

# Scalable Procedure for the Fragmentation of Hydroperoxides Mediated by Copper and Iron Tetrafluoroborate Salts

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## *Supplementary Information*

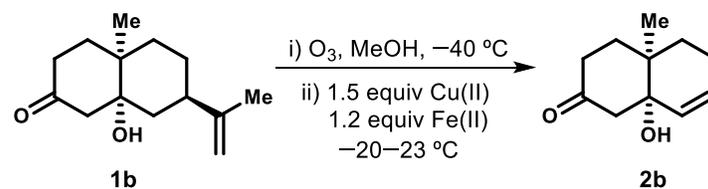
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## *General Experimental*

All reactions were carried out under an inert nitrogen atmosphere with dry solvents under anhydrous conditions unless otherwise stated. All reaction solvents were purified using a Seca solvent purification system by Glass Contour, with the exception of methanol and ethanol. Methanol for small scale reactions was purified by distillation over magnesium. Methanol for 100-gram reactions was purchased from Fisher Scientific International, Inc. (ACS Grade) and used without additional purification. Absolute ethanol was purchased from Decon Laboratories and used without additional purification. Reagents were used as received without further purification, unless otherwise stated. Ozonolysis reactions were conducted using an A2Z Ozone 856689005177 SP - 16G Swimming Pool Ozone Generator with a 16000 MG/H adjustable ozone concentration. Reactions were monitored by thin-layer chromatography (TLC) and carried out on 0.25 mm Merck silica gel plates (60F-254) using UV light as the visualizing agent and potassium permanganate, an acidic solution of *p*-anisaldehyde, and vanillin as developing agents. All new compounds were characterized by means of polarimetry, <sup>1</sup>H-NMR, <sup>13</sup>C-NMR, FT-IR (thin film), and HR-MS. Copies of the <sup>1</sup>H- and <sup>13</sup>C-NMR spectra can be found at the end of the Supporting Information. Optical rotation data was obtained using a Perkin-Elmer 341 polarimeter. NMR spectra were recorded using a Varian 400 MHz NMR spectrometer, Varian 500 MHz NMR spectrometer, or a Varian 600 MHz NMR spectrometer. All <sup>1</sup>H-NMR data are reported in δ units, parts per million (ppm), and were calibrated relative to the signals for residual chloroform (7.26 ppm) in deuteriochloroform (CDCl<sub>3</sub>). All <sup>13</sup>C-NMR data are reported in ppm relative to CDCl<sub>3</sub> (77.16 ppm) and were obtained with <sup>1</sup>H decoupling. The following abbreviations or combinations thereof were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, br = broad, m = multiplet, a = apparent. All IR spectra were taken on a FT-IR/Raman Thermo Nicolet 6700. High resolution mass spectra (HR-MS) were recorded on a Bruker micrOTOF mass spectrometer using ESI-TOF (electrospray ionization-time of flight).

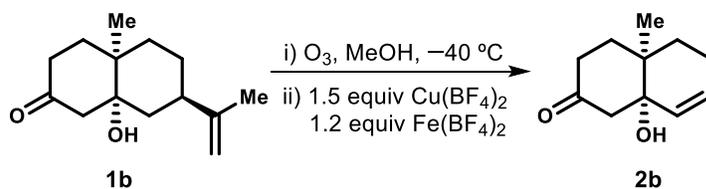
**Table S1. Copper and Iron Salt Optimization for  $\beta$ -Fragmentation**



Entry	Cu(II)	Fe(II)	% Yield <sup>a</sup>
1	None	FeSO <sub>4</sub>	9
2	Cu(OAc) <sub>2</sub>	FeSO <sub>4</sub>	77
3	Cu(acac) <sub>2</sub>	FeSO <sub>4</sub>	55
4	CuSO <sub>4</sub>	FeSO <sub>4</sub>	78
5	Cu(TFA) <sub>2</sub>	FeSO <sub>4</sub>	78
6	Cu(BF <sub>4</sub> ) <sub>2</sub>	None	0
7	Cu(BF <sub>4</sub> ) <sub>2</sub>	FeSO <sub>4</sub>	75
<b>8</b>	<b>Cu(BF<sub>4</sub>)<sub>2</sub></b>	<b>Fe(BF<sub>4</sub>)<sub>2</sub></b>	<b>71</b>
9	Cu(BF <sub>4</sub> ) <sub>2</sub>	Fe(acac) <sub>2</sub>	7
10	Cu(BF <sub>4</sub> ) <sub>2</sub>	Fe(C <sub>2</sub> O <sub>4</sub> ) <sub>2</sub>	17
11	Cu(2-ethylhexanoate) <sub>2</sub>	Fe(BF <sub>4</sub> ) <sub>2</sub>	47

<sup>a</sup> Yield determined by <sup>1</sup>H-NMR analysis after aqueous work-up using 1,3,5-trimethoxybenzene as an internal standard.

**Table S2. Temperature Optimization for  $\beta$ -Fragmentation**

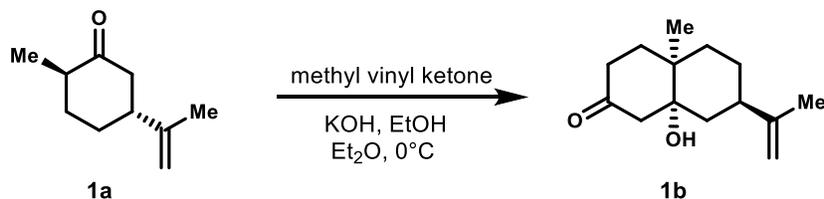


Entry	Temperature ( $^\circ\text{C}$ ) <sup>a</sup>	% Yield <sup>b</sup>
1	-78	33
2	-45	29
<b>3</b>	<b>-20</b>	<b>71</b>
4	0	13
5	23	2

<sup>a</sup> Metal salts were added at the indicated temperature, stirred for 30 minutes at this temperature, and warmed to  $23\text{ }^\circ\text{C}$ . <sup>b</sup> Yield determined by  $^1\text{H-NMR}$  analysis after aqueous work-up using 1,3,5-trimethoxybenzene as an internal standard.

## Experimental Procedures and Characterization Data for Starting Materials

### Alcohol **1b**



To a stirred solution of potassium hydroxide (884 mg, 15.8 mmol, 0.4 equiv) in a 15:1 mixture of Et<sub>2</sub>O and absolute EtOH (4 mL EtOH, 60 mL Et<sub>2</sub>O, 0.6 M) was added (+)-dihydrocarvone (**1a**) (mixture of isomers, 6.5 mL, 39 mmol, 1.0 equiv). The resulting solution was cooled to 0 °C and a solution of methyl vinyl ketone (2.3 mL, 24 mmol, 1.2 equiv) in Et<sub>2</sub>O (20 mL) was added dropwise over 20 minutes to the reaction vessel. After the addition was complete, the reaction mixture was allowed to stir for 1 hour at 0 °C. The reaction mixture was quenched by addition of sat. aq. NH<sub>4</sub>Cl (60 mL) and then diluted with 60 mL of Et<sub>2</sub>O. The aqueous layer was extracted with Et<sub>2</sub>O (3 x 60 mL). The combined organic extracts were washed with brine (150 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude yellow oil that was purified by flash column chromatography (SiO<sub>2</sub>) (1:9 Et<sub>2</sub>O:pentane) to give **1b** (2.84 g, 32%) as a flaky white solid.

$[\alpha]^{20.0}_{\text{D}}$ : +53° (*c* 1.0, CHCl<sub>3</sub>) lit: + 55.3° (*c* 1.7, CHCl<sub>3</sub>)<sup>1</sup>

**R<sub>f</sub>**: 0.29 in 1:4 hexanes:Et<sub>2</sub>O

**<sup>1</sup>H NMR** (400 MHz, CDCl<sub>3</sub>): δ 4.70 (s, 1H), 4.67 (s, 1H), 2.79 (d, *J* = 14.0 Hz, 1H), 2.54 (atd, *J* = 14.4, 7.6 Hz, 1H), 2.36–2.23 (m, 3H), 2.09 (atd, *J* = 14.4, 5.2 Hz, 1H), 1.86 (atd *J* = 13.6, 3.2 Hz, 1H), 1.70 (s, 3H), 1.62–1.58 (m, 3H), 1.48–1.40 (m, 4H), 1.21 (s, 3H)

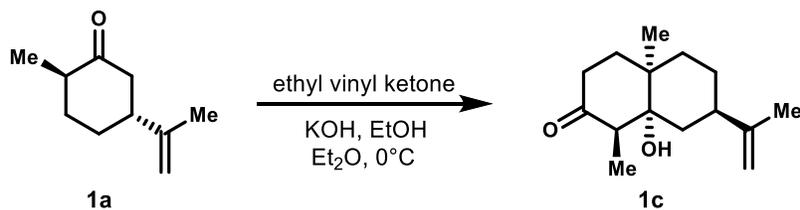
**<sup>13</sup>C NMR** (151 MHz, CDCl<sub>3</sub>): δ 209.4, 149.1, 109.1, 75.6, 53.6, 40.0, 39.9, 37.7, 36.9, 34.9, 31.8, 26.1, 21.8, 21.1

**IR** (cm<sup>-1</sup>): 3465 (br), 2930, 2871, 1702, 1441, 1378, 1280, 1212, 1149, 1131, 1059, 1043, 1006, 887, 546.

**ESI-HRMS** (*m/z*): [M+H] calc'd for C<sub>14</sub>H<sub>22</sub>O<sub>2</sub>: 223.1693; found:223.1676

<sup>1</sup> B. J. Jansen, J. A. Kreuger, and A. De Groot, *Tetrahedron*, 1989, **45**, 1447.

## Alcohol **1c**



To a stirred solution of potassium hydroxide (442 mg, 7.9 mmol, 0.4 equiv) 15:1 mixture of Et<sub>2</sub>O and absolute EtOH (2 mL EtOH, 30 mL Et<sub>2</sub>O, 0.6 M) was added (+)-dihydrocarvone (**1a**) (mixture of isomers, 3.2 mL, 20 mmol, 1.0 equiv). The resulting solution was cooled to 0 °C and a solution of ethyl vinyl ketone (2.3 mL, 24 mmol, 1.2 equiv) in Et<sub>2</sub>O (20 mL) was added dropwise over 10 minutes to the reaction vessel. After the addition was complete, the reaction mixture was allowed to stir for 1 hour at 0 °C. The reaction mixture was quenched by addition of sat. aq. NH<sub>4</sub>Cl (30 mL) and diluted with Et<sub>2</sub>O (20 mL). The layers were separated and the aqueous layer was extracted with Et<sub>2</sub>O (2 x 20 mL). The combined organic extracts were washed with brine (35 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a yellow semi-solid that was treated with a minimal amount of pentane at 0 °C. The precipitate was collected by vacuum filtration to give **1c** in an unoptimized yield (610 mg, 13%) as a white crystalline solid. The crystalline solid obtained was suitable for X-ray diffraction without further purification.

$[\alpha]^{20.0}_{\text{D}}$ :  $-40.3^\circ$  ( $c$  1.0, CHCl<sub>3</sub>) Lit:  $+84.1^\circ$  ( $c$  0.84, CHCl<sub>3</sub>)<sup>2</sup>

R<sub>f</sub>: 0.26 in 7:5 hexanes:Et<sub>2</sub>O

<sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  4.70 (s, 1H), 4.66 (s, 1H), 2.86 (q,  $J$  = 6.4 Hz, 1H), 2.57 (ddd,  $J$  = 13.6, 13.6, 6.8 Hz, 1H), 2.33 (ddd,  $J$  = 14.4, 4.8, 1.6 Hz, 1H), 2.24 (att  $J$  = 14, 4 Hz, 1H), 2.10 (atd,  $J$  = 14.0, 5.2 Hz, 1H), 1.88 (atd,  $J$  = 14.4, 4.0, 1H), 1.68 (s, 3H), 1.61–1.36 (m, 6H), 1.11–1.04 (m, 1H), 1.24 (s, 3H), 1.04 (d,  $J$  = 6.4 Hz, 3H)

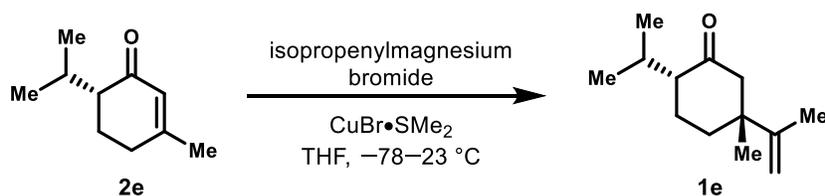
<sup>13</sup>C NMR (151 MHz, CDCl<sub>3</sub>):  $\delta$  210.7, 149.4, 109.2, 78.1, 51.9, 39.8, 37.8, 37.7, 35.6, 33.5, 31.7, 25.9, 21.8, 20.9, 6.7

IR (cm<sup>-1</sup>): 3513 (br), 2932, 2873, 1701, 1456, 1439, 1056, 989, 888, 584

ESI-HRMS ( $m/z$ ): [M–H<sub>2</sub>O+H] calc'd for C<sub>15</sub>H<sub>24</sub>O<sub>2</sub>: 219.1743; found: 219.1748

<sup>2</sup> J. Polonsky, Z. Varon, H. Jacquemin, D. M. X. Donnelly, and M. J. Meegan, *J. Chem. Soc., Perkin Trans. 1*, 1980, 2065.

## Ketone **1e**



To a flame dried flask equipped with a magnetic stir bar was added  $\text{CuBr}\cdot\text{SMe}_2$  (500 mg, 2.4 mmol, 0.1 equiv) and tetrahydrofuran (50 mL, 0.5 M). The solution was cooled down to  $-78$  °C with a dry ice acetone bath and allowed to stir for 5 minutes before adding isopropenylmagnesium bromide (97 mL, 49 mmol, 0.5 M in THF, 2.0 equiv) dropwise to the reaction mixture over 20 minutes. The resulting orange solution was allowed to stir for 45 minutes at  $-78$  °C before adding piperitone<sup>3</sup> (**2e**) (3.7 g, 24 mmol, 1.0 equiv) to the reaction mixture in a single portion by syringe. The reaction mixture was stirred at  $-78$  °C until the starting material was completely consumed as observed by TLC analysis ( $\text{SiO}_2$ ) (ca. 30 minutes after adding **2e**). The bath was then removed and the reaction mixture was allowed to stir for an additional hour slowly warming up to room temperature to give a dark brown solution. The reaction mixture was quenched by addition of sat. aq.  $\text{NH}_4\text{Cl}$  (150 mL) and diluted with  $\text{Et}_2\text{O}$  (100 mL). The layers were separated and the aqueous layer was extracted with  $\text{Et}_2\text{O}$  (2 x 100 mL). The combined organic extracts were washed with brine (200 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude yellow oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1:4 to 1:1  $\text{CH}_2\text{Cl}_2$ :pentane) to give **1e** (3.9 g, 83%), a yellow oil, as a mixture of diastereomers (8:1 dr). The diastereomeric ratio of products after aqueous workup was determined by  $^1\text{H}$  NMR to be 8:1.<sup>4</sup>

$[\alpha]^{20.0}_{\text{D}}$ :  $+3.44^\circ$  ( $c$  1.0,  $\text{CHCl}_3$ )

Rf: 0.88 minor, 0.65 major ( $\text{CH}_2\text{Cl}_2$ )

$^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.83 (s, 1H), 4.72 (s, 1H), 2.68 (dd,  $J = 14.0, 2.4$  Hz, 1H), 2.26–2.18 (m, 1H), 2.14 (d,  $J = 14.0$  Hz, 1H), 2.05–1.98 (m, 1H), 1.98–1.93 (m, 1H), 1.84–1.77 (m, 1H), 1.70 (s, 3H), 1.53–1.40 (m, 2H), 1.10 (s, 3H), 0.88 (d,  $J = 6.8$  Hz, 3H), 0.81 (d,  $J = 6.8$  Hz, 3H)

$^{13}\text{C}$  NMR (151 MHz,  $\text{CDCl}_3$ ):  $\delta$  212.1, 149.4, 112.6, 55.8, 52.6, 44.3, 34.4, 28.2, 25.9, 22.8, 20.9, 19.2, 18.7

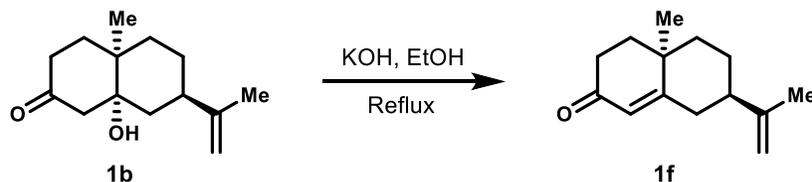
IR ( $\text{cm}^{-1}$ ): 2956, 2871, 1706, 1453, 1368, 1298, 1204, 1157, 1105, 1065, 901, 564

ESI-HRMS ( $m/z$ ):  $[\text{M}+\text{H}]$  calc'd for  $\text{C}_{13}\text{H}_{22}\text{O}$ : 195.1743; found: 195.1743

<sup>3</sup> (-)-Piperitone (tech. grade, 90%) was used as received from Pfaltz and Bauer with an optical activity of  $[\alpha]^{20.0}_{\text{D}}$ :  $-10.4^\circ$  ( $c$  1.0,  $\text{CHCl}_3$ ) Lit:  $-14.4$  ( $c$  1.0,  $\text{CHCl}_3$ ); E. Yamamoto, D. Gokuden, A. Nagai, T. Kamachi, K. Yoshizawa, A. Hamasaki, T. Ishida, and M. Tokunaga, *Org. Lett.*, 2012, **14**, 6178.

<sup>4</sup> P. Weyerstahl, R. Rilk, and H. M. Weyerstahl, *Liebigs Ann. Chem.*, 1987, 89.

## Enone **1f**



To a flame dried flask equipped with a magnetic stir bar was added a solution of potassium hydroxide (200 mg, 3.67 mmol, 3.3 equiv, 1.4 M) in absolute EtOH (1.27 mL, 1M) and a solution of alcohol **1b** (250 mg, 1.1 mmol, 1.0 equiv) in absolute EtOH (3.2 mL, 0.3 M). The reaction mixture was heated to reflux at 80 °C in an oil bath for 1 hour. The oil bath was then removed and the reaction mixture was allowed to cool to room temperature. To the reaction mixture was added water (15 mL) and the layers were separated. The aqueous layer was extracted with Et<sub>2</sub>O (3 x 10 mL) and the combined organic extracts were washed with brine (20 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude yellow residue that was purified by flash column chromatography (SiO<sub>2</sub>) (1:9 Et<sub>2</sub>O:pentane) to yield **1f** (161 mg, 70%) as a yellow oil.

$[\alpha]^{20.0}_{\text{D}}$ :  $-168^{\circ}$  ( $c$  1.0, CHCl<sub>3</sub>) Lit:  $-177^{\circ}$  ( $c$  1.0, CHCl<sub>3</sub>)<sup>5</sup>

R<sub>f</sub>: 0.32 in 1:1 hexanes:Et<sub>2</sub>O

<sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>): δ 5.81 (s, 1H), 4.86 (s, 1H), 4.75 (s, 1H), 2.65 (ddd,  $J$  = 15.5, 6.5, 2.0 Hz, 1H), 2.57–2.49 (m, 3H), 2.36 (ddd,  $J$  = 17.5, 4.0, 2.5 Hz, 1H), 1.96–1.73 (m, 4H), 1.71 (s, 3H), 1.48 (atd,  $J$  = 13.5, 3.5 Hz, 1H), 1.38 (dt,  $J$  = 14.0, 3.5 Hz, 1H), 1.27 (s, 3H)

<sup>13</sup>C NMR (126 MHz, CDCl<sub>3</sub>): δ 199.4, 170.5, 146.8, 125.8, 112.5, 40.5, 38.1, 35.9, 35.6, 35.3, 34.3, 23.7, 22.8, 22.8

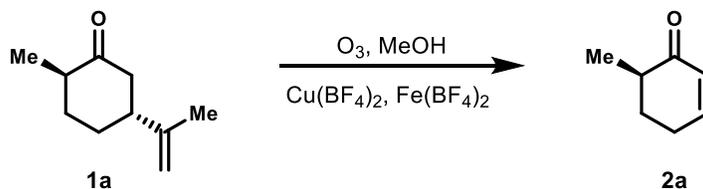
IR (cm<sup>-1</sup>): 2933, 1665, 1451, 1327, 1266, 1244, 1203, 1184, 981, 889, 858, 532

ESI-HRMS (m/z): [M+H] calc'd for C<sub>14</sub>H<sub>20</sub>O: 205.1518; found: 205.1515

<sup>5</sup> B. J. Jansen, J. A. Kreuger, and A. De Groot, *Tetrahedron*, 1989, **45**, 1447.

## Experimental Procedures and Characterization Data for $\beta$ -Fragmentation

### 6-methylcyclohexenone (**2a**)



### Preparation of 6-methylcyclohexenone (**2a**): 2-gram ( $\text{Cu(BF}_4)_2/\text{Fe(BF}_4)_2$ )

A stirred solution of (+)-dihydrocarvone<sup>6</sup> (**1a**) (2.0 g, 13 mmol, 1.0 equiv) open to air in methanol (45 mL, 0.15 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-45\text{ }^\circ\text{C}$ . Once the internal temperature of the solution reached  $-40\text{ }^\circ\text{C}$ , ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 30 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and 45% aqueous copper (II) tetrafluoroborate (8.4 g, 20 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate (6.6 g, 15.8 mmol, 1.2 equiv) were sequentially added dropwise to the reaction mixture over 5 minutes at  $-20\text{ }^\circ\text{C}$  to give a homogeneous blue-green solution. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^\circ\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (100 mL) and the methanol/water layer was extracted with 1:1  $\text{Et}_2\text{O}$ :pentane (3 x 100mL). The combined organic extracts were then washed with sat. aq.  $\text{NaHCO}_3$  (250 mL), brine (250 mL), dried over anhydrous sodium sulfate, filtered, and concentrated at  $10\text{ }^\circ\text{C}$  and 150 torr by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1:15  $\text{Et}_2\text{O}$ :pentane to 1:10  $\text{Et}_2\text{O}$ :pentane) to yield **2a** (600 mg, 41%) and the  $\beta,\gamma$ -enone (246 mg, 17%) as clear oils.

$[\alpha]^{20.0}_{\text{D}}$ :  $+90.6^\circ$  ( $c$  1.0,  $\text{CHCl}_3$ ), Lit:  $+91^\circ$  ( $c$  1.1,  $\text{CHCl}_3$ )<sup>7</sup>

### Preparation of 6-methylcyclohexenone (**2a**): 100-gram ( $\text{Cu(BF}_4)_2/\text{Fe(BF}_4)_2$ )

A stirred solution of (+)-dihydrocarvone (**1a**) (mixture of isomers, 100 g, 656 mmol, 1.0 equiv) open to air in methanol (2.18 L, 0.3 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-45\text{ }^\circ\text{C}$ . Once the internal temperature of the solution reached  $-40\text{ }^\circ\text{C}$ , ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 4.5 hours after bubbling ozone). At this point, bubbling of ozone was ceased, and 45% aqueous copper (II) tetrafluoroborate (425 g, 986 mmol, 1.5 equiv) was added dropwise over 20 minutes maintaining an internal temperature of  $-20\text{ }^\circ\text{C}$  to give a homogeneous blue

<sup>6</sup> The major *trans* diastereomer was isolated from the commercial material by silica gel chromatography using pentane as eluent.

<sup>7</sup> (a) G. Solladié, and J. Hutt, *J. Org. Chem.*, 1987, **52**, 3560; (b) J. D. White, U. M. Grether, and C. Lee, *Org. Synth.*, 2005, **82**, 108.

solution. Following this, 45% aqueous iron (II) tetrafluoroborate (329 g, 788 mmol, 1.2 equiv) was added dropwise to the solution over 20 minutes while maintaining an internal temperature of  $-20$  to  $-15$  °C to give a homogeneous purple solution. The mixture was allowed to stir at  $-20$  °C for 30 minutes. The dry ice acetone bath was then replaced with a room temperature water bath and the reaction mixture was allowed to stir for an additional 30 minutes. The reaction mixture was diluted with water (4.1 L) and the methanol/water layer was extracted with 2:1 Et<sub>2</sub>O:pentane (3 x 3 L). The combined organic extracts were then washed with sat. aq. NaHCO<sub>3</sub> (2.5 L), brine (2.5 L), dried over anhydrous sodium sulfate, filtered, and concentrated at 10 °C and 150 torr by rotary evaporation until 200 mL was left in the flask. This solution was cooled down to 0 °C and methanesulfonic acid (85 mL, 1.31 mol 2.0 equiv) was added to the flask over 2 minutes. The reaction mixture was stirred for 15 minutes at 0 °C and then quenched by the slow addition of sat. aq. NaHCO<sub>3</sub> (1.5 L). The mixture was then diluted with Et<sub>2</sub>O (500 mL) and the layers were separated. The aqueous layer was extracted with Et<sub>2</sub>O (2 x 500 mL) and the combined organic extracts were washed with brine (1.5 L), dried over anhydrous sodium sulfate, filtered, and concentrated at 10 °C and 150 torr by rotary evaporation to give a crude oil that was purified by vacuum distillation to yield **2a** (39 g, 55%) as a colorless oil.

#### **Preparation of 6-methylcyclohexenone (2a): 100-g (Cu(OAc)<sub>2</sub>/FeSO<sub>4</sub>)**

A solution of (+)-dihydrocarvone **1a** (mixture of isomers, 100 g, 656 mmol, 1.0 equiv) open to air in methanol (2.18 L, 0.3 M) was cooled with a dry ice acetone bath until bath temperature reached  $-45$  °C and stirring was commenced with an overhead stirring apparatus. Once the internal temperature of the solution reached  $-40$  °C ozone was bubbled through the solution until the starting material was completely consumed by TLC (SiO<sub>2</sub>) (ca. 4.5 h after bubbling ozone). At this point, copper (II) acetate monohydrate (262.1 g, 1313 mmol, 2.0 equiv) was added in 5 portions, every six minutes, over 30 minutes through one of the side-necks of the flask with a funnel, the internal temperature was maintained at  $-20$  °C throughout the addition, and then stirred at this temperature for 15 minutes. Following this, iron (II) sulfate heptahydrate (218 g, 787 mmol, 1.2 equiv) was added in 3 portions, every five minutes, over 15 minutes through one of the side-necks of the flask with a funnel, maintaining an internal temperature of  $-15$  °C during the addition. The resulting solution was stirred at  $-20$  °C for 15 minutes. The bath was removed and stirring was continued at room temperature for 30 minutes. The reaction mixture was diluted with water (4.1 L) and the methanol/water layer was extracted with a 2:1 Et<sub>2</sub>O:pentane mixture (3 x 3 L). The combined organic extracts were then washed with sat. aq. NaHCO<sub>3</sub> (2.5 L), brine (2.5 L), dried over anhydrous sodium sulfate, filtered, and concentrated at 10 °C and 150 torr by rotary evaporation until 200 mL was left in the flask. This solution was cooled down to 0 °C and methanesulfonic acid (85 mL, 1.31 mol, 2.0 equiv) was added to the flask over 2 minutes. The reaction mixture was stirred for 15 minutes at 0 °C and then quenched by the slow addition of sat. aq. NaHCO<sub>3</sub> (1.5 L). The mixture was then diluted with Et<sub>2</sub>O (500 mL) and the layers were separated. The aqueous layer was extracted with Et<sub>2</sub>O (2 x 500 mL) and the combined organic extracts were washed with brine (1.5 L), dried over anhydrous sodium sulfate, filtered, and

concentrated at 10 °C and 150 torr by rotary evaporation to give a crude oil that was purified by vacuum distillation to yield **2a** (21 g, 37%) as a colorless oil.

**Rf:** 0.3 in 3:7 Et<sub>2</sub>O:hexanes

**Bp:** 70 °C at 15 torr Lit: 165 °C at 760 torr<sup>8</sup>

**<sup>1</sup>H NMR** (400 MHz, CDCl<sub>3</sub>): δ 6.92 (td, *J* = 11.5, 4.0 Hz 1H), 5.97 (dt, *J* = 10.4, 2.4 Hz, 1H), 2.38 (m, 3H), 2.09–2.02 (ddd, *J* = 13.6, 9.2, 4.8 Hz, 1H), 1.77–1.67 (m, 1H), 1.13 (d, *J* = 6.8 Hz, 3H)

**<sup>13</sup>C NMR** (151 MHz, CDCl<sub>3</sub>): δ 202.5, 149.8, 129.5, 41.7, 30.9, 25.6, 15.2

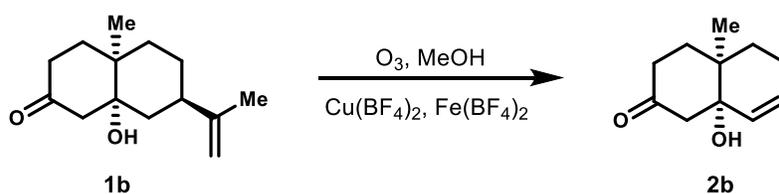
**IR** (cm<sup>-1</sup>): 3033, 2964, 2931, 2862, 1674, 1457, 1427, 1388, 1375, 1215, 1130, 887, 800, 702, 634, 529

**ESI-HRMS** (m/z): [M+H] calc'd for C<sub>7</sub>H<sub>10</sub>O: 111.0804; found: 111.0871

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<sup>8</sup> H. J. Reich, J. M. Renga, and I. L. Reich, *J. Am. Chem. Soc.*, 1975, **97**, 5434.

## Allylic alcohol **2b**



A stirred solution of alcohol **1b** (200.0 mg, 0.9 mmol, 1.0 equiv) open to air in methanol (6 mL, 0.15 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-40\text{ }^{\circ}\text{C}$ . After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 10 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and 45% aqueous copper (II) tetrafluoroborate (580 mg, 1.35 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate 675 mg, 1.6 mmol, 1.2 equiv) were sequentially added dropwise to the reaction mixture over 5 minutes at  $-20\text{ }^{\circ}\text{C}$  to give a homogeneous blue-green mixture. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^{\circ}\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (20 mL) and the methanol/water layer was extracted with 1:1  $\text{Et}_2\text{O}$ :pentane (3 x 15 mL). The combined organic extracts were then washed with sat. aq.  $\text{NaHCO}_3$  (25 mL), brine (25 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1:1  $\text{Et}_2\text{O}$ :hexanes) to yield **2b** (113 mg, 70%) as a yellow crystalline solid.

$[\alpha]^{20.0}_{\text{D}}$ :  $-9.2^{\circ}$  ( $c$  1.1,  $\text{CHCl}_3$ )

R<sub>f</sub>: 0.25 in 1:4 hexanes: $\text{Et}_2\text{O}$

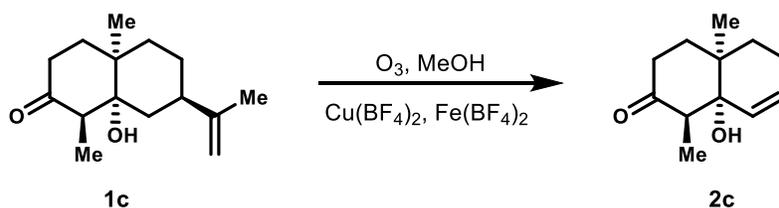
$^1\text{H NMR}$  (600 MHz,  $\text{CDCl}_3$ ):  $\delta$  5.67–5.64 (m, 1H), 5.58–5.54 (m, 1H), 2.63 (dd,  $J = 15.0, 0.6$  Hz, 1H), 2.46 (dddd,  $J = 16.2, 9.6, 7.2, 0.6$  Hz, 1H), 2.40–2.35 (m, 2H), 2.31 (dd,  $J = 15.0, 1.8$  Hz, 1H), 2.23–2.18 (m, 1H), 2.04–1.96 (m, 3H), 1.63 (ddd,  $J = 13.8, 7.2, 5.4$  Hz, 1H), 1.48 (brs, 1H), 1.09 (s, 3H)

$^{13}\text{C NMR}$  (151 MHz,  $\text{CDCl}_3$ ):  $\delta$  210.8, 125.4, 123.7, 75.3, 50.5, 38.3, 37.7, 36.1, 35.9, 33.2, 21.1

IR ( $\text{cm}^{-1}$ ): 3416 (br), 3030, 2982, 2939, 2917, 1701, 1460, 1438, 1426, 1407, 1327, 1149, 1137, 667, 598

ESI-HRMS ( $m/z$ ):  $[\text{M}-\text{H}_2\text{O}+\text{H}]$  calc'd for  $\text{C}_{11}\text{H}_{16}\text{O}_2$ : 163.1117; found: 163.1165

## Allylic alcohol **2c**



A stirred solution of **1c** (150.0 mg, 0.635 mmol, 1.0 equiv) open to air in methanol (4.2 mL, 0.15 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-40\text{ }^\circ\text{C}$ . After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 10 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and 45% aqueous copper (II) tetrafluoroborate (598 mg, 0.953 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate (318 mg, 0.762 mmol, 1.2 equiv) were sequentially added dropwise to the solution over 5 minutes at  $-20\text{ }^\circ\text{C}$  to give a homogeneous blue-green mixture. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^\circ\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (15 mL) and the methanol/water layer was extracted with 1:1  $\text{Et}_2\text{O}$ :pentane (3 x 10 mL). The combined organic extracts were then washed with sat. aq.  $\text{NaHCO}_3$  (20 mL), brine (20 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1:1  $\text{Et}_2\text{O}$ :Hexanes) to yield **2c** (70.1 mg, 57%) as a white powder.

$[\alpha]^{20.0}_{\text{D}}$ :  $-12.4^\circ$  ( $c$  1.0,  $\text{CHCl}_3$ )

R<sub>f</sub>: 0.3 in 1:1 hexanes: $\text{Et}_2\text{O}$

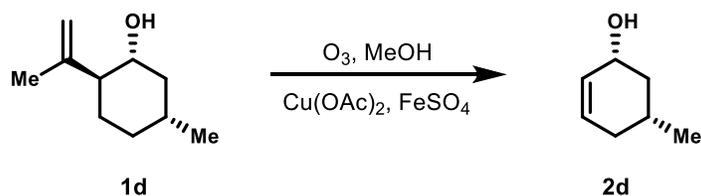
$^1\text{H NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  5.70–5.65 (m, 1H), 5.52–5.48 (m, 1H), 2.86 (q,  $J = 6.4$  Hz, 1H), 2.54 (ddd,  $J = 14.4, 14.4, 7.6$  Hz, 1H), 2.38–2.28 (m, 2H), 2.08–2.03 (m, 1H), 1.87 (dd,  $J = 18.4, 5.6$  Hz, 1H), 1.83–1.78 (m, 2H), 1.66 (s, 1H), 1.47 (ddd,  $J = 13.6, 7.2, 1.2$  Hz, 1H), 1.25 (s, 3H), 1.09 (d,  $J = 6.8$  Hz, 3H)

$^{13}\text{C NMR}$  (151 MHz,  $\text{CDCl}_3$ ):  $\delta$  211.1, 125.7, 121.8, 75.4, 50.8, 37.7, 37.0, 36.8, 32.0, 31.9, 29.9, 20.6, 6.8

IR ( $\text{cm}^{-1}$ ): 3497 (br), 3026, 2974, 2887, 2831, 1700, 1455, 1426, 1375, 1057, 1000, 884, 662, 580

ESI-HRMS ( $m/z$ ):  $[\text{M}+\text{H}]$  calc'd for  $\text{C}_{12}\text{H}_{18}\text{O}_2$ : 195.1380; found: 195.1396

## Allylic alcohol **2d**



A stirred solution of isopulegol (**1d**)<sup>9</sup> (200 mg, 1.3 mmol, 1.0 equiv) open to air in methanol (4.3 mL, 0.3 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-40$  °C. After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC (SiO<sub>2</sub>) (ca. 10 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and copper (II) acetate monohydrate (520 mg, 2.6 mmol, 2.0 equiv) was added to the reaction mixture at  $-20$  °C and the resulting heterogeneous blue mixture was stirred at  $-20$  °C for 15 minutes. Next, iron (II) sulfate heptahydrate (435 mg, 1.6 mmol, 1.2 equiv) was added to the solution at  $-20$  °C and the heterogeneous dark purple solution was stirred at  $-20$  °C for an additional 30 minutes. The reaction mixture was diluted with water (15 mL) and the methanol/water layer was extracted with 1:1 Et<sub>2</sub>O:pentane (3 x 10mL). The combined organic extracts were then washed with sat. aq. NaHCO<sub>3</sub> (25 mL), brine (25 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography (SiO<sub>2</sub>) (1:9 Et<sub>2</sub>O:pentane) to yield **2d** (62 mg, 43%) as a yellow oil.

$[\alpha]^{20.0}_{\text{D}} -5.5^{\circ}$  (*c* 0.6, CHCl<sub>3</sub>) Lit:  $-7.0^{\circ}$  (*c* 1.0, CHCl<sub>3</sub>)<sup>10</sup>,  $-86.2^{\circ}$  (*c* 5.0, CHCl<sub>3</sub>)<sup>11</sup>

R<sub>f</sub>: 0.28 in 7:3 hexanes:Et<sub>2</sub>O

<sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  5.77–5.73 (m, 1H), 5.66 (ad, *J* = 9.9 Hz, 1H), 4.36–4.26 (m, 1H), 2.07–2.02 (m, 2H), 1.81–1.69 (m, 1H), 1.67–1.59 (m, 1H), 1.40 (brs, 1H), 1.23 (q, *J* = 12.0 Hz, 1H), 0.99 (d, *J* = 7.2 Hz, 3H)

<sup>13</sup>C NMR (151 MHz, CDCl<sub>3</sub>):  $\delta$  131.1, 129.0, 68.4, 41.7, 33.9, 28.3, 22.1.

IR (cm<sup>-1</sup>): 3324 (br), 3026, 2951, 2925, 2872, 2855, 2831, 1456, 1433, 1375, 1294, 1066, 1023, 735, 676, 555

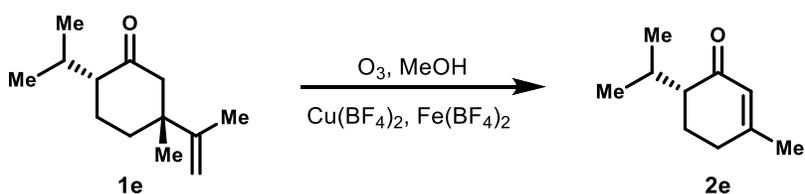
ESI-HRMS (*m/z*): [M+H] calc'd for C<sub>7</sub>H<sub>12</sub>O: 113.0961; found: 113.0975

<sup>9</sup> (-)-Isopulegol (tech. grade) was purified by silica gel chromatography (1:9 Et<sub>2</sub>O:pentane)

<sup>10</sup> H. L. Goering, W. W. Schmidt, and V. D. Singleton, *J. Org. Chem.*, **44**, 1979, 2282.

<sup>11</sup> H. L. Goering and J. P. Blanchard, *J. Am. Chem. Soc.*, **76**, 1954, 5405.

## Piperitone (2e)



A stirred solution of **1e** (3.90 g, 20 mmol, 1.0 equiv) open to air in methanol (67 mL, 0.15 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-40\text{ }^\circ\text{C}$ . After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $SiO_2$ ) (ca. 30 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and 45% aqueous copper (II) tetrafluoroborate (13.0 g, 30 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate (10.0 g, 24 mmol, 1.2 equiv) were sequentially added dropwise to the solution over 15 minutes at  $-20\text{ }^\circ\text{C}$  to give a homogeneous blue-green mixture. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^\circ\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (150 mL) and the methanol/water layer was extracted with 1:1  $Et_2O$ :pentane (3 x 100 mL). The combined organic extracts were then washed with sat. aq.  $NaHCO_3$  (250 mL), brine (250 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation until 30 mL was left in the flask. To this solution was added methane sulfonic acid (2.6 mL, 40 mmol, 2.0 equiv) and the reaction mixture was stirred for 15 minutes at room temperature, then cooled to  $0\text{ }^\circ\text{C}$  and quenched with sat. aq.  $NaHCO_3$  (45 mL). The solution was diluted with  $Et_2O$  (50 mL) and the layers were separated. The aqueous layer was then extracted with  $Et_2O$  (2 x 50 mL) and the combined organic extracts were washed with brine (100 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $SiO_2$ ) (1:9  $Et_2O$ :hexanes) to yield **2e** (1.77 g, 58%) as a pale yellow liquid.

$[\alpha]^{20.0}_D$ :  $-8.6^\circ$  ( $c$  1.1,  $CHCl_3$ ) Lit:  $-14.4^\circ$  ( $c$  1.0,  $CHCl_3$ )<sup>12</sup>

R<sub>f</sub>: 0.54 in 3:2 hexanes: $Et_2O$

$^1H$  NMR (400 MHz,  $CDCl_3$ ):  $\delta$  5.83 (s, 1H), 2.40–2.26 (m, 3H), 2.05–1.94 (m, 2H), 1.93 (s, 3H), 1.86–1.76 (m, 1H), 0.94 (d,  $J = 7.2$  Hz, 3H), 0.85 (d,  $J = 7.2$  Hz, 3H)

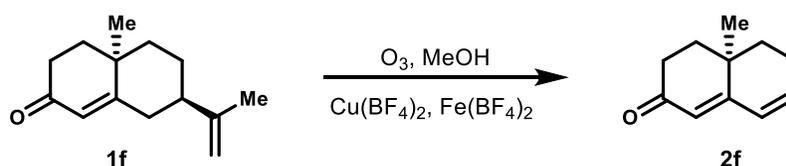
$^{13}C$  NMR (151 MHz,  $CDCl_3$ ):  $\delta$  201.4, 161.2, 126.9, 51.7, 30.5, 25.9, 24.2, 23.1, 20.8, 18.7

IR ( $cm^{-1}$ ): 2958, 2871, 1664, 1430, 1379, 1367, 1311, 1208, 1021, 891, 873, 551

ESI-HRMS ( $m/z$ ):  $[M+H]$  calc'd for  $C_{10}H_{16}O$ : 153.1274; found: 153.1275

<sup>12</sup> E. Yamamoto, D. Gokuden, A. Nagai, T. Kamachi, K. Yoshizawa, A. Hamasaki, T. Ishida, and M. Tokunaga, *Org. Lett.* 2012, **14**, 6178.

## Dienone **2f**



A stirred solution of enone **1f** (150 mg, 0.74 mmol, 1.0 equiv) open to air in methanol (4.8 mL, 0.15 M) was cooled with a dry ice acetone bath until the bath temperature reached  $-40\text{ }^{\circ}\text{C}$ . After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 4 minutes after bubbling ozone). At this point, bubbling of ozone was ceased and 45% aqueous copper (II) tetrafluoroborate (475 mg, 1.10 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate (480 mg, 0.881 mmol, 1.2 equiv) were sequentially added dropwise over 5 minutes to the solution at  $-20\text{ }^{\circ}\text{C}$  to give a homogeneous blue-green mixture. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^{\circ}\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (20 mL) and the methanol/water layer was extracted with 1:1 EtOAc:hexanes (3 x 20 mL). The combined organic extracts were then washed with sat. aq.  $\text{NaHCO}_3$  (50 mL), brine (50 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1:9 to 3:7 EtOAc:hexanes) to yield **2f** (72 mg, 61%) a yellow oil.

$[\alpha]^{20.0}_{\text{D}}$ :  $-205.3^{\circ}$  ( $c$  1.5,  $\text{CHCl}_3$ ) Lit:  $-177^{\circ}$  ( $c$  2.1,  $\text{CHCl}_3$ )<sup>13</sup>

R<sub>f</sub>: 0.32 in 1:1 hexanes:Et<sub>2</sub>O

<sup>1</sup>H NMR (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.23 (m, 1H), 6.15 (dd,  $J = 9.5, 2.2$  Hz, 1H), 5.68 (s, 1H), 2.65 (ddd,  $J = 18, 14.5, 5.5$  Hz, 1H), 2.43 (dd,  $J = 18.0, 4.0$  Hz, 2H), 2.29 (atd,  $J = 19.5, 5.0$  Hz 1H), 1.89 (atd,  $J = 14.0, 5.0$  Hz, 1H), 1.78 (ddd  $J = 13.0, 5.5, 1.5$  Hz, 1H) 1.58 (m, 2 H), 1.18 (s, 3H)

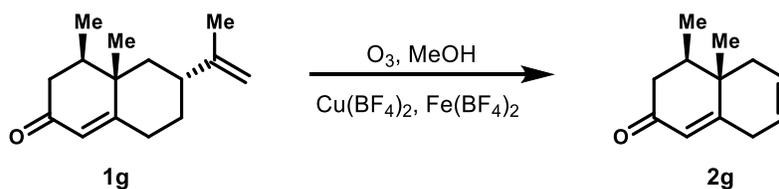
<sup>13</sup>C NMR (126 MHz,  $\text{CDCl}_3$ ):  $\delta$  199.7, 161.9, 137.8, 127.7, 123.5, 36.9, 35.8, 34.2, 33.2, 23.5, 21.2

IR ( $\text{cm}^{-1}$ ): 2923, 2859, 1658, 1585, 1452, 1417, 1325, 1252, 1211, 1026, 977, 872

ESI-HRMS ( $m/z$ ):  $[\text{M}+\text{H}]$  calc'd for  $\text{C}_{11}\text{H}_{14}\text{O}$ : 163.1117; found: 163.1180

<sup>13</sup> B. J. Jansen, J. A. Kreuger, and A. De Groot, *Tetrahedron*, 1989, **45**, 1447.

Dienone **2g**



A stirred solution of **1g** (100 mg, 0.458 mmol, 1.0 equiv) in methanol (1.6 mL, 0.3 M) under inert atmosphere was cooled with a dry ice acetone bath until the bath temperature reached  $-40\text{ }^\circ\text{C}$ . After stirring at this temperature for 5 minutes, ozone was bubbled through the solution until the starting material was completely consumed as observed by TLC ( $\text{SiO}_2$ ) (ca. 15 minutes after bubbling ozone). At this point, bubbling of ozone was ceased, nitrogen was bubbled through the solution for 2 minutes and the reaction vessel was sealed under an atmosphere of  $\text{N}_2$  with a septum. To this solution 45% aqueous copper (II) tetrafluoroborate (253 mg, 0.687 mmol, 1.5 equiv) and 45% aqueous iron (II) tetrafluoroborate (319 mg, 0.549 mmol, 1.2 equiv) were sequentially added dropwise to the solution over 2 minutes at  $-20\text{ }^\circ\text{C}$  to give a homogeneous blue-green mixture. The mixture became a darker color after it was allowed to stir at  $-20\text{ }^\circ\text{C}$  for 30 minutes. The bath was then removed and the reaction mixture was allowed to stir for an additional 30 minutes at room temperature. The reaction mixture was diluted with water (20 mL) and the methanol/water layer was extracted with 1:1  $\text{Et}_2\text{O}$ :pentane (3 x 10 mL). The combined organic extracts were then washed with sat. aq.  $\text{NaHCO}_3$  (30 mL), brine (30 mL), dried over anhydrous sodium sulfate, filtered, and concentrated under reduced pressure by rotary evaporation to give a crude oil that was purified by flash column chromatography ( $\text{SiO}_2$ ) (1.5:8.5  $\text{Et}_2\text{O}$ :hexanes to 2.5:7.5  $\text{Et}_2\text{O}$ :hexanes) to yield **2g** (47 mg, 58%) as a white solid, as a 10:1 inseparable mixture of **2g** and the  $\alpha$ - $\beta$ , $\gamma$ - $\delta$ -dienone .

$[\alpha]^{20.0}_{\text{D}}$ :  $+295.6^\circ$  ( $c$  1.3,  $\text{CHCl}_3$ )

**Rf**: 0.30 in 1:1  $\text{Et}_2\text{O}$ :hexanes

**$^1\text{H NMR}$**  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  5.85 (s, 1H), 5.75–5.71 (m, 1H), 5.66 (adq,  $J = 9.5, 3.3$  Hz, 1H), 3.12 (d,  $J = 22.5$  Hz, 1H), 2.92 (d,  $J = 22.5$  Hz, 1H), 2.35–2.23 (m, 4H), 2.07–1.96 (m, 2H), 1.09 (s, 3H), 1.00 (d,  $J = 6.5$  Hz, 3H)

**$^{13}\text{C NMR}$**  (126 MHz,  $\text{CDCl}_3$ ):  $\delta$  199.4, 167.6, 124.8, 124.7, 123.2, 42.4, 39.7, 38.4, 38.2, 32.1, 17.2, 15.2

**IR** ( $\text{cm}^{-1}$ ): 3262, 3037, 2967, 2938, 2884, 1657, 1586, 1454, 1413, 1387, 1362, 1289, 1263, 1209, 1027, 877, 552

**ESI-HRMS** ( $m/z$ ):  $[\text{M}+\text{H}]$  calc'd for  $\text{C}_{11}\text{H}_{14}\text{O}$ : 177.1274; found: 177.1344

## X-Ray Experimental

Low-temperature diffraction data ( $\omega$ -scans) were collected on a Rigaku MicroMax-007HF diffractometer coupled to a Saturn994+ CCD detector with Cu K $\alpha$  ( $\lambda = 1.54178 \text{ \AA}$ ) for the structure of 007-16030. The diffraction images were processed and scaled using the Rigaku Oxford Diffraction software (CrysAlisPro; Rigaku OD: The Woodlands, TX, 2015). The structure was solved with SHELXT and was refined against  $F^2$  on all data by full-matrix least squares with SHELXL (Sheldrick, G. M. Acta Cryst. 2008, A64, 112–122). All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in the model at geometrically calculated positions and refined using a riding model. The isotropic displacement parameters of all hydrogen atoms were fixed to 1.2 times the U value of the atoms to which they are linked (1.5 times for methyl groups). The only exception is atom H1, which was freely refined. Atom H1 is also included in a refined hydrogen bond interaction. The alkene moiety, which contains atoms C12 and C13, is disordered equally over two positions. The site occupancies of the atoms are fixed to 0.5 and the two disordered positions are distinguished with the suffixes “a” and “b”. The hydrogen atoms associated with C12a, C13b, C12b and C13b were placed in expected positions. The full numbering scheme of compound 007-16030 can be found in the full details of the X-ray structure determination (CIF), which is included as Supporting Information. CCDC number 1477346 (007-16030) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Center via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).

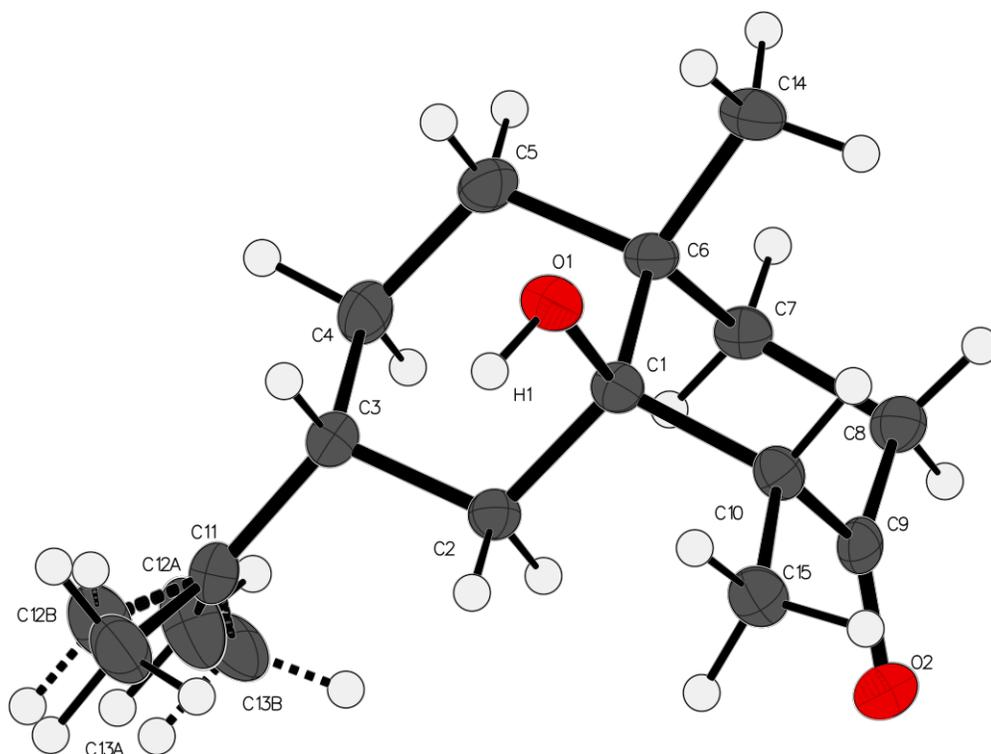


Figure 1. The complete numbering scheme of **1c** with 50% thermal ellipsoid probability levels. The hydrogen atoms are shown as circles for clarity.

Table 1. Crystal data and structure refinement for 007-16030.

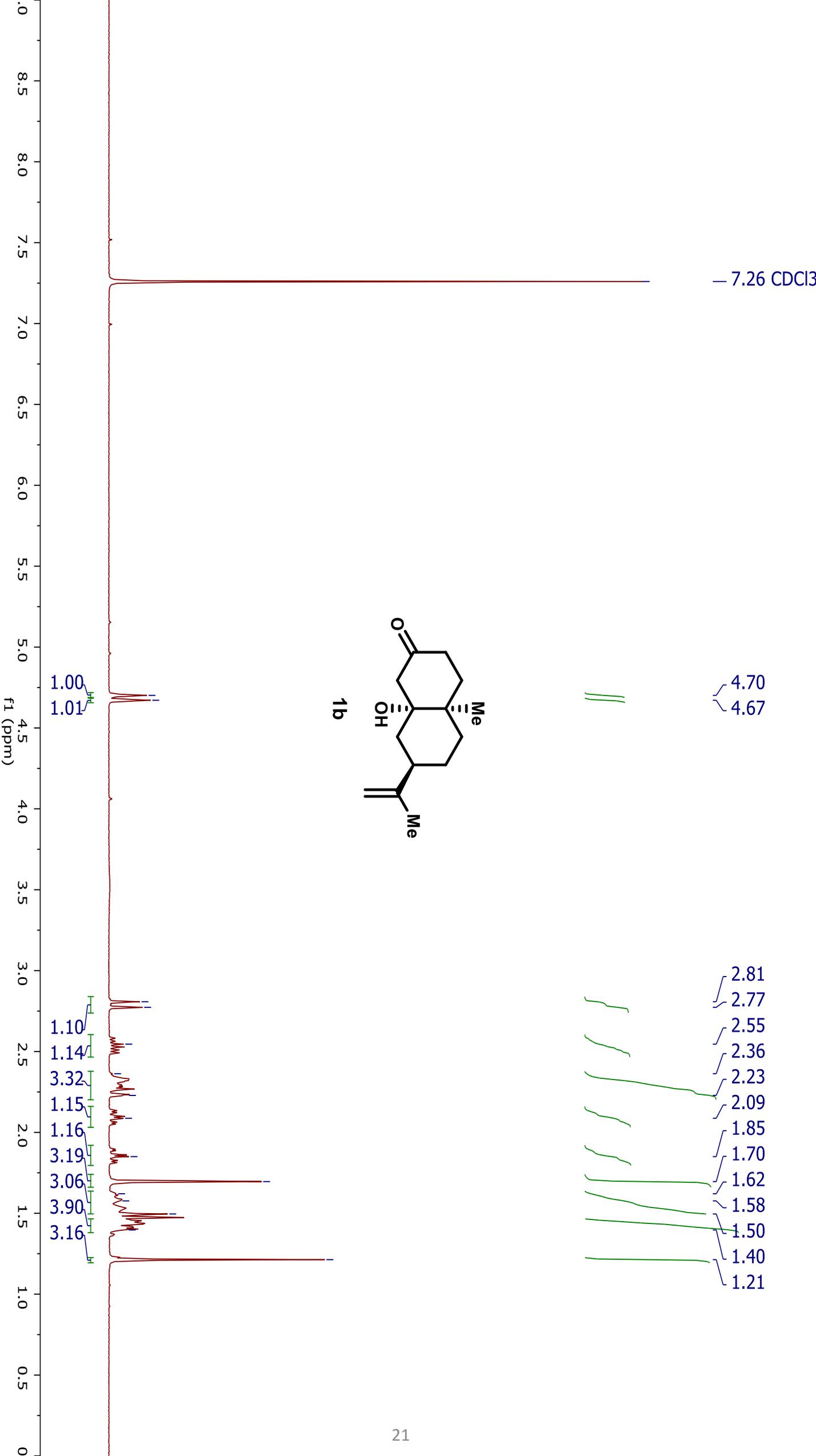
Identification code	007-16030	
Empirical formula	C <sub>15</sub> H <sub>24</sub> O <sub>2</sub>	
Formula weight	236.34	
Temperature	93(2) K	
Wavelength	1.54184 Å	
Crystal system	Orthorhombic	
Space group	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>	
Unit cell dimensions	a = 7.49844(12) Å	α = 90°.
	b = 10.97341(19) Å	β = 90°.
	c = 16.2847(3) Å	γ = 90°.
Volume	1339.96(4) Å <sup>3</sup>	
Z	4	
Density (calculated)	1.172 Mg/m <sup>3</sup>	
Absorption coefficient	0.589 mm <sup>-1</sup>	
F(000)	520	
Crystal size	0.080 x 0.050 x 0.040 mm <sup>3</sup>	
Theta range for data collection	4.860 to 66.663°.	
Index ranges	-8 ≤ h ≤ 8, -13 ≤ k ≤ 13, -19 ≤ l ≤ 19	
Reflections collected	49496	
Independent reflections	2366 [R(int) = 0.0449]	
Completeness to theta = 66.663°	99.8 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	1.00000 and 0.70883	
Refinement method	Full-matrix least-squares on F <sup>2</sup>	
Data / restraints / parameters	2366 / 0 / 180	
Goodness-of-fit on F <sup>2</sup>	1.058	
Final R indices [I > 2σ(I)]	R1 = 0.0245, wR2 = 0.0626	
R indices (all data)	R1 = 0.0252, wR2 = 0.0632	
Absolute structure parameter	-0.03(5)	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.194 and -0.113 e.Å <sup>-3</sup>	

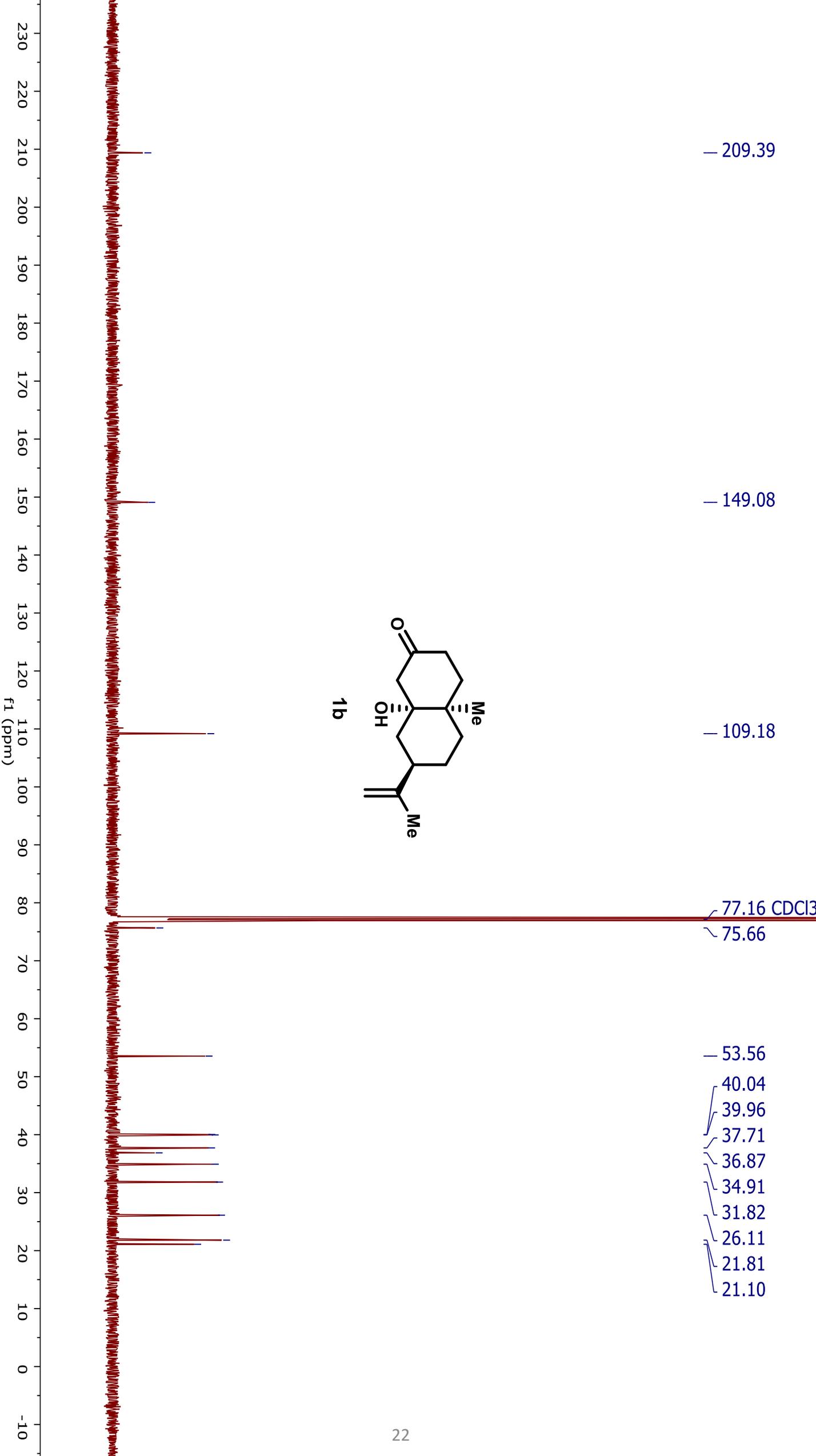
Table 7. Hydrogen bonds for 007-16030 [ $\text{\AA}$  and  $^\circ$ ].

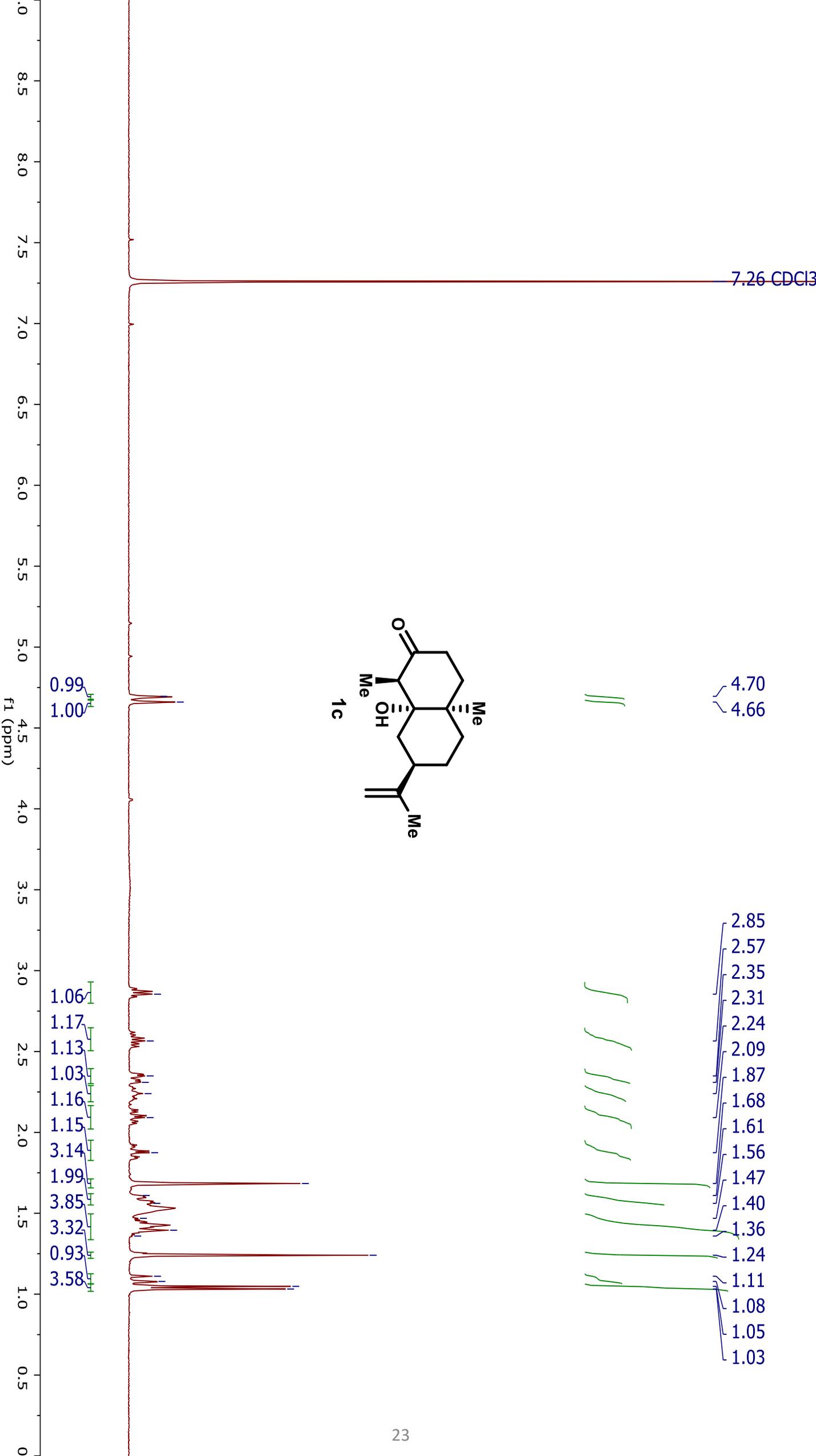
D-H...A	d(D-H)	d(H...A)	d(D...A)	$\angle$ (DHA)
O(1)-H(1)...O(2)#1	0.87(2)	2.20(2)	3.0424(16)	163.3(18)

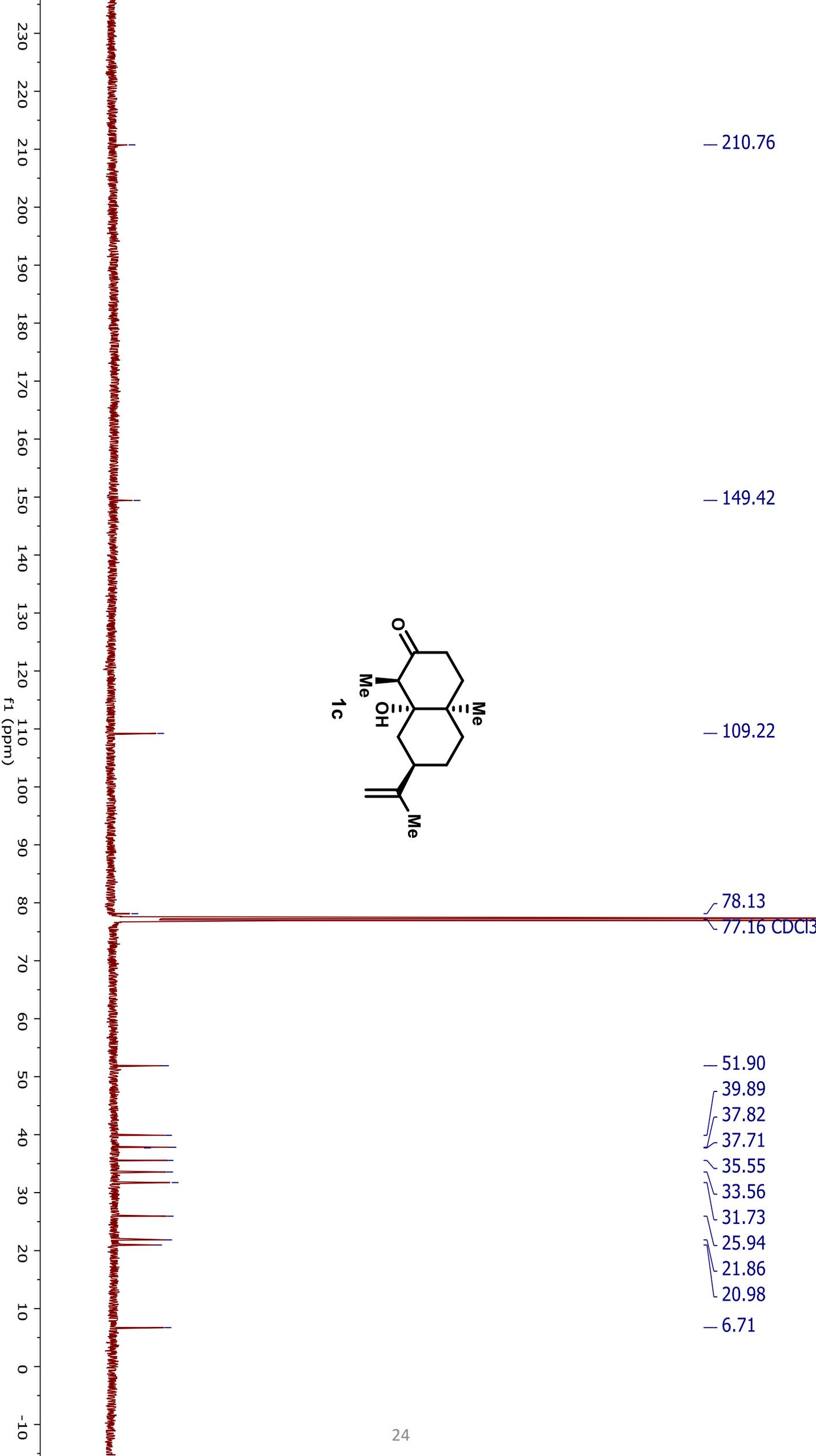
Symmetry transformations used to generate equivalent atoms:

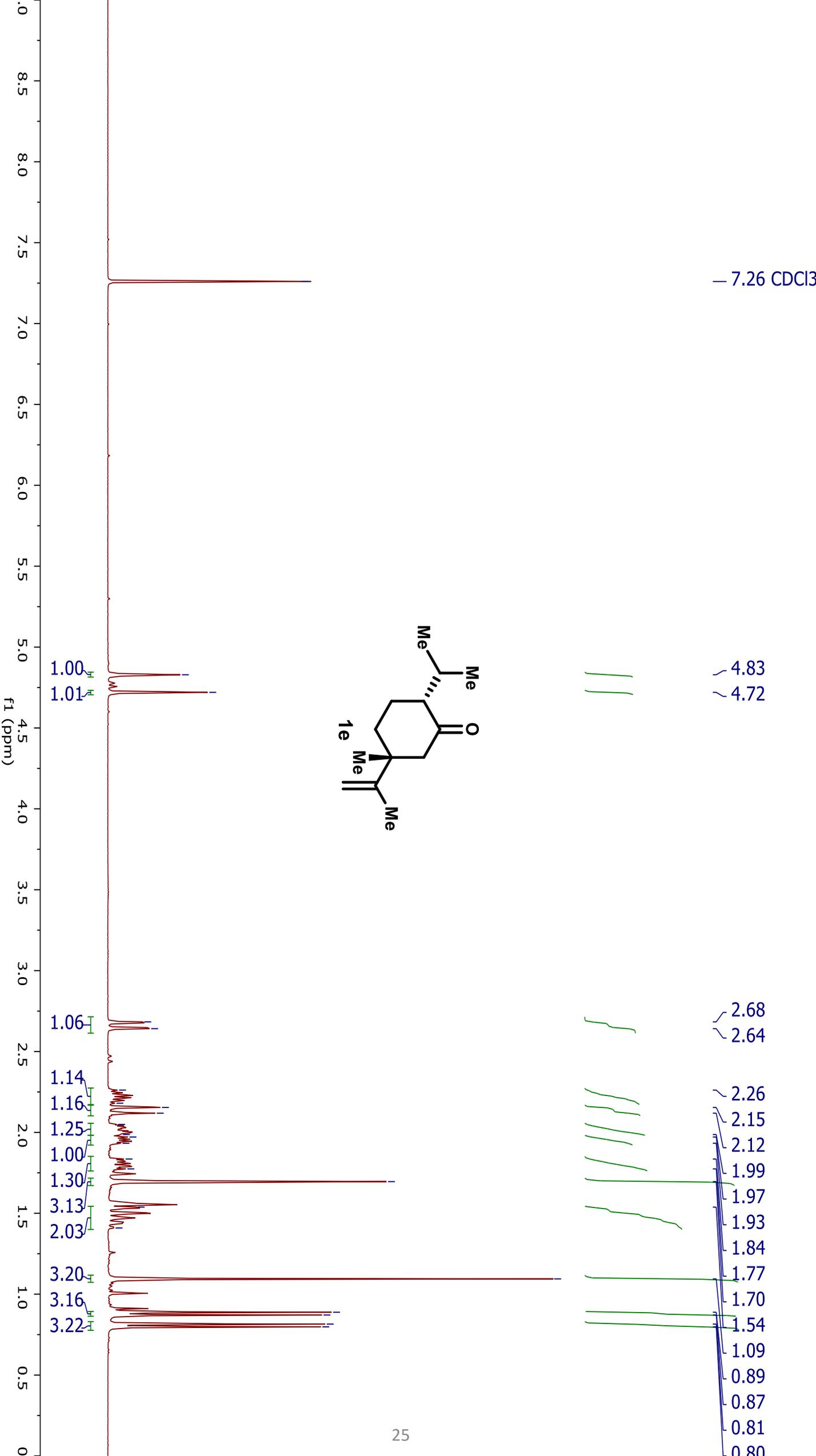
#1  $-x+1, y-1/2, -z+1/2$

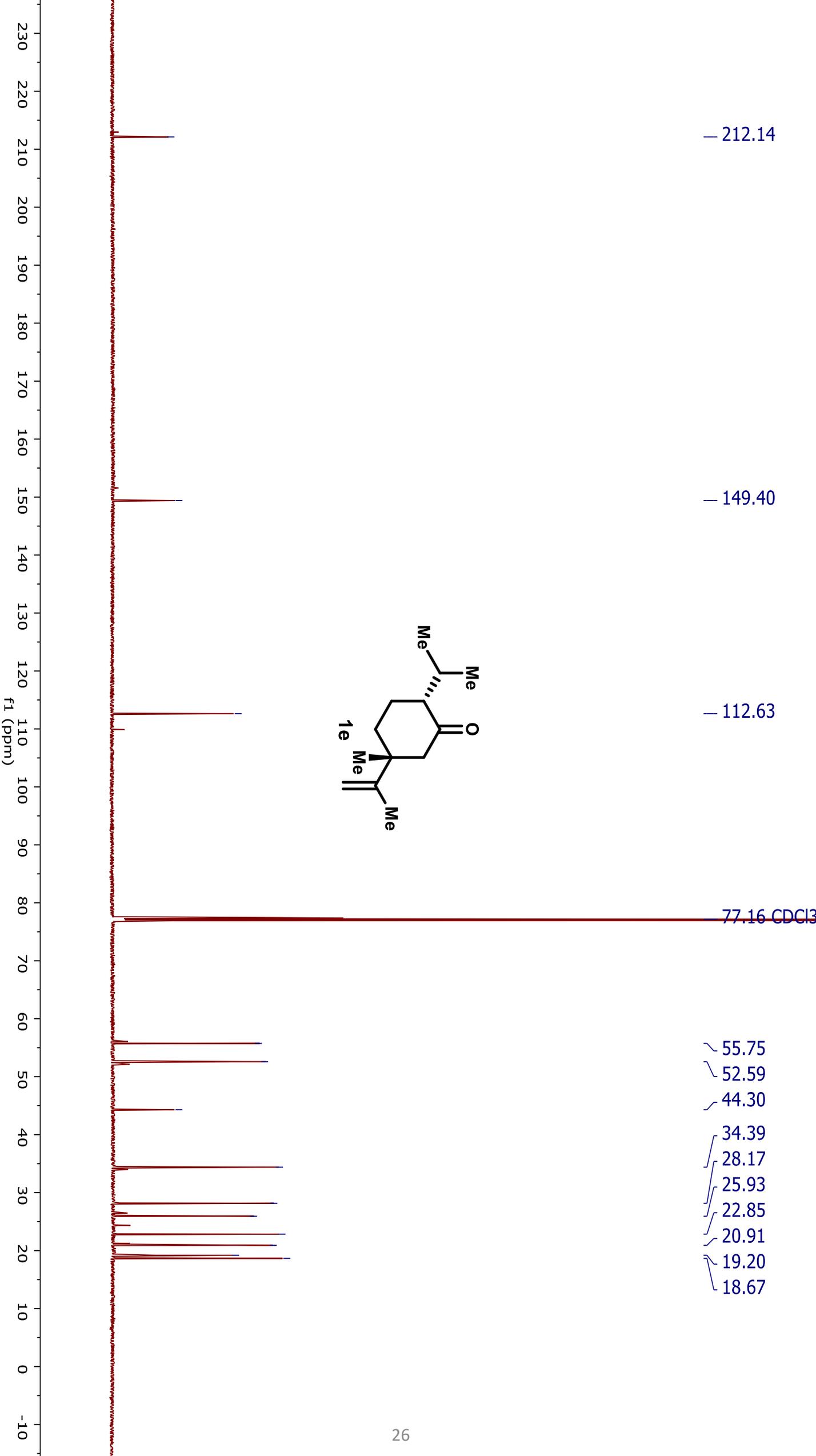




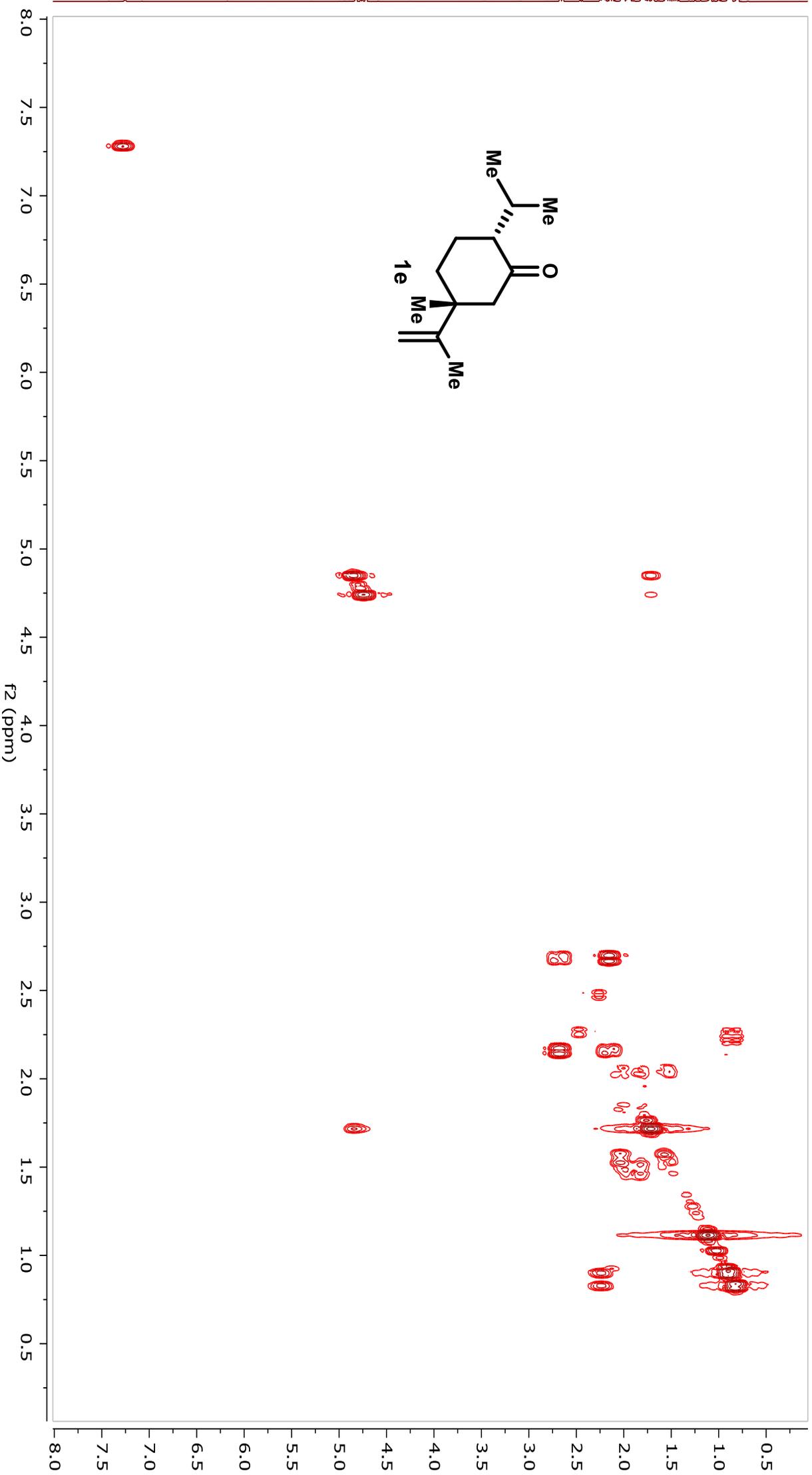








HH-COSY



NOESY

