Supporting information

# Non-Catalyzed Formation of *gem*-Dihydroperoxides from Ketones under Neutral Conditions: Activation of Hydrogen Peroxide by *in situ* Concentration

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**Materials and methods**

Ketones and 30% aqueous solution of $H_2O_2$ were obtained from commercial sources and were used as received. 1H and 13C spectra were obtained with DMSO as internal standards on a 300 MHz spectrometer. Mass spectra ESI and HR-MS were measured by Q-TOF Premier (Waters-Micromass). IR spectra were measured by Perkin Elmer (Spectrum 400, FT-IR/FT-FIR Spectrometer). Element analysis was done by Vario EL cube, Elementar. Melting points were determined by Buchi 535.

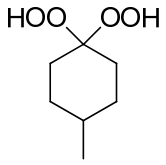
**Caution:** Although we have encountered no difficulties in working with these peroxides, routine precautions (shields, fume hoods, avoidance of transition metal salts) should be observed whenever possible, as organic peroxides are potentially hazardous compounds.

**Preparation of dihydroperoxides**

**Standard procedure 1:** 1 mmol of ketone was dissolved in 10 ml of acetonitrile and then 4 or 8 mmol (453 mg or 906 mg) of 30% aqueous solution of $H_2O_2$ was added. The solution was evaporated under reduced pressure for 20 minutes. Then another portion of solvent (10ml) was added and the solution was evaporated again for 20 minutes. The reaction mixture was left at 20-40°C for 2-24 h. The dihydroperoxide was purified by column chromatography (eluent DCM:EtOAc=8:2) if not stated differently.

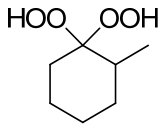
**Standard procedure 2:** 100% $H_2O_2$ was prepared before the reaction by dissolving 4 mmol (453 mg) of 30% aqueous solution of $H_2O_2$ in 10 ml of acetonitrile. The solution was evaporated under reduced pressure for 20 minutes. Then another portion of solvent (10ml) was added and the solution was evaporated again for 20 minutes. 1 mmol of ketone was then added to previously prepared $H_2O_2$ and was left reacting at 20°C for 1,5-16 h. The product was purified by column chromatography (eluent DCM:EtOAc=8:2).

**1,1-Dihydroperoxy-4-methylcyclohexane (2a)[1]**



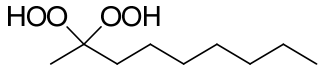

**2a** was prepared according to standard procedure 1 from 4-methylcyclohexanone **1a** (112 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 20 °C for 2 h and after purification 130 mg of **2a** (80% yield) was isolated as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 0.87 (d, 3H, *J*=6 Hz), 1.00-1.14 (m, 2H), 1.28-1.38 (m, 3H), 1.49-1.54 (m, 2H), 1.98-2.02 (m, 2H), 10.82 (s, 1H), 10.88 (s, 1H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 21.6, 29.1, 30.5, 31.2, 107.8; MS (ESI) m/z (%) = 161 $[M-H]^-$ (40), 111 (100); HRMS calcd for $C_7H_{13}O_4$: 161.0814, found: 161.0811; IR $\nu_{max}$ ($cm^{-1}$) 3350, 2928, 2860, 1446, 1378, 1255, 1098, 1043, 974; mp 55-58°C (lit.[2] 54-56°C).

**1,1-Dihydroperoxy-2-methylcyclohexane (2b)**[1]



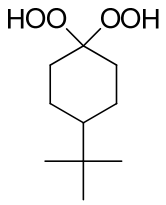

**2b** was prepared according to standard procedure 1 from 2-methylcyclohexanone **1b** (112 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 20 °C for 2 h and after purification 137 mg of **2b** (70% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 0.96 (d, 3H, *J*=6 Hz), 1.30-1.61 (m, 7H), 1.74-1.78 (m, 1H), 2.05-2.14 (m, 1H), 10.72 (s, 1H), 10.79 (s, 1H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 14.4, 20.1, 22.2, 24.8, 29.4, 31.7, 110.0; MS (ESI) m/z (%) = 161 $[M-H]^-$ (20), 143 (100); HRMS calcd for $C_7H_{13}O_4$: 161.0814, found: 161.0813; IR $\nu_{max}$ ($cm^{-1}$) 3415, 2939, 2865, 1447, 1378, 1066, 945.

**2,2-Dihydroperoxynonane (2c)**[1]



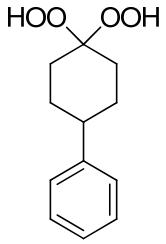

**2c** was prepared according to standard procedure 1 from nonan-2-one **1c** (142 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification 154 mg of **2c** (82% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 0.86 (t, 3H, *J*= 6 Hz), 1.22 (s, 3H), 1.20-1.36 (m, 10H), 1.52-1.57 (m, 2H), 10.88 (s, 2H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 13.9, 18.1, 22.1, 23.5, 28.6, 29.3, 31.2, 33.0, 109.6; MS (ESI) m/z (%) = 191 $[M-H]^-$ (60), 141 (100); HRMS calcd for $C_9H_{19}O_4$: 191.1283, found: 191.1282; IR $\nu_{max}$ ($cm^{-1}$) 3416, 2957, 2927, 1856, 1466, 1375, 1132, 1099.

**4-(tert-Butyl)-1,1-dihydroperoxycyclohexane (2d)**[1]



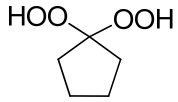

**2d** was prepared according to standard procedure 1 from 4-*tert*-butylcyclohexanone **1d** (154 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 5 h and after purification 178 mg of **2d** (89% yield) was isolated as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 0.83 (s, 9H), 0.96-1.30 (m, 5H), 1.58 (m, 2H), 2.10 (m, 2H), 10.82 (s, 1H), 10.89 (s, 1H).; $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 23.0, 27.5, 29.7, 32.0, 46.9, 107.7; MS (ESI) m/z (%) = 203 $[M-H]^-$ (60), 153 (100); HRMS calcd for $C_{10}H_{19}O_4$: 203.1283, found: 203.1277; IR $\nu_{max}$ ($cm^{-1}$) 3415, 2952, 1366, 1053, 906; mp 83-84 °C (lit.[1] 79-81 °C).

**(4,4-Dihydroperoxycyclohexyl)benzene (2e)**



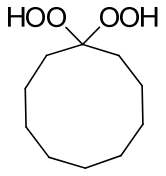

**2e** was prepared according to standard procedure 1 from 4-phenylcyclohexanone **1e** (154 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification 221 mg of **2e** (99% yield) was isolated as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.43-1.72 (m, 6H), 2.17 (d, 2H, *J*=12 Hz), 2.53-2.63 (m, 1H), 7.15-7.31 (m, 5H), 10.95 (s, 1H), 11.03 (s, 1H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 29.6, 29.8, 42.6, 107.4, 126.0, 126.6, 128.3, 146.3; MS (ESI) m/z (%) =223 $[M-H]^-$ (60), 205 (100); HRMS calcd for $C_{12}H_{15}O_4$: 223.0970, found: 223.0971; IR $\nu_{max}$ ($cm^{-1}$) 3216, 2938, 1394, 1123, 1051; Element. Anal. calcd 64.27% C, 7.19% H, found 64.23% C, 7.14% H; mp 123-125 °C.

**1,1-Dihydroperoxycyclopentane (2g)[1]**



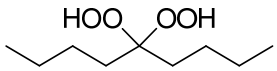

**2g** was prepared according to standard procedure 2 from cyclopentanone **1g** (84 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 20 °C for 24 h and after purification 131 mg of **2g** (94% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.57-1.62 (m, 4H), 1.74-1.79 (m, 4H), 11.24 (s, 2H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 24.2, 32.9, 119.8; HRMS calcd for $C_5H_9O_4$: 133.0501, found: 133.0497; IR $\nu_{max}$ ($cm^{-1}$) 3382, 2962, 2876, 1437, 1378, 1328, 1198, 1184, 1076, 969.

**1,1-Dihydroperoxycyclodecane (2h)**



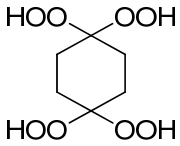

**2h** was prepared according to standard procedure 1 from cyclodecanone **1h** (154 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification 159 mg of **2h** (78% yield) was isolated as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.42-1.57 (m, 14H), 1.70 (t, 4H, *J*= 6 Hz), 10.78 (s, 2H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 20.6, 23.0, 25.1, 25.4, 25.6, 112.8; HRMS calcd for $C_{10}H_{19}O_4$: 203.1283, found: 203.1280; IR $\nu_{max}$ ($cm^{-1}$) 3396, 2902, 1486, 1394, 1256, 1077; Element. anal. calcd 58.80% C, 9.87% H, found 58.87% C, 10.07% H; mp 96-97 °C.

**5,5-Dihydroperoxynonane (2i)**[1]



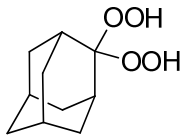

**2i** was prepared according to standard procedure 1 from nonan-5-one **1i** (142 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification 166 mg of **2i** (86% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 0.87 (t, 6H, *J*= 6 Hz),1.23-1.33 (m, 8H), 1.47-1.52 (m, 4H), 10.77 (s, 2H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 13.9, 22.4, 25.3, 28.9, 111.5; MS (ESI) m/z (%) = 191 $[M-H]^-$ (70), 141 (100); HRMS calcd for $C_9H_{19}O_4$: 191.1283, found: 191.1288; IR $\nu_{max}$ ($cm^{-1}$) 3415, 2960, 2933, 2873, 1457, 1380, 1259, 1134, 1078, 967.

**1,1,4,4-Tetrahydroperoxycyclohexane (2j)**



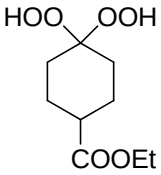

**2j** was prepared according to standard procedure 1 from cyclohexan-1,4-dione **1j** (112 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 20 °C for 24 h and the reaction mixture was washed with 20% EtOAc/DCM to obtain 152 mg of **2j** (72% yield) as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.72 (s, 8H), 11.10 (s, 4H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 26.1, 107.9; MS (ESI) m/z (%) =211 $[M-H]^-$ (100), 161 (20), 111 (30), 110 (35); HRMS calcd for $C_6H_{11}O_8$: 211.0454, found: 211.0455; IR $\nu_{max}$ ($cm^{-1}$) 3264, 2839, 1370, 1364, 1070, 955; mp 126-128 °C (decomp.).

**2,2-Dihydroperoxyadamantane (2k)**[1]



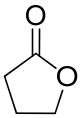

**2k** was prepared according to standard procedure 1 from adamantanone **1k** (150 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification 193 mg of **2k** (95% yield) was isolated as white solid; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.50-1.65 (m, 6H), 1.75-1.92 (m, 6H), 2.17 (s, 2H), 10.72 (s, 2H); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 26.7, 30.8, 33.3, 36.8, 109.5; MS (ESI) m/z (%) = 199 $[M-H]^-$(100), 181 (70); HRMS calcd for $C_{10}H_{15}O_4$: 199.0970, found: 199.0974; IR $\nu_{max}$ ($cm^{-1}$) 3341, 2908, 1424, 1093, 1057, 993, 919; mp 98-101 °C (decomp.) (lit.[3] 86-88 °C decomp.).

**Ethyl 4,4-dihydroperoxycyclohexanecarboxylate (2l)**[4]




**2l** was prepared according to standard procedure 1 from ethyl 4-oxocyclohexanecarboxylate **1l** (170 mg) with 8 equiv. $H_2O_2$. The reaction mixture was left at 40 °C for 24 h and after purification by column chromatography (eluent 5% MeOH/DCM) 206 mg of **2l** (94% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 1.17 (t, 3H, *J*=6 Hz), 1.40-1.61 (m, 4H), 1.71-1.78 (m, 2H), 1.93-2.02 (m, 2H), 2.34-2.44 (m, 1H), 4.05 (q, 2H, *J*=6 Hz), 10.96 (s, 1H), 11.01 (s, 1H). $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 14.1, 24.7, 28.1, 40.9, 59.8, 107.2, 174.5; HRMS $[M-H]^-$ calcd for $C_9H_{15}O_6$: 219.0869, found: 219.0866; IR $\nu_{max}$ ($cm^{-1}$) 3440, 3340, 2942, 1675, 1370, 1290, 1266, 1239, 1062, 1035, 927, 860.

**Dihydrofurane-2(3H)-one (3f)**[5]




**3f** was prepared according to standard procedure 2 from cyclobutanone **1f** (70 mg) with 4 equiv. $H_2O_2$. The reaction mixture was left at 20 °C for 16 h and after purification 80 mg of **3f** (48% yield) was isolated as colourless oil; $^1$H NMR (300MHz, DMSO-d6) δ [ppm] = 2.09-2.19 (m, 2H), 2.42 (t, 2H, *J*= 8 Hz), 4.26 (t, 2H, *J*= 6 Hz); $^{13}$C NMR (76 MHz, DMSO-d6) δ [ppm] = 21.8, 27.4, 68.3, 177.9; MS (ESI) m/z (%)= 87 $[M+H]^+$ (100); HRMS calcd for $C_4H_7O_2$: 87.0446, found: 87.0444; IR $\nu_{max}$ ($cm^{-1}$) 2988, 1766, 1377, 1164, 1035, 990.

**References**

(1) (a) Zmitek, K.; Zupan, M.; Stavber, S.; Iskra, J., *Org. Lett.* **2006,** *8*, 2491; (b) Zmitek, K.; Zupan, M.; Stavber, S.; Iskra, J., *J. Org. Chem.* **2007,** *72*, 6534.

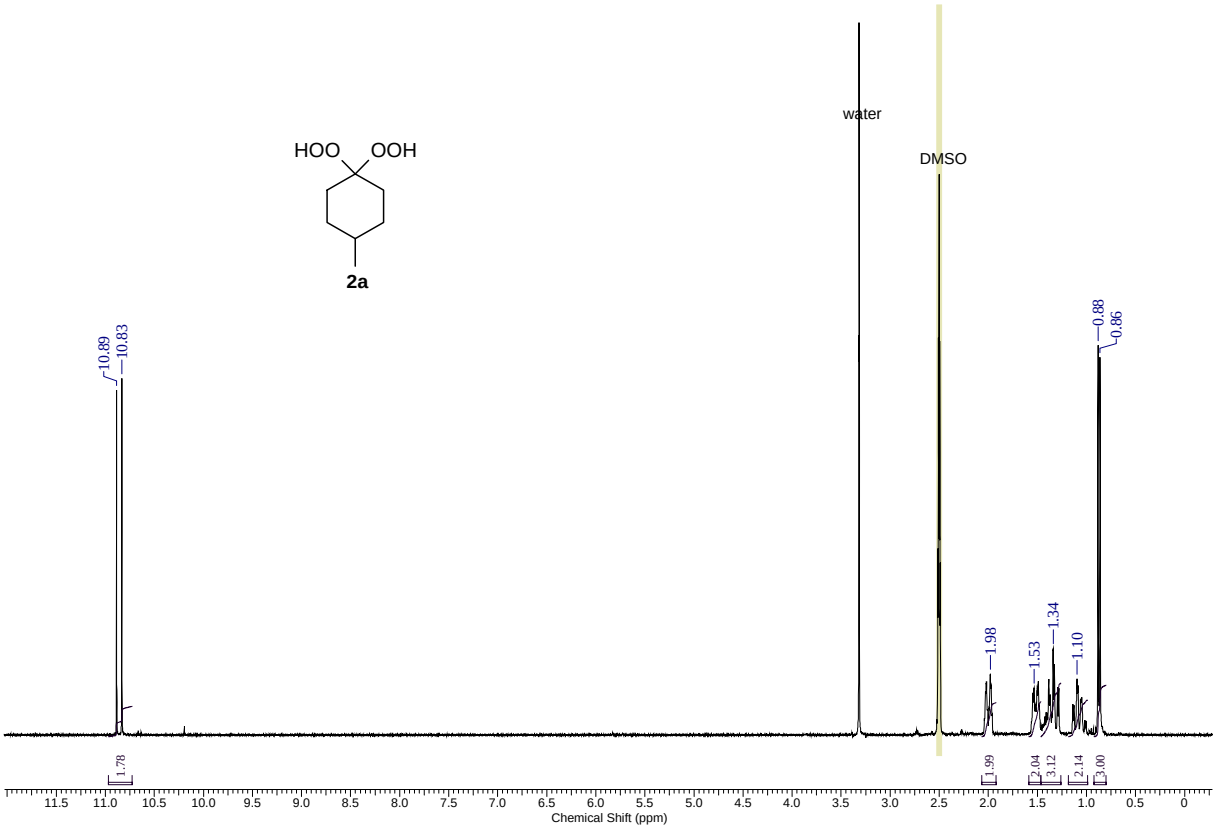
(2) Arzumanyan, A. V.; Novikov, R. A.; Terent'ev, A. O.; Platonov, M. M.; Lakhtin, V. G.; Arkhipov, D. E.; Korlyukov, A. A.; Chernyshev, V. V.; Fitch, A. N.; Zdvizhkov, A. T.; Krylov, I. B.; Tomilov, Y. V.; Nikishin, G. I., *Organometallics* **2014,** *33*, 2230.

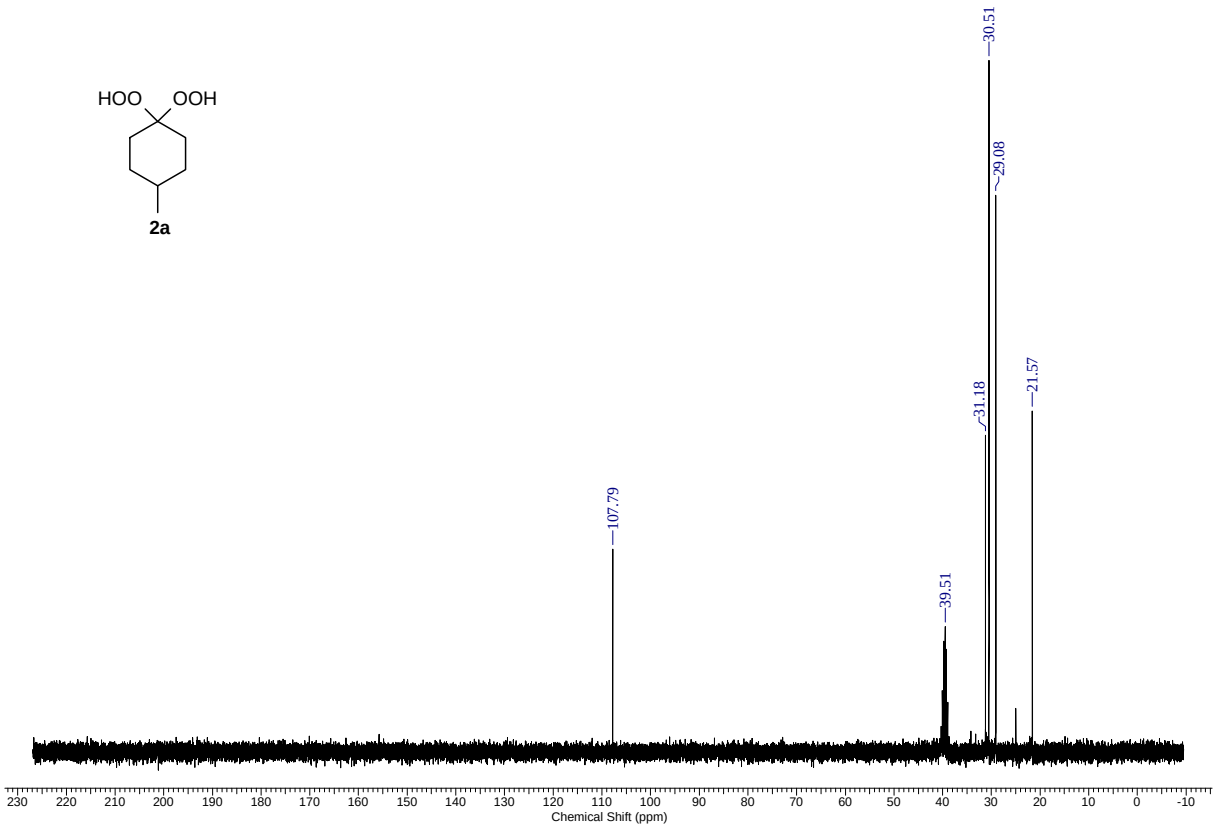
(3) Terent'ev, A. O.; Platonov, M. M.; Ogibin, Y. N.; Nikishin, G. I., *Synth. Commun.* **2007,** *37*, 1281.

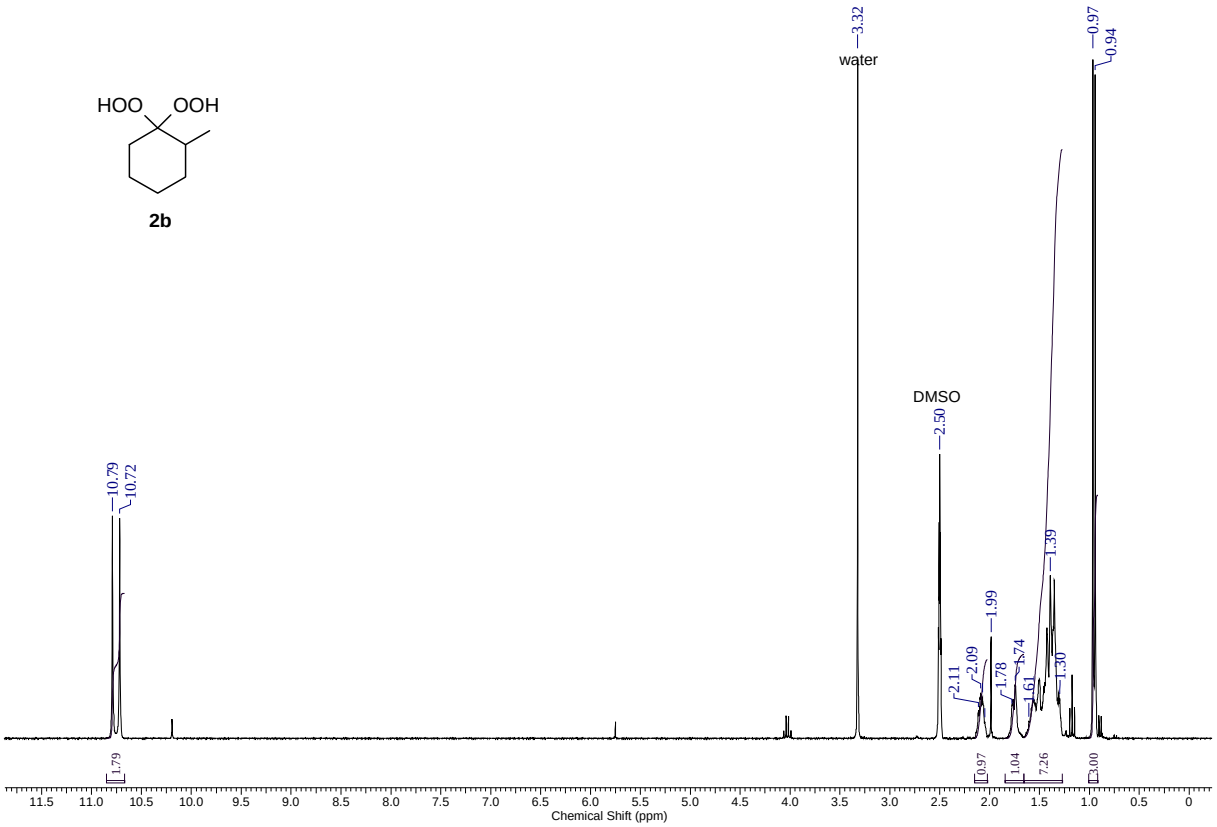
(4) Liu, Y.-H.; Deng, J.; Gao, J.-W.; Zhang, Z.-H., *Adv. Synth. Catal.* **2012,** *354*, 441.

(5) Mitsudome, T.; Noujima, A.; Mizugaki, T.; Jitsukawa, K.; Kaneda, K., *Green Chem.* **2009,** *11*, 793.

## $^{1}H$ and $^{13}C$ NMR spectra




HOO
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0.94
DMSO
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1.99
1.39
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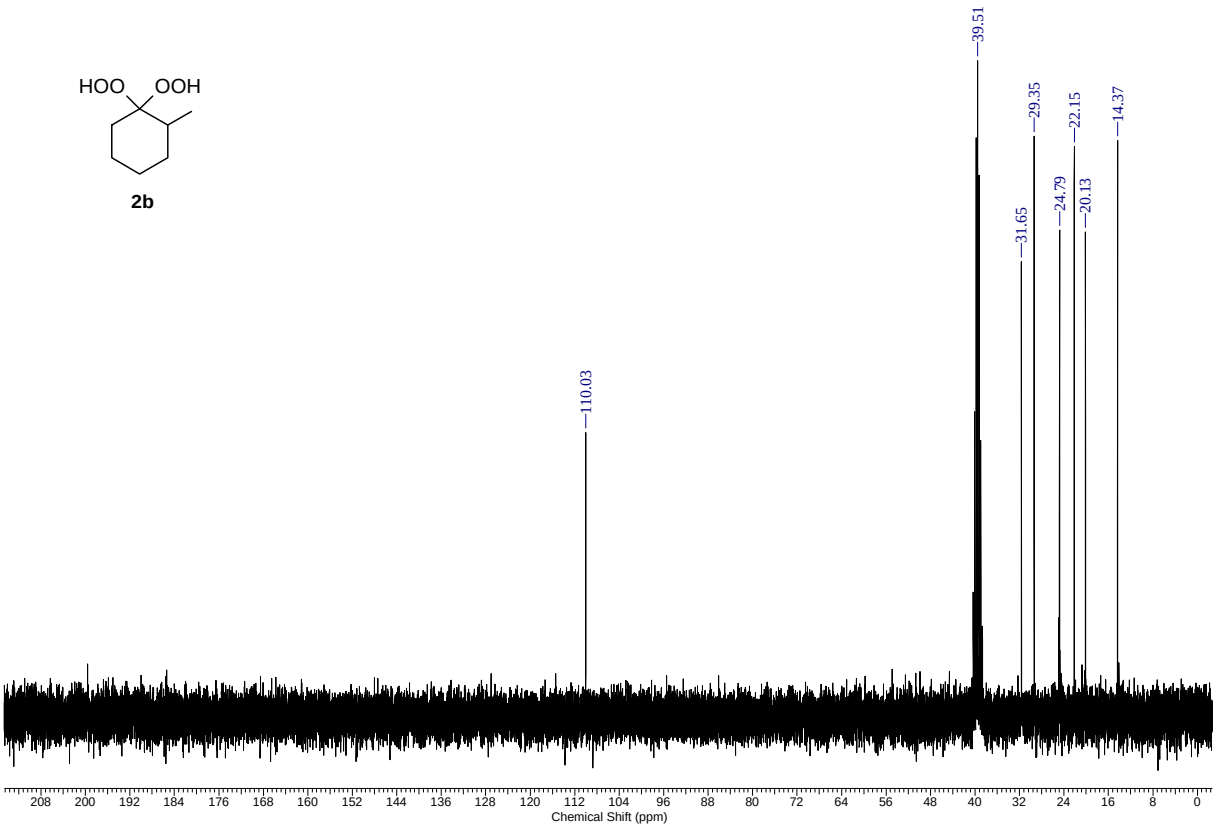
1.04
7.26
3.00
Chemical Shift (ppm)


HOO
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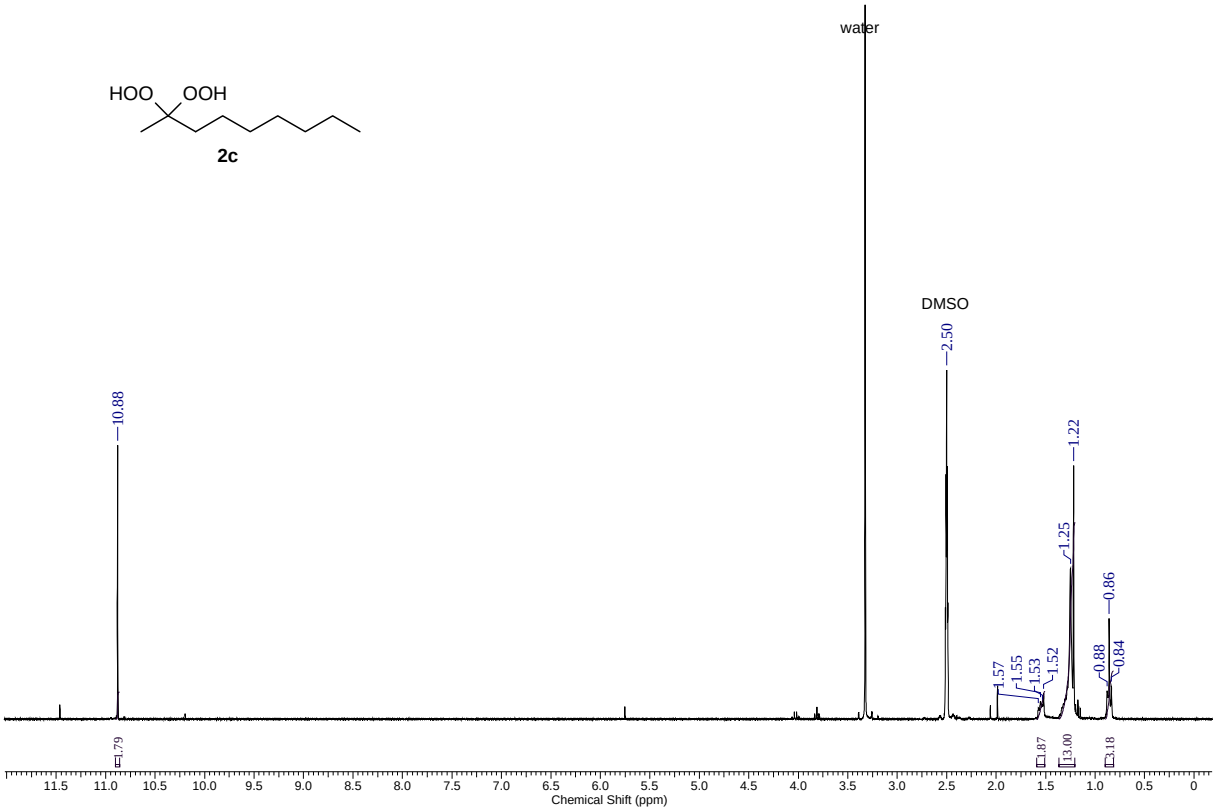
110.03
Chemical Shift (ppm)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DMSO
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1.53
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0.84
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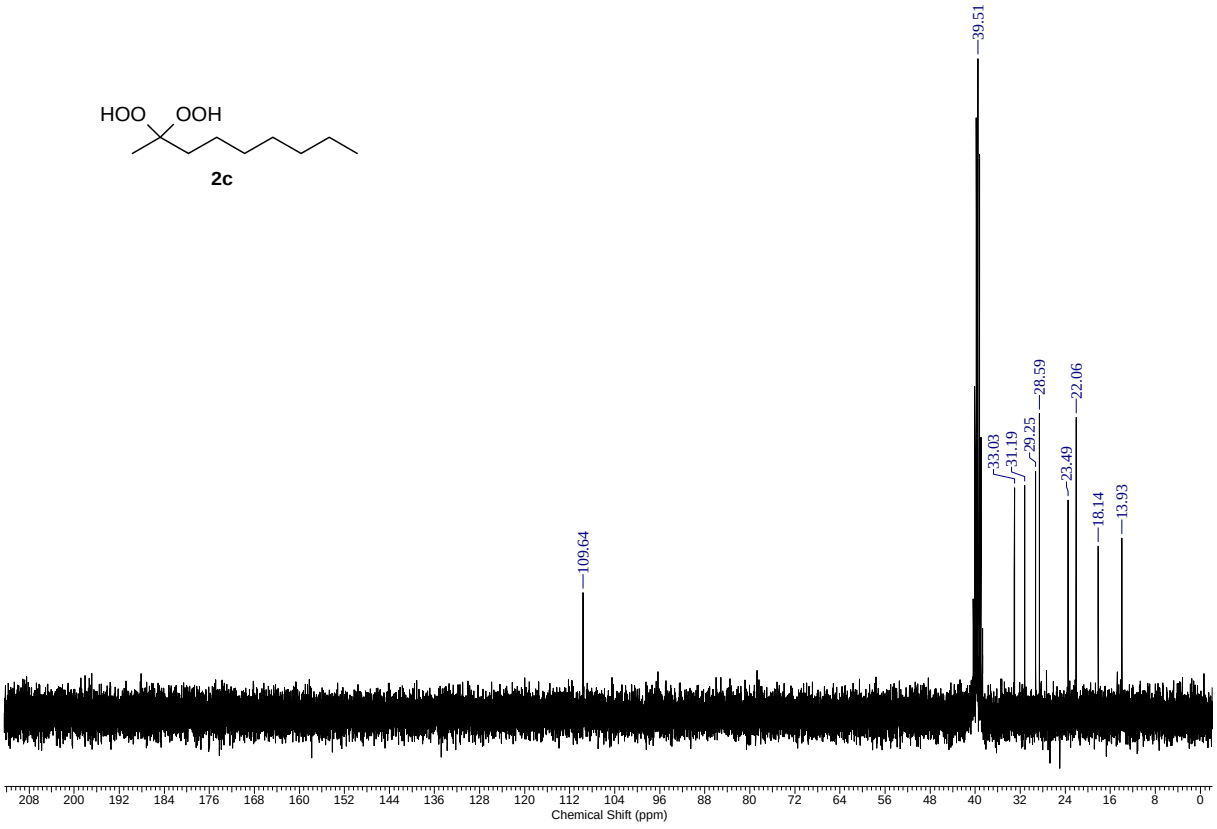
Chemical Shift (ppm)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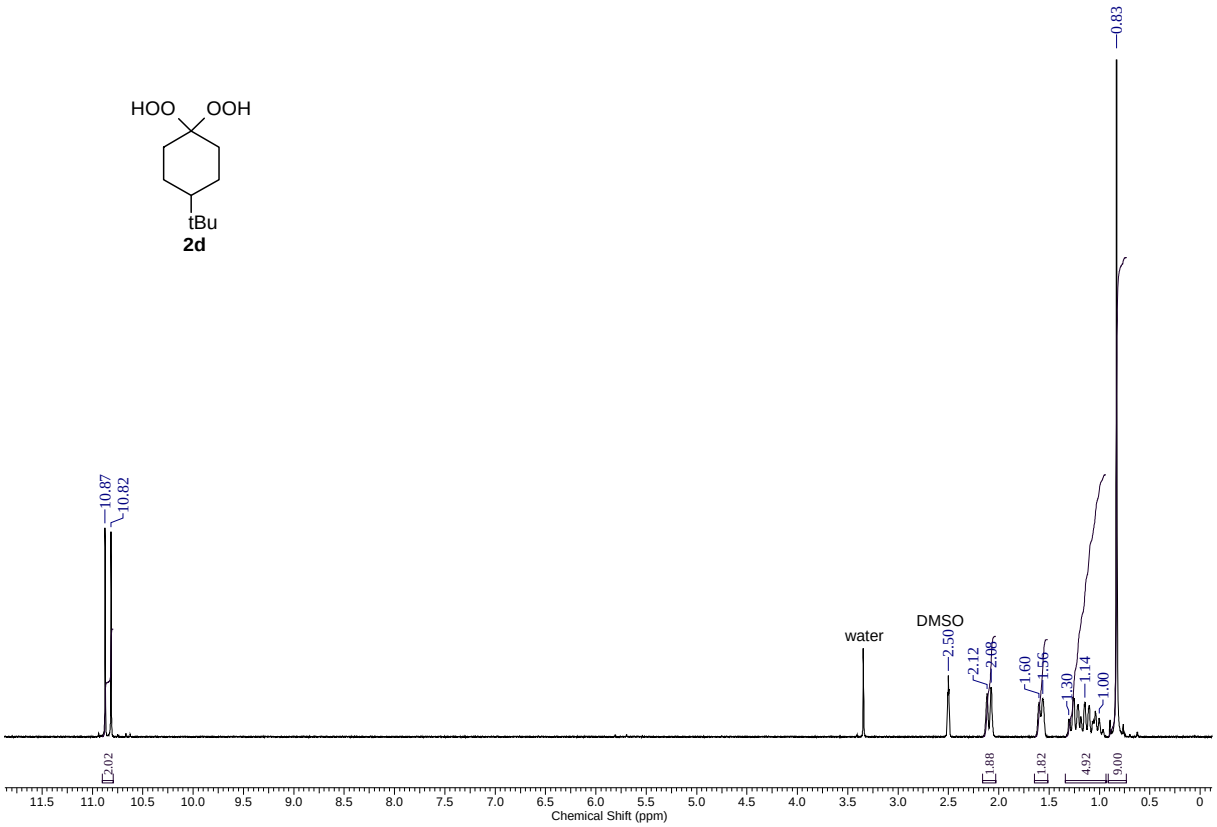
13.93
Chemical Shift (ppm)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OOH
tBu
2d
10.87
10.82
water
DMSO
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2.12
2.08
1.60
1.56
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1.00
0.83
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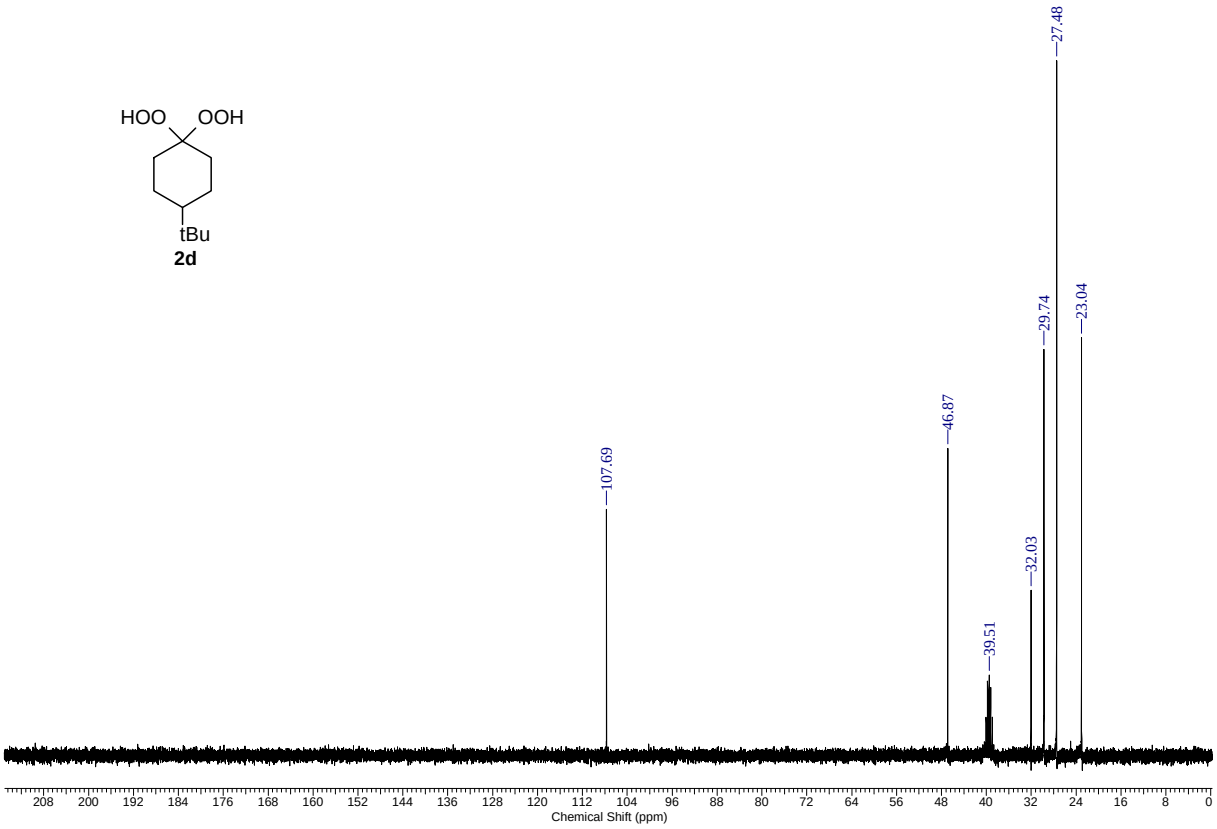
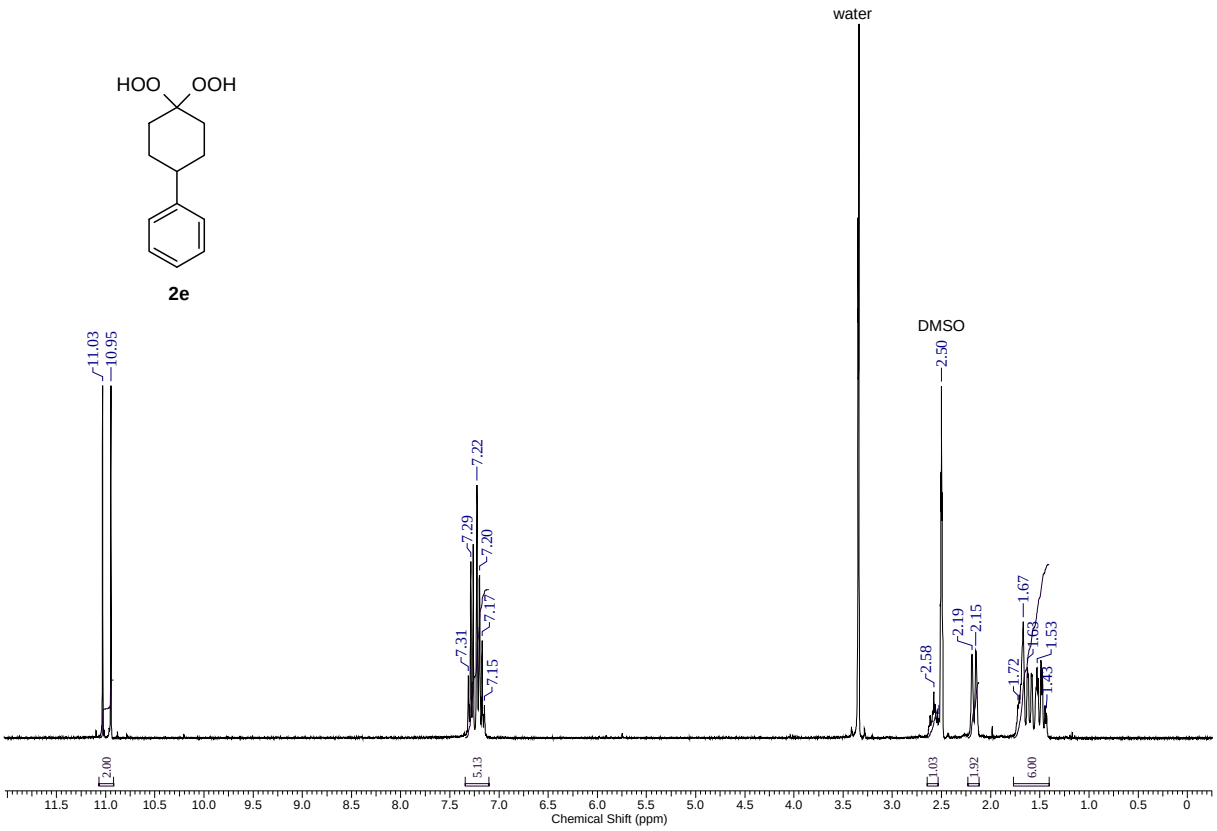
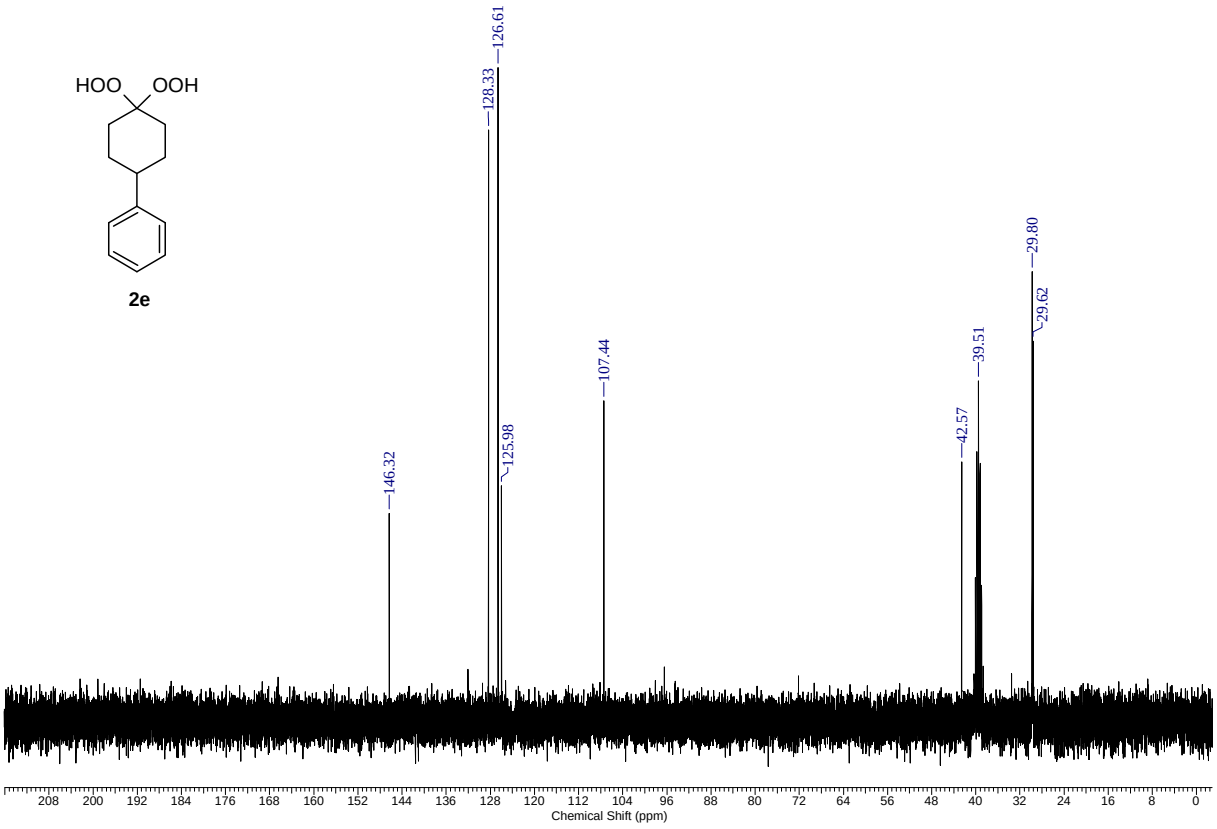
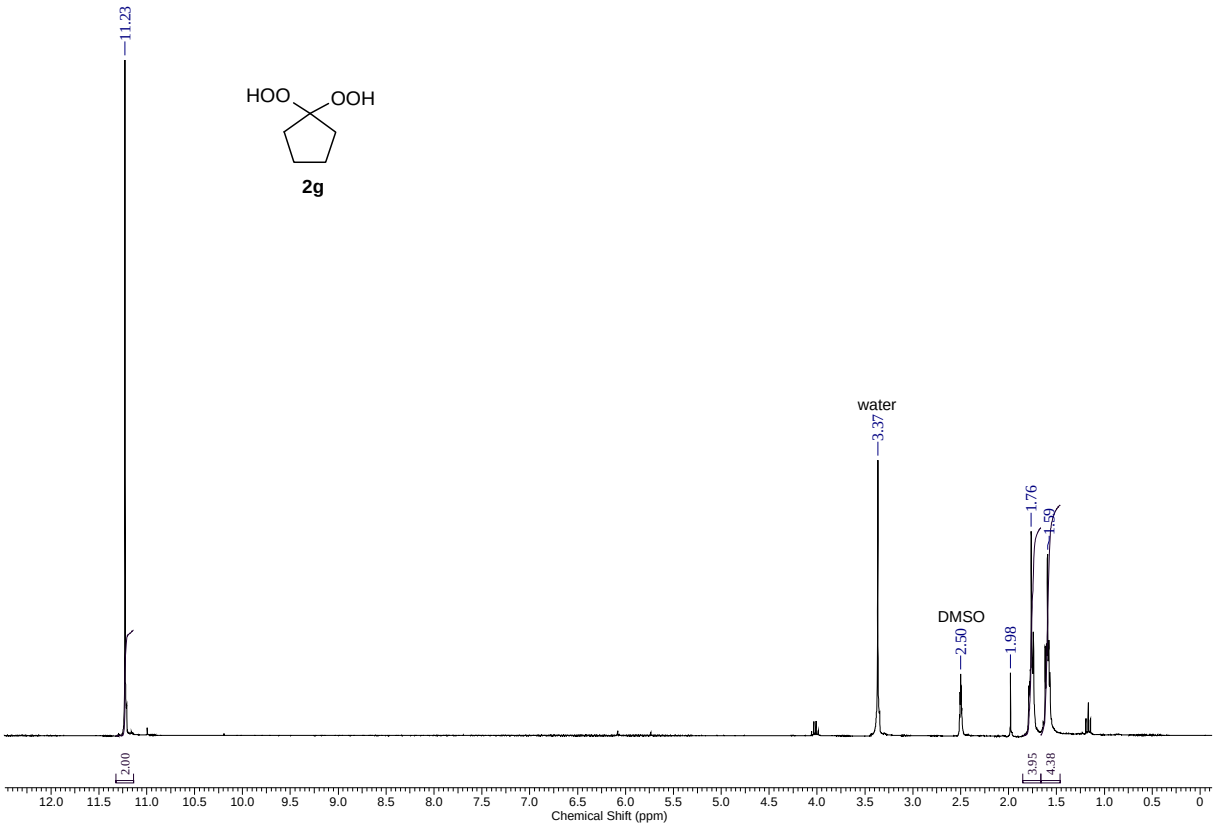
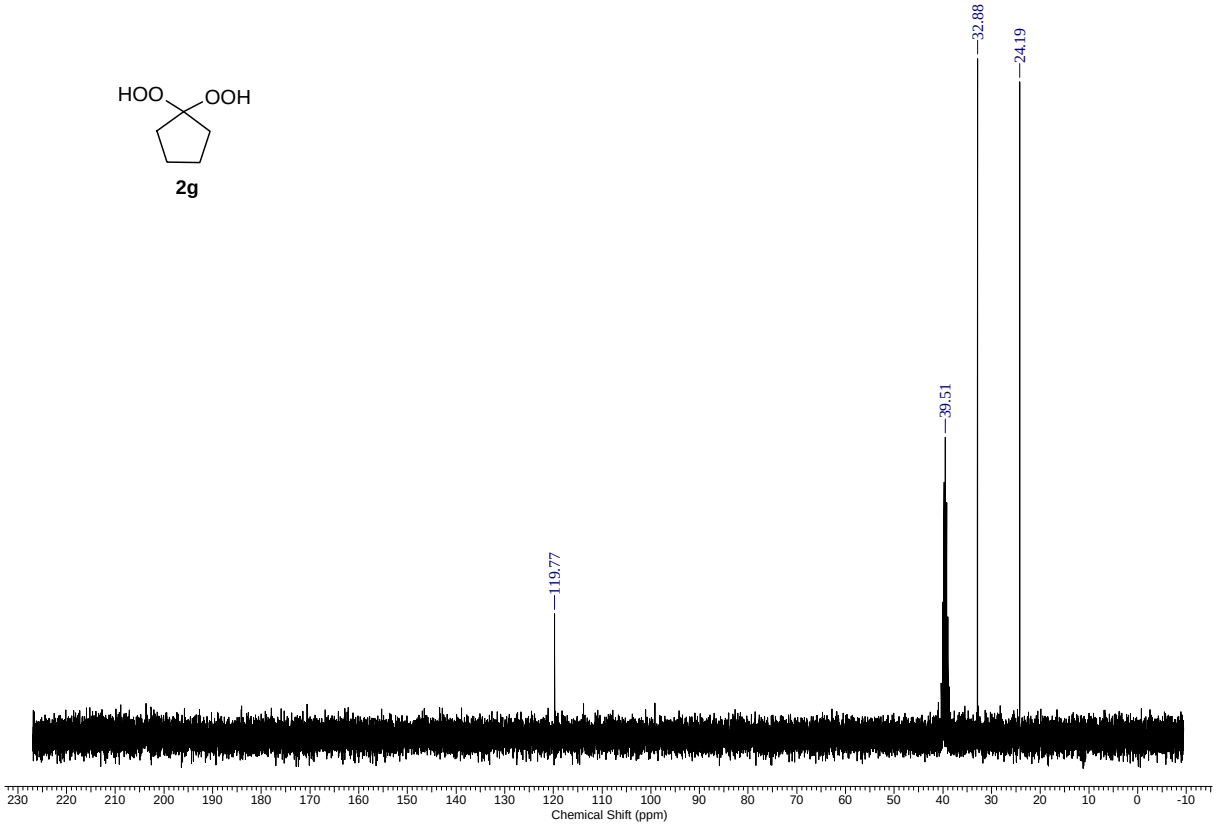
1.82
4.92
9.00
Chemical Shift (ppm)

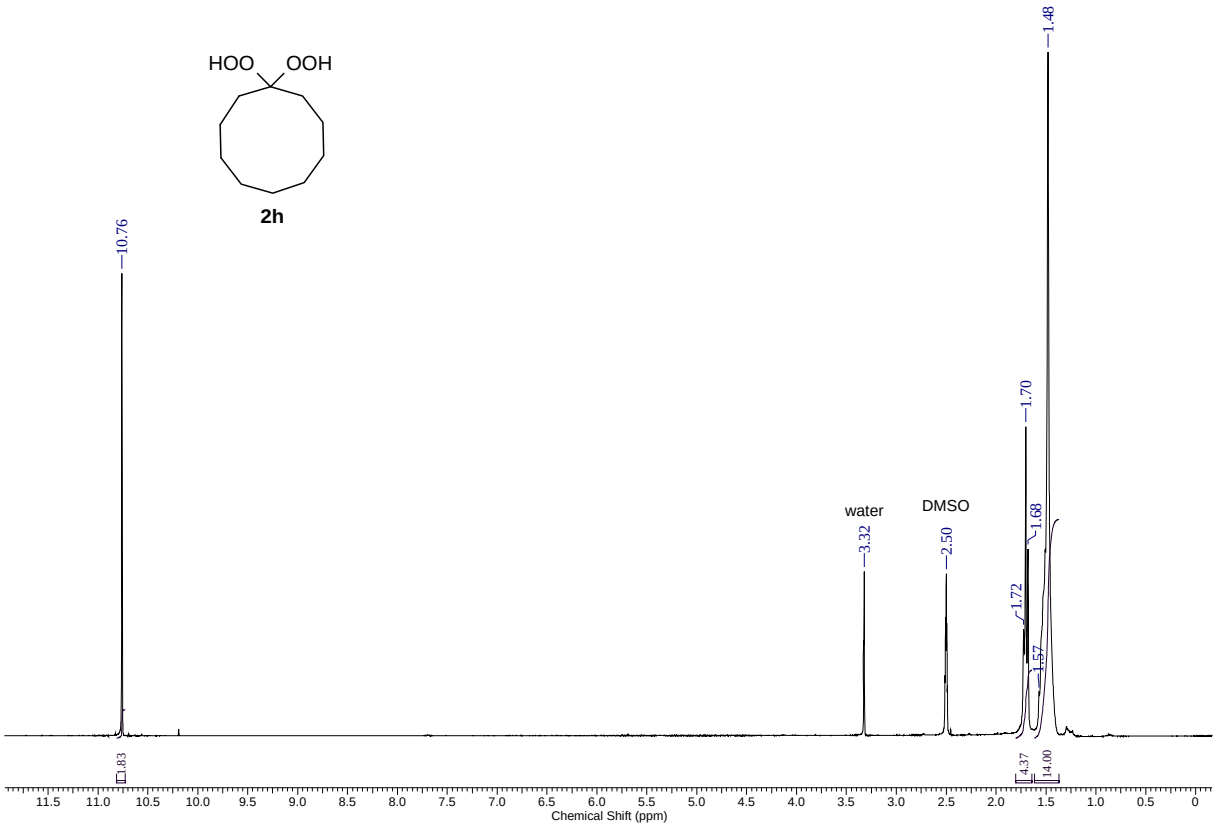

HOO
OOH
tBu
2d
107.69
46.87
39.51
32.03
29.74
27.48
23.04
Chemical Shift (ppm)

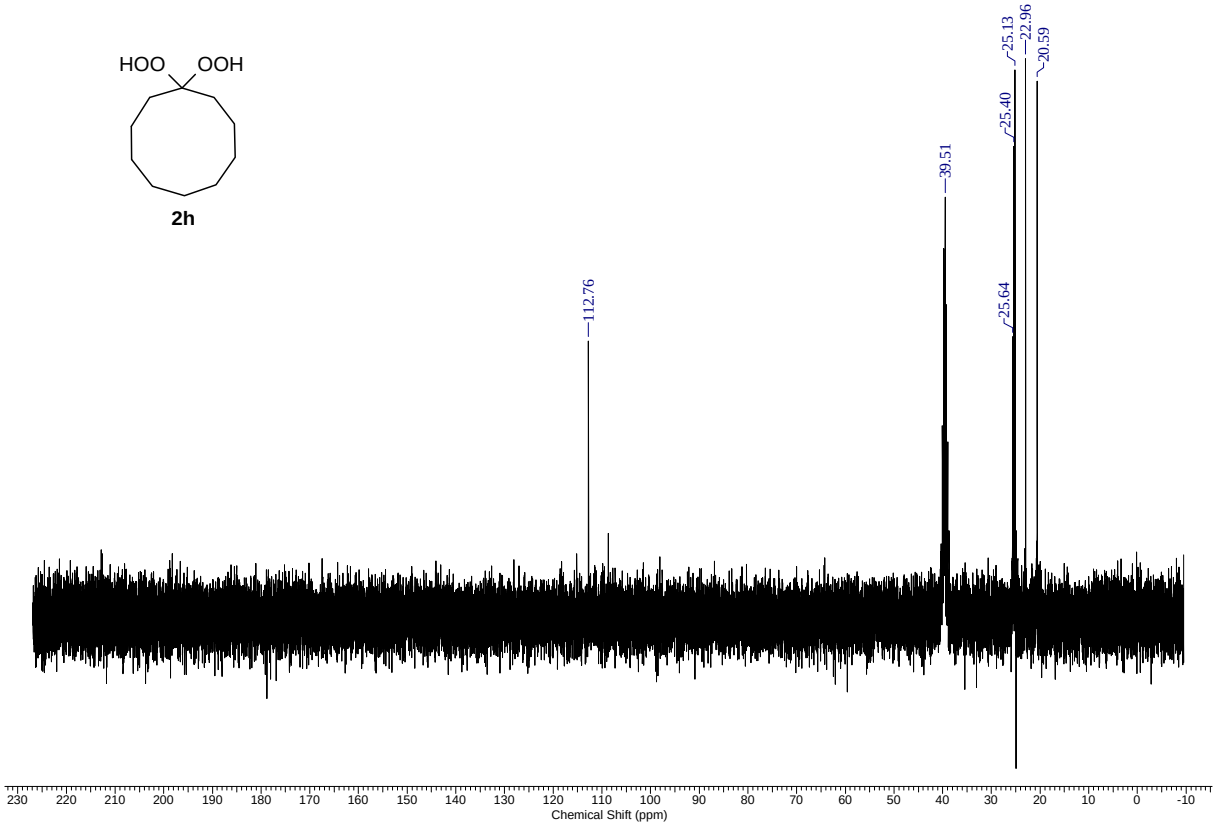

HOO
OOH
2e
water
DMSO
11.03
10.95
7.31
7.29
7.22
7.20
7.17
7.15
2.58
2.50
2.19
2.15
1.72
1.67
1.63
1.53
1.43
2.00
5.13
1.03
1.92
6.00
Chemical Shift (ppm)

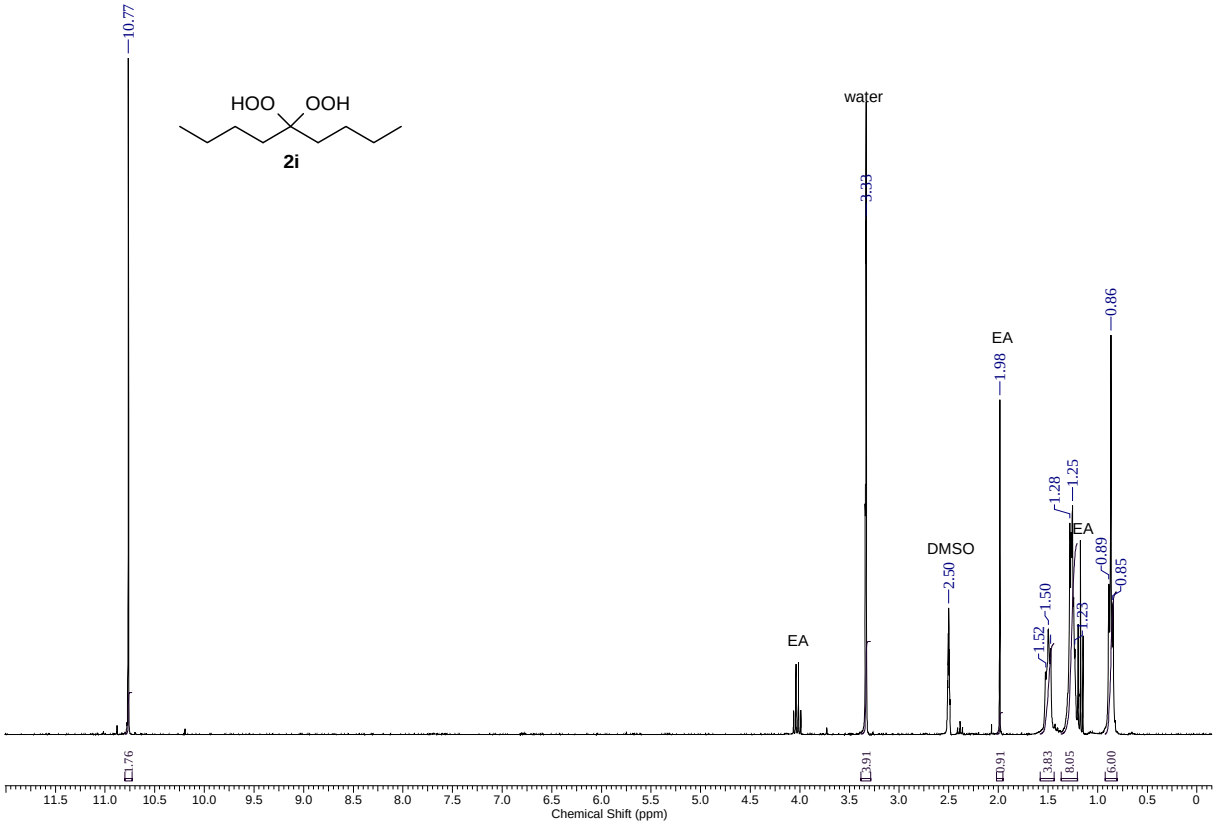

HOO
OOH
2e
146.32
128.33
126.61
125.98
107.44
42.57
39.51
29.80
29.62
Chemical Shift (ppm)

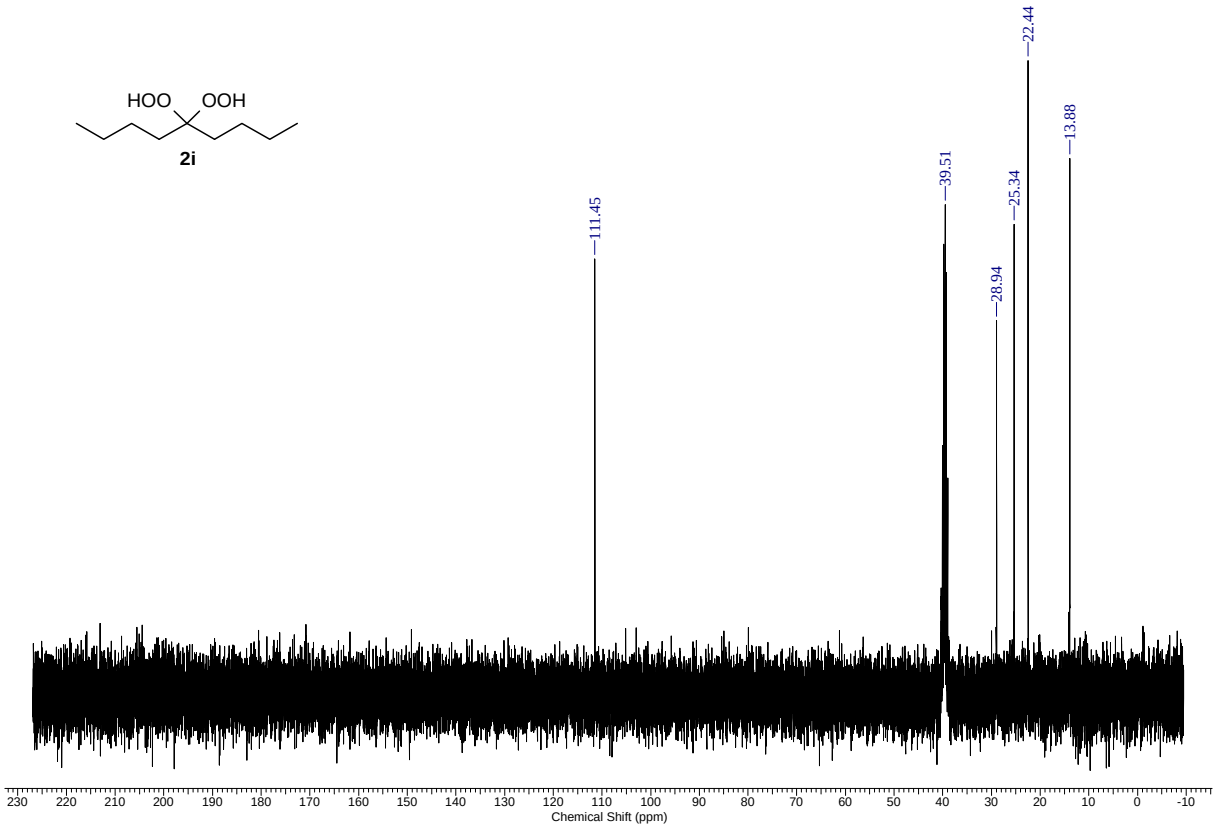

11.23
HOO
OOH
2g
water
3.37
DMSO
2.50
1.98
1.76
1.58
2.00
3.95
4.38
Chemical Shift (ppm)

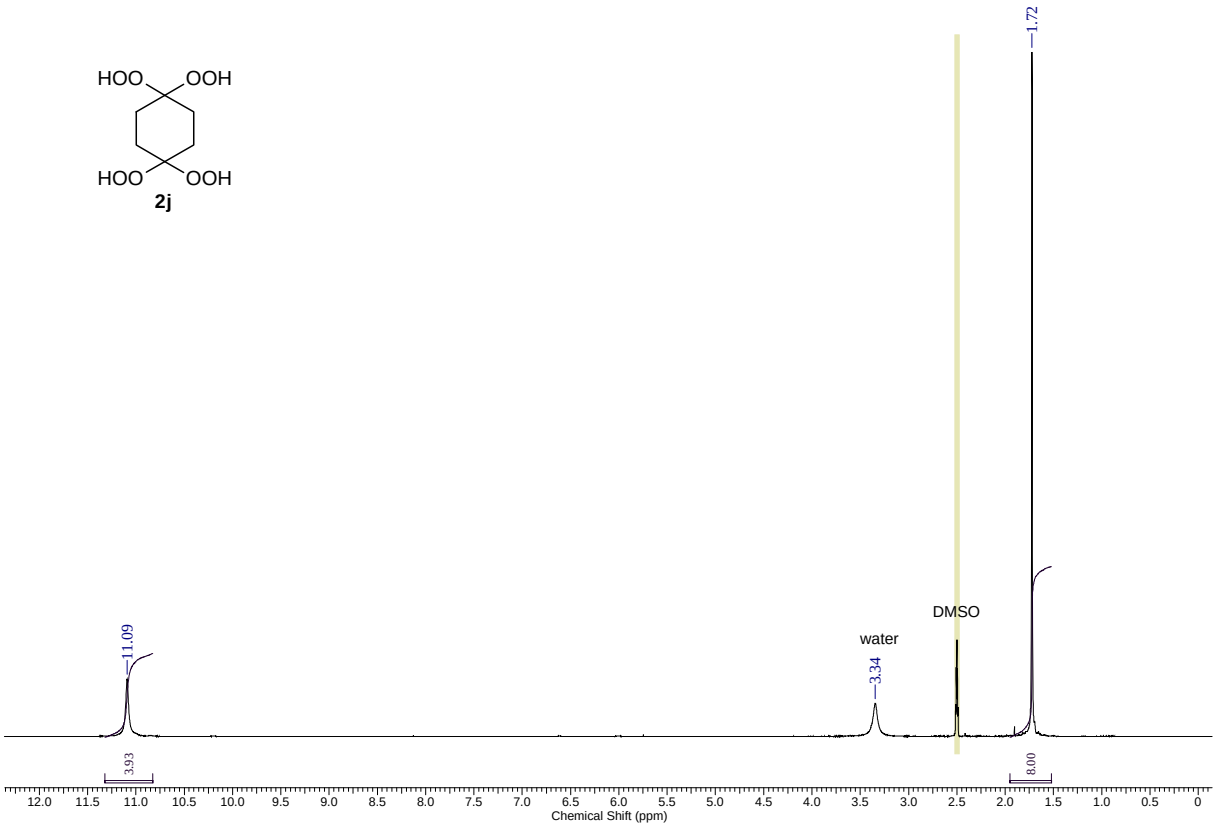

HOO
OOH
2g
32.88
24.19
39.51
119.77
Chemical Shift (ppm)

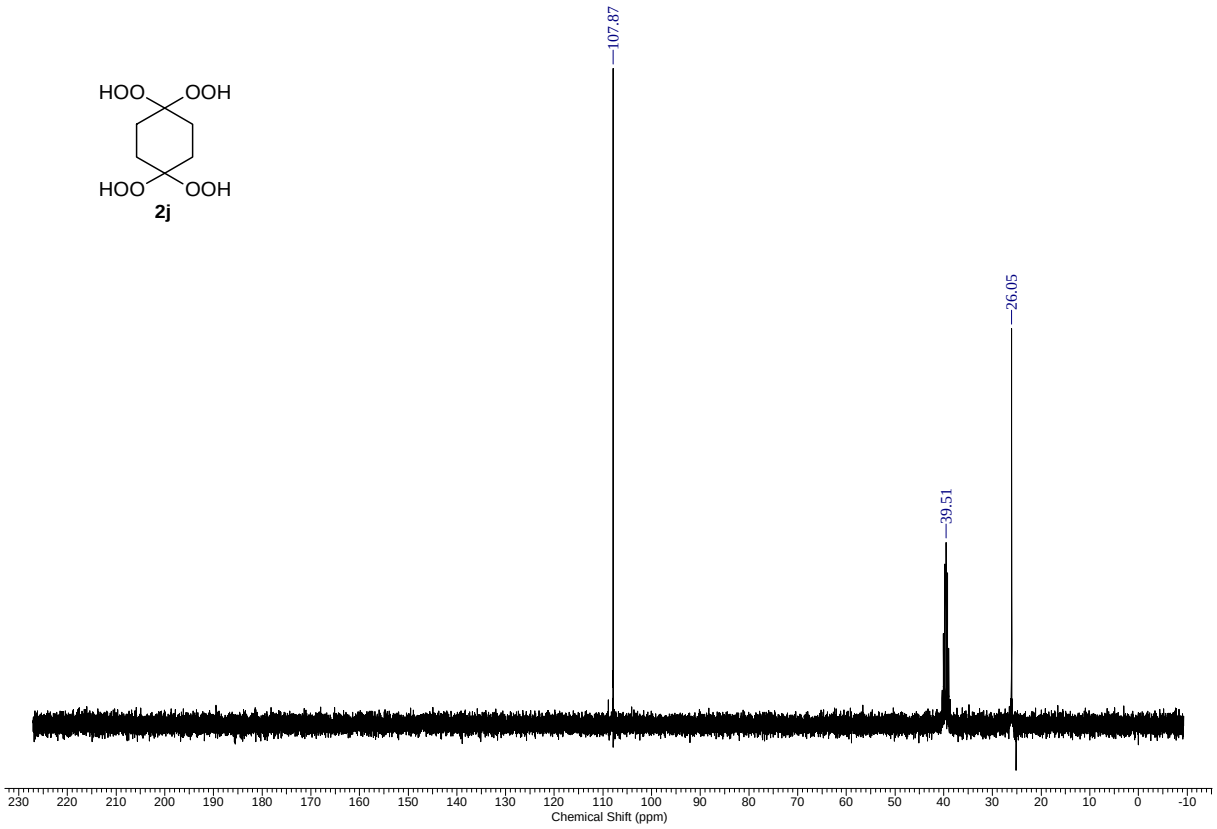

HOO
OOH
2h
10.76
1.48
1.70
1.68
1.72
1.57
water
DMSO
3.32
2.50
0.83
4.37
14.00
Chemical Shift (ppm)

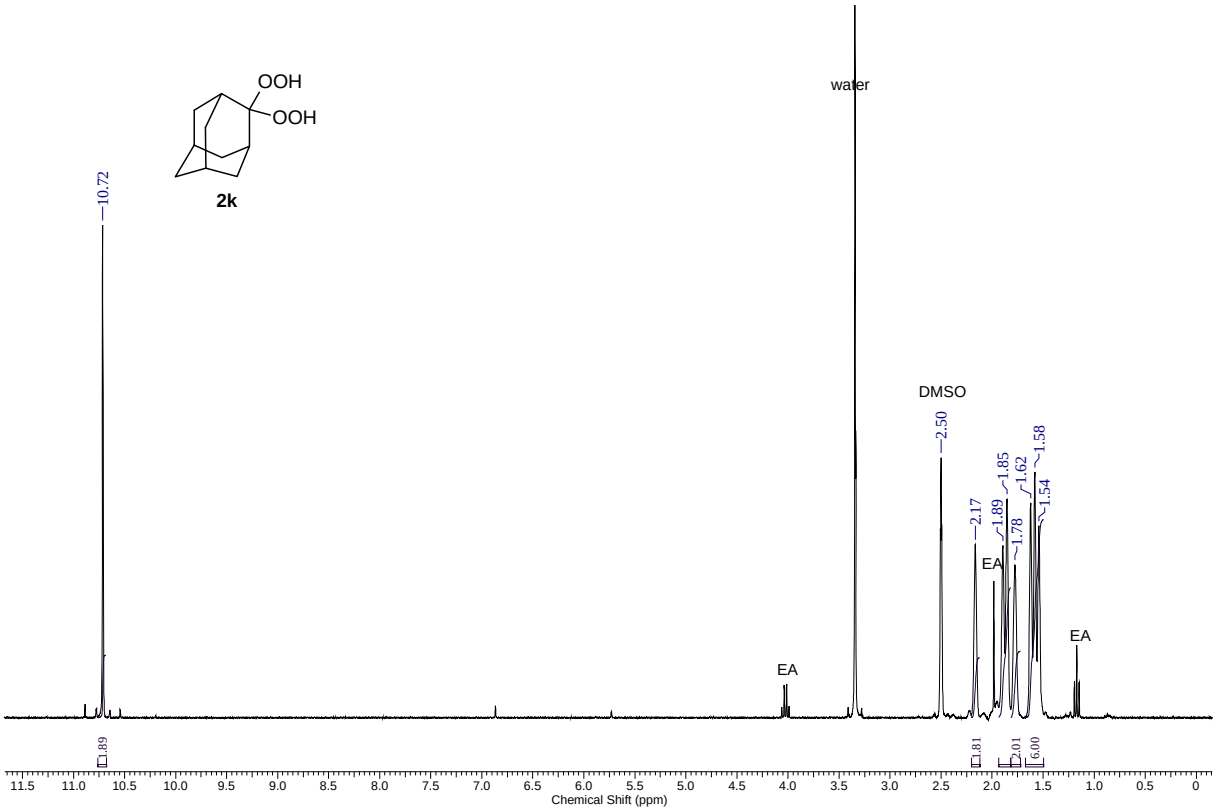

HOO
OOH
2h
25.13
22.96
20.59
25.40
39.51
112.76
25.64
Chemical Shift (ppm)

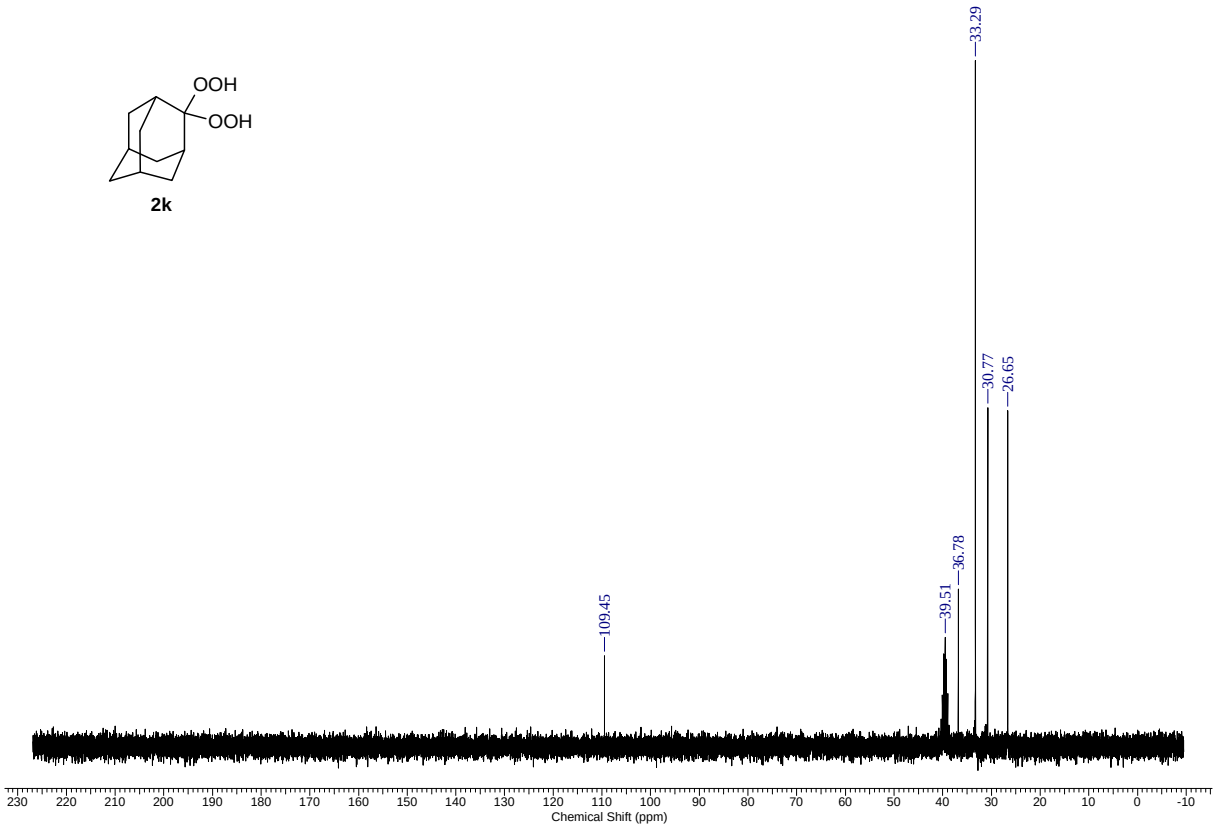

HOO
OOH
2i
10.77
water
3.33
EA
1.98
0.86
DMSO
2.50
1.28
1.25
EA
0.89
0.85
1.50
1.23
1.52
EA
1.76
3.91
1.91
3.83
8.05
6.00
Chemical Shift (ppm)

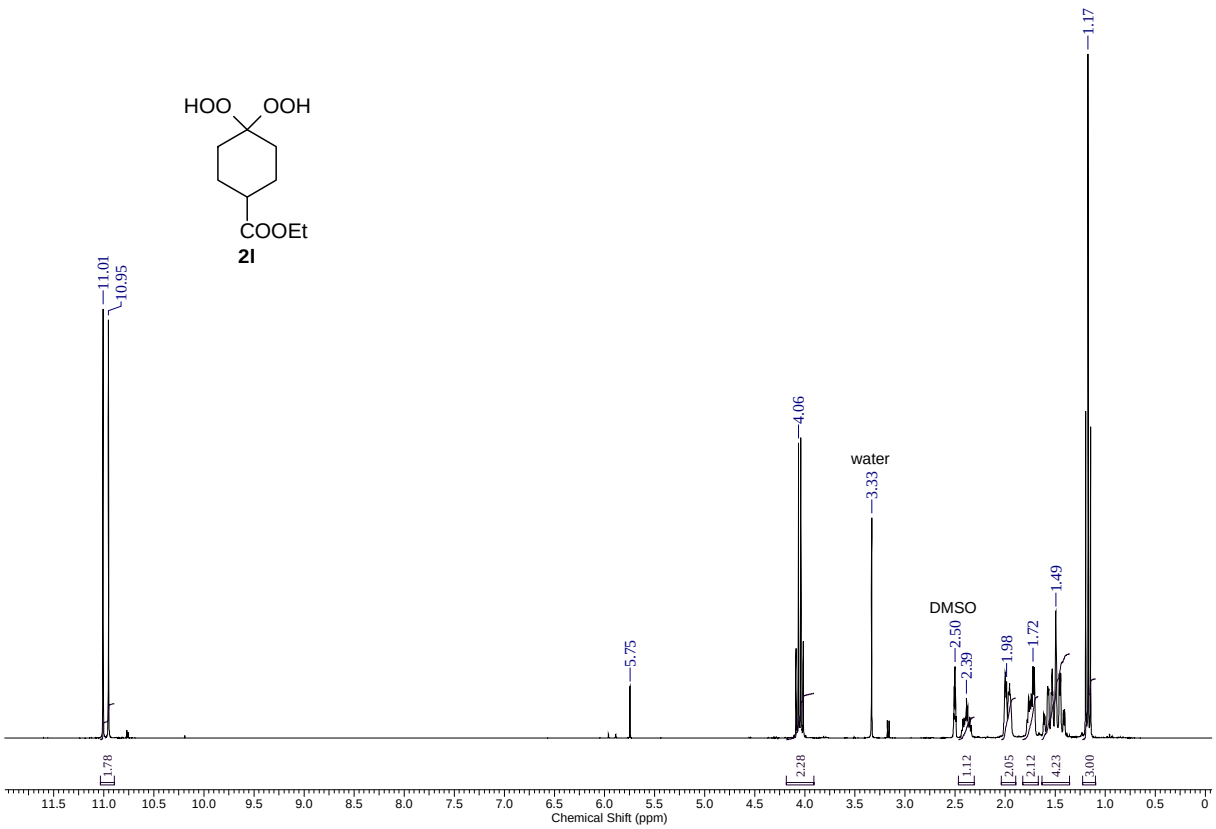

HOO
OOH
2i
111.45
39.51
28.94
25.34
22.44
13.88
Chemical Shift (ppm)

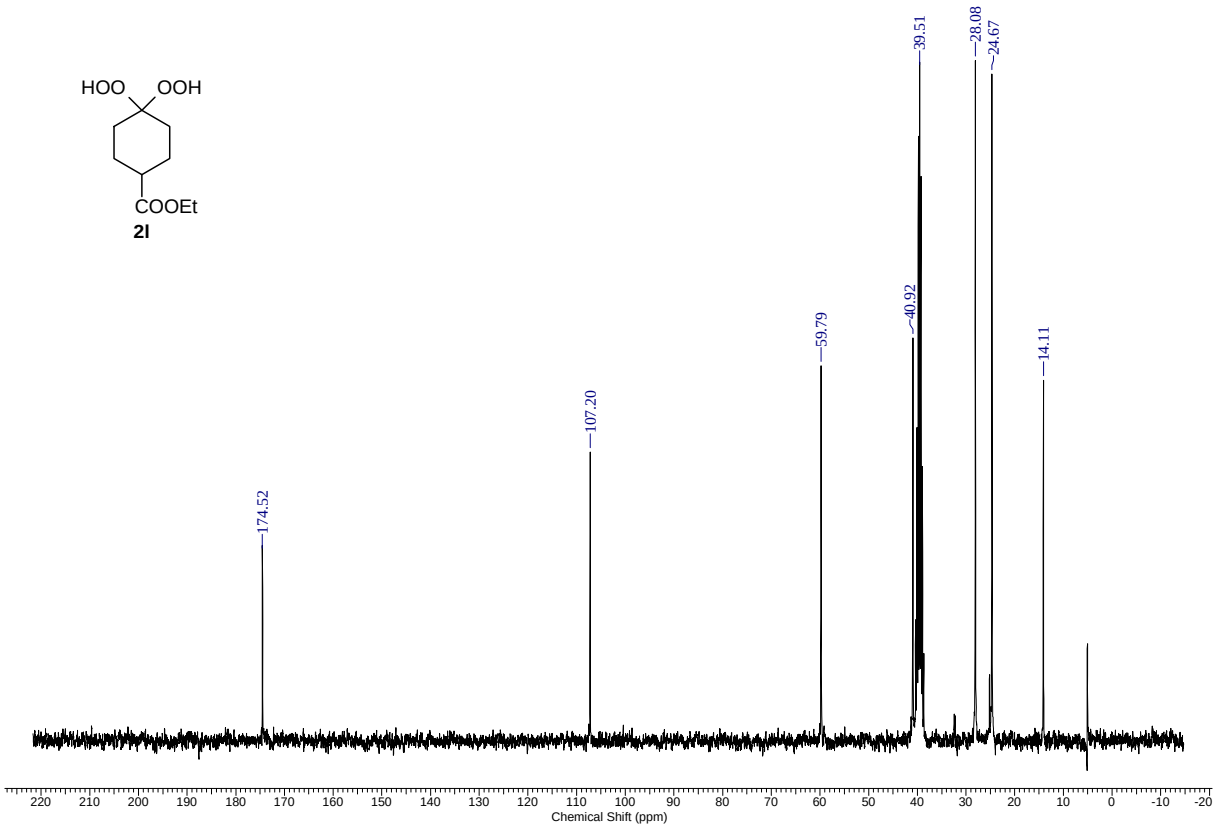

HOO
OOH
HOO
OOH
2j
1.72
11.09
water
3.34
DMSO
3.93
8.00
Chemical Shift (ppm)

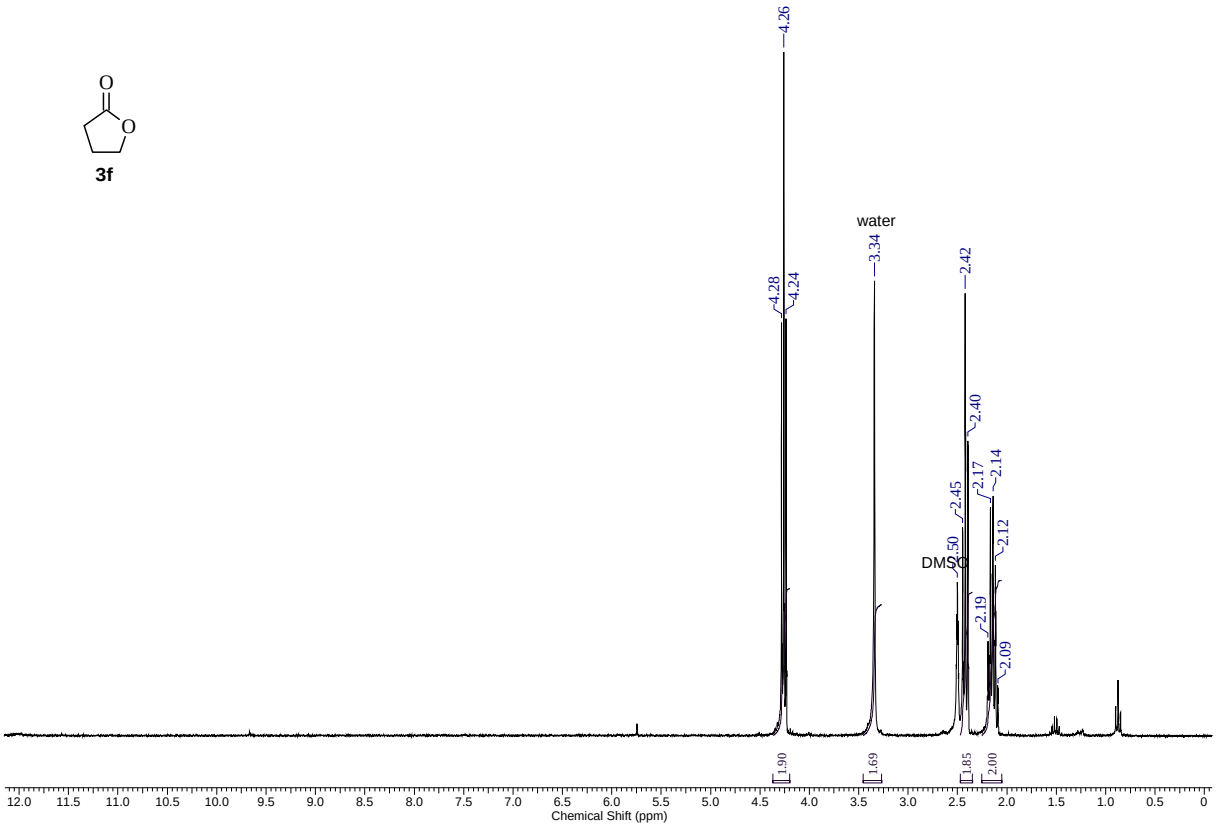

HOO
OOH
HOO
OOH
2j
107.87
26.05
39.51
Chemical Shift (ppm)

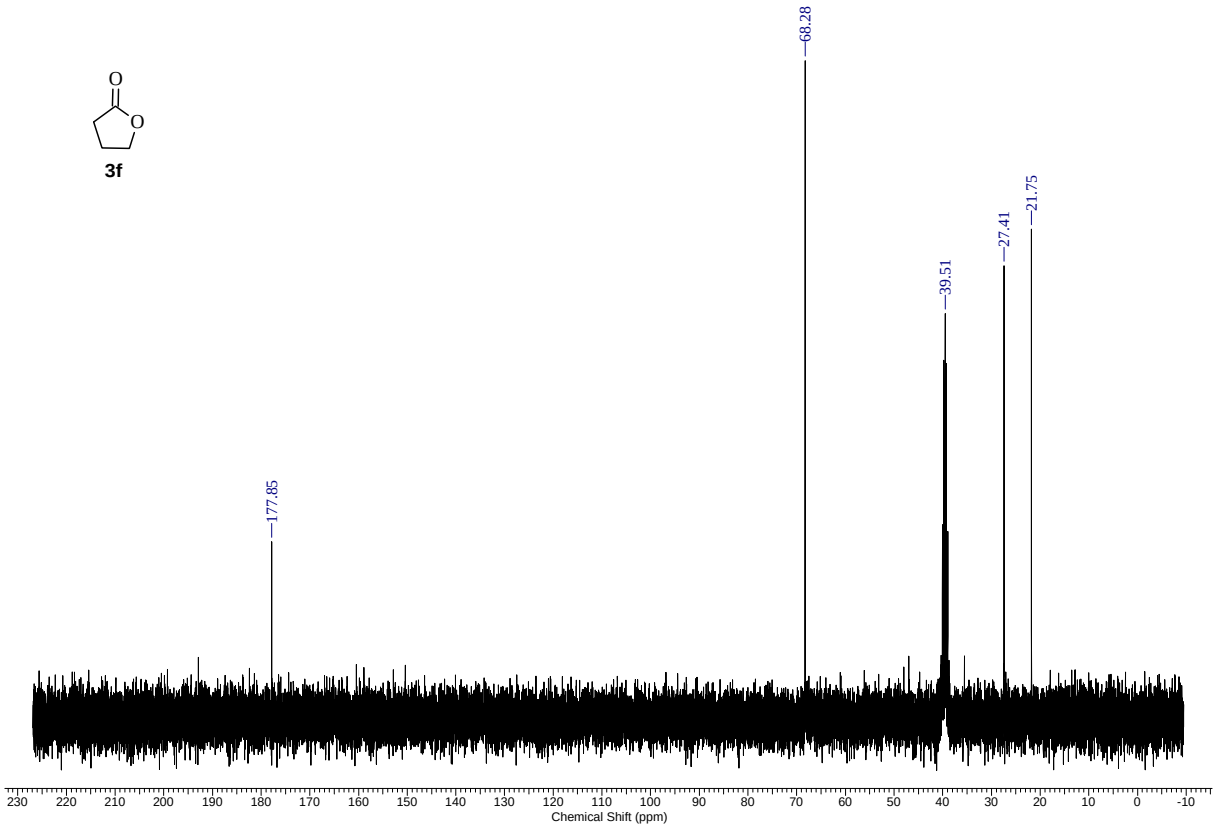

OOH
OOH
2k
10.72
water
DMSO
2.50
2.17
1.89
1.85
1.78
1.62
1.58
1.54
EA
EA
EA
1.89
1.81
2.01
6.00
Chemical Shift (ppm)


OOH
OOH
2k
33.29
30.77
26.65
36.78
39.51
109.45
Chemical Shift (ppm)


HOO
OOH
COOEt
2l
11.01
10.95
5.75
4.06
water
3.33
DMSO
2.50
2.39
1.98
1.72
1.49
1.17
1.78
2.28
1.12
2.05
2.12
4.23
3.00
Chemical Shift (ppm)


HOO
OOH
COOEt
2l
174.52
107.20
59.79
40.92
39.51
28.08
24.67
14.11
Chemical Shift (ppm)


3f
4.26
water
3.34
4.28
4.24
2.42
2.40
2.17
2.14
2.45
2.12
DMSO
2.50
2.19
2.09
1.90
1.69
1.85
2.00
Chemical Shift (ppm)


3f
68.28
39.51
27.41
21.75
177.85
Chemical Shift (ppm)