Supplementary Information

Enantioselective Decarboxylative Protonation and Deuteration of β-Ketocarboxylic Acids

Haruna Mizutani, Ryouta Kawanishi and Kazutaka Shibatomi

Department of Applied Chemistry and Life Science, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi 441-8580, Japan
E-mail: shiba@chem.tut.ac.jp.

Table of contents

1. General information

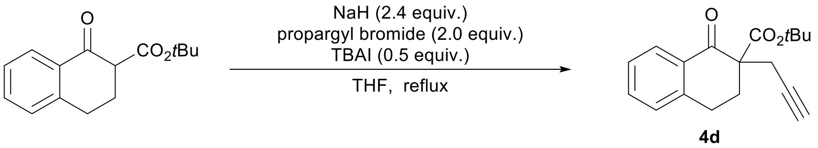
Methods: All non-aqueous reactions were carried out in dried glassware under an argon atmosphere and stirred using magnetic stir-plates. Thin-layer chromatography analyses were performed using pre-coated silica gel plates with a fluorescent indicator (F254) (Merck Millipore, Darmstadt, Germany). Visualization was accomplished by ultraviolet (UV) light (254 nm), phosphomolybdic acid, or *p*-anisaldehyde. Flash column chromatography was performed using silica gel 60 (mesh size 40–100) supplied by Kanto Chemical Co., Inc. (Tokyo, Japan). ^{1}H and ^{13}C nuclear magnetic resonance (NMR) spectra were recorded on a JNM-ECS400 (400 MHz ^{1}H, 100 MHz ^{13}C) or a JNM-ECX500 (500 MHz ^{1}H, 126 MHz ^{13}C) instrument (JEOL Ltd., Tokyo, Japan). Chemical shift values (δ) are reported in ppm (tetramethylsilane δ 0.00 ppm or residual benzene δ 7.16 ppm for ^{1}H; residual chloroform δ 77.0 ppm or residual benzene δ128.1 ppm for ^{13}C). The high-resolution mass spectra (HRMS) were conducted on a JMS-T100TD time-of-flight mass spectrometer (DART) (JEOL Ltd.) or a microTOF-Q II HRMS/MS instrument with electrospray ionizer (ESI) (Bruker, Billerica, MA, USA). Optical rotations were measured on a P-1030 digital polarimeter (JASCO Co., Ltd., Tokyo, Japan). Analytical high-performance liquid chromatography (HPLC) was performed on a PU1586 instrument with a MD-2018 plus diode array detector or PU1586 with a UV-1575 UV/V is detector (JASCO Co., Ltd.) using a chiral column under the conditions described below. The enantiomeric purity of the compounds was determined by HPLC analyses using chiral stationary phase columns.

Materials: Commercial grade reagents and solvents were used without further purification unless otherwise noted. Anhydrous dichloromethane and tetrahydrofuran (THF) were purchased from Kanto Chemical Co., Inc. and used after purification by a Glass Contour solvent dispensing system (Pure Process Technology, Nashua, NH, USA). Anhydrous *n*-hexane was purchased from Sigma-Aldrich (St. Louis, MO, USA). Deuterium oxide (99.8atom%D) was purchased from Tokyo Chemical Industry Co., Ltd (Tokyo, Japan). 2-(Bromomethyl)thiophen and 1-(bromomethyl)naphthalene were prepared according to literature procedures.[1,2] Catalyst **6** was prepared by following a previously reported procedure.[3] β-Ketocarboxylic acids **2** were synthesized by acidolysis of the corresponding *tert*-butyl β-ketoesters **4**.[4]

2. Synthesis of substrates and catalyst

2.1 Synthesis of *t*-butyl β-ketoesters 4

tert-butyl 1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylate (4d)

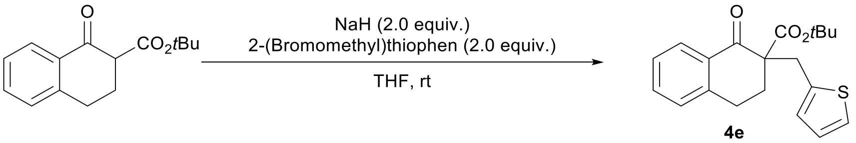


tert-Butyl 1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (289 mg, 0.83 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 77 mg, 1.98 mmol) in THF (4.1 mL) at 0 °C, and the mixture was stirred at room temperature for 30 min. Propargyl bromide (193 mg, 1.62 mmol) and tetrabutylammonium iodide (TBAI) (151 mg, 0.41 mmol) were added to the mixture, and the reaction mixture was stirred under reflux for 20 h. The reaction was quenched by adding saturated

NH_4Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a pale yellow oil (194 mg, 82% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.05 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.47 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 3.19–3.12 (m, 1H), 2.99–2.94 (m, 1H), 2.90 (dd, *J* = 16.8, 2.7 Hz, 1H), 2.81 (dd, *J* = 16.8, 2.7 Hz, 1H), 2.59–2.55 (m, 1H), 2.46–2.40 (m, 1H), 2.00 (t, *J* = 2.7 Hz, 1H), 1.34 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 194.1, 169.8, 142.9, 133.4, 132.1, 128.6, 127.8, 126.7, 82.6, 80.0, 70.9, 57.0, 30.8, 27.7, 25.9, 24.1; **IR** (NaCl): 2979, 1728, 1690, 1602, 1455, 1369, 1254, 1153, 737, 641 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{18}H_{21}O_3$, 285.1491; found, 285.1491.

***tert*-butyl 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylate (4e)**

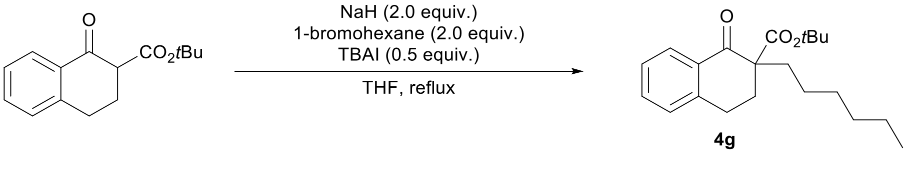


4e

tert-Butyl 1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (719 mg, 2.92 mmol) in THF (2.0 mL) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 228 mg, 5.69 mmol) in THF (8.0 mL) at 0 °C, and the mixture was stirred at room temperature for 30 min. 2-(Bromomethyl)thiophen (1.0 g, 5.84 mmol) in THF (4.6 mL) was added to the mixture at 0 °C, and the reaction mixture was stirred at room temperature for 3.5 h. The reaction was quenched by adding saturated NH_4Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a yellow oil (820 mg, 82% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.07 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.44 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.18 (d, *J* = 7.6 Hz, 1H), 7.13–7.11 (m, 1H), 6.89–6.88 (m, 2H), 3.65 (d, *J* = 14.5 Hz, 1H), 3.40 (d, *J* = 14.5 Hz, 1H), 3.08 (ddd, *J* = 16.1, 11.1, 4.6 Hz, 1H), 2.92–2.87 (m, 1H), 2.47–2.43 (m, 1H), 2.04 (ddd, *J* = 16.1, 11.1, 5.0 Hz, 1H), 1.32 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 195.1, 170.6, 142.8, 138.5, 133.2, 132.5, 128.6, 128.0, 127.8, 126.6, 126.4, 124.8, 82.4, 59.2, 33.9, 30.5, 27.7, 26.0; **IR** (NaCl): 2978, 2924, 1727, 1685, 1253, 1224, 1151, 732, 700, 515 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{20}H_{23}O_3S_1$, 343.1368; found, 343.1368.

***tert*-butyl 2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (4g)**



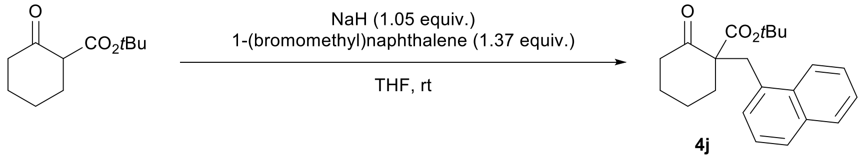
4g

tert-Butyl 1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (766 mg, 3.11 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 243 mg, 6.06 mmol) in THF (15.2 mL) at 0 °C, and the mixture was stirred at room temperature for 30 min. 1-Bromohexane (1.0 g, 6.06

mmol) and tetrabutylammonium iodide (TBAI) (559 mg, 1.52 mmol) were added to the mixture, and the reaction mixture was stirred under reflux for 18 h. The reaction was quenched by adding saturated NH_4Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a yellow oil (944 mg, 94% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.01 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.45 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.20 (d, *J* = 7.6 Hz, 1H), 3.11–3.05 (m, 1H), 2.93–2.87 (m, 1H), 2.51–2.46 (m, 1H), 2.14–2.08 (m, 1H), 1.94–1.81 (m, 2H), 1.48–1.40 (m, 1H), 1.34 (s, 9H), 1.32–1.29 (m, 7H), 0.89–0.86 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 196.1, 171.3, 142.8, 133.0, 132.7, 128.6, 127.7, 126.6, 81.7, 58.0, 33.9, 31.6, 30.8, 29.8, 27.8, 26.1, 24.6, 22.6, 14.0; **IR** (NaCl): 2954, 2930, 1727, 1692, 1368, 1296, 1252, 1150, 844, 737 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{21}H_{31}O_3$, 331.2273; found, 331.2273.

***tert*-butyl 1-(naphthalen-1-ylmethyl)-2-oxocyclohexane-1-carboxylate (4j)**



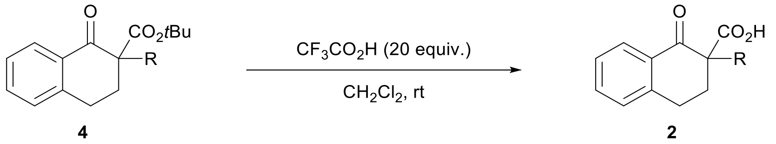
tert-butyl 2-oxocyclohexane-1-carboxylate (700 mg, 3.53 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 148 mg, 3.71 mmol) in THF (11.7 mL) at 0 °C, and the mixture was stirred at room temperature for 1 h. 1-(bromomethyl)naphthalene (1.0 g, 4.24 mmol) were added to the mixture, and the reaction mixture was stirred at room temperature for 18 h. The reaction mixture was quenched by adding saturated NH_4Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 10 : 1) to provide the title compound as an colorless oil (797 mg, 67% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.07 (d, *J* = 8.4 Hz, 1H), 7.82–7.80 (m, 1H), 7.72 (d, *J* = 8.4 Hz, 1H), 7.48–7.36 (m, 4H), 3.78 (d, *J* = 14.5 Hz, 1H), 3.49 (d, *J* = 14.5 Hz, 1H), 2.54–2.46 (m, 2H), 2.39–2.36 (m, 1H), 2.01–1.98 (m, 1H), 1.65–1.41 (m, 4H), 1.22 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 207.6, 170.4, 133.8, 133.5, 133.2, 128.80, 128.6, 127.2, 125.6, 125.2, 125.1, 124.6, 80.1, 62.9, 42.3, 36.7, 34.7, 27.6, 27.5, 22.7.

Spectroscopic data are consistent with those previously reported: J. L. Nôtre, D. van Melea and C. G. Frost *Adv. Synth. Catal.*, 2007, **349**, 432.

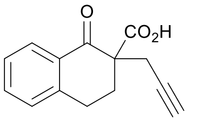
2.2 Synthesis of β-ketocarboxylic acids **2**

General procedure



Trifluoroacetic acid (20 equiv.) was added to a stirred solution of β-ketoesters **4** in dichloromethane at 0 °C, and the reaction mixture was stirred at room temperature. The reaction mixture was concentrated, and then purified by flush column chromatography on silica gel to give β-ketocarboxylic acid **2**.

1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2d)

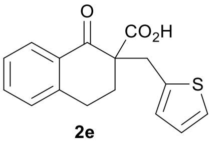


2d

The title compound was prepared following **General procedure**, using **4d** (500 mg, 1.75 mmol) and trifluoroacetic acid (4.0 g, 35.0 mmol) in dichloromethane (8.8 mL), and the reaction mixture was stirred for 40 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 10 : 1 to 2 : 1) to provide the title compound as a brown solid (341 mg, 85% yield) .

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.73 (br, 1H), 8.06 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.50 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.32 (t, *J* = 7.6 Hz, 1H), 7.25 (d, *J* = 7.6 Hz, 1H), 3.22–3.15 (m, 1H), 3.02–2.97 (m, 1H), 2.94 (dd, *J* = 16.8, 2.7 Hz, 1H), 2.87 (dd, *J* = 16.8, 2.7 Hz, 1H) 2.64–2.59 (m, 1H), 2.53 (ddd, *J* = 14.7, 10.3, 5.0 Hz, 1H), 2.03 (t, *J* = 2.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 193.7, 176.1, 143.3, 134.1, 131.2, 128.9, 128.3, 127.0, 79.1, 71.7, 56.3, 30.1, 25.5, 24.1; **IR** (NaCl): 3293, 2935, 1719, 1685, 1601, 1455, 1238, 793, 742, 650 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{14}H_{16}O_3N_1$, 246.1130; found, 246.1130.

1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2e)

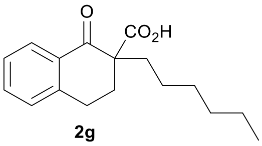


2e

The title compound was prepared following **General procedure**, using **4e** (695 mg, 2.03 mmol) and trifluoroacetic acid (4.6 g, 40.6 mmol) in dichloromethane (10.1 mL), and the reaction mixture was stirred for 45 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 4 : 1 to 1 : 2) to provide the title compound as a white solid (424 mg, 73% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.10 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.51 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.34 (t, *J* = 7.6 Hz, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 7.14 (dd, *J* = 5.0, 1.2 Hz, 1H), 6.91 (dd, *J* = 5.4, 3.4 Hz, 1H), 6.88–6.87 (m, 1H), 3.66 (d, *J* = 14.9 Hz, 1H), 3.47 (d, *J* = 14.9 Hz, 1H), 3.13 (ddd, *J* = 14.1, 9.2, 5.0 Hz, 1H), 3.03–2.97 (m, 1H), 2.51–2.46 (m, 1H), 2.22 (ddd, *J* = 14.1, 9.2, 5.0 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 195.0, 176.5, 143.3, 137.2, 134.1, 131.4, 128.8, 128.4, 128.2, 127.0, 126.7, 125.1, 58.3, 34.0, 29.5, 25.6; **IR** (NaCl): 3068, 2931, 1709, 1684, 1599, 1455, 1277, 1229, 742, 701 cm^{-1}; **HRMS** (ESI): No data. Protonated product **2e** was measured.

2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2g)

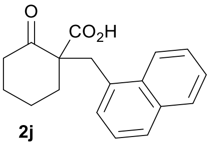


2g

The title compound was prepared following **General procedure**, using **4g** (480 mg, 1.46 mmol) and trifluoroacetic acid (3.3 g, 29.2 mmol) in dichloromethane (7.3 mL), and the reaction mixture was stirred for 60 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 5 : 1 to 1 : 1) to provide the title compound as a pale red oil (322 mg, 82% yield), including 4% of **3g**.

^{1}**H NMR** (500 MHz, $CDCl_3$): δ 8.09 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.54 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.35 (t, *J* = 7.6 Hz, 1H), 7.26 (d, *J* = 7.6 Hz, 1H), 3.04 (t, *J* = 6.1 Hz, 2H) 2.43 (t, *J* = 6.1 Hz, 2H), 1.95–1.86 (m, 2H), 1.41–1.21 (m, 8H), 0.89–0.84 (m, 3H); ^{13}**C NMR** (126 MHz, $CDCl_3$): δ 199.7, 174.4, 143.8, 134.6, 130.7, 128.9, 128.5, 127.1, 55.7, 34.5, 31.4, 29.4, 29.3, 25.2, 24.6, 22.5, 14.0; **IR** (NaCl): 2954, 2929, 2857, 1710, 1688, 1601, 1455, 1297, 1228, 741 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{17}H_{23}O_3$, 275.1647; found, 275.1647.

1-(naphthalen-1-ylmethyl)-2-oxocyclohexane-1-carboxylic acid (2j)

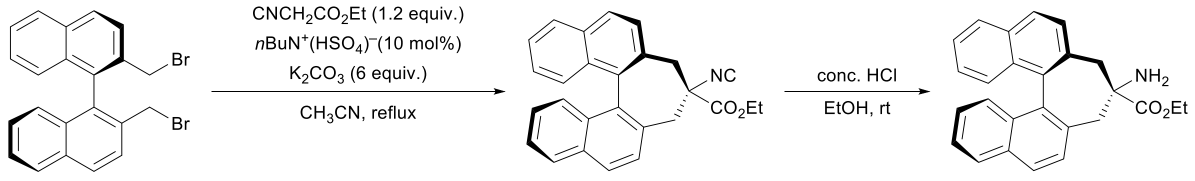


2j

The title compound was prepared following **General procedure**, using **4j** (400 mg, 1.18 mmol) and trifluoroacetic acid (2.7 g, 23.63 mmol) in dichloromethane (5.9 mL), and the reaction mixture was stirred for 60 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 4 : 1 to 1 : 1) to provide the title compound as a colorless powder (199 mg, 60% yield).

^{1}**H NMR** (500 MHz, $CDCl_3$): δ 8.02 (d, *J* = 8.0 Hz, 1H), 7.83–7.80 (m, 1H), 7.73 (d, *J* = 8.0 Hz, 1H), 7.46–7.40 (m, 2H), 7.38–7.35 (m, 1H), 7.32–7.30 (m, 1H), 3.84 (d, *J* = 14.5 Hz, 1H), 3.54 (d, *J* = 14.5 Hz, 1H), 2.59–2.55 (m, 1H), 2.52–2.46 (m, 1H), 2.30–2.27 (m, 1H), 2.04–2.00 (m, 1H), 1.72–1.54 (m, 4H); ^{13}**C NMR** (126 MHz, $CDCl_3$): δ 207.1, 177.3, 133.8, 133.0, 132.5, 128.8, 128.7, 127.7, 125.7, 125.3, 125.1, 124.0, 61.6, 41.6, 35.6, 35.3, 27.3, 22.4; **IR** (NaCl): 3048, 2941, 2866, 2335, 1705, 1596, 1509, 1396, 1271, 1218, 1126, 801, 781, 737 cm^{-1} **HRMS** (ESI): No data. Protonated product **3j** was measured.

2.3 Synthesis of catalyst **5**



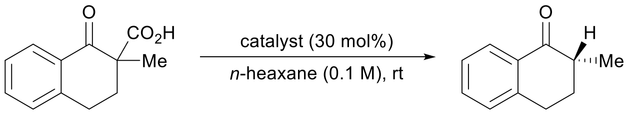
2

To a suspension of (*R*)-2,2'-bis(bromomethyl)-1,1'-binaphthalene (1.5 g, 3.41 mmol), tetrabutylammonium hydrogen sulfate (115 mg, 0.34 mmol, 10 mol%) and K_2CO_3 (2.8 g, 20.4 mmol) in CH_3CN (34 mL) was added ethyl isocyanoacetate (449 µL, 4.08 mmol). The solution was refluxed for 18 h under argon atmosphere. The resulting mixture was filtered and the filtrate was concentrated. The residue was dissolved in ethanol (34 mL) was added conc. HCl (2.0 mL) at 0 ºC. The solution was stirred at room temperature for 4.5 h under argon atmosphere. The reaction mixture was quenched by adding saturated $NaHCO_3$ aqueous solution and then extracted with CH_2Cl_2. The combined organic layer was dried over anhydrous Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography (CH_2Cl_2 : Methanol = 20 : 1) to provide **5** as a pale yellow powder (1077 mg, 83% yield).

^{1}H NMR (500 MHz, C_6D_6): δ 7.76–7.70 (m, 4H), 7.57–7.54 (m, 3H), 7.32 (d, *J* = 8.4 Hz, 1H), 7.23–7.18 (m, 2H), 7.00–6.95 (m, 2H) 2.43 (t, *J* = 6.1 Hz, 2H), 3.93–3.83 (m, 2H), 3.08 (d, *J* = 13.4 Hz, 1H), 3.05 (d, *J* = 13.4 Hz, 1H), 2.55 (d, *J* = 13.4 Hz, 1H), 2.27 (d, *J* = 1.34 Hz, 1H), 0.87 (t, *J* = 7.3 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 175.3, 136.9, 135.3, 134.8, 134.5, 133.6, 133.5, 132.5, 129.3, 129.1, 128.6, 128.3, 129.2, 125.5, 125.4, 69.0, 60.8, 43.7, 43.5, 14.1; **IR** (NaCl): 3374, 3051, 2979, 2932, 1726, 1508, 1444, 1365, 1224, 1210, 1039, 1026, 817, 750, 705 cm^{-1}; **HRMS** (ESI): $[M + H]^+$ calcd. for $C_{26}H_{24}NO_2$, 382.1802; found, 382.1796.

3. Screening of amine catalysts

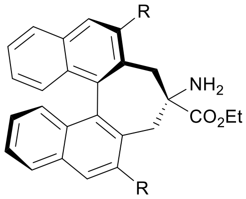
Amine catalyst (30 mol%) was added to a stirred solution of **2a** in *n*-hexane (0.1 M), and the reaction mixture was stirred at rt. The mixture was purified by flash column chromatography on silica gel to give **3a**.



entry	catalyst	temp. [°C]	time [h]	yield [%][a]	ee [%][b]
1	**1**	rt	8	86	83
2	**5**	rt	46	89	2
3	**6**	rt	56	100	27

[a] Isolated yield.

[b] Ee value were determind by chiral HPLC analysis.



1: R = 3,5-(tBu)$_2$Ph

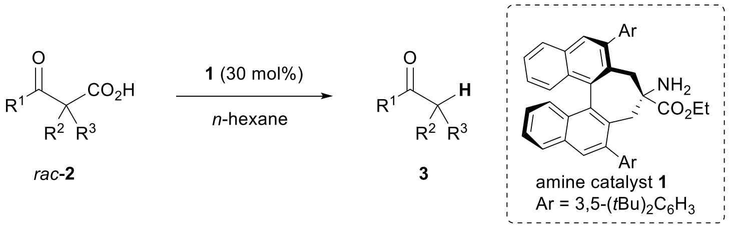
5: R = H

6: R = Ph

4. Enantioselective decarboxylative protonation

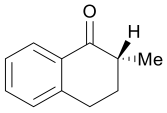
General procedure

Enantioselective decarboxylative protonation of **2** was performed by **General procedure** described below. When the reactions were performed, some starting compounds **2** contained 1–4% of *rac*-**3** because a few starting carboxylic acids **2** slowly decomposed to give **3** while standing at ambient temperature.



Amine catalyst **1** (30 mol%) was added to a stirred solution of α,α-dialkyl-β-ketocarboxylic acids **2** (0.2–0.3 mmol) in *n*-hexane (2.0–3.0 mL), and the reaction mixture was stirred at 0 °C–room temperature. The mixture was purified by flash column chromatography on silica gel to give **3**.

(*R*)-2-methyl-3,4-dihydronaphthalen-1(2H)-one (3a) [5]



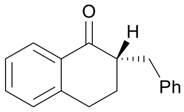
3a

The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2a** (61 mg, 0.3 mmol) and amine catalyst **1** (68 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 182 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (47 mg, 98% yield, 89% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.04 (dd, J = 7.6, 1.2 Hz, 1H), 7.45 (dt, J = 7.6, 1.2 Hz, 1H), 7.29 (t, J = 7.6 Hz, 1H), 7.23 (d, J = 7.6 Hz, 1H), 3.07–2.94 (m, 2H), 2.62–2.55 (m, 1H), 2.20 (ddd, J = 13.4, 8.8, 4.6 Hz, 1H), 1.92–1.84 (m, 1H), 1.27 (d, J = 6.9 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.8, 144.2, 133.0, 132.4, 128.7, 127.4, 126.5, 42.6, 31.3, 28.8, 15.4; **IR** (NaCl): 2963, 2931, 1686, 1602, 1455, 1267, 1228, 968, 907, 739 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{11}H_{13}O_1$, 161.0966; found, 161.0969; $[\alpha]_D^{26}$ +39.0 (c = 1.32, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OZ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 12.6 min (major) and 13.4 min (minor)).

(*S*)-2-benzyl-3,4-dihydronaphthalen-1(2H)-one (3b) [5]



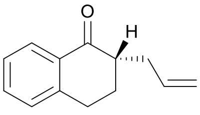
3b

The title compound was prepared following **General procedure**, using 2-benzyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2b** (91 mg, 0.3 mmol) and amine catalyst **1** (74 mg, 0.10 mmol) in *n*-hexane (3.3 mL), and the reaction mixture was stirred at 10 °C for 20 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (70 mg, 91% yield, 62% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.07 (dd, J = 7.6, 1.2 Hz, 1H), 7.45 (dt, J = 7.6, 1.2 Hz, 1H), 7.31–7.28 (m, 3H), 7.23–7.20 (m, 4H), 3.49 (dd, J = 13.8, 3.8 Hz, 1H), 2.97–2.86 (m, 2H), 2.77–2.71 (m, 1H), 2.64 (dd, J = 13.8, 9.6 Hz, 1H), 2.09 (ddd, J = 13.4, 8.8, 4.6 Hz, 1H), 1.82–1.73 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 199.3, 144.0, 140.0, 133.2, 132.4, 129.2, 128.7, 128.3, 127.5, 126.6, 126.1, 49.4, 35.6, 28.6, 27.6; **IR** (NaCl): 3025, 2927, 1682, 1599, 1454, 1291, 1220, 933, 740, 700 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{17}H_{20}O_1N_1$, 254.1545; found, 254.1545; $[\alpha]_D^{26}$ –8.4 (c = 1.63, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.8 mL/min, retention time; 22.0 min (minor) and 24.0 min (major)).

(*S*)-2-allyl-3,4-dihydronaphthalen-1(2H)-one (3c) [5]



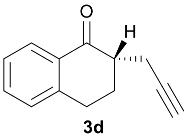
3c

The title compound was prepared following **General procedure**, using 2-allyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2c** (69 mg, 0.3 mmol) and amine catalyst **1** (68 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at room temperature for 4 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (54 mg, 96% yield, 87% ee).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.04 (d, *J* = 7.6 Hz, 1H), 7.46 (t, *J* = 7.6 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.24 (d, *J* = 7.6 Hz, 1H), 5.89–5.81 (m, 1H), 5.13–5.06 (m, 2H), 2.99 (dd, *J* = 7.6, 4.6 Hz, 2H), 2.79–2.74 (m, 1H), 2.58–2.52 (m, 1H), 2.30–2.21 (m, 2H), 1.91–1.83 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 199.5, 144.1, 136.2, 133.2, 132.5, 128.7, 127.4, 126.6, 116.8, 47.2, 34.0, 28.6, 27.9; **IR** (NaCl): 2930, 2862, 1684, 1601, 1455, 1280, 1221, 996, 911, 744 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{13}H_{15}O_1$, 187.1123; found, 187.1123; $[\alpha]_D^{26}$ +20.7 (c = 2.36, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 16.0 min (major) and 17.1 min (minor)).

1-(prop-2-yn-1-yl)-3,4-dihydronaphthalen-1(2H)-one (3d)



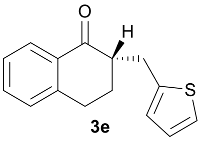
3d

The title compound was prepared following **General procdure**, using 1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2d** (69 mg, 0.3 mmol) and amine catalyst **1** (68 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at 10 °C for 21 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a white solid (48 mg, 86% yield, 67% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.04 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.48 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.26–7.25 (m, 1H), 3.13–3.01 (m, 2H), 2.91 (ddd, *J* = 6.9, 4.2, 2.7 Hz, 1H), 2.68 (ddd, *J* = 13.0, 8.4, 4.2 Hz, 1H), 2.52–2.44 (m, 2H), 2.00 (t, *J* = 2.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 197.8, 144.1, 133.4, 132.1, 128.7, 127.4, 126.6, 82.2, 69.7, 46.6, 28.9, 28.1, 19.3; **IR** (NaCl): 3292, 2931, 2862, 1684, 1600, 1684, 1455, 1284, 1221, 744, 636 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{13}H_{16}O_1N_1$, 202.1232; found, 202.1232; $[\alpha]_D^{26}$ –6.6 (c = 1.36, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 99 : 1, flow rate = 0.7 mL/min, retention time; 21.9 min (major) and 23.5 min (minor)).

2-(thiophen-2-ylmethyl)-3,4-dihydronaphthalen-1(2H)-one (3e)

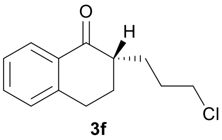

3e

The title compound was prepared following **General procedure**, using 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2e** (87 mg, 0.3 mmol) and amine catalyst **1** (68 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at room temperature for 3 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (72 mg, 98% yield, 67% ee).

^{1}**H NMR** (500 MHz, $CDCl_3$): δ 8.07 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.47 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 7.14 (d, *J* = 5.0 Hz, 1H), 6.93 (dd, *J* = 5.0, 3.4 Hz, 1H), 6.86 (d, *J* = 3.4 Hz, 1H), 3.59 (dd, *J* = 14.9, 4.2 Hz, 1H), 3.04 (dd, *J* = 14.9, 4.2 Hz, 1H), 3.00–2.95 (m, 2H), 2.77 (ddd, *J* = 13.0, 8.8, 4.2 Hz, 1H), 2.23 (ddd, *J* = 13.0, 8.8, 4.2 Hz, 1H), 1.89–1.80 (m, 1H); ^{13}**C NMR** (126 MHz, $CDCl_3$): δ 198.7, 144.0, 142.2, 133.3, 132.3, 128.7, 127.5, 126.7, 126.6, 125.8, 123.6, 49.6, 29.8, 28.7, 27.8; **IR** (NaCl): 3067, 2928, 2862, 1677, 1599, 1455, 1287, 1225, 753, 698 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{15}H_{14}O_1S_1Na_1$, 265.0658; found, 265.0654; $[\alpha]_D^{27}$ –31.3 (c = 2.28, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IE-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 98 : 2, flow rate = 0.7 mL/min, retention time; 23.5 min (major) and 26.0 min (minor)).

2-(3-chloropropyl)-3,4-dihydronaphthalen-1(2H)-one (3f)

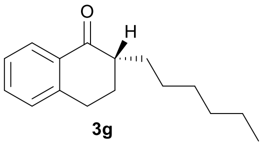

3f

The title compound was prepared following **General procedure**, using 2-(3-chloropropyl)-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2f** (80 mg, 0.3 mmol) and amine catalyst **1** (68 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 23 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (63 mg, 95% yield, 76% ee).

^{1}**H NMR** (500 MHz, $CDCl_3$): δ 8.02 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.46 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.24 (d, *J* = 7.6 Hz, 1H), 3.63–3.55 (m, 2H), 3.02 (dd, *J* = 7.6, 5.0 Hz, 2H), 2.54–2.48 (m, 1H), 2.24 (ddd, *J* = 13.4, 9.6, 5.0 Hz, 1H), 2.09–2.02 (m, 1H), 1.95–1.89 (m, 3H), 1.71–1.65 (m, 1H); ^{13}**C NMR** (126 MHz, $CDCl_3$): δ 199.8, 143.8, 133.2, 132.4, 128.7, 127.4, 126.6, 46.9, 45.1, 30.2, 28.6, 28.5, 27.2; **IR** (NaCl): 2931, 2858, 1682, 1601, 1455, 1293, 1228, 914, 741, 649 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{13}H_{19}O_1N_1Cl_1$, 240.1155; found, 240.1155; $[\alpha]_D^{27}$ +17.8 (c = 1.01, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 38.0 min (major) and 40.2 min (minor)).

2-hexyl-3,4-dihydronaphthalen-1(2H)-one (3g)



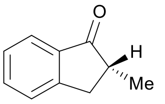
3g

The title compound was prepared following **General procedure**, using 2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2g** (83 mg, 0.3 mmol) and amine catalyst **1** (69 mg, 0.09 mmol) in *n*-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 28 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (56 mg, 80% yield, 82% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.02 (d, *J* = 7.6 Hz, 1H), 7.44 (t, *J* = 7.6 Hz, 1H), 7.29 (t, *J* = 7.6 Hz, 1H), 7.22 (t, *J* = 7.6 Hz, 1H), 3.04–2.93 (m, 2H), 2.49–2.44 (m, 1H), 2.23 (ddd, *J* = 14.1, 9.6, 4.6 Hz, 1H), 1.97–1.86 (m, 2H), 1.53–1.21 (m, 9H), 0.90–0.87 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.5, 143.9, 133.0, 132.5, 128.6, 127.4, 126.5, 47.5, 31.7, 29.4, 29.4, 28.3, 28.1, 27.0, 22.6, 14.1; **IR** (NaCl): 2951, 2926, 2854, 1685, 1600, 1455, 1286, 1224, 910, 742 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{16}H_{23}O_1$, 231.1749; found, 231.1749; $[\alpha]_D^{27}$ +17.2 (c = 1.28, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 1.0 mL/min, retention time; 10.3 min (minor) and 10.8 min (major)).

(*R*)-2-methyl-2,3-dihydro-1H-inden-1-one (3h) [5]



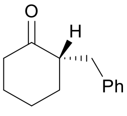
3h

The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylic acid **2h** (44 mg, 0.23 mmol) and amine catalyst **1** (52 mg, 0.07 mmol) in *n*-hexane (2.3 mL), and the reaction mixture was stirred at 0 °C for 6 h. The crude product was purified by flash column chromatography (hexane : diethyl ether = 8 : 1) to provide the title compound as a colorless oil (24 mg, 70% yield, 57% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.76 (d, *J* = 7.6 Hz, 1H), 7.59 (t, *J* = 7.6 Hz, 1H), 7.45 (d, *J* = 7.6 Hz, 1H), 7.37 (t, *J* = 7.6 Hz, 1H), 3.43–3.38 (m, 1H), 2.76–2.68 (m, 2H), 1.32 (d, *J* = 7.6 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 209.5, 153.5, 136.3, 134.7, 127.3, 126.5, 124.0, 42.0, 34.9, 16.3; **IR** (NaCl): 2963, 2929, 1713, 1608, 1464, 1293, 1204, 965, 787, 742 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{10}H_{14}O_1N_1$, 164.1075; found, 164.1076; $[\alpha]_D^{26}$ –24.6 (c = 0.53, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 9 : 1, flow rate = 0.5 mL/min, retention time; 11.0 min (minor) and 11.6 min (major)).

(*S*)-2-benzylcyclohexan-1-one (3i) [6]



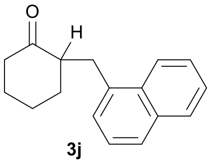
3i

The title compound was prepared following **General procedure**, using 1-benzyl-2-oxocyclohexane-1-carboxylic acid **2i** (68 mg, 0.29 mmol) and amine catalyst **1** (66 mg, 0.09 mmol) in *n*-hexane (2.9 mL), and the reaction mixture was stirred at room temperature for 1 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a colorless oil (38 mg, 69% yield, 24% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.29–7.26 (m, 2H), 7.20–7.15 (m, 3H), 3.24 (dd, *J* = 13.8, 4.6 Hz, 1H), 2.58–2.52 (m, 1H), 2.46–2.39 (m, 2H), 2.36–2.30 (m, 1H), 2.09–1.99 (m, 2H), 1.85–1.81 (m, 1H), 1.73–1.53 (m, 2H), 1.40–1.31 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 212.6, 140.3, 129.1, 128.3, 52.5, 42.2, 35.4, 33.4, 28.0, 25.0; **IR** (NaCl): 2936, 2862, 1710, 1452, 1131, 769, 732, 700, 516 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{13}H_{16}O_1Na_1$, 211.1093; found, 211.1093; $[\alpha]_D^{24}$ –10.1 (c = 0.45, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 98 : 2, flow rate = 1.0 mL/min, retention time; 10.5 min (minor) and 11.7 min (major))

2-(naphthalen-1-ylmethyl)cyclohexan-1-one (3j)



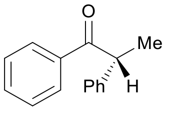
3j

The title compound was prepared following **General procedure**, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid **2j** (56 mg, 0.20 mmol) and amine catalyst **1** (46 mg, 0.06 mmol) in *n*-hexane (2.0 mL), and the reaction mixture was stirred at room temperature for 11 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 10 : 1 to 4 : 1) to provide the title compound as a colorless oil (30 mg, 64% yield, 30% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.94–7.92 (m, 1H), 7.87–7.85 (m, 1H), 7.72 (d, *J* = 8.0 Hz, 1H), 7.51–7.46 (m, 2H), 7.38 (dd, *J* = 8.0, 7.1 Hz 1H), 7.31 (d, *J* = 6.9 Hz, 1H), 3.85 (dd, *J* = 13.8, 3.6 Hz, 1H), 2.75 (dd, *J* = 13.8, 9.2 Hz, 1H), 2.72–2.66 (m, 1H), 2.48 (dddd, *J* = 13.8, 4.6, 3.1, 1.5 Hz, 1H), 2.34 (dddd, *J* = 13.4, 13.4, 6.1, 1.2 Hz, 1H), 2.09–2.03 (m, 1H), 2.01–1.96 (m, 1H), 1.83–1.79 (m, 1H), 1.75–1.62 (m, 1H), 1.55–1.40 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 212.5, 136.3, 133.9, 131.9, 128.9, 127.4, 126.8, 125.8, 125.4, 125.3, 123.7, 51.4, 42.2, 33.8, 32.4, 28.0, 25.1; **IR** (NaCl): 2935, 2860, 1708, 1596, 1509, 1447, 1396, 1127, 801, 780, 506 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{17}H_{18}O_1Na_1$, 261.1250; found,261.1252; $[\alpha]_D^{26}$ –10.5 (c = 1.42, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL IC-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 50 : 1, flow rate = 1.0 mL/min, retention time; 13.6 min (major) and 15.7 min (minor)).

(*R*)-1,2-diphenylpropan-1-one (3k)[7]



3k

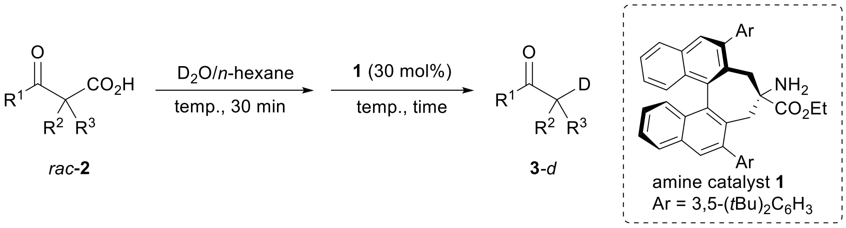
The title compound was prepared following **General procedure**, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid **3k** (64 mg, 0.25 mmol) and amine catalyst **1** (57 mg, 0.08 mmol) in *n*-hexane (2.5 mL), and the reaction mixture was stirred at room temperature for 2 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (32 mg, 61% yield, 23% ee).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.96–7.94 (m, 2H), 7.49–7.46 (m, 1H), 7.40–7.36 (m, 2H), 7.30–7.28 (m, 4H), 7.23–7.18 (m, 1H), 4.69 (q, *J* = 6.9 Hz, 1H), 1.54 (d, *J* = 6.9 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.3, 141.4, 136.4, 132.7, 128.9, 128.7, 128.4, 127.7, 126.8, 47.8, 19.5; **IR** (NaCl): 2975, 2930, 1683, 1597, 1448, 1222, 952, 758, 698, 564 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{15}H_{14}O_1Na_1$, 233.0937; found, 233.0937; $[\alpha]_D^{24}$ –40.1 (c = 1.49, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 99 : 1, flow rate = 1.0 mL/min, retention time; 18.6 min (minor) and 21.6 min (major)).

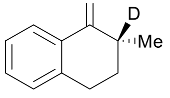
5. Enantioselective decarboxylative deuteration

General procedure



α,α-Dialkyl-β-ketocarboxylic acid **2** (0.3 mmol) was added to a stirred solution of deuterium oxide and *n*-hexane (1 : 1, 1.5 mL), and the mixture was stirred for 30 min. Then, amine catalyst **1** (30 mol%) was added to the mixture and stirred for a further 1–66 h. The reaction mixture was directly purified by flash column chromatography on silica gel to give corresponding α-deuterated ketone **3-*d***.

2-methyl-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3a-*d*)[8]



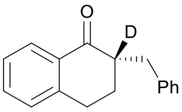
3a-*d*

The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2a** (61 mg, 0.3 mmol) in *n*-hexane : D_2O (1 : 1, 1.5 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst **1** (68 mg, 0.09 mmol), and stirred at room temperature for 15 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (43 mg, 90% yield, 84% ee, 90% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.03 (d, *J* = 7.6 Hz, 1H), 7.44 (t, *J* = 7.6 Hz, 1H), 7.29 (t, *J* = 7.6 Hz, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 3.07–2.94 (m, 2H), 2.19 (dt, *J* = 13.4, 4.6 Hz, 1H), 1.90–1.84 (m, 1H), 1.26 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.8, 144.1, 133.0, 132.3, 128.7, 127.3, 126.5, 42.1 (t, *J* = 19.2 Hz), 31.2, 28.7, 15.3; **IR** (NaCl): 2963, 2931, 1686, 1601, 1455, 1303, 1227, 968, 765, 729 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{11}H_{15}O_1N_1D_1$, 179.1295; found, 179.1295; $[\alpha]_D^{27}$ +35.3 (c = 1.33, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OZ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 13.0 min (major) and 13.9 min (minor))

2-benzyl-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3b-*d*)



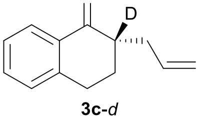
3b-*d*

The title compound was prepared following **General procedure**, using 2-benzyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2b** (92 mg, 0.33 mmol) in *n*-hexane : D_2O (1 : 1, 1.6 mL), and the reaction mixture was stirred at 10 °C for 30 min. Then, the reaction mixture was added amine catalyst **1** (75 mg, 0.10 mmol), and stirred at 10 °C for 19 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (68 mg, 87% yield, 62% ee, 87% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.06 (d, *J* = 7.6 Hz, 1H), 7.46 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.32–7.29 (m, 3H), 7.23–7.21 (m, 4H), 3.47 (d, *J* = 13.8 Hz, 1H), 2.98–2.87 (m, 2H), 2.64 (d, *J* = 13.8 Hz, 1H), 2.10 (ddd, *J* = 13.4, 9.2, 4.6 Hz, 1H), 1.83–1.76 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 199.3, 143.9, 139.9, 133.2, 132.4, 129.2, 128.6, 128.3, 127.4, 126.5, 126.0, 48.8 (t, *J* = 19.2 Hz), 35.5, 28.4, 27.4; **IR** (NaCl): 3026, 2927, 1677, 1600, 1496, 1454, 1291, 1231, 745, 700 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{17}H_{18}O_1N_1D_1$, 254.1529; found, 254.1530; $[\alpha]_D^{26}$ –6.2 (c = 2.49, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.8 mL/min, retention time; 21.9 min (minor) and 23.5 min (major)).

2-allyl-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3c-*d*)



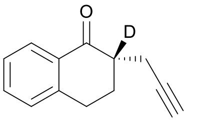
3c-*d*

The title compound was prepared following **General procedure**, using 2-allyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2c** (73 mg, 0.32 mmol) in *n*-hexane : D_2O (1 : 1, 1.6 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst **1** (72 mg, 0.09 mmol), and stirred at room temperature for 6 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (59 mg, 98% yield, 87% ee, 87% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.04 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.46 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.24 (d, *J* = 7.6 Hz, 1H), 5.89–5.81 (m, 1H), 5.15–5.06 (m, 2H), 3.00 (dd, *J* = 7.6, 4.6 Hz, 2H), 2.77–2.73 (m, 1H), 2.30–2.21 (m, 2H), 1.91–1.83 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 199.5, 144.0, 136.1, 133.1, 132.4, 128.7, 127.4, 126.5, 116.8, 46.6 (t, *J* = 19.2 Hz), 33.9, 28.5, 27.8; **IR** (NaCl): 3073, 2931, 1684, 1601, 1455, 1237, 1156, 995, 915, 740 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{13}H_{14}O_1D_1$, 188.1186; found, 188.1186; $[\alpha]_D^{26}$ +25.8 (c = 1.99, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 16.3 min (major) and 17.3 min (minor)).

2-(prop-2-yn-1-yl)-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3d-*d*)



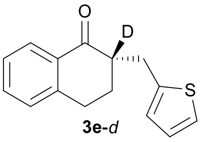
3d-*d*

The title compound was prepared following **General procedure**, using 1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2d** (69 mg, 0.3 mmol) in *n*-hexane : D_2O (1 : 1, 1.5 mL), and the reaction mixture was stirred at 10 °C for 30 min. Then, the reaction mixture was added amine catalyst **1** (68 mg, 0.09 mmol), and stirred at 10 °C for 22 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a white solid (53 mg, 95% yield, 69% ee, 90% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.04 (d, *J* = 7.6 Hz, 1H), 7.48 (t, *J* = 7.6 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.26–7.25 (m, 1H), 3.13–3.01 (m, 2H), 2.90 (dd, *J* = 17.2, 2.7 Hz, 1H), 2.51–2.45 (m, 2H), 2.00 (t, *J* = 2.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 198.0, 144.1, 133.4, 132.2, 128.7, 127.5, 126.6, 82.3, 69.7, 46.2 (t, *J* = 19.2 Hz), 28.9, 28.1, 19.2; **IR** (NaCl): 3295, 2933, 1681, 1600, 1455, 1290, 1238, 1217, 766, 740 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{13}H_{12}O_1D_1$, 186.1030; found, 186.1030; $[\alpha]_D^{27}$ –11.7 (c = 1.93, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 99 : 1, flow rate = 0.7 mL/min, retention time; 22.2 min (major) and 23.8 min (minor)).

2-(thiophen-2-ylmethyl)-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3e-*d*)



3e-*d*

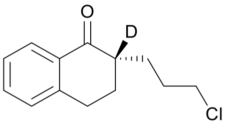
The title compound was prepared following **General procedure**, using 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2e** (86 mg, 0.3 mmol) in *n*-hexane : D_2O (1 : 1, 1.5 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst **1** (68 mg, 0.09 mmol), and stirred at room temperature for 6.5 h.

The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (72 mg, 98% yield, 64% ee, 90% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.06 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.46 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.22 (d, *J* = 7.6 Hz, 1H), 7.14 (dd, *J* = 5.0, 1.2 Hz, 1H), 6.93 (dd, *J* = 5.0, 3.4 Hz, 1H), 6.85 (d, *J* = 3.4 Hz, 1H), 3.57 (d, *J* = 14.9 Hz, 1H), 3.03 (d, *J* = 14.9 Hz, 1H), 2.99–2.95 (m, 2H), 2.24–2.19 (m, 1H), 1.88–1.80 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 198.9, 144.0, 142.2, 133.3, 132.4, 128.7, 127.5, 126.8, 126.6, 125.9, 123.7, 49.1 (t, *J* = 19.2 Hz), 29.7, 28.7, 27.8; **IR** (NaCl): 3067, 2928, 2854, 1681, 1599, 1455, 1292, 1227, 751, 698 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{15}H_{13}O_1D_1S_1Na_1$, 266.0720; found, 266.0721; $[\alpha]_D^{26}$ –24.9 (c = 3.03, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IE-3 (0.46 cmφ×25 cm), exane : *i*-PrOH = 98 : 2, flow rate = 0.7 mL/min, retention time; 23.5 min (major) and 26.1 min (minor)).

2-(3-chloropropyl)-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3f-*d*)



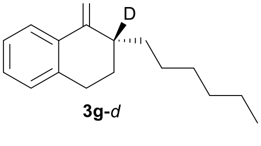
3f-*d*

The title compound was prepared following **General procedure**, using 2-(3-chloropropyl)-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2f** (80 mg, 0.3 mmol) in *n*-hexane : D_2O (1 : 1, 1.5 mL) and sodium chloride (100 mg), and the reaction mixture was stirred at 0 °C for 30 min. Then, the reaction mixture was added amine catalyst **1** (68 mg, 0.09 mmol), and stirred at 0 °C for 40 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (66 mg, 98% yield, 81% ee, 82% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.02 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.46 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.24 (d, *J* = 7.6 Hz, 1H), 3.63–3.54 (m, 2H), 3.04–3.00 (m, 2H), 2.26–2.21 (m, 1H), 2.07–2.01 (m, 1H), 1.96–1.88 (m, 3H), 1.72–1.65 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 199.8, 143.8, 133.2, 132.4, 128.7, 127.4, 126.6, 46.4 (t, *J* = 19.2 Hz), 45.1, 30.1, 28.5, 28.4, 27.0; **IR** (NaCl): 2931, 2862, 1683, 1601, 1455, 1293, 1228, 935, 764, 738 cm^{-1}; **HRMS** (DART): $[M + NH_4]^+$ calcd. for $C_{13}H_{18}O_1N_1D_1Cl_1$, 241.1218; found, 241.1218; $[\alpha]_D^{26}$ +14.0 (c = 1.77, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 37.6 min (major) and 40.0 min (minor)).

2-hexyl-3,4-dihydronaphthalen-1(2H)-one-2-*d* (3g-*d*)



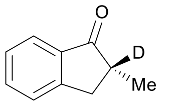
3g-*d*

The title compound was prepared following **General procedure**, using 2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid **2g** (94 mg, 0.34 mmol) in *n*-hexane : D_2O (1 : 1, 3.6 mL) and sodium chloride (516 mg), and the reaction mixture was stirred at 0 °C for 30 min. Then, the reaction mixture was added amine catalyst **1** (78 mg, 0.10 mmol), and stirred at 0 °C for 66 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (63 mg, 79% yield, 88% ee, 87% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 8.03 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.45 (dt, *J* = 7.6, 1.2 Hz, 1H), 7.30 (t, *J* = 7.6 Hz, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 3.04–2.93 (m, 2H), 2.27–2.21 (m, 1H), 1.95–1.86 (m, 2H), 1.52–1.21 (m, 9H), 0.90–0.87 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.5, 143.9, 133.0, 132.5, 128.6, 127.4, 126.5, 46.9 (t, *J* = 19.2 Hz), 31.7, 29.4, 29.2, 28.1, 28.0, 26.9, 22.6, 14.1; **IR** (NaCl): 2953, 2926, 2857, 1685, 1602, 1455, 1296, 1227, 764, 739 cm^{-1}; **HRMS** (DART): $[M + H]^+$ calcd. for $C_{16}H_{22}O_1D_1$, 232.1812; found, 232.1812; $[\alpha]_D^{24}$ +12.4 (c = 2.13, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : *i*-PrOH = 150 : 1, flow rate = 1.0 mL/min, retention time; 10.3 min (minor) and 11.0 min (major)).

2-methyl-2,3-dihydro-1H-inden-1-one-2-*d* (3h-*d*)



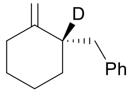
3h-*d*

The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylic acid **2h** (57 mg, 0.3 mmol) in *n*-hexane : D_2O (1 : 1, 1.5 mL), and the reaction mixture was stirred at 15 °C for 30 min. Then, the reaction mixture was added amine catalyst **1** (68 mg, 0.09 mmol), and stirred at 15 °C for 2.5 h. The crude product was purified by flash column chromatography (hexane : diethyl ether = 8 : 1) to provide the title compound as a colorless oil (33 mg, 74% yield, 60% ee, 87% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.76 (d, *J* = 7.6 Hz, 1H), 7.58 (t, *J* = 7.6 Hz, 1H), 7.45 (t, *J* = 7.6 Hz 1H), 7.37 (t, *J* = 7.6 Hz, 1H), 3.39 (d, *J* =17.2 Hz, 1H), 2.73 (d, *J* =17.2 Hz, 1H), 1.31 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 209.5, 153.5, 136.3, 134.7, 127.3, 126.5, 123.9, 41.5 (t, *J* = 19.2 Hz), 34.8, 16.2; **IR** (NaCl): 2927, 1713, 1609, 1465, 1327, 1283, 993, 766, 738, 715 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{10}H_9O_1D_1Na_1$, 170.0687; found, 170.0687; $[\alpha]_D^{26}$ –30.2 (c = 0.55, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 9 : 1, flow rate = 0.5 mL/min, retention time; 11.8 min (minor) and 12.5 min (major)).

2-benzylcyclohexan-1-one-2-*d* (3i-*d*)



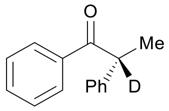
3i-*d*

The title compound was prepared following **General procedure**, using 1-benzyl-2-oxocyclohexane-1-carboxylic acid **2i** (61 mg, 0.26 mmol) and amine catalyst **1** (60 mg, 0.08 mmol) in *n*-hexane : D_2O (1 : 1, 1.3 mL), and the reaction mixture was stirred at room temperature for 1.5 h. The crude product was purified by flash column chromatography (hexane : diethyl ether = 15 : 1) to provide the title compound as a yellow oil (21mg, 43% yield, 22% ee, 73% D).

^{1}H NMR (500 MHz, $CDCl_3$): δ 7.29–7.26 (m, 2H), 7.20–7.15 (m, 3H), 3.22 (d, J = 14.1 Hz, 1H), 2.46–2.39 (m, 2H), 2.36–2.29 (m, 1H), 2.09–2.00 (m, 2H), 1.85–1.80 (m, 1H), 1.73–1.53 (m, 2H), 1.39–1.31 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 212.6, 140.3, 129.1, 128.2, 52.0 (t, J = 19.2 Hz), 42.1, 35.3, 33.3, 28.0, 25.0; **IR** (NaCl): 2936, 2859, 1709, 1605, 1496, 1451, 1128, 730, 700, 512 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{13}H_{15}O_1Na_1D_1$, 212.1156; found, 212.1150; $[\alpha]_D^{24}$ –6.8 (c = 0.85, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 98 : 2, flow rate = 1.0 mL/min, retention time; 10.2 min (minor) and 11.4 min (major)).

1,2-diphenylpropan-1-one-2-*d* (3k-*d*)



3k-*d*

The title compound was prepared following **General procedure**, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid **2k** (64 mg, 0.25 mmol) and amine catalyst **1** (57 mg, 0.08 mmol) in *n*-hexane : D_2O (1 : 1, 1.3 mL), and the reaction mixture was stirred at room temperature for 6 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (33mg, 62% yield, 23% ee, 93% D).

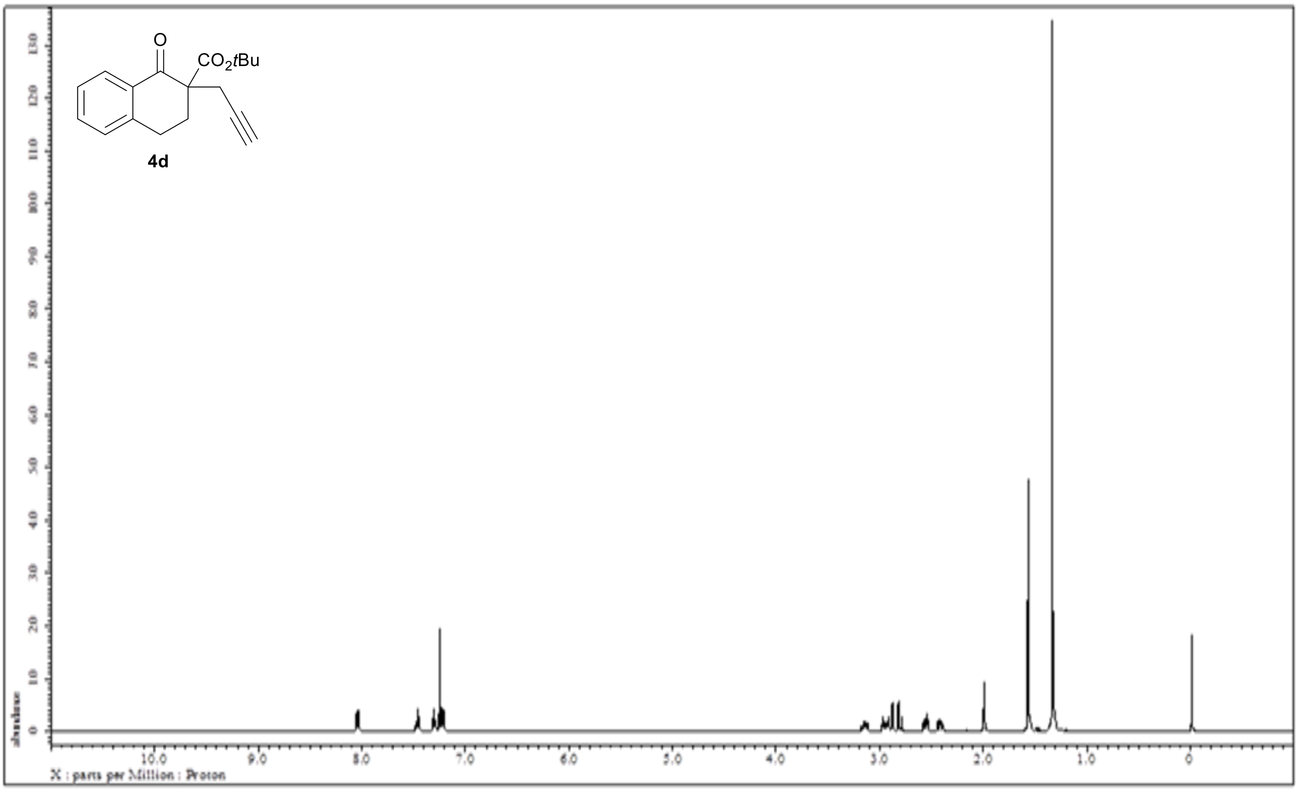
^{1}H NMR (500 MHz, $CDCl_3$): δ 7.96–7.94 (m, 2H), 7.49–7.46 (m, 1H), 7.40–7.37 (m, 2H), 7.30–7.29 (m, 4H), 7.23–7.18 (m, 1H), 1.53 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$): δ 200.3, 141.4, 136.4, 132.7, 128.9, 128.7, 128.4, 127.7, 126.8, 47.4 (t, J = 19.2 Hz), 19.4; **IR** (NaCl): 2975, 2931, 1682, 1597, 1447, 1263, 976, 739, 696, 559 cm^{-1}; **HRMS** (ESI): $[M + Na]^+$ calcd. for $C_{15}H_{13}O_1Na_1D_1$, 234.1000; found, 234.0995; $[\alpha]_D^{24}$ –39.1 (c = 0.45, $CHCl_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : *i*-PrOH = 99 : 1, flow rate = 1.0 mL/min, retention time; 18.5 min (minor) and 21.2 min (major)).

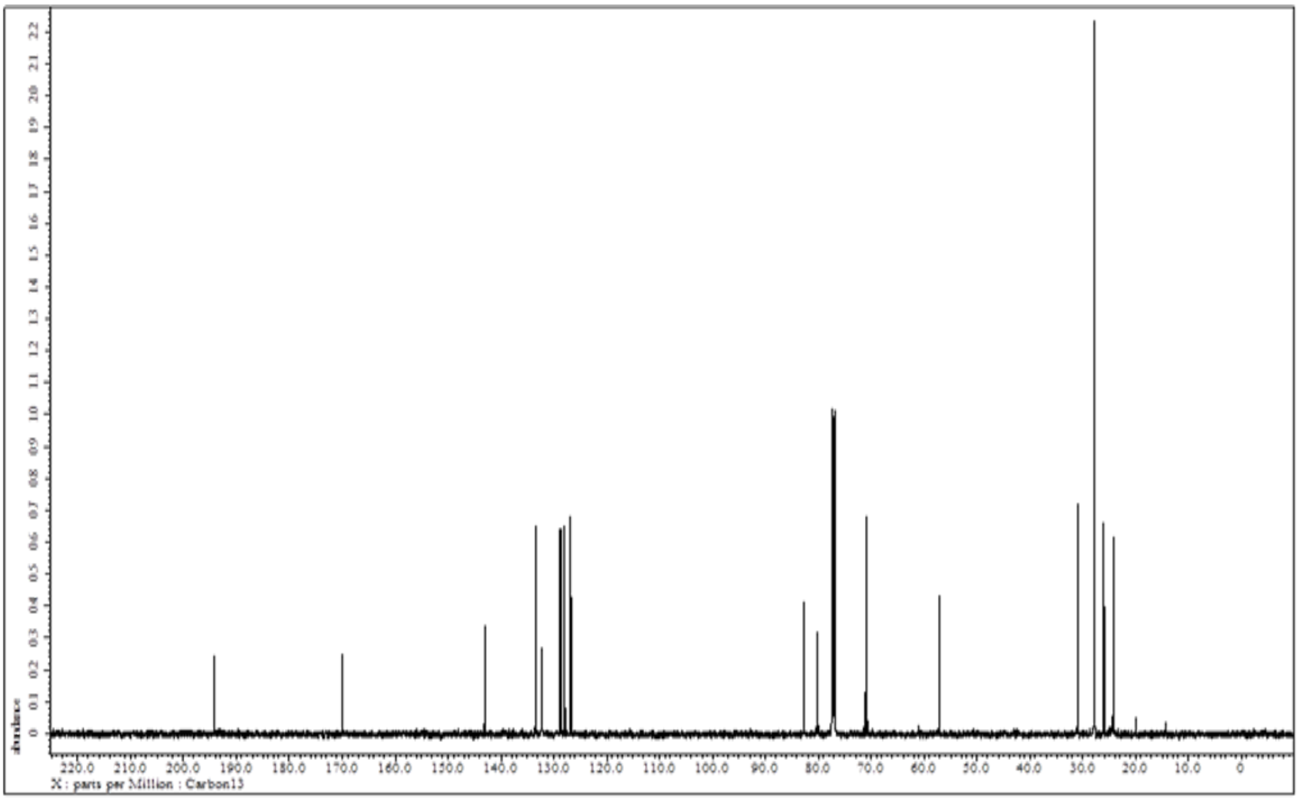
6. References

1. M. Leolukman, P. Paoprasert, Y. Wang, V. Makhija, D. J. McGee and P. Gopalan, *Macromolecules,* 2008, **41**, 4651.
2. M. Schönleber, R. Hilgraf and A. Pfaltz, *Adv. Synth. Catal.*, 2008, **350**, 2033.
3. K. Shibatomi, K. Kitahara, T. Okimi, Y. Abe and S. Iwasa, *Chem. Sci.,* 2016, **7**, 1388.
4. K. Shibatomi, K. Kitahara, N. Sasaki, Y. Kawasaki, I. Fuzisawa and S. Iwasa, *Nat. Commun.*, 2017, **8**, 15600.
5. A. Yanagisawa, T. sugita and K. Yoshida, *Chem. Eur. J.*, 2013, **19**, 16200.
6. a) M. Biosca, A. Paptchikhine, O. Pàmies, P. G. Andersson and M. Diéguez, *Chem. Eur. J.*, 2015, **21**, 3455; b) S.-M. Lu and C. Bolm, *Angew. Chem. Int. Ed.,* 2008, **47**, 8920.
7. S. Lou and G. C. Fu, *J. Am. Chem. Soc.*, 2010, **132**, 1264.
8. J. Eames, N. Weerasooriya and G. C. Coumbarides, *Eur. J. Org. Chem.*, 2002, 181.

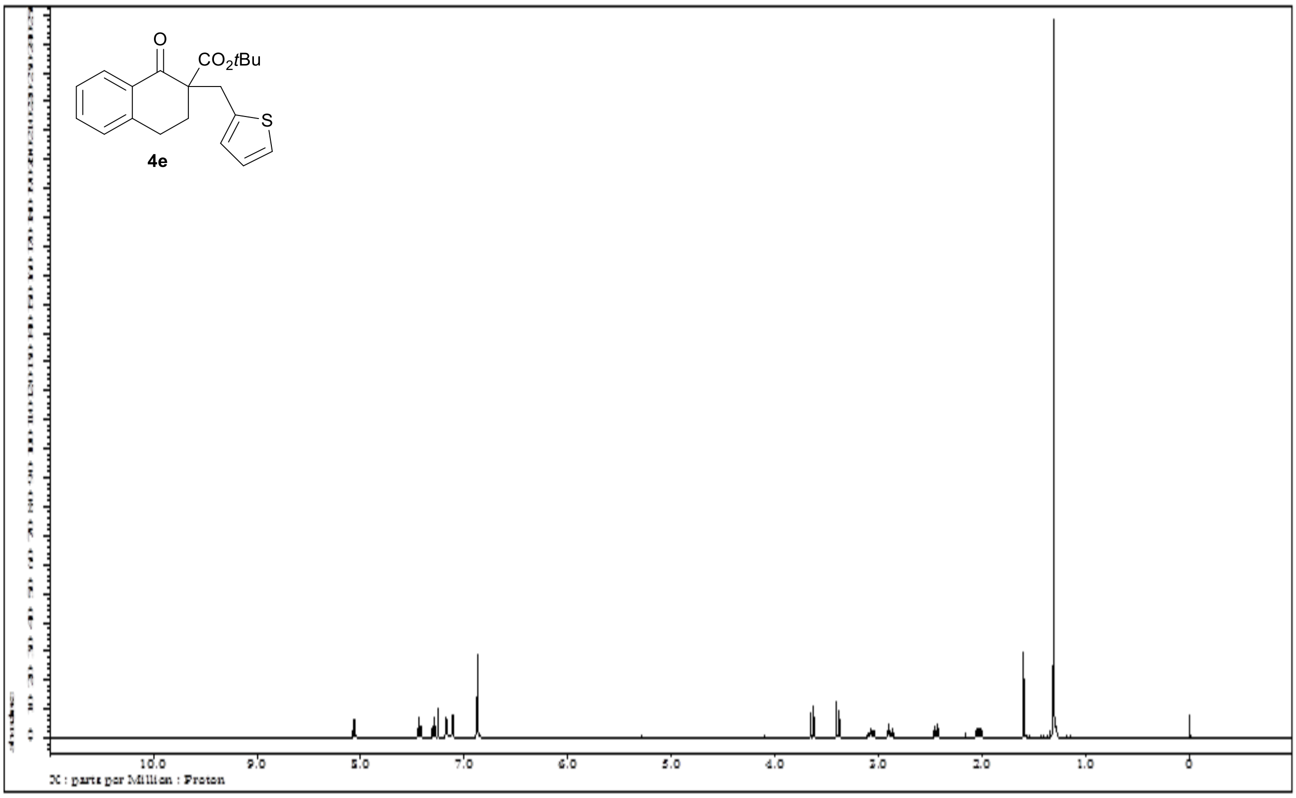
7. NMR spectra



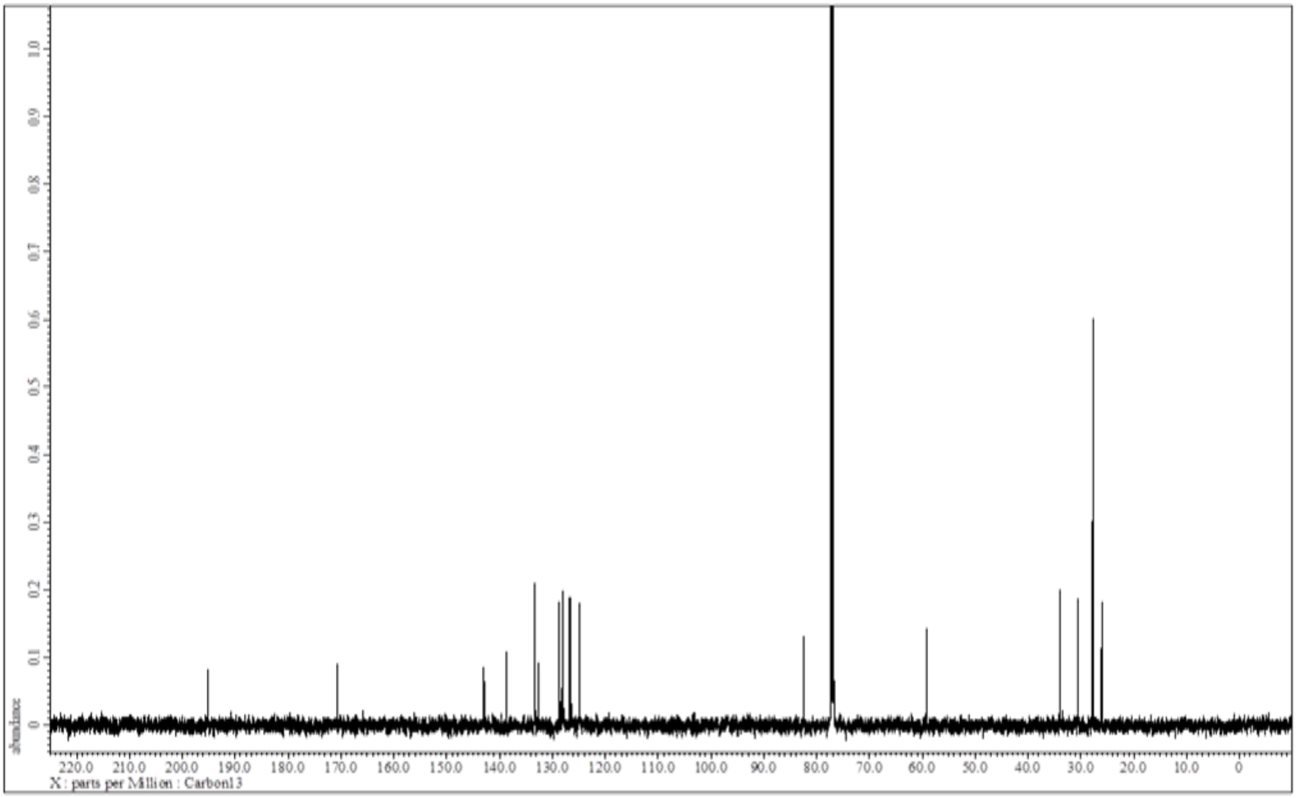
Supplementary figure 1. ^{1}H NMR spectrum for β-ketoester **4d**



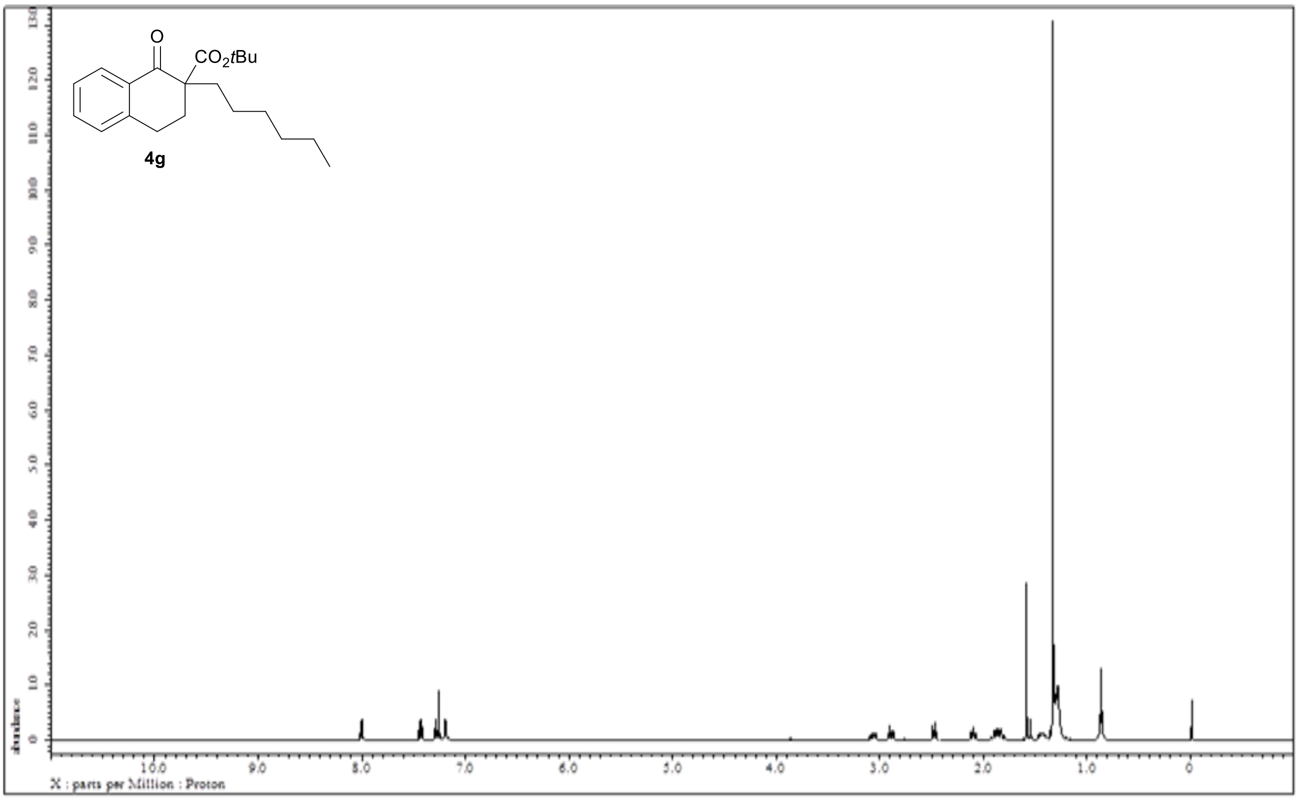
Supplementary figure 2. ^{13}C NMR spectrum for β-ketoester **4d**



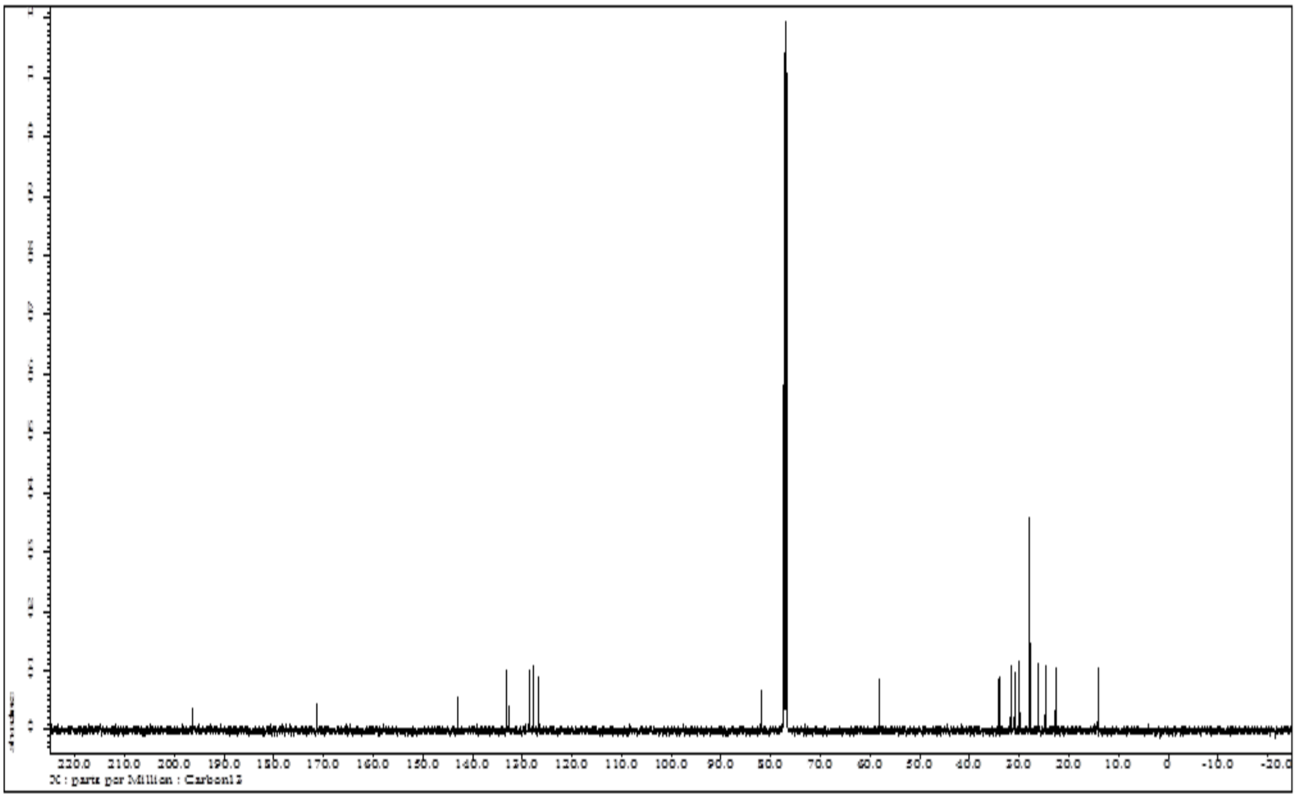
Supplementary figure 3. **^{1}**H NMR spectrum for β-ketoester **4e**



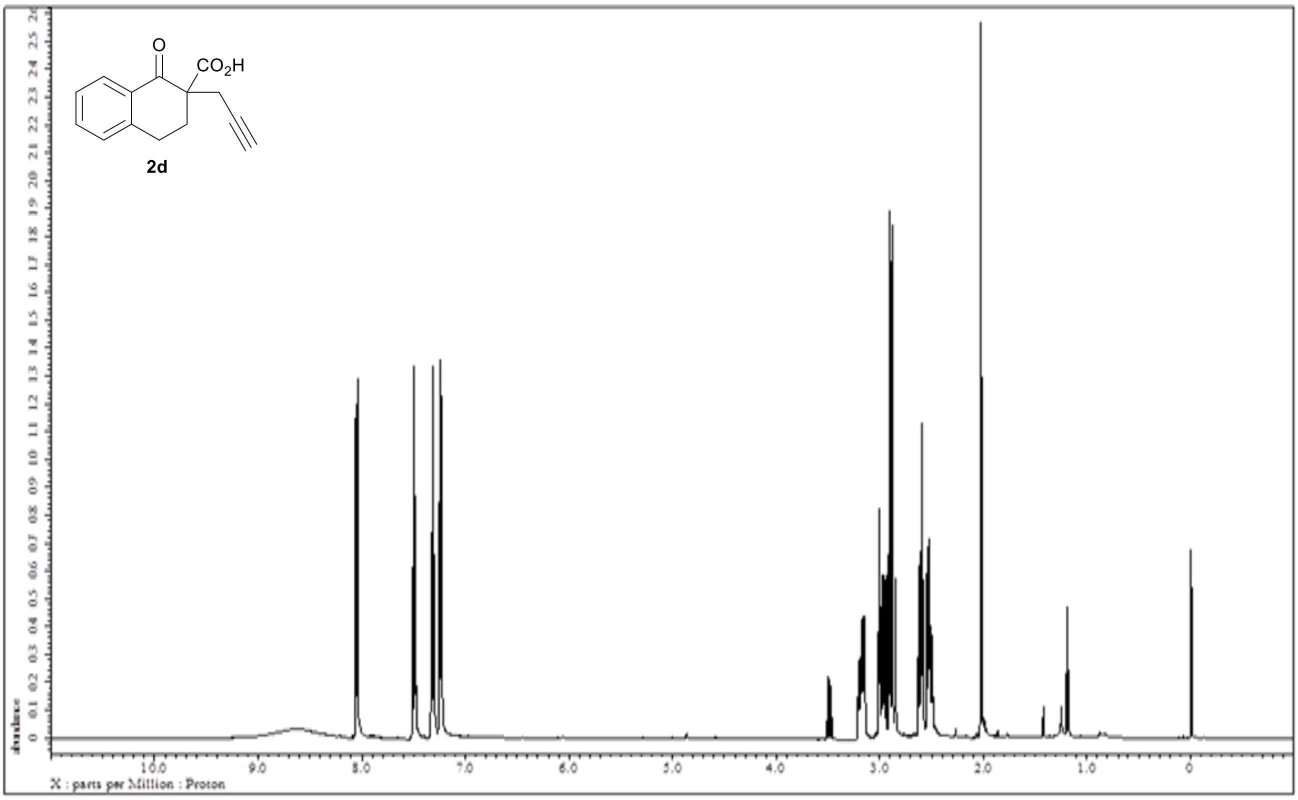
Supplementary figure 4. ^{13}C NMR spectrum for β-ketoester **4e**



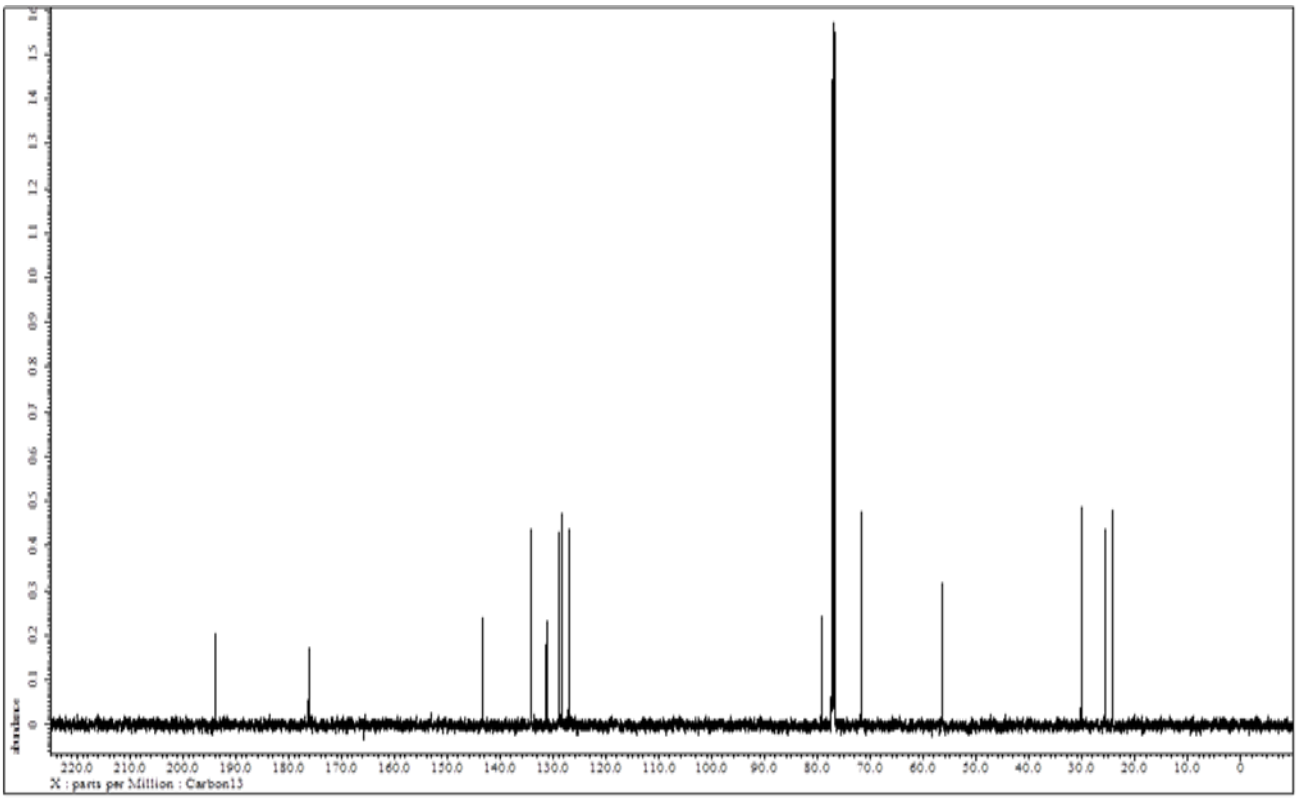
Supplementary figure 5. ^{1}H NMR spectrum for β-ketoester **4g**



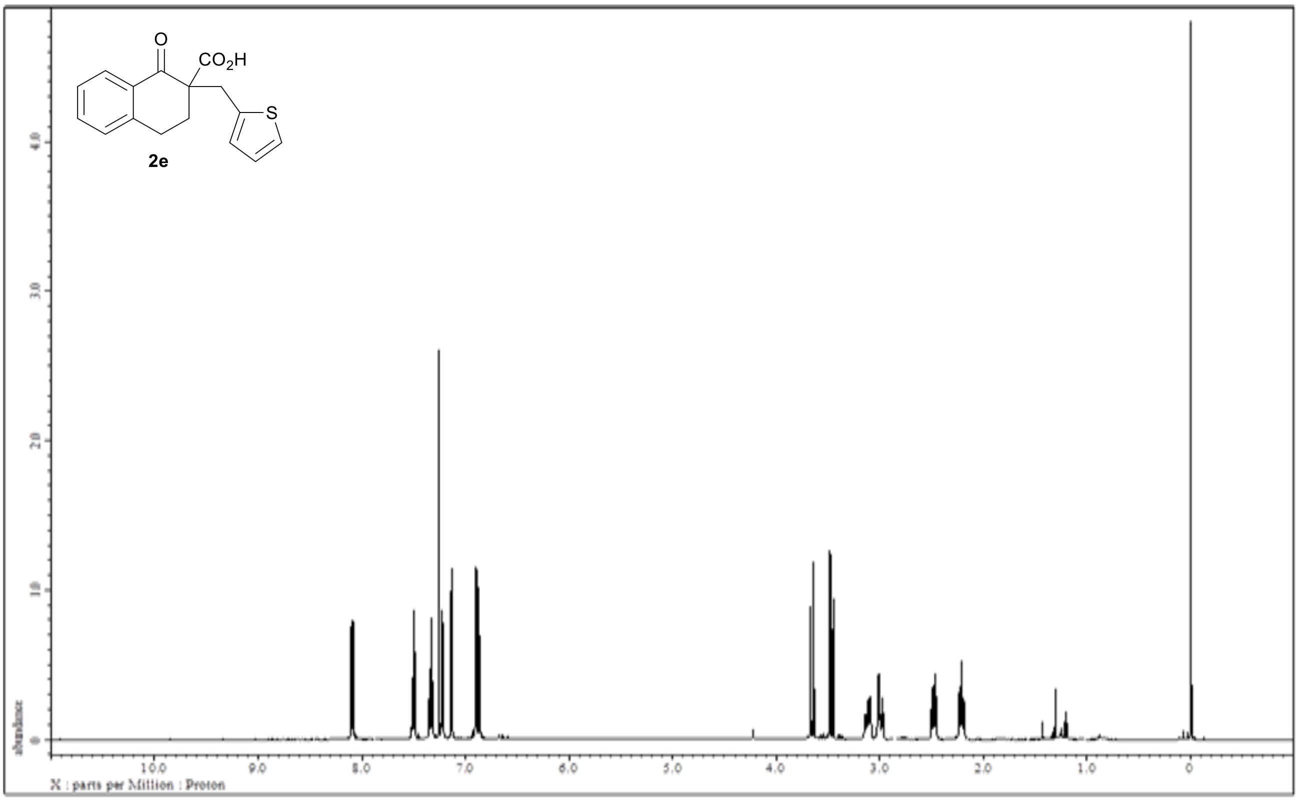
Supplementary figure 6. ^{13}C NMR spectrum for β-ketoester **4g**



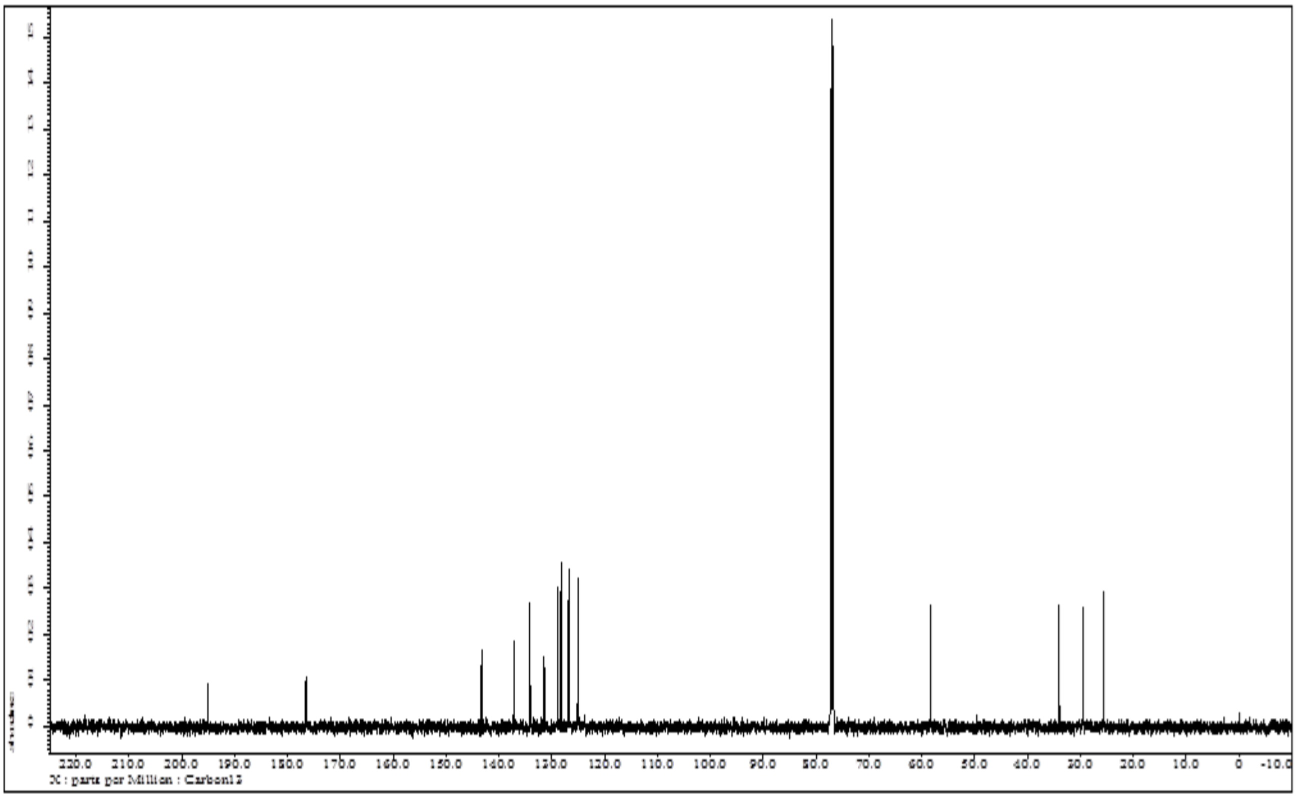
Supplementary figure 7. ^{1}H NMR spectrum for β-ketocarboxylic acid **2d**



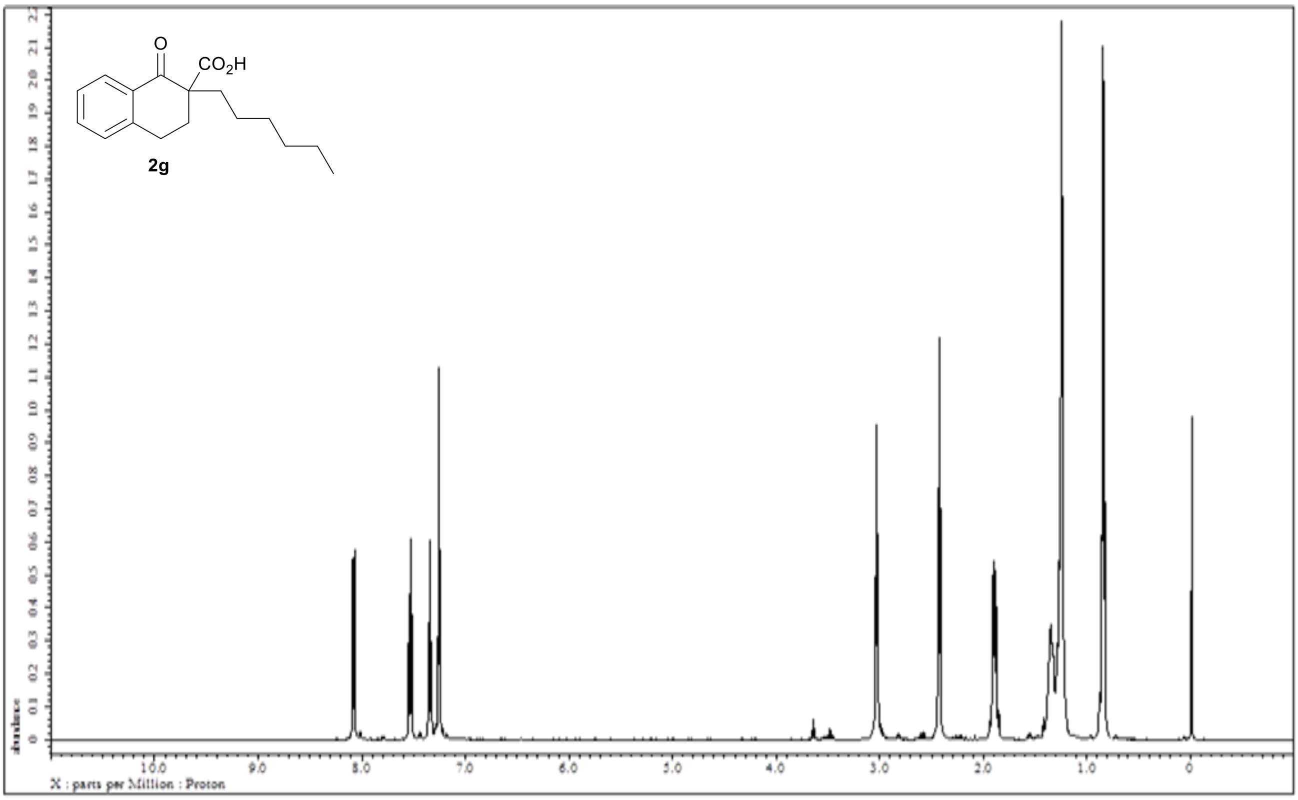
Supplementary figure 8. ^{13}C NMR spectrum for β-ketocarboxylic acid **2d**



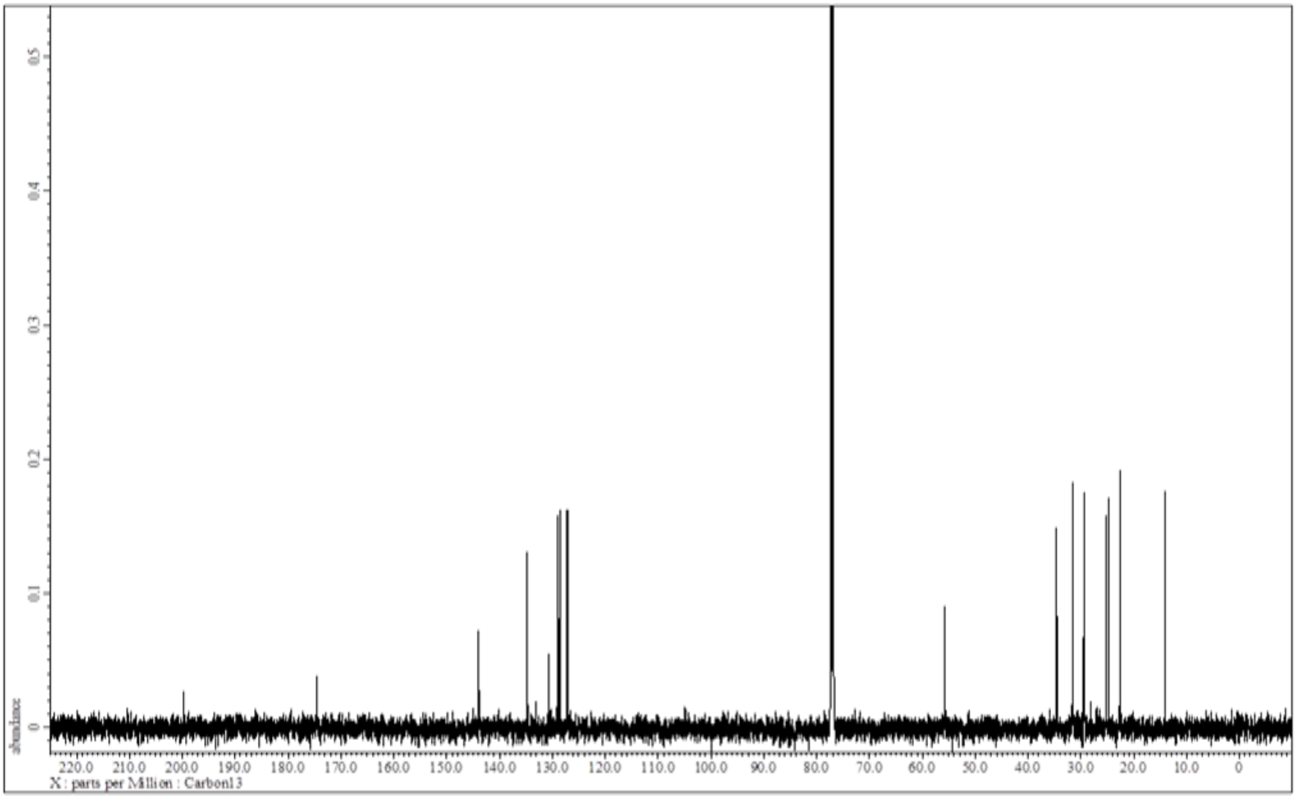
Supplementary figure 9. ^{1}H NMR spectrum for β-ketocarboxylic acid **2e**



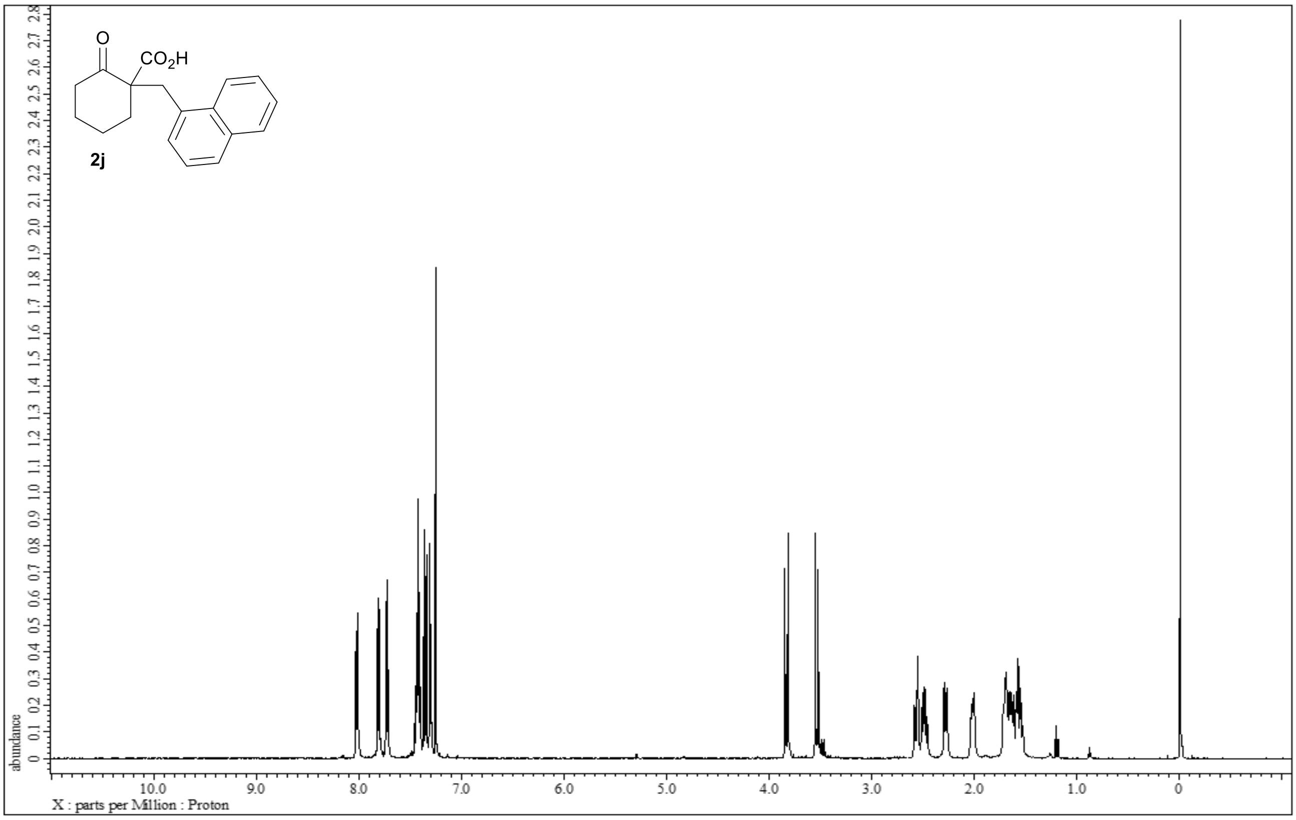
Supplementary figure 10. ^{13}C NMR spectrum for β-ketocarboxylic acid **2e**



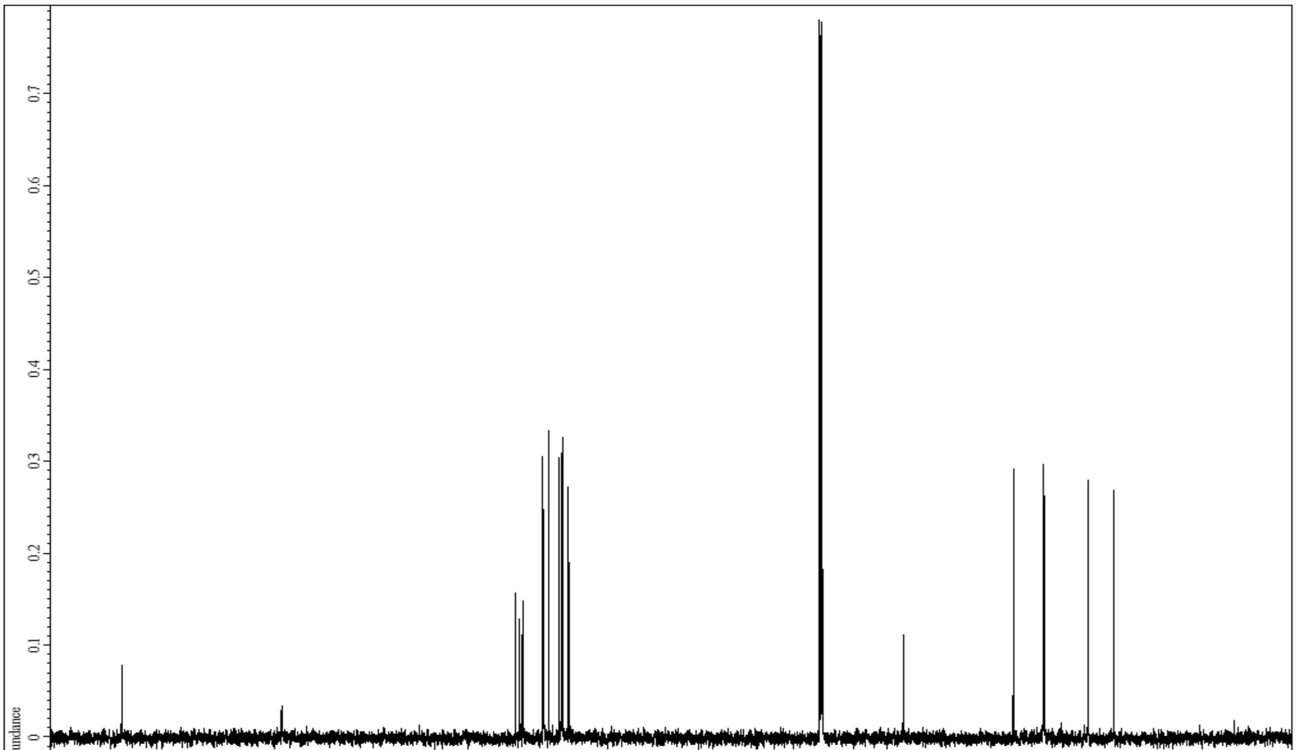
Supplementary figure 11. ^{1}H NMR spectrum for β-ketocarboxylic acid **2g**



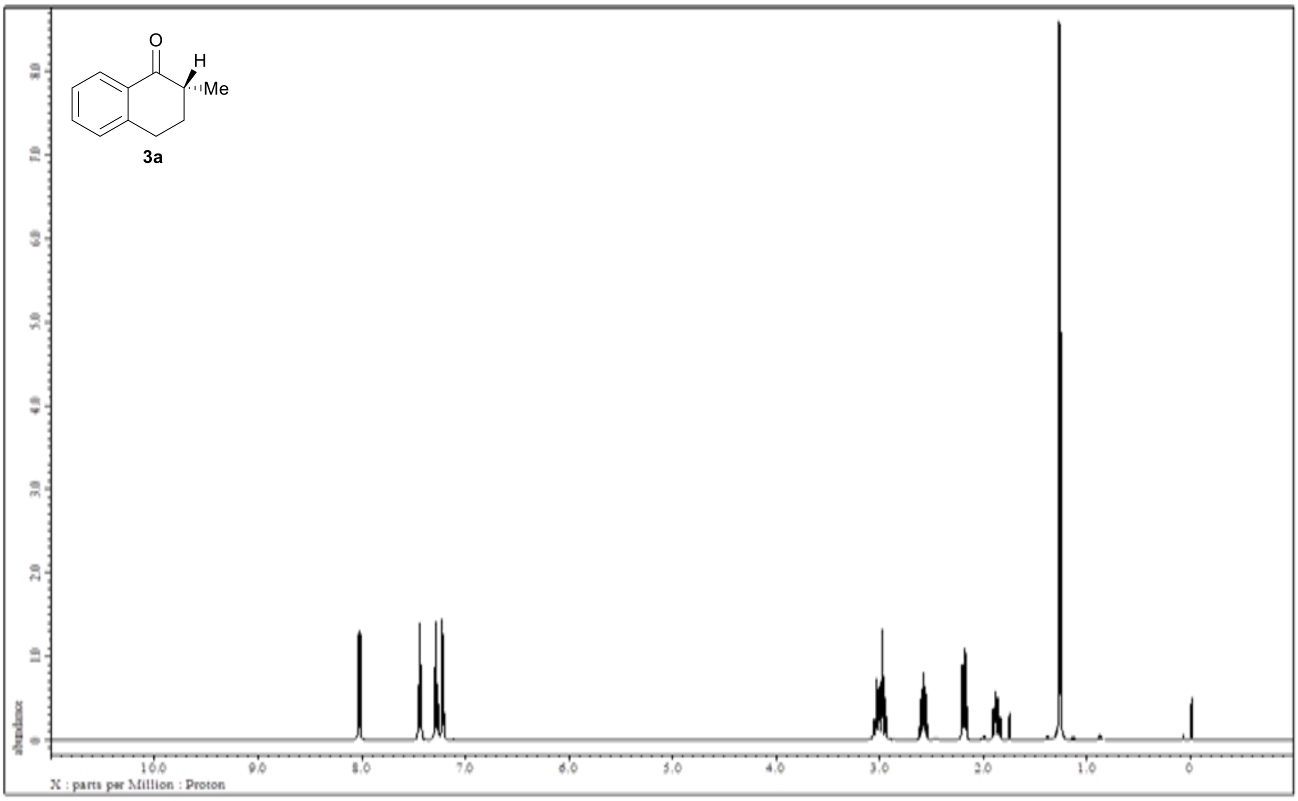
Supplementary figure 12. ^{13}C NMR spectrum for β-ketocarboxylic acid **2g**



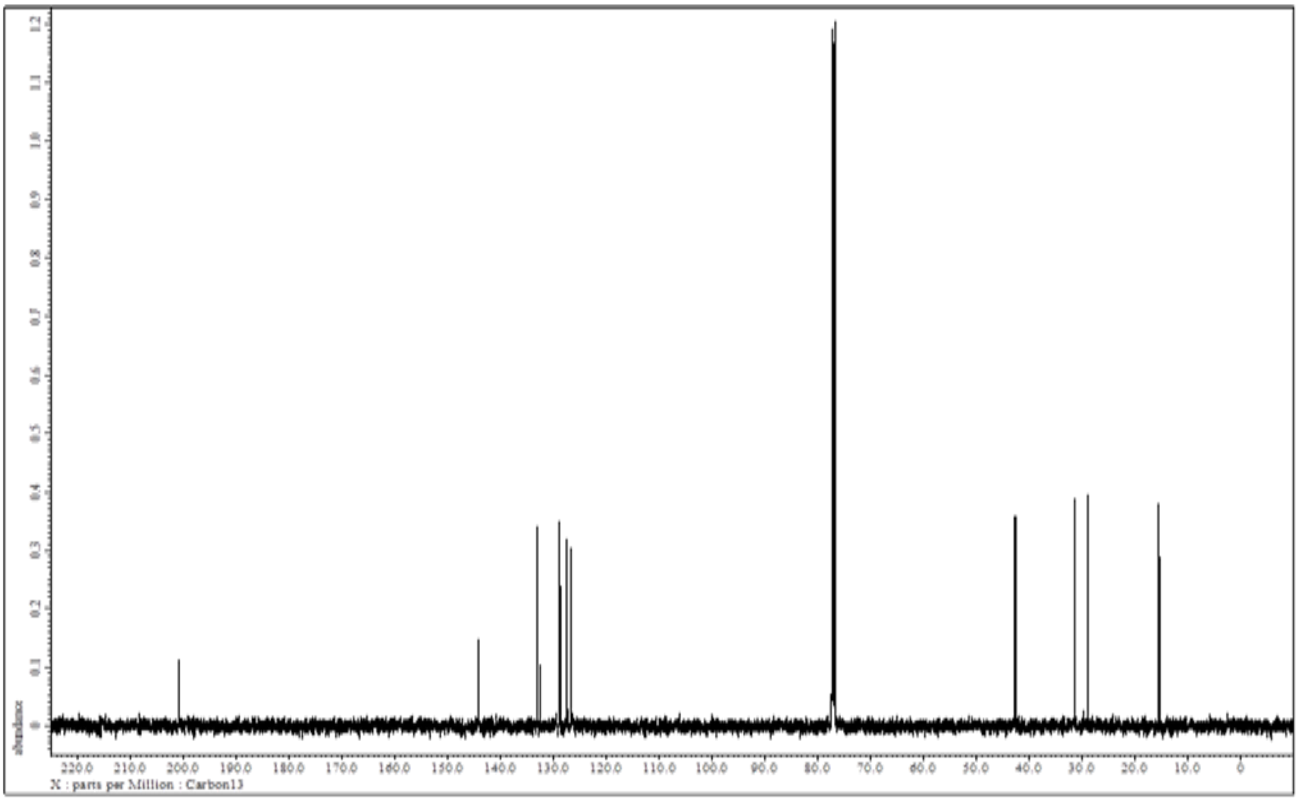
Supplementary figure 13. ^{1}H NMR spectrum for β-ketocarboxylic acid **2j**



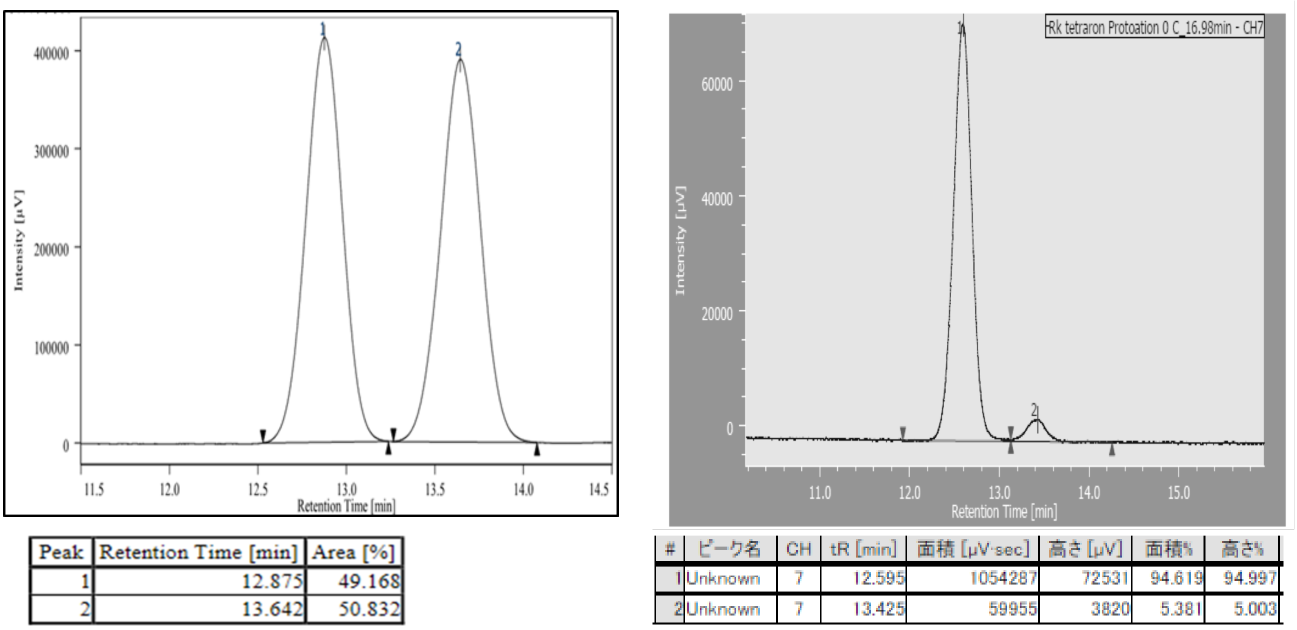
Supplementary figure 14. ^{13}C NMR spectrum for β-ketocarboxylic acid **2j**



Supplementary figure 15. ^{1}H NMR spectrum for **3a**



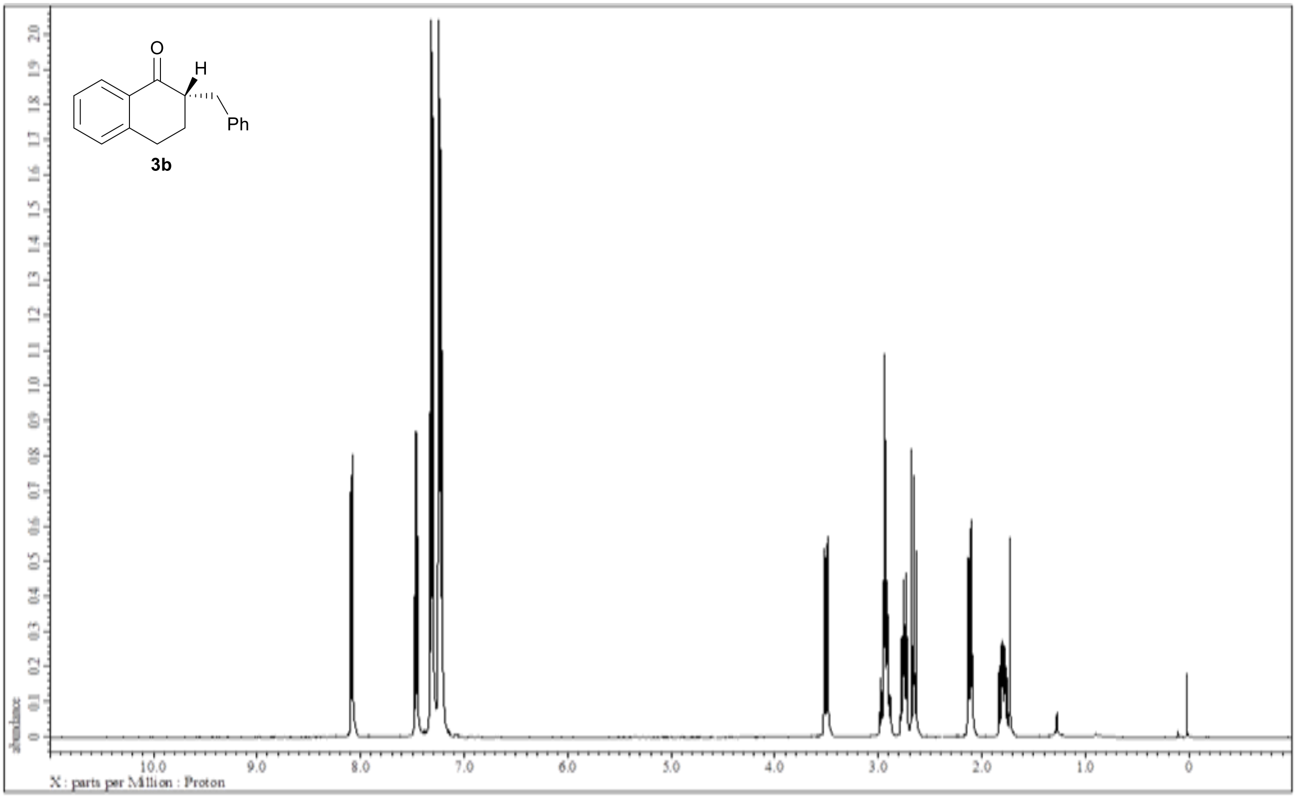
Supplementary figure 16. ^{13}C NMR spectrum for **3a**



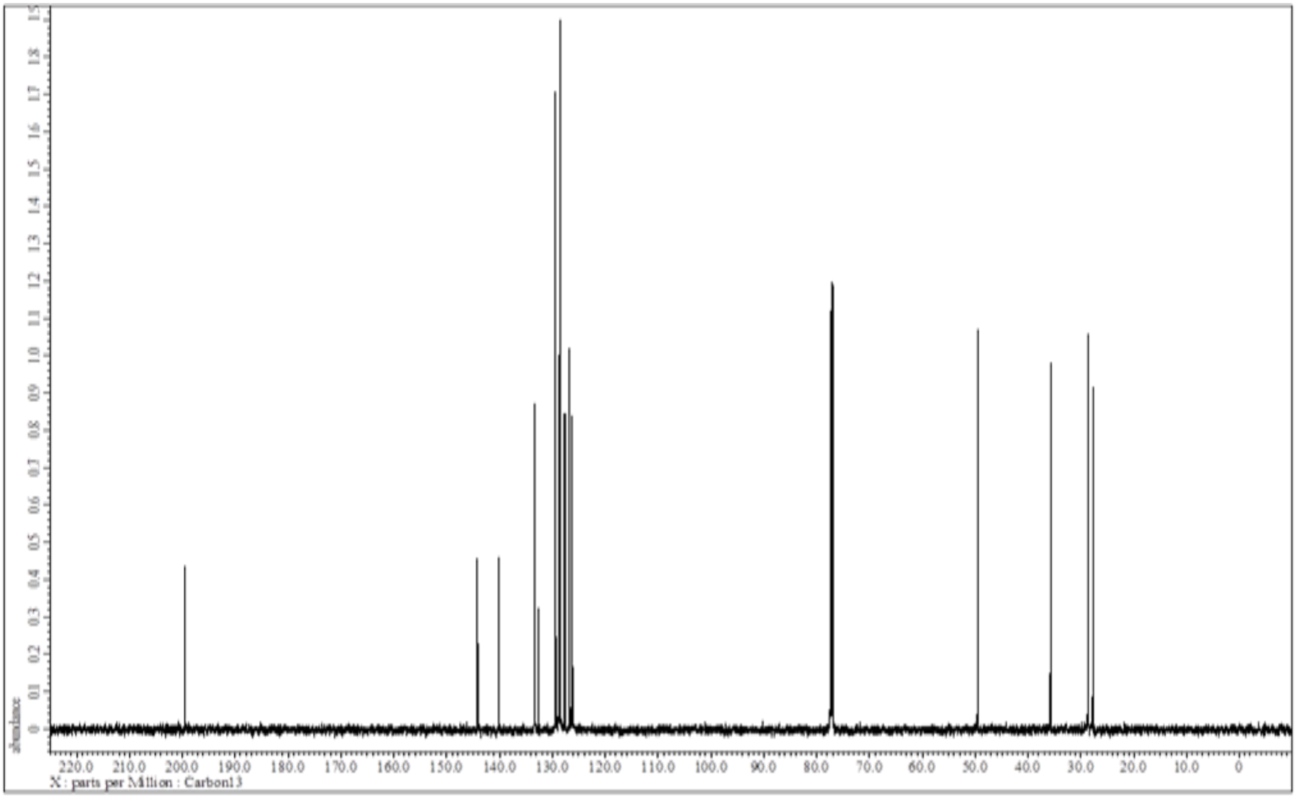
Peak	Retention Time [min]	Area [%]
1	12.875	49.168
2	13.642	50.832

#	ピーク名	CH	tR [min]	面積 [µV·sec]	高さ [µV]	面積%	高さ%
1	Unknown	7	12.595	1054287	72531	94.619	94.997
2	Unknown	7	13.425	59955	3820	5.381	5.003

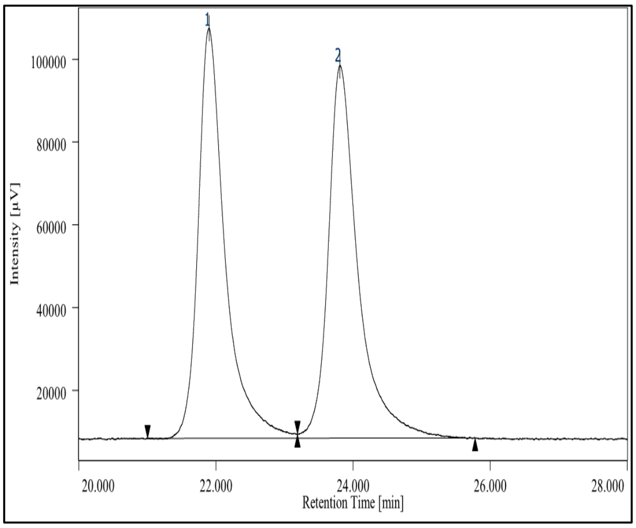
Supplementary figure 17. HPLC spectra for **3a**

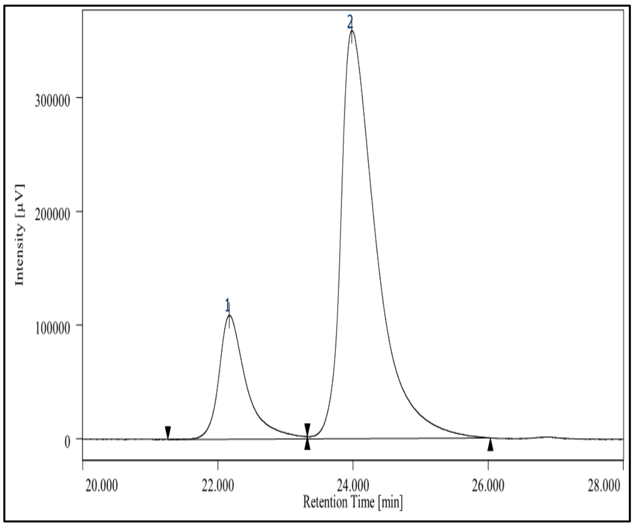


Supplementary figure 18. ^{1}H NMR spectrum for **3b**



Supplementary figure 19. ^{13}C NMR spectrum for **3b**

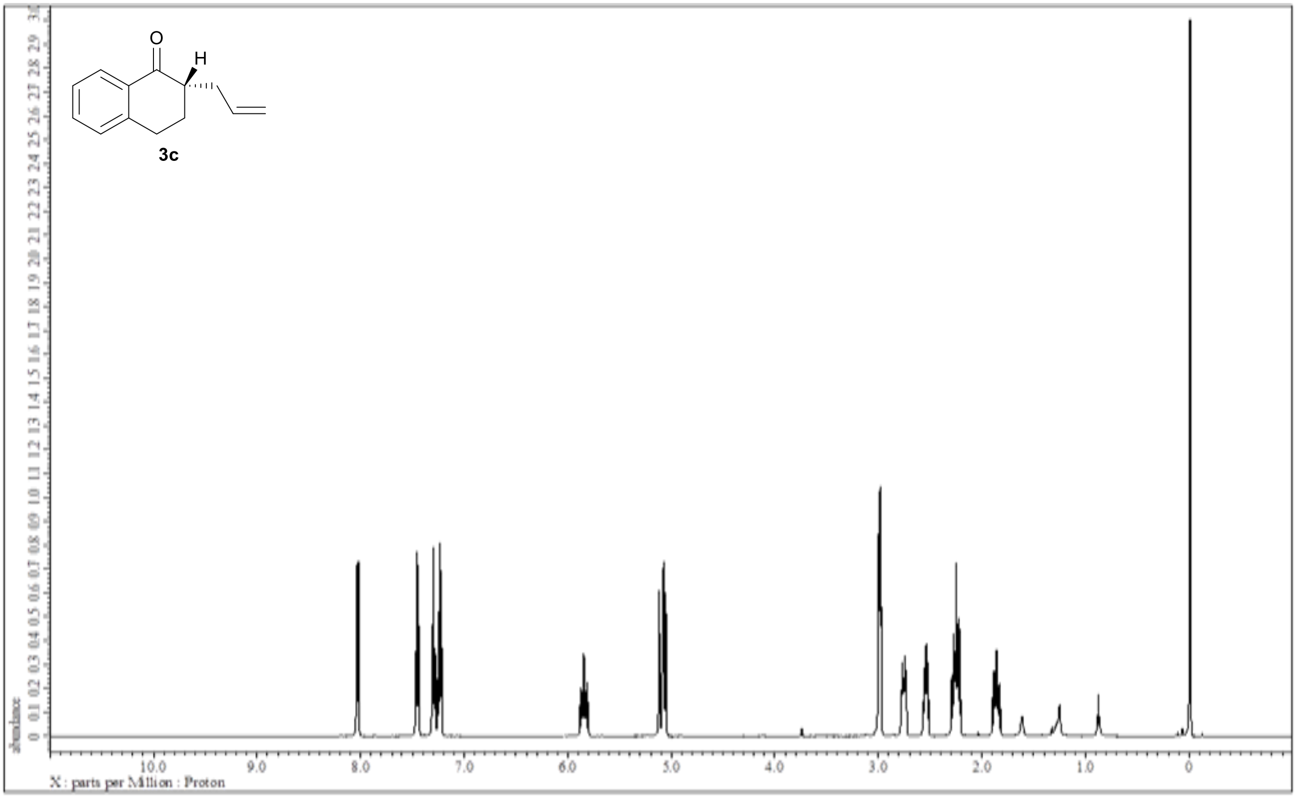




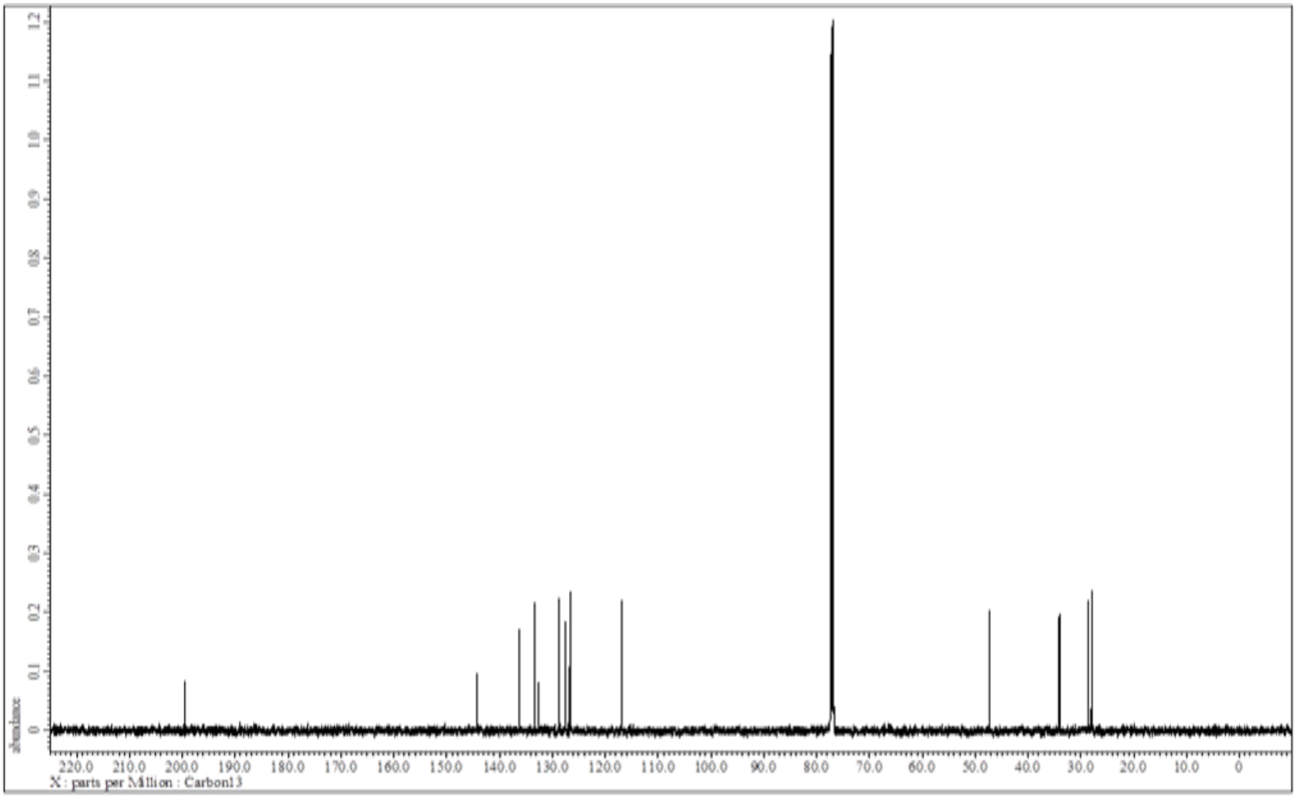
Peak	Retention Time [min]	Area [%]
1	22.170	18.964
2	23.982	81.036

Peak	Retention Time [min]	Area [%]
1	21.902	49.880
2	23.807	50.120

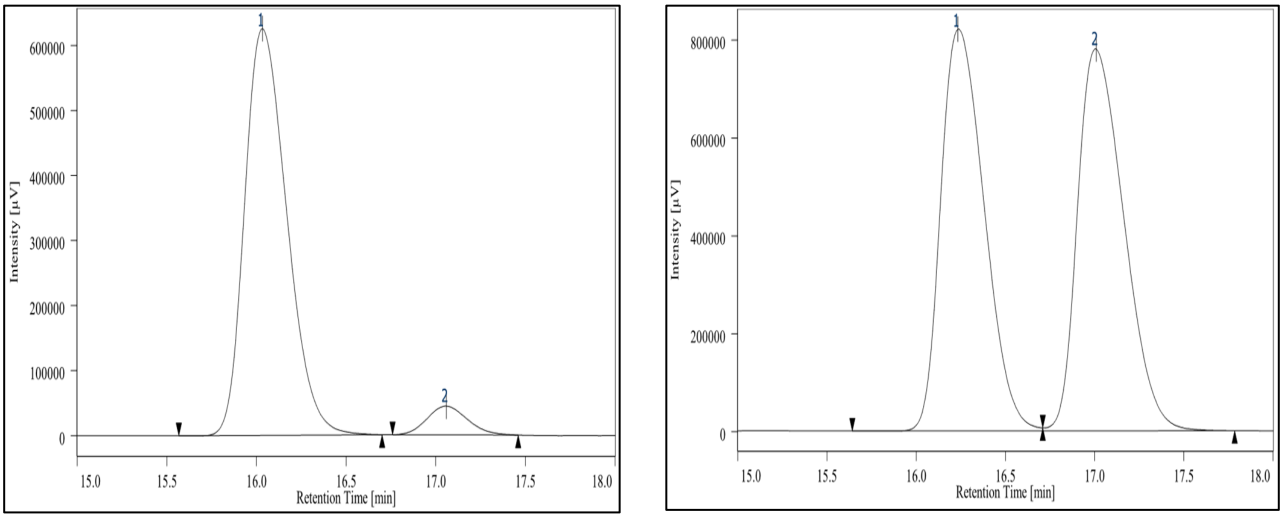
Supplementary figure 20. HPLC spectra for **3b**



Supplementary figure 21. ^{1}H NMR spectrum for **3c**



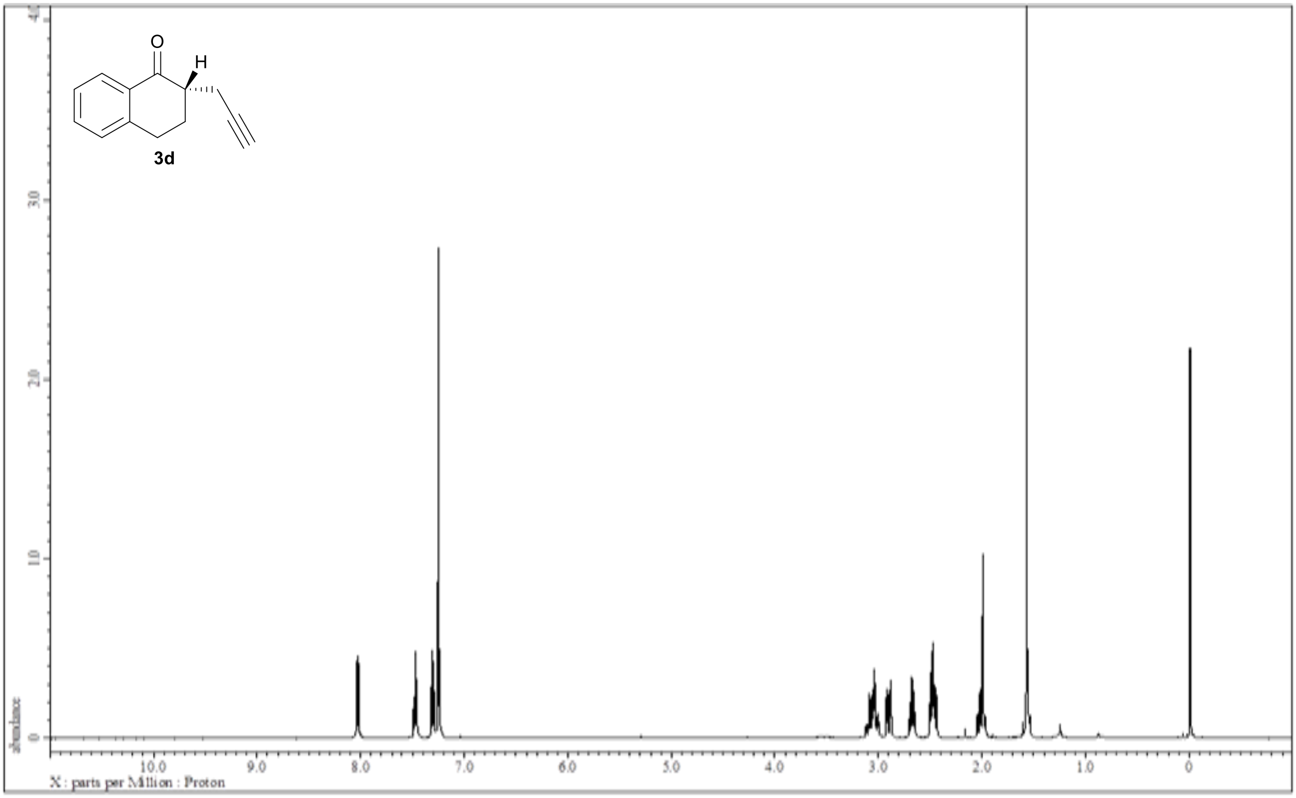
Supplementary figure 22. ^{13}C NMR spectrum for **3c**



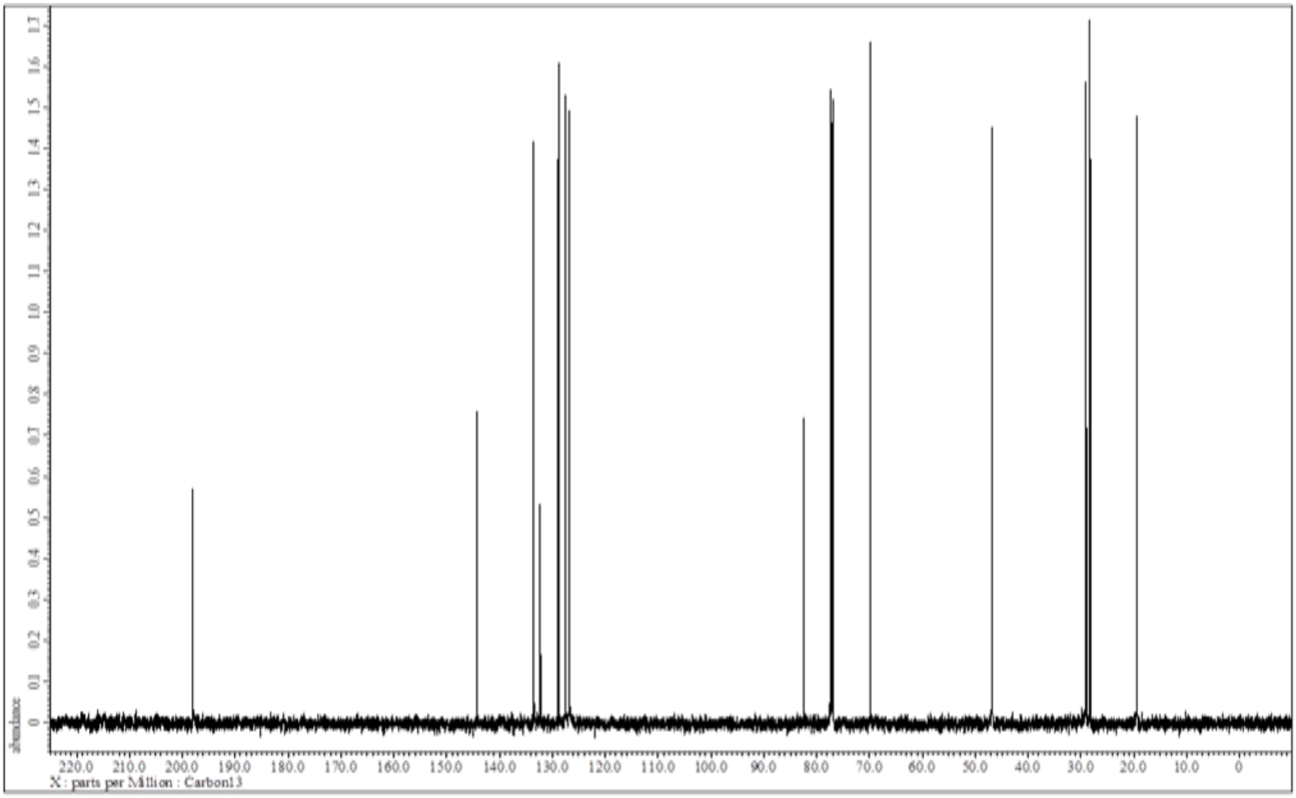
Peak	Retention Time [min]	Area [%]
1	16.233	49.594
2	17.008	50.406

Peak	Retention Time [min]	Area [%]
1	16.033	93.674
2	17.058	6.326

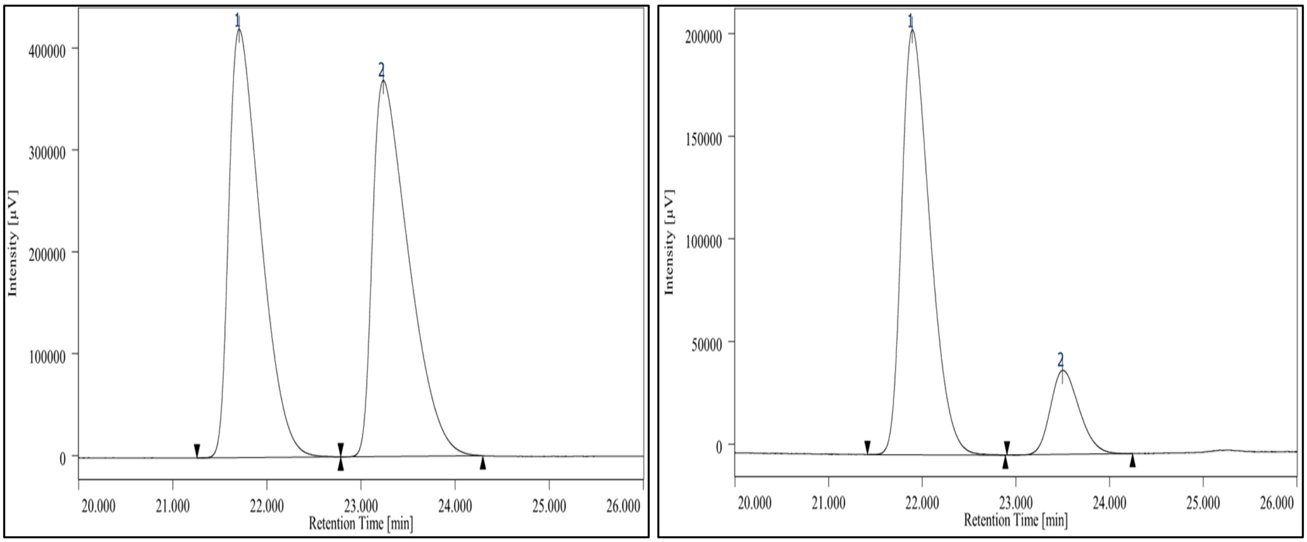
Supplementary figure 23. HPLC spectra for **3c**



Supplementary figure 24. ^{1}H NMR spectrum for **3d**



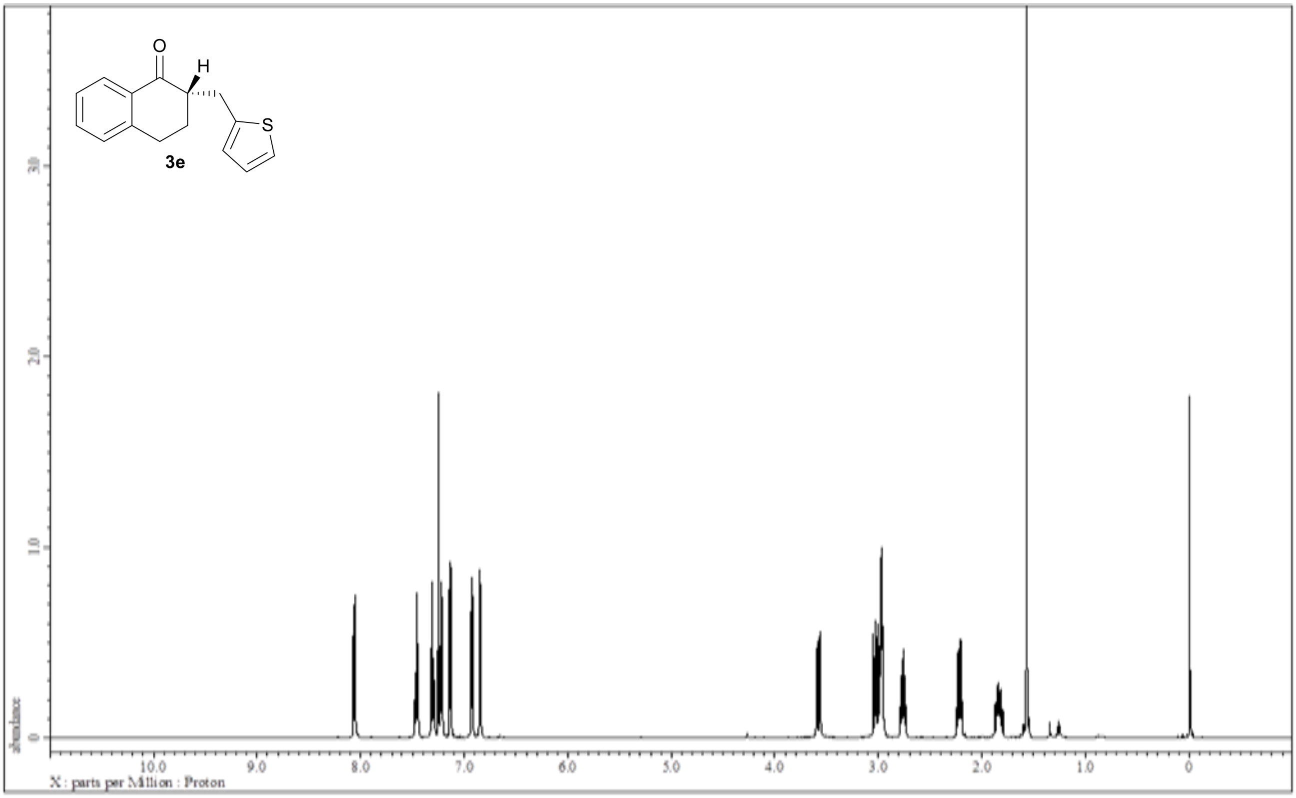
Supplementary figure 25. ^{13}C NMR spectrum for **3d**



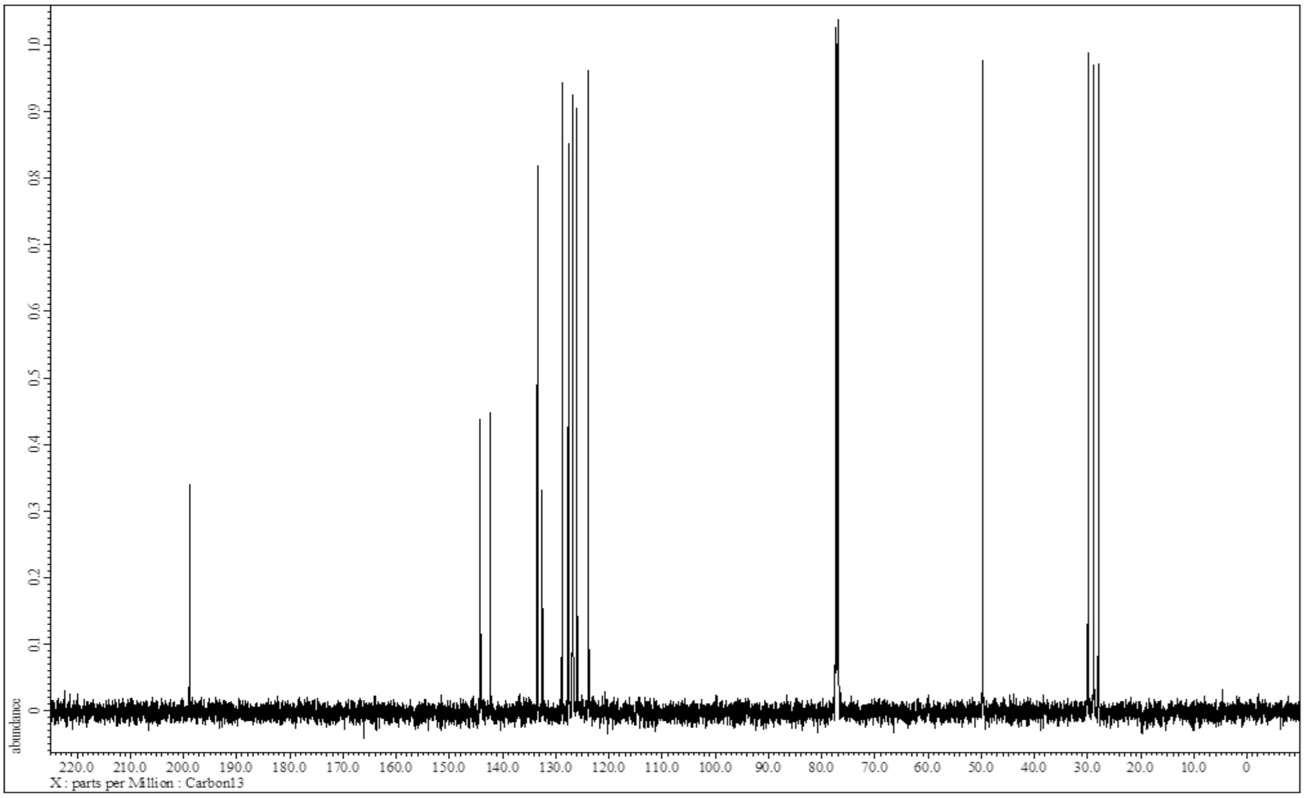
Peak	Retention Time [min]	Area [%]
1	21.705	49.952
2	23.235	50.048

Peak	Retention Time [min]	Area [%]
1	21.893	83.332
2	23.495	16.668

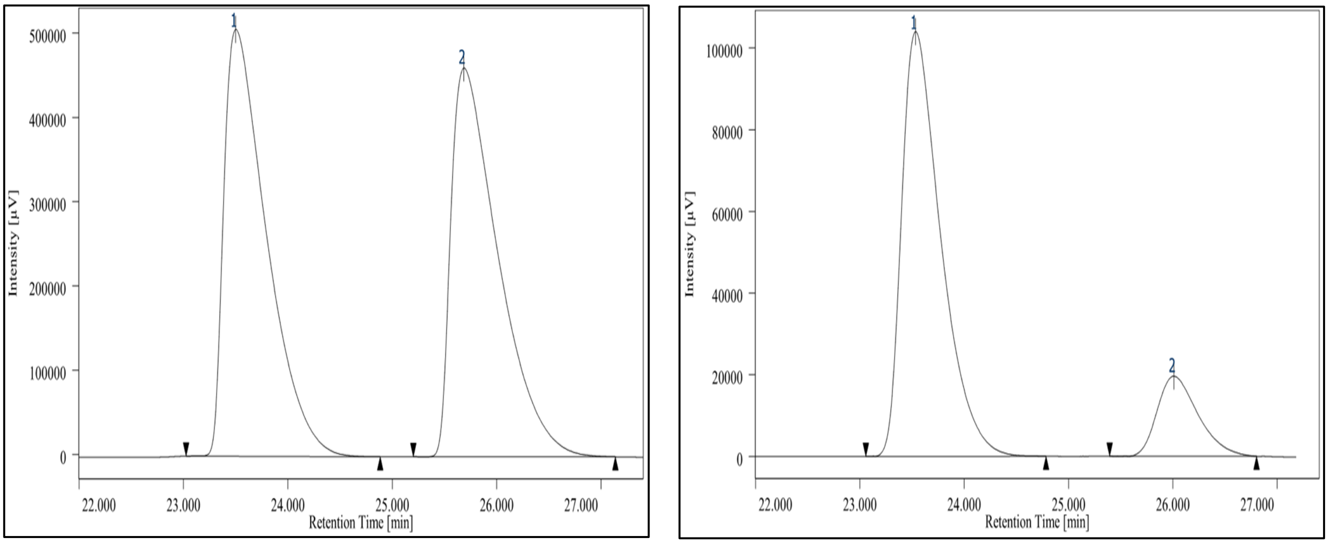
Supplementary figure 26. HPLC spectra for **3d**

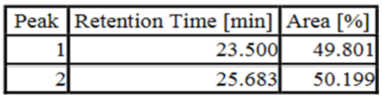


Supplementary figure 27. ^{1}H NMR spectrum for **3e**

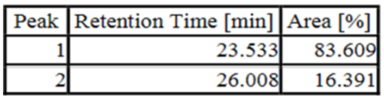


Supplementary figure 28. ^{13}C NMR spectrum for **3e**



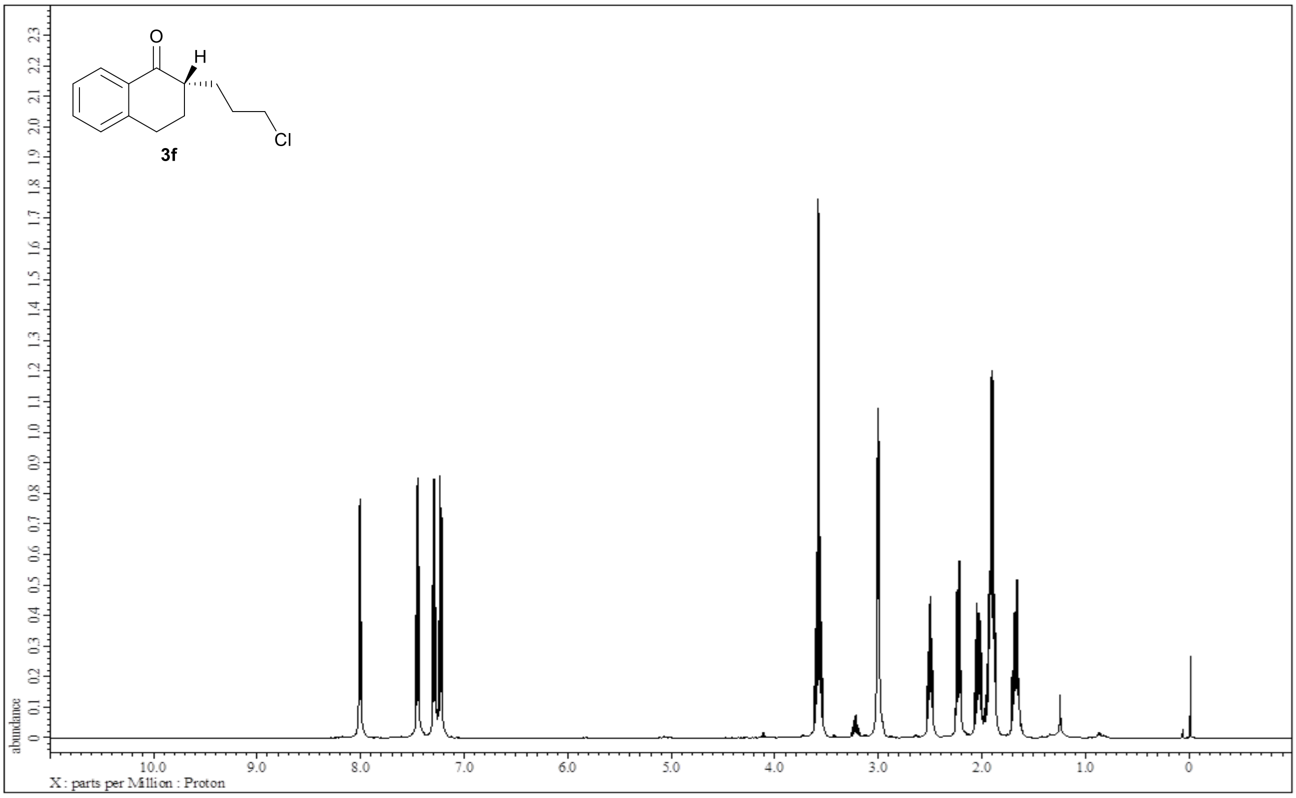


Peak	Retention Time [min]	Area [%]
1	23.500	49.801
2	25.683	50.199

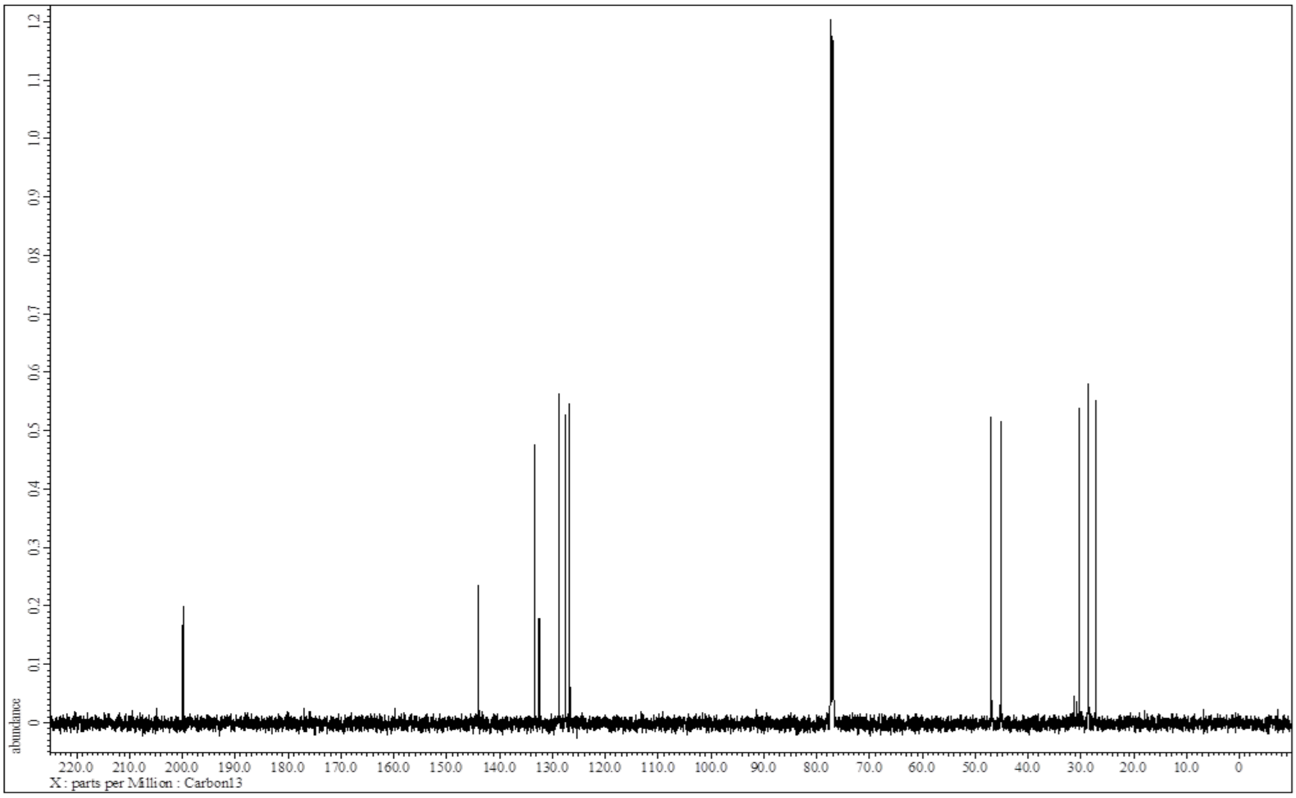


Peak	Retention Time [min]	Area [%]
1	23.533	83.609
2	26.008	16.391

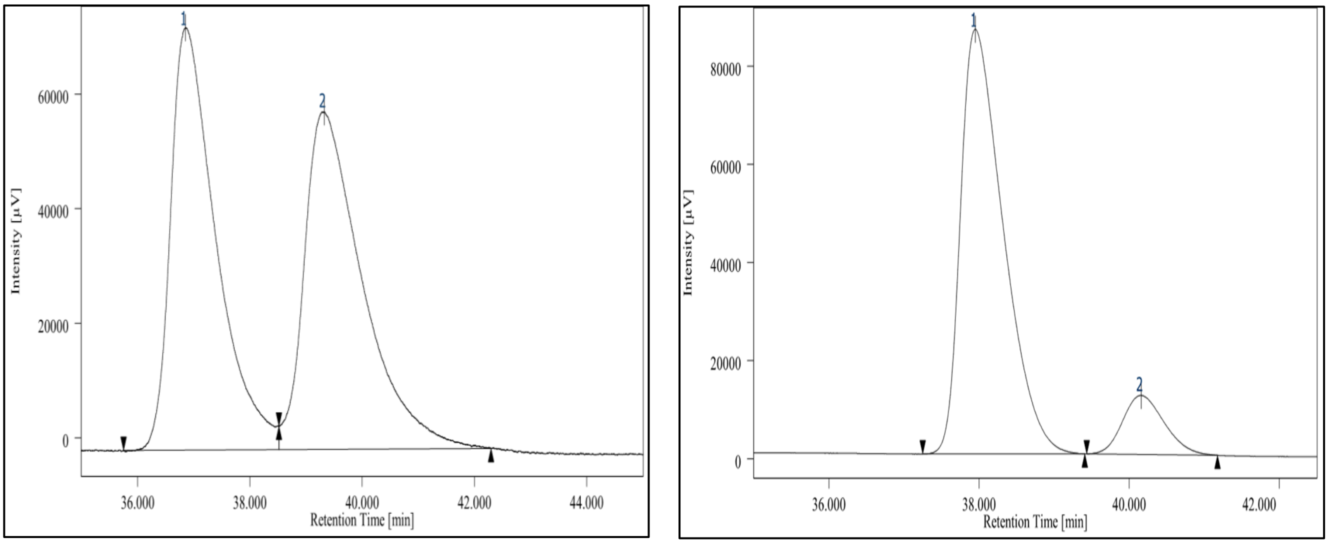
Supplementary figure 29. HPLC spectra for **3e**



Supplementary figure 30. ^{1}H NMR spectrum for **3f**



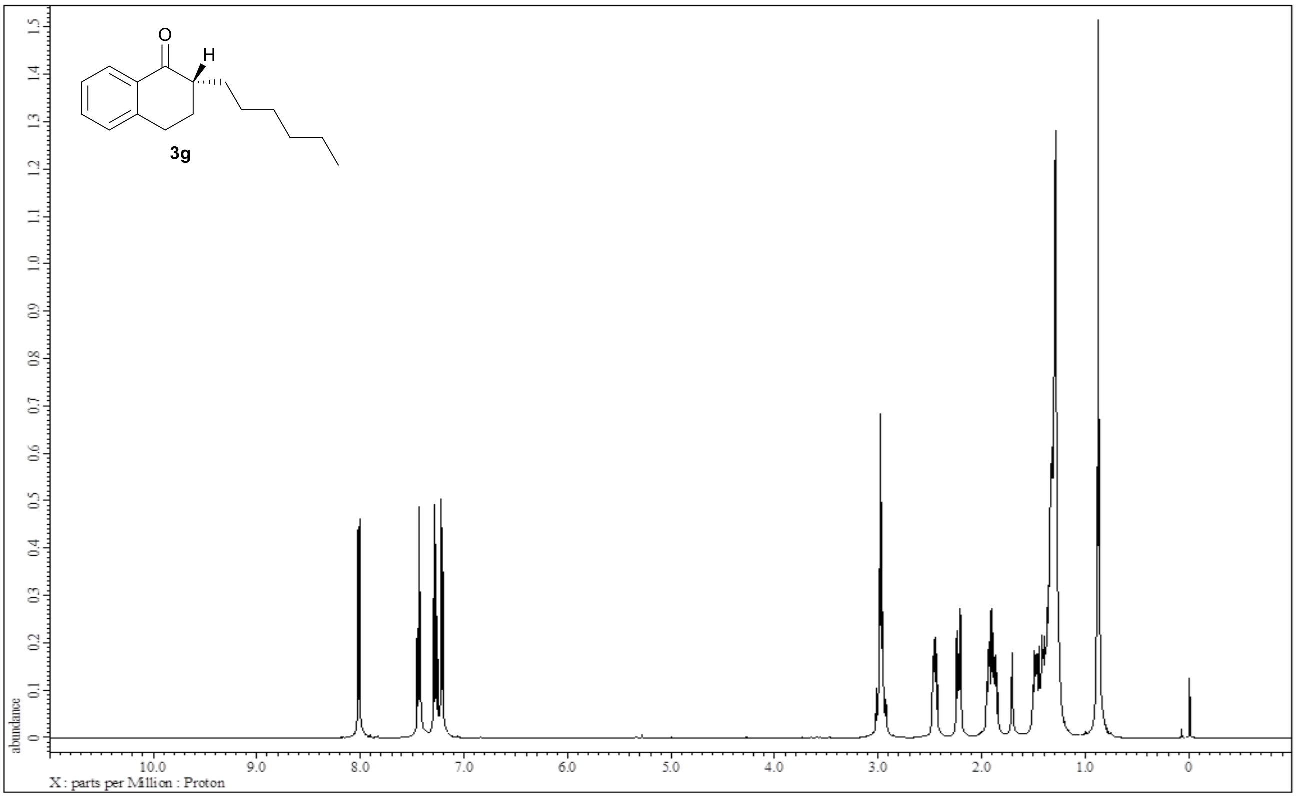
Supplementary figure 31. ^{13}C NMR spectrum for **3f**



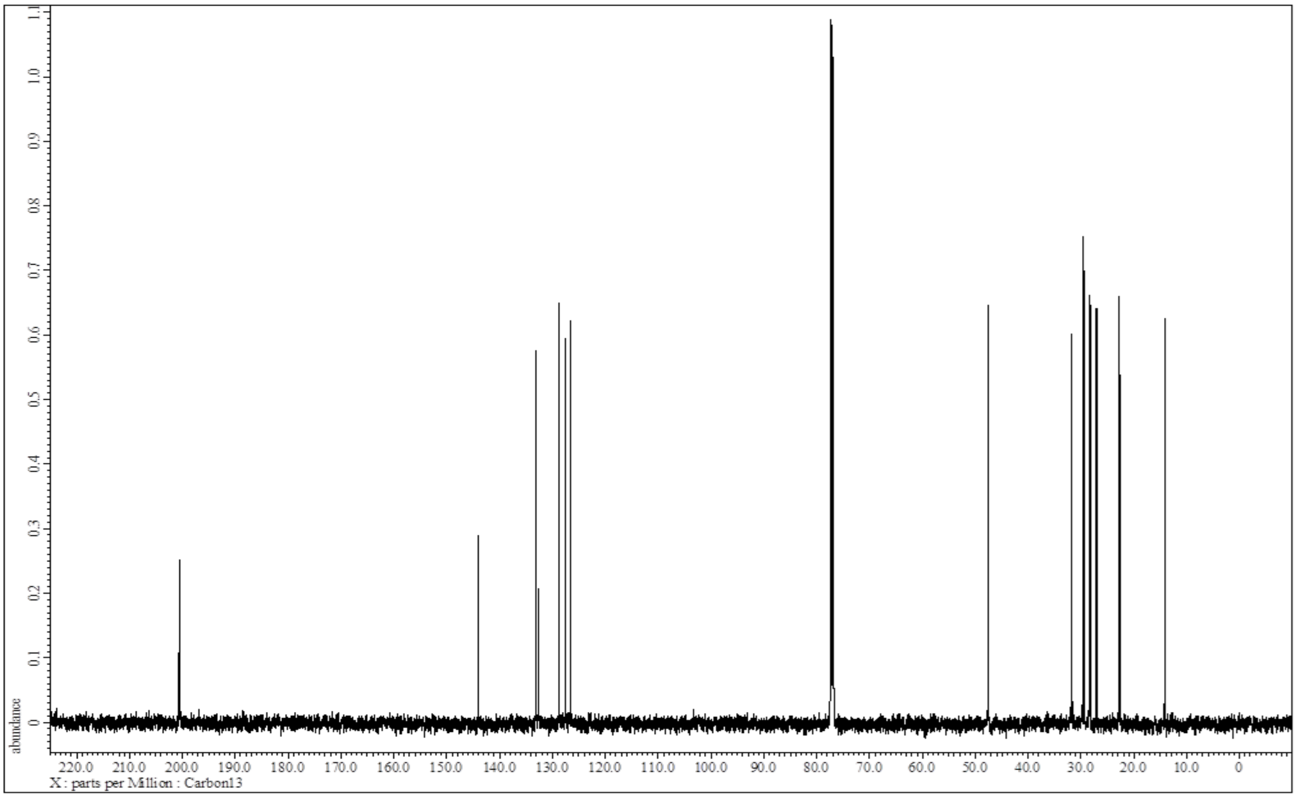
Peak	Retention Time [min]	Area [%]
1	36.852	49.485
2	39.325	50.515

Peak	Retention Time [min]	Area [%]
1	37.950	88.077
2	40.158	11.923

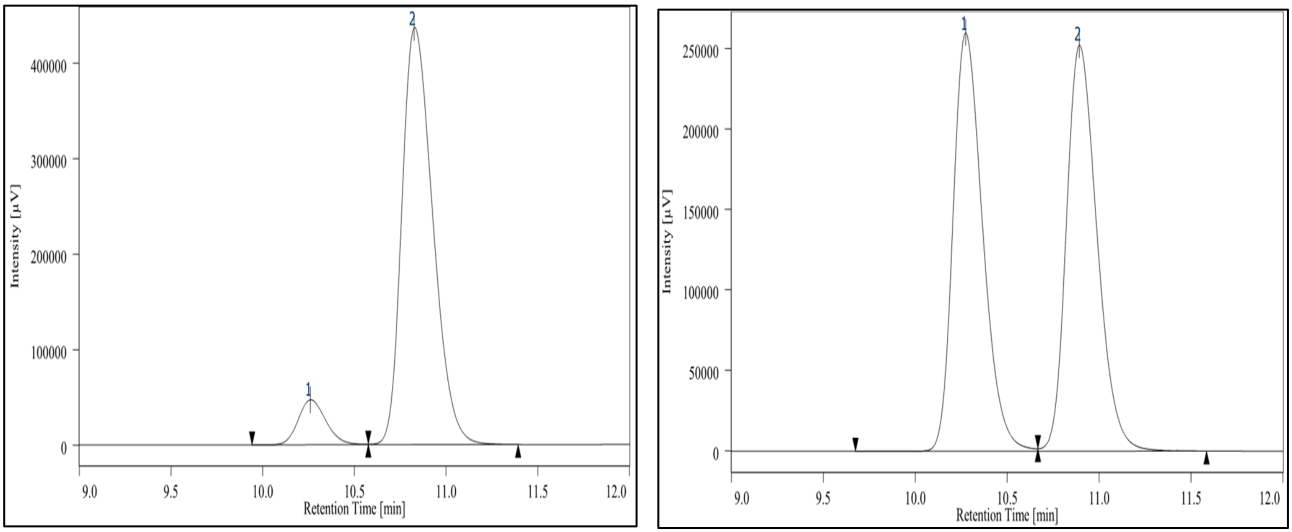
Supplementary figure 32. HPLC spectra for **3f**

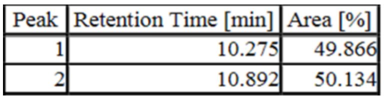


Supplementary figure 33. ^{1}H NMR spectrum for **3g**

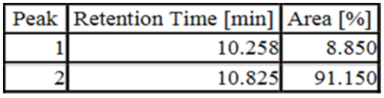


Supplementary figure 34. ^{13}C NMR spectrum for **3g**



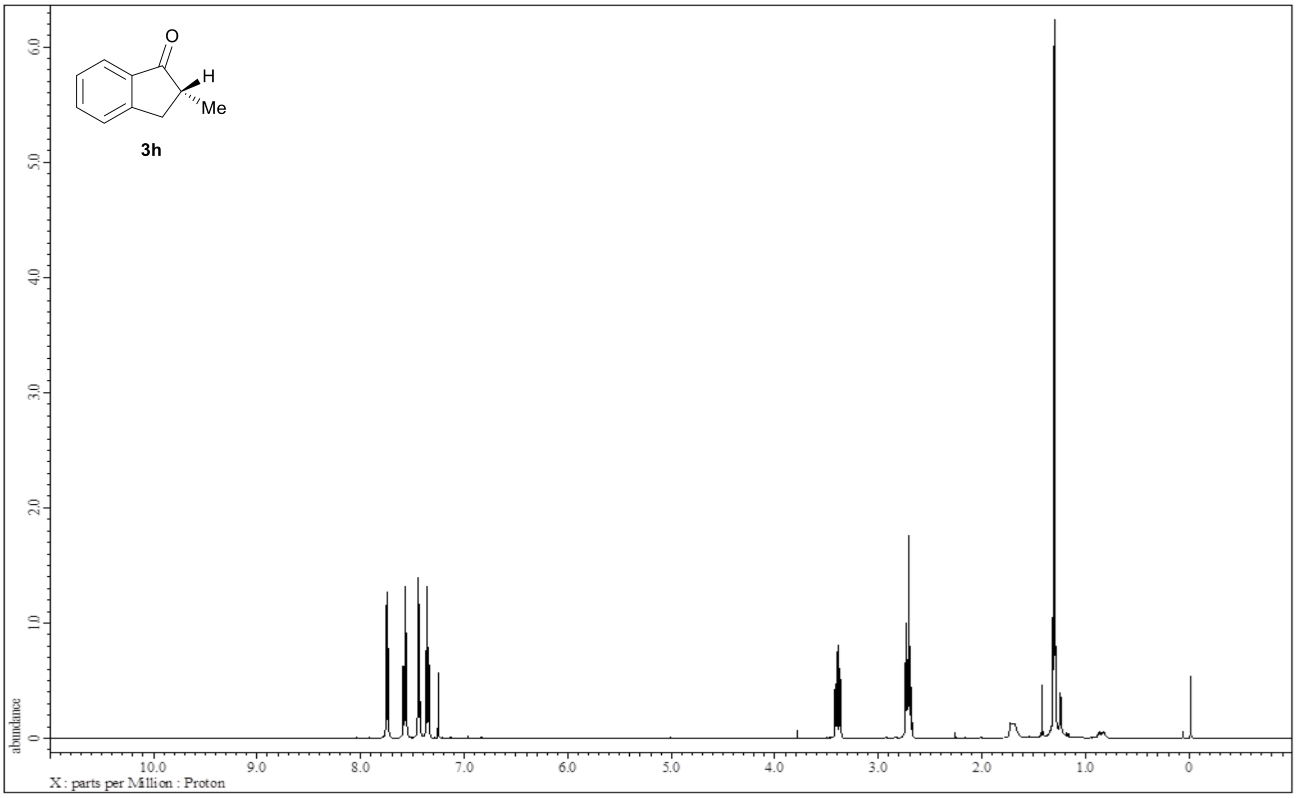


Peak	Retention Time [min]	Area [%]
1	10.275	49.866
2	10.892	50.134

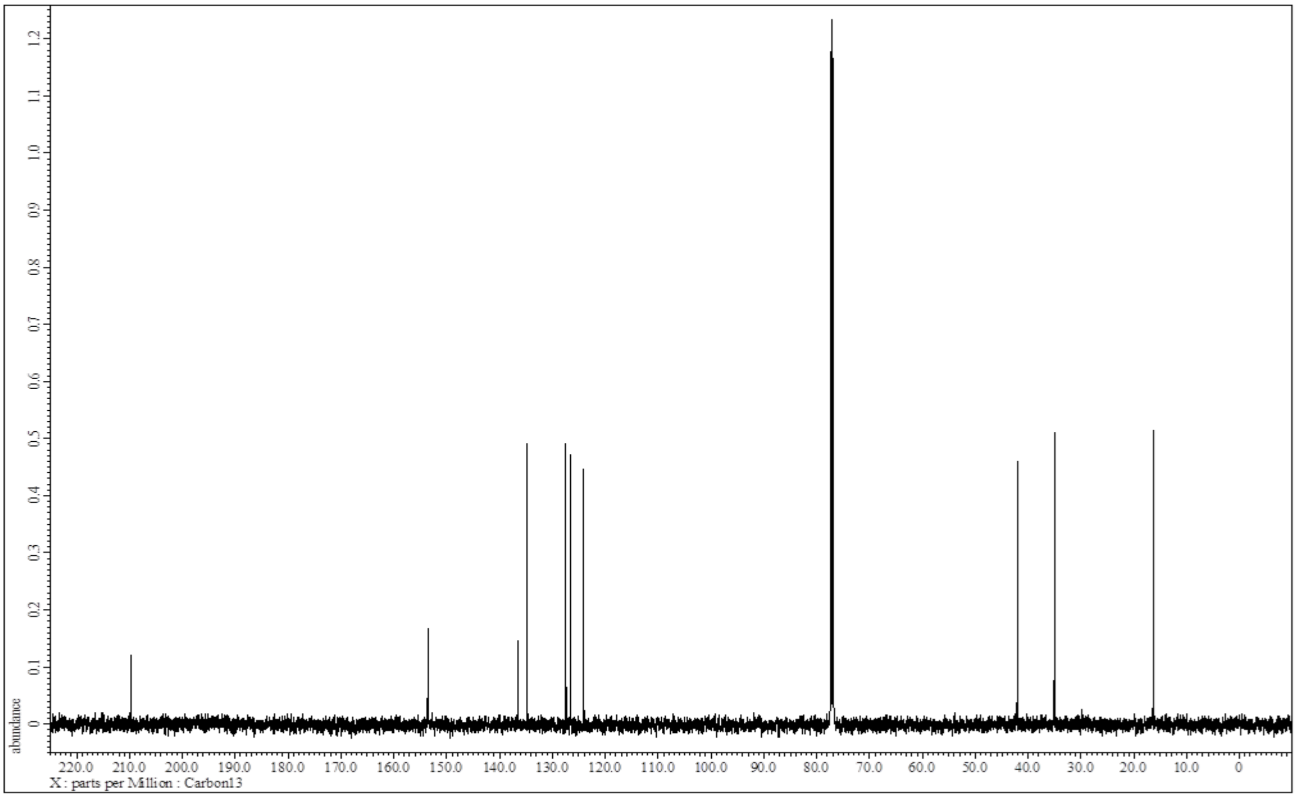


Peak	Retention Time [min]	Area [%]
1	10.258	8.850
2	10.825	91.150

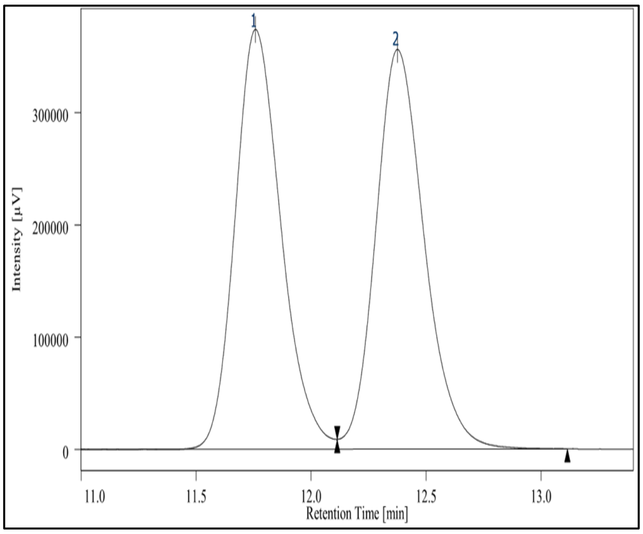
Supplementary figure 35. HPLC spectra for **3g**

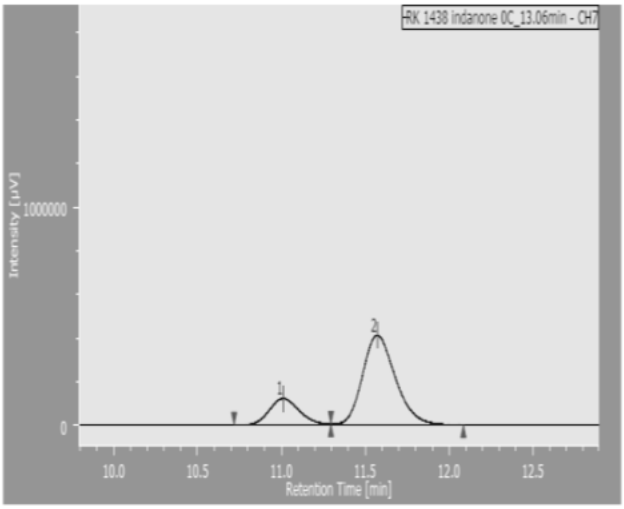


Supplementary figure 36. ^{1}H NMR spectrum for **3h**



Supplementary figure 37. ^{13}C NMR spectrum for **3h**

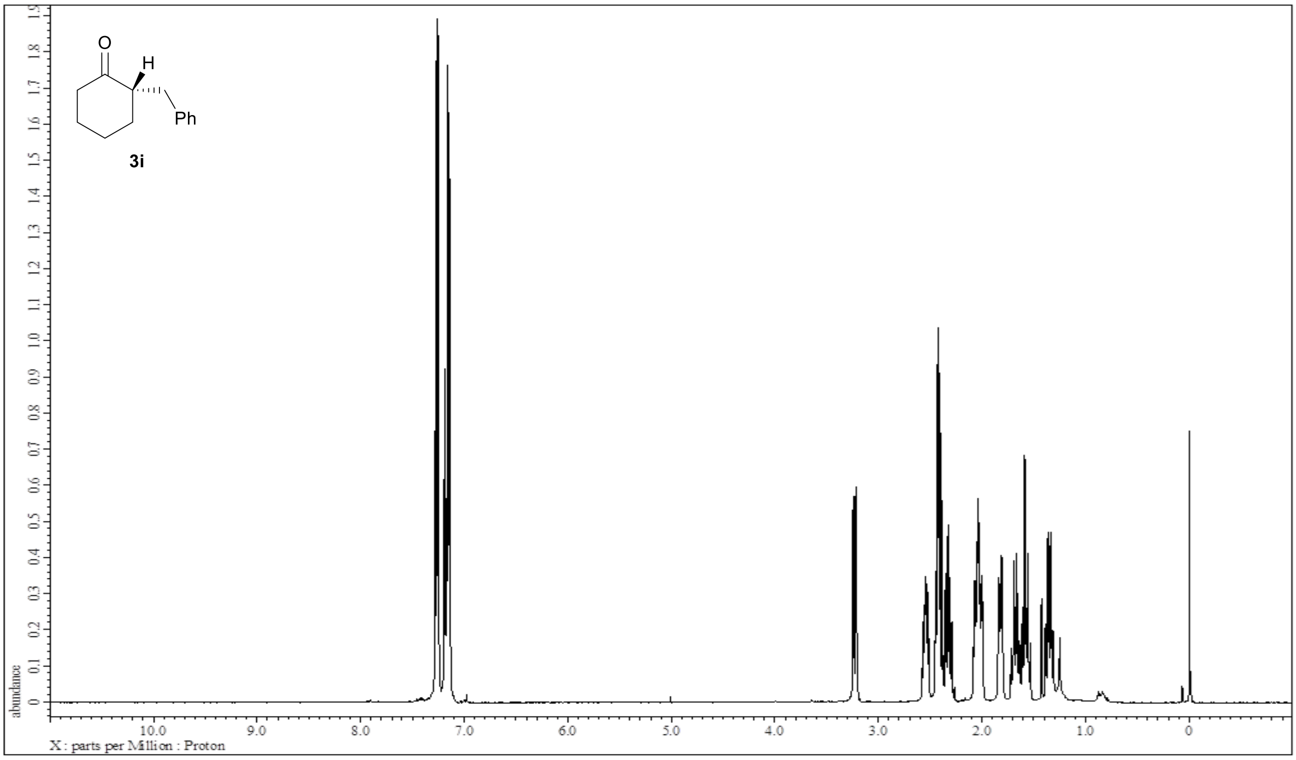




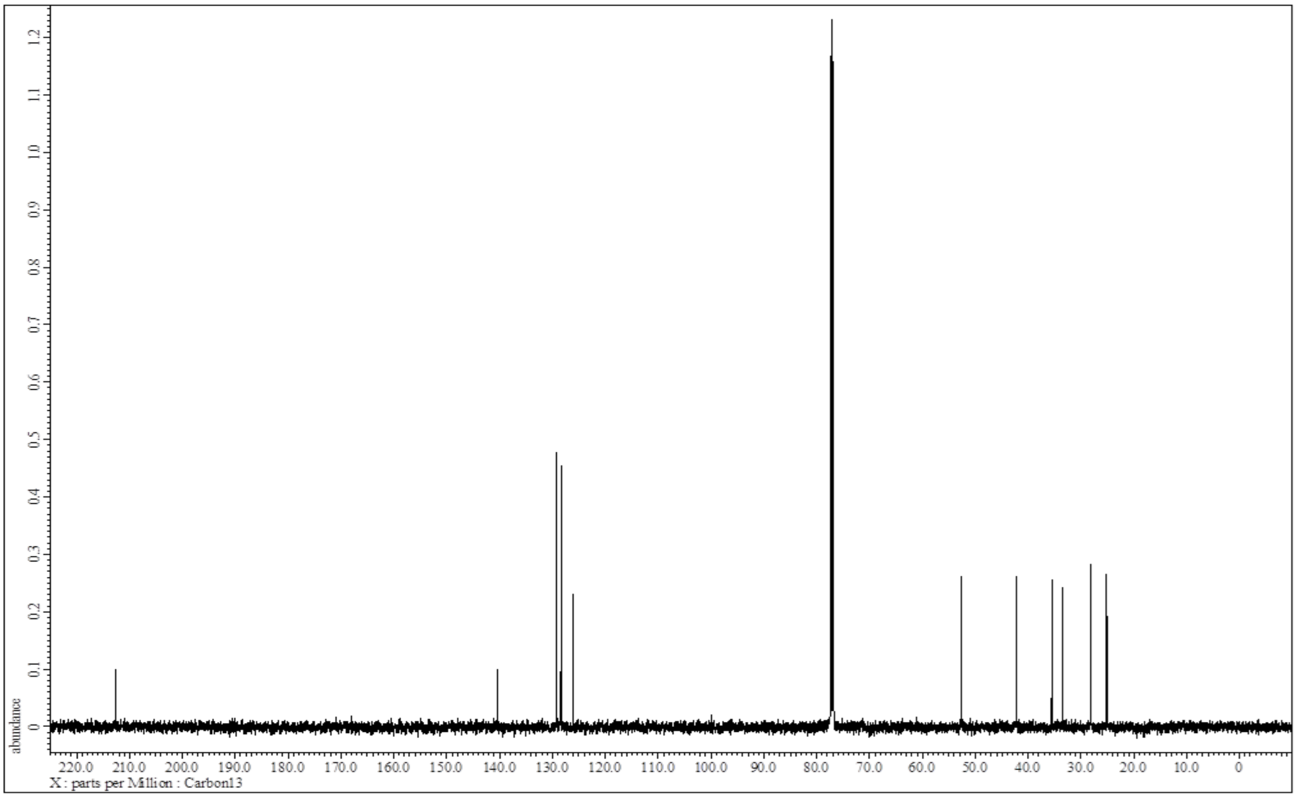
Peak	Retention Time [min]	Area [%]
1	11.758	49.794
2	12.375	50.206

#	ピーク名	CH	tR [min]	面積 [µV·sec]	高さ [µV]	面積%	高さ%
1	Unknown	7	11.010	1528590	121592	21.426	22.897
2	Unknown	7	11.572	5605644	409443	78.574	77.103

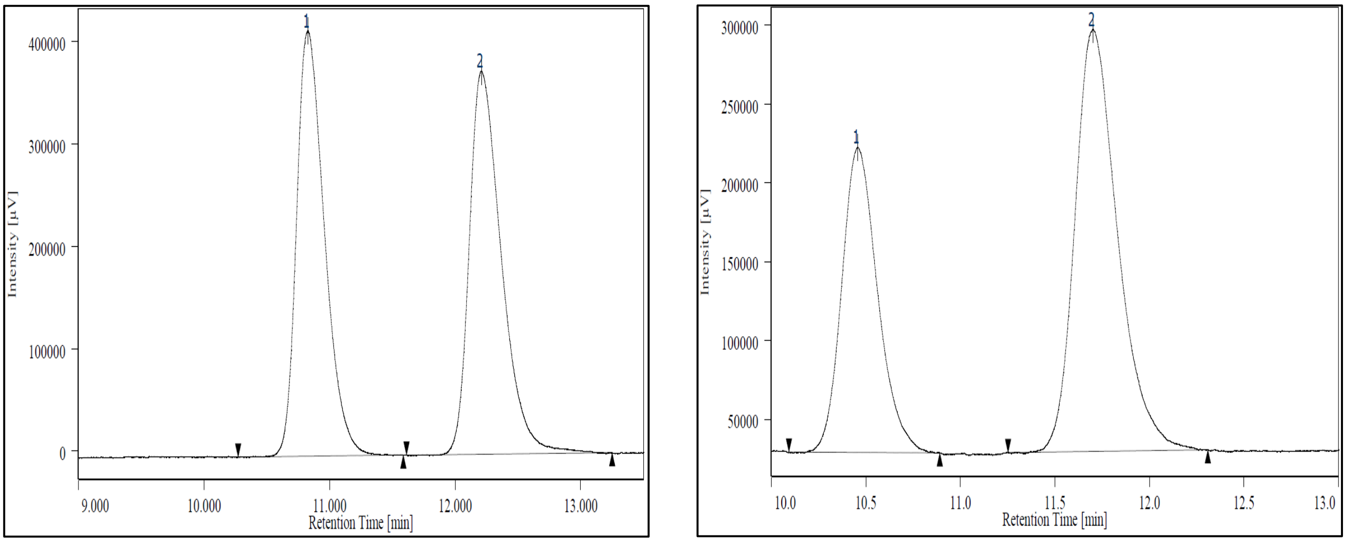
Supplementary figure 38. HPLC spectra for **3h**



Supplementary figure 39. ^{1}H NMR spectrum for **3i**



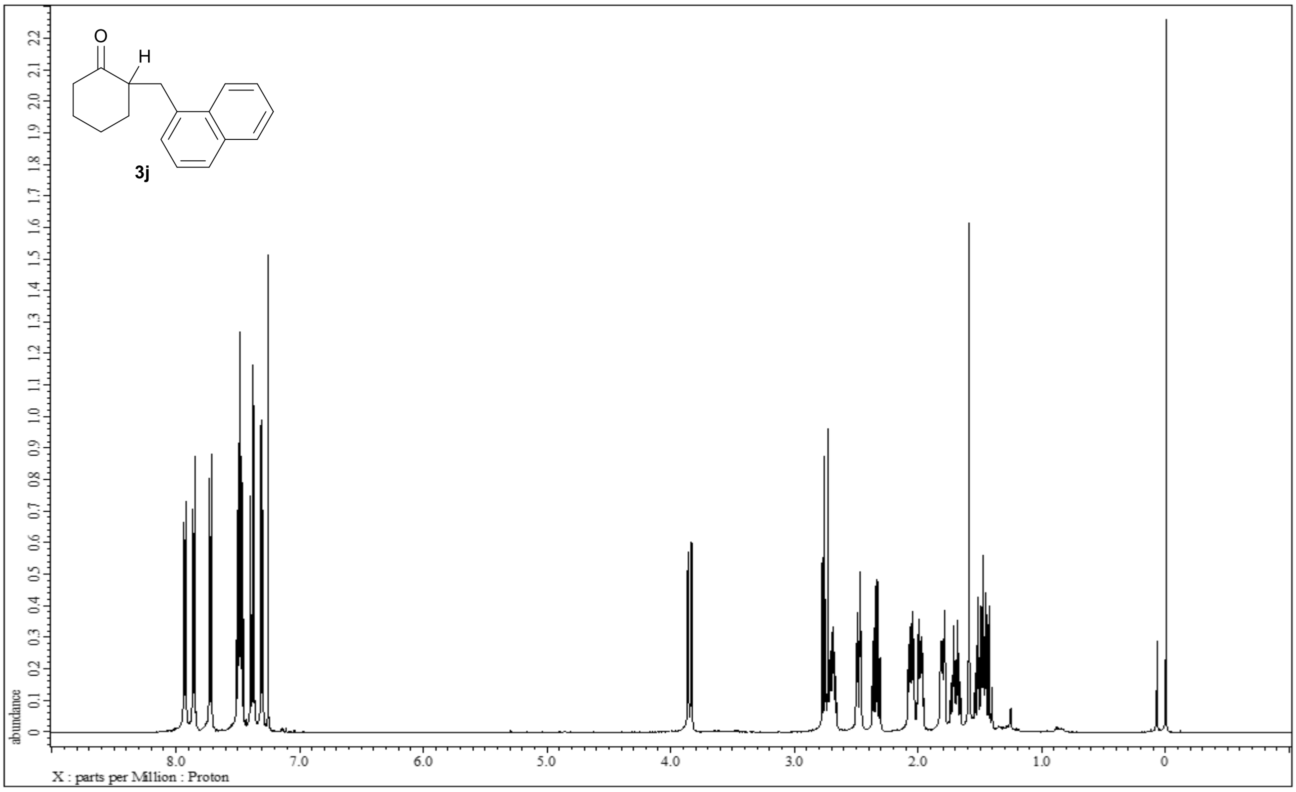
Supplementary figure 40. ^{13}C NMR spectrum for **3i**



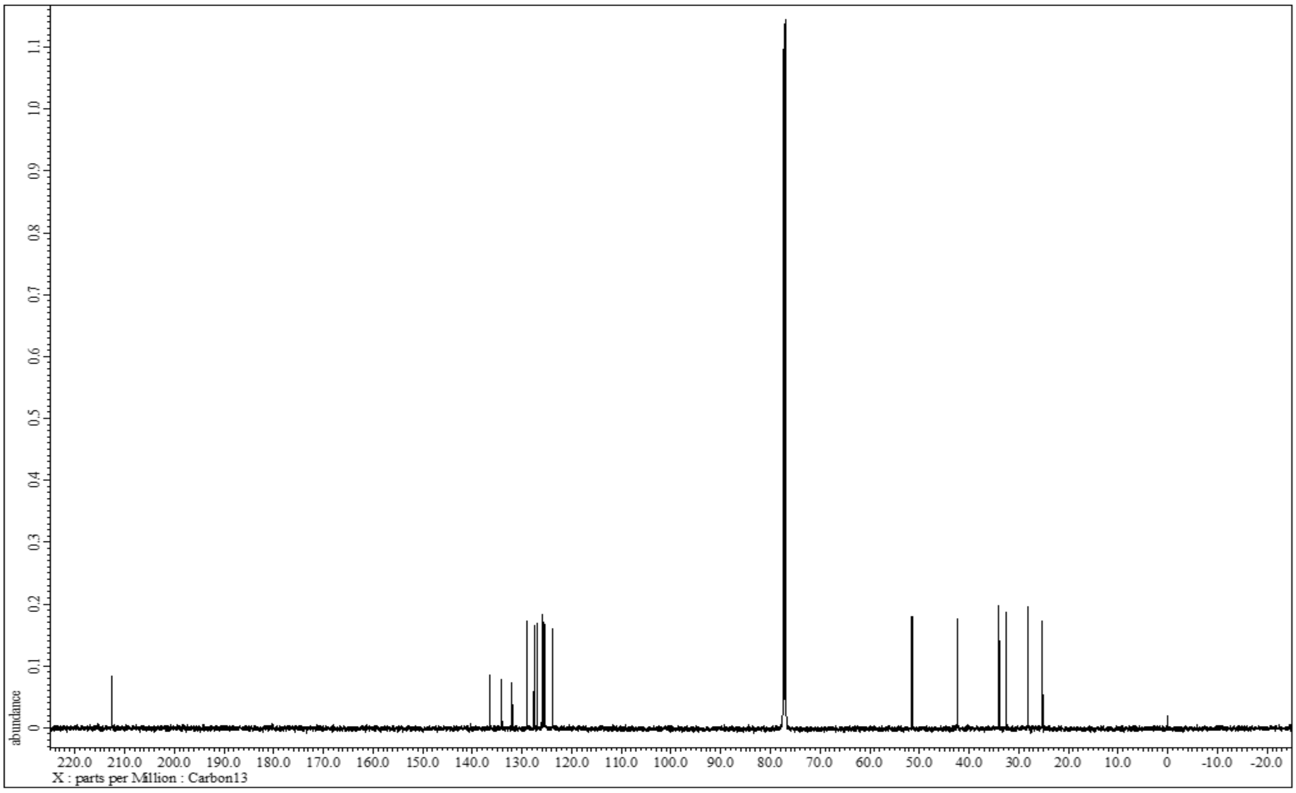
Peak	Retention Time [min]	Area [%]
1	10.828	49.130
2	12.210	50.870

Peak	Retention Time [min]	Area [%]
1	10.458	37.789
2	11.702	62.211

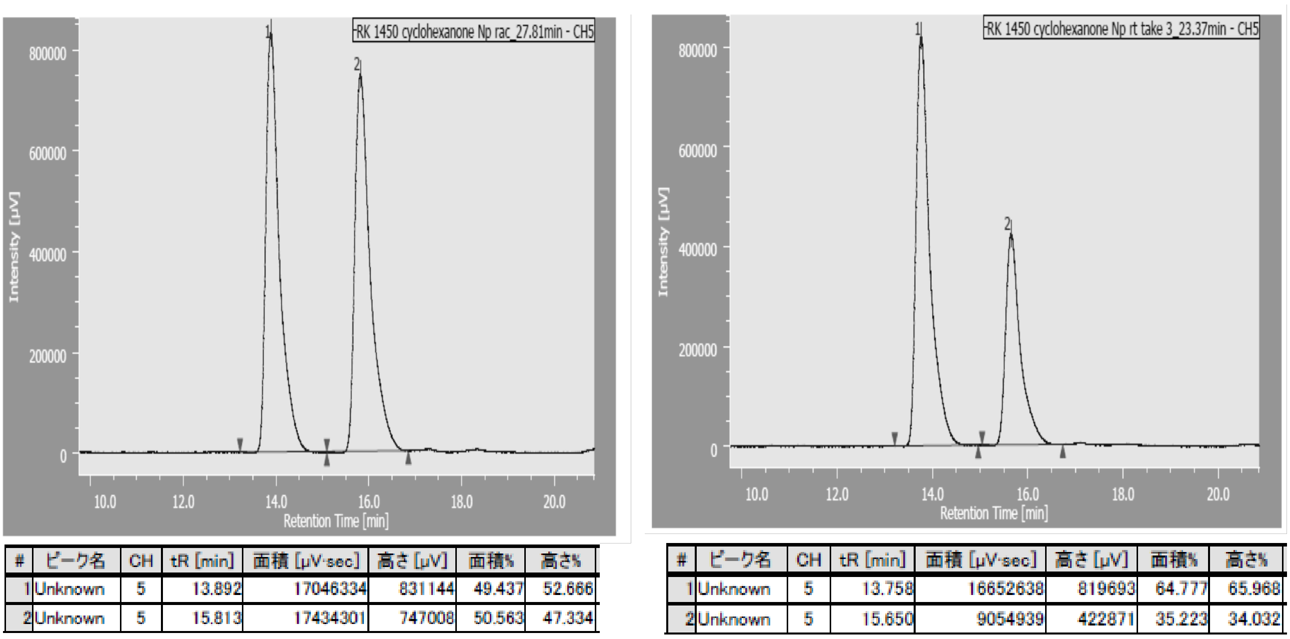
Supplementary figure 41. HPLC spectra for **3i**



Supplementary figure 42. ^{1}H NMR spectrum for **3j**



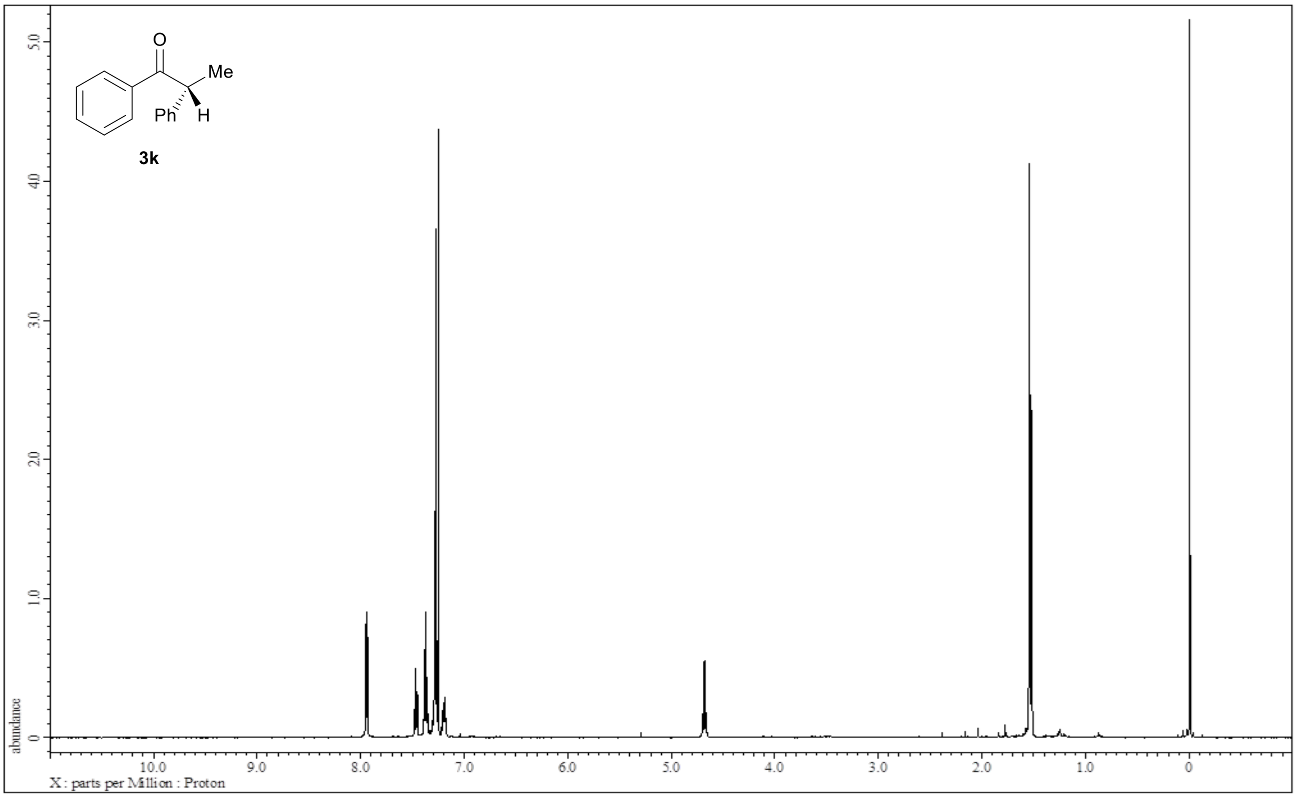
Supplementary figure 43. ^{13}C NMR spectrum for **3j**



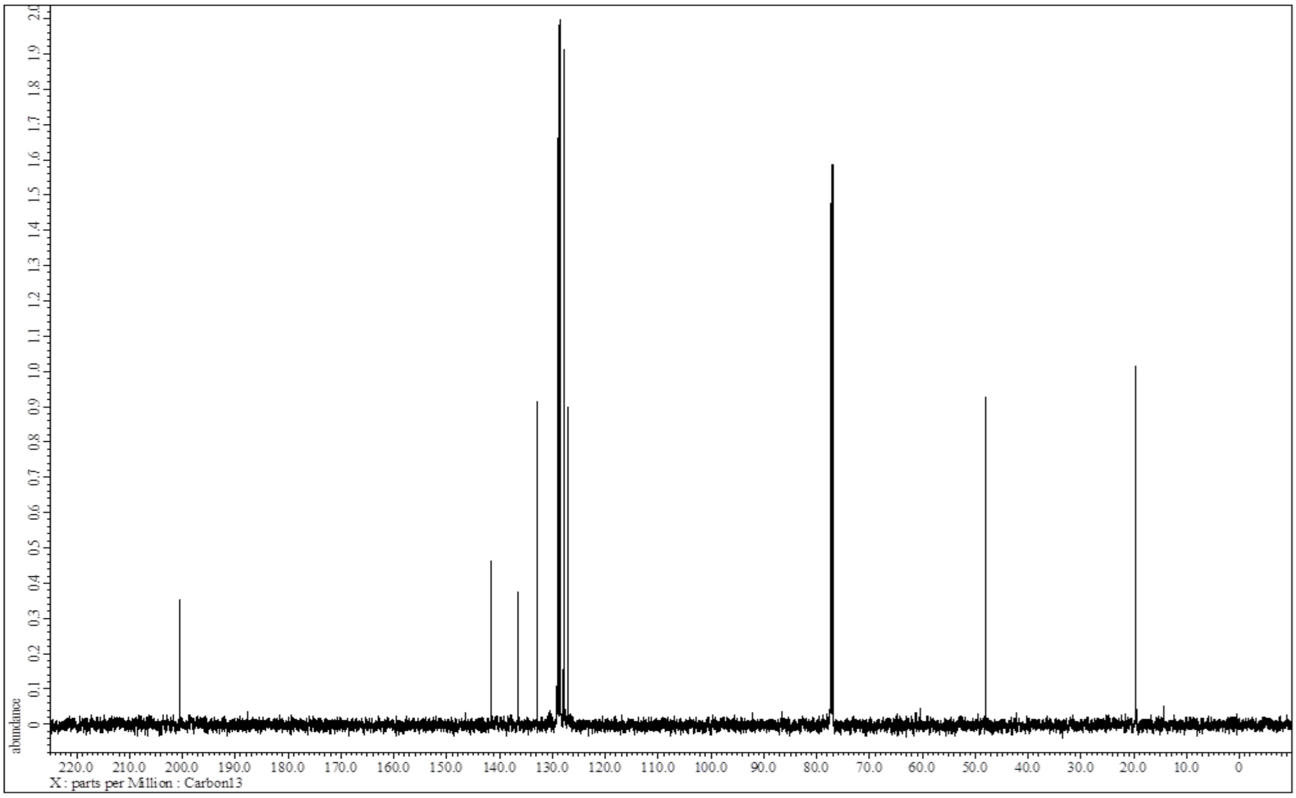
#	ピーク名	CH	tR [min]	面積 [µV·sec]	高さ [µV]	面積%	高さ%
1	Unknown	5	13.892	17046334	831144	49.437	52.666
2	Unknown	5	15.813	17434301	747008	50.563	47.334

#	ピーク名	CH	tR [min]	面積 [µV·sec]	高さ [µV]	面積%	高さ%
1	Unknown	5	13.758	16652638	819693	64.777	65.968
2	Unknown	5	15.650	9054939	422871	35.223	34.032

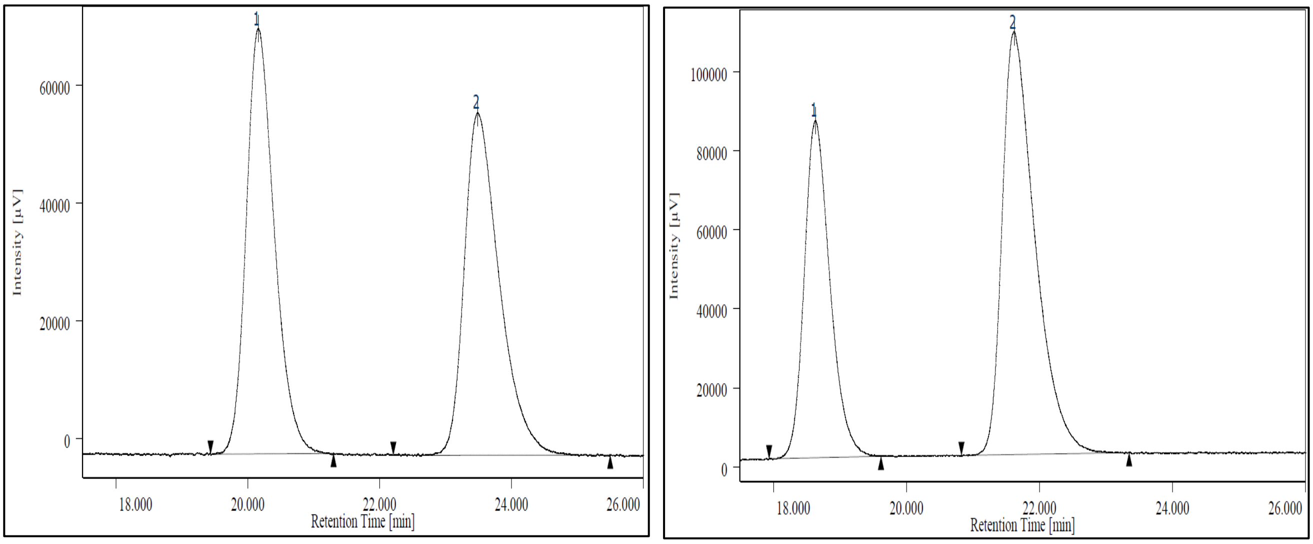
Supplementary figure 44. HPLC spectra for **3j**



Supplementary figure 45. ^{1}H NMR spectrum for **3k**



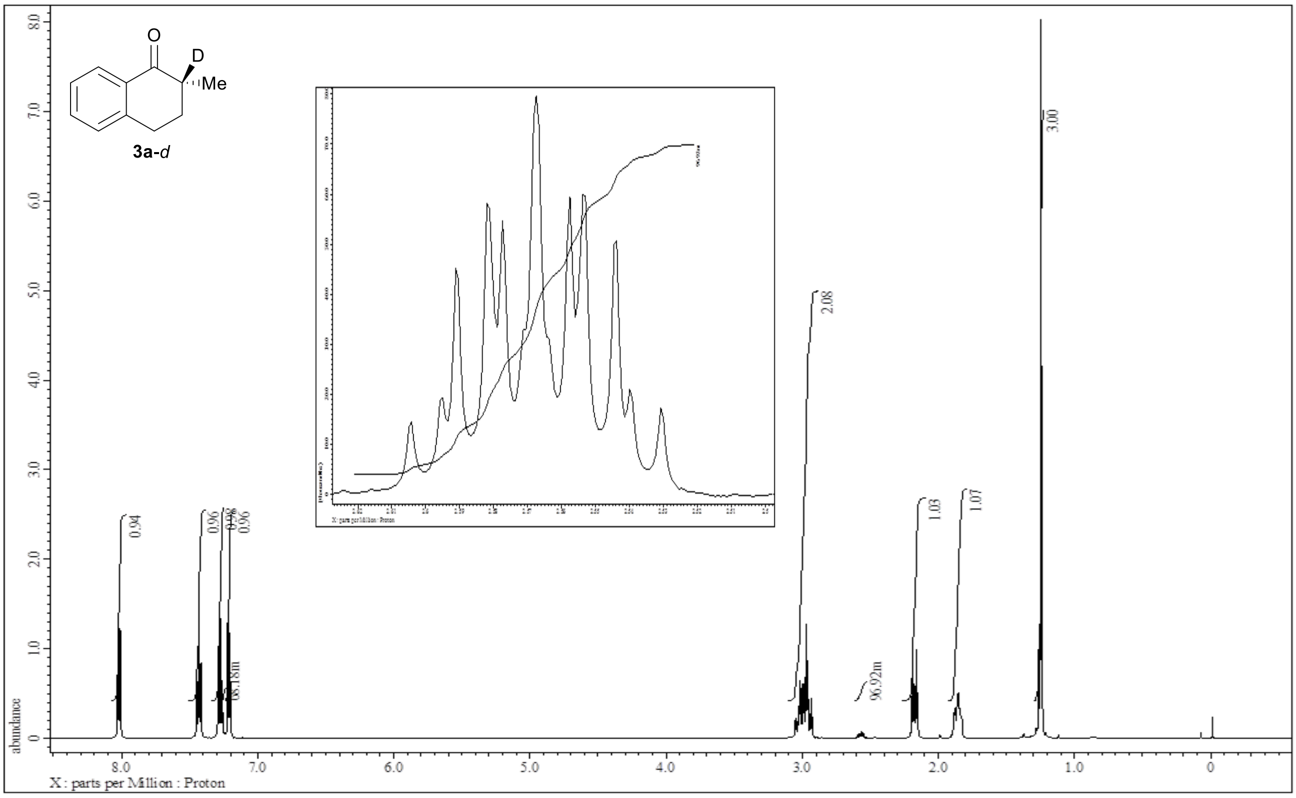
Supplementary figure 46. ^{13}C NMR spectrum for **3k**



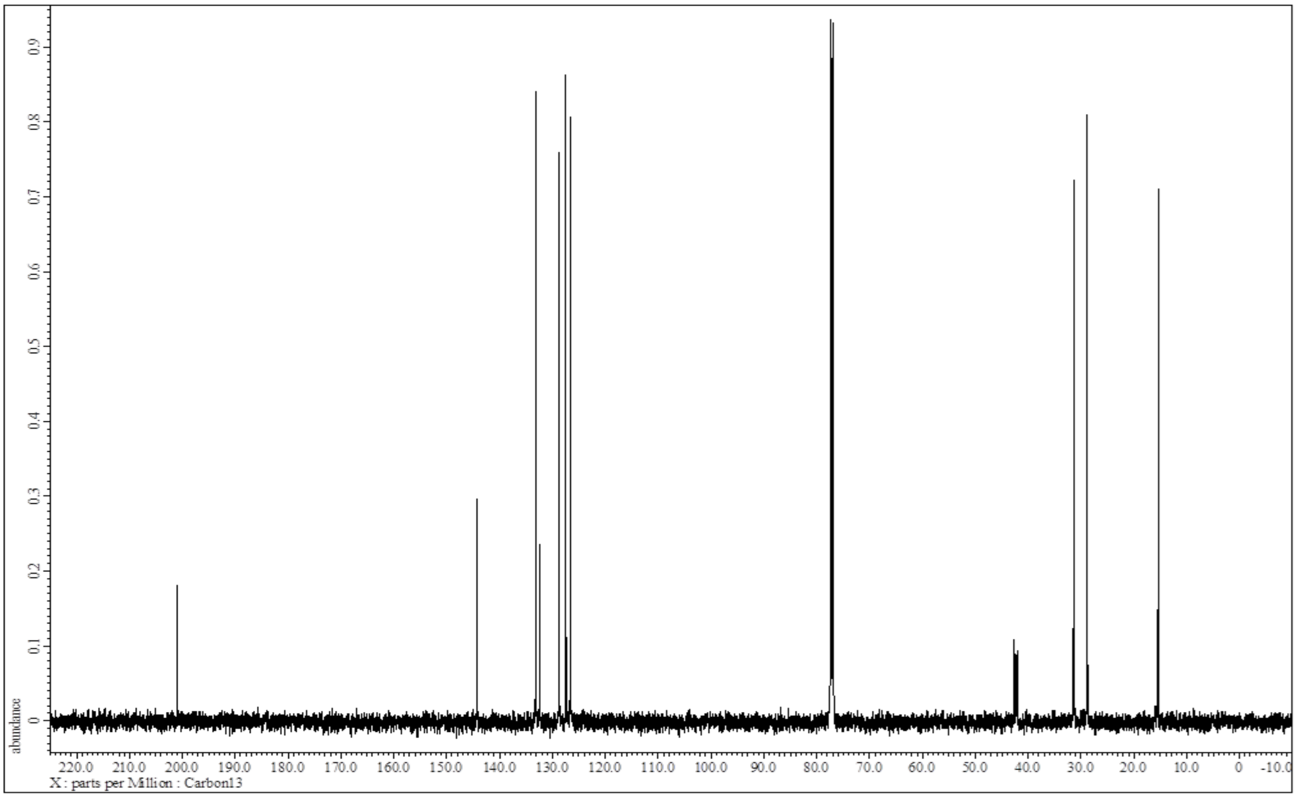
Peak	Retention Time [min]	Area [%]
1	20.162	49.945
2	23.490	50.055

Peak	Retention Time [min]	Area [%]
1	18.633	38.429
2	21.625	61.571

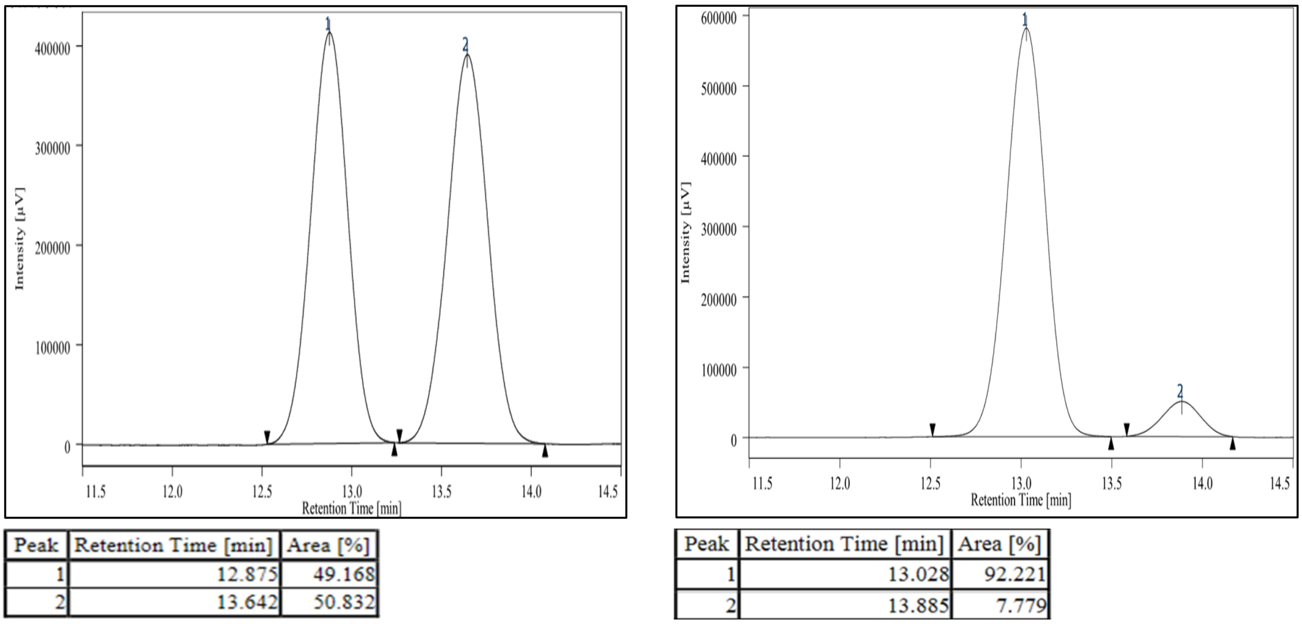
Supplementary figure 47. HPLC spectra for **3k**



Supplementary figure 48. ^{1}H NMR spectrum for **3a**-*d*



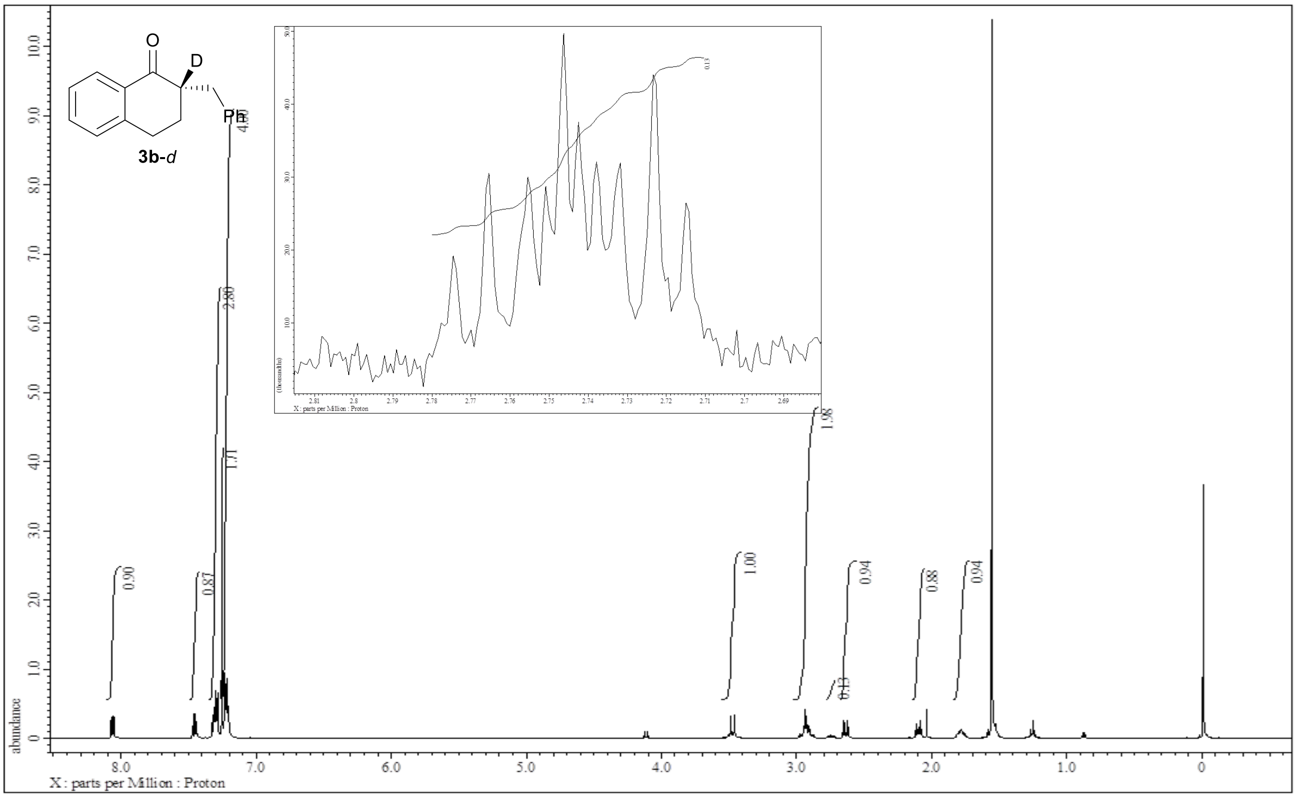
Supplementary figure 49. ^{13}C NMR spectrum for **3a**-*d*



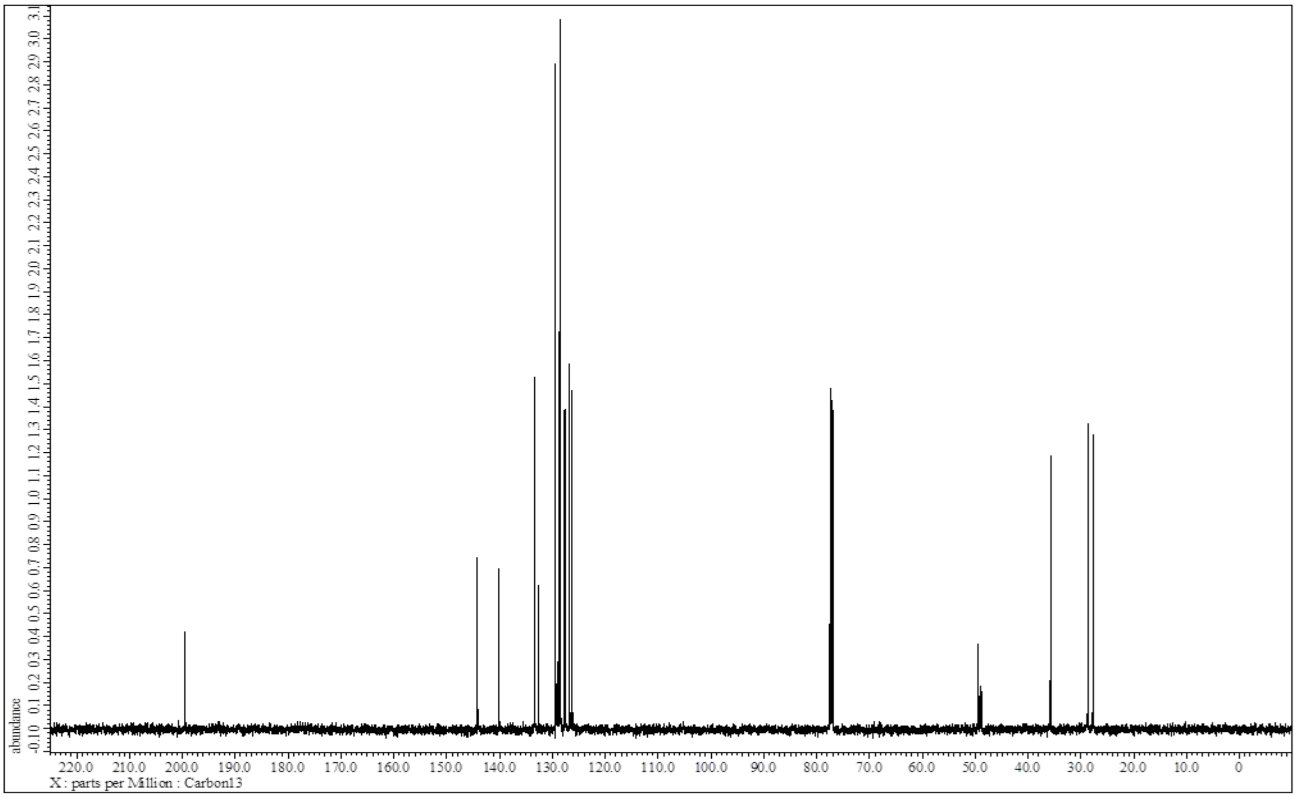
Peak	Retention Time [min]	Area [%]
1	12.875	49.168
2	13.642	50.832

Peak	Retention Time [min]	Area [%]
1	13.028	92.221
2	13.885	7.779

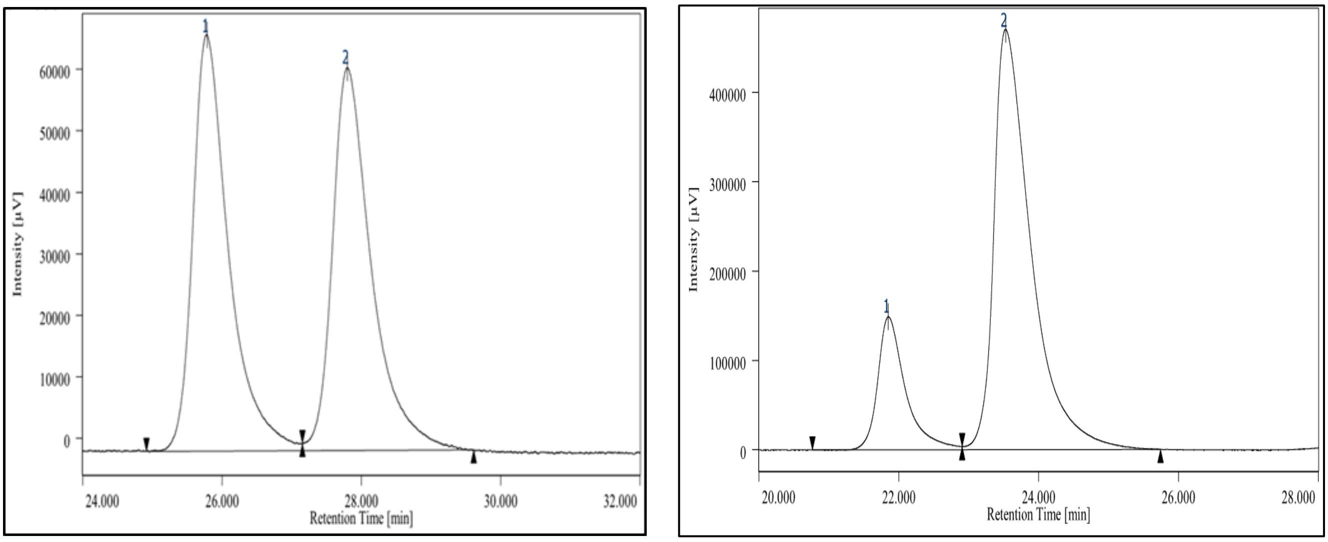
Supplementary figure 50. HPLC spectra for **3a**-*d*



Supplementary figure 51. ^{1}H NMR spectrum for **3b**-*d*



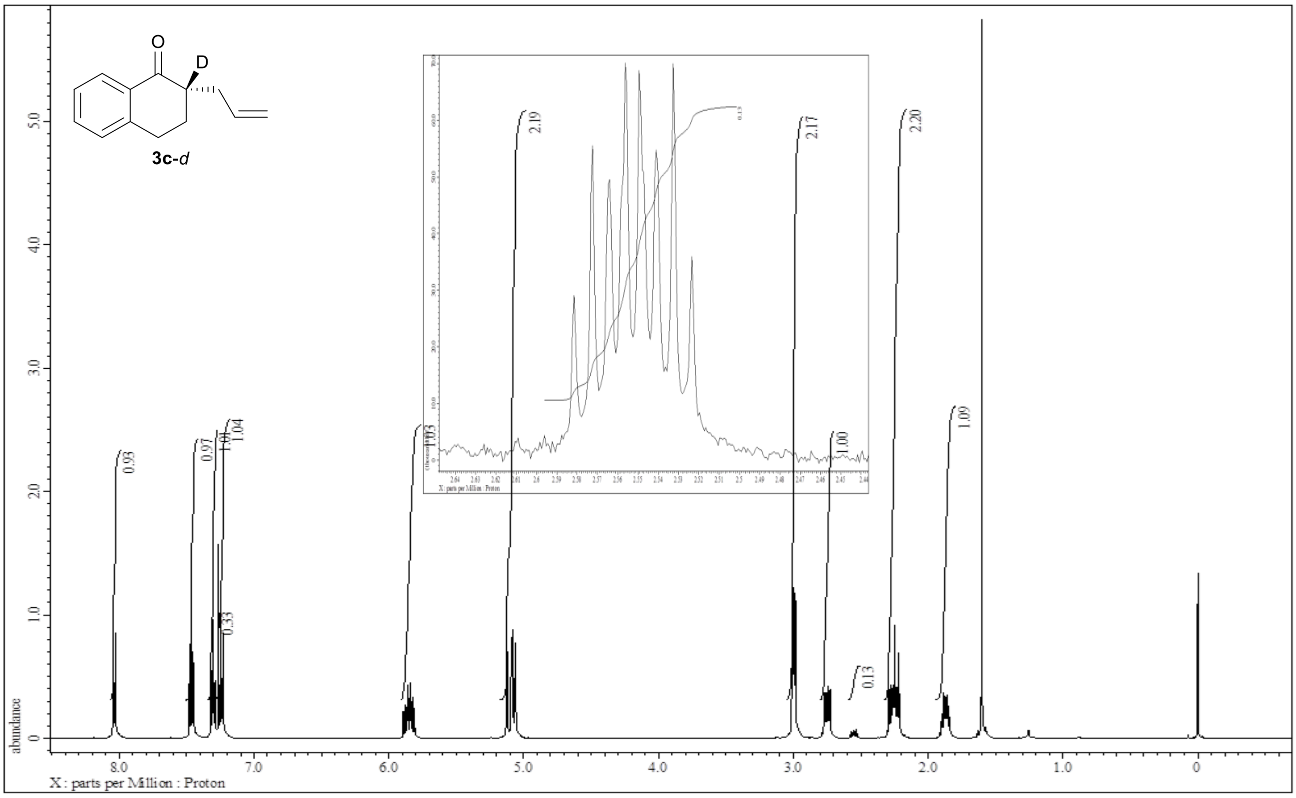
Supplementary figure 52. ^{13}C NMR spectrum for **3b**-*d*



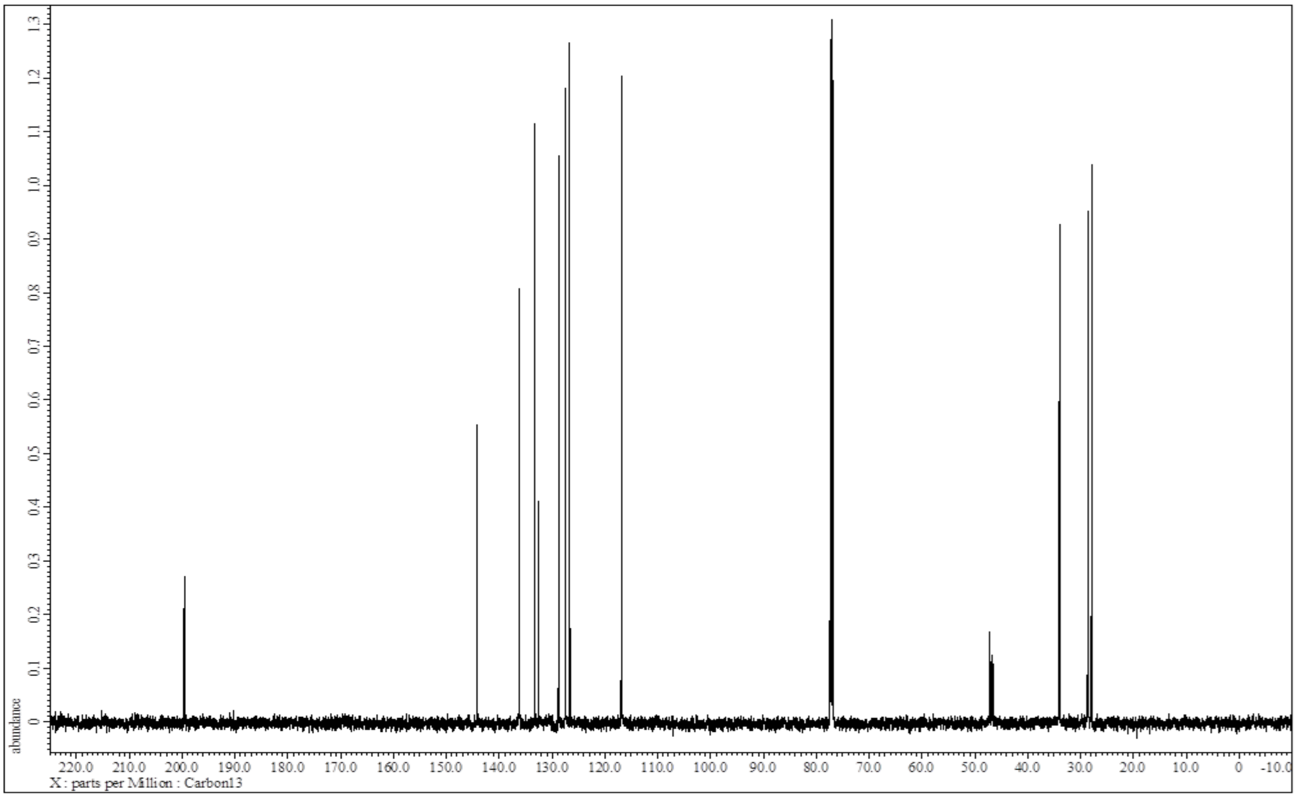
Peak	Retention Time [min]	Area [%]
1	21.902	49.880
2	23.807	50.120

Peak	Retention Time [min]	Area [%]
1	21.850	19.140
2	23.528	80.860

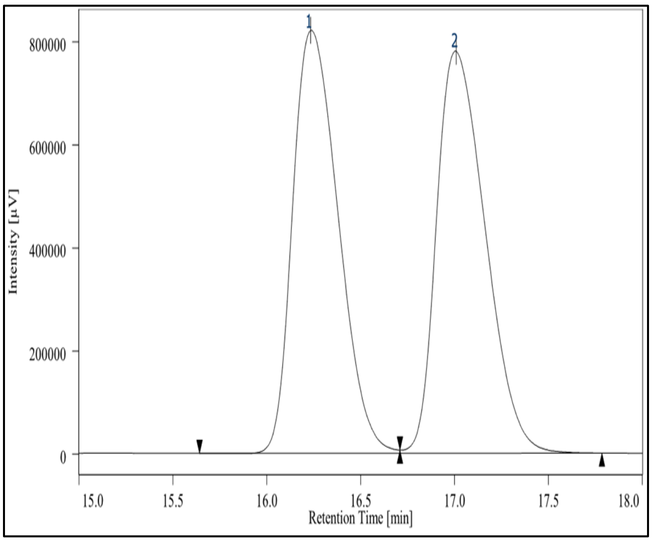
Supplementary figure 53. HPLC spectra for **3b**-*d*

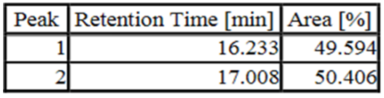


Supplementary figure 54. **^{1}**H NMR spectrum for **3c**-*d*

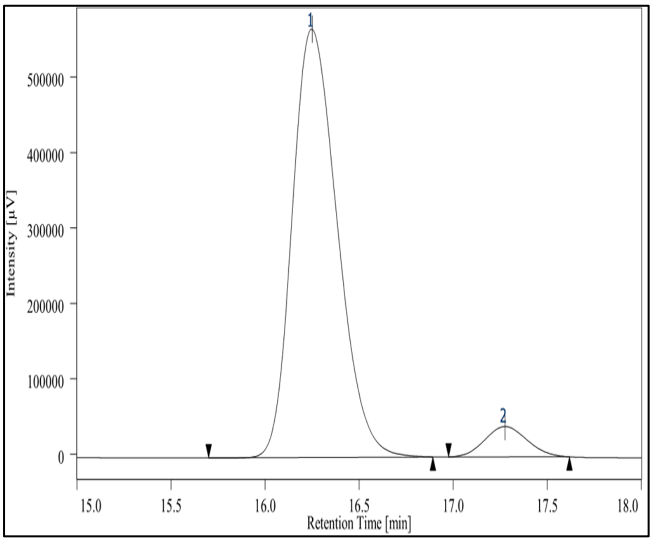


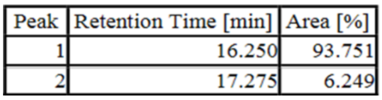
Supplementary figure 55. ^{13}C NMR spectrum for **3c**-*d*





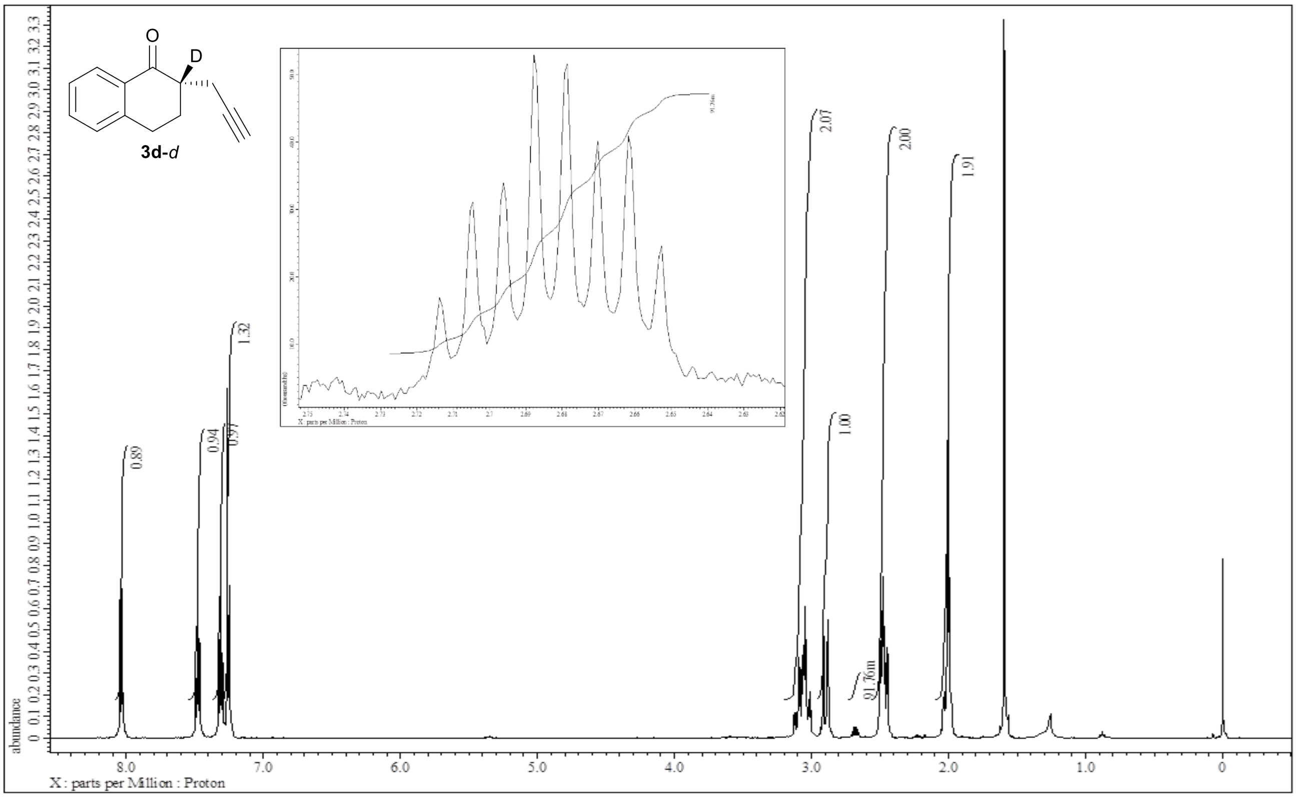
Peak	Retention Time [min]	Area [%]
1	16.233	49.594
2	17.008	50.406



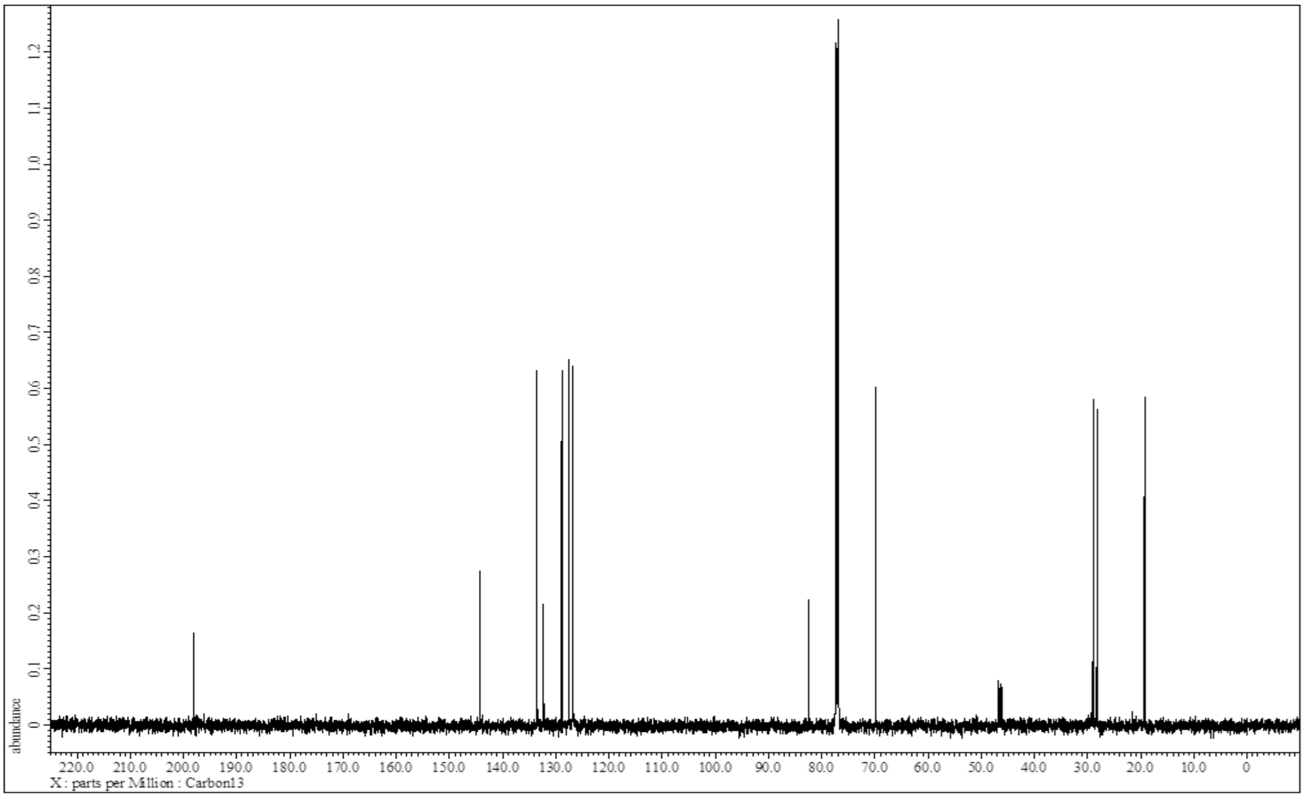


Peak	Retention Time [min]	Area [%]
1	16.250	93.751
2	17.275	6.249

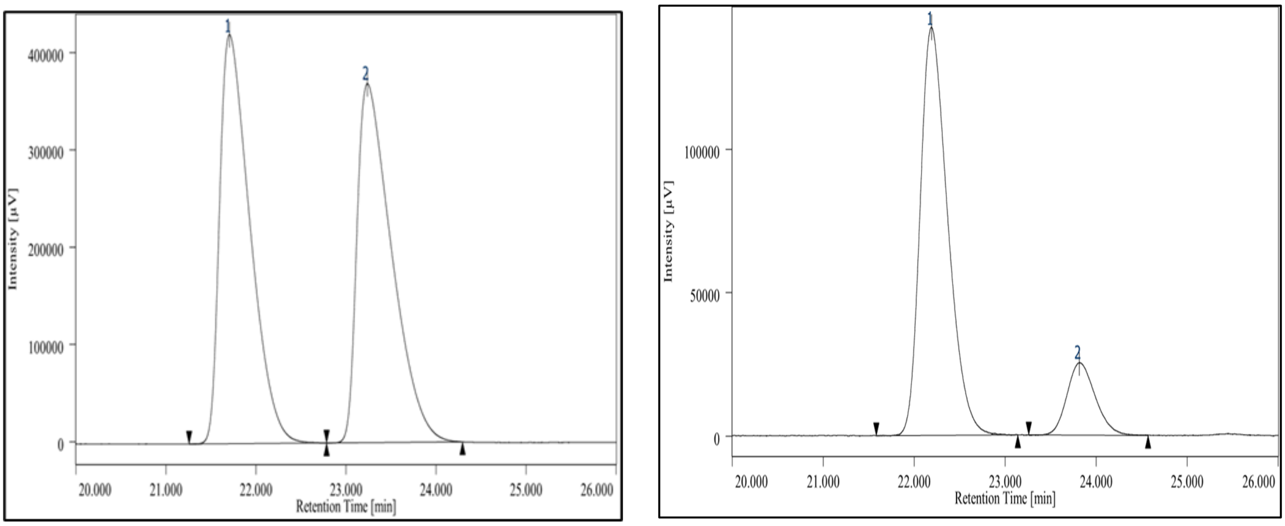
Supplementary figure 56. HPLC spectra for **3c**-*d*



Supplementary figure 57. ^{1}H NMR spectrum for **3d**-*d*



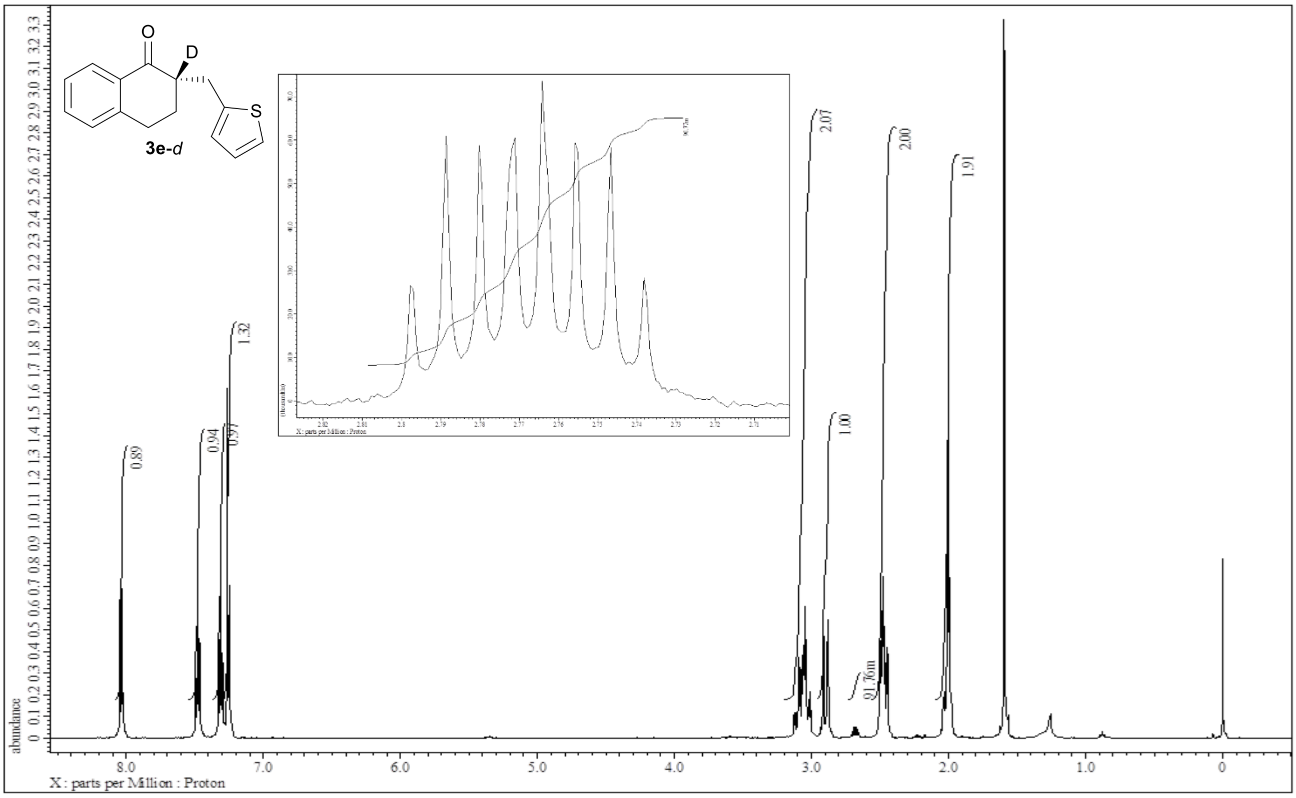
Supplementary figure 58. ^{13}C NMR spectrum for **3d**-*d*



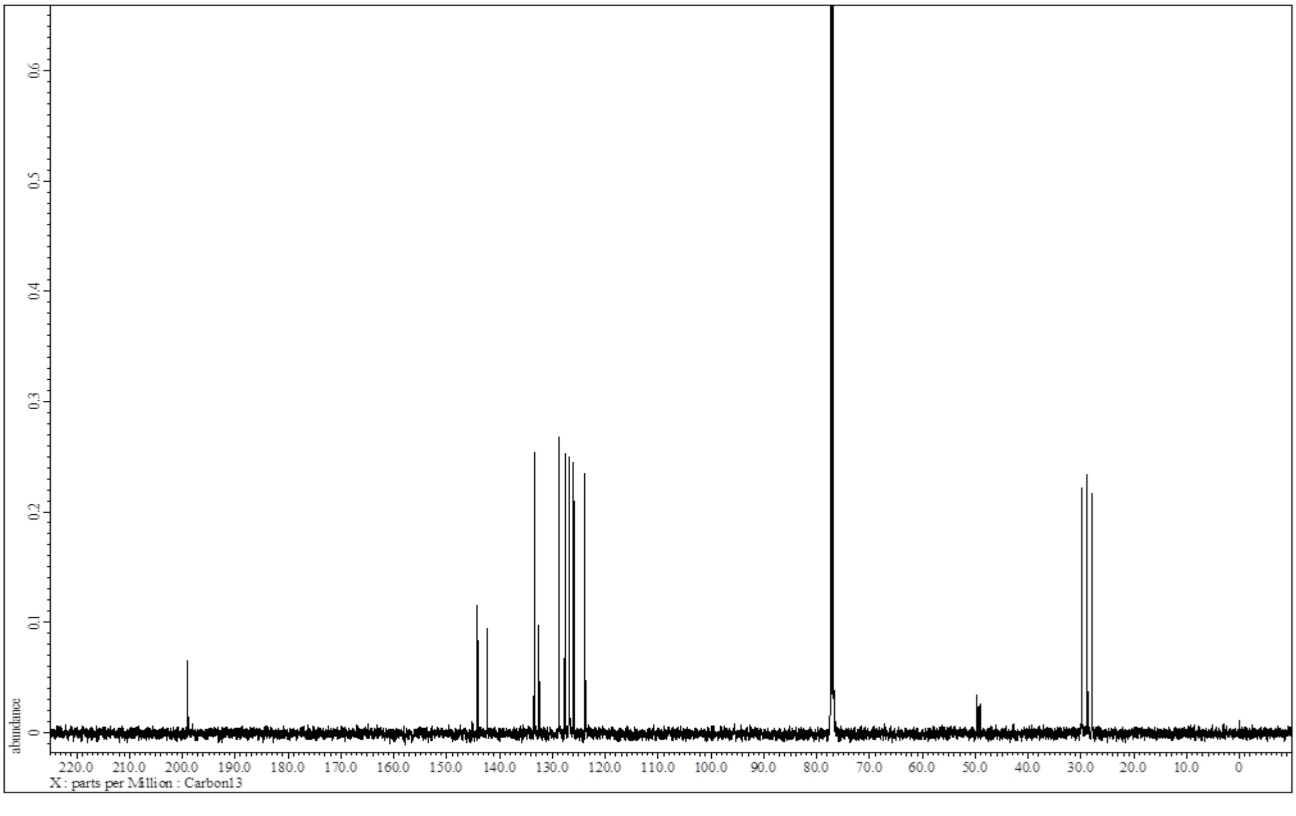
Peak	Retention Time [min]	Area [%]
1	21.705	49.952
2	23.235	50.048

Peak	Retention Time [min]	Area [%]
1	22.192	84.632
2	23.813	15.368

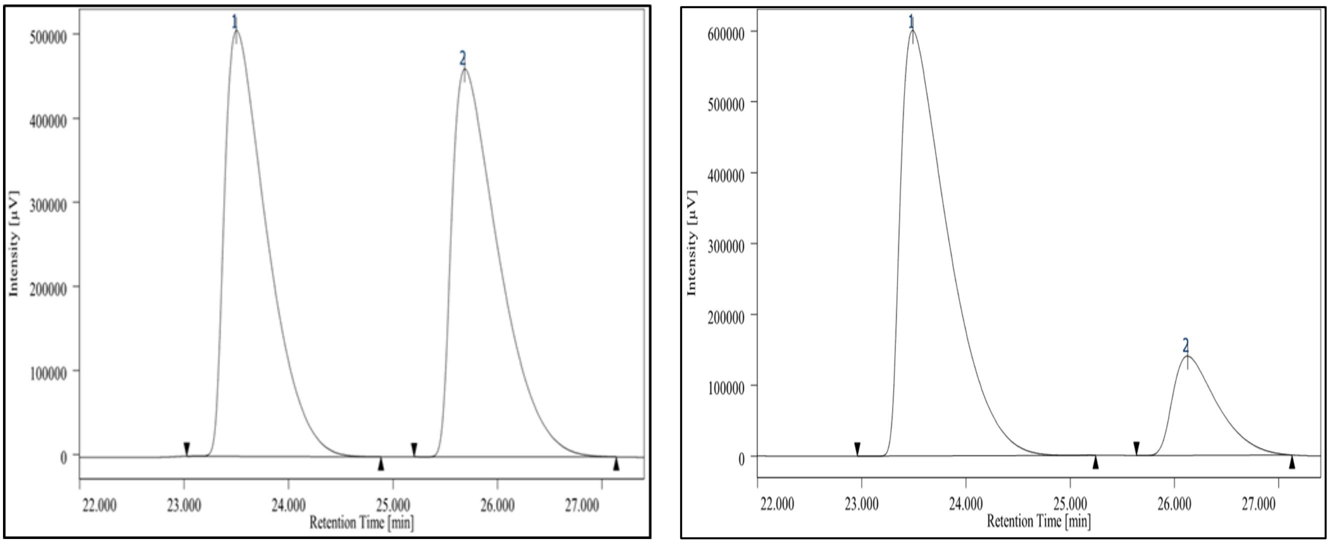
Supplementary figure 59. HPLC spectra for **3d**-*d*



Supplementary figure 60. ^{1}H NMR spectrum for **3e**-*d*



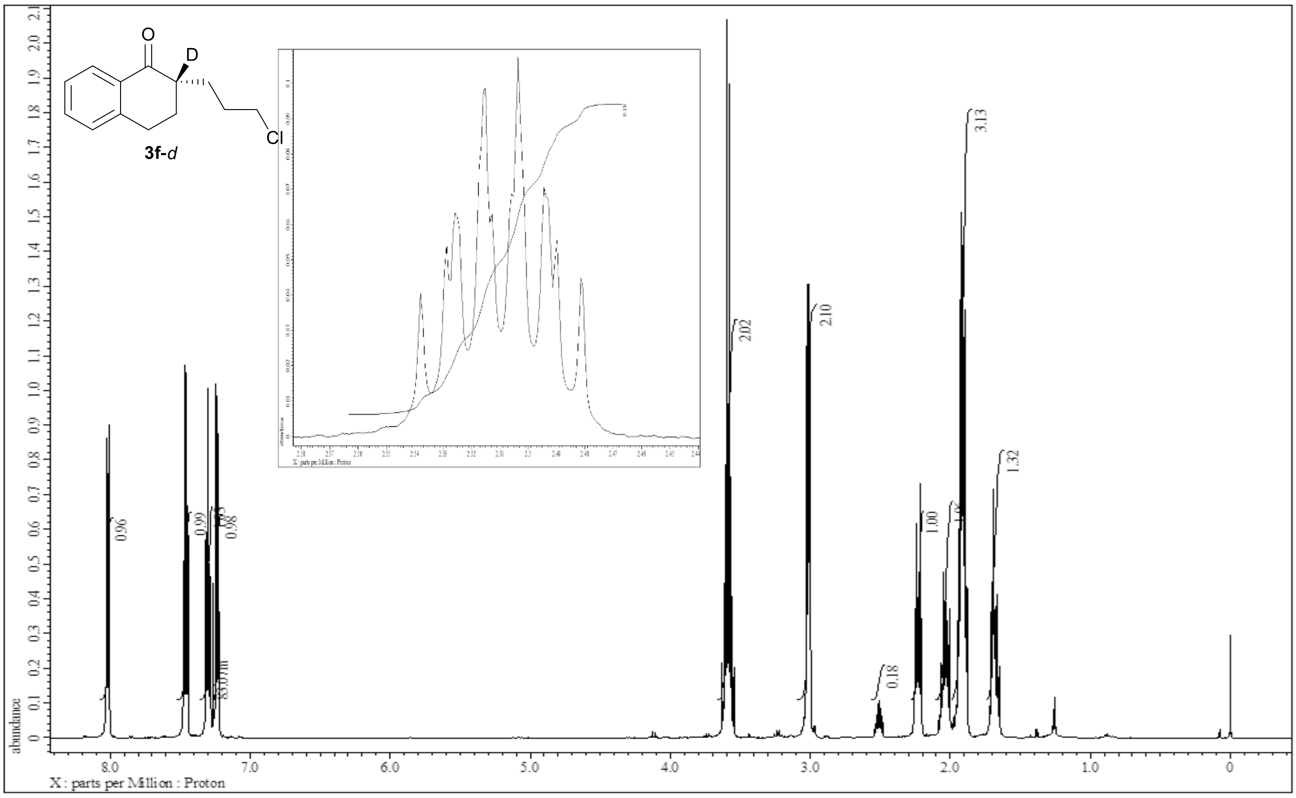
Supplementary figure 61. ^{13}C NMR spectrum for **3e**-*d*



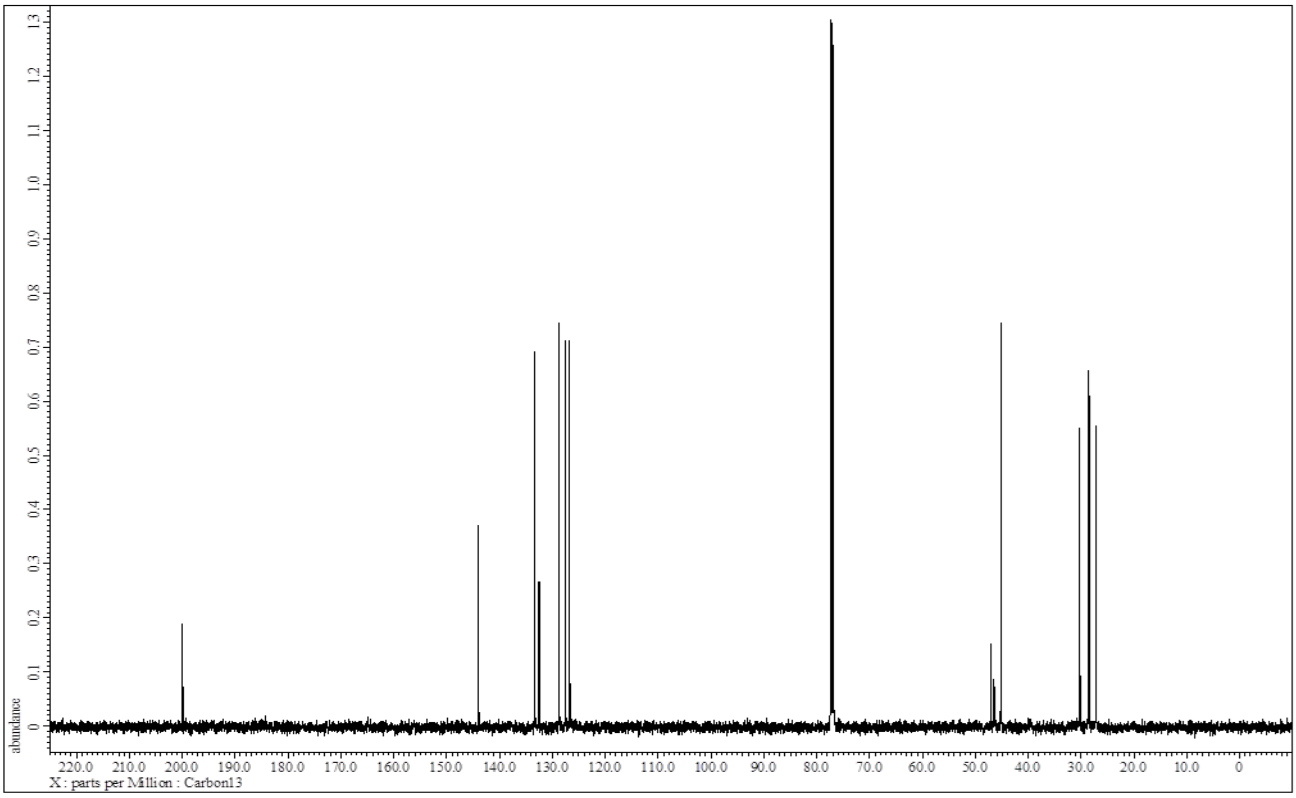
Peak	Retention Time [min]	Area [%]
1	23.500	49.801
2	25.683	50.199

Peak	Retention Time [min]	Area [%]
1	23.492	82.053
2	26.125	17.947

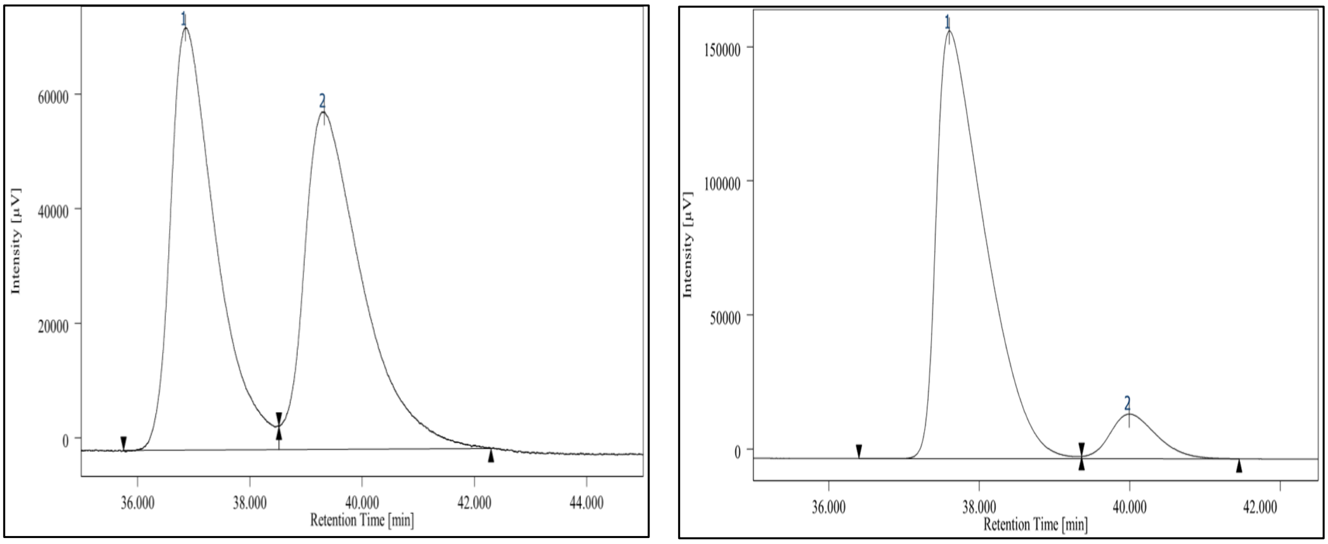
Supplementary figure 62. HPLC spectra for **3e**-*d*

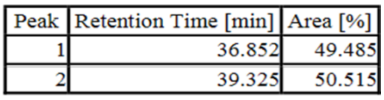


Supplementary figure 63. ^{1}H NMR spectrum for **3f**-*d*

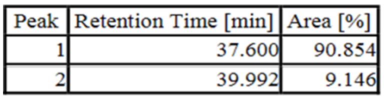


Supplementary figure 64. ^{13}C NMR spectrum for **3f**-*d*



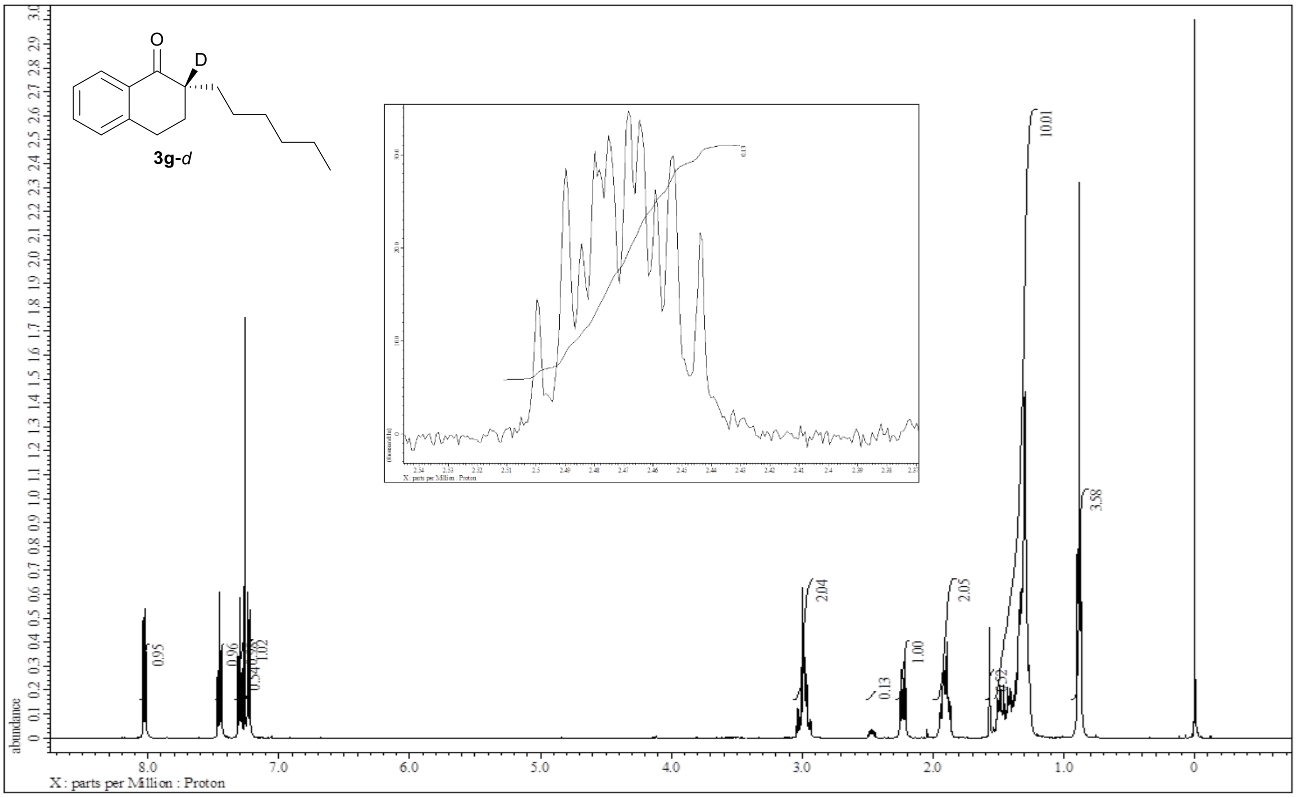


Peak	Retention Time [min]	Area [%]
1	36.852	49.485
2	39.325	50.515

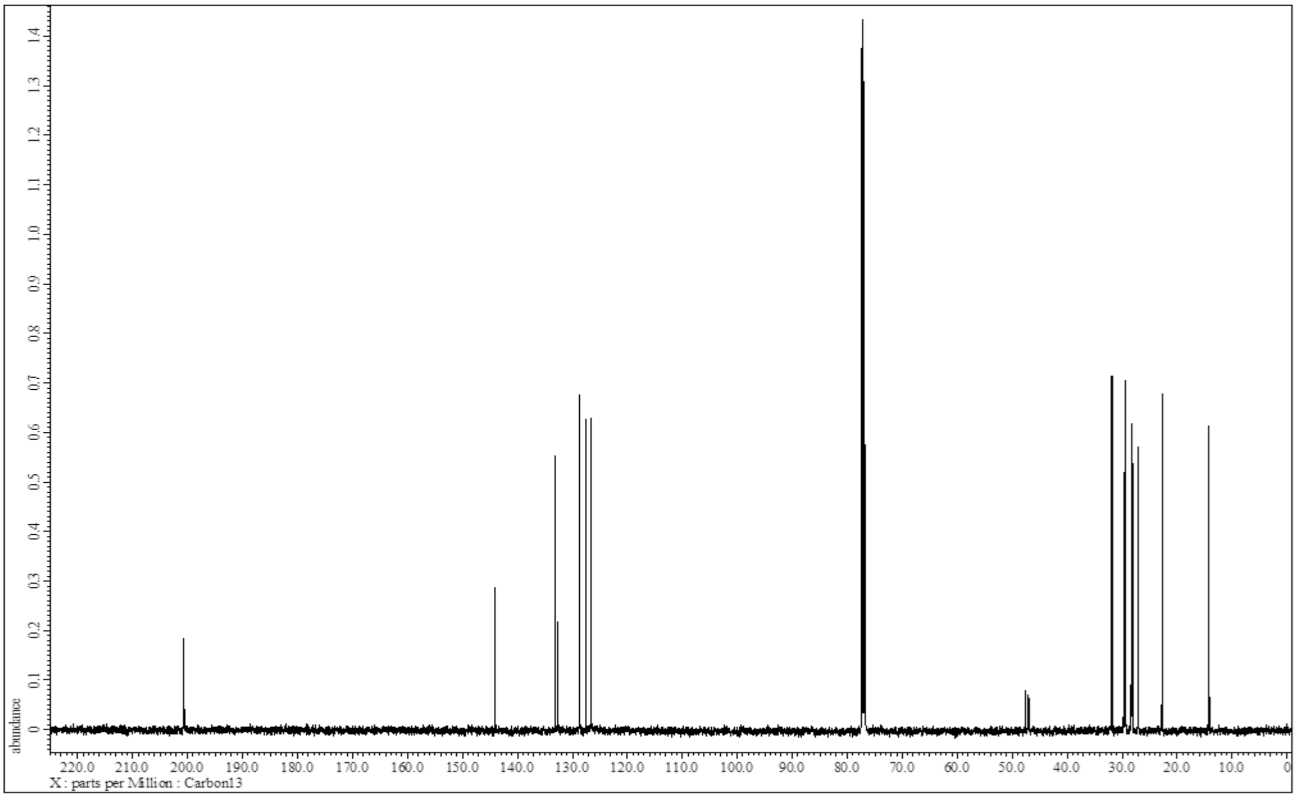


Peak	Retention Time [min]	Area [%]
1	37.600	90.854
2	39.992	9.146

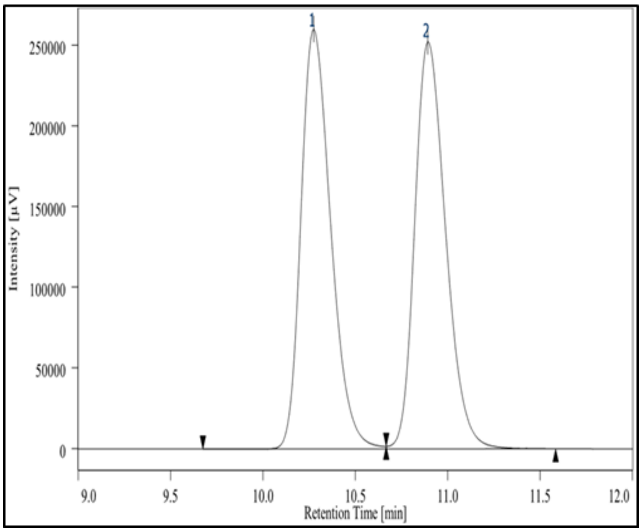
Supplementary figure 65. HPLC spectra for **3f**-*d*



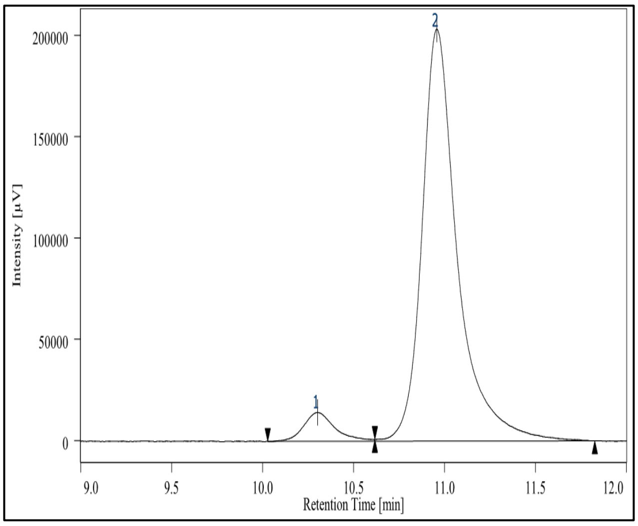
Supplementary figure 66. ^{1}H NMR spectrum for **3g**-*d*



Supplementary figure 67. ^{13}C NMR spectrum for **3g**-*d*

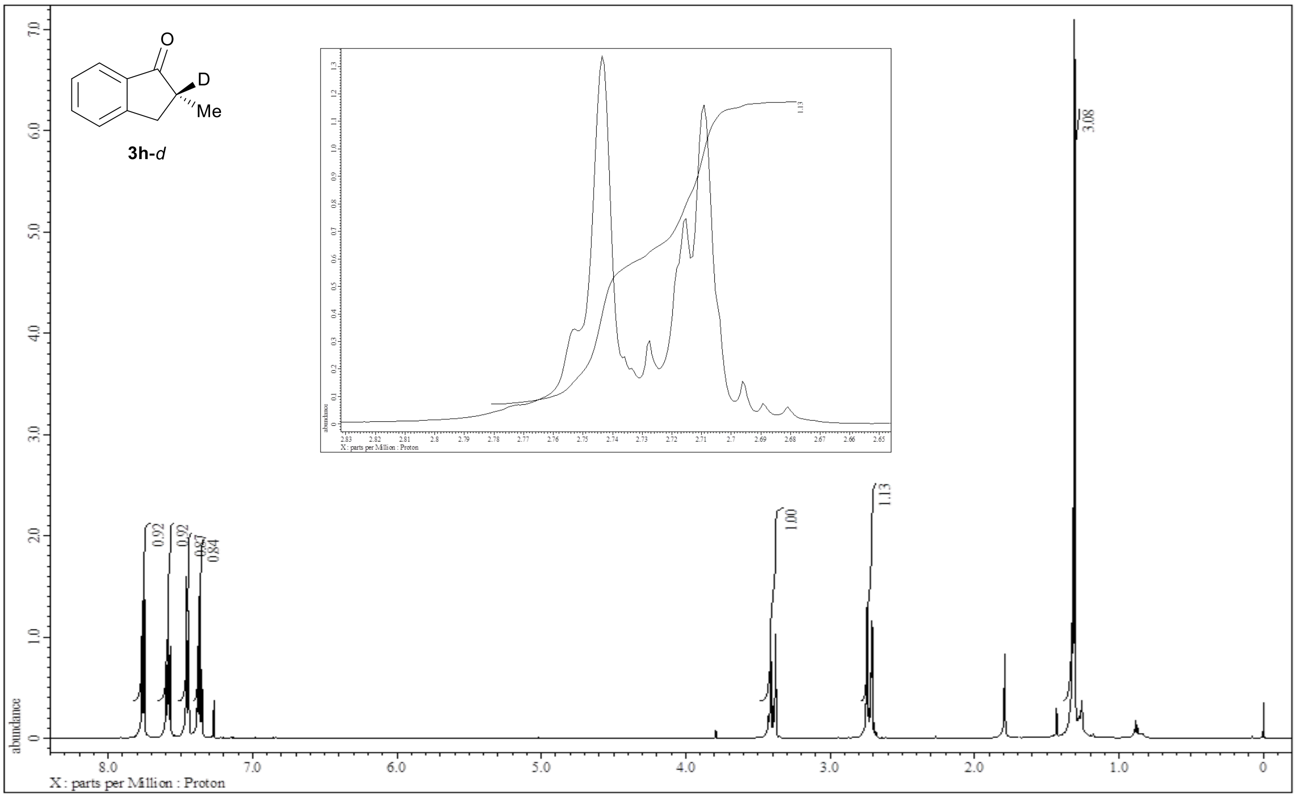


Peak	Retention Time [min]	Area [%]
1	10.275	49.866
2	10.892	50.134

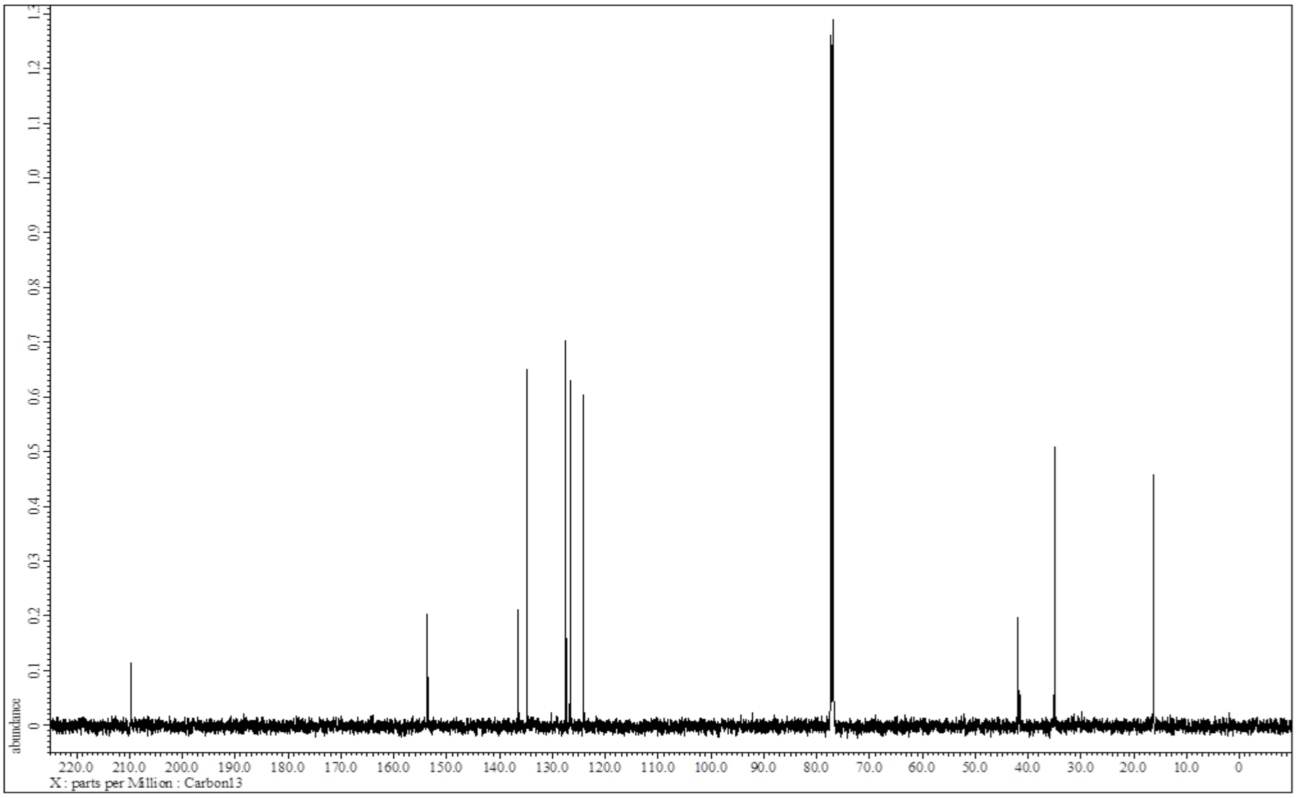


Peak	Retention Time [min]	Area [%]
1	10.302	5.879
2	10.957	94.121

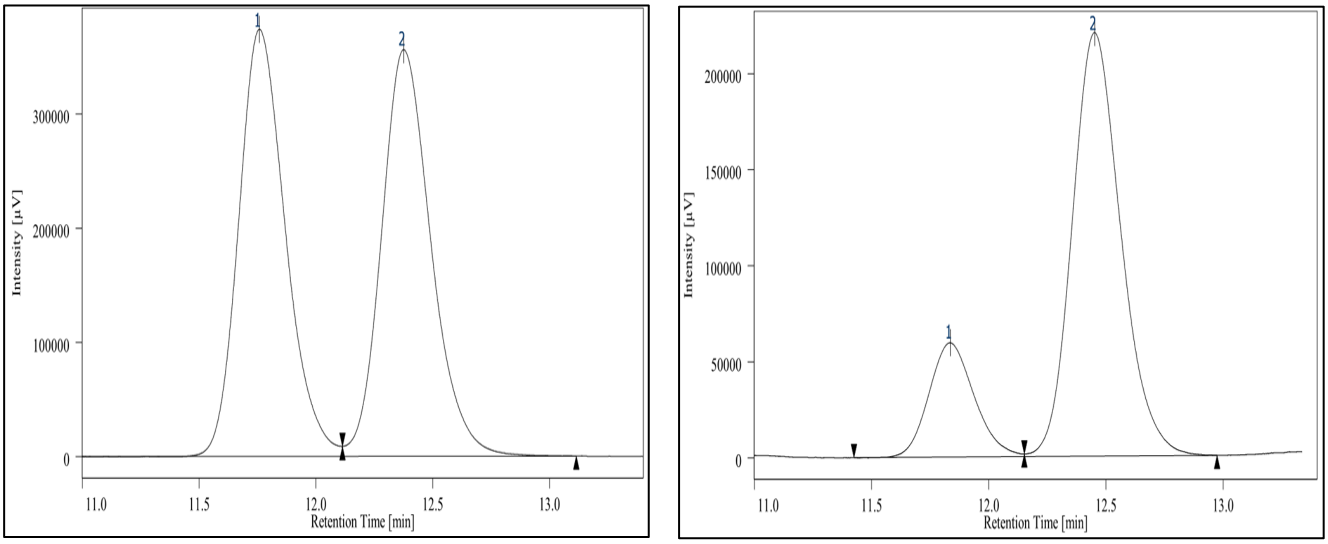
Supplementary figure 68. HPLC spectra for **3g**-*d*



Supplementary figure 69. ^{1}H NMR spectrum for **3h**-*d*



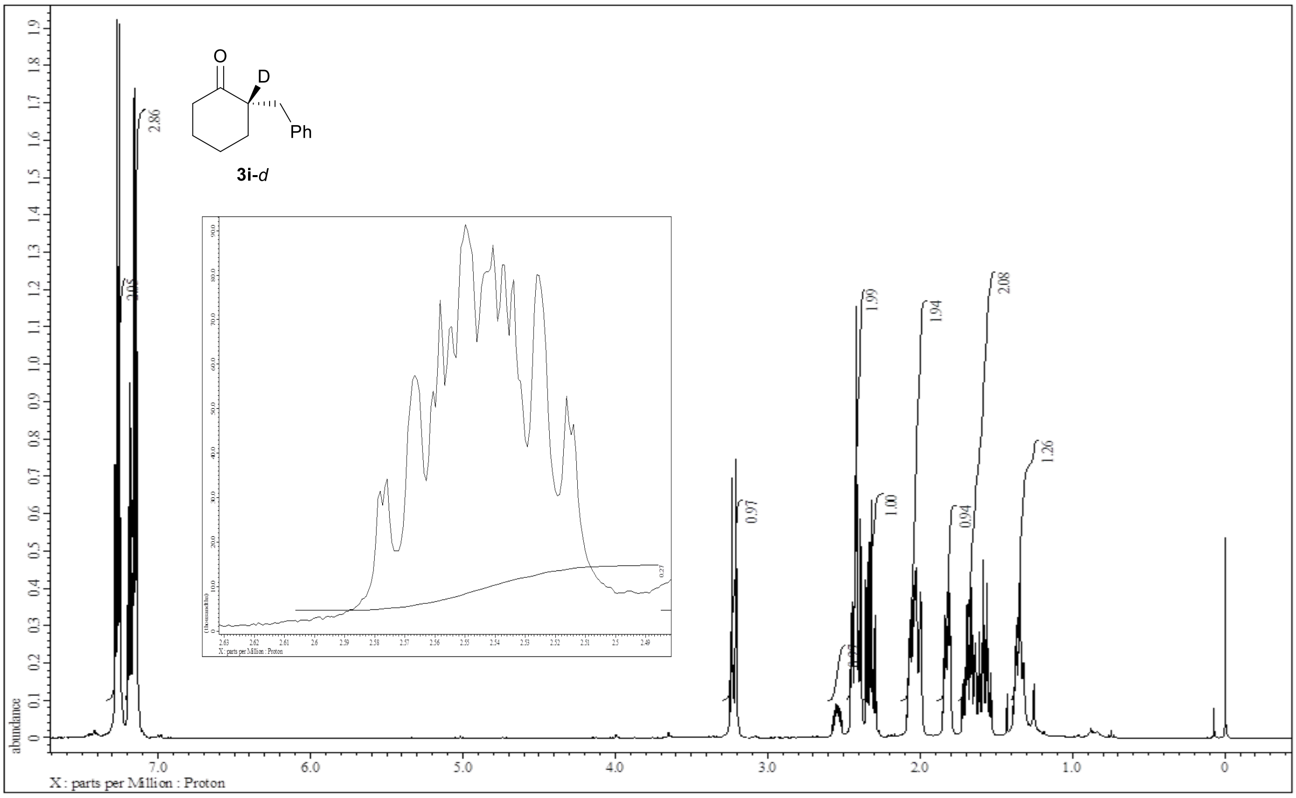
Supplementary figure 70. ^{13}C NMR spectrum for **3h**-*d*



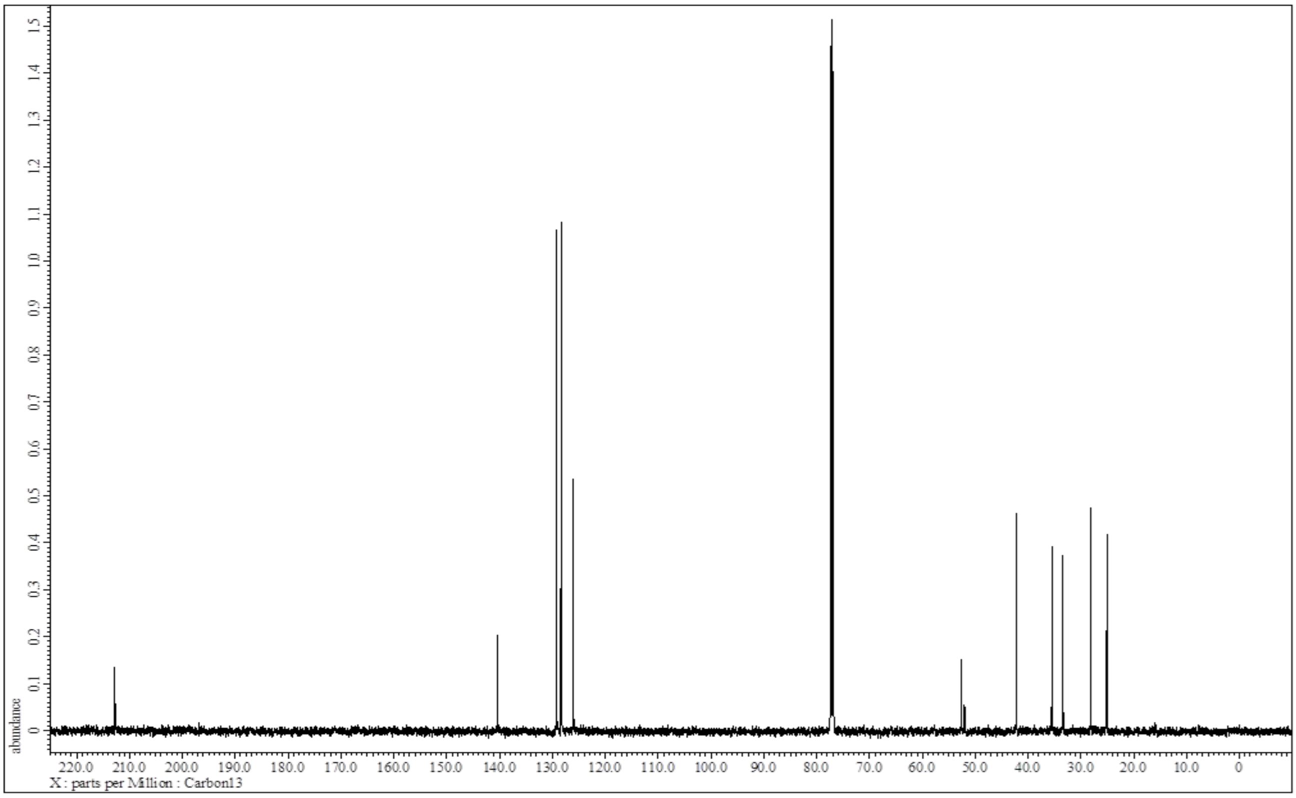
Peak	Retention Time [min]	Area [%]
1	11.758	49.794
2	12.375	50.206

Peak	Retention Time [min]	Area [%]
1	11.837	20.061
2	12.452	79.939

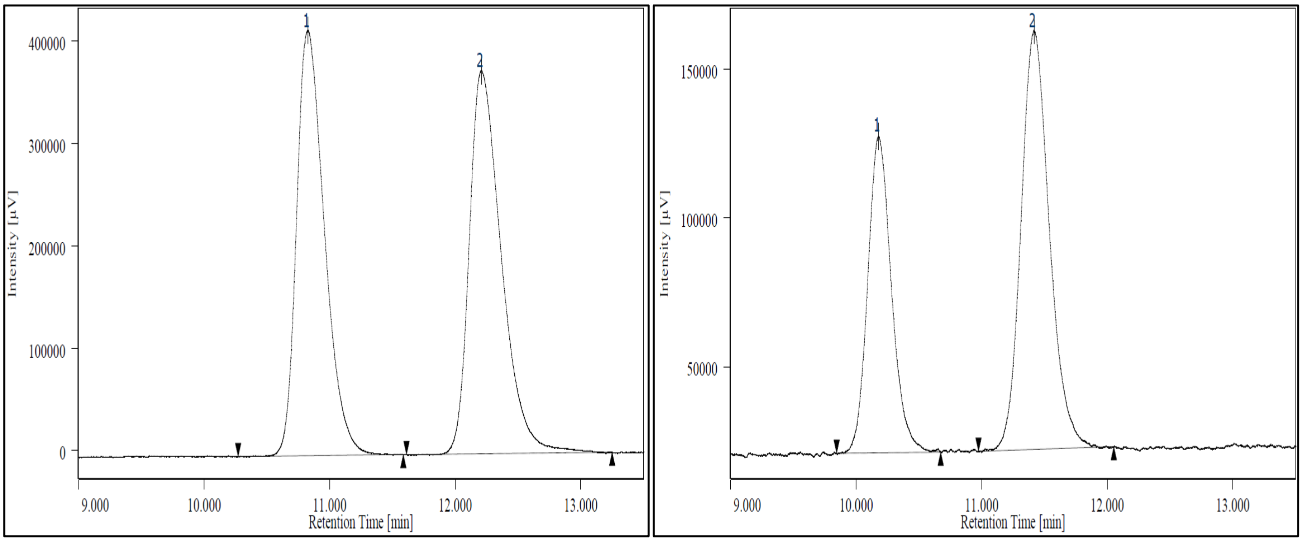
Supplementary figure 71. HPLC spectra for **3h**-*d*



Supplementary figure 71. ^{1}H NMR spectrum for **3i**-*d*



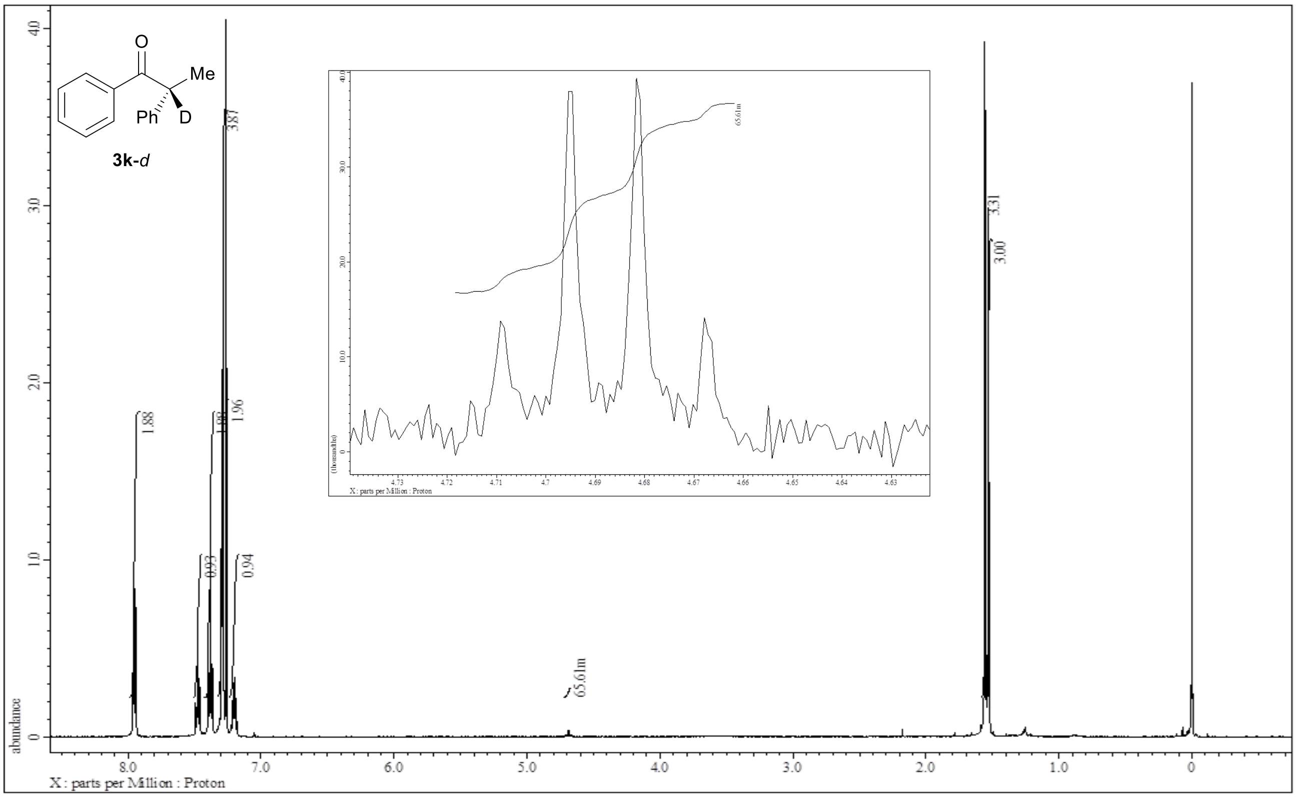
Supplementary figure 72. ^{13}C NMR spectrum for **3i**-*d*



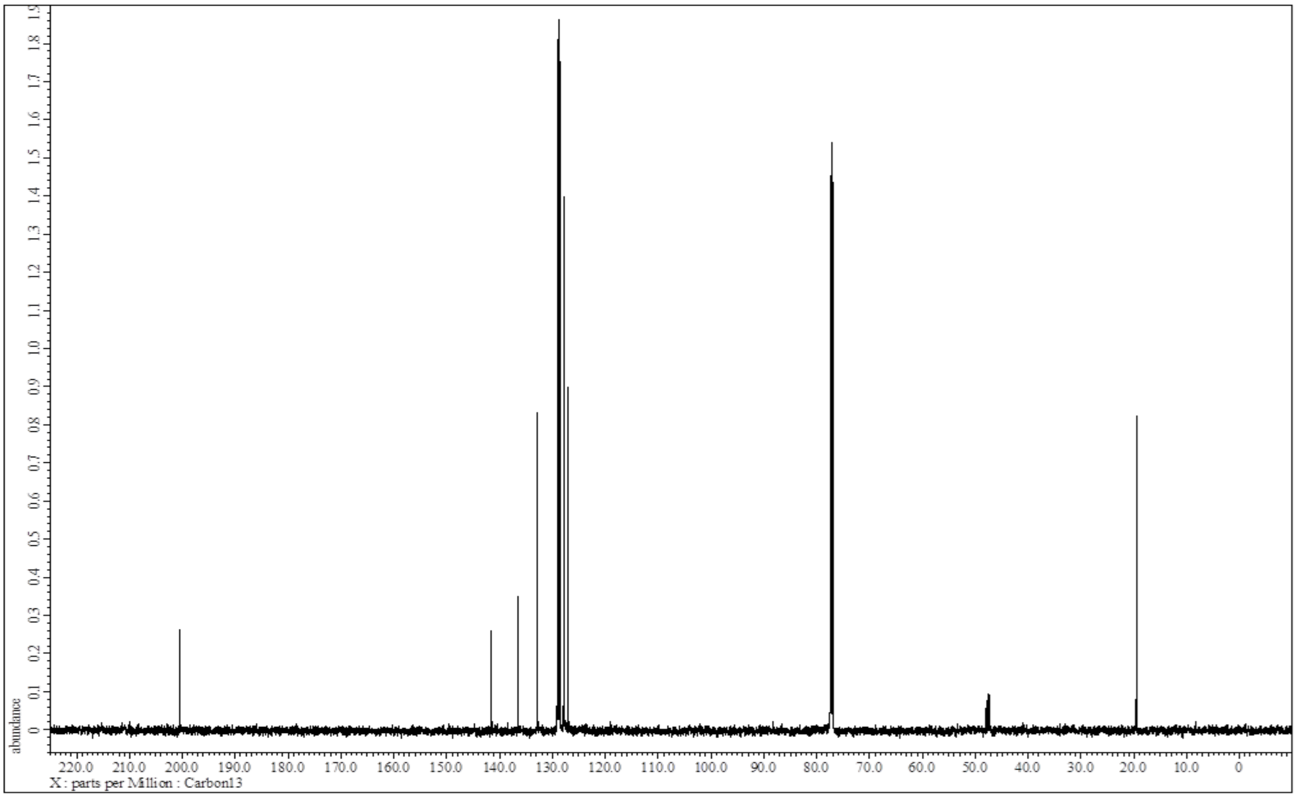
Peak	Retention Time [min]	Area [%]
1	10.828	49.130
2	12.210	50.870

Peak	Retention Time [min]	Area [%]
1	10.180	38.787
2	11.417	61.213

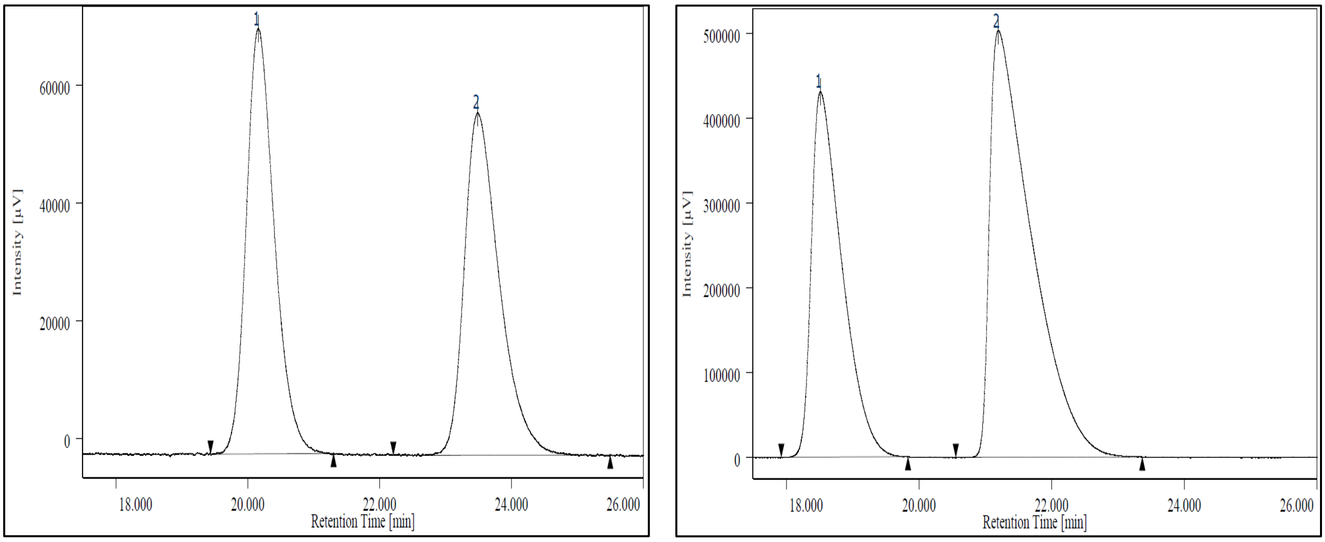
Supplementary figure 73. HPLC spectra for **3i**-*d*



Supplementary figure 74. ^{1}H NMR spectrum for **3k**-*d*



Supplementary figure 75. ^{13}C NMR spectrum for **3k**-*d*



Peak	Retention Time [min]	Area [%]
1	20.162	49.945
2	23.490	50.055

Peak	Retention Time [min]	Area [%]
1	18.515	38.577
2	21.195	61.423

Supplementary figure 76. HPLC spectra for **3k**-*d*