Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers.

Supporting Information

Au/TiO_2 Catalyzed Reductive Amination of Aldehydes and Ketones Using Formic Acid as Reductant

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1. General

^{1}H NMR spectra were recorded at 400 MHz using $CDCl_3$ as a solvent and TMS as internal standard. The chemical shifts are reported in δ (ppm) values, multiplicities are indicated by s (singlet), d (doublet), t (triplet), q (quartet), p (pentet), h (hextet), m (multiplet) and br (broad). Coupling constants (*J*), are reported in Hertz (Hz). All reagents and solvents were employed without further purification. The products were purified using a commercial flash chromatography system. TLC was developed on silica gel 60 F254 aluminum sheets. All reagents were purchased from Aldrich or Alfa Aesar and used as received without any further purification. Au/TiO_2 (1% wt/wt loading; average size of AuNPs is around 2-3 nm) was purchased from Strem.

2. General procedures

General procedure for reductive amination of ketones and aldehydes

Au/TiO_2 (49.3 mg, 1 mol %) was added to a solution of ketone **1** or aldehyde **3** (0.25 mmol), amine **2** (1.0 mmol, 4 equiv) in *t*-BuOH (0.25 mL). Then HCOOH (1.0 mmol, 4 equiv) was also added into the mixture. The reaction mixture was stirred in an oil bath at 60 ^{o}C for the designated time and cooled down to room temperature. Then the solid Au/TiO_2 was filtered, the filtrate was concentrated to dryness and it was subjected to flash chromatography.

General one-pot procedure for reduction and formylation of aldehydes

Au/TiO_2 (197 mg, 1 mol %) was added to a mixture of aldehyde **3** (1 mmol), and HCOOH (4 mmol, 4 equiv) in THF (0.25 mL). The mixture was stirred in an oil bath at 80 ^{o}C for the designated time and cooled down to room temperature. Then the solid Au/TiO_2 was filtered, the filtrate was concentrated to dryness and it was subjected to flash chromatography.

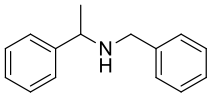
Procedure for Au/TiO_2 recycling test

Au/TiO_2 (49.3 mg, 1 mol %) was added to a solution of benzaldehyde (0.25 mmol), benzylamine (1.0 mmol) in *t*-BuOH (0.25 mL), then HCOOH (1.0 mmol) and internal standard 1,3,5-trimethoxybenzene were also added. The mixture was stirred for 3 hours at 60 ^{o}C. After cooled down to room temperature, Au/TiO_2 was filtered out and washed with *t*-BuOH. And then it was transferred into a fresh solution of benzaldehyde (0.25 mmol), benzylamine (1.0 mmol) in *t*-BuOH (0.25 ml). The mixture was stirred for another 3 hours at 60 ^{o}C. And this process was repeated until 5 runs were completed. The yields of each run were determined by ^{1}H NMR.

3. Characterization of 4, 5 and 6

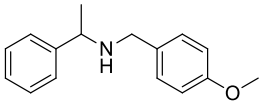
All the compounds are known and their spectroscopic data agree well with the spectra reported in the literature noted for each of them.

N-benzyl-1-phenylethanamine (**4a**)[1]



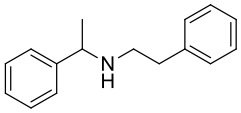
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.16 (m, 10H), 3.81 (d, *J* = 6.6 Hz, 1H), 3.63 (q, *J* = 13.2 Hz, 2H), 1.61 – 1.48 (s, 1H), 1.37 (d, *J* = 6.6 Hz, 3H).

N-(4-methoxybenzyl)-1-phenylethanamine (**4b**)[2]



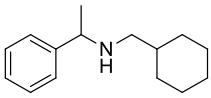
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.32 (m, 3H), 7.30 – 7.13 (m, 4H), 6.84 (d, *J* = 8.5 Hz, 2H), 3.80 (m, *J* = 6.0 Hz, 3H), 3.56 (q, *J* = 12.9 Hz, 2H), 1.52 (s, 1H), 1.36 (d, *J* = 6.6 Hz, 1H).

N-phenethyl-1-phenylethanamine (**4c**)[3]



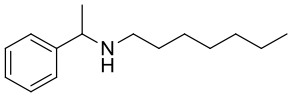
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.10 (m, 10H), 3.77 (q, *J* = 6.6 Hz, 1H), 2.87 – 2.63 (m, 4H), 1.33 (d, *J* = 6.6 Hz, 4H).

N-(cyclohexylmethyl)-1-phenylethanamine (**4d**)[4]



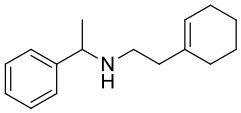
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.15 (m, 5H), 3.79 – 3.66 (m, 1H), 2.43 – 2.17 (m, 2H), 1.82 – 1.56 (m, 5H), 1.51 – 1.03 (m, 8H), 0.86 (p, *J* = 12.0 Hz, 2H).

N-(1-phenylethyl)heptan-1-amine (**4e**)[5]



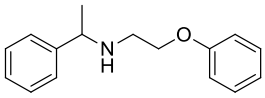
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 – 7.15 (m, 5H), 3.75 (q, *J* = 6.5 Hz, 1H), 2.44 (ddd, *J* = 19.0, 11.2, 3.9 Hz, 2H), 1.55 – 1.14 (m, 14H), 0.86 (t, *J* = 6.2 Hz, 3H).

2-(cyclohex-1-en-1-yl)-N-(1-phenylethyl)ethanamine (**4f**)[6]



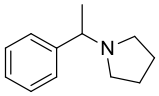
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.17 (m, 5H), 5.43 (s, 1H), 3.75 (q, *J* = 6.5 Hz, 1H), 2.62 – 2.41 (m, 2H), 2.10 (t, *J* = 6.9 Hz, 2H), 1.97 (m, 2H), 1.82 (m, 2H), 1.66 – 1.47 (m, 4H), 1.34 (d, *J* = 6.6 Hz, 4H).

2-phenoxy-N-(1-phenylethyl)ethanamine (**4g**)[7]



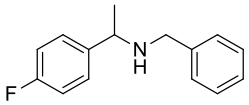
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.18 (m, 7H), 6.98 – 6.84 (m, 3H), 4.03 (dd, *J* = 9.9, 5.3 Hz, 2H), 3.85 (q, *J* = 6.6 Hz, 1H), 2.86 (ddd, *J* = 17.4, 12.8, 6.8 Hz, 2H), 1.82 (s, 1H), 1.39 (d, *J* = 6.6 Hz, 3H).

1-(1-phenylethyl)pyrrolidine (**4h**)[1]



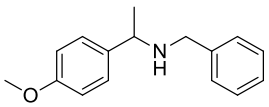
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28 (m, 5H), 3.18 (q, *J* = 6.6 Hz, 1H), 2.55 (dd, *J* = 9.6, 3.7 Hz, 2H), 2.37 (dd, *J* = 9.6, 4.5 Hz, 2H), 1.75 (m, 5H), 1.40 (d, *J* = 6.6 Hz, 3H).

N-benzyl-1-(4-fluorophenyl)ethanamine (**4i**)[2]



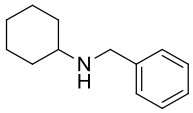
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.18 (m, 7H), 7.02 (m, 2H), 3.80 (q, *J* = 6.6 Hz, 1H), 3.60 (q, *J* = 13.2 Hz, 2H), 1.56 (s, 1H), 1.34 (d, *J* = 6.6 Hz, 3H).

N-benzyl-1-(4-methoxyphenyl)ethanamine (**4j**)[8]



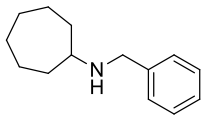
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.16 (m, 7H), 6.89 (d, *J* = 8.5 Hz, 2H), 3.88 – 3.72 (m, 4H), 3.62 (q, *J* = 13.2 Hz, 2H), 1.35 (d, *J* = 6.6 Hz, 3H).

N-benzylcyclohexanamine (**4k**)[9]



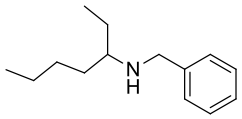
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 – 7.16 (m, 5H), 3.81 (s, 2H), 2.54 – 2.41 (m, 1H), 1.91 (d, *J* = 12.3 Hz, 2H), 1.79 – 1.68 (m, 2H), 1.61 (d, *J* = 11.5 Hz, 1H), 1.39 – 1.01 (m, 6H).

N-benzylcycloheptanamine (**4l**)[9]



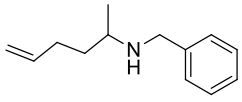
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.15 (m, 5H), 3.77 (s, 2H), 2.74 – 2.64 (m, 1H), 1.93 – 1.80 (m, 2H), 1.76 – 1.31 (m, 11H).

N-benzylheptan-3-amine (**4m**)[10]



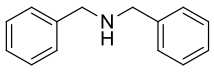
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 – 7.14 (m, 5H), 3.83 – 3.72 (m, 2H), 2.50 (p, *J* = 5.8 Hz, 1H), 1.57 – 1.19 (m, 9H), 0.97 – 0.83 (m, 6H).

N-benzylhex-5-en-2-amine (**4n**)[11]



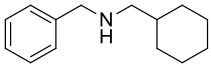
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 – 7.19 (m, 5H), 5.89 – 5.72 (m, 1H), 5.06 – 4.89 (m, 2H), 3.78 (dd, *J* = 36.5, 13.0 Hz, 2H), 2.71 (dd, *J* = 12.5, 6.3 Hz, 1H), 2.15 – 2.01 (m, 2H), 1.64 – 1.34 (m, 3H), 1.08 (dd, *J* = 11.2, 4.4 Hz, 3H).

dibenzylamine (**5a**)[12]



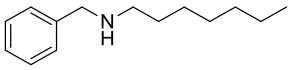
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.28 (m, 8H), 7.25 (dq, *J* = 5.1, 2.5 Hz, 2H), 3.82 (s, 4H).

N-benzyl-1-cyclohexylmethanamine (**5b**)[9]



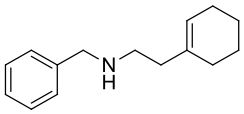
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 – 7.16 (m, 5H), 3.77 (s, 2H), 2.46 (d, *J* = 6.7 Hz, 2H), 1.71 (dd, *J* = 32.7, 14.7 Hz, 5H), 1.54 – 1.08 (m, 5H), 0.91 (dd, *J* = 22.7, 11.0 Hz, 2H).

N-benzylheptan-1-amine (**5c**)[13]



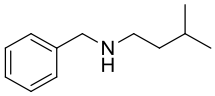
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.15 (m, 5H), 3.79 (d, *J* = 1.7 Hz, 2H), 2.67 – 2.52 (m, 2H), 1.56 – 1.41 (m, 2H), 1.28 (m, 9H), 0.88 (dd, *J* = 6.7, 5.0 Hz, 3H).

N-benzyl-2-(cyclohex-1-en-1-yl)ethanamine (**5d**)[14]



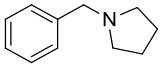
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.19 (m, 5H), 5.46 (s, 1H), 3.79 (s, 2H), 2.69 (t, *J* = 6.9 Hz, 2H), 2.16 (t, *J* = 6.9 Hz, 2H), 1.98 (d, *J* = 1.7 Hz, 2H), 1.87 (d, *J* = 4.6 Hz, 2H), 1.64 – 1.50 (m, 4H), 1.41 (s, 1H).

N-benzyl-3-methylbutan-1-amine (**5e**)[15]



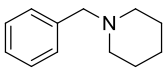
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28 (dd, J = 27.7, 5.6 Hz, 5H), 3.79 (s, 2H), 2.71 – 2.57 (m, 2H), 1.68 – 1.54 (m, 1H), 1.43-1.38 (m, 3H), 0.89 (d, J = 6.6 Hz, 6H).

1-benzylpyrrolidine (**5f**)[16]



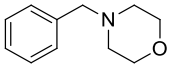
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 – 7.15 (m, 5H), 3.61 (s, 2H), 2.50 (m, 4H), 1.78 (m, 4H).

1-benzylpiperidine (**5g**)[17]



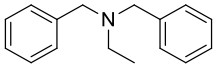
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.17 (m, 5H), 3.47 (s, 2H), 2.38 (m, 4H), 1.64 – 1.52 (m, 4H), 1.48 – 1.36 (m, 2H).

4-benzylmorpholine (**5h**)[12]



^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.14 (m, 5H), 3.79 – 3.66 (m, 4H), 3.50 (s, 2H), 2.56 – 2.38 (m, 4H).

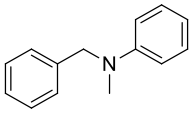
N,N-dibenzylethanamine (**5i**)[18]



^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (d, *J* = 7.2 Hz, 4H), 7.36 (t, *J* = 7.6 Hz, 4H), 7.27 (t, *J* = 7.3 Hz, 2H), 3.63 (s, 4H), 2.56 (q, *J* = 7.1 Hz, 2H), 1.13 (t, *J* = 7.1 Hz, 3H).

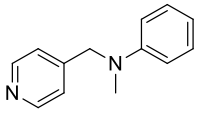
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 – 7.14 (m, 5H), 3.79 – 3.66 (m, 4H), 3.50 (s, 2H), 2.56 – 2.38 (m, 4H).

N-benzyl-N-methylaniline (**5j**)[18]



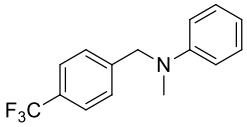
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.13 (m, 7H), 6.82 – 6.66 (m, 3H), 4.54 (s, 2H), 2.99 (d, *J* = 28.5 Hz, 3H).

N-methyl-N-(pyridin-4-ylmethyl)aniline (**5k**)[19]



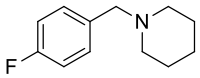
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.53 (d, *J* = 5.5 Hz, 2H), 7.31 – 7.12 (m, 4H), 6.79 – 6.64 (m, 3H), 4.52 (s, 2H), 3.05 (s, 3H).

N-methyl-N-(4-(trifluoromethyl)benzyl)aniline (**5l**)[20]



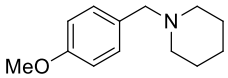
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, *J* = 8.2 Hz, 2H), 7.36 (d, *J* = 8.1 Hz, 2H), 7.25 (dd, *J* = 9.9, 5.9 Hz, 2H), 6.76 (t, *J* = 8.7 Hz, 3H), 4.59 (s, 2H), 3.05 (s, 3H).

1-(4-fluorobenzyl)piperidine (**5m**)[21]



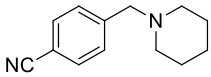
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (t, *J* = 7.4 Hz, 1H), 7.22 (d, *J* = 6.6 Hz, 1H), 7.09 (t, *J* = 7.4 Hz, 1H), 7.01 (t, *J* = 9.1 Hz, 1H), 3.55 (s, 2H), 2.42 (m, 4H), 1.64 – 1.50 (m, 4H), 1.44-1.41 (m, 2H)

1-(4-fluorobenzyl)piperidine (**5n**)[21]



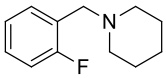
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26 – 7.17 (m, 2H), 6.84 (d, *J* = 8.5 Hz, 2H), 3.79 (s, 3H), 3.41 (s, 2H), 2.35 (s, 4H), 1.61 – 1.48 (m, 4H), 1.42 (d, *J* = 5.1 Hz, 2H).

4-(piperidin-1-ylmethyl)benzonitrile (**5o**)[21]



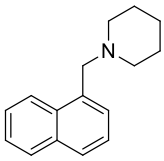
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (d, *J* = 7.1 Hz, 2H), 7.43 (d, *J* = 7.7 Hz, 2H), 3.49 (s, 2H), 2.35 (s, 4H), 1.56 (dd, *J* = 10.9, 5.5 Hz, 4H), 1.44 (d, *J* = 5.1 Hz, 2H).

1-(2-fluorobenzyl)piperidine (**5p**)[22]



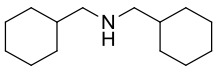
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (t, *J* = 7.4 Hz, 1H), 7.22 (d, *J* = 6.6 Hz, 1H), 7.09 (t, *J* = 7.4 Hz, 1H), 7.01 (t, *J* = 9.1 Hz, 1H), 3.55 (s, 2H), 2.42 (s, 4H), 1.66 – 1.50 (m, 4H), 1.42 (d, *J* = 5.0 Hz, 2H).

1-(naphthalen-1-ylmethyl)piperidine (**5q**)[22]



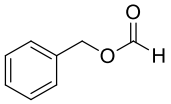
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (d, *J* = 8.0 Hz, 1H), 7.86 (d, *J* = 8.1 Hz, 1H), 7.78 (d, *J* = 7.9 Hz, 1H), 7.55 – 7.37 (m, 4H), 3.88 (s, 2H), 2.48 (s, 4H), 1.65 – 1.53 (m, 4H), 1.47 (d, *J* = 5.0 Hz, 2H).

bis(cyclohexylmethyl)amine (**5r**)[23]



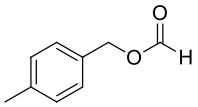
^{1}H NMR (400 MHz, $CDCl_3$) δ 2.39 (d, *J* = 6.7 Hz, 4H), 1.69 (dd, *J* = 24.2, 13.2 Hz, 10H), 1.57 – 1.38 (m, 2H), 1.20 (dd, *J* = 24.6, 12.0 Hz, 7H), 0.89 (t, *J* = 11.5 Hz, 4H).

benzyl formate (**6a**)[24]



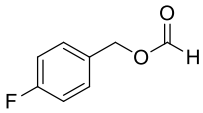
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15 (d, *J* = 0.9 Hz, 1H), 7.41 – 7.30 (m, 5H), 5.21 (s, 2H).

4-methylbenzyl formate (**6b**)[25]



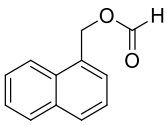
^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (s, 1H), 7.27 (t, *J* = 5.7 Hz, 2H), 7.19 (d, *J* = 8.0 Hz, 2H), 5.17 (s, 2H), 2.37 (s, 4H).

4-fluorobenzyl formate (**6c**)[26]

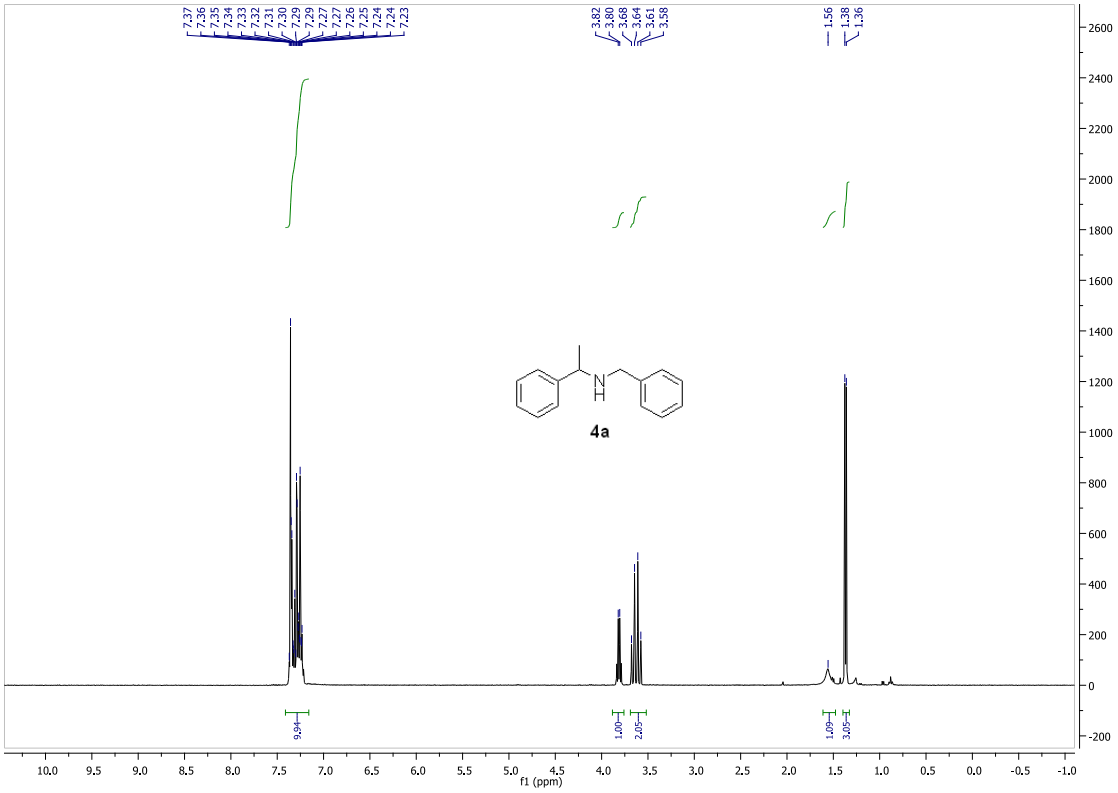


^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12 (s, 1H), 7.41 – 7.30 (m, 2H), 7.06 (t, *J* = 8.6 Hz, 2H), 5.17 (s, 2H).

naphthalen-1-ylmethyl formate (**6d**)[27]



^{1}H NMR (400 MHz, $CDCl_3$) δ 8.19 (s, 1H), 8.02 (d, *J* = 8.4 Hz, 1H), 7.89 (t, *J* = 8.5 Hz, 2H), 7.63 – 7.40 (m, 4H), 5.68 (s, 2H).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7.24
7.24
7.23
3.82
3.80
3.68
3.64
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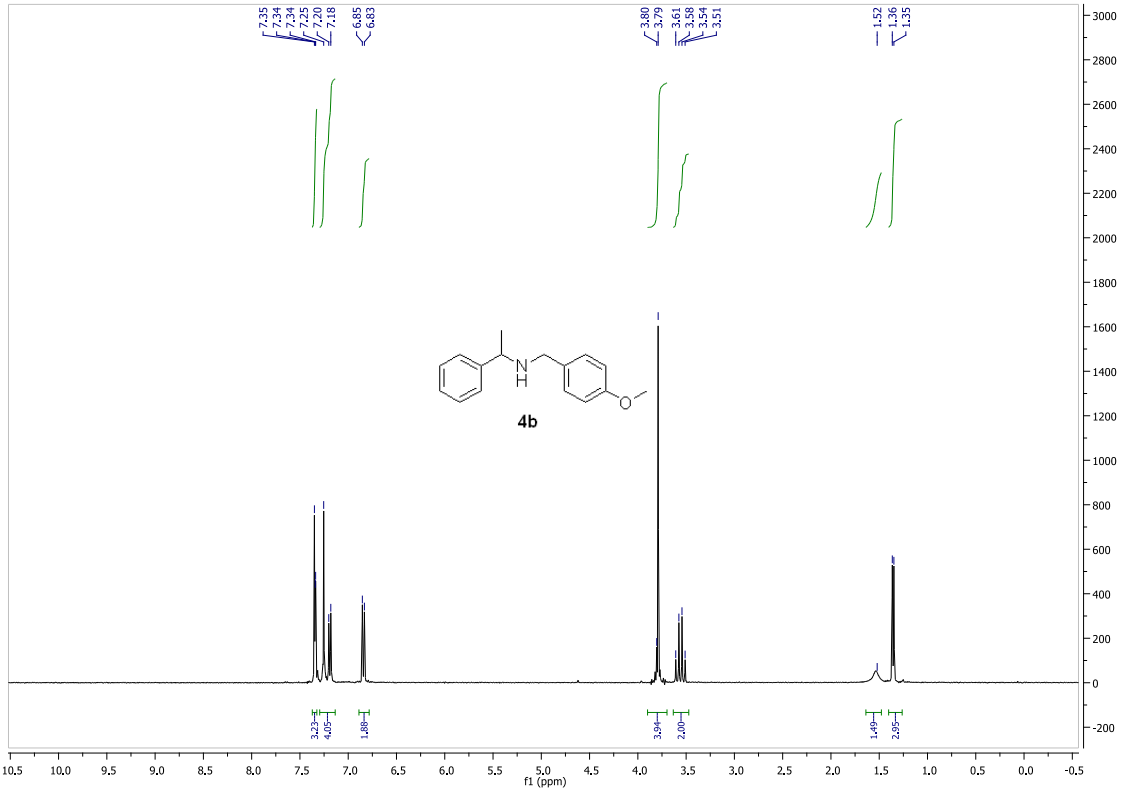
f1 (ppm)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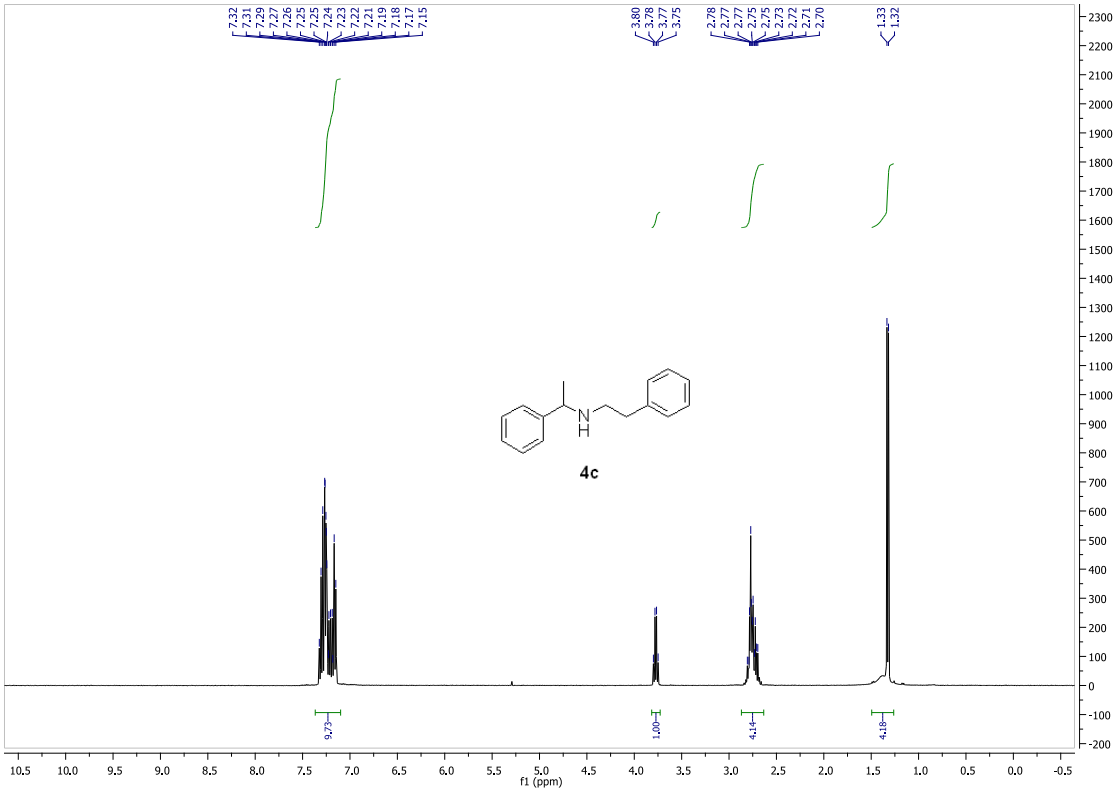
f1 (ppm)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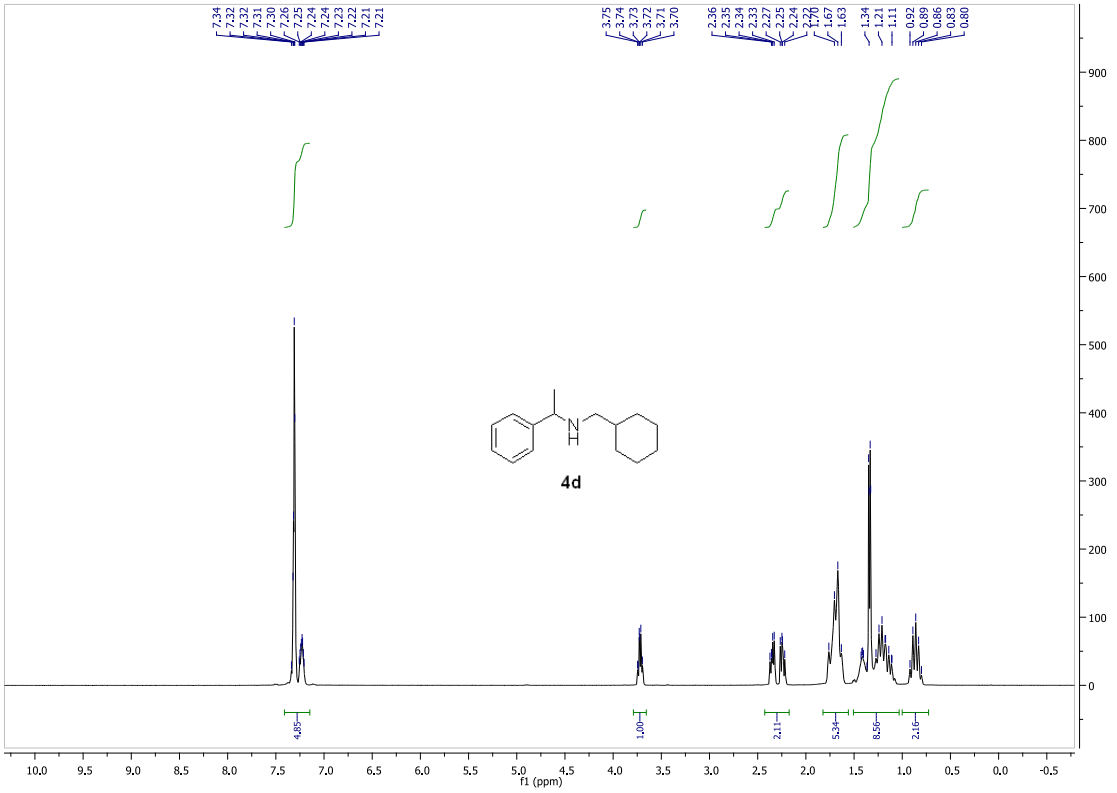
f1 (ppm)

4c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1.34
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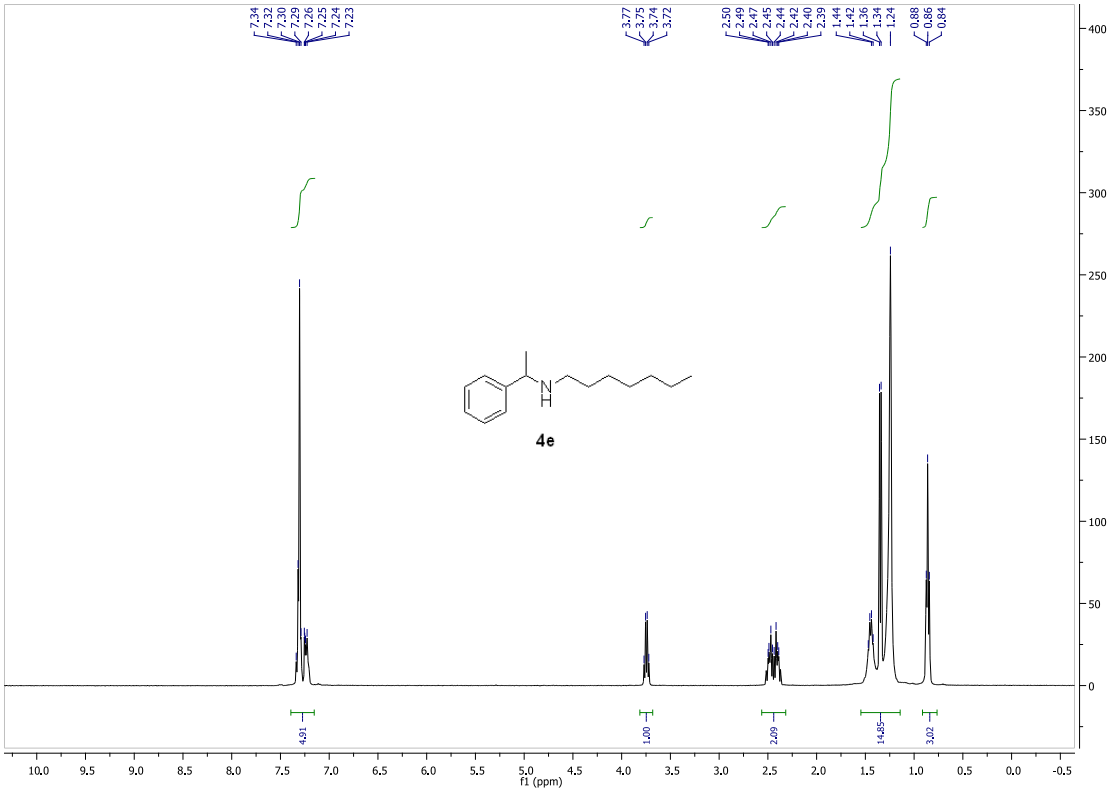
f1 (ppm)

4d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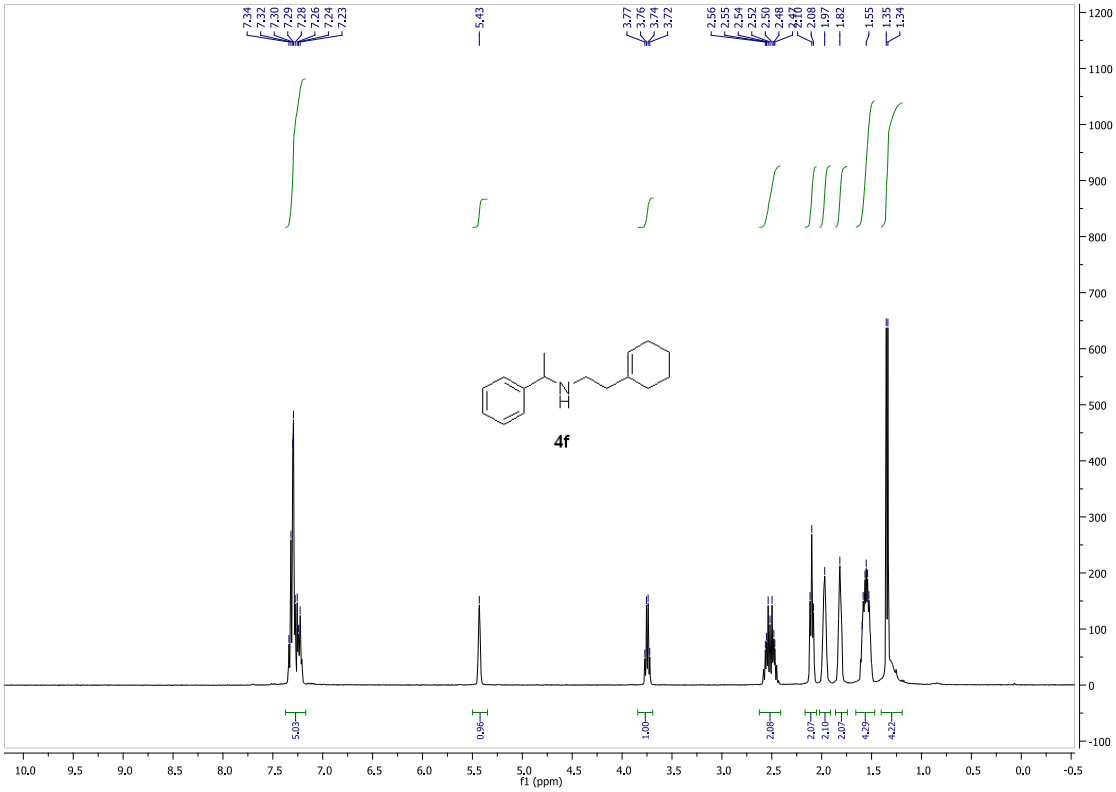
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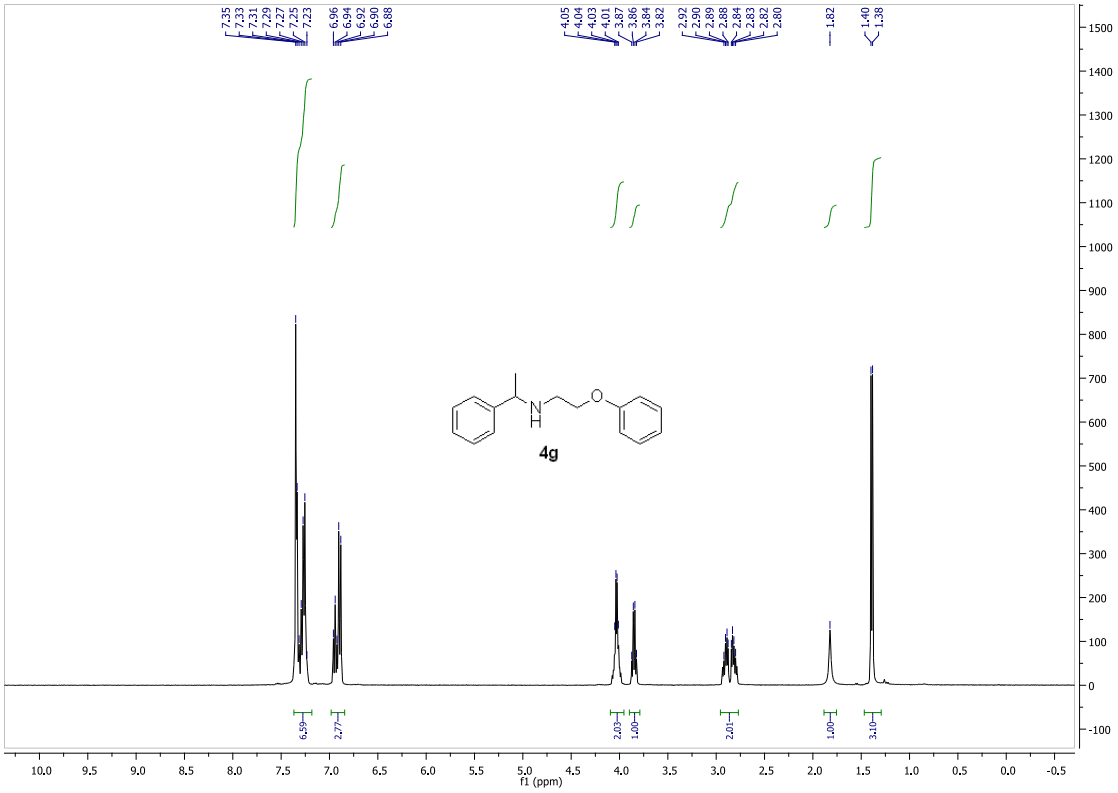
f1 (ppm)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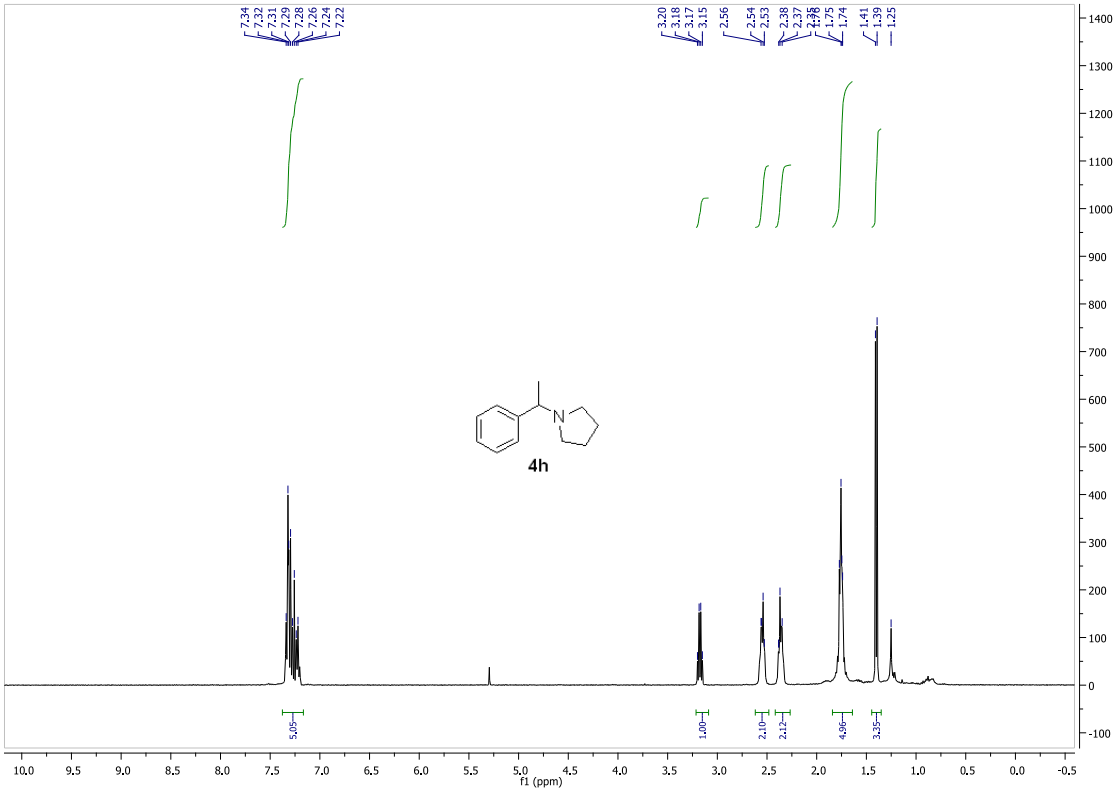
f1 (ppm)

4g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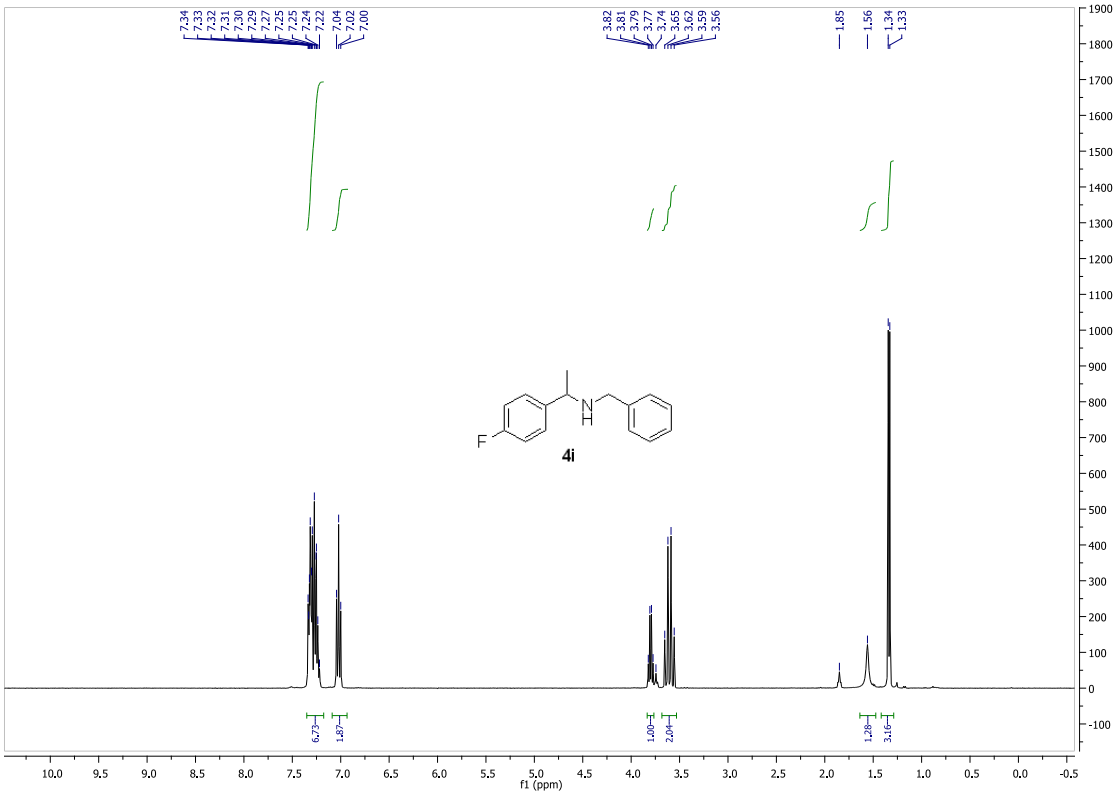
f1 (ppm)

4h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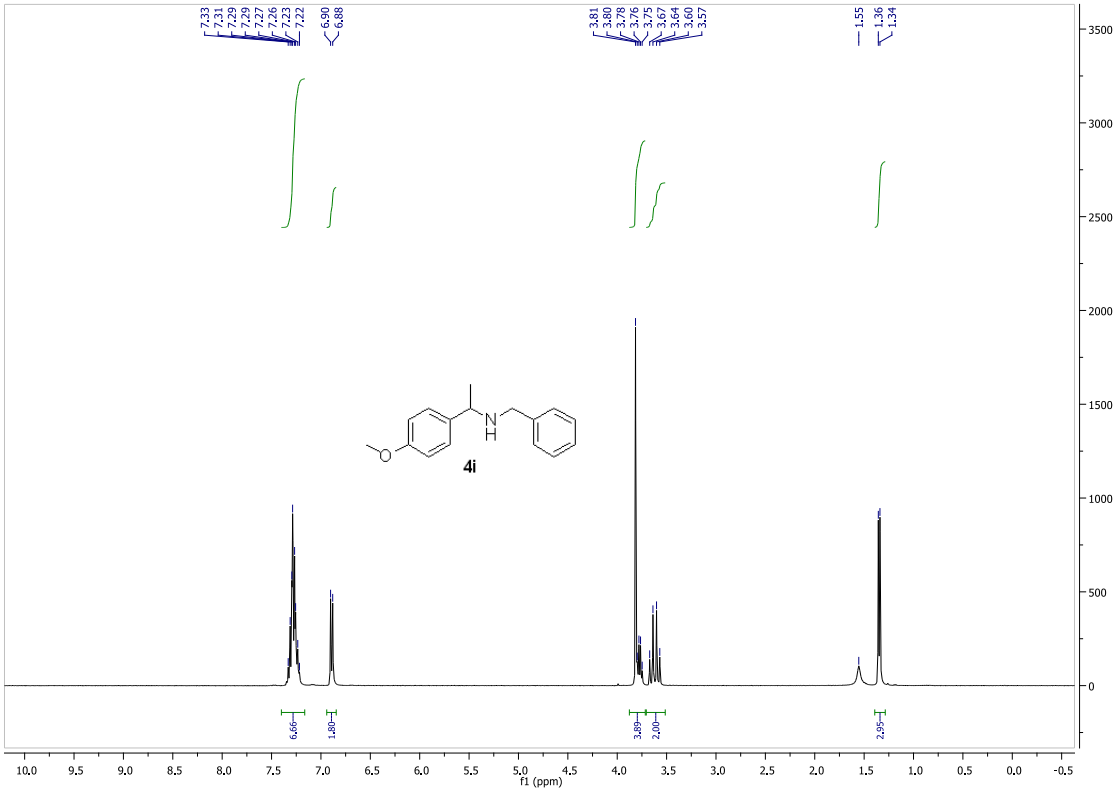
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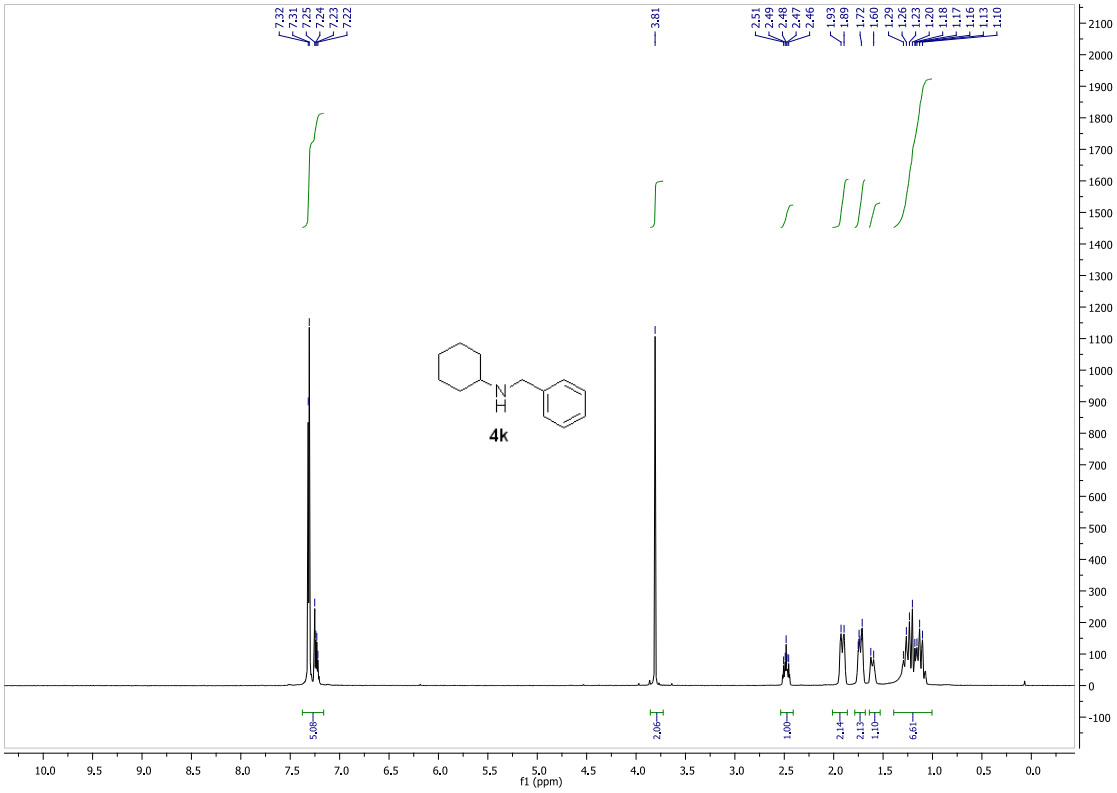
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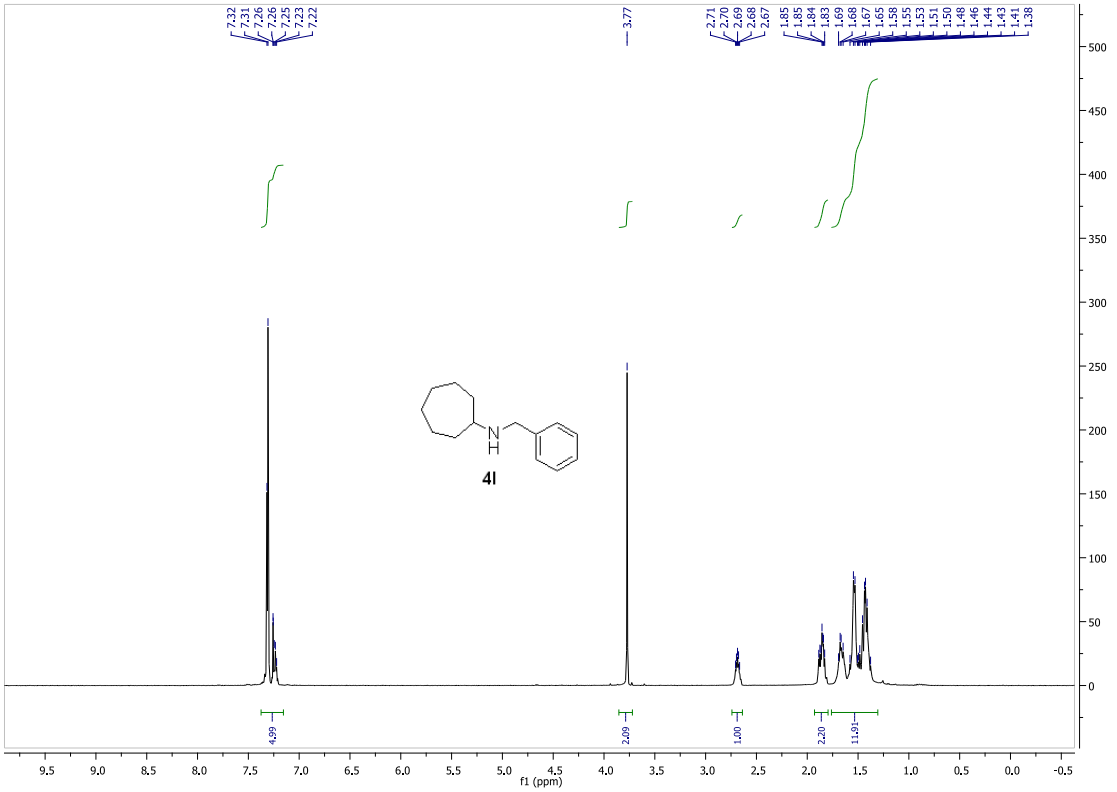
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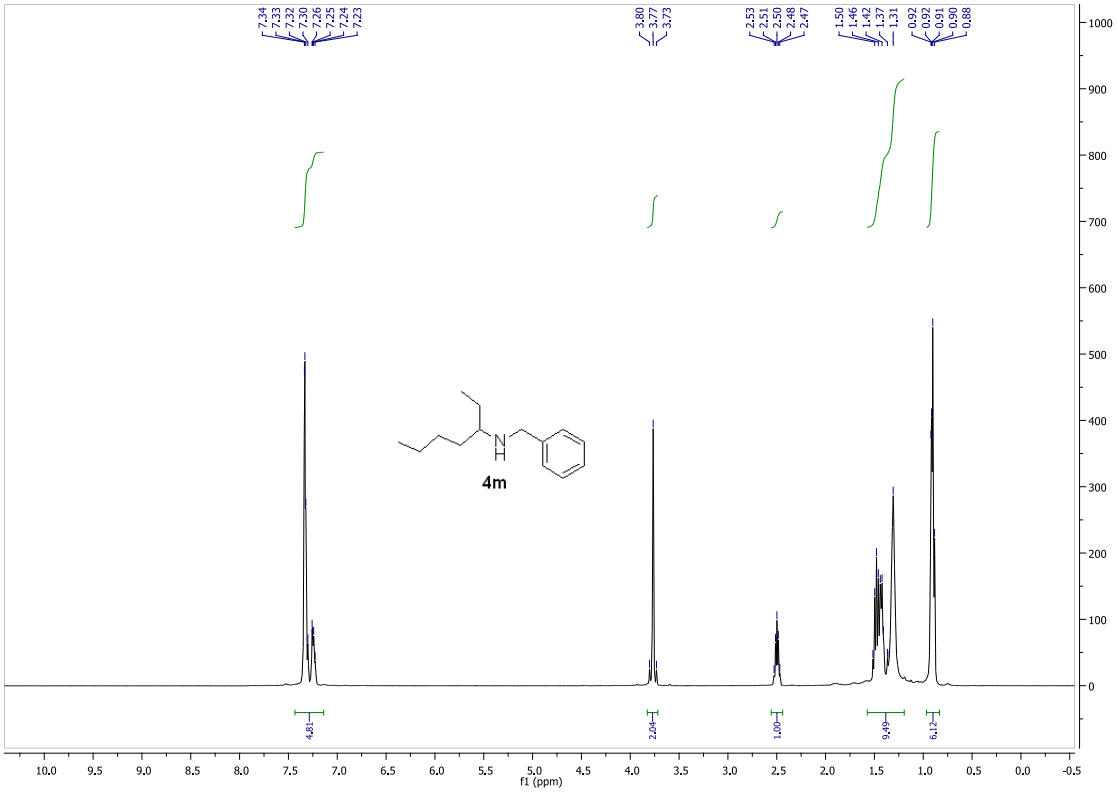
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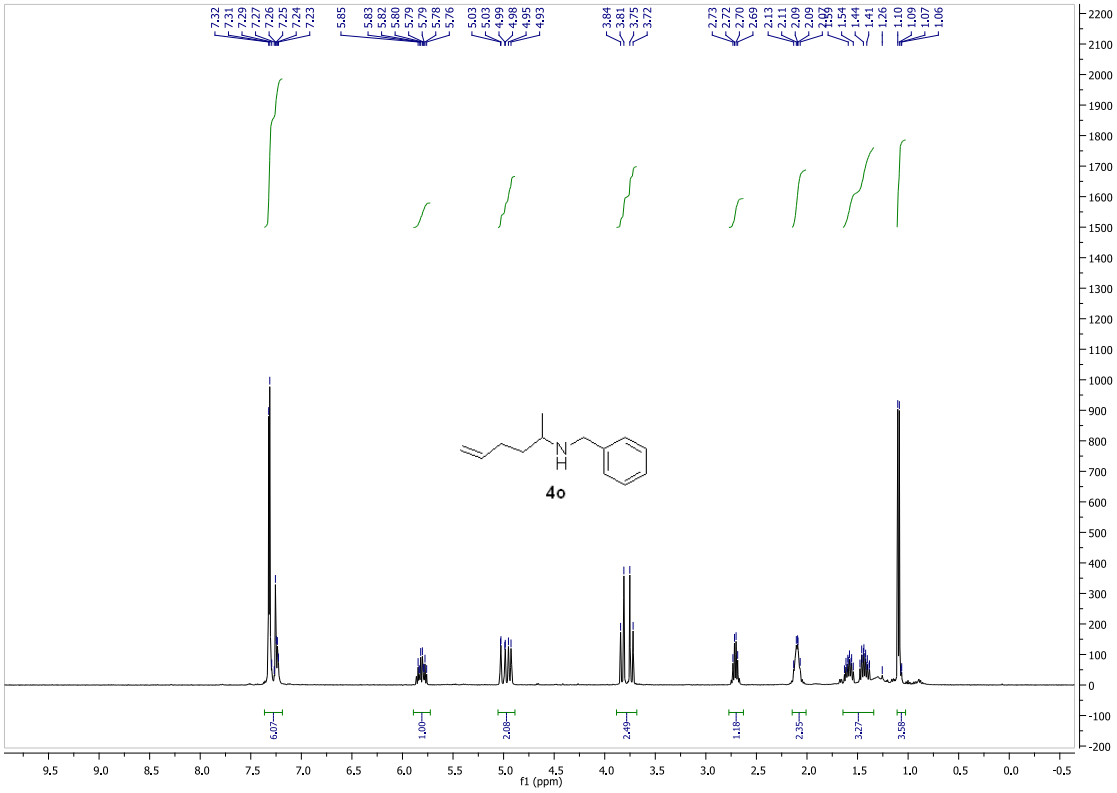
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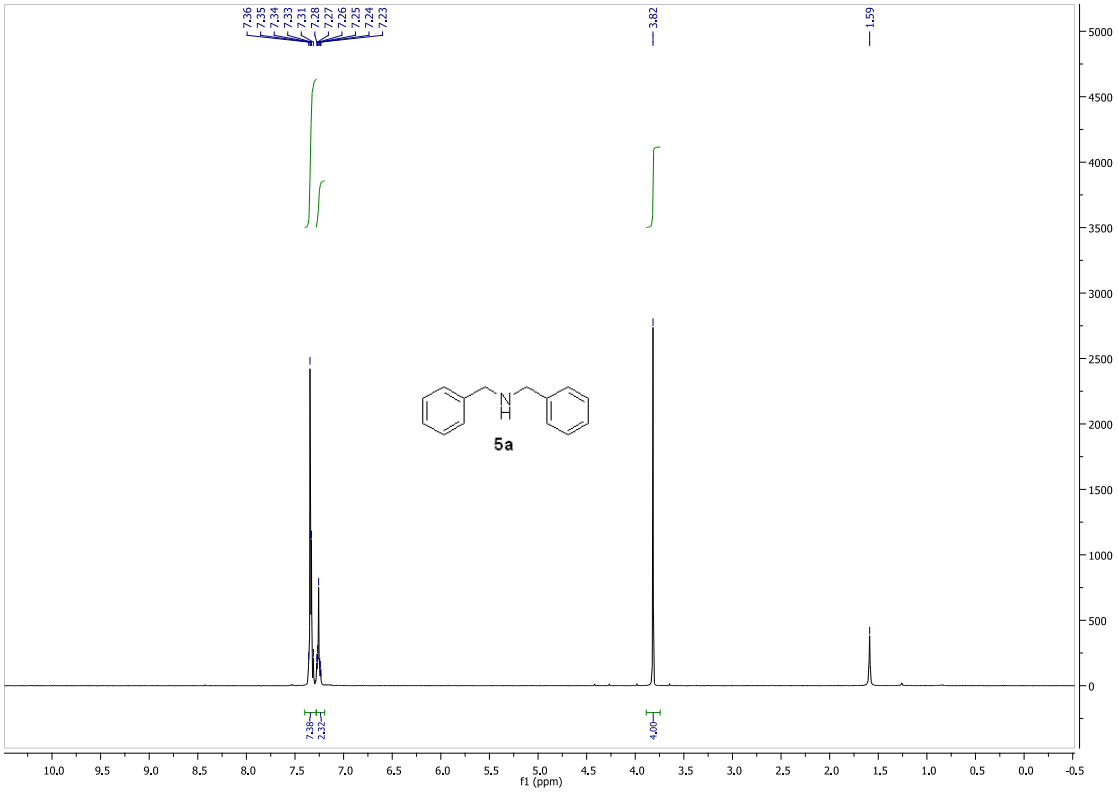
4o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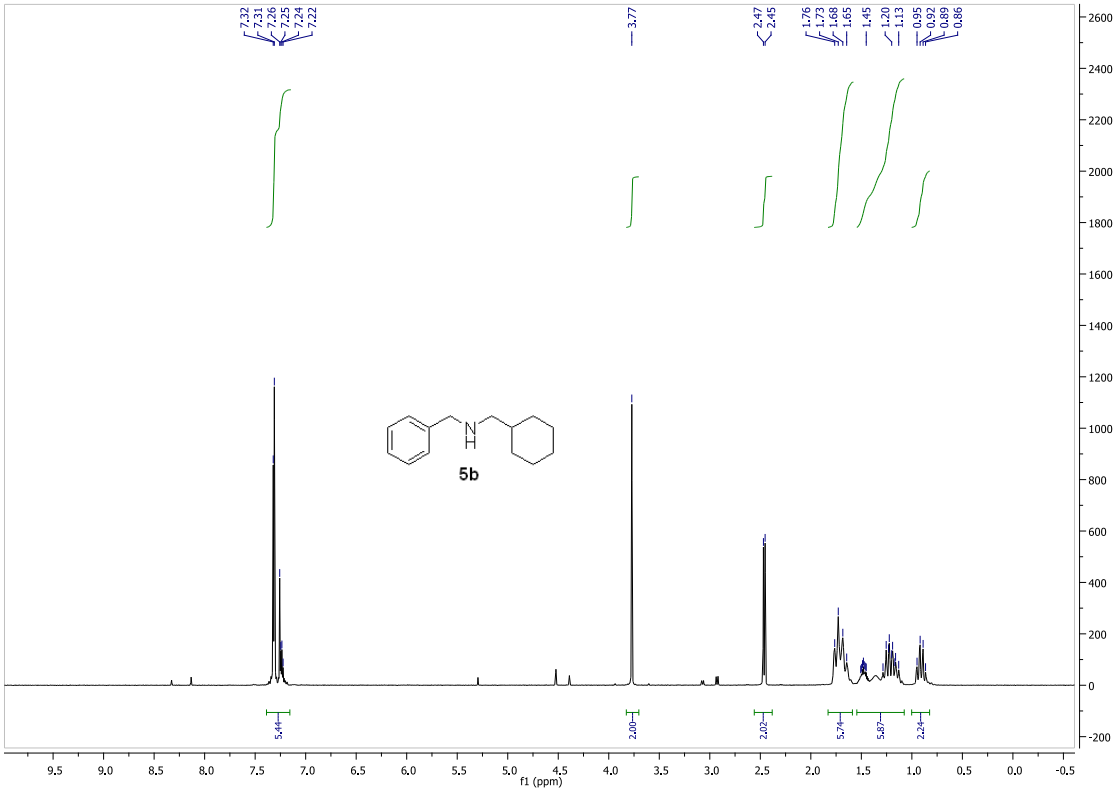
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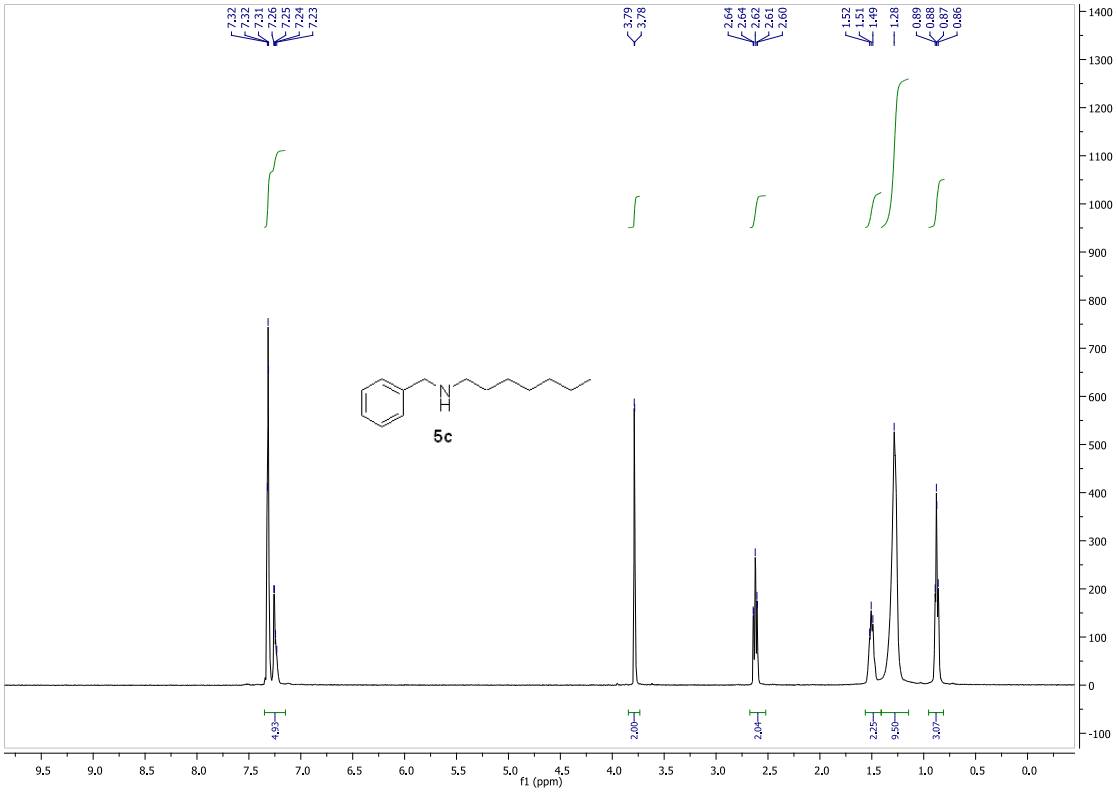
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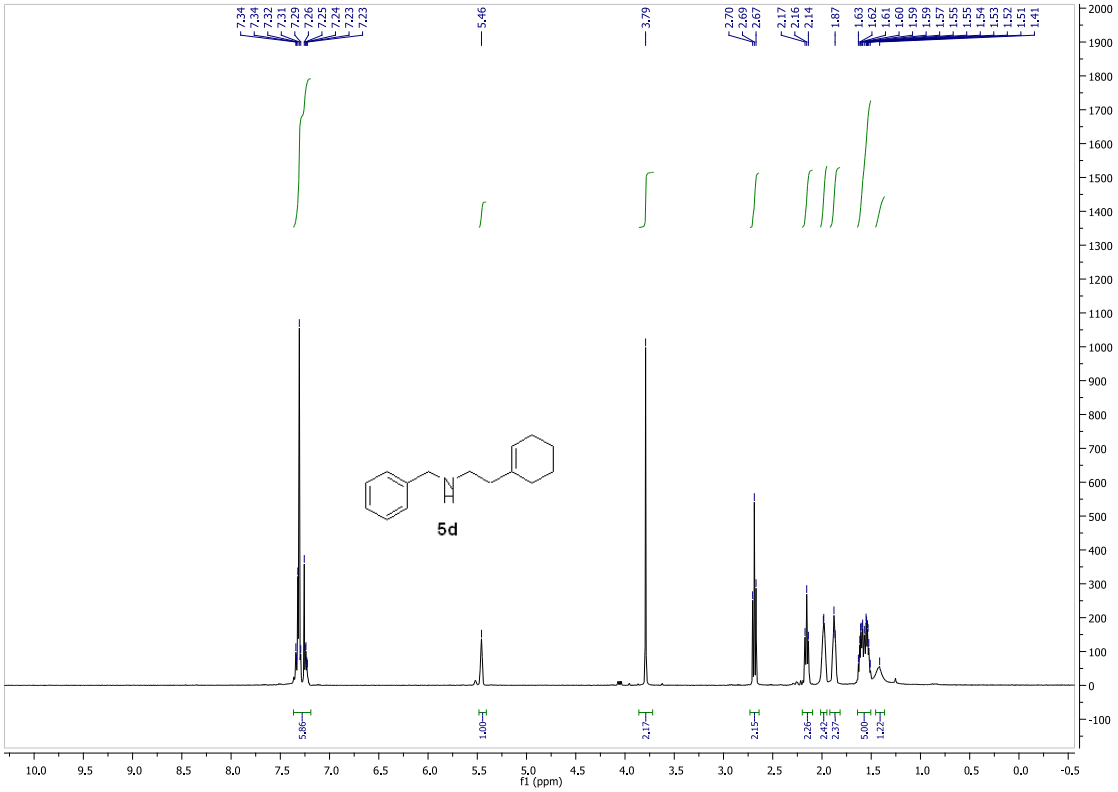
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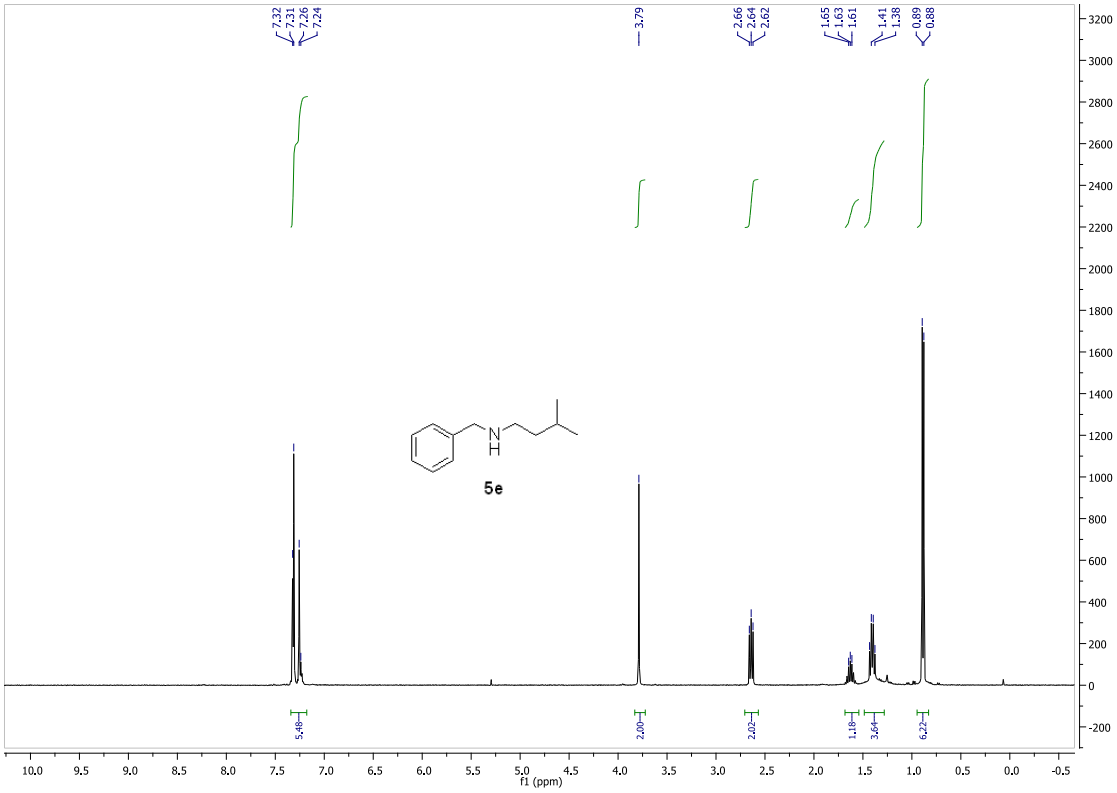
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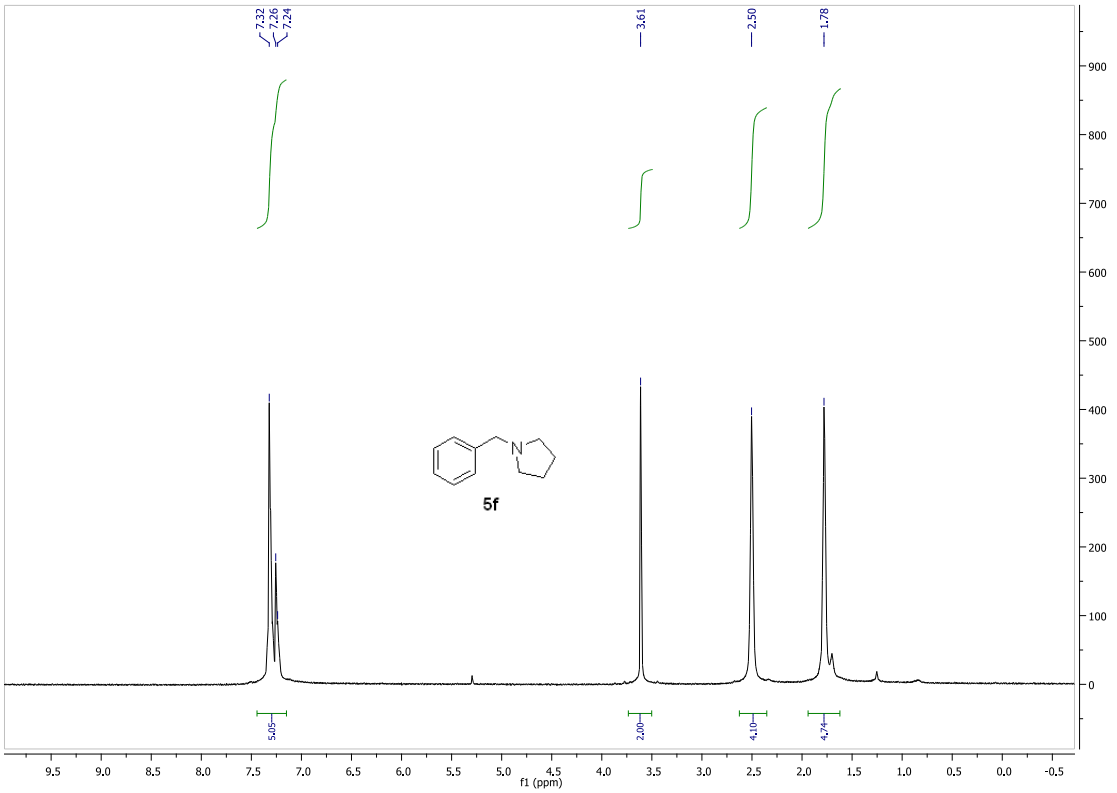
f1 (ppm)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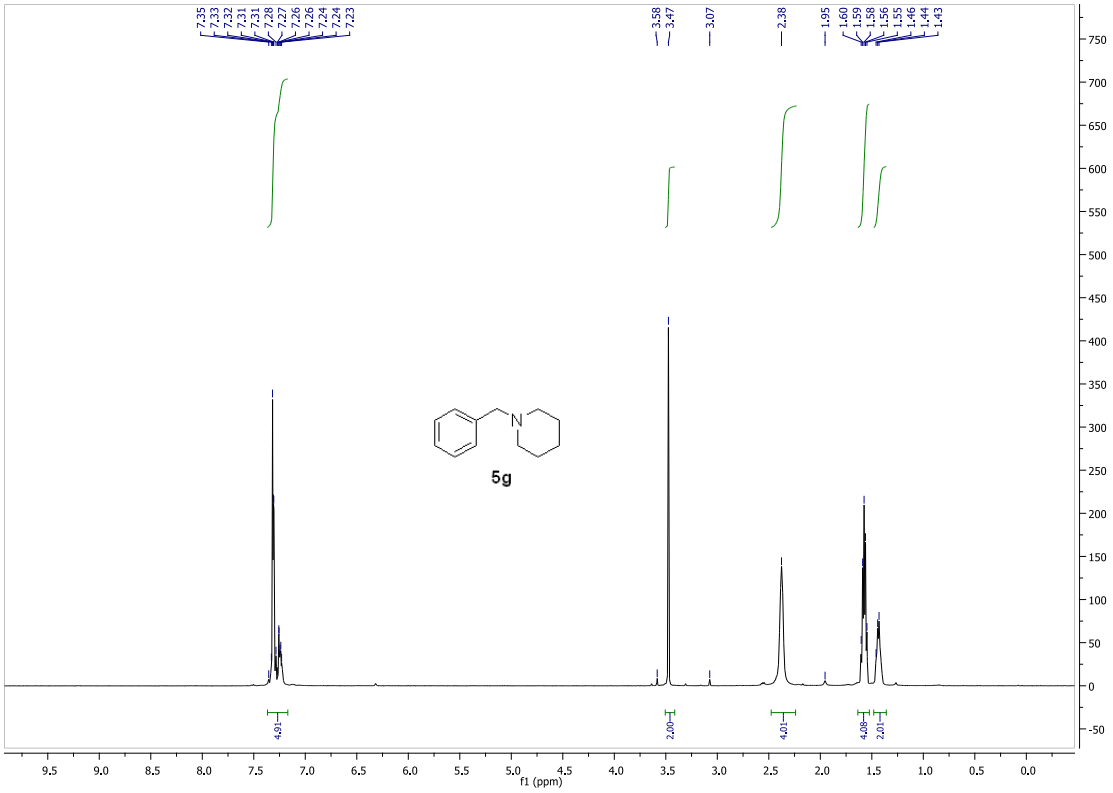
4.74
f1 (ppm)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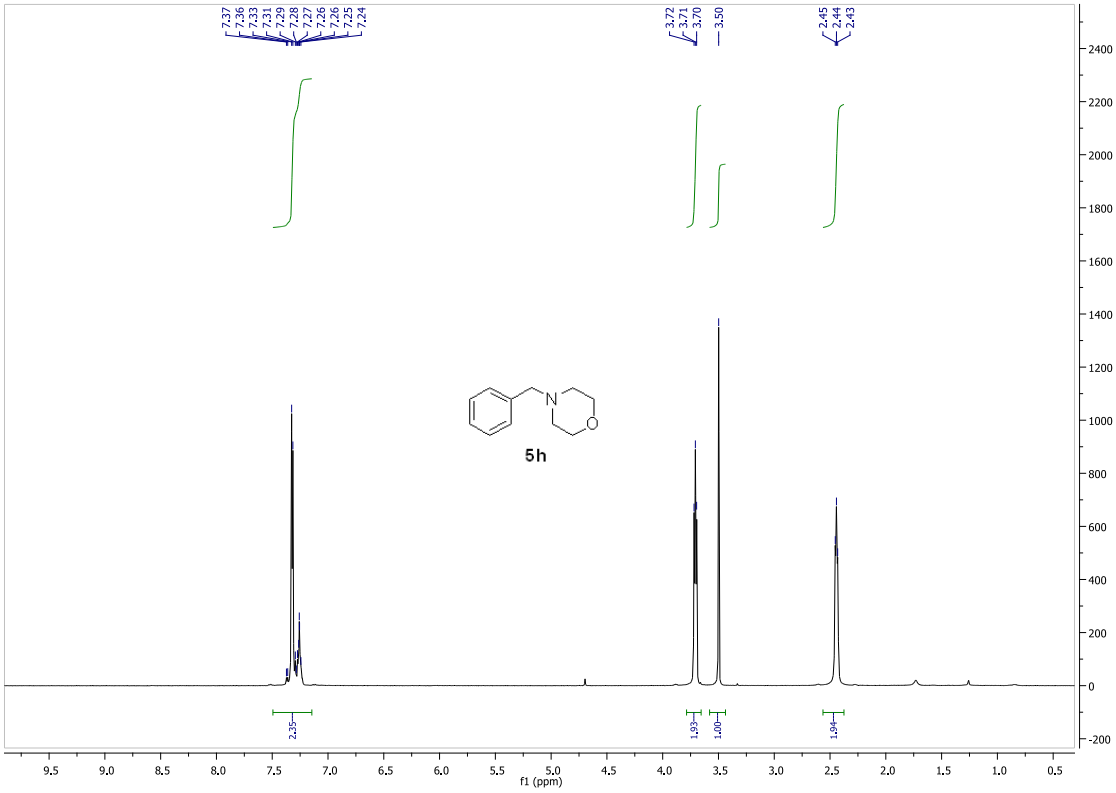
7.33
7.32
7.31
7.31
7.28
7.27
7.26
7.26
7.24
7.24
7.23
3.58
3.47
3.07
2.38
1.95
1.60
1.59
1.58
1.56
1.55
1.46
1.44
1.43
5g
4.91
2.00
4.01
4.08
2.01
f1 (ppm)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7.28
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7.26
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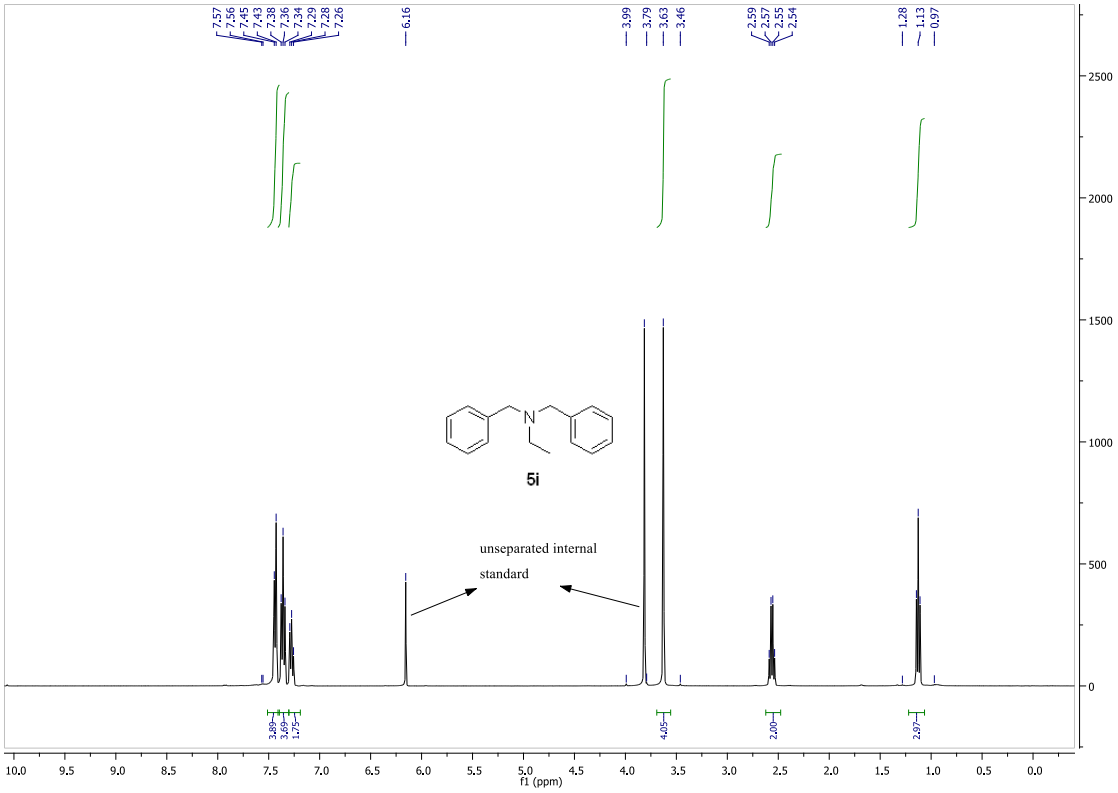
7.24
3.72
3.71
3.70
3.50
2.45
2.44
2.43
5h
2.35
1.93
1.00
1.94
f1 (ppm)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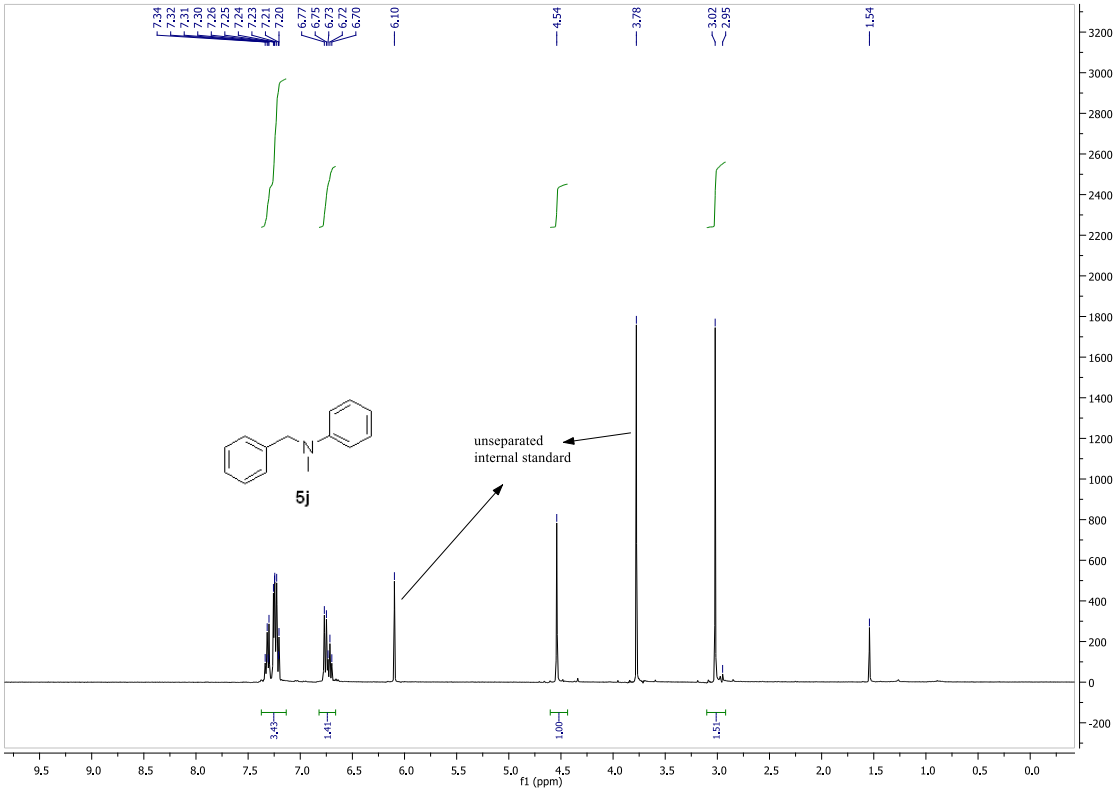
7.29
7.28
7.26
6.16
3.99
3.79
3.63
3.46
2.59
2.57
2.55
2.54
1.28
1.13
0.97
5i
unseparated internal
standard
3.88
3.69
1.75
4.05
2.00
2.07
f1 (ppm)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7.23
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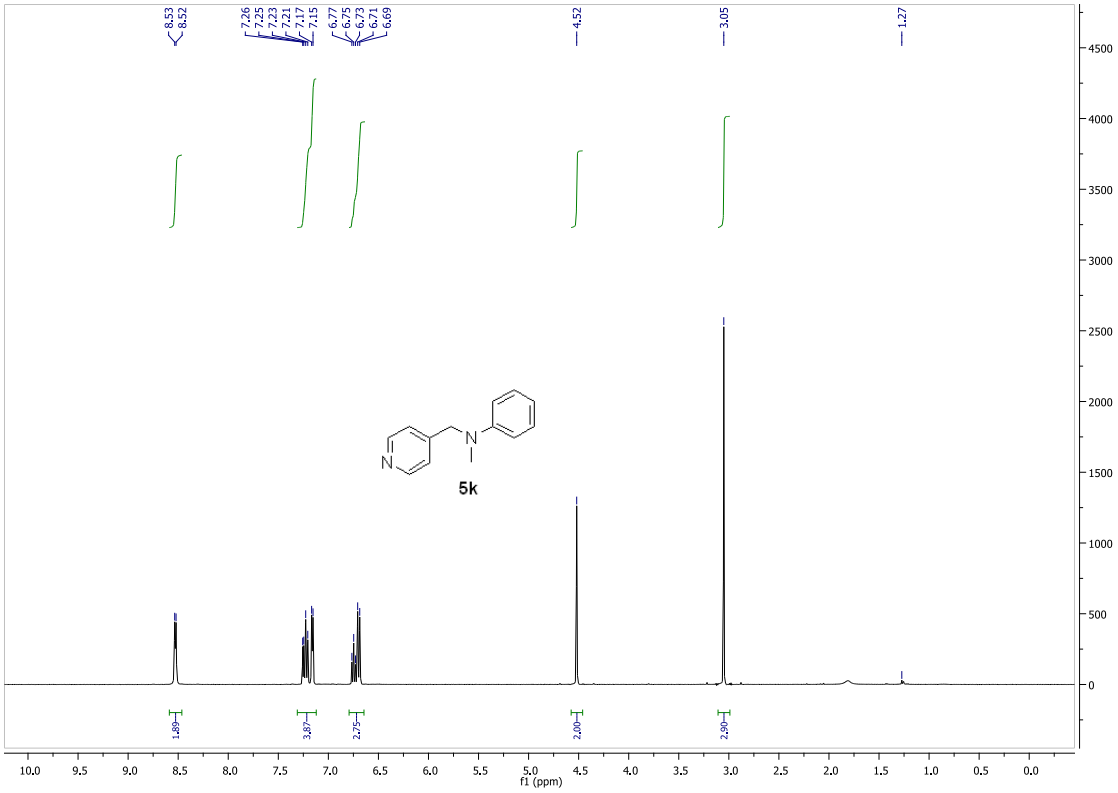
7.20
6.77
6.75
6.73
6.72
6.70
6.10
4.54
3.78
3.02
2.95
1.54
5j
unseparated
internal standard
3.43
1.41
1.00
1.51
f1 (ppm)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7.25
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7.21
7.17
7.15
6.77
6.75
6.73
6.71
6.69
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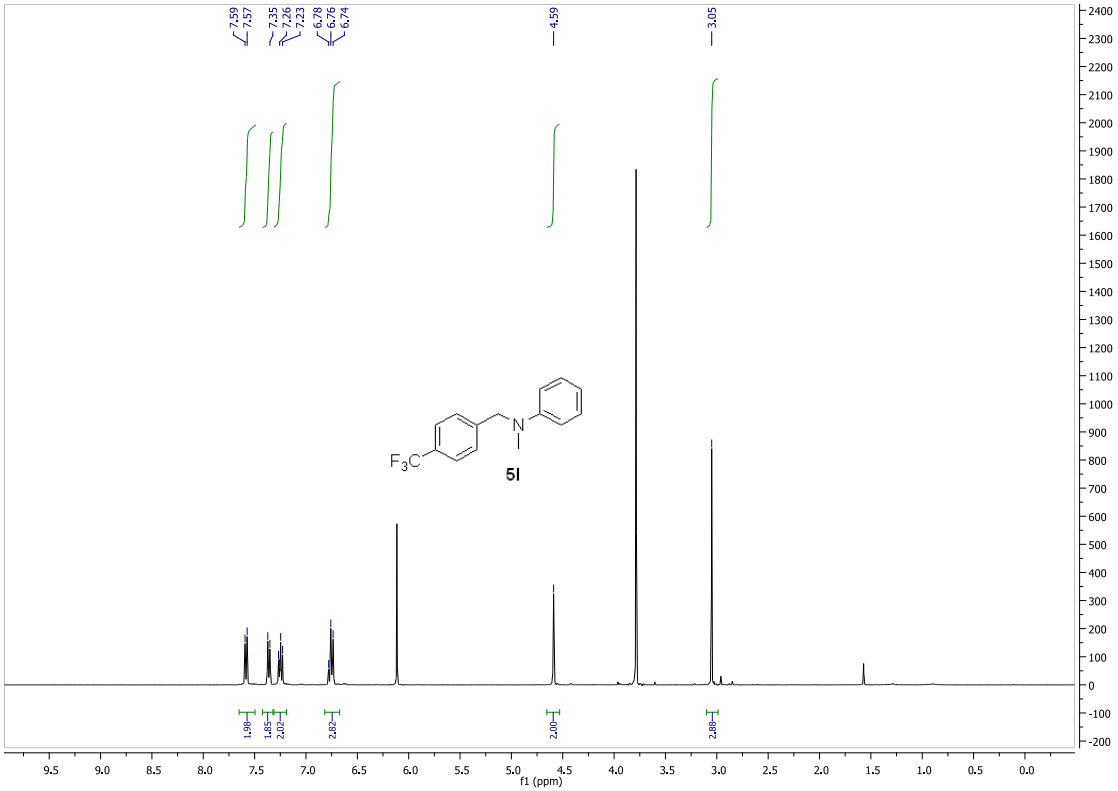
3.05
1.27
5k
1.89
3.87
2.75
2.00
2.90
f1 (ppm)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7.23
6.78
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4.59
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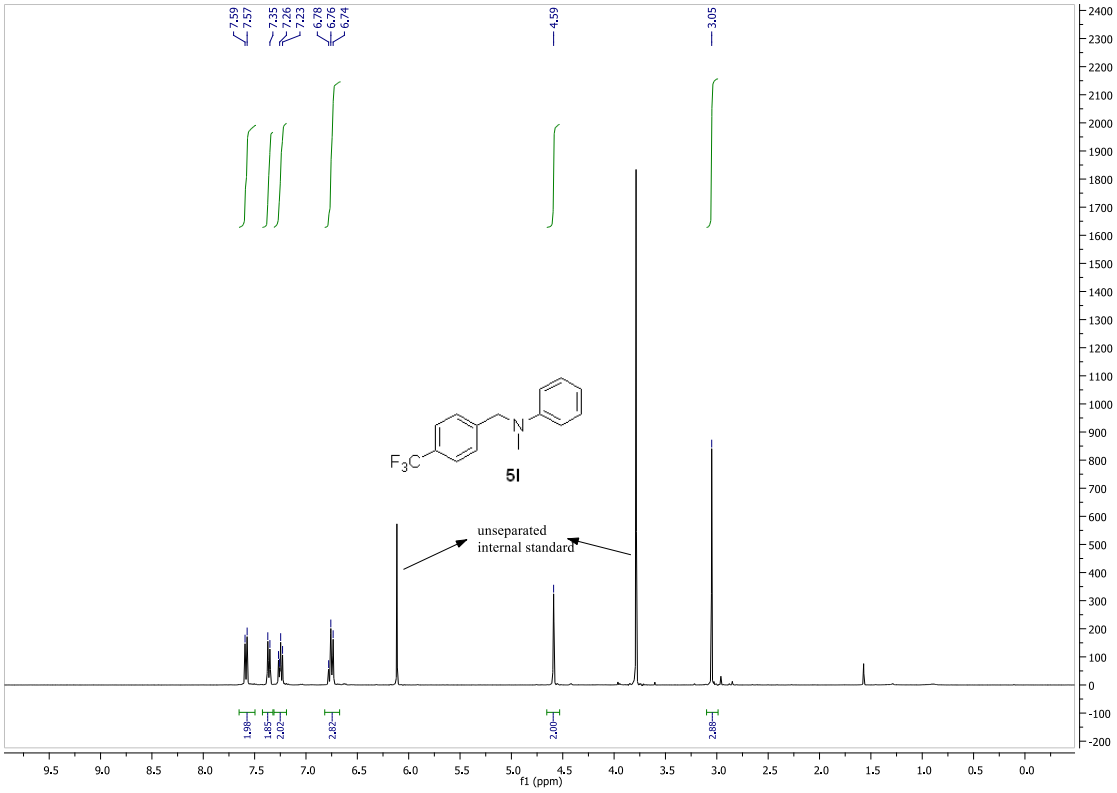
5l
1.98
1.85
2.02
2.82
2.00
2.88
f1 (ppm)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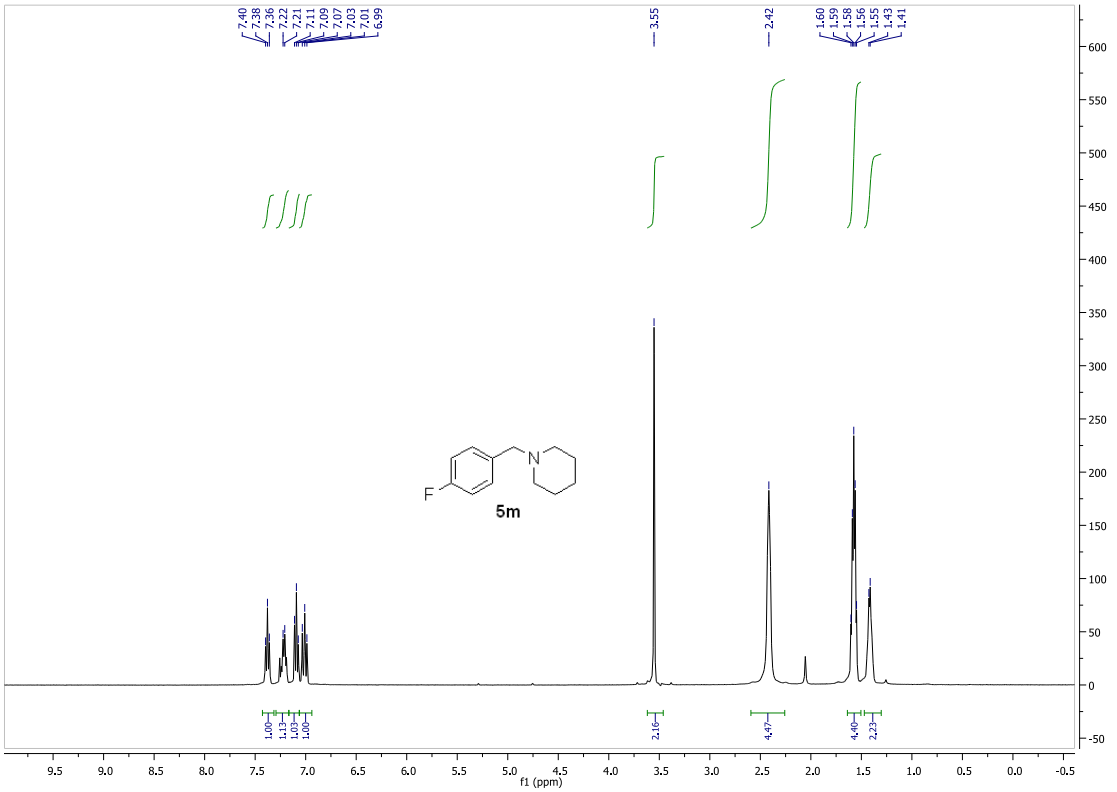
7.57
7.35
7.26
7.23
6.78
6.76
6.74
4.59
3.05
F3C
N
5l
unseparated
internal standard
1.98
1.85
2.02
2.82
2.00
2.88
f1 (ppm)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7.36
7.22
7.21
7.11
7.09
7.07
7.03
7.01
6.99
3.55
2.42
1.60
1.59
1.58
1.56
1.55
1.43
1.41
F
N
5m
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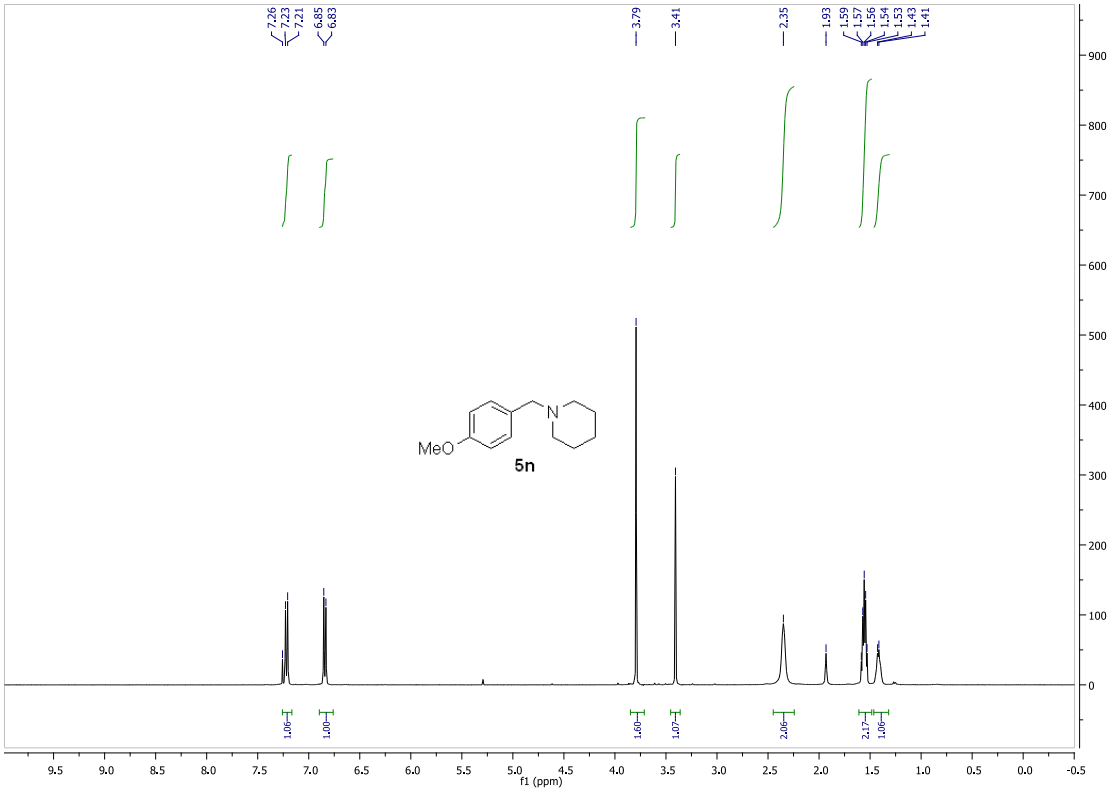
1.13
1.03
1.00
2.16
4.47
4.40
2.23
f1 (ppm)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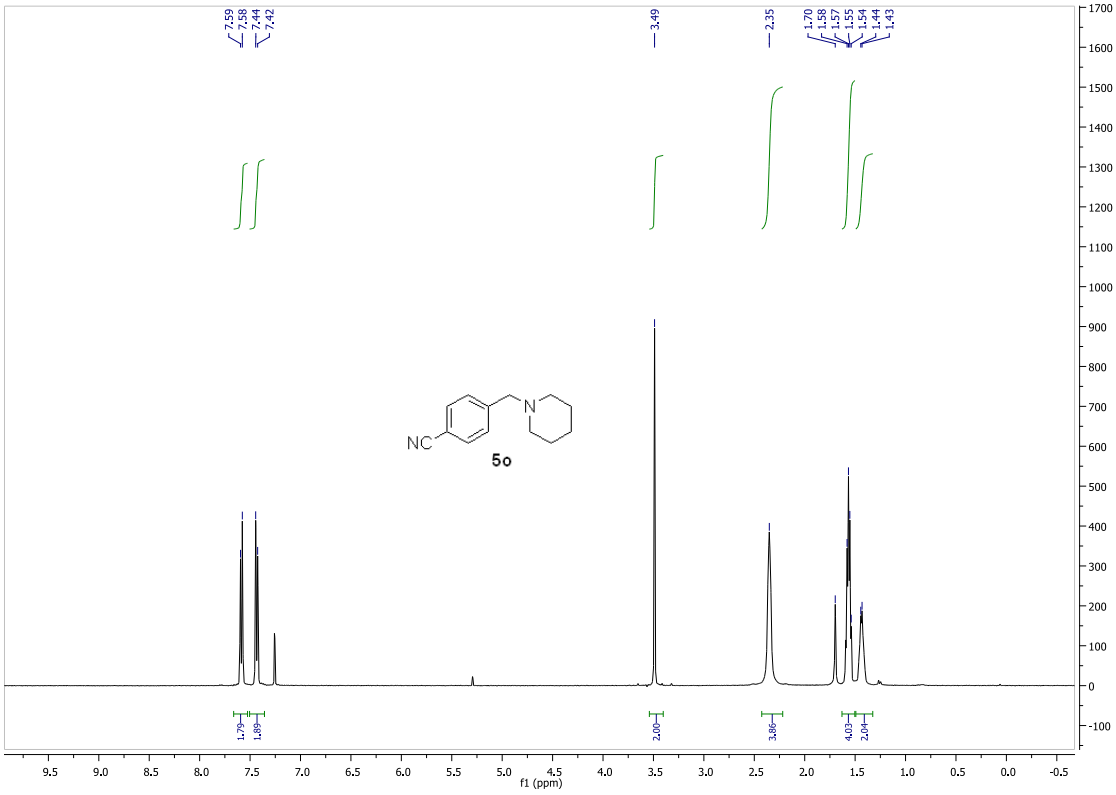
7.23
7.21
6.85
6.83
3.79
3.41
2.35
1.93
1.59
1.57
1.56
1.54
1.53
1.43
1.41
MeO
N
1.08
1.00
1.60
1.07
2.06
2.17
1.06
f1 (ppm)

5n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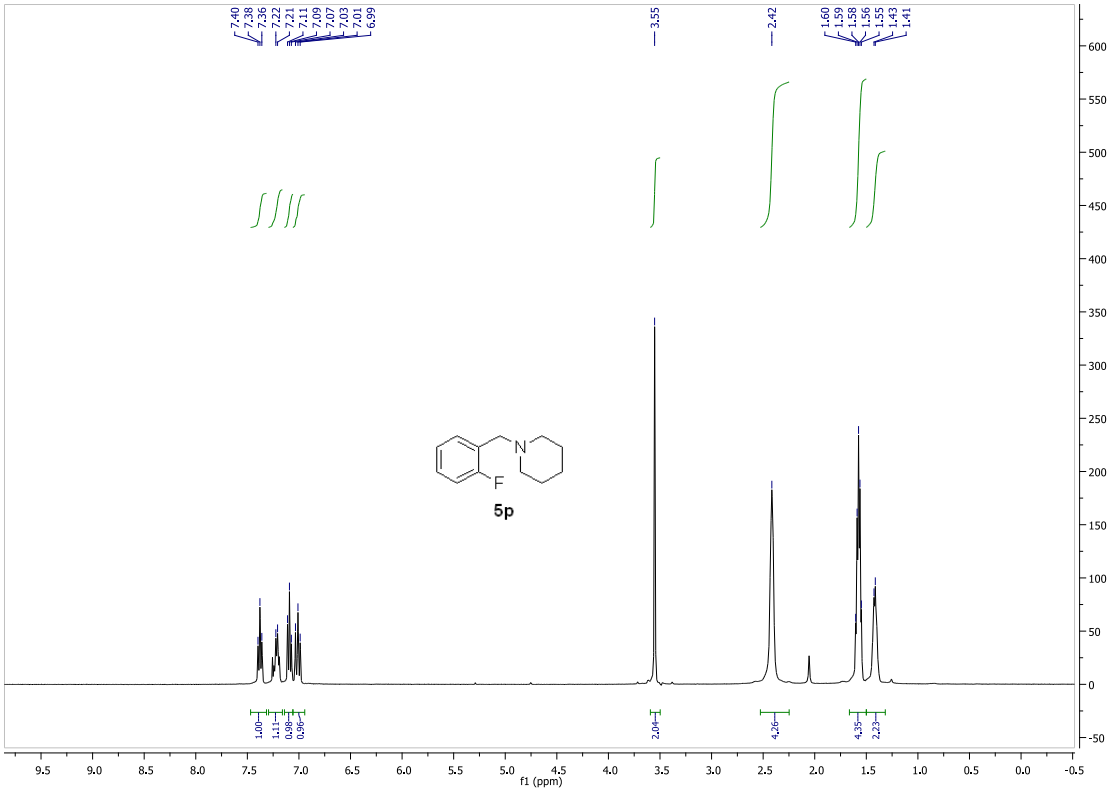
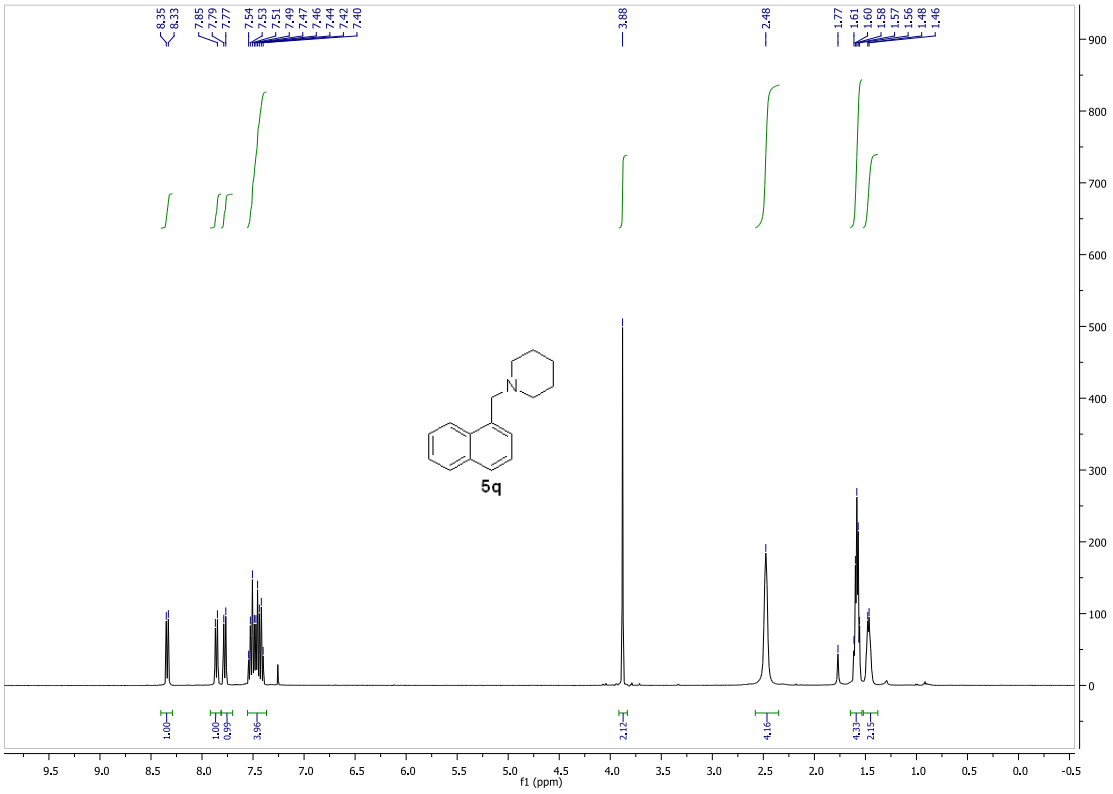
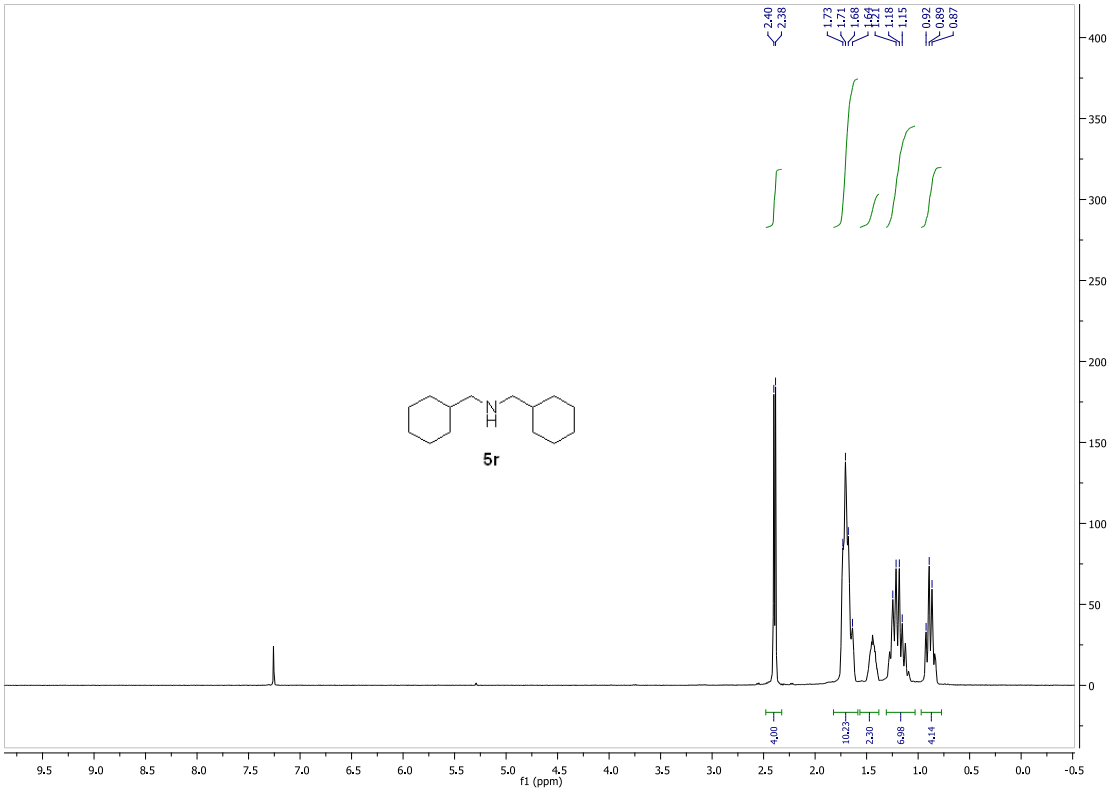
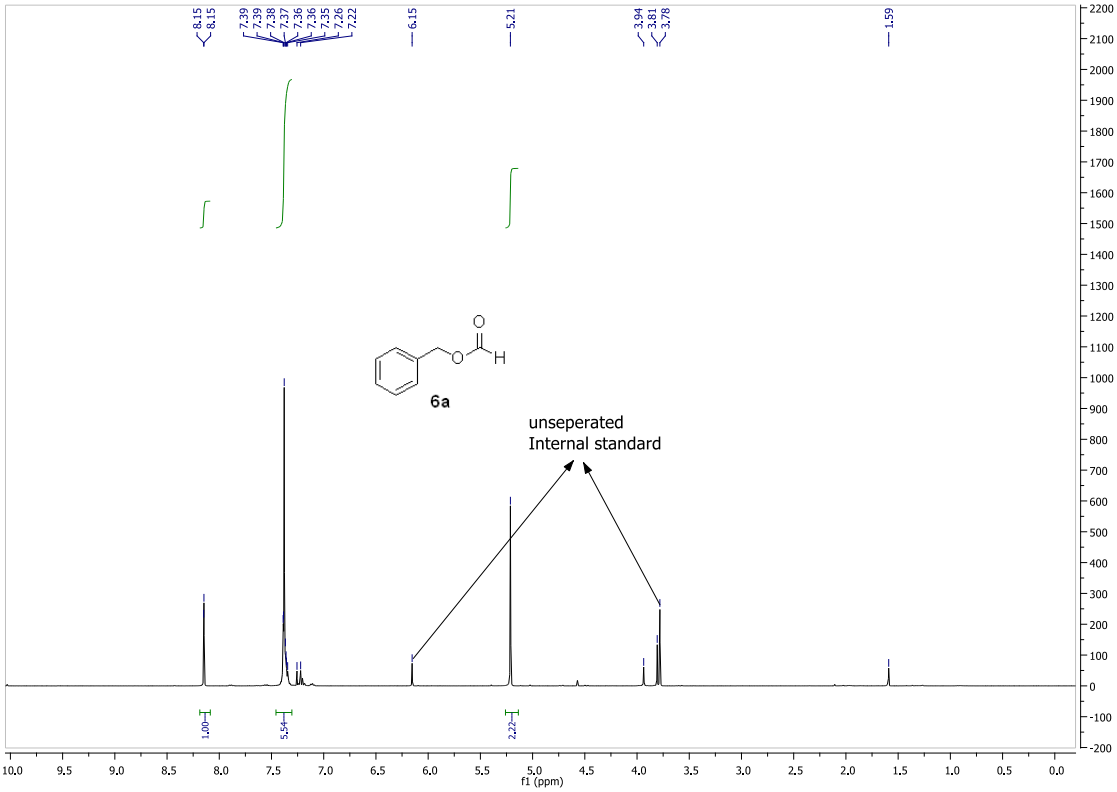
7.58
7.44
7.42
3.49
2.35
1.70
1.58
1.57
1.55
1.54
1.44
1.43
NC
N
1.79
1.89
2.00
3.86
4.03
2.04
f1 (ppm)

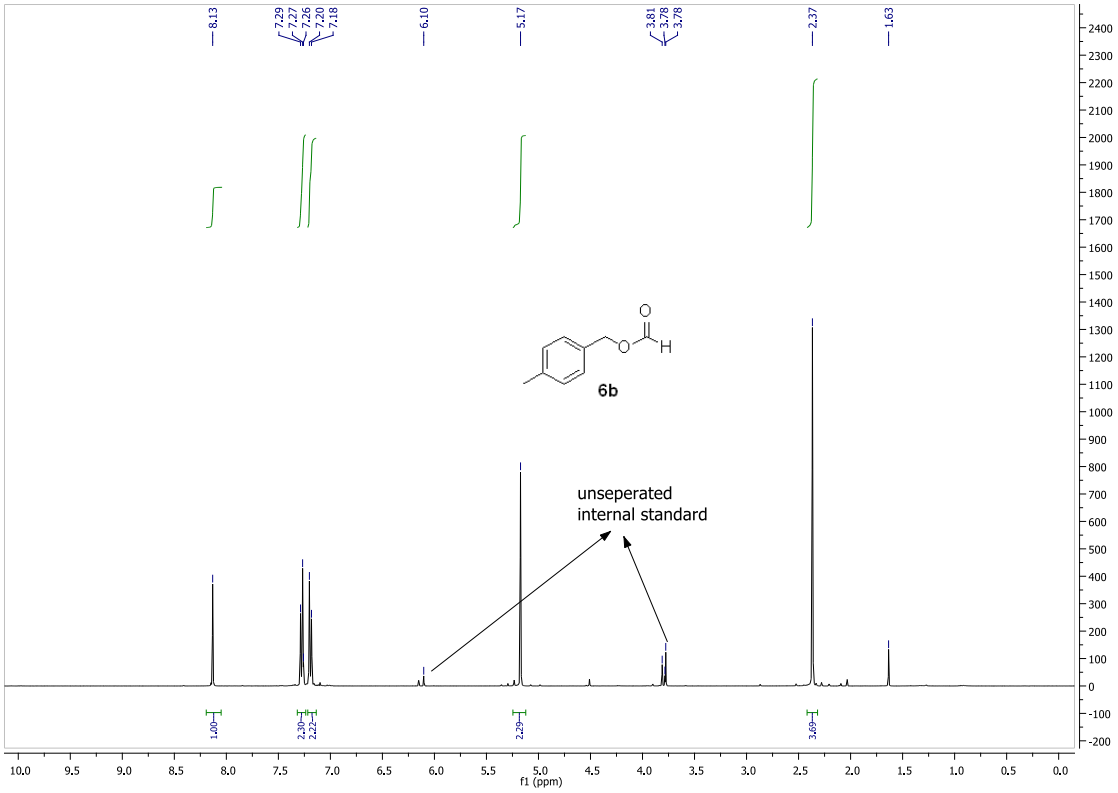
5o

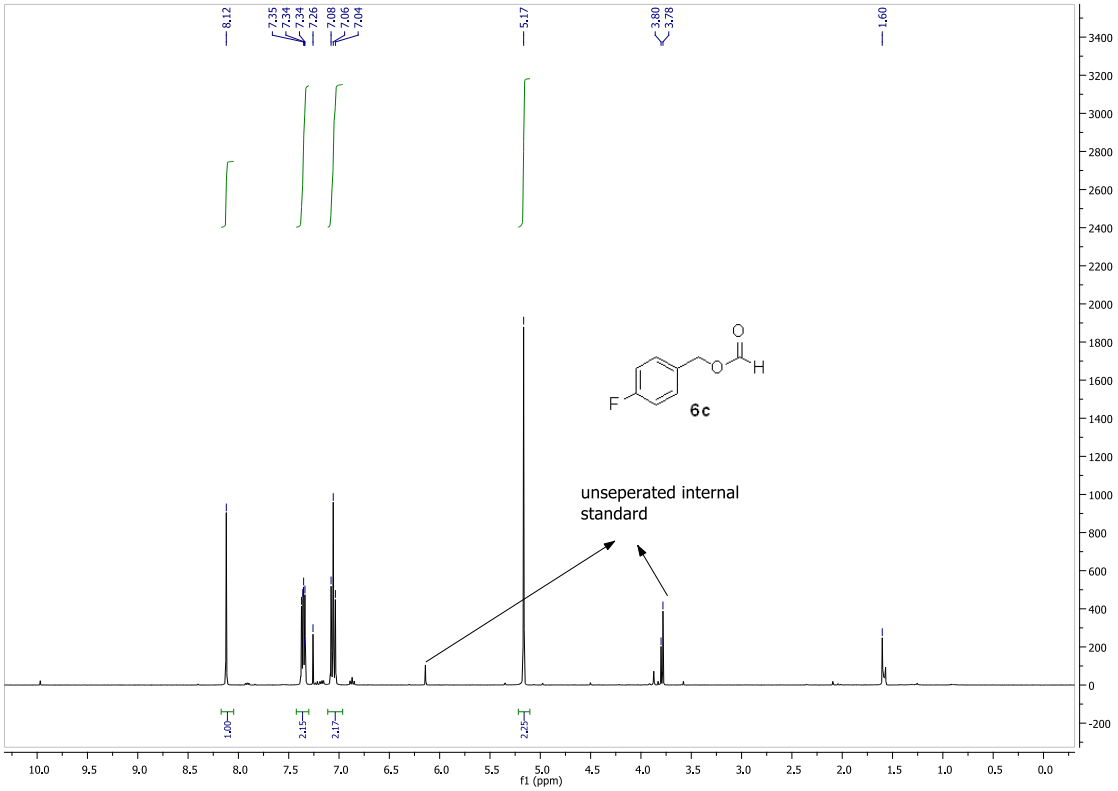

7.40
7.38
7.36
7.22
7.21
7.11
7.09
7.07
7.03
7.01
6.99
3.55
2.42
1.60
1.59
1.58
1.56
1.55
1.43
1.41
N
F
5p
1.00
1.11
0.98
0.96
2.04
4.26
4.35
2.23
f1 (ppm)

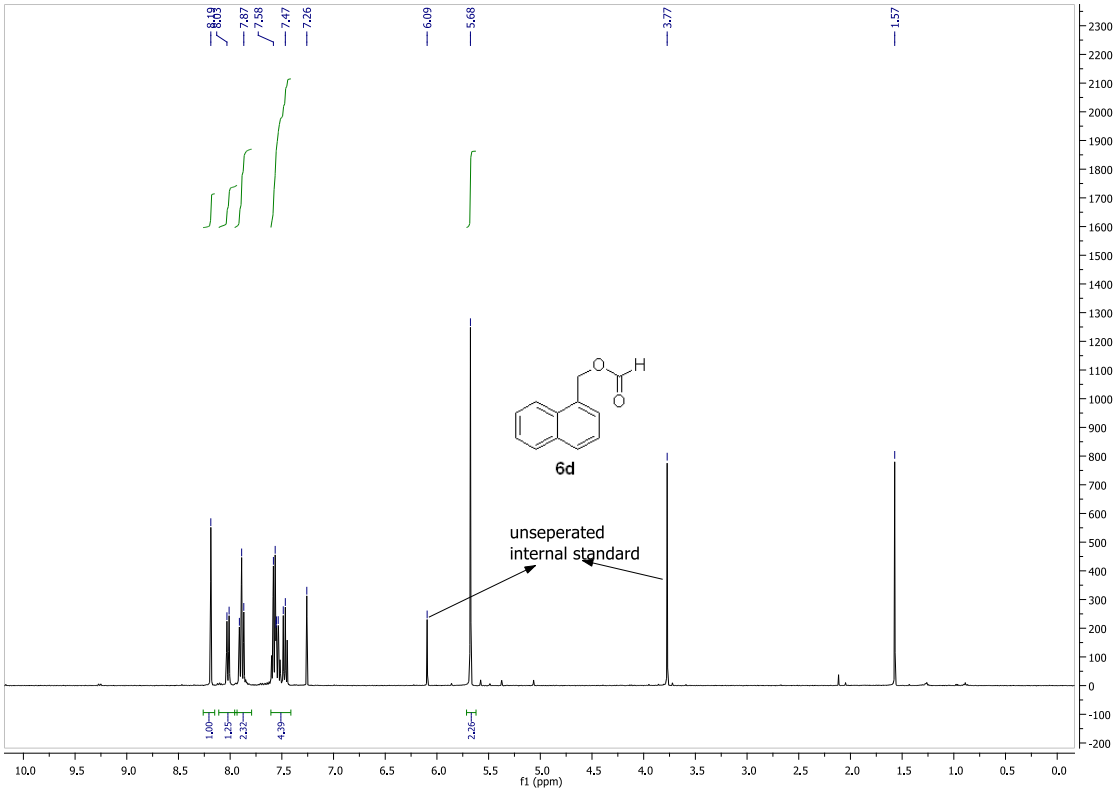

8.35
8.33
7.85
7.79
7.77
7.54
7.53
7.51
7.49
7.47
7.46
7.44
7.42
7.40
3.88
2.48
1.77
1.61
1.60
1.58
1.57
1.56
1.48
1.46
N
5q
1.00
1.00
0.99
3.96
2.12
4.16
4.33
2.15
f1 (ppm)


2.40
2.38
1.73
1.71
1.68
1.64
1.21
1.18
1.15
0.92
0.89
0.87
5r
4.00
10.23
2.30
6.88
4.14
f1 (ppm)


8.15
8.15
7.39
7.39
7.38
7.37
7.36
7.36
7.35
7.26
7.22
6.15
5.21
3.94
3.81
3.78
1.59
6a
unseperated
Internal standard
1.00
5.54
2.22
f1 (ppm)


8.13
7.29
7.27
7.26
7.20
7.18
6.10
5.17
3.81
3.78
3.78
2.37
1.63
6b
unseperated
internal standard
1.00
2.20
2.22
2.29
3.69
f1 (ppm)


8.12
7.35
7.34
7.34
7.26
7.08
7.06
7.04
5.17
3.80
3.78
1.60
F
6c
unseperated internal
standard
1.00
2.15
2.17
2.25
f1 (ppm)



References

1. C. Wang, A. Pettman, J. Bacsa and J. Xiao, *Angew. Chem. Int. Ed.*, 2010, 49, 7548-7552.
2. C. Wang, X. Wu, L. Zhou and J. Sun, *Chem. Eur. J.*, 2008, 14, 8789-8792.
3. O. Saidi, A. J. Blacker, M. M. Farah, S. P. Marsden and J. M. J. Williams, *Angew. Chem. Int. Ed.*, 2009, 48, 7375-7378.
4. O. Saidi, A. J. Blacker, M. M. Farah, S. P. Marsden and J. M. J. Williams, *Chem. Commun.*, 2010, 46, 1541-1543.
5. B. T. Cho and Y. S. Chun, *Tetrahedron: Asymmetry*, 1992, 3, 1583-1590.
6. J. E. M. N. Klein, H. Muller-Bunz and P. Evans, *Org. Biomol. Chem.*, 2009, 7, 986-995.
7. T. N. Riley and F. W. Crawford, *J. Pharm. Sci.*, 1976, 65, 544-547.
8. S. Guizzetti, M. Benaglia and G. Celentano, *Eur. J. Org. Chem.*, 2009, 2009, 3683-3687.
9. O.-Y. Lee, K.-L. Law and D. Yang, *Org. Lett.*, 2009, 11, 3302-3305.
10. C. B. Huehls, A. Lin and J. Yang, *Org. Lett.*, 2014, 16, 3620-3623.
11. C. Quinet, P. Jourdain, C. Hermans, A. Ates, I. Lucas and I. E. Markó, *Tetrahedron*, 2008, 64, 1077-1087.
12. D. B. Bagal, R. A. Watile, M. V. Khedkar, K. P. Dhake and B. M. Bhanage, *Catal. Sci. Technol.*, 2012, 2, 354-358.
13. P. R. Likhar, R. Arundhathi, M. L. Kantam and P. S. Prathima, *Eur. J. Org. Chem.*, 2009, 2009, 5383-5389.
14. J. C. H. Yim, J. A. Bexrud, R. O. Ayinla, D. C. Leitch and L. L. Schafer, *J. Org. Chem.*, 2014, 79, 2015-2028.
15. W. Zhang, X. Dong and W. Zhao, *Org. Lett.*, 2011, 13, 5386-5389.

16. B. Sezen and D. Sames, *J. Am. Chem. Soc.*, 2005, 127, 5284-5285.
17. K.-i. Fujita, Y. Enoki and R. Yamaguchi, in *Organic Syntheses*, John Wiley & Sons, Inc., 2003, DOI: 10.1002/0471264229.os083.28.
18. S. Zhou, K. Junge, D. Addis, S. Das and M. Beller, *Angew. Chem. Int. Ed.*, 2009, 48, 9507-9510.
19. X. Frogneux, E. Blondiaux, P. Thuéry and T. Cantat, *ACS Catal.*, 2015, 5, 3983-3987.
20. S. C. A. Sousa and A. C. Fernandes, *Adv. Synth. Catal.*, 2010, 352, 2218-2226.
21. O. O. Kovalenko, A. Volkov and H. Adolfsson, *Org. Lett.*, 2015, 17, 446-449.
22. P. W. Tan, M. Haughey and D. J. Dixon, *Chem. Commun.*, 2015, 51, 4406-4409.
23. X. Cui, X. Dai, Y. Deng and F. Shi, *Chem. Eur. J.*, 2013, 19, 3665-3675.
24. L. De Luca, G. Giacomelli and A. Porcheddu, *J. Org. Chem.*, 2002, 67, 5152-5155.
25. H. Suezawa, A. Mori, M. Sato, R. Ehama, I. Akai, K. Sakakibara, M. Hirota, M. Nishio and Y. Kodama, *J. Phys. Org. Chem.*, 1993, 6, 399-406.
26. A. Khazaei, A. Rostami and F. Mantashlo, *Chin. Chem. Lett.*, 2010, 21, 1430-1434.
27. H. Konishi, T. Ueda, T. Muto and K. Manabe, *Org. Lett.*, 2012, 14, 4722-4725.