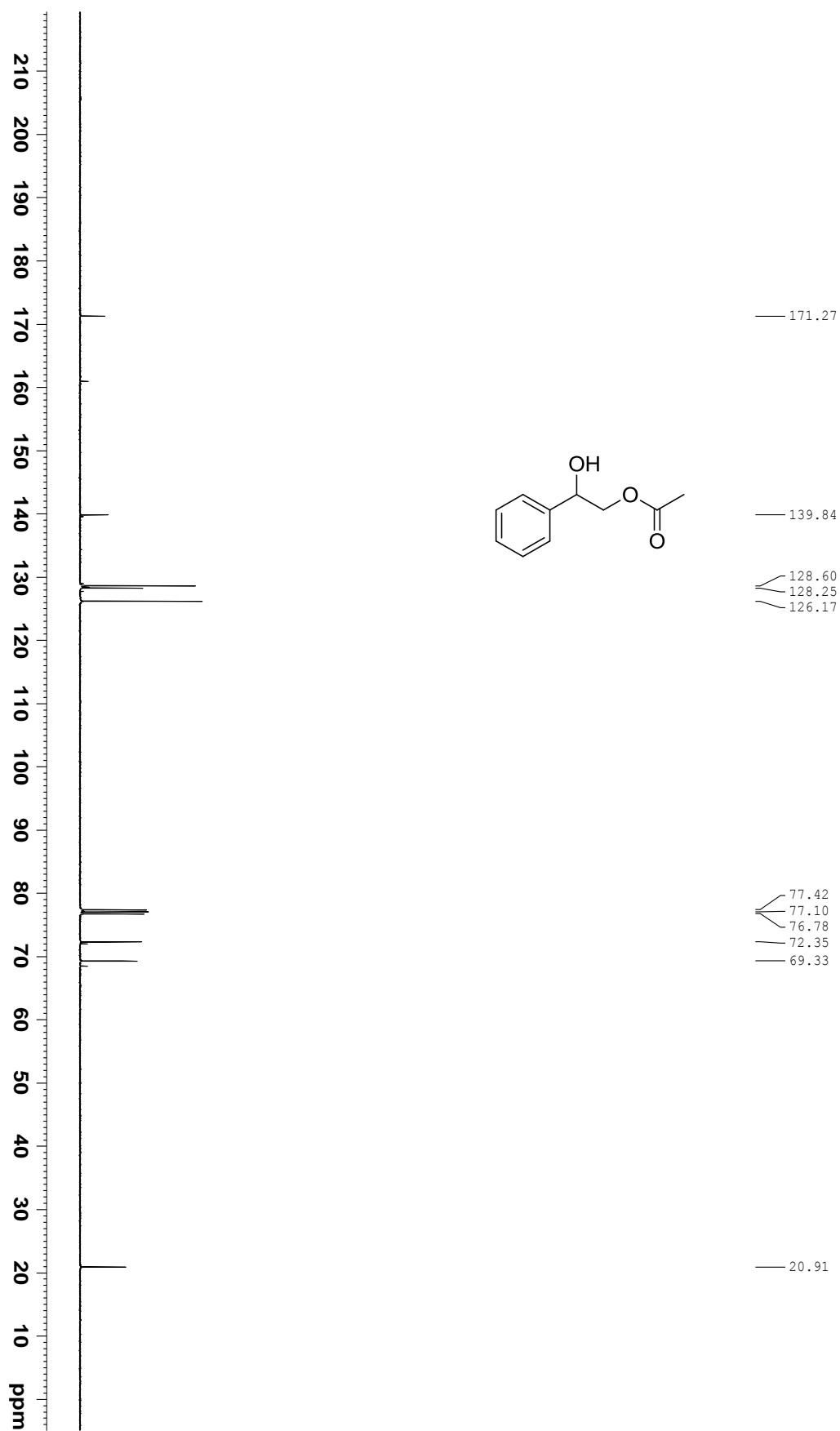
1-Phenylethane-1,2-diol (4b)



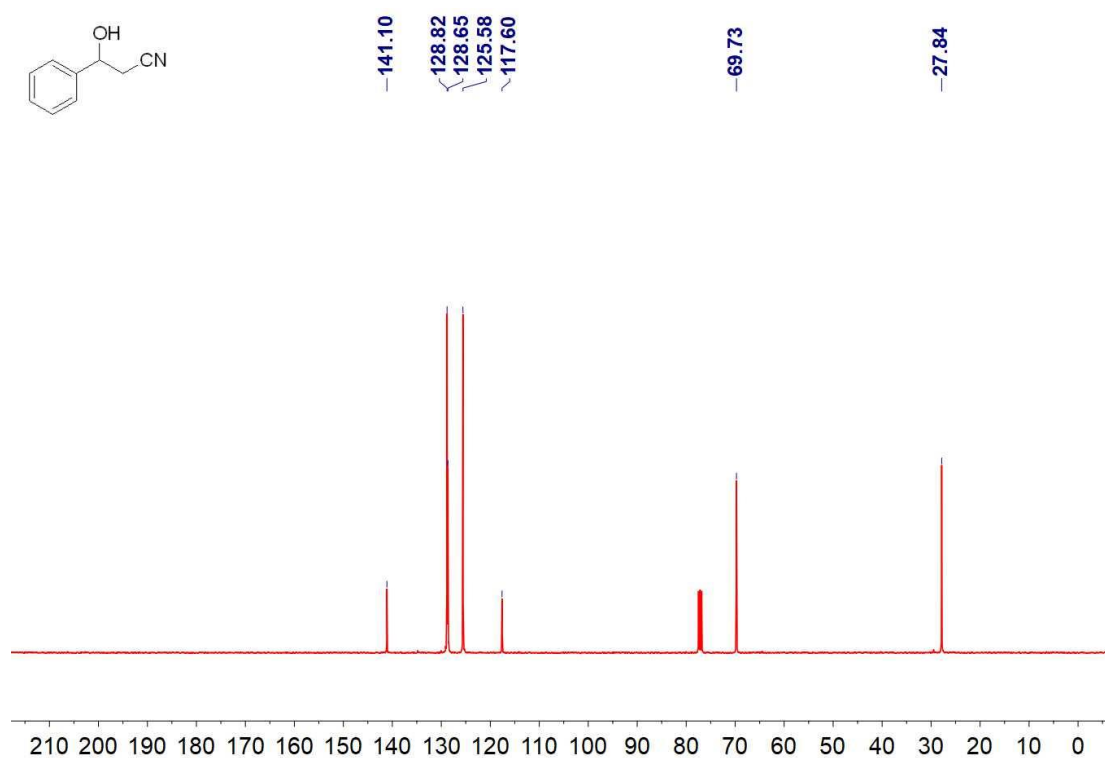
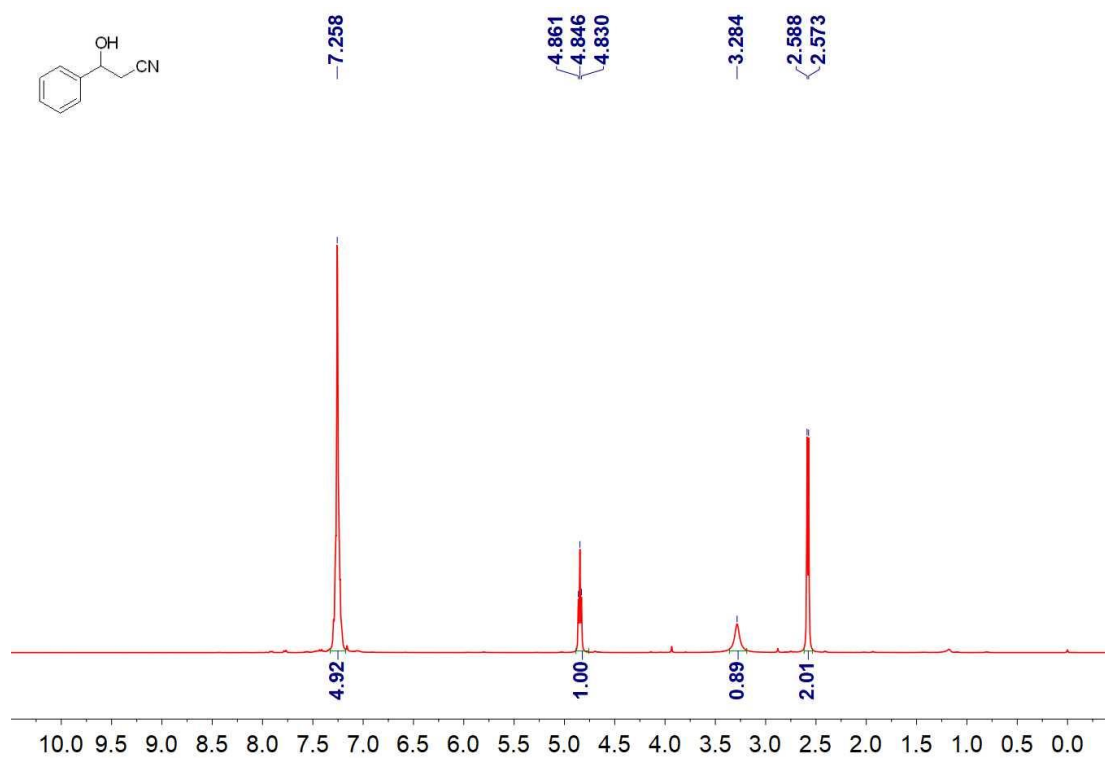


2-Hydroxy-2-phenylethyl acetate (4c).

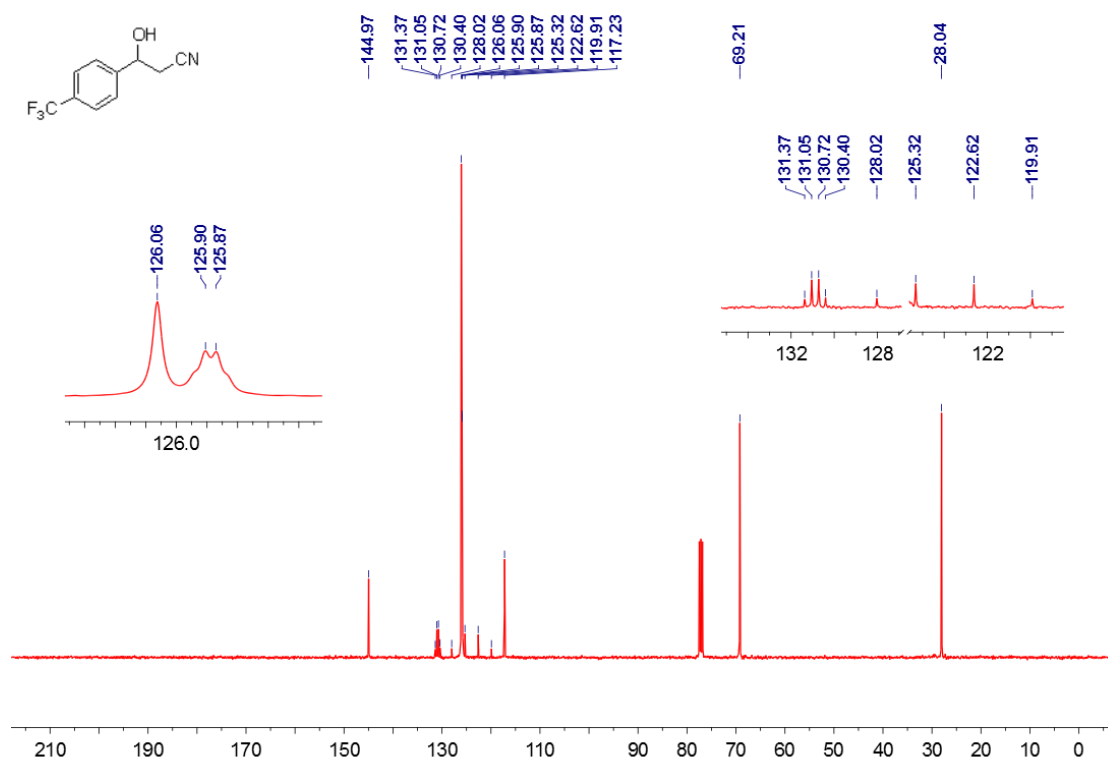
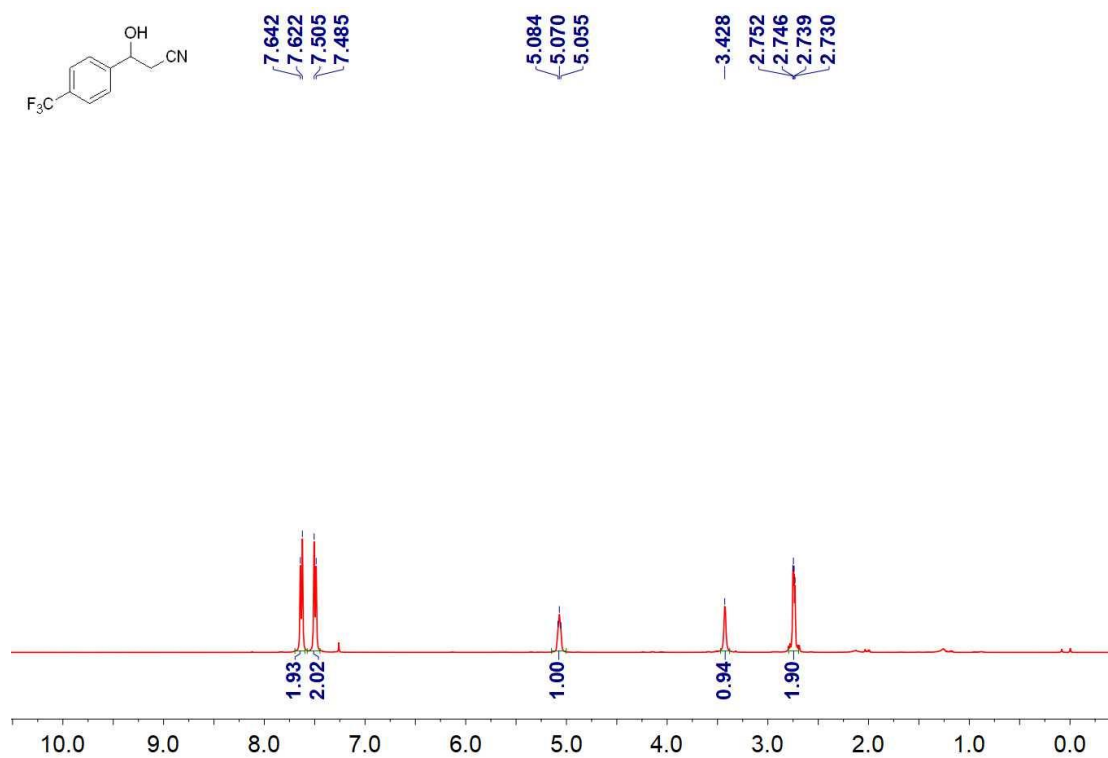




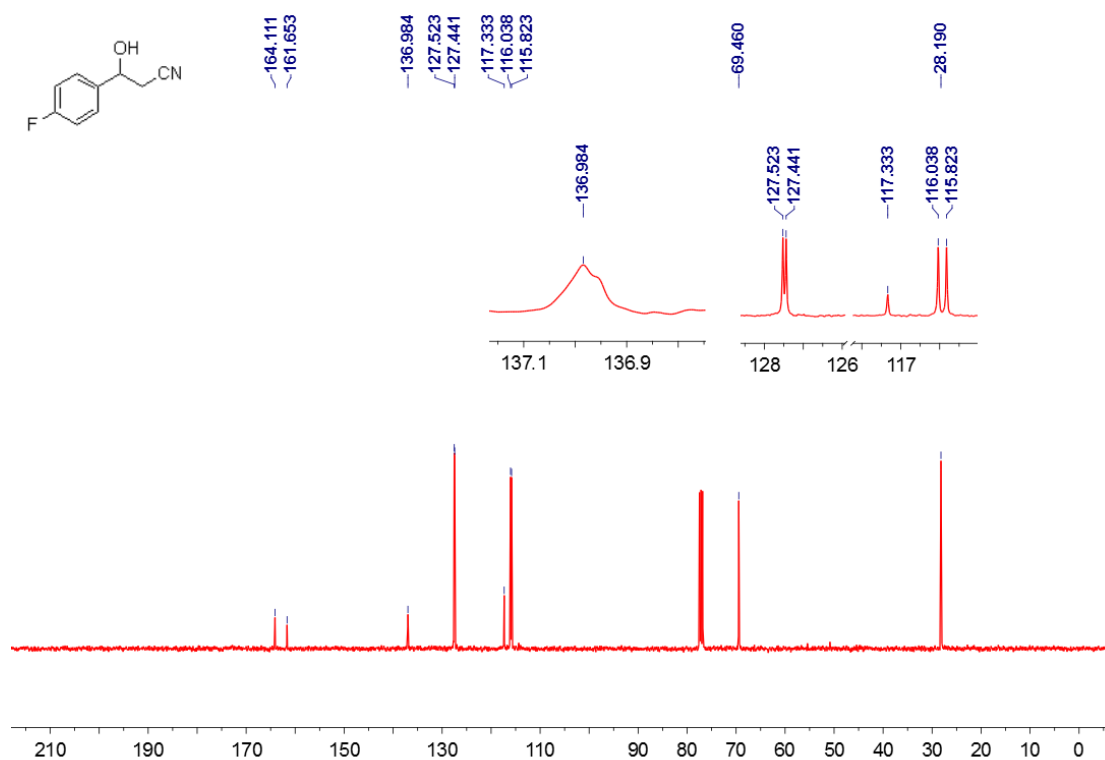
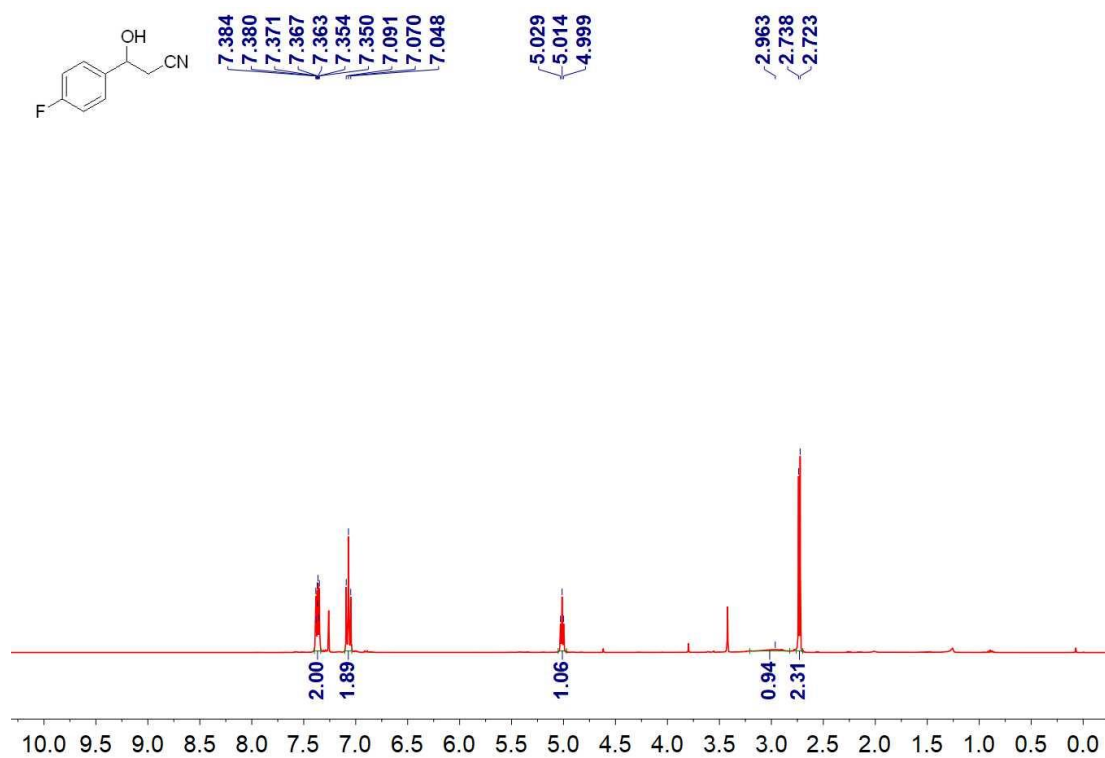
3-Hydroxy-3-phenylpropanenitrile (4d)



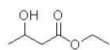
3-hydroxy-3-(4-(trifluoromethyl)phenyl)propanenitrile (4e)



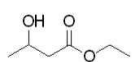
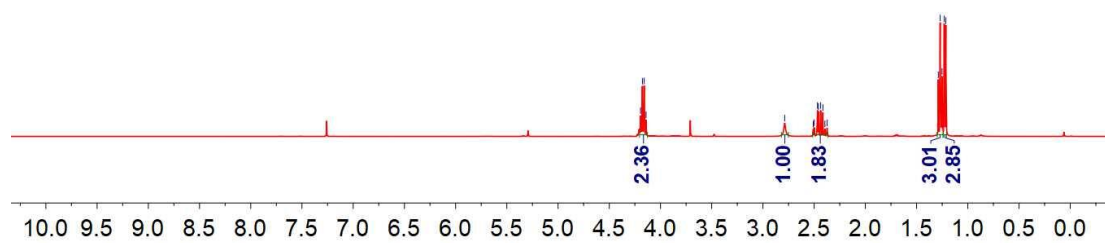
3-(4-fluorophenyl)-3-hydroxypropanenitrile (4f)



3-Hydroxy-butyrac acid ethyl ester (4g)



4.195
4.177
4.159
4.141
2.787
2.508
2.500
2.467
2.458
2.436
2.415
2.395
2.373
1.288
1.270
1.252
1.230
1.214



173.083

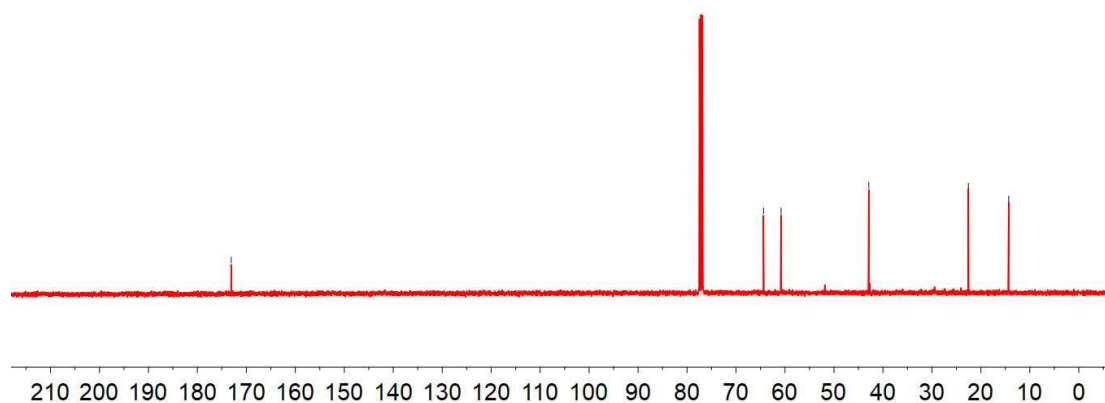
64.388

60.805

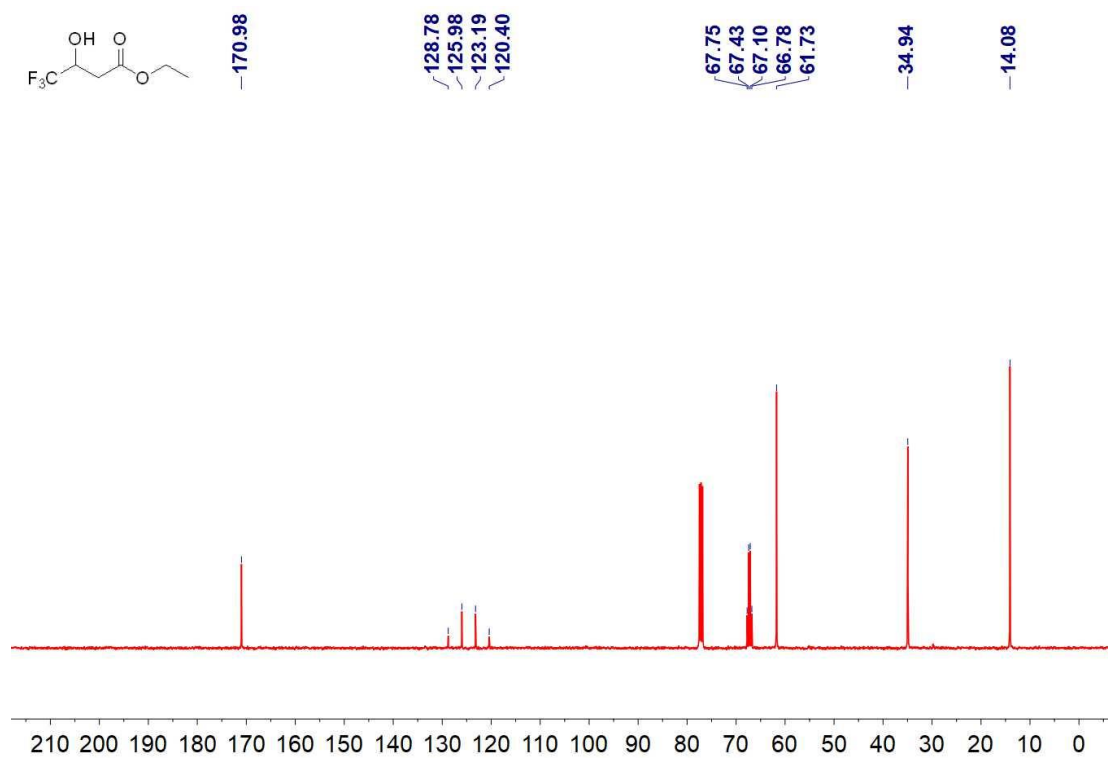
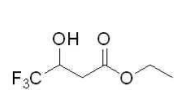
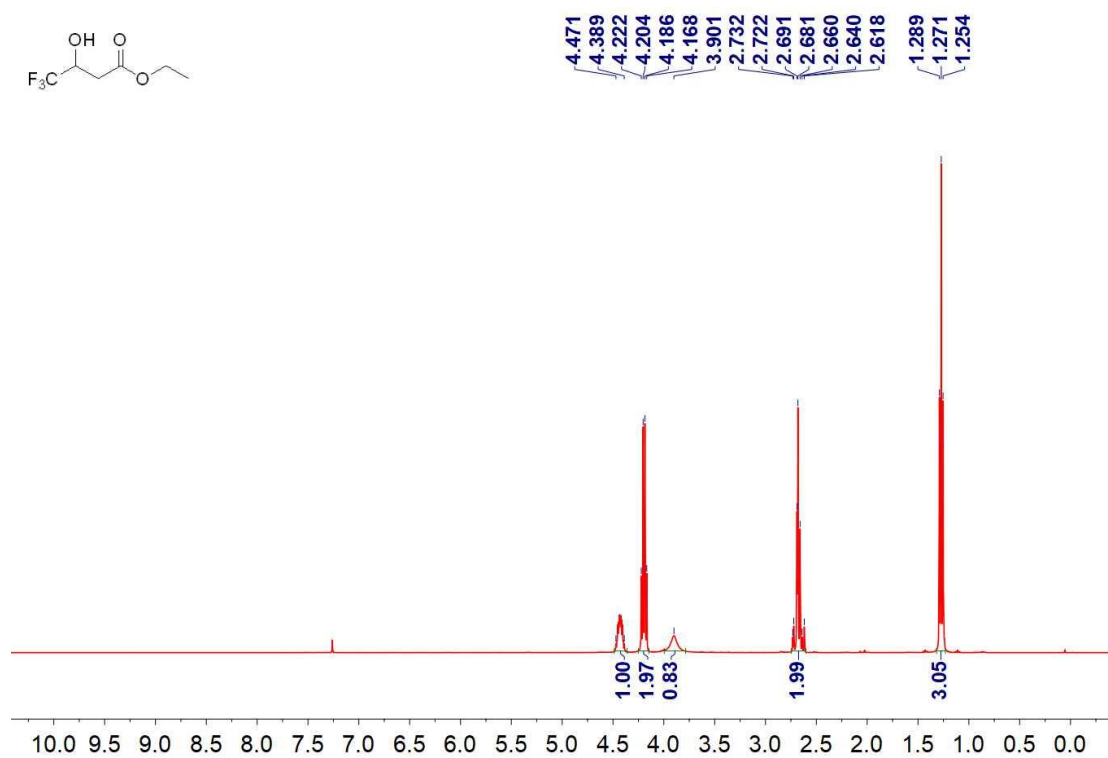
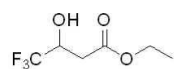
42.884

22.546

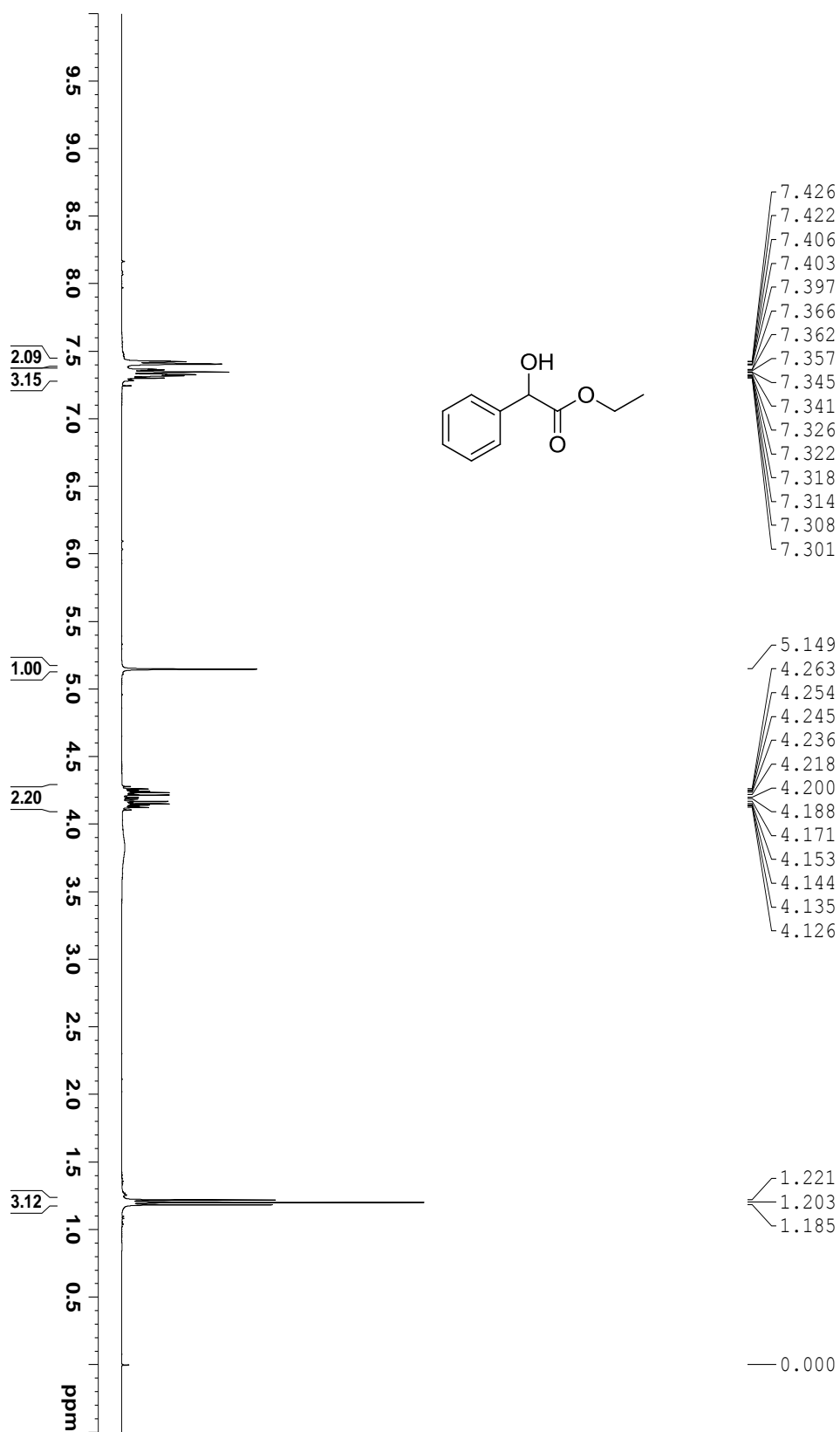
14.316



Ethyl 4,4,4-trifluoro-3-hydroxybutanoate (4h)

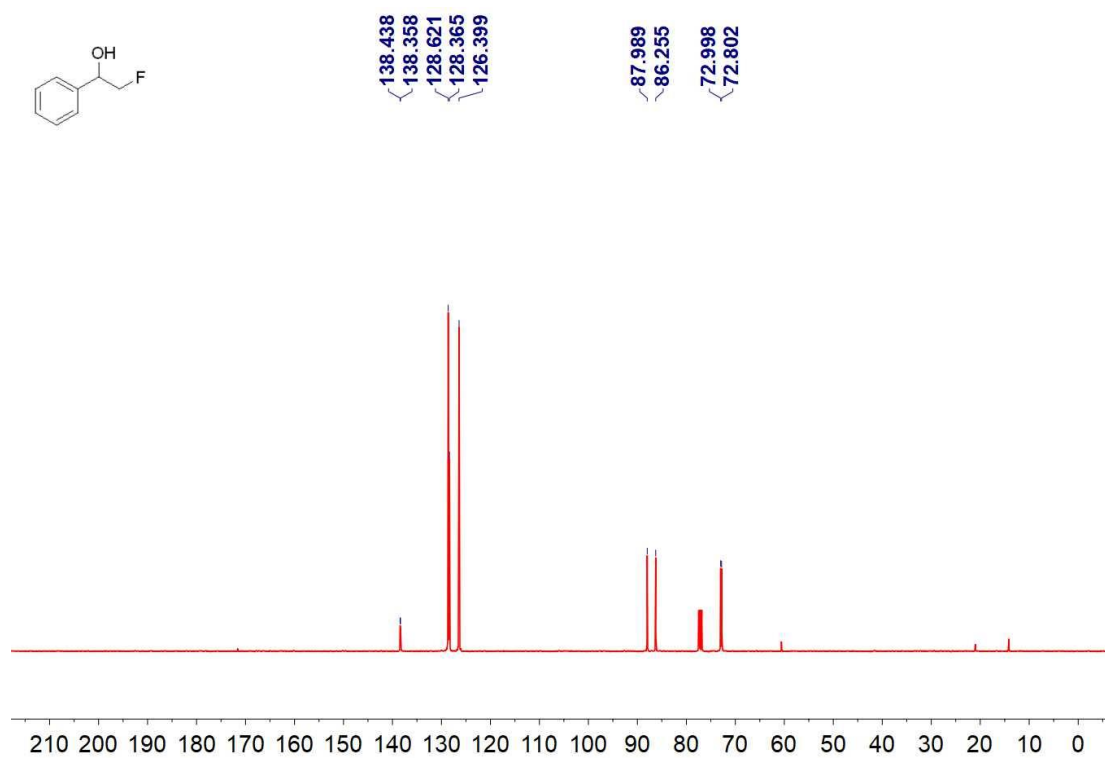
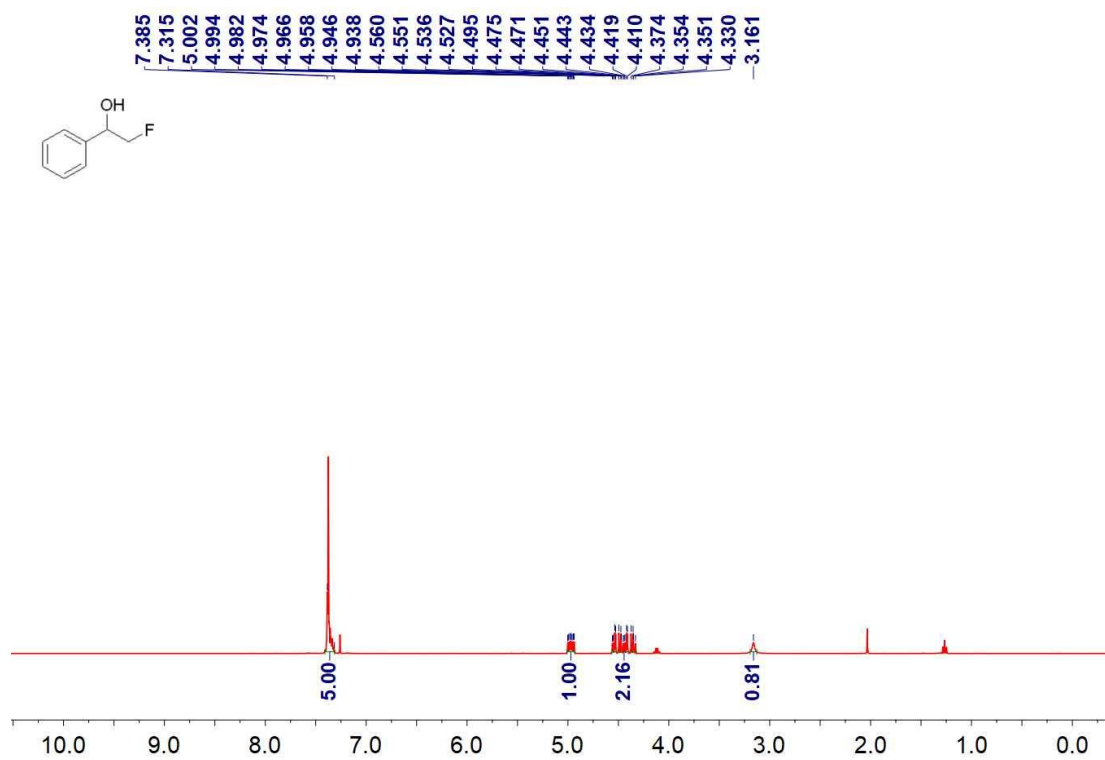


Ethyl 2-hydroxy-2-phenylacetate (4i)

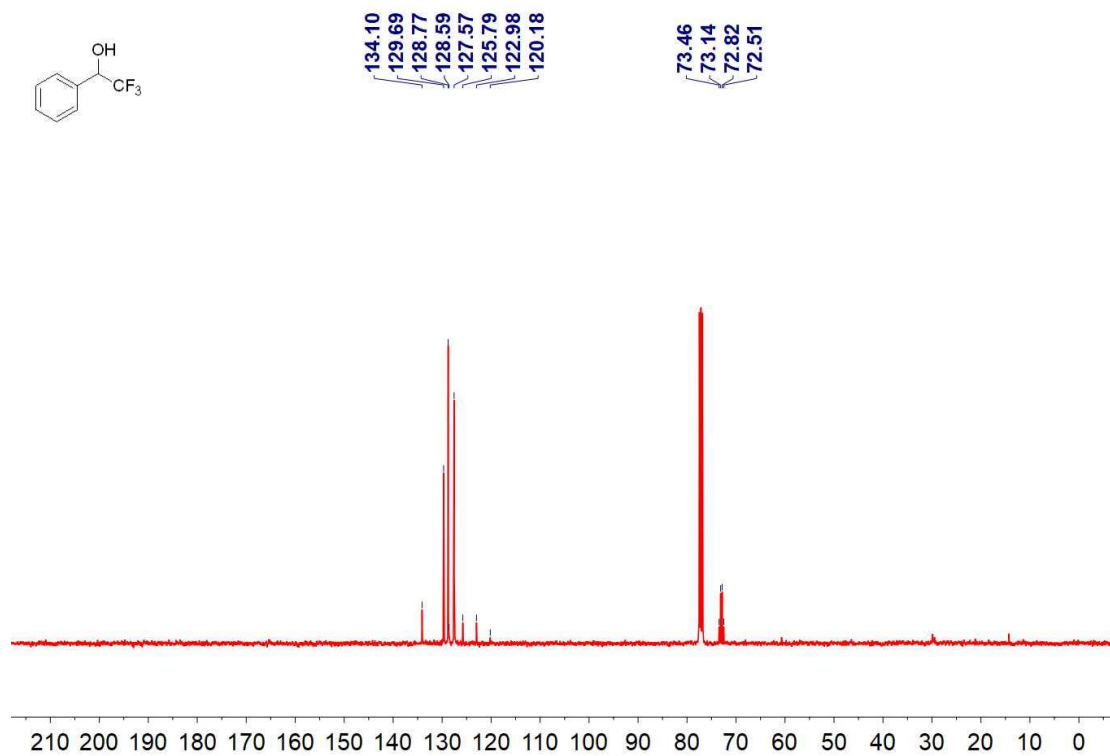
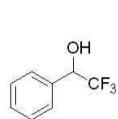
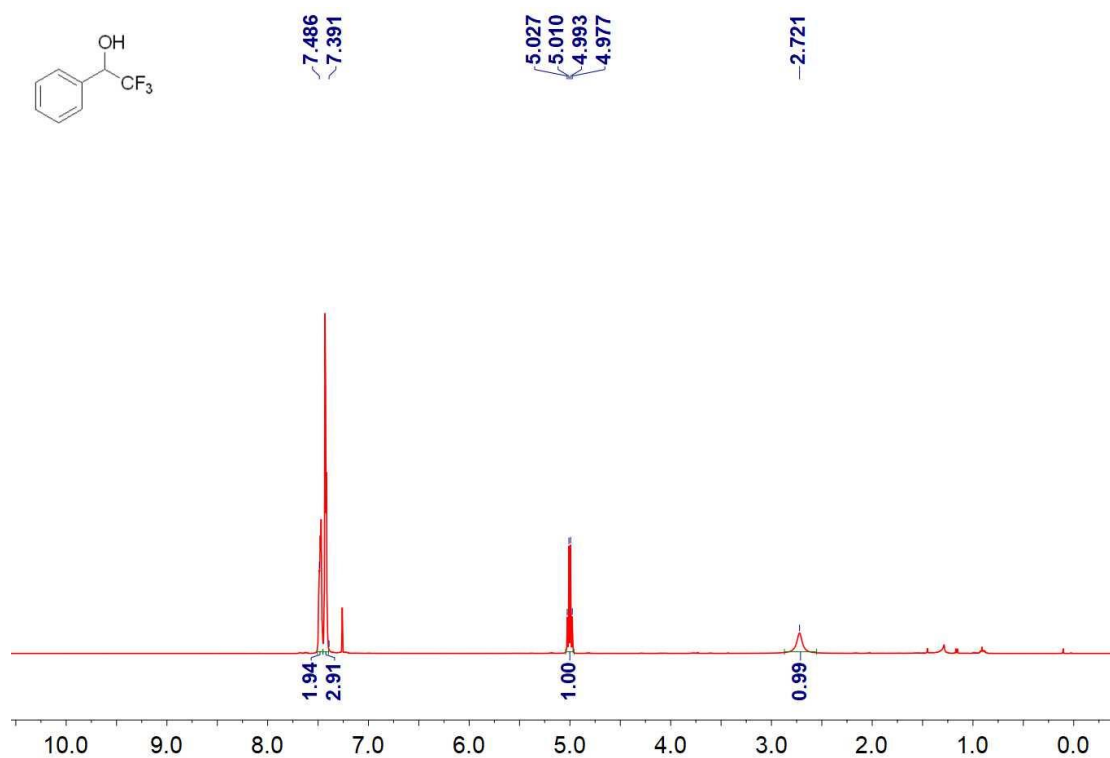
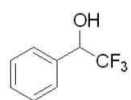




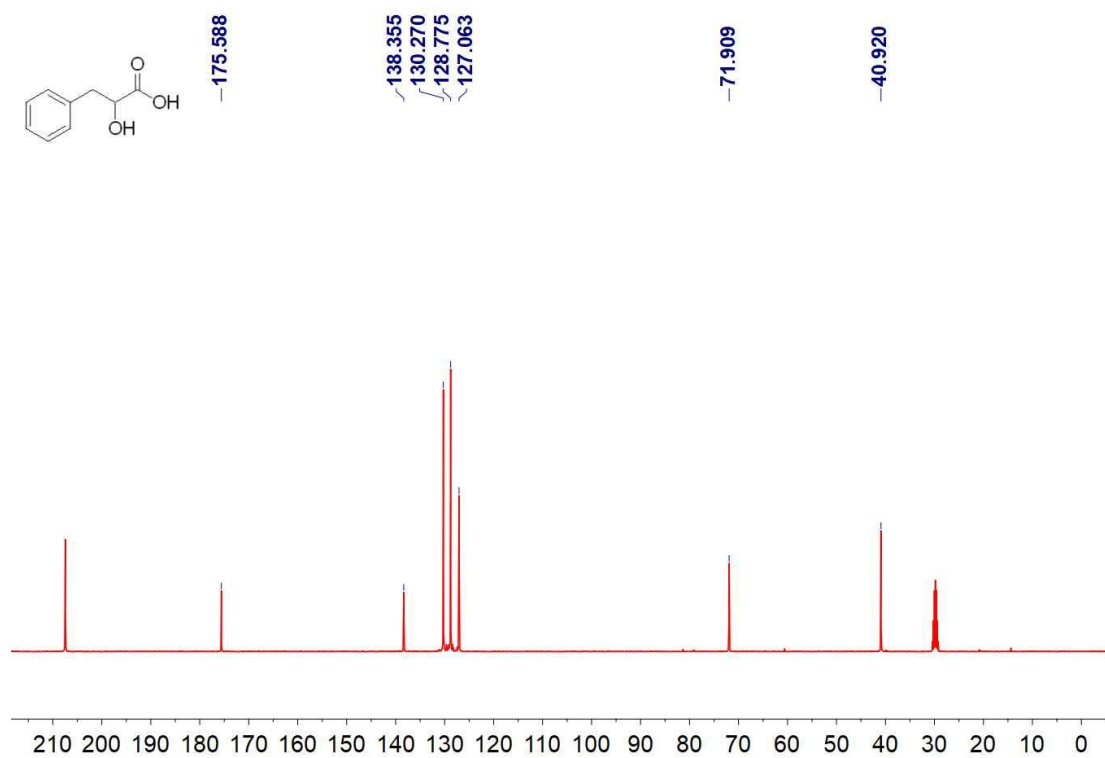
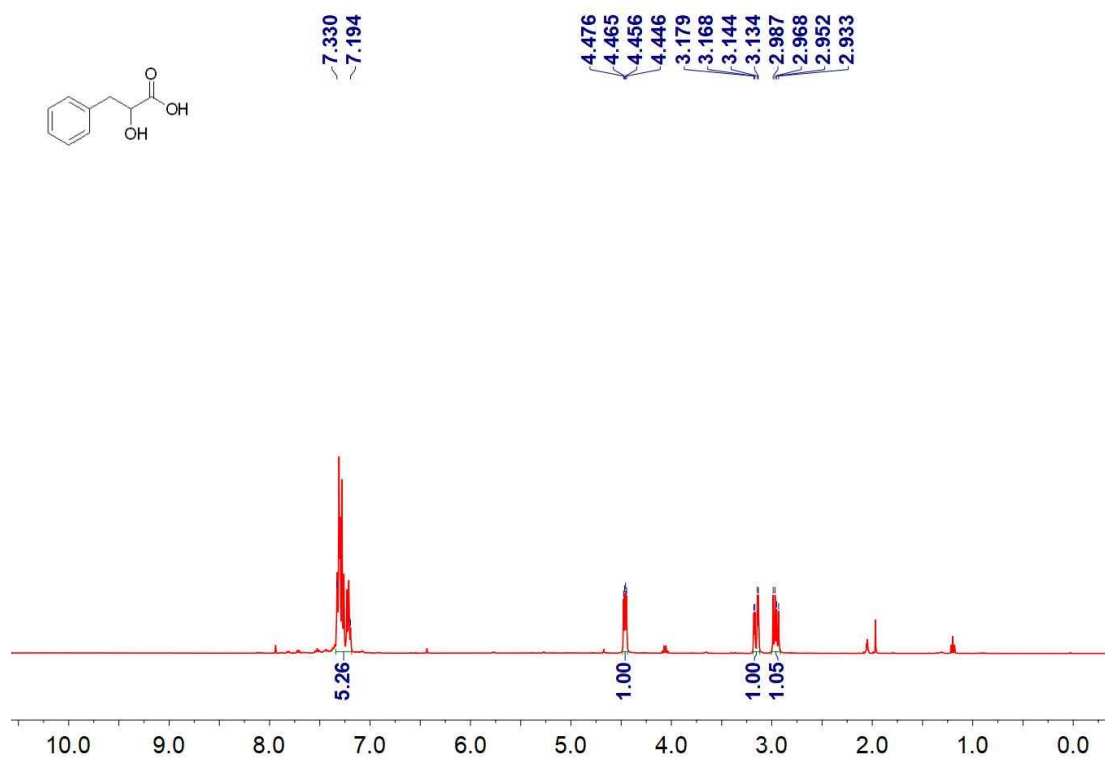
2-Fluoro-1-phenylethan-1-ol (4j)



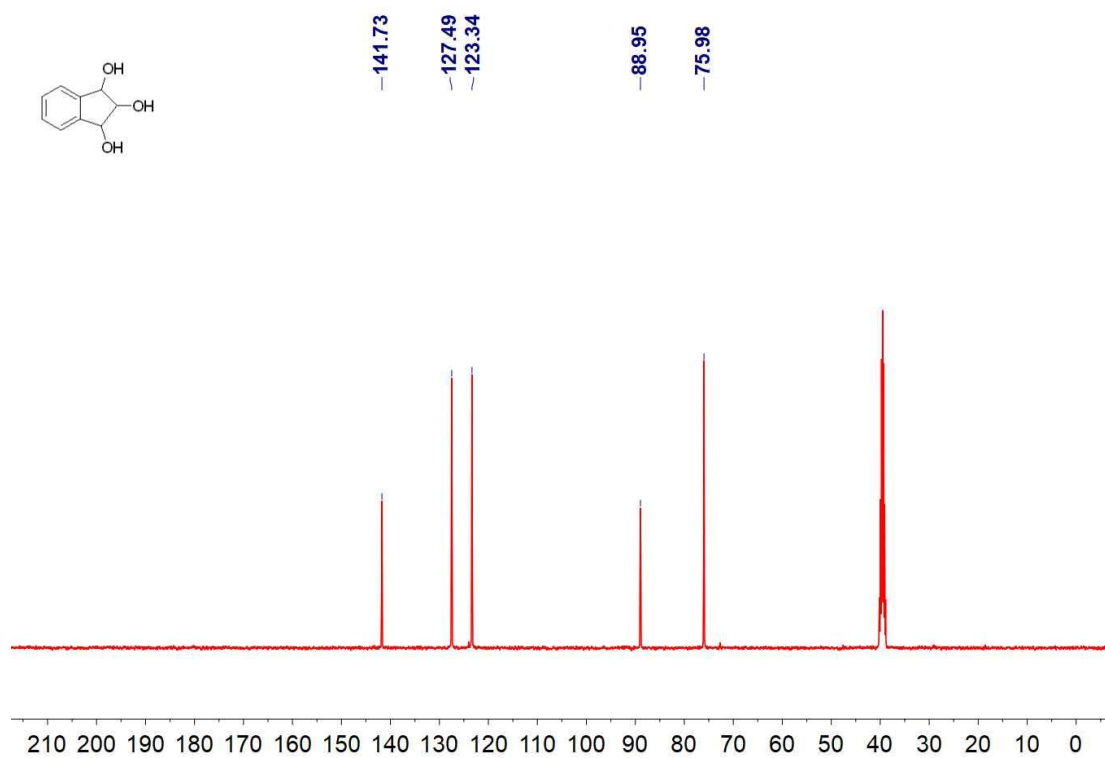
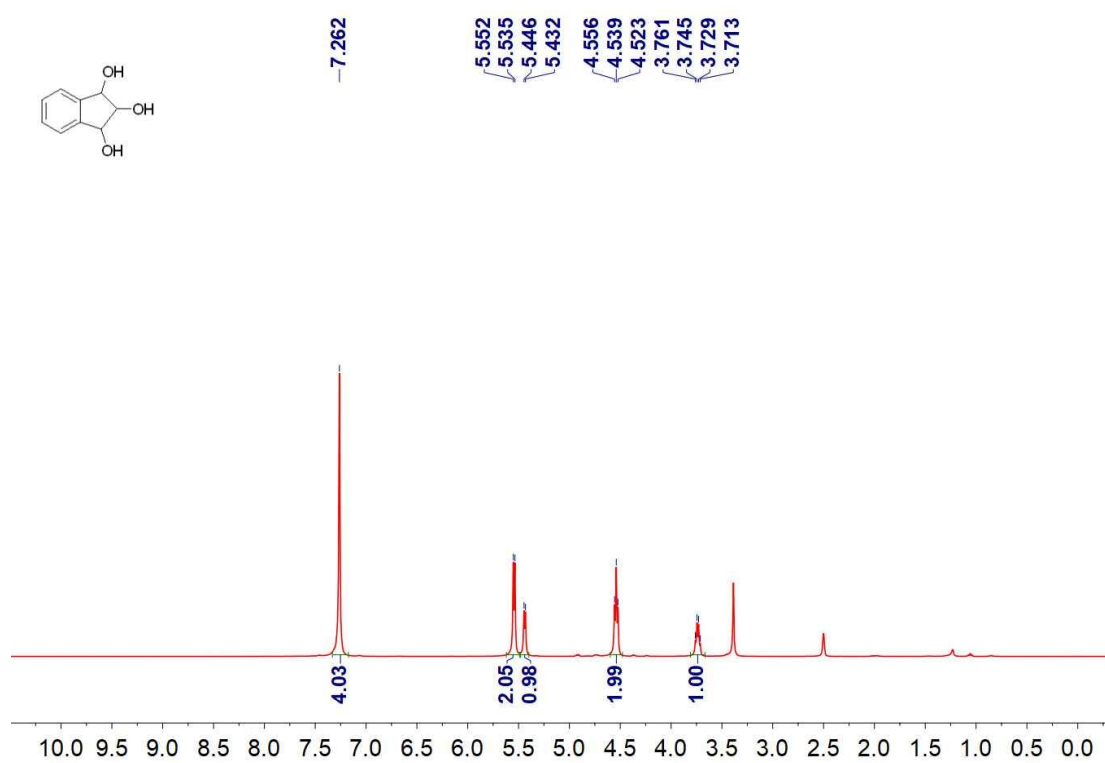
2,2,2-Trifluoro-1-phenylethan-1-ol (4k)



2-Hydroxy-3-phenylpropanoic acid (4l)



2,3-Dihydro-1H-indene-1,2,3-triol (4o) (400 MHz, DMSO-*d*₆)



15. ¹H NMR spectra of crude reaction mixtures in optimization
under nitrogen (Table 1 in full text)

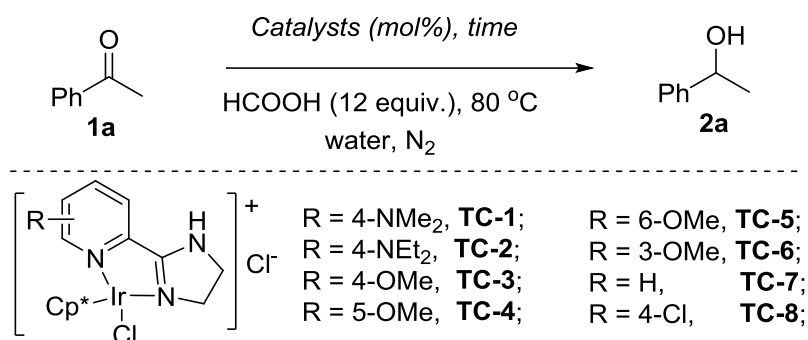


Table 1, entry 1.

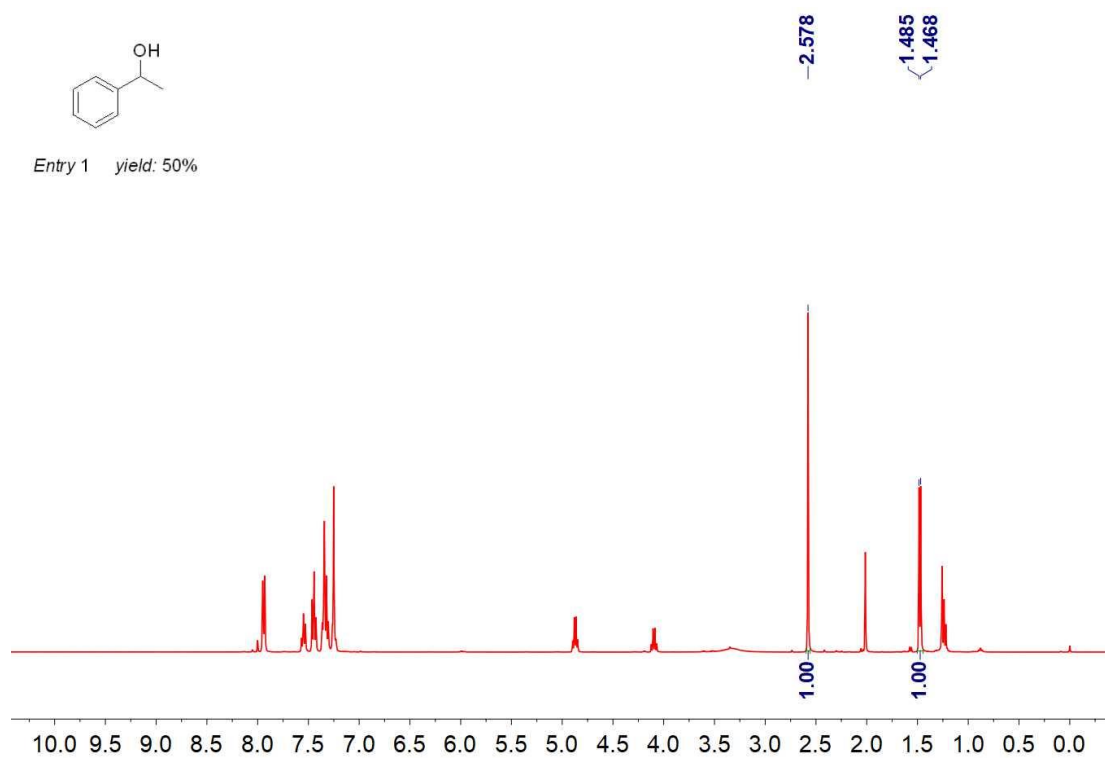
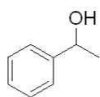


Table 1, entry 2.



Entry 2 yield: 44%

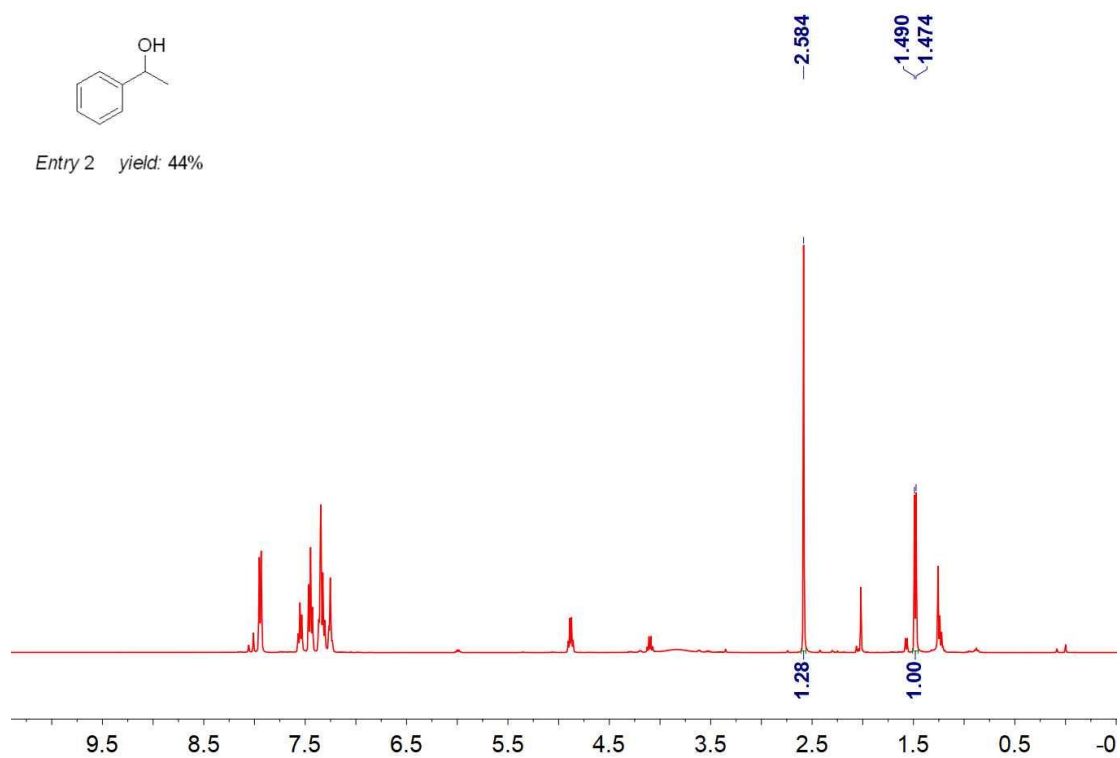


Table 1, entry 3.



Entry 3 yield: 67%

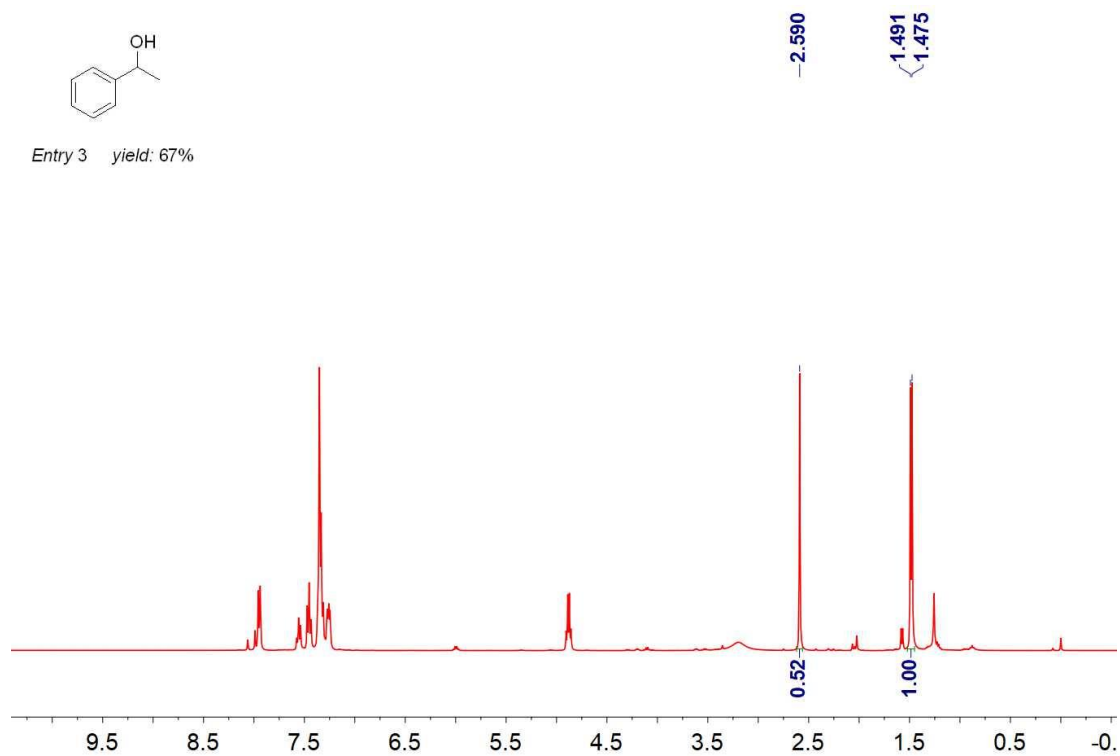
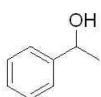


Table 1, entry 4.



Entry 4 yield: 78%

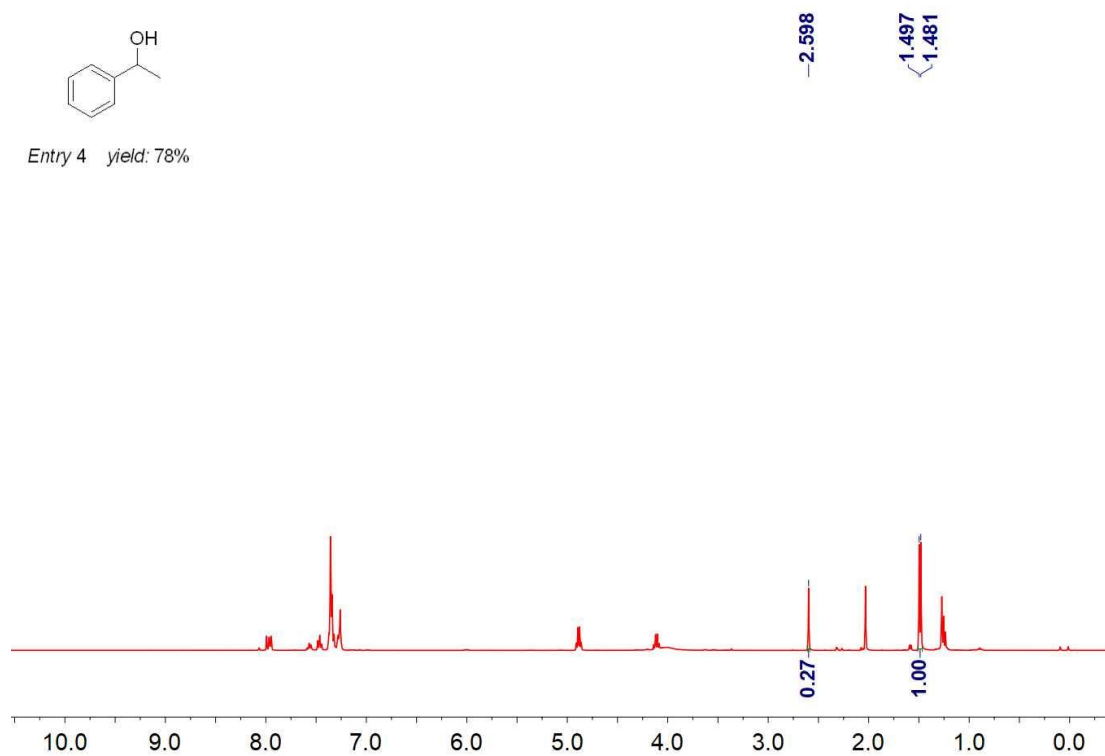
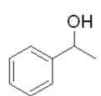


Table 1, entry 5.



Entry 5 yield: 70%

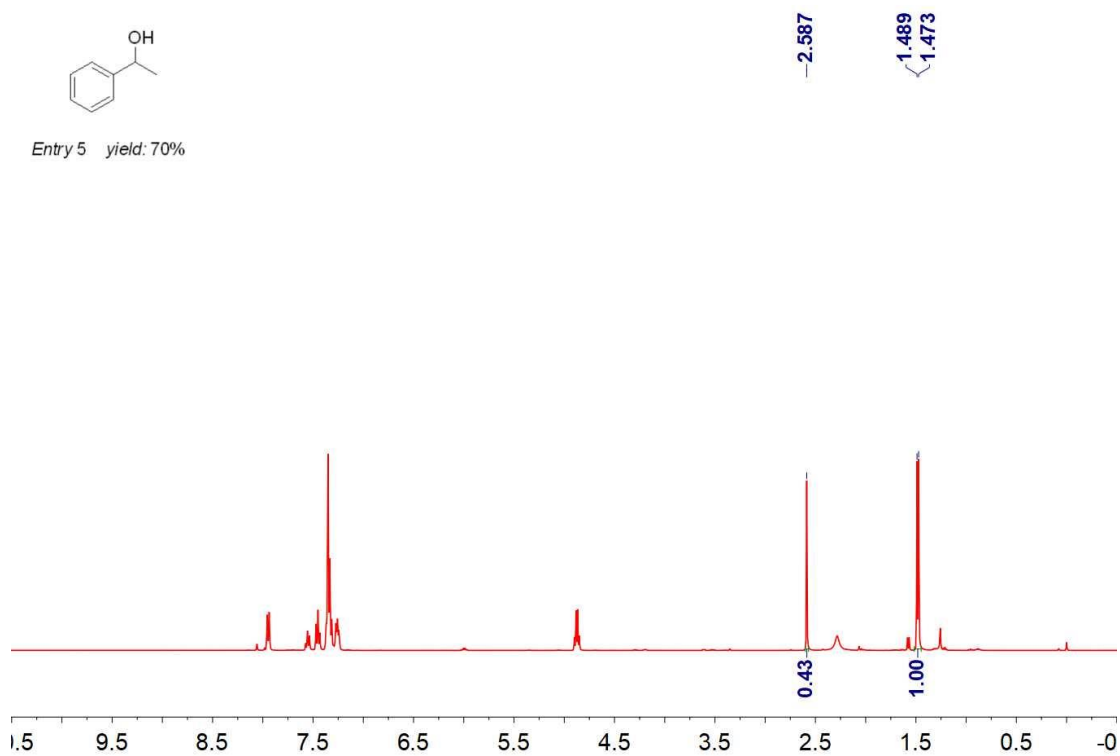
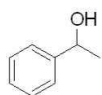


Table 1, entry 6.



Entry 6 yield: 5%

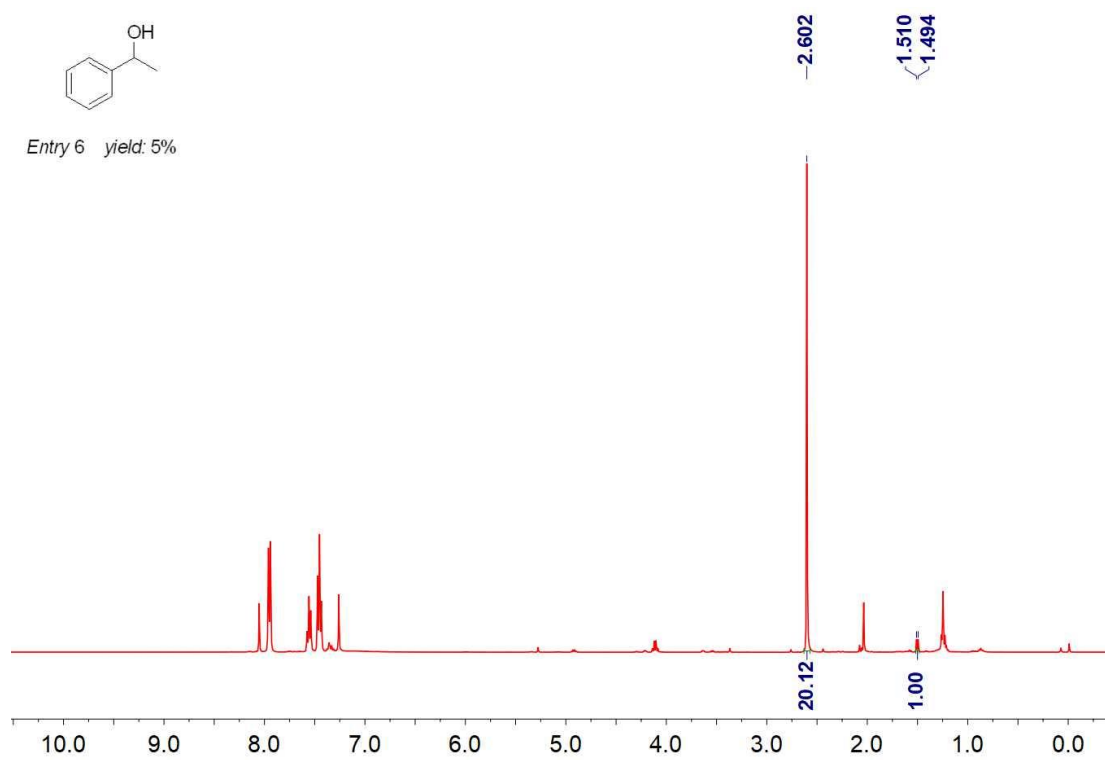


Table 1, entry 7.



Entry 7 yield: 88%

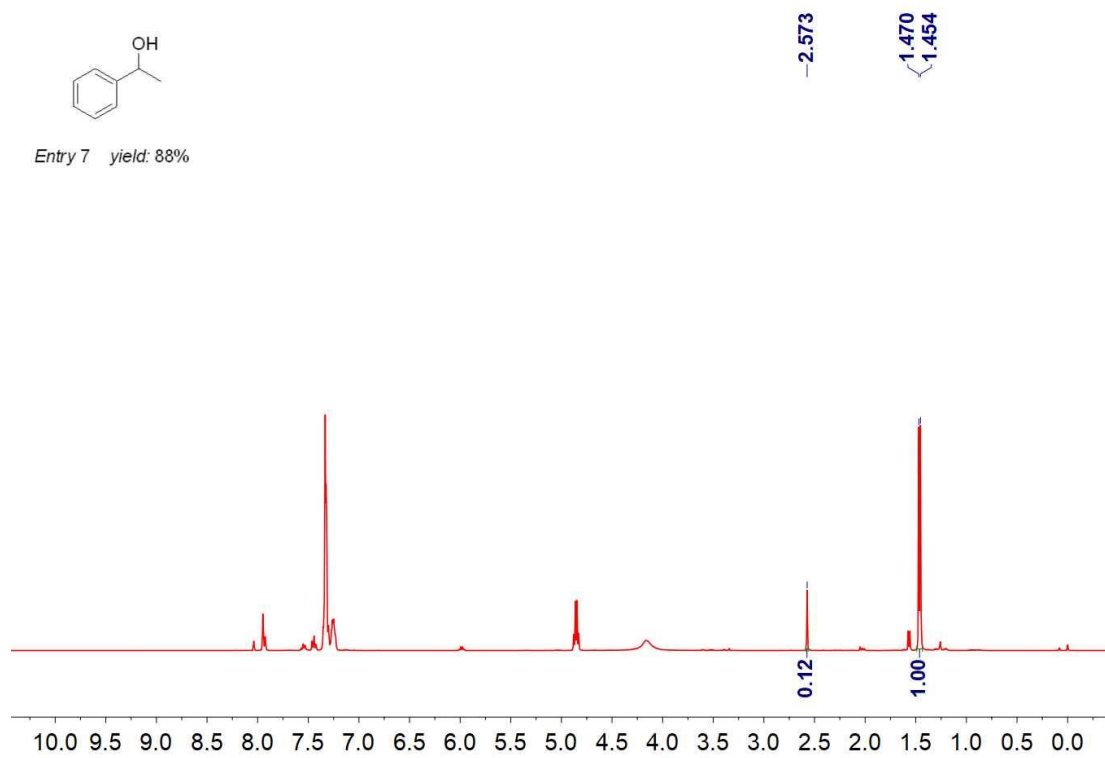


Table 1, entry 8.



Entry 8 yield: 39%

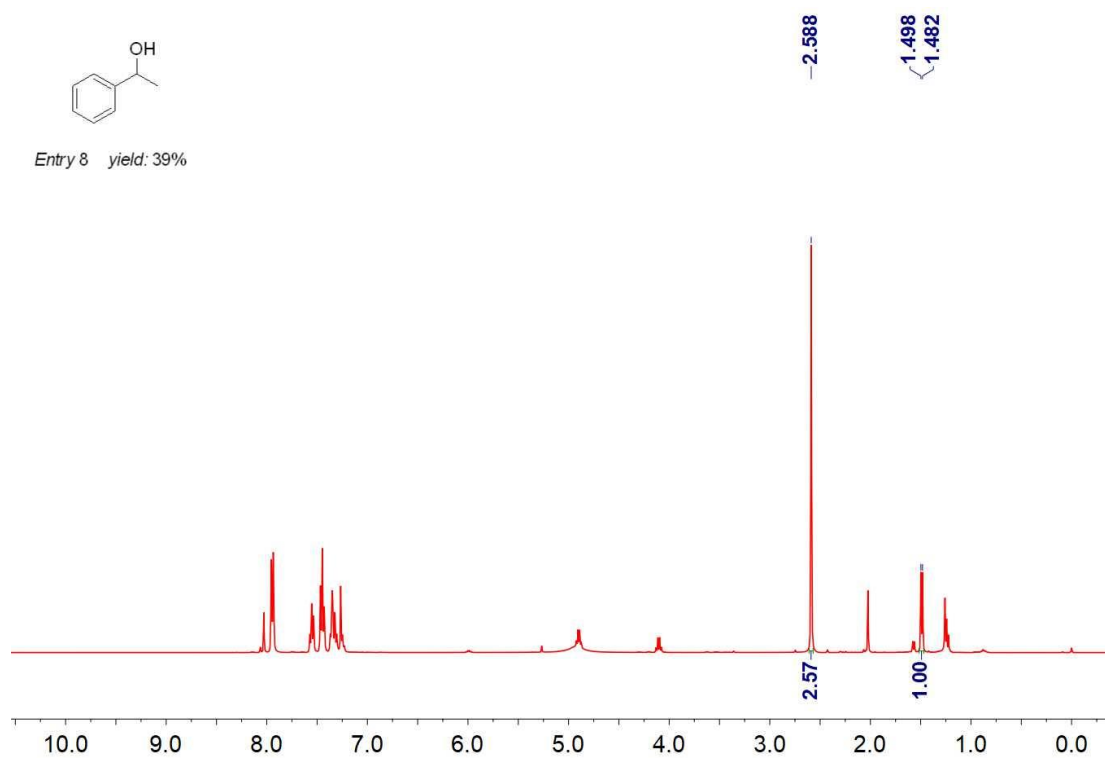


Table 1, entry 9.



Entry 9 yield: 18%

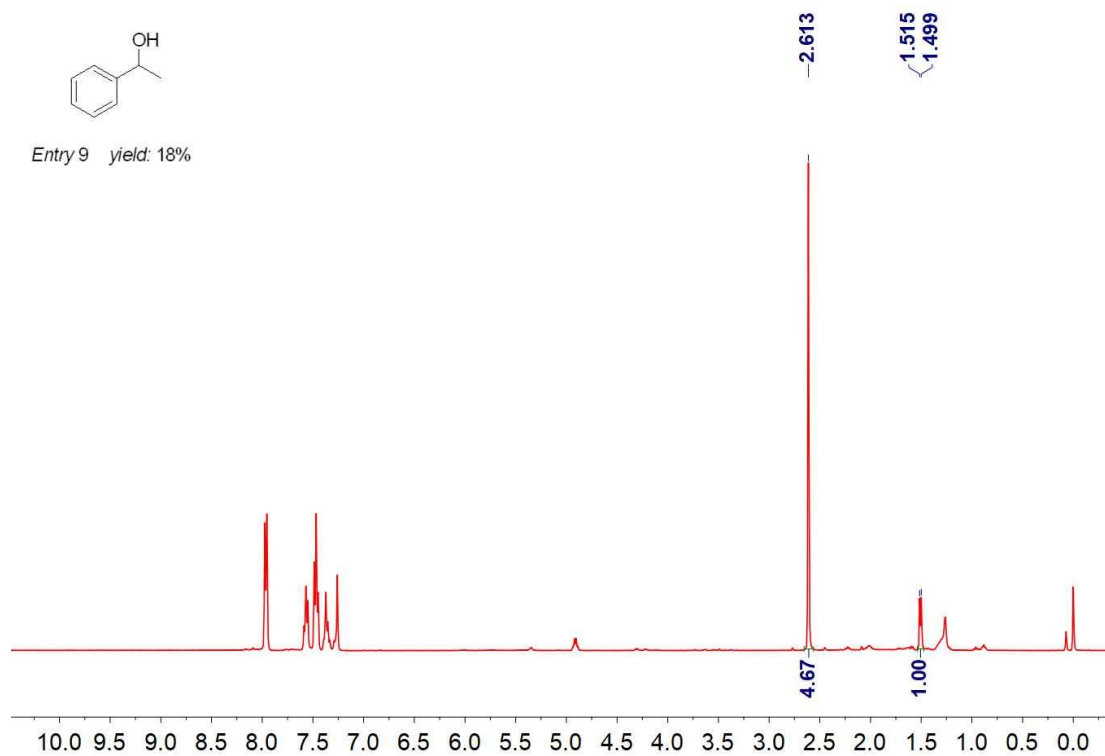
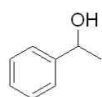


Table 1, entry 10.



Entry 10 yield: 52%

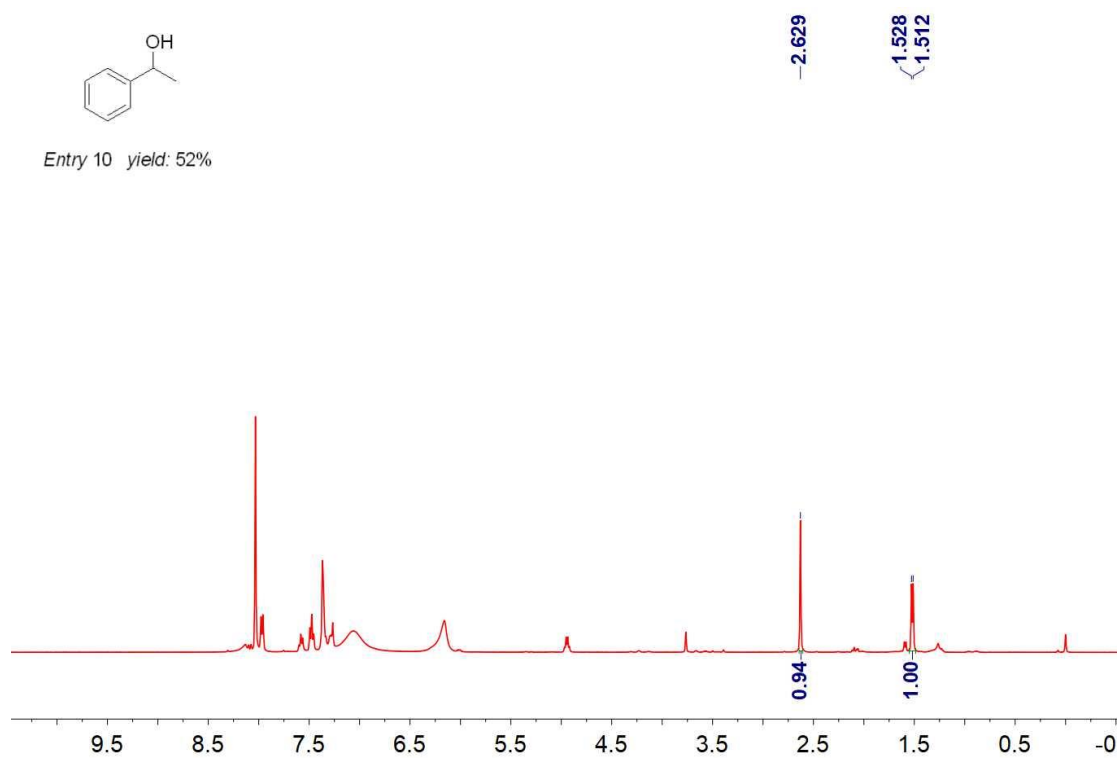


Table 1, entry 11.



Entry 11 yield: 72%

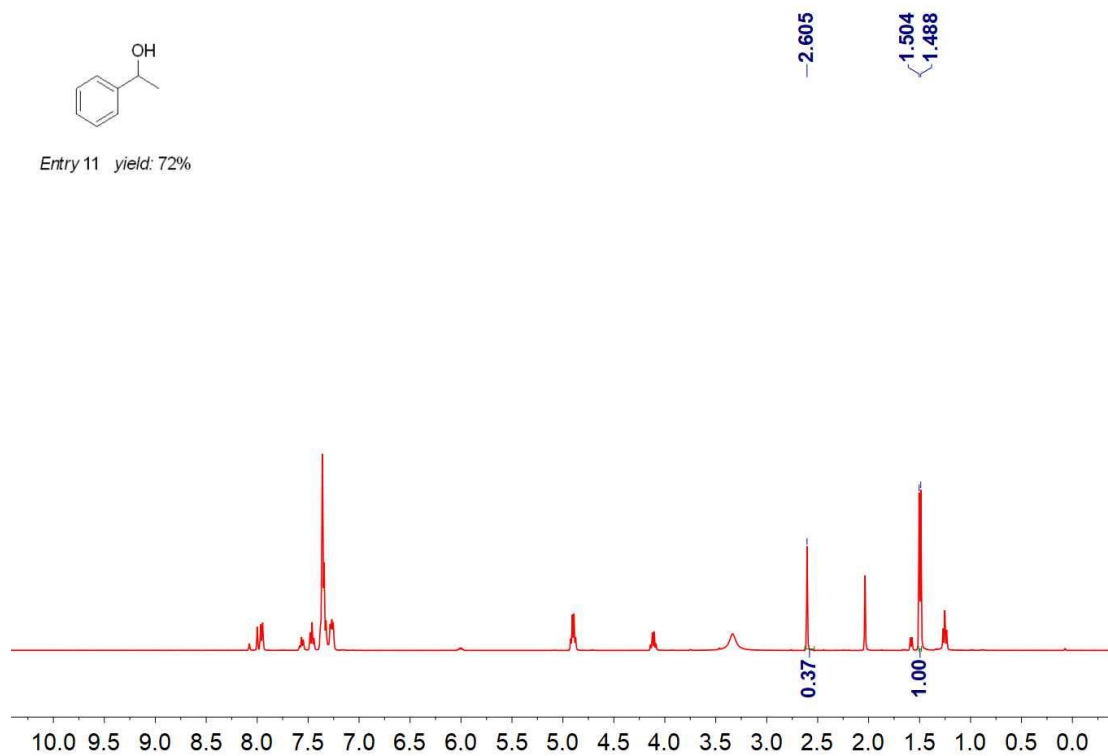


Table 1, entry 12.



Entry 12 yield: 92%

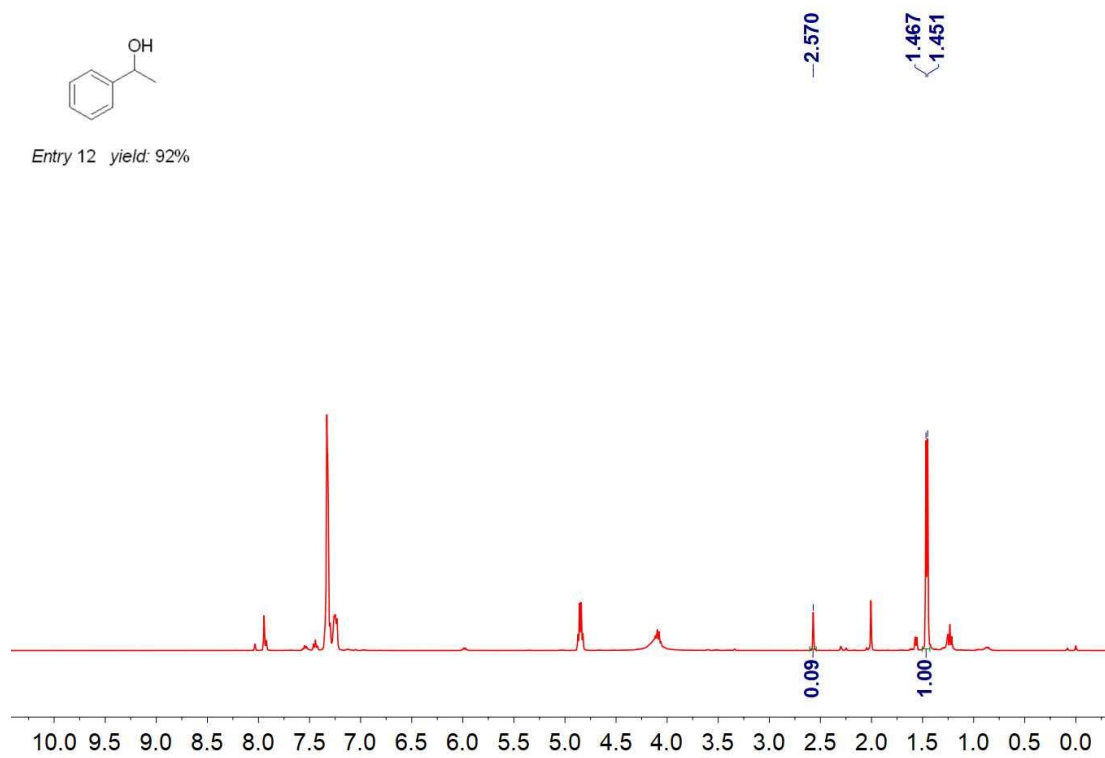


Table 1, entry 13.



Entry 13 yield: 38%

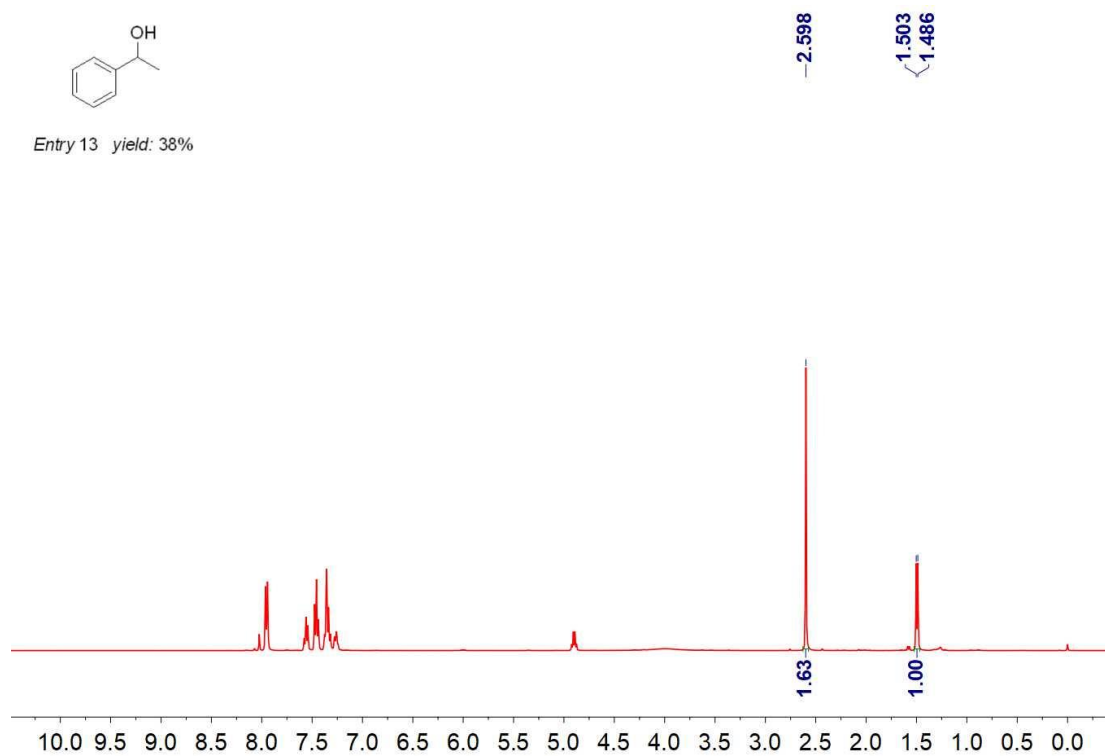


Table 1, entry 15.



Entry 15 yield: 99%

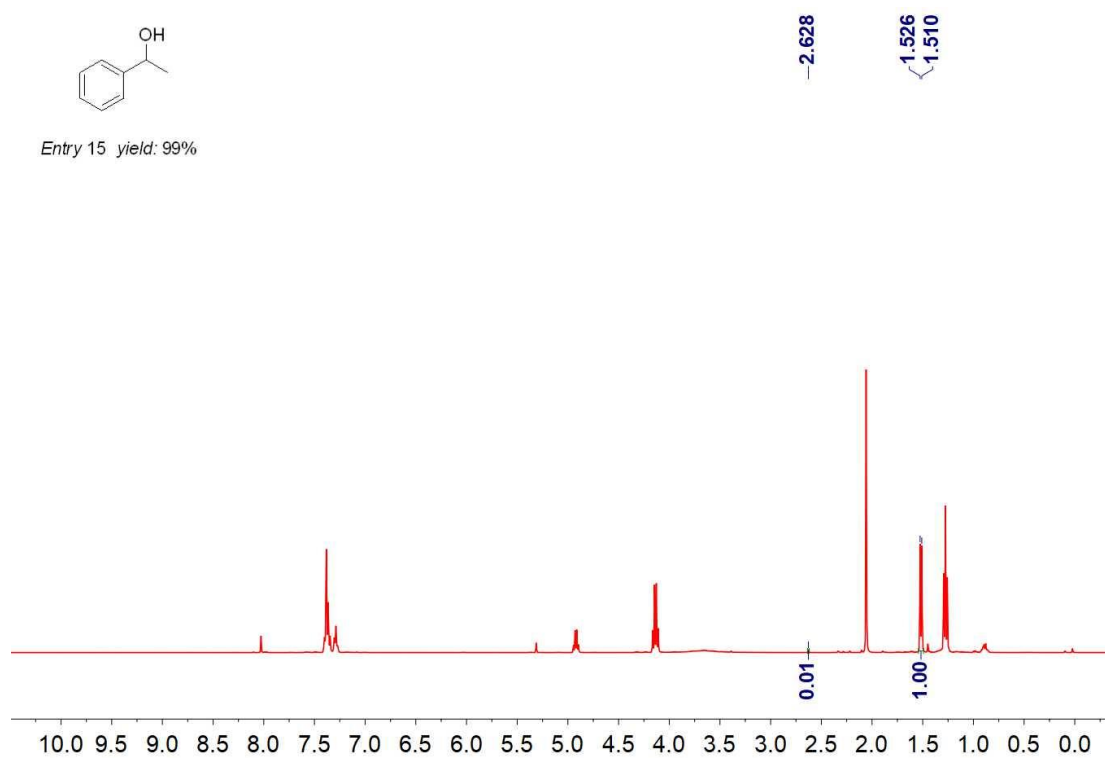


Table 1, entry 16.



Entry 16 yield: 97%

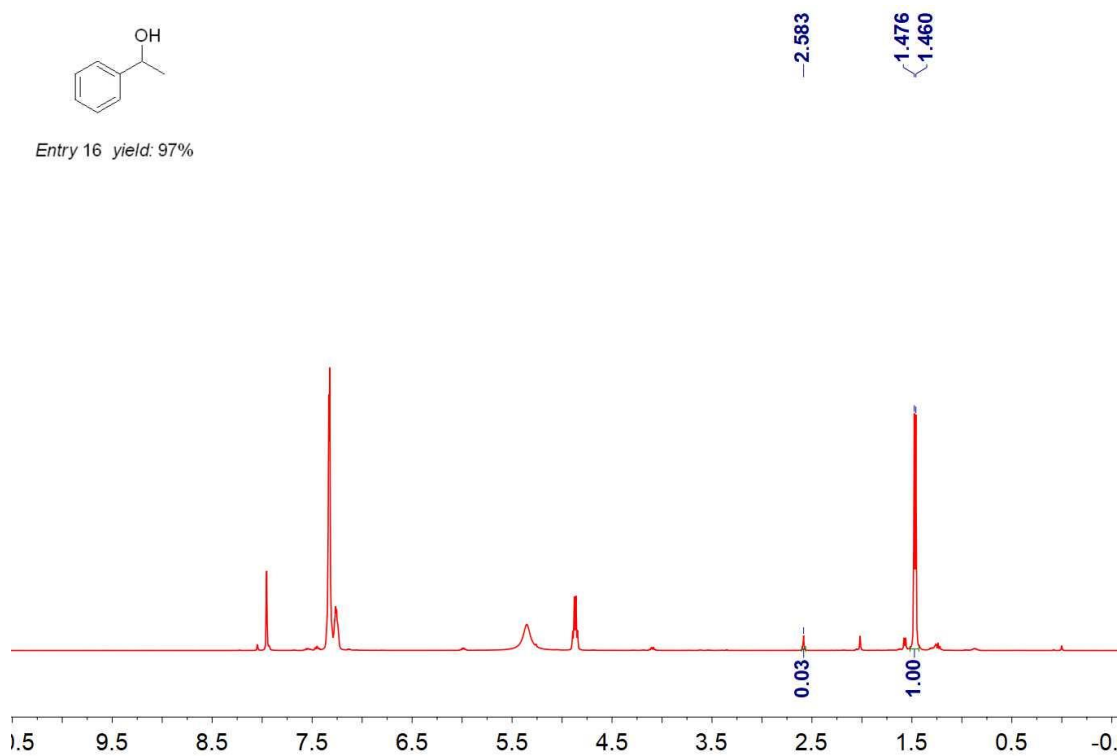
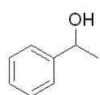
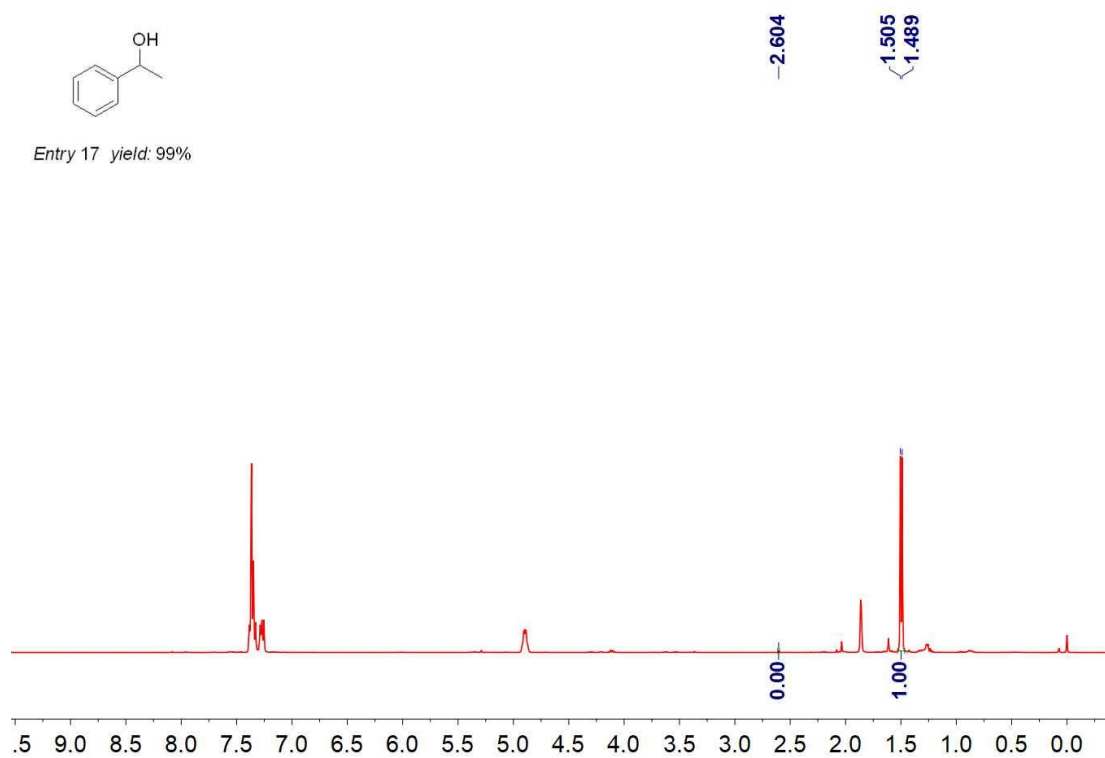


Table 1, entry 17.

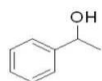


Entry 17 yield: 99%



16. ^1H NMR spectra of the reaction mixtures of acetophenone at different pH values (Table S2)

Table S2, pH = 1.46;



For pH=1.46 yield: 88%

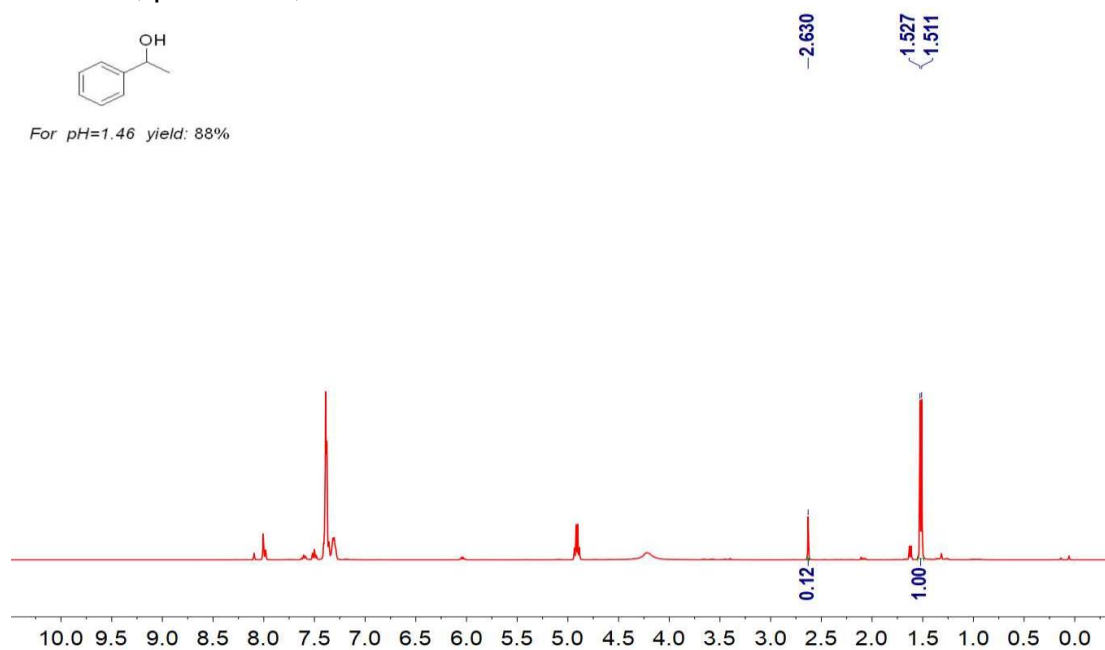


Table S2, pH = 2.48.



For pH=2.48 yield: 68%

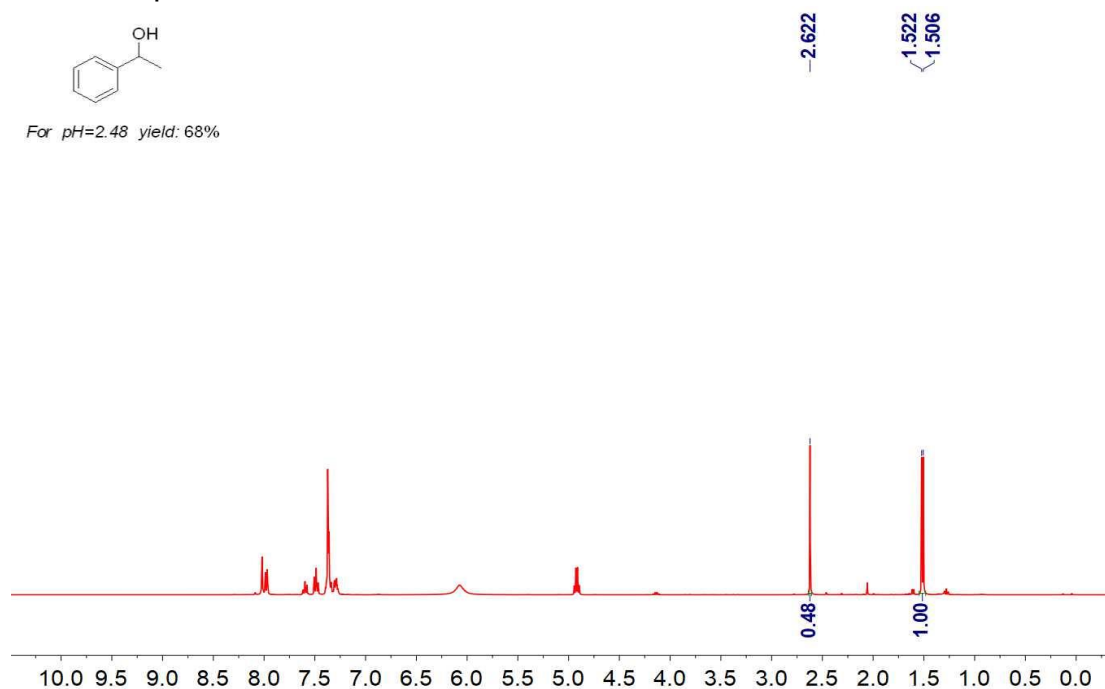
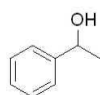


Table S2, pH = 2.99.



For pH=2.99 yield: 32%

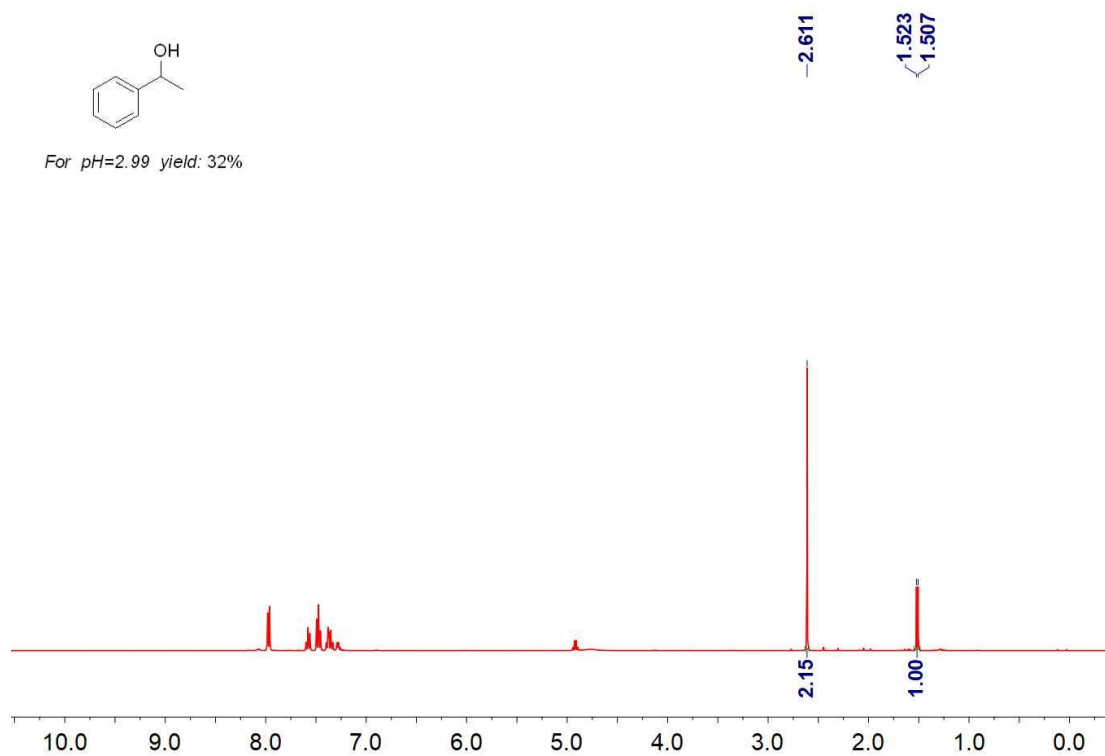
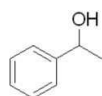


Table S2, pH = 3.37.



For pH=3.37 yield: 25%

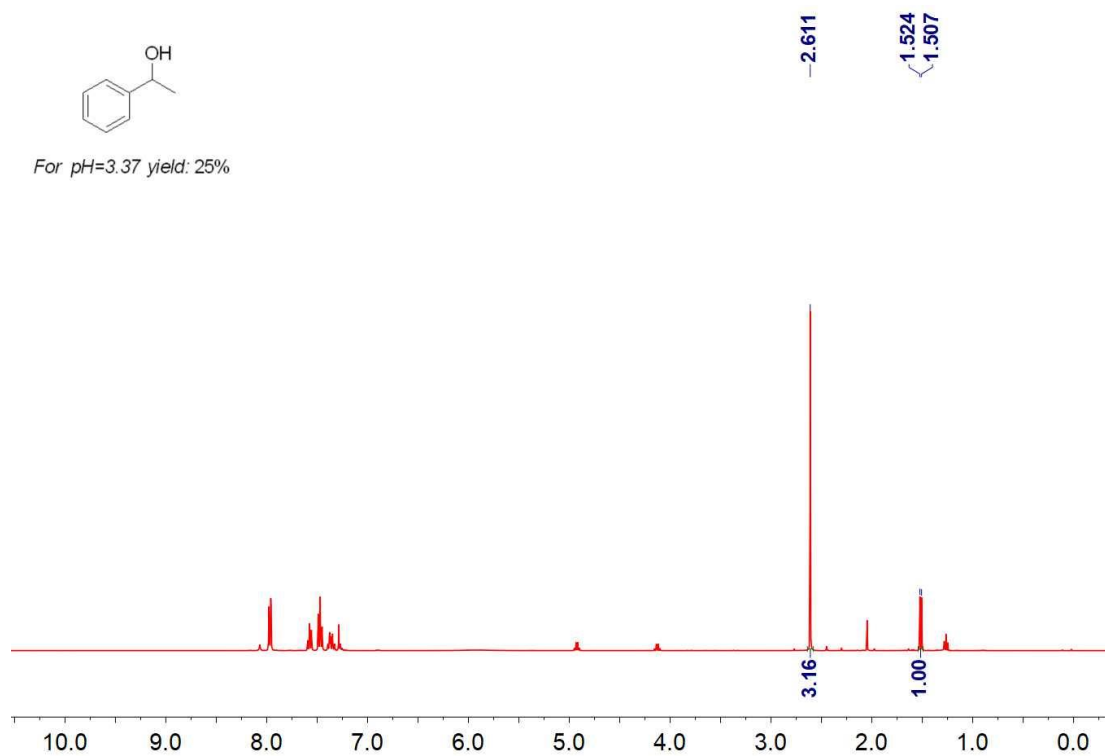
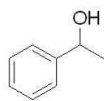


Table S2, pH = 3.76.



For pH=3.76 yield: 13%

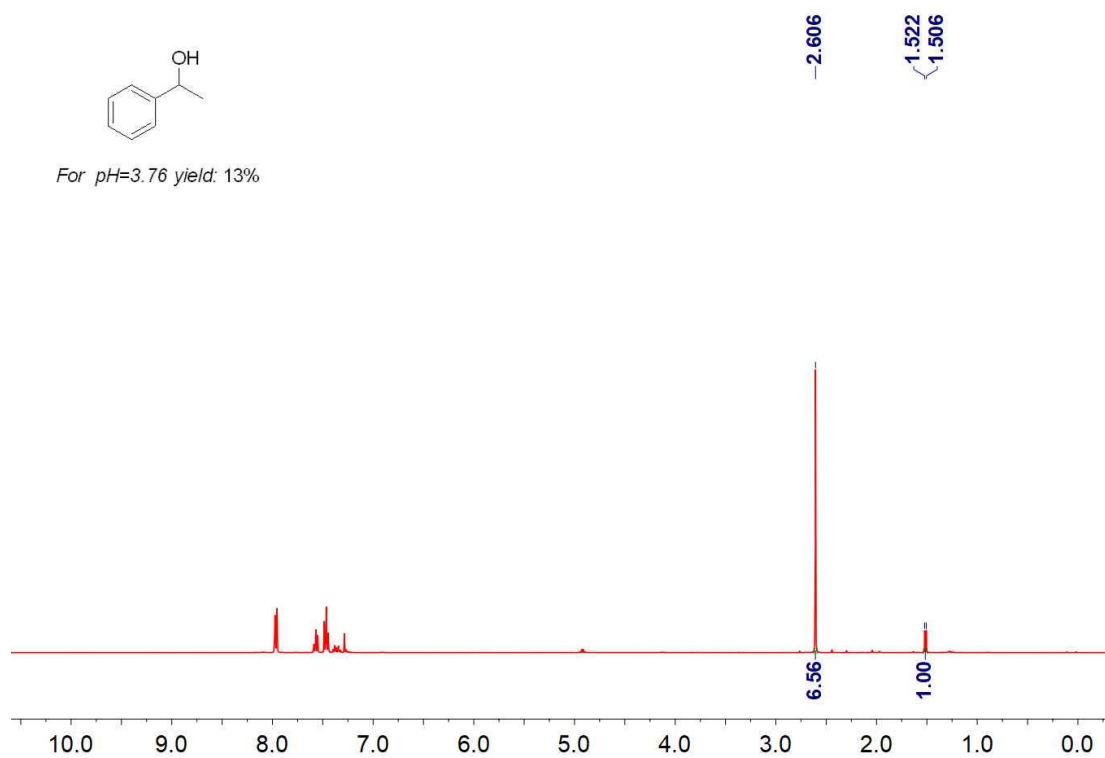
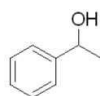


Table S2, pH = 4.18.



For pH=4.18 yield: 8%

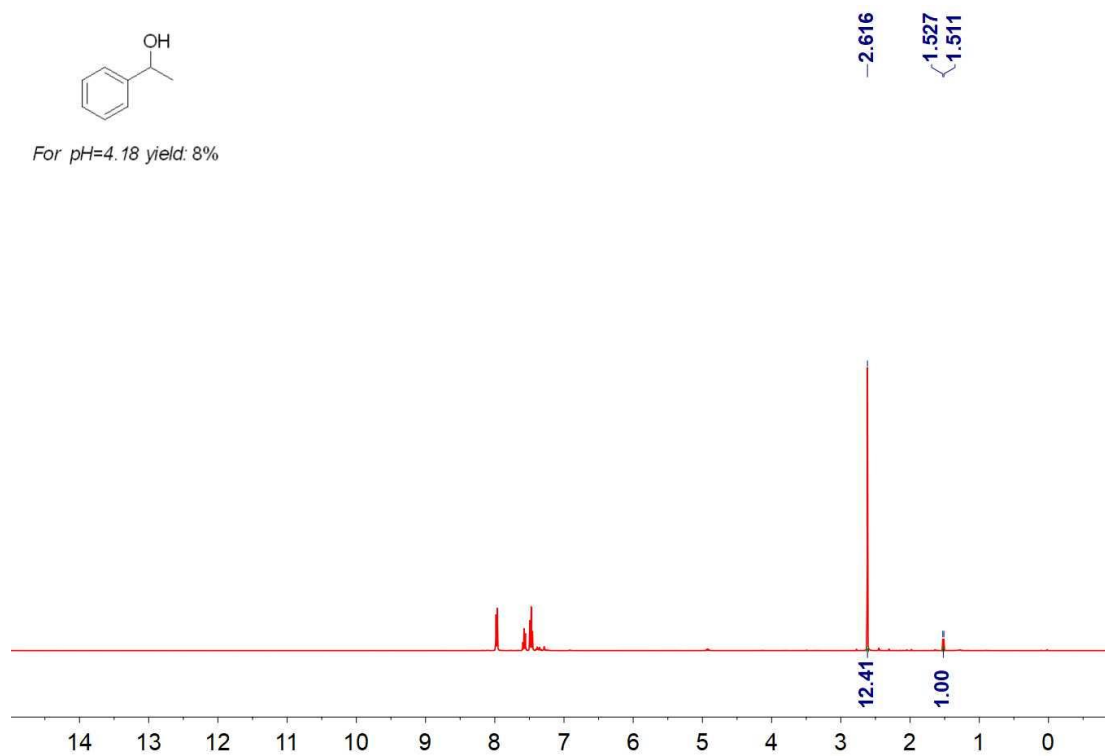
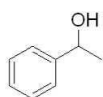
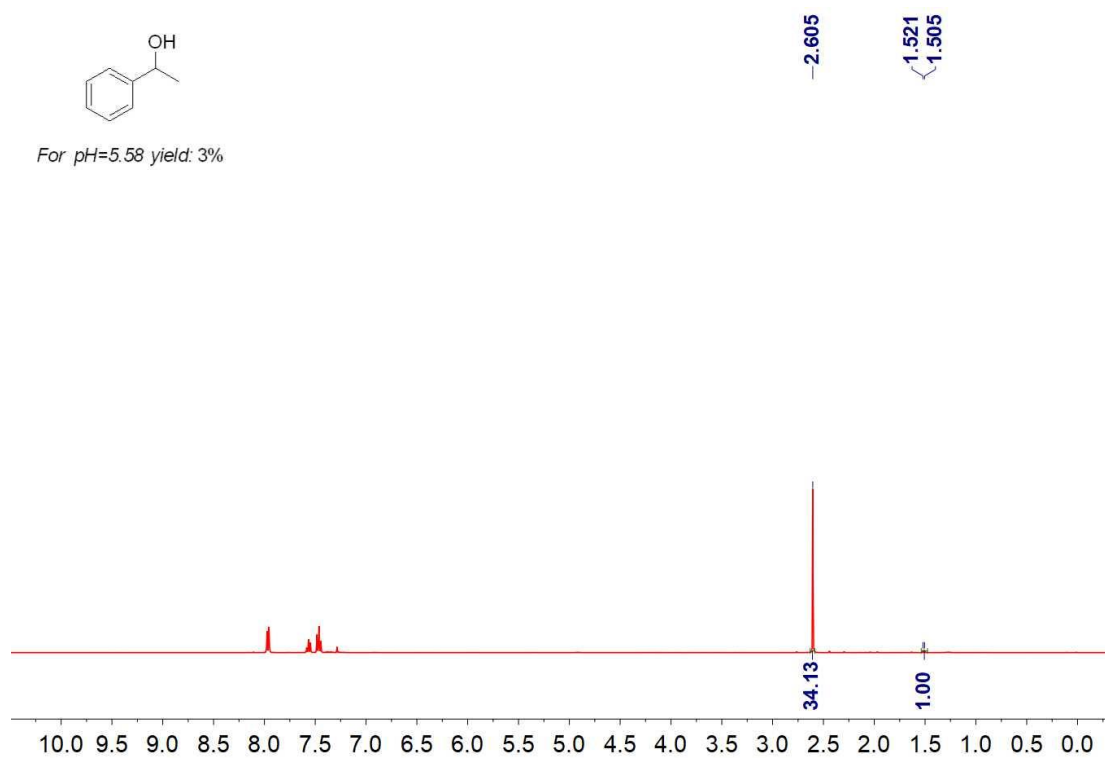


Table S2, pH = 5.58.



For pH=5.58 yield: 3%



17. ¹H NMR spectra of crude reaction mixtures in optimization in open air (Table S1 in ESI)

Table S1, entry 1.

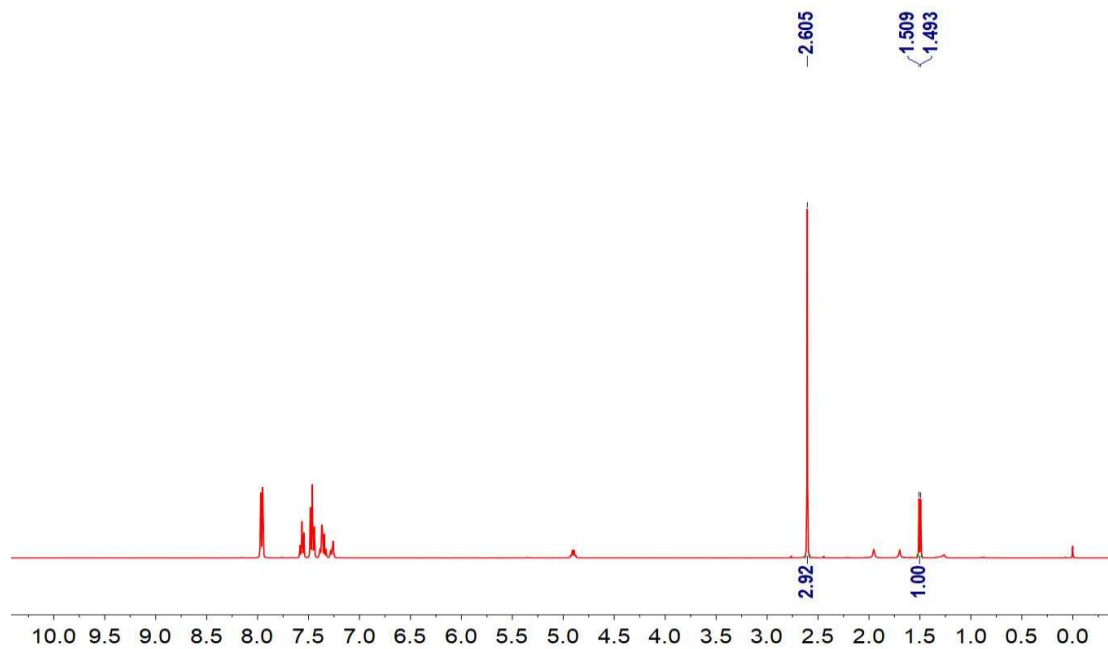


Table S1, entry 2.

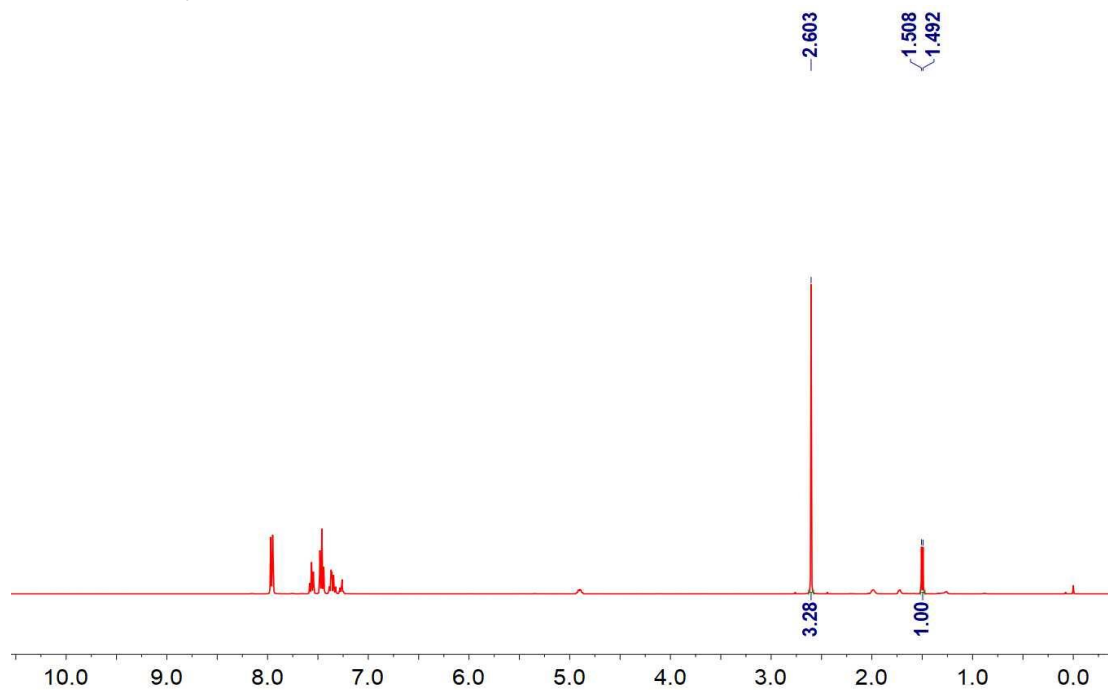


Table S1, entry 3.

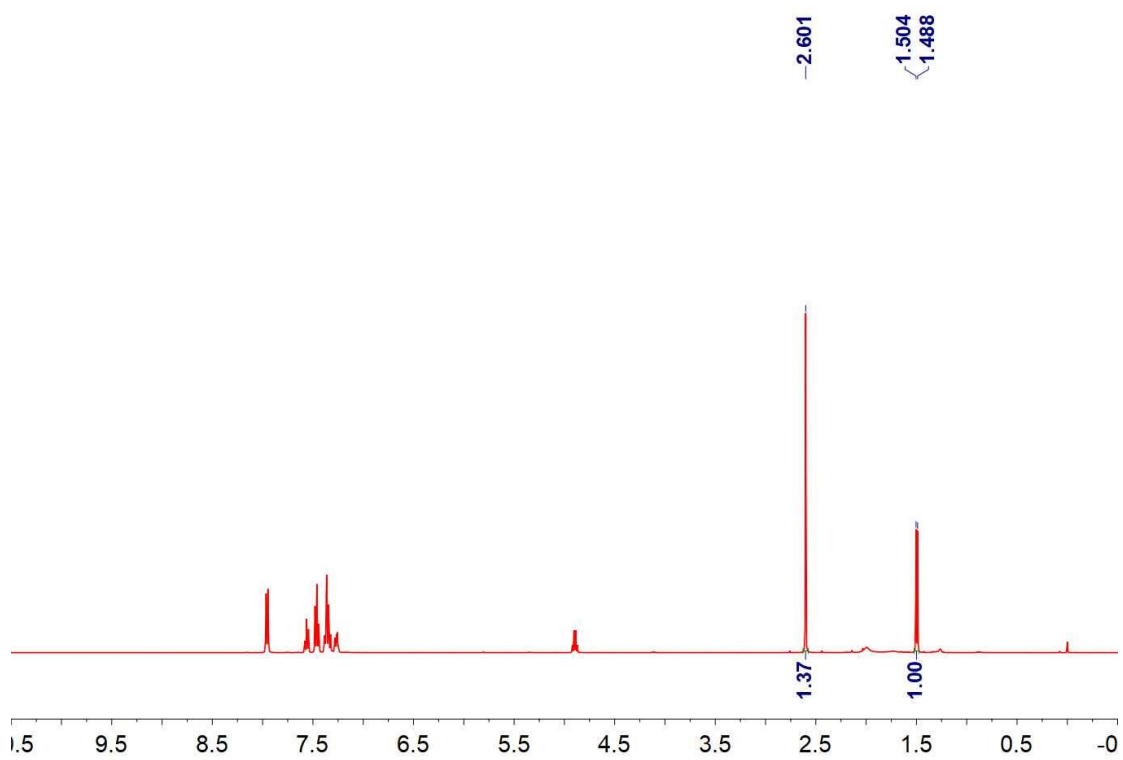


Table S1, entry 4.

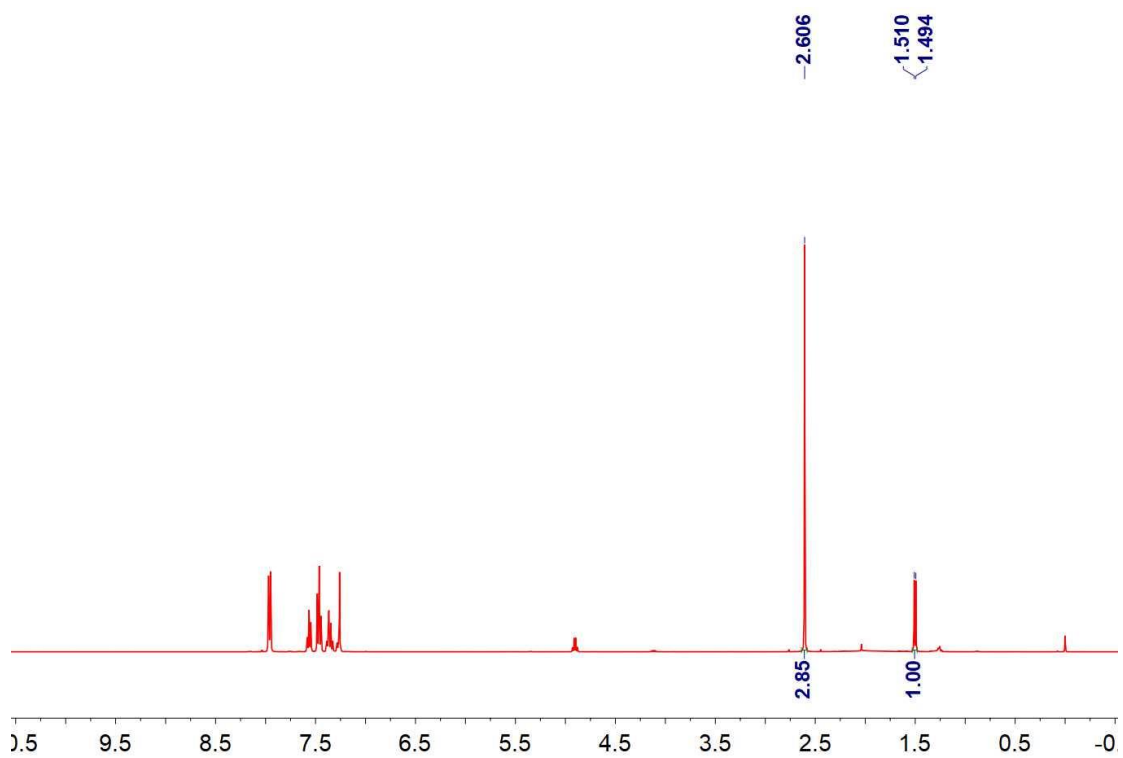


Table S1, entry 5.

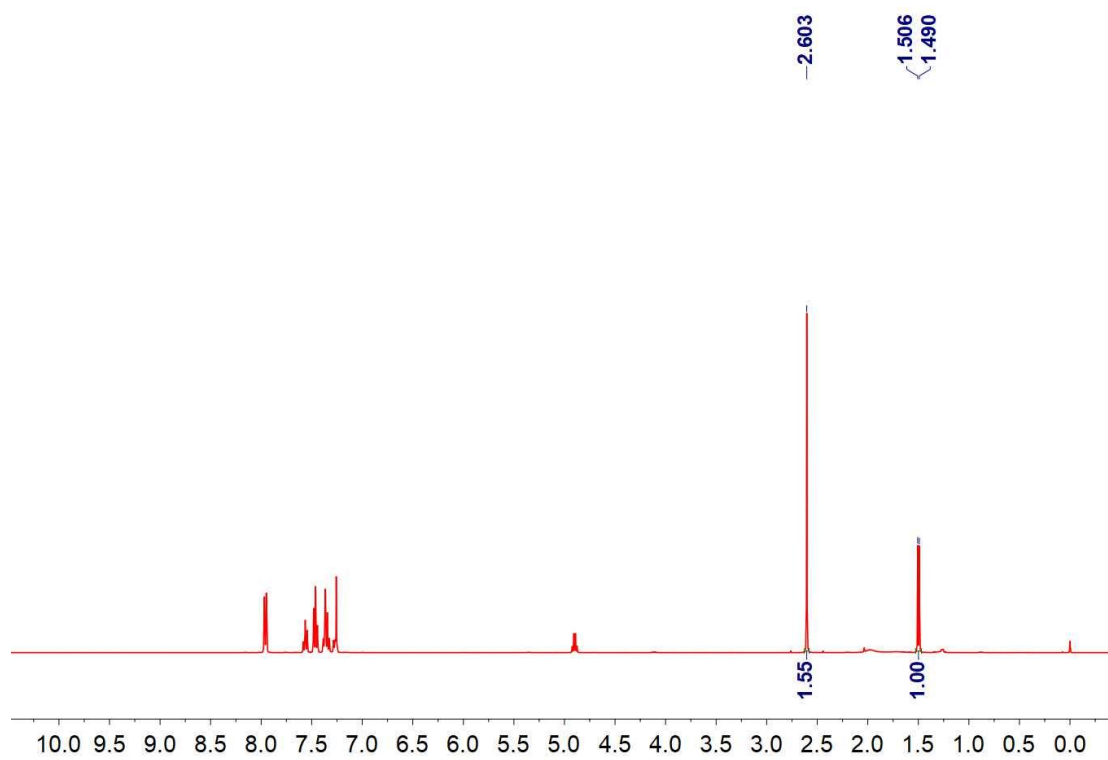


Table S1, entry 6.

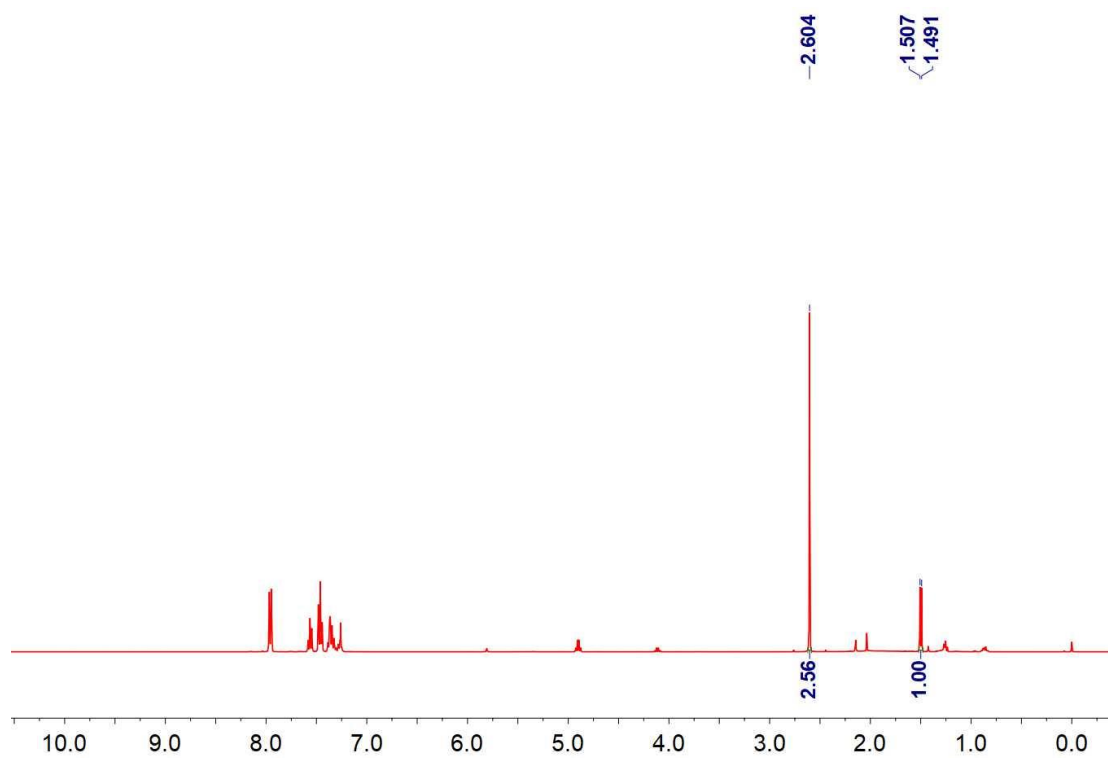


Table S1, entry 7.

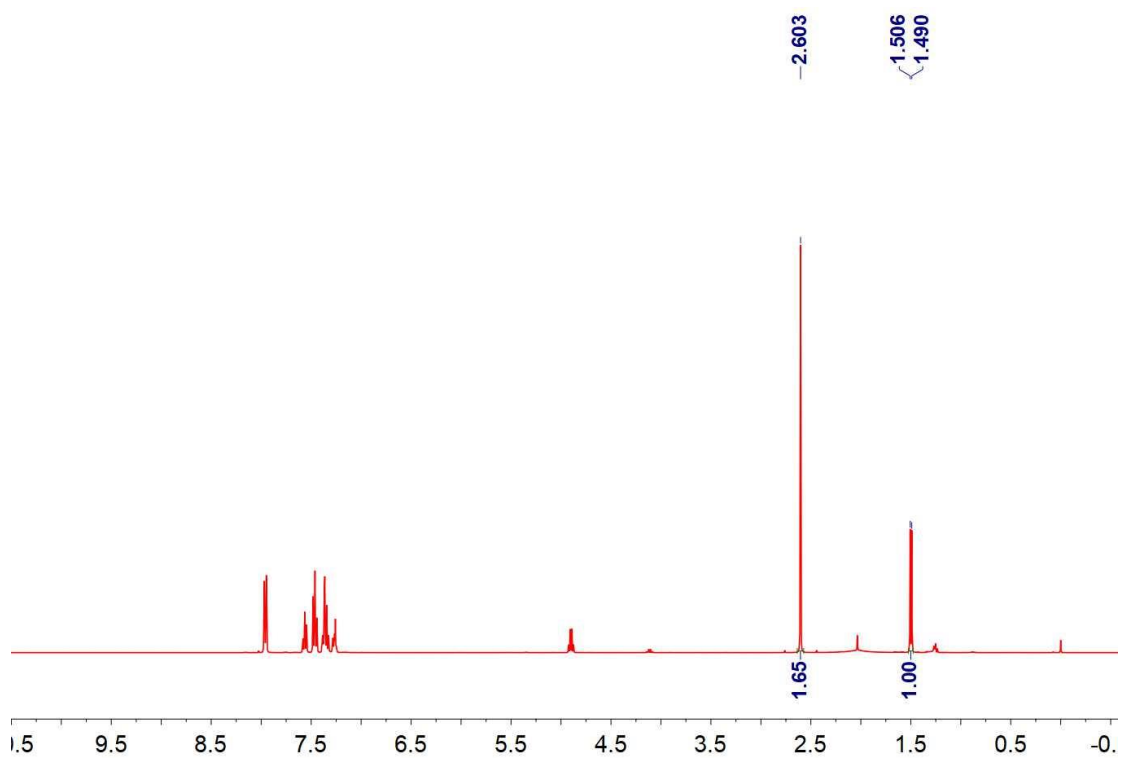


Table S1, entry 8.

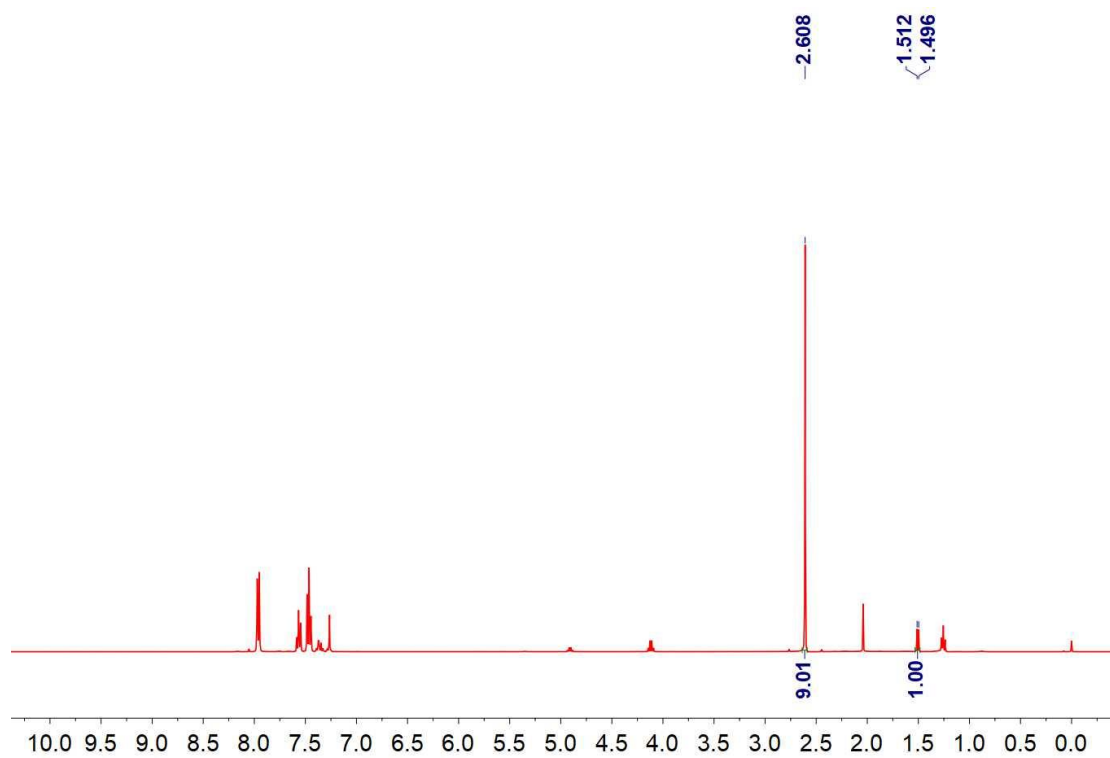


Table S1, entry 9

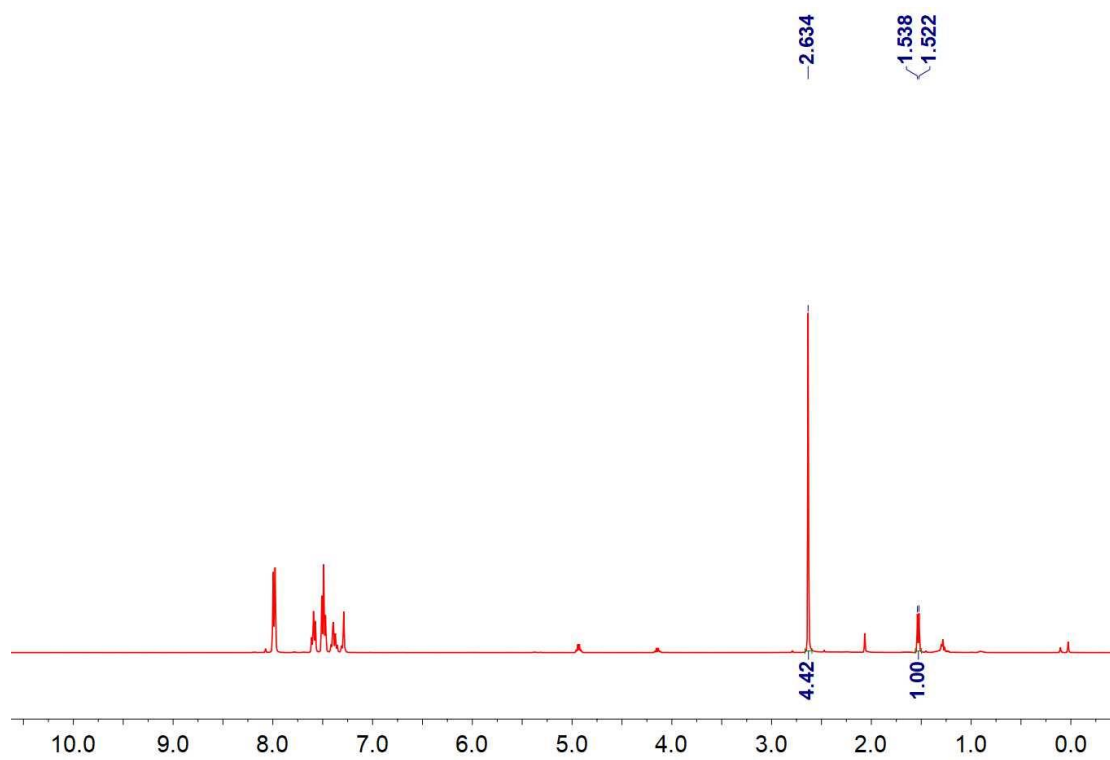


Table S1, entry 10.

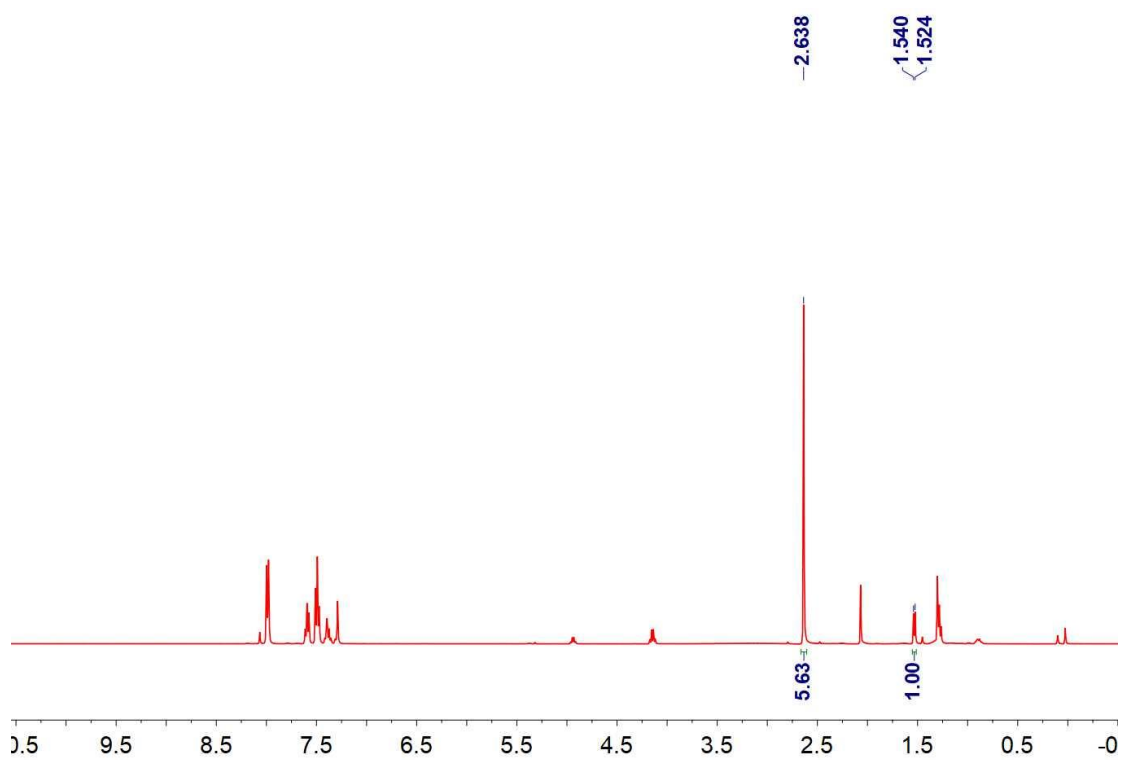


Table S1, entry 11.

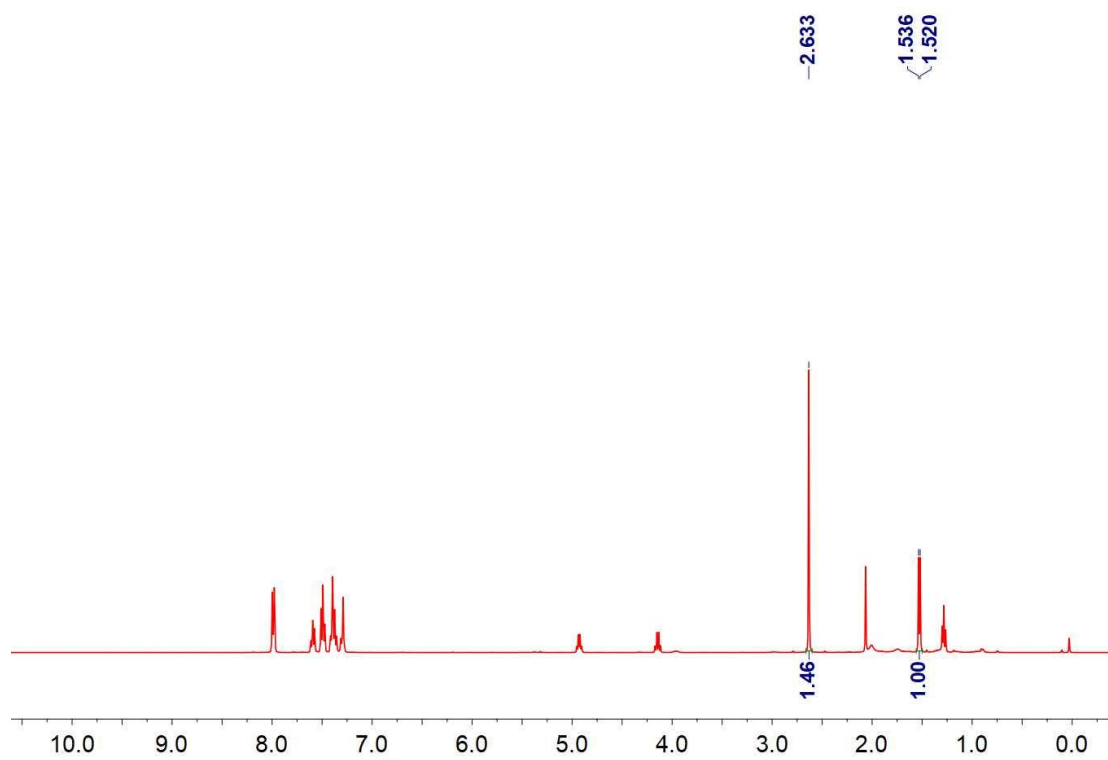


Table S1, entry 12.

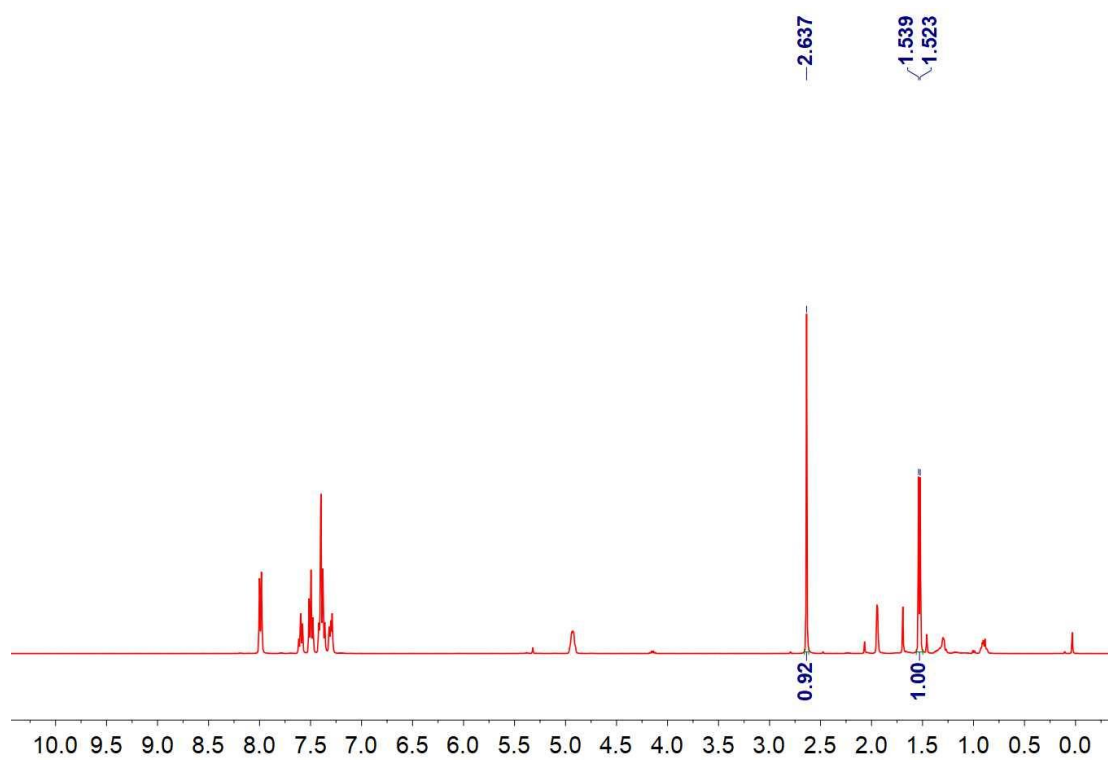


Table S1, entry 13.

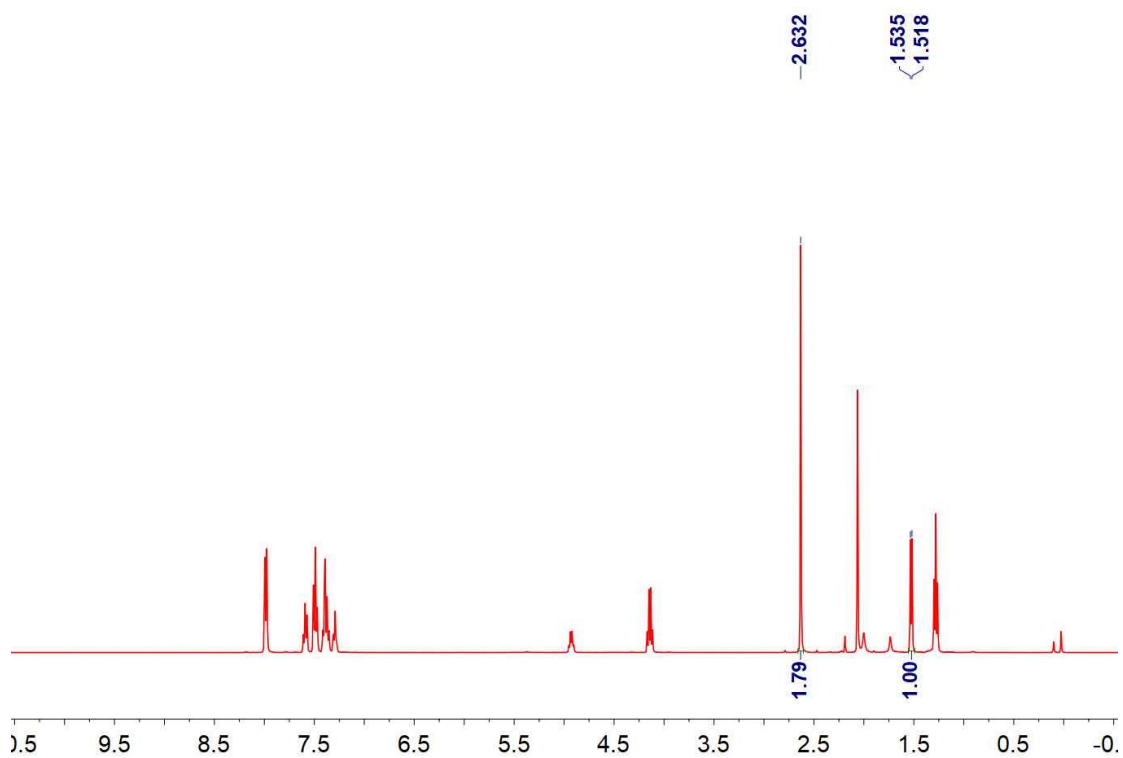


Table S1, entry 14.

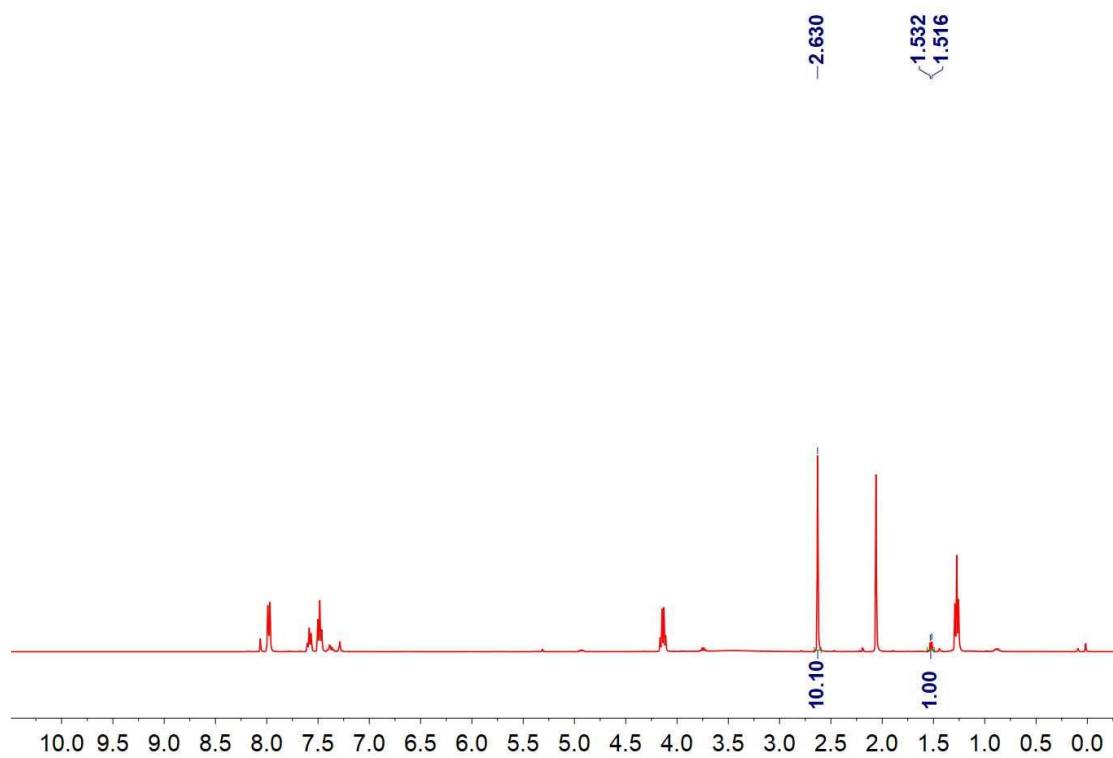


Table S1, entry 15.

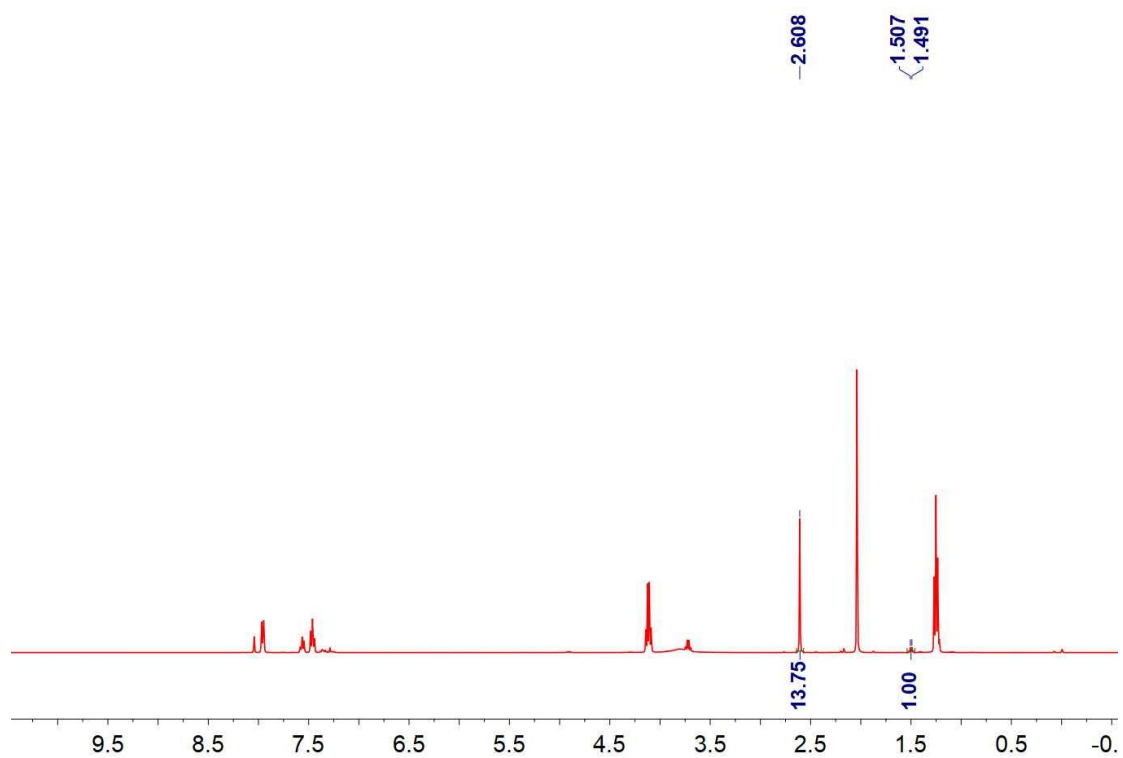


Table S1, entry 16.

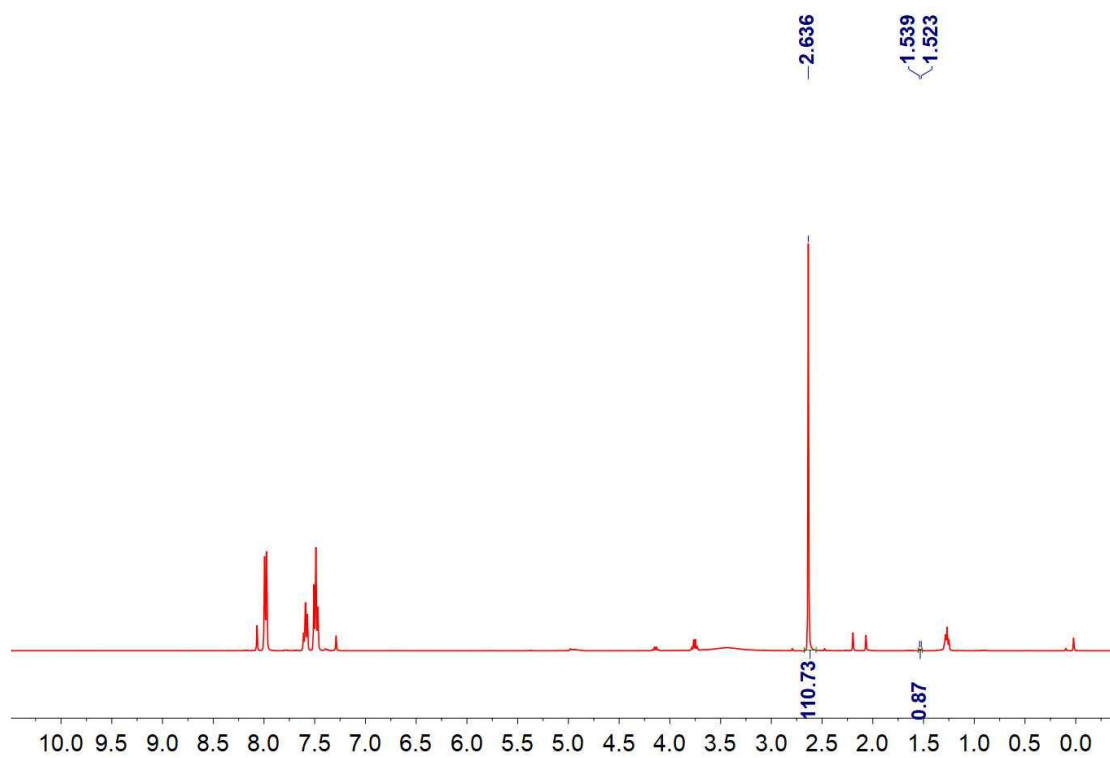


Table S1, entry 17.

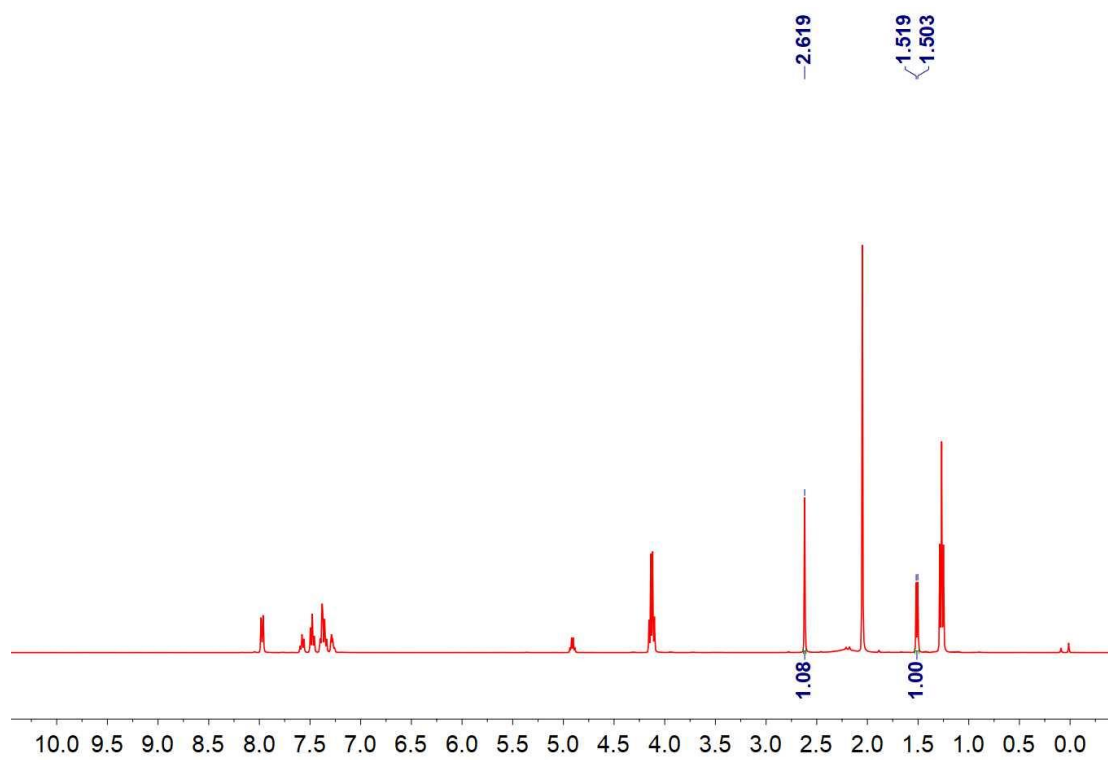


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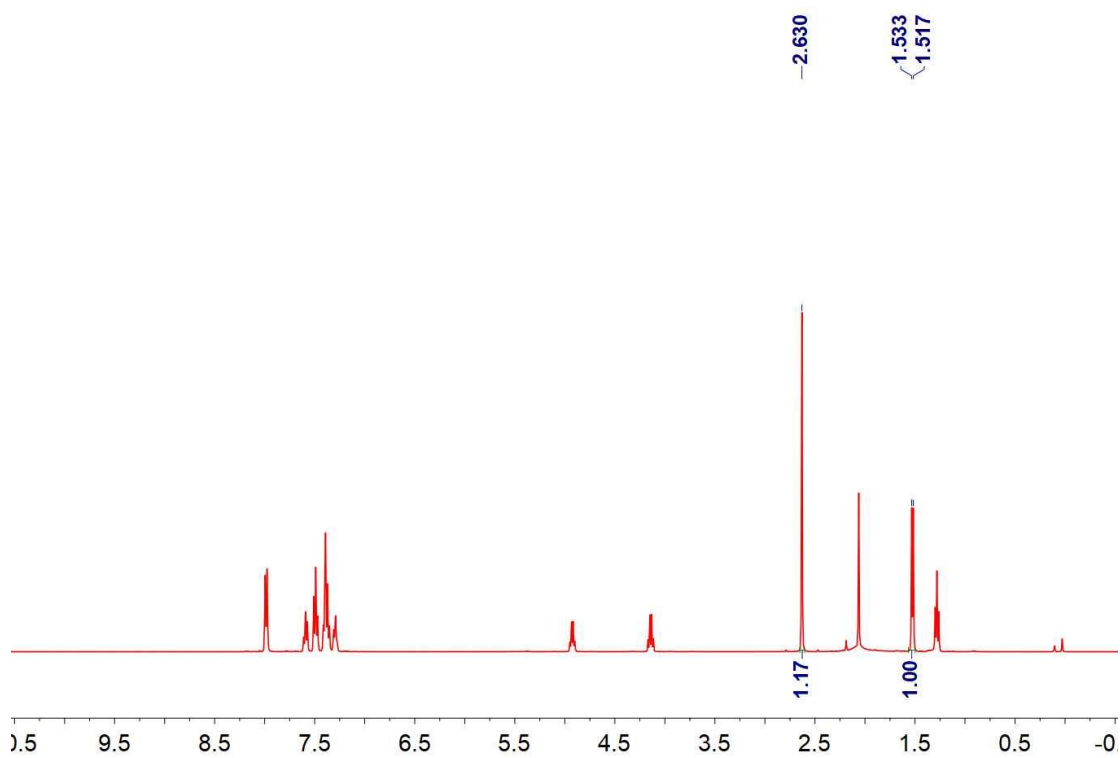


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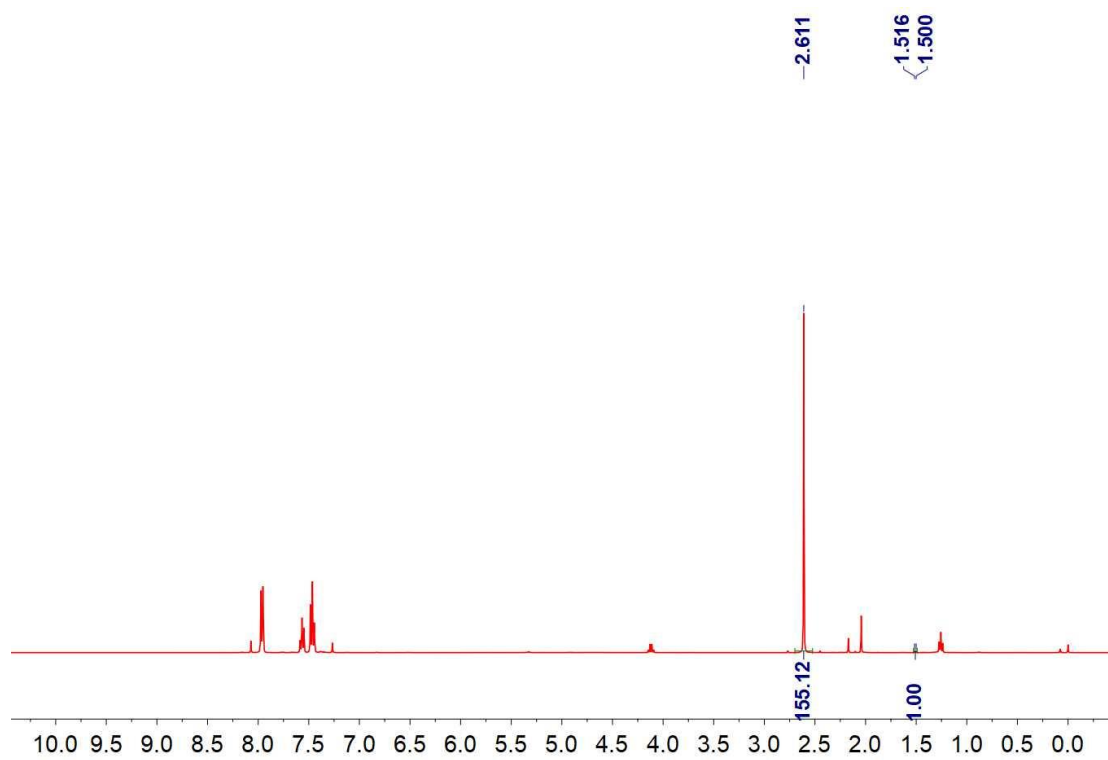


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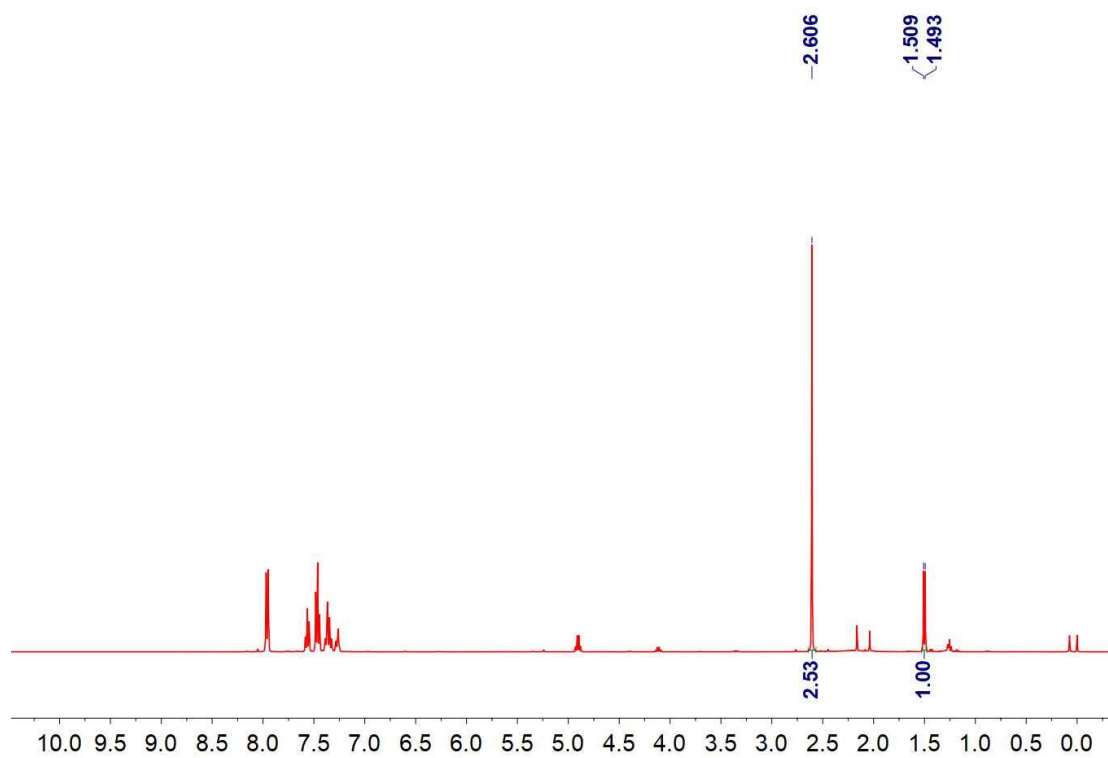


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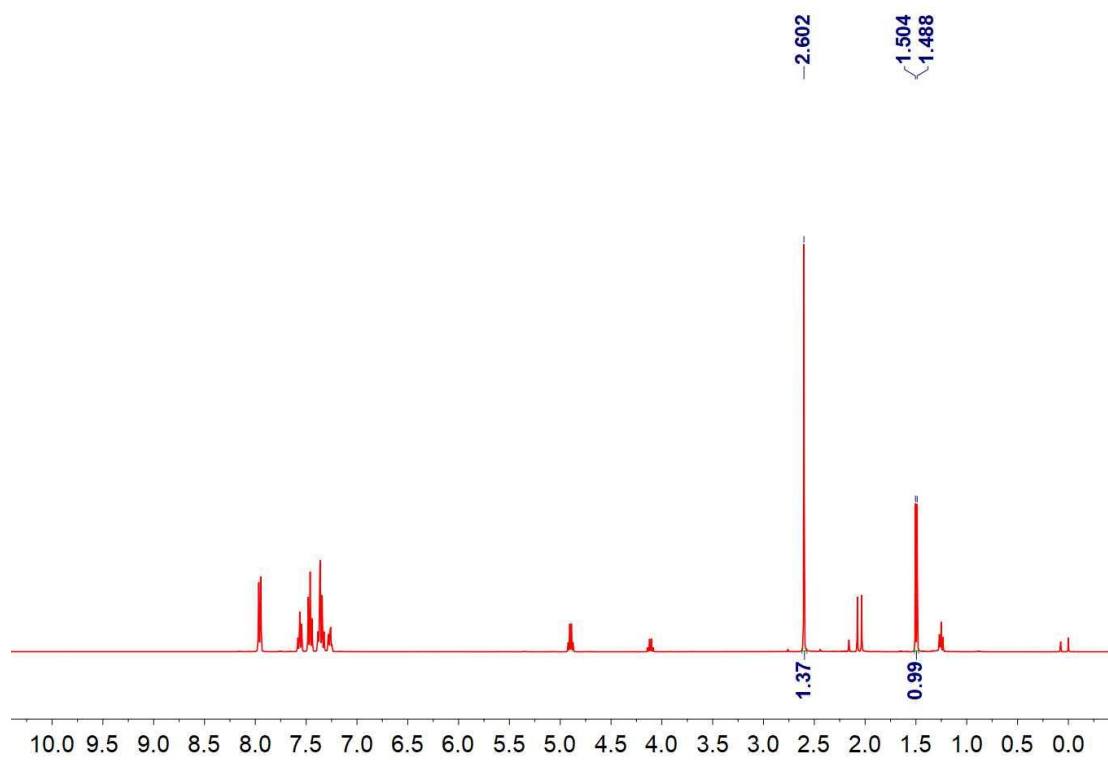


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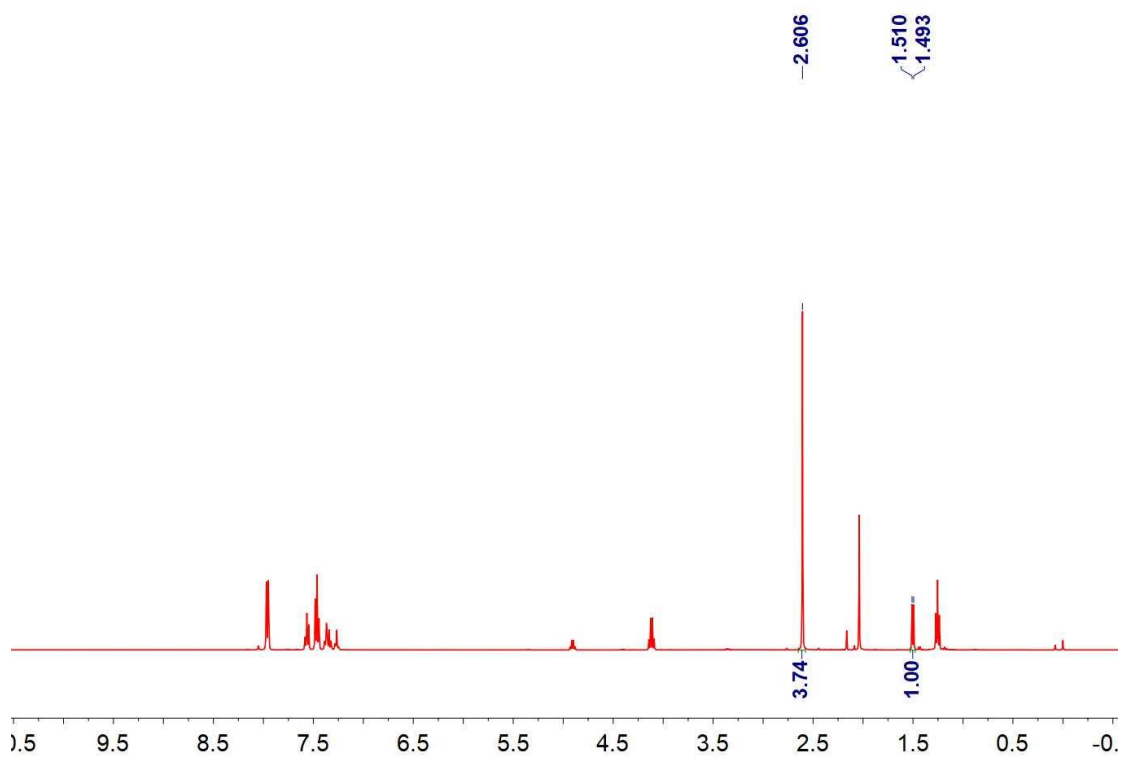


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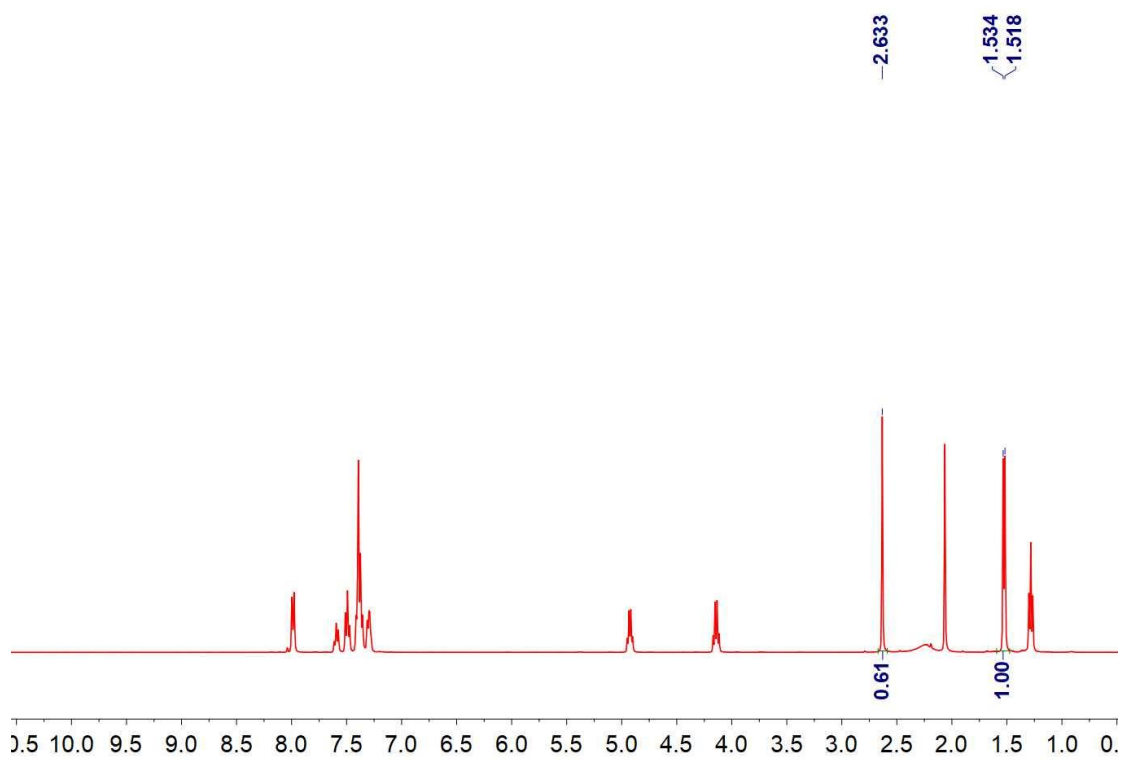


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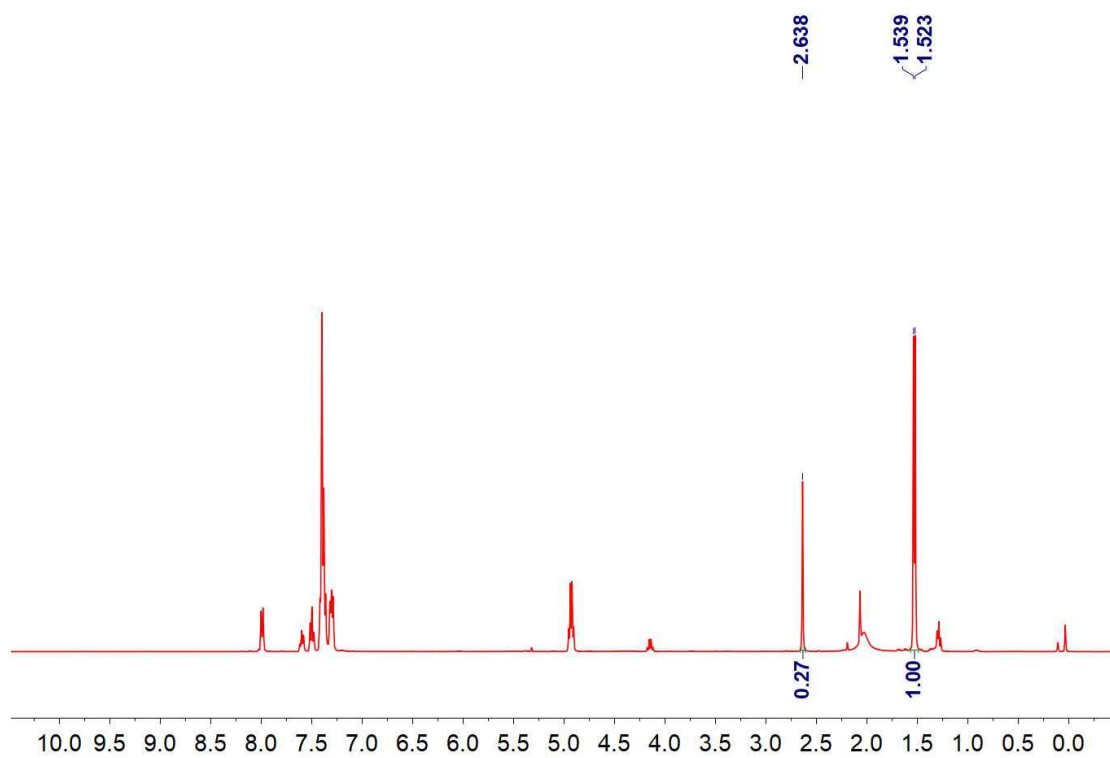


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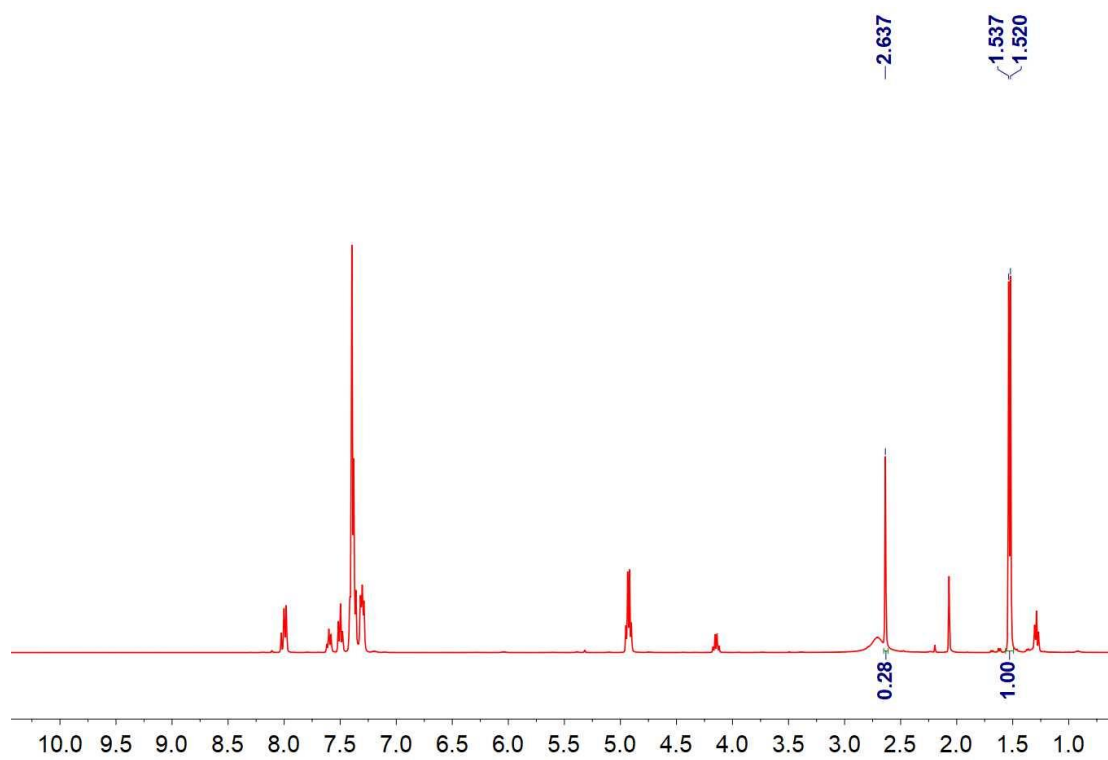


Table S1, entry 26.

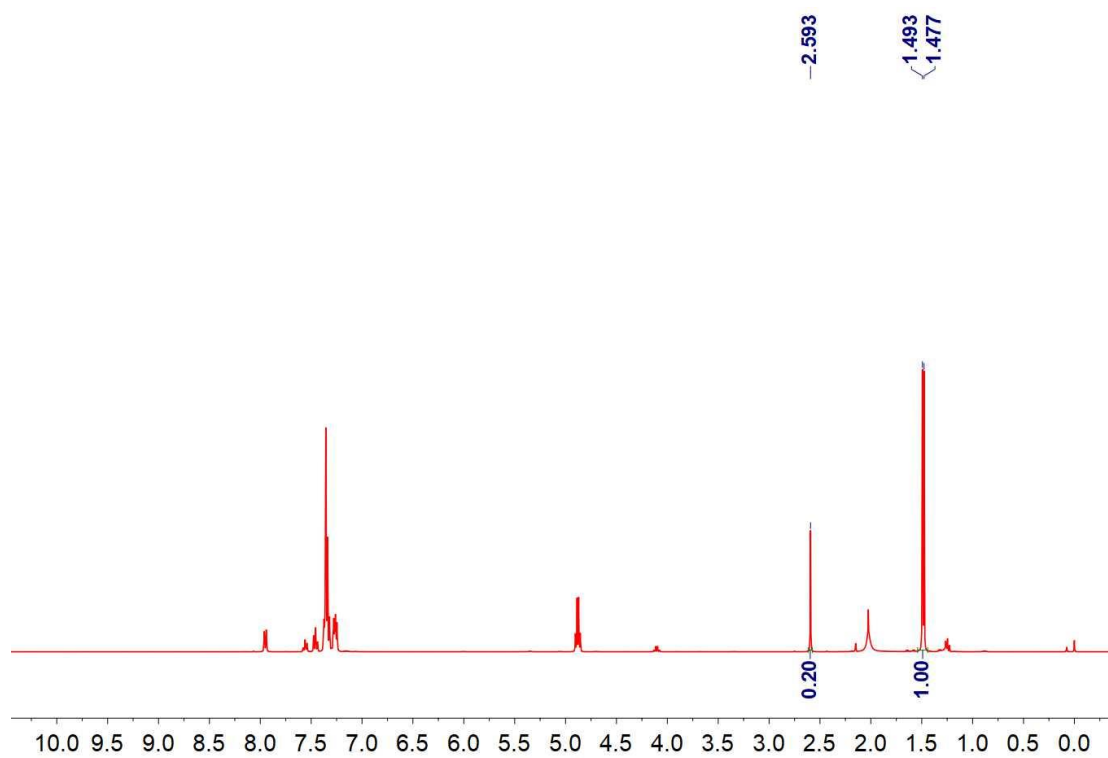


Table S1, entry 27.

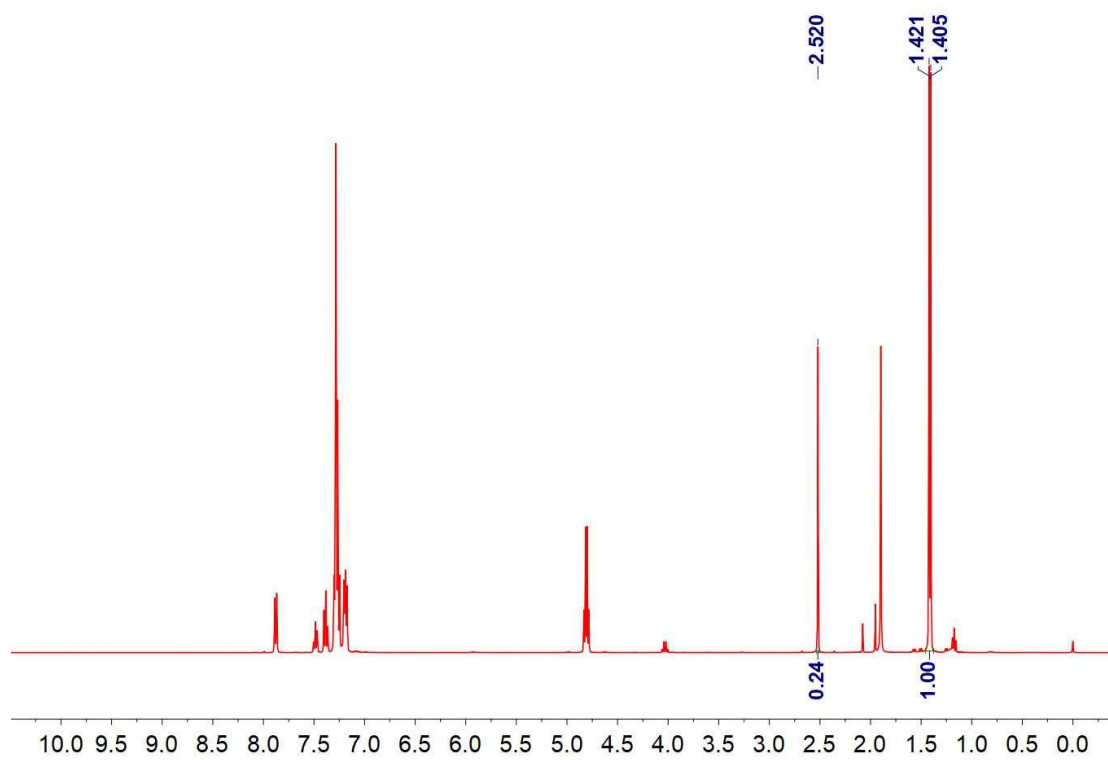


Table S1, entry 28.

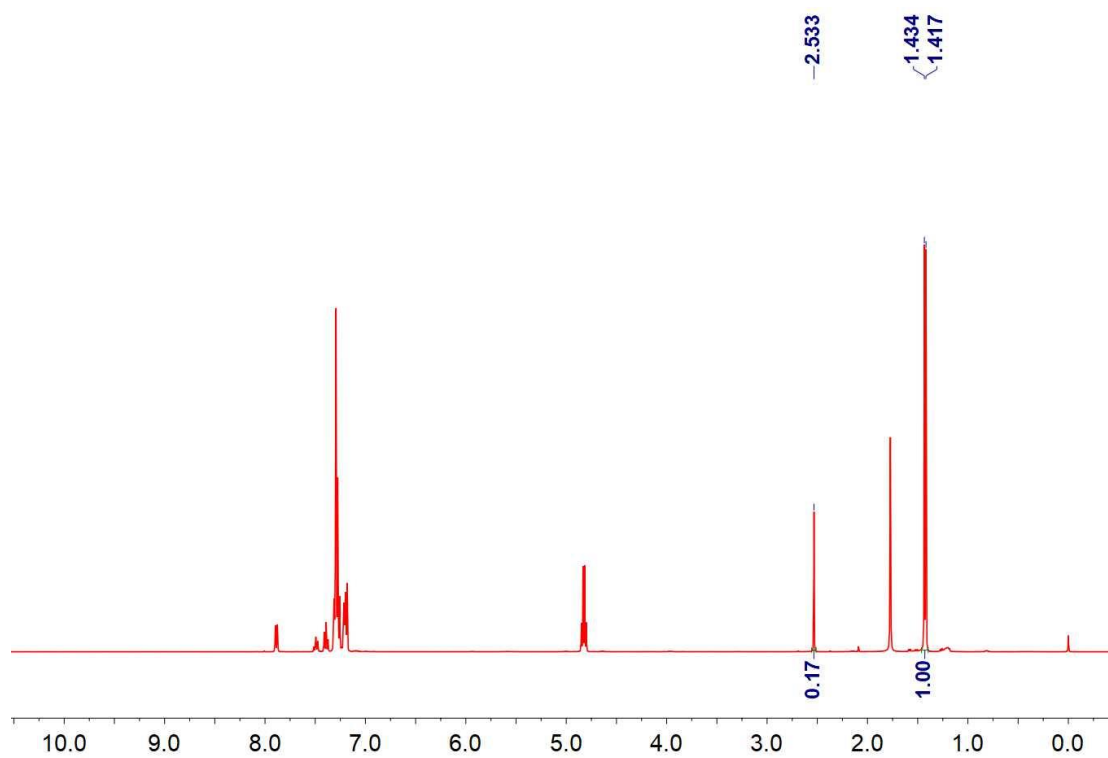
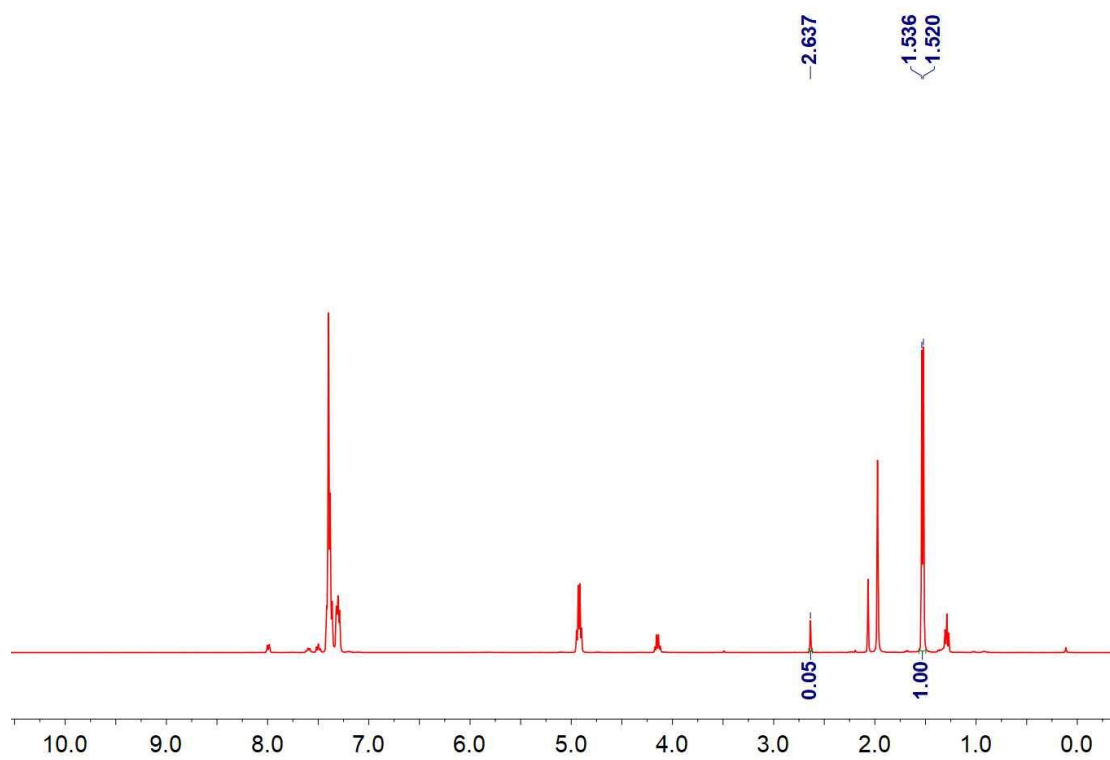


Table S1, entry 29.



18. ^1H NMR spectra in the yield-confirming and KIE studies.

Table 4, entry 1.

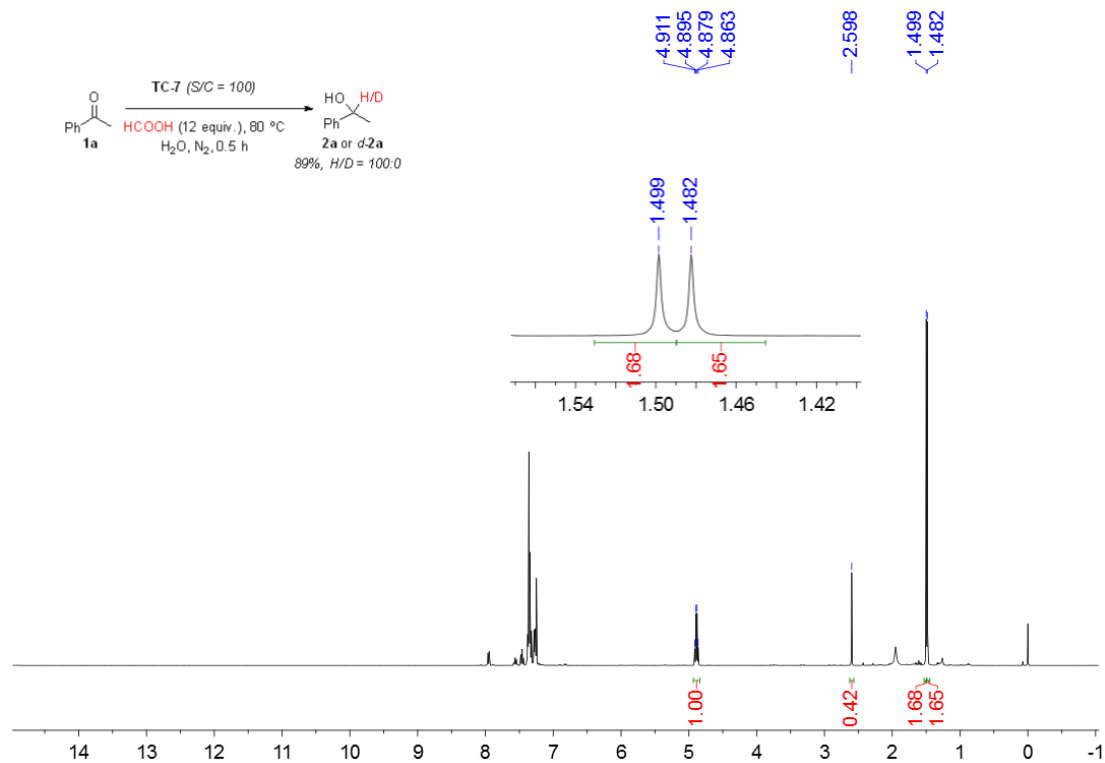


Table 4, entry 2.

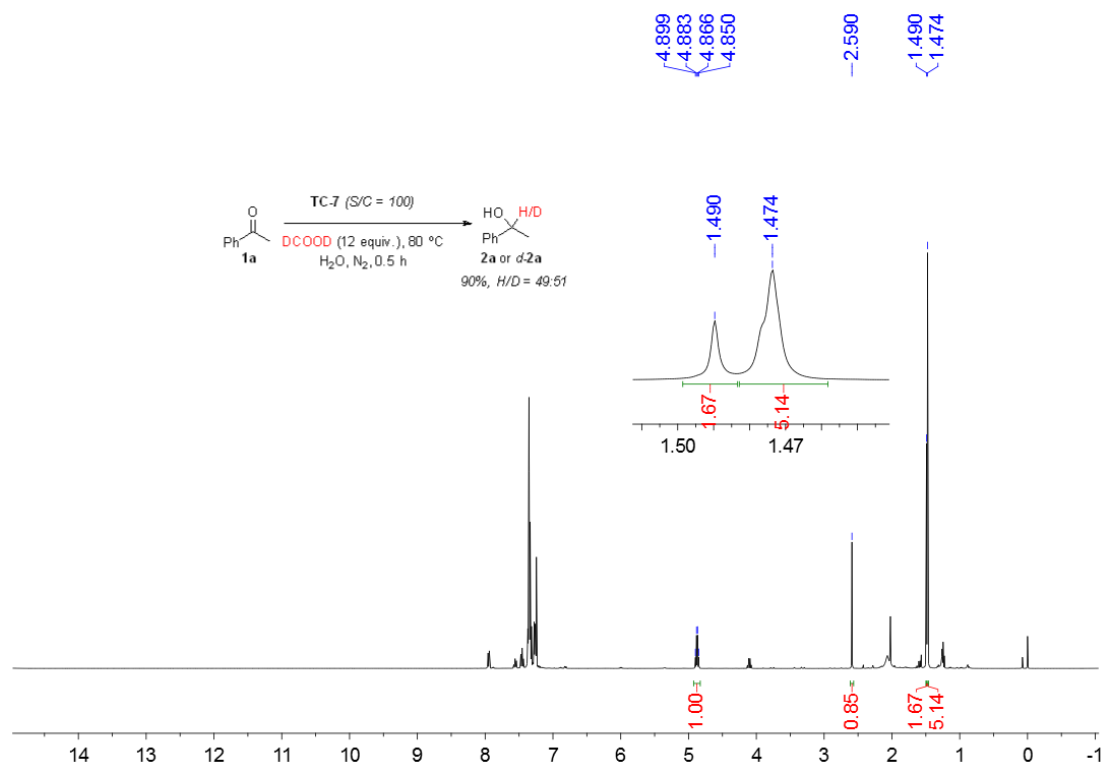


Table 4, entry 3

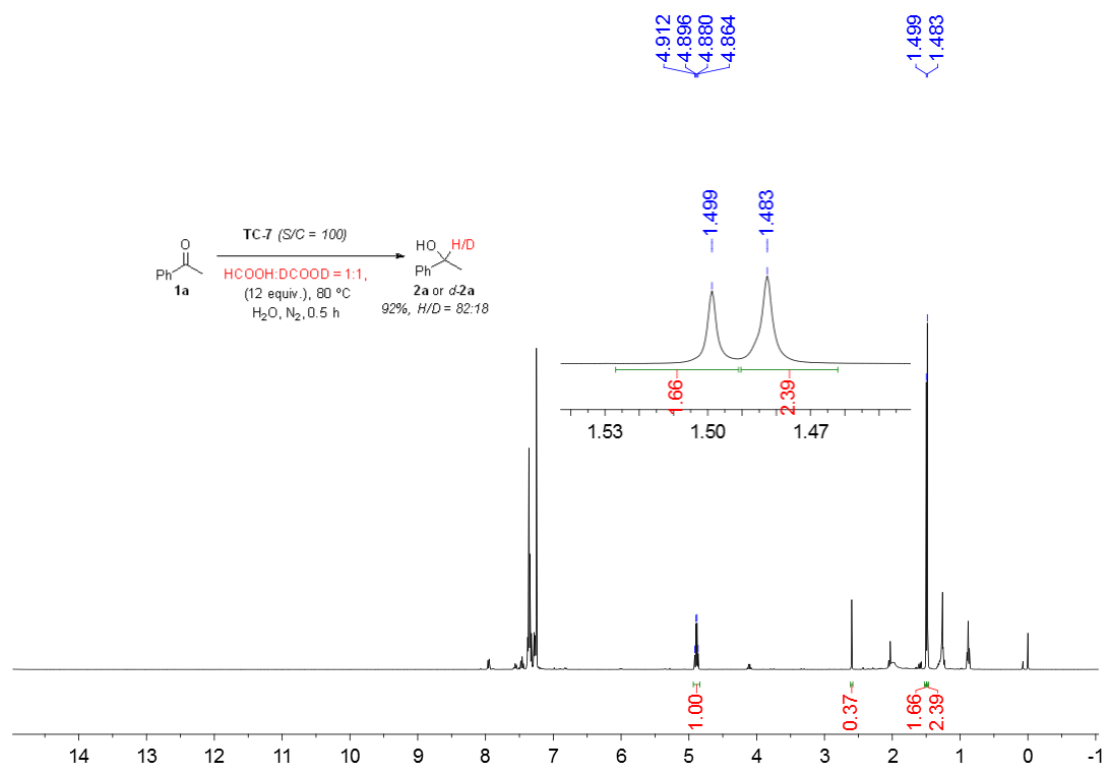


Table 4, entry 4

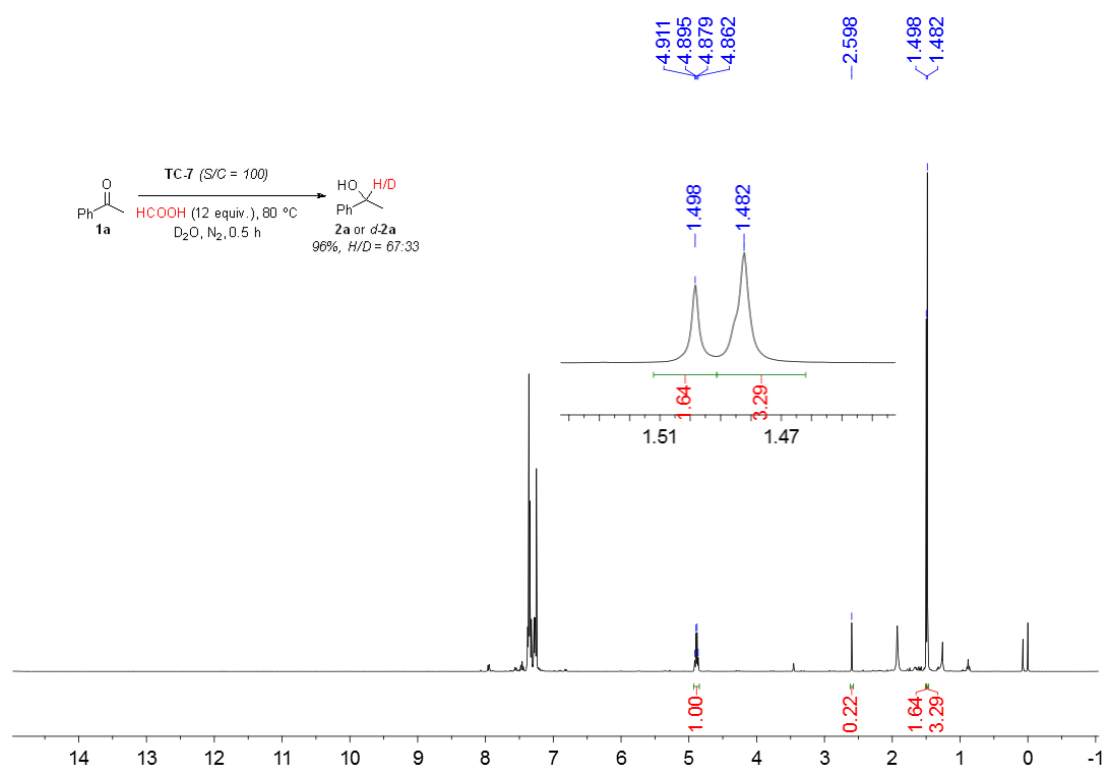


Table 4, entry 5

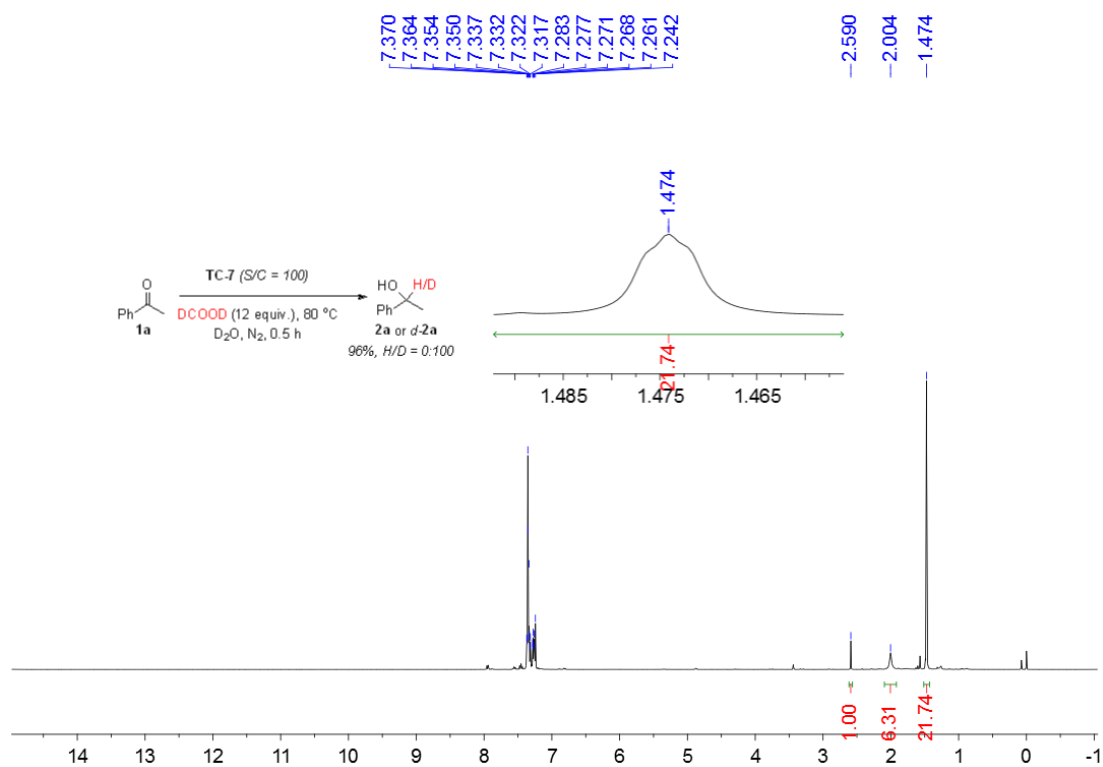
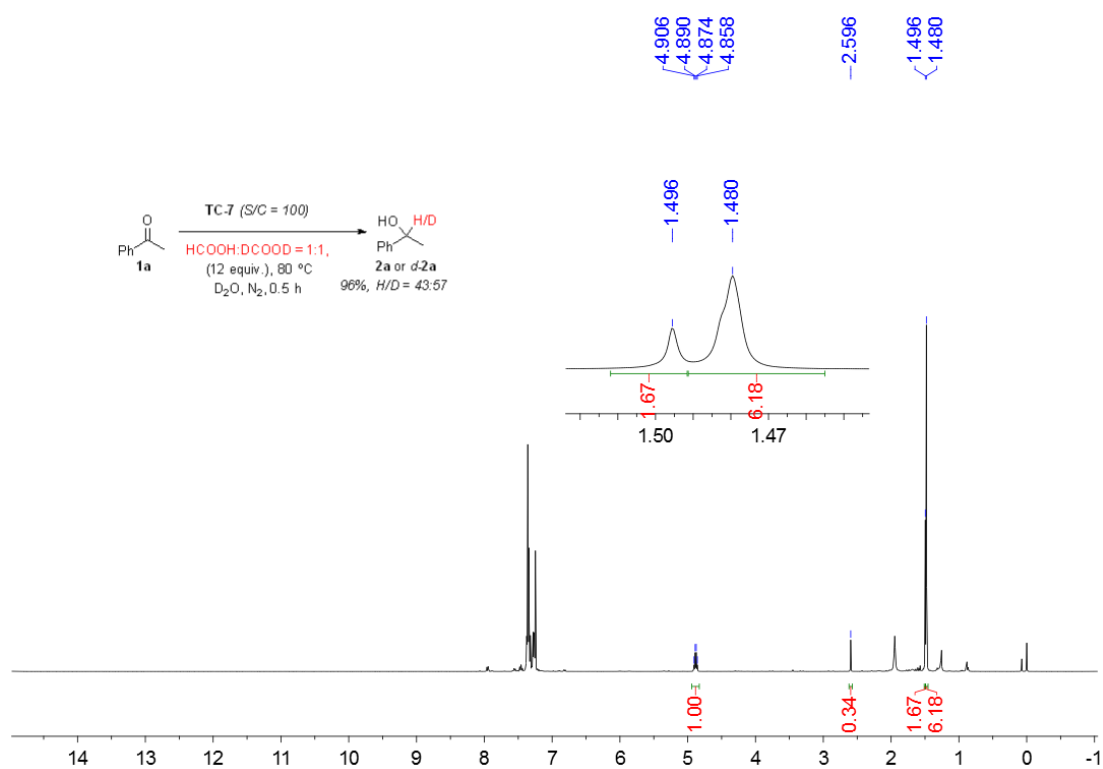
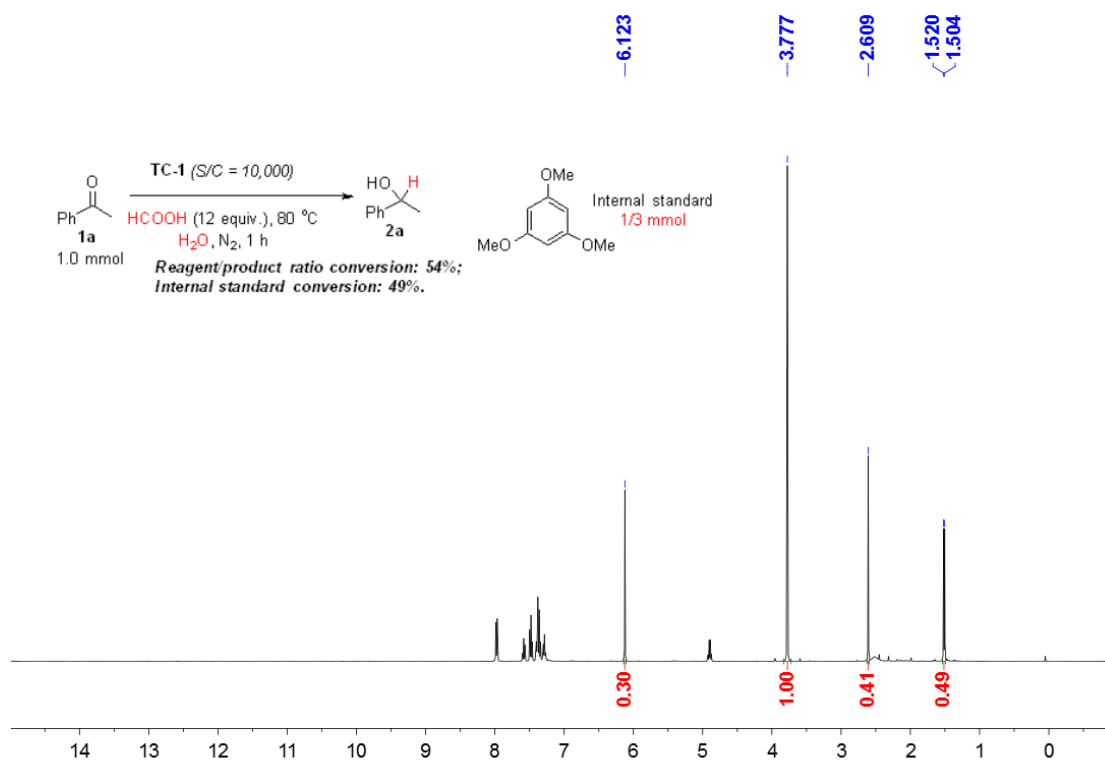


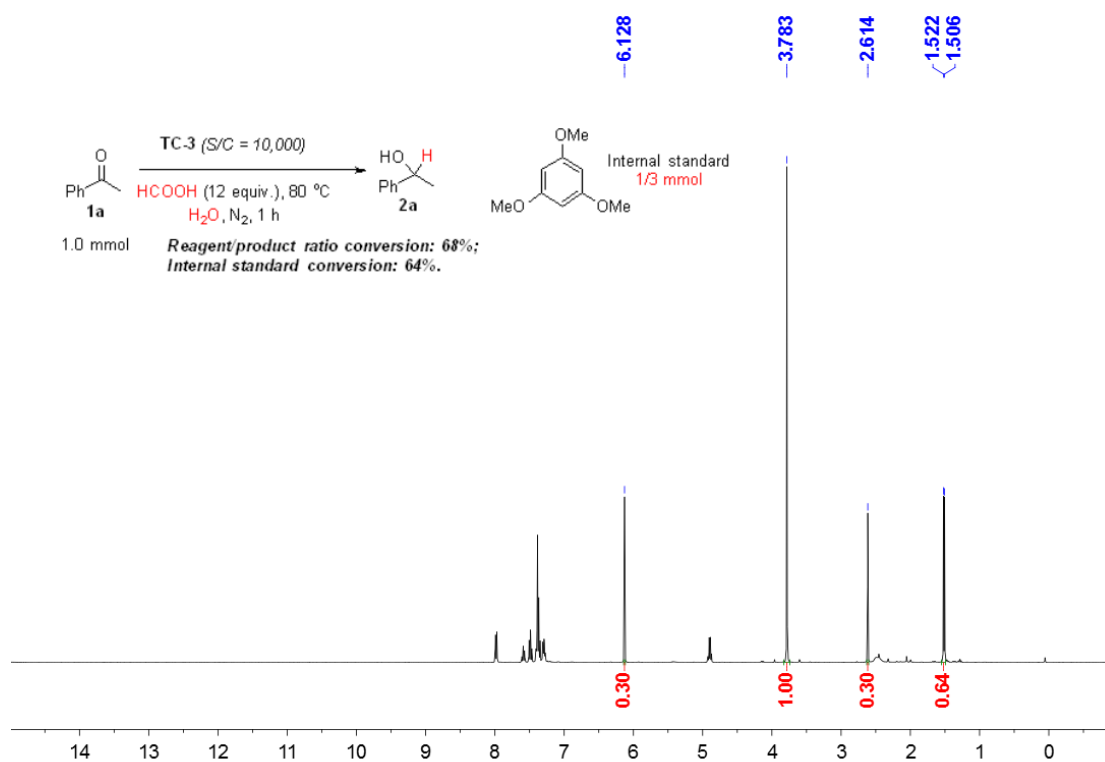
Table 4, entry 6



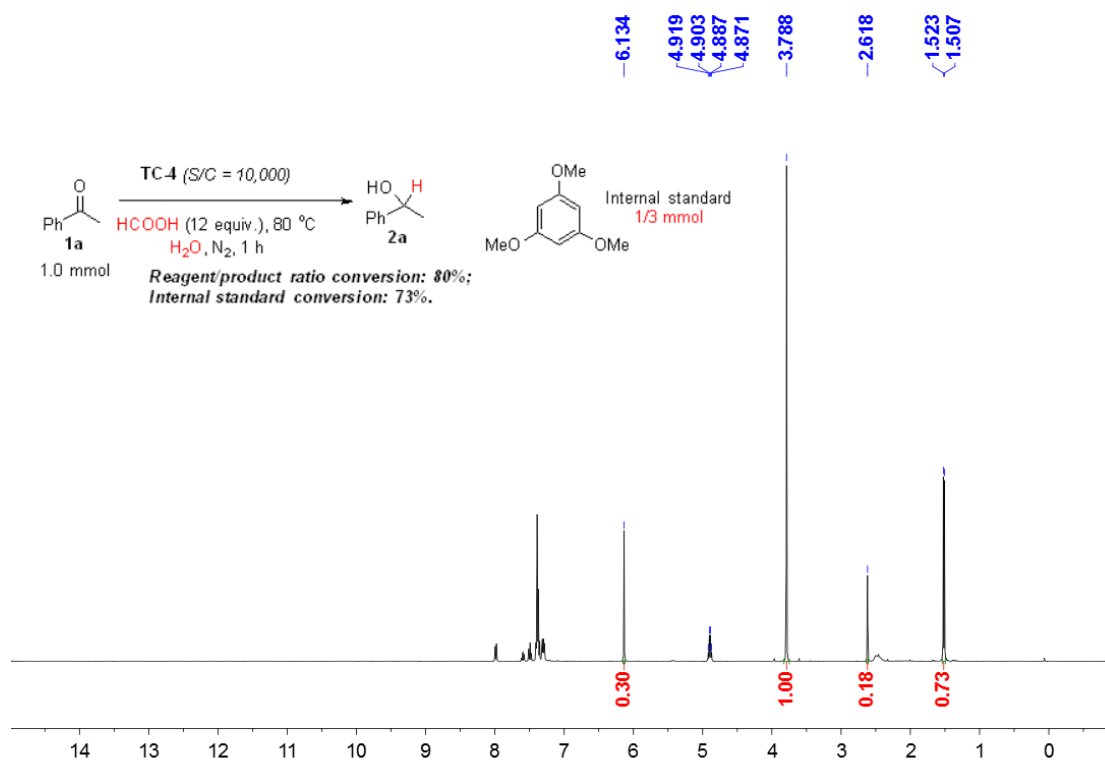
Scheme S1, eqn. S1



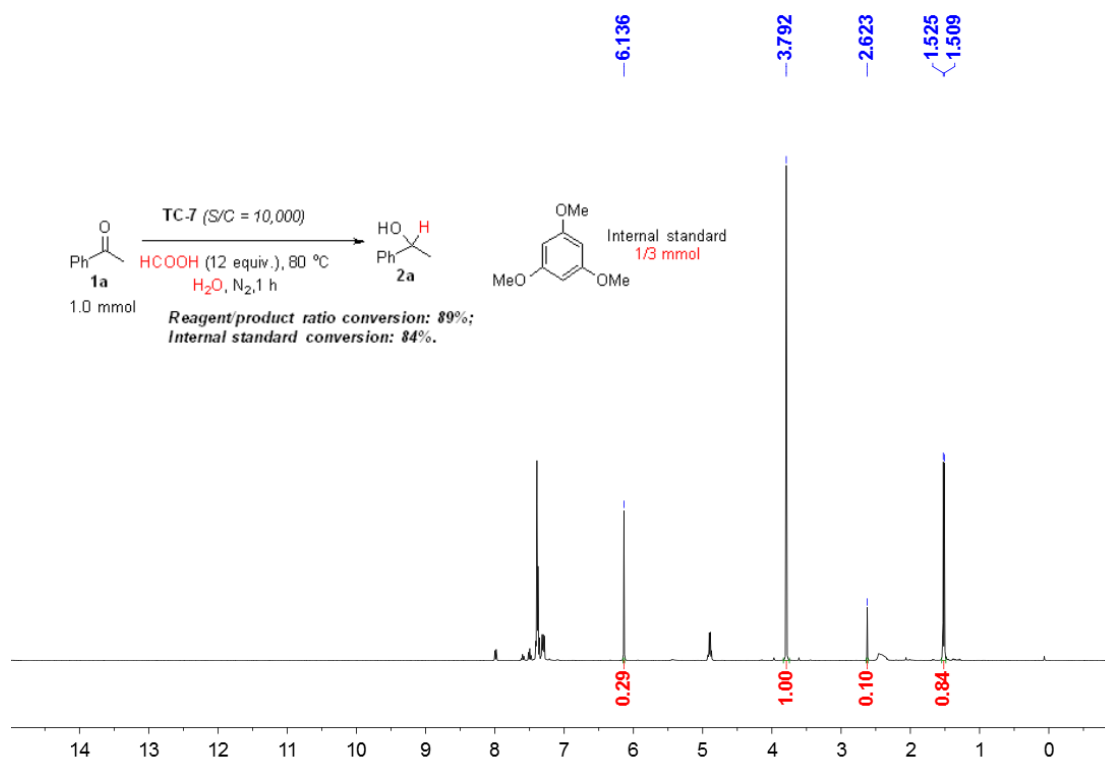
Scheme S1, eqn. S2



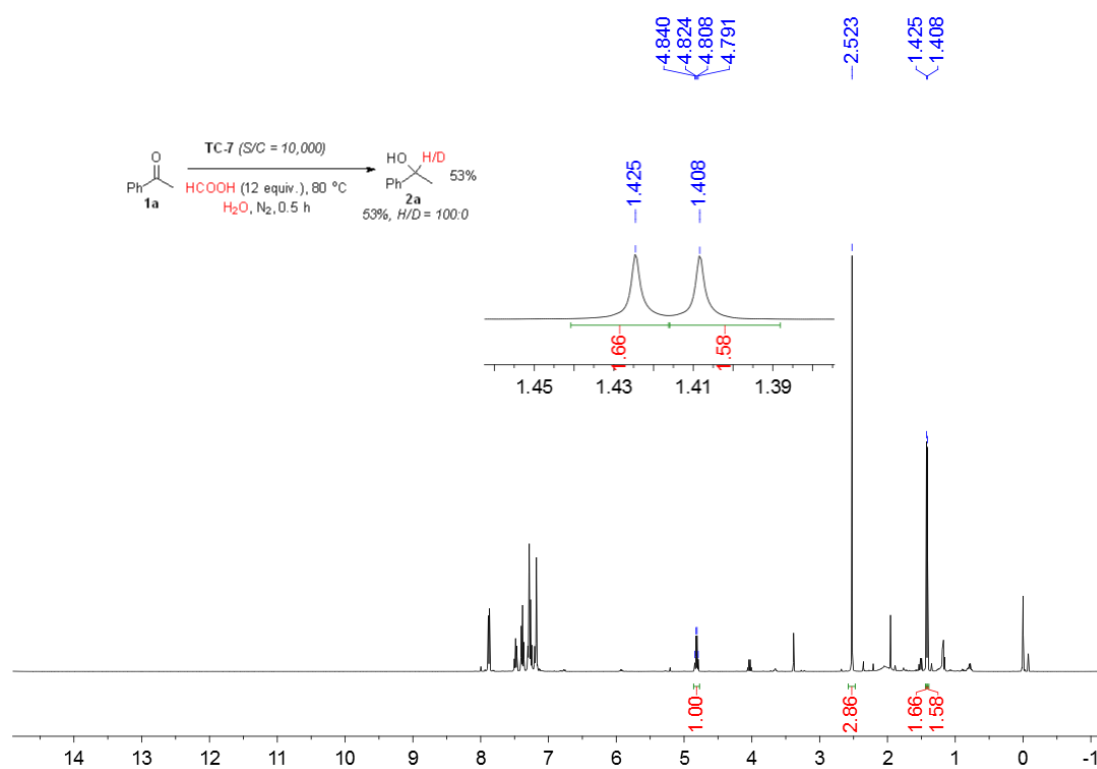
Scheme S1, eqn. S3



Scheme S1, eqn. S4.



Scheme S2, eqn. S5



Scheme S2, eqn. S8

