

# Highly Effective Vinylogous Mukaiyama-Michael Reaction Catalyzed by Silyl Methide Species Generated from 1,1,3,3-Tetrakis(trifluoromethanesulfonyl)propane

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### 1. General and materials

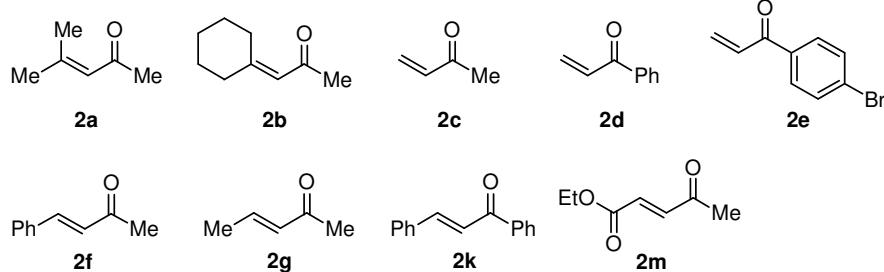
Melting points were uncorrected.  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were taken on a 400 MHz spectrometer, and chemical shifts were reported in parts per million (ppm) using  $\text{CHCl}_3$  (7.26 ppm) in  $\text{CDCl}_3$  or  $\text{C}_6\text{D}_5\text{H}$  (7.16 ppm) in  $\text{C}_6\text{D}_6$  for  $^1\text{H}$  NMR, and  $\text{CDCl}_3$  (77.01 ppm) or  $\text{C}_6\text{D}_6$  (128.00 ppm) for  $^{13}\text{C}$  NMR as an internal standard, respectively. Mass spectra were recorded by an electrospray ionization-time of flight (ESI-TOF) mass spectrometer. Column chromatography was performed on silica gel (75-150  $\mu\text{m}$ ). Medium-pressure liquid chromatography (MPLC) was performed on a 30 x 4 cm i.d. prepakced column (silica gel, 50  $\mu\text{m}$ ) with a UV detector.

### 2. Preparation of starting materials

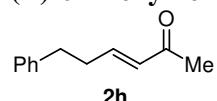
#### 2.1. Preparation of $\alpha,\beta$ -enone substrates

4-Methylpent-3-en-2-one **2a**, but-3-en-2-one **2c**, (*E*)-4-phenylbut-3-en-2-one **2f** and (*E*)-chalcone **2k** are available commercially. 1-Cyclohexylideneacetone **2b**,<sup>1</sup> 1-phenylprop-2-en-1-one **2d**,<sup>2</sup> 1-(4-bromophenyl)-prop-2-en-1-one

**2e**,<sup>3</sup> (*E*)-pent-3-en-2-one **2g**<sup>4</sup> and ethyl (*E*)-4-oxopent-2-enoate **2m**<sup>5</sup> were prepared by the reported procedure.

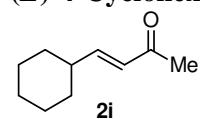


#### (*E*)-6-Phenylhex-3-en-2-one (**2h**)



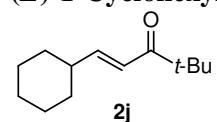
To a solution of 2-phenylpropanal (1.3 mL, 10 mmol) in toluene (50 mL), (2-oxopropyl)triphenylphosphonium chloride (4.0 g, 12 mmol) and  $\text{K}_2\text{CO}_3$  (2.1 g, 15 mmol) were added at room temperature. After being stirred at 80 °C for 5 h, the aqueous layer was extracted with EtOAc (20 mL x 3). The combined organic layer was dried over anhydrous  $\text{MgSO}_4$  and concentrated under reduced pressure. Purification of the residue by column chromatography (hexane/EtOAc = 10 : 1) gave  $\alpha,\beta$ -enone **2h** in 64% yield (1.1 g, 8.4 mmol) as colorless oil. The structure was confirmed by comparison to the reported spectrum data.<sup>6</sup>

#### (*E*)-4-Cyclohexylbut-3-en-2-one (**2i**)



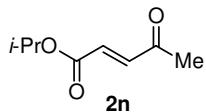
According to the synthetic procedure for **2h**,  $\alpha,\beta$ -enone **2i** was prepared in 56% yield (1.3 g, 8.4 mmol) by the reaction of cyclohexanecarbaldehyde (1.8 mL, 15 mmol), (2-oxopropyl)triphenylphosphonium chloride (8.0 g, 23 mmol) and  $\text{K}_2\text{CO}_3$  (4.2 g, 30 mmol) in a mixed solvent of  $\text{CH}_2\text{Cl}_2$  (25 mL) and  $\text{H}_2\text{O}$  (25 mL) at 50 °C for 24 h. The structure was confirmed by comparison to the reported spectrum data.<sup>7</sup>

#### (*E*)-1-Cyclohexyl-4,4-dimethylpent-1-en-3-one (**2j**)



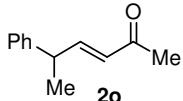
To a solution of cyclohexanecarbaldehyde (2.5 mL, 20 mmol) in a mixed solvent of EtOH (8 mL) and  $\text{H}_2\text{O}$  (3 mL), 3,3-dimethylbutan-2-one (7.3 mL, 24 mmol) and 0.25 M aqueous solution of NaOH (2 mL, 5 mmol) were added at room temperature. After being stirred at the same temperature for 50 h, the reaction mixture was diluted with  $\text{H}_2\text{O}$  (30 mL) and extracted with EtOAc (50 mL x 3). The combined organic layer was washed with brine (50 mL), dried over anhydrous  $\text{MgSO}_4$  and evaporated. The obtained residue was purified by column chromatography on silica gel (hexane/EtOAc = 20 : 1) to give  $\alpha,\beta$ -enone **2j** in 46% yield (1.8 g, 9.2 mmol) as colorless oil. The structure was confirmed by comparison to the reported data.<sup>8</sup>

#### Isopropyl (*E*)-4-oxopent-2-enoate (**2n**)



A solution of ethyl 4-oxopentanoate (5.7 mL, 40 mmol) in propan-2-ol (25 mL) was treated by a catalytic amount of iodine (250 mg, 0.97 mmol) for 7 days at 100 °C, then the reaction mixture was evaporated to give a crude mixture of isopropyl 4-oxopentanoate. To a solution of this crude mixture in Et<sub>2</sub>O (50 mL), bromine (1.2 mL, 23 mmol) was added at 0 °C. After being stirred at the same temperature for 3 h, the resultant mixture was quenched with H<sub>2</sub>O (30 mL) and extracted with Et<sub>2</sub>O (20 mL x 3). The organic layer was dried over anhydrous MgSO<sub>4</sub> and concentrated under reduced pressure to give a crude mixture of isopropyl 3-bromo-4-oxopentanoate. A crude mixture was dissolved in AcOH (1.9 mL) and treated with NaOAc (2.7 g) at 80 °C for 2 h. After usual extractive work up, the reaction mixture was purified by column chromatography on silica gel (pentane/Et<sub>2</sub>O = 10 : 1) to give **2n** (874 mg, 5.6 mmol, 14 % yield over 3 steps). Colorless oil; IR (neat)  $\nu$  2984, 1722, 1702, 1687, 1108, 980 cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.29 (6H, d, *J* = 6.2 Hz), 2.35 (3H, s), 5.12 (1H, septet, *J* = 6.2 Hz), 6.62 (1H, d, *J* = 16.1 Hz), 6.99 (1H, d, *J* = 16.1 Hz); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  21.4, 27.6, 68.7, 131.8, 139.5, 164.6, 197.3; MS (ESI-TOF) *m/z* 157 [M+H]<sup>+</sup>; HRMS calcd for C<sub>8</sub>H<sub>13</sub>O<sub>3</sub> [M+H]<sup>+</sup>, 157.0865; found, 157.0859;

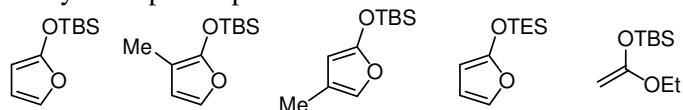
### (E)-5-Phenylhex-3-en-2-one (**2o**)



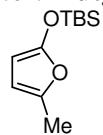
According to the synthetic procedure for **2h**,  $\alpha,\beta$ -enone **2o** was prepared in 64% yield (1.7 g, 6.4 mmol) by the reaction of 2-phenylpropanal (1.3 mL, 10 mmol), (2-oxopropyl)triphenylphosphonium chloride (4.0 g, 12 mmol), and K<sub>2</sub>CO<sub>3</sub> (2.1 g, 15 mmol) in toluene (50 mL) at 80 °C for 5 h. The structure was confirmed by comparison to the reported spectrum data.<sup>9</sup>

## 2.2. Preparation of 2-silyloxyfurans and ketene silyl acetal

*tert*-Butyl(furan-2-yloxy)dimethylsilane,<sup>10</sup> *tert*-butyl(dimethyl)[(3-methylfuran-2-yl)oxy]silane,<sup>11</sup> and *tert*-butyl(dimethyl)[(4-methylfuran-2-yl)oxy]silane,<sup>11</sup> triethyl(furan-2-yloxy)silane,<sup>12</sup> and *tert*-butyl(1-ethoxyvinyloxy)-dimethylsilane<sup>13</sup> were prepared by the reported procedures.



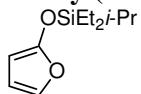
### *tert*-Butyl(dimethyl)[(5-methylfuran-2-yl)oxy]silane



To a solution of 5-methylfuran-2(3*H*)-one (0.9 mL, 10 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (2 mL), *tert*-butyl(dimethyl)silyl trifluoromethanesulfonate (2.1 mL, 10 mmol) and Et<sub>3</sub>N (2.1 mL, 15 mmol) were added at 0 °C. After being stirred at room temperature for 2 h, extractive work-up and purification by silica gel column chromatography (hexane) gave *tert*-butyl(dimethyl)[(5-methylfuran-2-yl)oxy]silane (1.27 g, 6.0 mmol, 60% yield). Colorless oil; IR

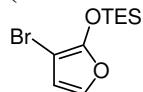
(neat)  $\nu$  1628, 1592  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.27 (6H, s), 1.01 (9H, s), 2.19 (3H, s), 4.99 (1H, d,  $J$  = 3.0 Hz), 5.75-5.80 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  -4.9, 13.5, 18.1, 25.6, 83.7, 106.1, 141.3, 155.3; MS (EI)  $m/z$  212 [M] $^+$ . Anal. Calcd for  $\text{C}_{11}\text{H}_{20}\text{O}_2\text{Si}$ : C, 62.21; H, 9.49. Found: C, 61.97; H, 9.25.

### Diethyl(furan-2-yloxy)isopropylsilane



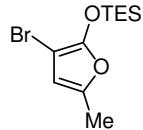
Furan-2(*5H*)-one (0.7 mL, 10 mmol) and  $\text{Et}_3\text{N}$  (2.1 mL 15 mmol) were added diethylisopropylsilyl chloride (1.8 mL, 10 mmol) at room temperature. After being stirred at the same temperature for 2 h, the desired silyloxyfuran was obtained in 71 % yield (1.6 g, 7.1 mmol) by direct distillation of the reaction mixture under reduced pressure (bp. 80  $^{\circ}\text{C}$  at 3 mmHg). Colorless oil; IR (neat)  $\nu$  2958, 2879, 1619, 1523, 1261, 957, 837, 735, 708  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  0.60-0.77 (4H, m), 0.92-1.03 (13H, m), 5.11 (1H, d,  $J$  = 3.0 Hz), 6.02-6.08 (1H, m), 6.62-6.68 (1H, m);  $^{13}\text{C}$  NMR (100 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  4.4, 7.3, 13.7, 17.5, 84.4, 112.0, 133.0, 158.1; MS (EI)  $m/z$  212 [M] $^+$ .

### (3-Bromofuran-2-yloxy)triethylsilane



To a solution of 3-bromofuran-2(*5H*)-one<sup>14</sup> (490 mg, 3.0 mmol) in  $\text{CH}_2\text{Cl}_2$  (0.5 mL), triethylsilyl triflate (0.68 mL, 3.0 mmol) and  $\text{Et}_3\text{N}$  (0.46 mL 3.6 mmol) were added at 0  $^{\circ}\text{C}$ . After being stirred at 0  $^{\circ}\text{C}$  for 15 min, the reaction mixture was diluted with hexane (20 mL), then washed with  $\text{H}_2\text{O}$  (10 mL). The resultant organic layer was evaporated to give (3-bromofuran-2-yloxy)triethylsilane in 82% yield (680 mg, 2.5 mmol) as a dark red oil. Due to the low stability of this compound, the crude mixture was used without further purifications (>94% purity based on  $^1\text{H}$  NMR). IR (neat)  $\nu$  2958, 2914, 2879, 1636, 1518, 886, 839, 749  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.74-0.82 (6H, m), 0.98-1.02 (9H, m), 6.26 (1H, d,  $J$  = 2.4 Hz), 6.80 (1H, d,  $J$  = 2.4 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  4.9, 6.2, 73.6, 114.1, 132.1, 153.4; MS (EI)  $m/z$  276 [M] $^+$ .

### (3-Bromo-5-methylfuran-2-yloxy)triethylsilane



To a solution of 5-methylfuran-2(*5H*)-one<sup>15</sup> (1.0 g, 10 mmol) in  $\text{CCl}_4$  (40 mL), bromine (0.8 mL, 15 mmol) was added at room temperature. After being stirred at 50  $^{\circ}\text{C}$  for 2 h, the resultant mixture was quenched with saturated  $\text{NaHCO}_3$  aqueous solution (30 mL) and extracted with  $\text{CH}_2\text{Cl}_2$  (20 mL x 3). The organic layer was dried over anhydrous  $\text{MgSO}_4$  and concentrated under reduced pressure to give a crude mixture of 3,4-dibromo-5-methylfuran-2(*3H*)-one. This crude mixture was dissolved to  $\text{CH}_2\text{Cl}_2$  (40 mL) and treated with  $\text{Et}_3\text{N}$  (1.1 mL) at 0  $^{\circ}\text{C}$  for 30 min. After usual extractive work up, the reaction mixture was purified by column chromatography on silica gel (hexane/AcOEt = 3 : 1) to give 3-bromo-5-methylfuran-2(*5H*)-one (1.4 g, 8.2 mmol, 82 % yield over 2 steps). Pale yellow oil; IR (neat)  $\nu$  3092, 2985, 2935, 1767, 1608, 1314, 993  $\text{cm}^{-1}$ ;

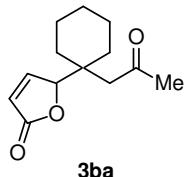
<sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.49 (3H, d, *J* = 6.8 Hz), 5.08 (1H, qd, *J* = 6.8, 1.6 Hz), 7.50 (1H, d, *J* = 1.6 Hz); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  18.5, 79.2, 112.6, 154.1, 168.2; MS (ESI-TOF) *m/z* 177 [M+H]<sup>+</sup>, 179 [M+2+H]<sup>+</sup>; HRMS calcd for C<sub>5</sub>H<sub>6</sub>BrO<sub>2</sub> [M+H]<sup>+</sup>, 176.9551; found, 176.9544; Anal. Calcd for C<sub>5</sub>H<sub>5</sub>BrO<sub>2</sub>: C, 33.93; H, 2.85. Found: C, 34.05; H, 3.01.

According to the synthetic procedure for (3-bromofuran-2-yloxy)triethylsilane, (3-bromo-5-methylfuran-2-yloxy)triethylsilane was obtained in 90% yield (780 mg, 2.7 mmol, >90% purity based on <sup>1</sup>H NMR) by the reaction of 3-bromo-5-methylfuran-2(5*H*)-one (530 mg, 3.0 mmol), triethylsilyl triflate (0.68 mL, 3.0 mmol) and Et<sub>3</sub>N (0.46 mL, 3.6 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (0.5 mL). Colorless oil; IR (neat)  $\nu$  2957, 2916, 2879, 1641, 1598, 1057, 854 cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  0.78 (6H, q, *J* = 7.9 Hz), 1.02 (9H, t, *J* = 7.9 Hz), 2.15 (1H, brs), 5.83 (1H, brs); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  4.9, 6.2, 13.6, 73.3, 109.1, 141.3, 151.7. Due to low stability of this compound, it was not possible to measure its MS spectrum.

### **3. Vinylgous Mukaiyama-Michael (VMM) reaction**

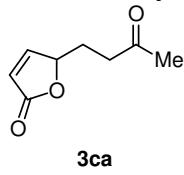
#### **3.1. Carbon acid catalyzed VMM reaction (Tables 1, 2)**

##### **5-[1-(2-Oxopropyl)cyclohexyl]furan-2(5*H*)-one (3ba)**



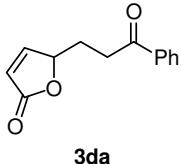
According to the synthesis of 3aa, 3ba was obtained in 90% yield (100.0 mg, 0.45 mmol) by the reaction of (*tert*-butyldimethylsilyloxy)furan (109 mg, 0.55 mmol) and 2b (69 mg, 0.50 mmol) in the presence of 1 (0.74 mg, 1.3  $\mu$ mol) at -24 °C for 3 h. Colorless oil; IR (neat)  $\nu$  1757, 1713 cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.10-1.45 (5H, m), 1.45-1.63 (4H, m), 1.74-1.82 (1H, m), 2.12 (3H, s), 2.54 (1H, d, *J* = 17.4 Hz), 2.67 (1H, d, *J* = 17.4 Hz), 5.34-5.37 (1H, m), 6.07 (1H, dd, *J* = 5.8, 2.1 Hz), 7.51 (1H, dd, *J* = 5.8, 1.4 Hz); <sup>13</sup>C NMR (100.6 MHz, CDCl<sub>3</sub>)  $\delta$  21.0, 21.1, 25.6, 30.5, 30.6, 32.1, 40.3, 43.6, 87.7, 121.9, 154.7, 172.9, 208.2; MS (ESI-TOF) *m/z* 223 [M+H]<sup>+</sup>; HRMS calcd for C<sub>13</sub>H<sub>19</sub>O<sub>3</sub> [M+H]<sup>+</sup>, 223.1334; found, 223.1320. Anal. Calcd for C<sub>13</sub>H<sub>18</sub>O<sub>3</sub>: C, 70.24; H, 8.16. Found: C, 70.45; H, 8.12.

##### **5-(3-Oxobutyl)furan-2(5*H*)-one (3ca)**



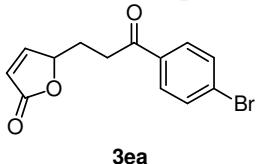
According to the synthesis of 3aa, the reaction of 2c (35 mg, 0.50 mmol) and *tert*-butyl(furan-2-yloxy)dimethylsilane (109 mg, 0.55 mmol) in the presence of 1 (0.14 mg, 0.25  $\mu$ mol) for 2 h at -78 °C give 1,4-adduct 3ca (63.1 mg, 0.41 mmol, 82% yield). The structure was confirmed by comparison of spectrum data with those reported in the literature.<sup>16</sup>

**5-(3-Oxo-3-phenylpropyl)furan-2(5H)-one (3da)**



To a solution of *tert*-butyl(furan-2-yloxy)dimethylsilane (109 mg, 0.55 mmol) in  $\text{CH}_2\text{Cl}_2$  (1 mL), a solution of **1** (1.5 mM in  $\text{CH}_2\text{Cl}_2$ , 2.0 mL, 0.50  $\mu\text{mol}$ ) and **2d** (66 mg, 0.50 mmol) in  $\text{CH}_2\text{Cl}_2$  (0.8 mL) were added at  $-78^\circ\text{C}$  over 10 min. After being stirred for 1 h at  $-78^\circ\text{C}$ , reaction mixture was quenched with saturated  $\text{NaHCO}_3$  aqueous solution and extracted with  $\text{EtOAc}$  (20 mL x 3). The organic layer was dried over anhydrous  $\text{MgSO}_4$ , then it was concentrated under reduced pressure. The resulting residue was treated by  $\text{TfOH}$  (150 mg, 1.0 mmol) in  $\text{CH}_2\text{Cl}_2$  (100 mL) for 1 h at  $-78^\circ\text{C}$ . The reaction mixture was diluted with  $\text{H}_2\text{O}$  (50 mL), extracted with  $\text{CH}_2\text{Cl}_2$  (40 mL), dried over anhydrous  $\text{MgSO}_4$  and evaporated. Purification of the resulting residue by column chromatography on silica gel (hexane/EtOAc = 3 : 1) gave **3da** (96.2 mg, 0.45 mmol, 89% yield). White solid; Mp. 91.1-91.5  $^\circ\text{C}$ ; IR (KBr)  $\nu$  1769, 1682  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400MHz,  $\text{CDCl}_3$ )  $\delta$  1.97-2.03 (1H, m), 2.37-2.48 (1H, m), 3.08-3.28 (2H, m), 5.17-5.27 (1H, m), 6.11 (1H, dd,  $J$  = 5.7, 2.0 Hz), 7.44-7.52 (3H, m), 7.55-7.61 (1H, m), 7.93-7.98 (2H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  27.1, 33.2, 82.3, 121.6, 127.9, 128.6, 133.3, 136.4, 156.2, 172.8, 198.5; MS (ESI-TOF)  $m/z$  239 [ $\text{M}+\text{Na}]^+$ ; HRMS calcd for  $\text{C}_{13}\text{H}_{12}\text{NaO}_3$  [ $\text{M}+\text{Na}]^+$ , 239.0684; found, 239.0671.

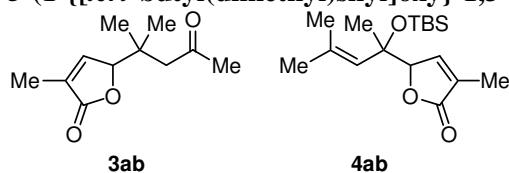
**5-[3-(4-Bromophenyl)-3-oxopropyl]furan-2(5H)-one (3ea)**



According to the synthetic procedure for **3da**, **3ea** was obtained in 88% yield (129.9 mg, 0.44 mmol) by the reaction of **2e** (106 mg, 0.50 mmol) and *tert*-butyl(furan-2-yloxy)dimethylsilane (109 mg, 0.55 mmol) in the presence of **1** (0.14 mg, 0.25  $\mu\text{mol}$ ) for 1 h at  $-78^\circ\text{C}$ . White solid; Mp. 84.3-84.9  $^\circ\text{C}$ ; IR (KBr)  $\nu$  1746, 1687  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400MHz,  $\text{CDCl}_3$ )  $\delta$  1.88-1.99 (1H, m), 2.40 (1H, dtd,  $J$  = 14.5, 7.3, 3.8 Hz), 3.03-3.23 (2H, m), 5.16-5.22 (1H, m), 6.12 (1H, dd,  $J$  = 5.7, 2.0 Hz), 7.49 (1H, dd,  $J$  = 5.7, 1.5 Hz), 7.58-7.63 (2H, m), 7.78-7.83 (2H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  27.1, 33.3, 82.1, 121.8, 128.7, 129.5, 132.0, 135.2, 156.0, 172.7, 197.5; MS (ESI-TOF)  $m/z$  295 [ $\text{M}+\text{H}]^+$ ; HRMS calcd for  $\text{C}_{13}\text{H}_{12}\text{BrO}_3$  [ $\text{M}+\text{H}]^+$ , 294.9970; found, 294.9966. Anal. Calcd for  $\text{C}_{13}\text{H}_{11}\text{BrO}_3$ : C, 52.91; H, 3.76. Found: C, 52.61; H, 4.00.

**5-(1,1-Dimethyl-3-oxobutyl)-3-methylfuran-2(5H)-one (3ab) and**

**5-(1-{[*tert*-butyl(dimethyl)silyloxy]-1,3-dimethylbut-2-enyl}-3-methylfuran-2(5H)-one (4ab).**

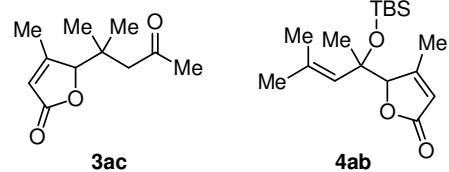


According to the synthetic procedure for **3aa**, the reaction of **2a** (49 mg, 0.50 mmol) and *tert*-butyl(dimethyl)[(3-methylfuran-2-yl)oxy]silane (117 mg, 0.55 mmol) in the presence of **1** (0.71 mg, 1.3  $\mu\text{mol}$ ) for 2 h at  $-78^\circ\text{C}$

give 1,4-adduct **3ab** (82.3 mg, 0.42 mmol, 84% yield) and two diastereomers of 1,2-adduct **4ab** (major isomer, 2.1 mg, 0.007 mmol 1.3% yield; minor isomer, 2.0 mg 0.006 mmol, 1.3% yield). For **3ab** Colorless oil; IR (neat)  $\nu$  1756, 1713  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.89 (3H, s), 1.14 (3H, s), 1.92-1.94 (3H, m), 2.14 (3H, s), 2.38 (1H, d,  $J$  = 16.9 Hz), 2.65 (1H, d,  $J$  = 16.9 Hz), 5.03-5.08 (1H, m), 7.04 (1H, t,  $J$  = 1.5 Hz);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  10.8, 22.4, 23.3, 32.0, 37.1, 50.5, 86.1, 131.2, 146.4, 174.2, 207.7; MS (ESI-TOF)  $m/z$  197 [M+H] $^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{17}\text{O}_3$  [M+H] $^+$ , 197.1178; found, 197.1186. Anal. Calcd for  $\text{C}_{11}\text{H}_{16}\text{O}_3$ : C, 67.32; H, 8.22. Found: C, 67.30; H, 8.24. For **4ab-major** Colorless oil; IR (neat)  $\nu$  1767  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  0.11 (6H, s), 0.96 (9H, s), 1.26 (3H, s), 1.52 (3H, d,  $J$  = 1.3 Hz), 1.64 (3H, t,  $J$  = 1.8 Hz), 1.69 (3H, d,  $J$  = 1.3 Hz), 4.47-4.51 (1H, m), 4.92-4.96 (1H, m) 6.42-6.46 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  -2.3, -1.9, 10.6, 18.5, 19.4, 26.1, 26.1, 27.6, 77.2, 86.8, 127.6, 131.4, 136.4, 145.6, 173.2; MS (ESI-TOF)  $m/z$  333 [M+Na] $^+$ ; HRMS calcd for  $\text{C}_{17}\text{H}_{30}\text{NaO}_3\text{Si}$  [M+Na] $^+$ , 333.1862; found, 333.1877. For **4ab-minor** Colorless oil; IR (neat)  $\nu$  1767  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  0.06 (3H, s), 0.09 (3H, s), 0.91 (9H, s), 1.26 (3H, s), 1.55 (3H, d,  $J$  = 1.3 Hz), 1.58 (3H, d,  $J$  = 1.3 Hz), 1.69 (3H, t,  $J$  = 1.7 Hz), 4.46-4.50 (1H, m), 5.09-5.14 (1H, m), 6.48-6.52 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  -2.3, -1.9, 10.7, 18.4, 19.5, 25.5, 26.1, 27.5, 76.3, 85.9, 129.7, 131.5, 135.4, 145.8, 173.4; MS (ESI-TOF)  $m/z$  333 [M+Na] $^+$ ; HRMS calcd for  $\text{C}_{17}\text{H}_{30}\text{NaO}_3\text{Si}$  [M+Na] $^+$ , 333.1862; found, 333.1880.

### 5-(1,1-Dimethyl-3-oxobutyl)-4-methylfuran-2(5H)-one (**3ac**) and

### 5-(1-{[*tert*-butyl(dimethyl)silyl]oxy}-1,3-dimethylbut-2-enyl)-4-methylfuran-2(5H)-one (**4ac**)

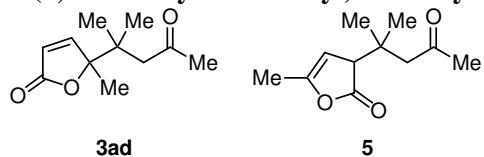


According to the synthetic procedure for **3aa**, the reaction of **2a** (49 mg, 0.50 mmol) and *tert*-butyl [(4-methylfuran-2-yl)oxy]silane (159 mg, 0.75 mmol) in the presence of **1** (0.71 mg, 1.3  $\mu\text{mol}$ ) for 2 h at -78  $^{\circ}\text{C}$  give 1,4-adduct **3ac** (72.0 mg, 0.39 mmol, 78% yield) and two diastereomers of 1,2-adduct **4ac** (major isomer, 9.4 mg, 0.03 mmol 6.3% yield; minor isomer, 2.6 mg, 0.009 mmol, 1.8% yield). For **3ac** Colorless oil; IR (neat)  $\nu$  1763, 1713  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.83 (3H, s), 1.18 (3H, s), 2.09 (3H, s), 2.13-2.15 (3H, m), 2.64 (1H, d,  $J$  = 17.4 Hz), 2.74 (1H, d,  $J$  = 17.4 Hz), 5.15 (1H, brs), 5.78 (1H, quin,  $J$  = 1.5 Hz);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  16.5, 22.4, 23.6, 31.5, 36.9, 51.7, 88.8, 119.1, 167.6, 172.6, 207.5; MS (ESI-TOF)  $m/z$  219 [M+Na] $^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{16}\text{NaO}_3$  [M+Na] $^+$ , 219.0997; found, 219.0977. Anal. Calcd for  $\text{C}_{11}\text{H}_{16}\text{O}_3$ : C, 67.32; H, 8.22. Found: C, 67.31; H, 8.21. For **4ac-major** Colorless oil; IR (neat)  $\nu$  1767  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  0.03 (3H, s), 0.06 (3H, s), 0.89 (9H, s), 1.21 (3H, s), 1.52 (3H, s), 1.53 (3H, s), 1.67-1.70 (3H, m), 5.17 (1H, s), 5.28 (1H, s), 5.51 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  -2.3, -1.8, 16.0, 18.4, 19.4, 24.9, 26.2, 27.4, 76.5, 88.4, 119.5, 131.1, 134.4, 166.5, 171.9; MS (ESI-TOF)  $m/z$  333 [M+Na] $^+$ ; HRMS calcd for  $\text{C}_{17}\text{H}_{30}\text{NaO}_3\text{Si}$  [M+Na] $^+$ , 333.1862; found, 333.1881. For **4ac-minor** Colorless oil; IR (neat)  $\nu$  1769  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  0.09 (3H, s), 0.11 (3H, s), 0.93 (9H, s), 1.40 (3H, s), 1.50 (3H, d,  $J$  = 1.4), 1.52-1.56 (3H, m), 1.70 (3H, d,  $J$  = 1.4 Hz), 4.31 (1H, brs), 4.88 (1H, brs), 5.43-5.46 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  -2.1, -2.0, 16.1, 18.4, 19.2, 26.2, 26.7, 27.8, 77.9, 89.5, 119.3, 126.9, 136.7, 166.2, 171.5; MS

(ESI-TOF)  $m/z$  333 [M+Na]<sup>+</sup>; HRMS calcd for  $C_{17}H_{30}NaO_3Si$  [M+Na]<sup>+</sup>, 333.1862; found, 333.1854.

### 5-(1,1-Dimethyl-3-oxobutyl)-5-methylfuran-2(5*H*)-one (3ad) and

### 3-(1,1-dimethyl-3-oxobutyl)-5-methylfuran-2(3H)-one (5)

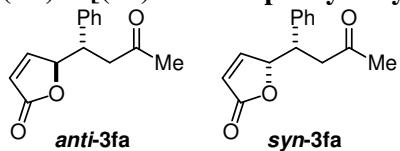


According to the synthetic procedure for **3aa**, the reaction of **2a** (49 mg, 0.50 mmol) and *tert*-butyl(dimethyl)[(5-methylfuran-2-yl)oxy]silane (159 mg, 0.75 mmol) in the presence of **1** (0.71 mg, 1.3  $\mu$ mol) for 2 h at  $-78$   $^{\circ}$ C, then 2 h at  $-24$   $^{\circ}$ C gave **3ad** (51.0 mg, 0.28 mmol, 55% yield) and **5** (27.0 mg, 0.15 mmol, 29% yield). For **3ad** White solid; Mp. 55.3-55.7  $^{\circ}$ C; IR (KBr) 1752, 1705  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400MHz,  $\text{CDCl}_3$ )  $\delta$  1.04 (3H, s), 1.13 (3H, s), 1.39 (3H, s), 2.09 (3H, s), 2.40 (1H, d,  $J$  = 15.5 Hz), 2.46 (1H, d,  $J$  = 15.5 Hz), 6.00 (1H, d,  $J$  = 5.8 Hz), 7.46 (1H, d,  $J$  = 5.8 Hz);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  19.8, 22.0, 22.5, 32.7, 39.6, 48.5, 93.5, 121.0, 159.5, 172.5, 207.7; MS (ESI-TOF)  $m/z$  197 [ $\text{M}+\text{H}$ ] $^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{17}\text{O}_3$  [ $\text{M}+\text{H}$ ] $^+$ , 197.1178; found, 197.1177. Anal. Calcd for  $\text{C}_{11}\text{H}_{16}\text{O}_3$ : C, 67.32; H, 8.22. Found: C, 67.33; H, 8.17. For **5** Colorless oil; IR (neat)  $\nu$  1789, 1713  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.96 (3H, s), 1.12 (3H, s), 1.97-2.02 (3H, m), 2.15 (3H, s), 2.44 (1H, d,  $J$  = 17.2 Hz), 2.91 (1H, d,  $J$  = 17.2 Hz), 3.68 (1H, quin,  $J$  = 2.4 Hz), 5.08-5.12 (1H, m);  $^{13}\text{C}$  NMR (100.6 MHz,  $\text{CDCl}_3$ )  $\delta$  14.0, 24.5, 25.6, 31.8, 35.7, 50.9, 52.2, 101.6, 152.5, 177.8, 208.0; MS (ESI-TOF)  $m/z$  197 [ $\text{M}+\text{H}$ ] $^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{17}\text{O}_3$  [ $\text{M}+\text{H}$ ] $^+$ , 197.1178; found, 197.1183. Anal. Calcd for  $\text{C}_{11}\text{H}_{16}\text{O}_3$ : C, 67.32; H, 8.22. Found: C, 67.52; H, 8.32.

### **3.2. Diastereoselective VMM reaction (Tables 3, 4 and Eqn. 1, 2)**

**(S\*)-5-[(S\*)-3-Oxo-1-phenylbutyl]furan-2(5H)-one (*anti*-3fa) and**

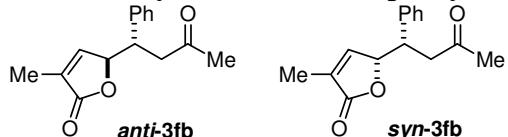
**(R<sup>\*</sup>)-5-[(S<sup>\*</sup>)-3-oxo-1-phenylbutyl]furan-2(5H)-one (*syn*-3fa)**



To a solution of  $\alpha,\beta$ -enone **2f** (73 mg, 0.5 mmol) and triethyl(furan-2-yloxy)silane (119 mg, 0.60 mmol) in  $\text{CH}_2\text{Cl}_2$  (0.5 mL), freshly prepared solution of carbon acid **1** in  $\text{CH}_2\text{Cl}_2$  (10 mM, 0.5 mL, 5.0  $\mu\text{mol}$ ) were added at  $-78^\circ\text{C}$  over 30 min. After being stirred for 2 h at  $-24^\circ\text{C}$ , the reaction mixture was quenched with saturated  $\text{NaHCO}_3$  aqueous solution and extracted with  $\text{EtOAc}$  (20 mL x 3). The organic layer was dried over anhydrous  $\text{MgSO}_4$  and concentrated under reduced pressure. The resultant residue was treated with 1 M aqueous solution of  $\text{HCl}$  (10 mL) in  $\text{THF}$  (10 mL) for 30 min at room temperature. This reaction mixture was diluted with  $\text{H}_2\text{O}$  (10 mL), extracted with  $\text{EtOAc}$  (20 mL x 3), dried over anhydrous  $\text{MgSO}_4$  and evaporated. Purification of the obtained residue by column chromatography on silica gel (hexane/ $\text{EtOAc}$  = 2 : 1) gave an inseparable mixture of **anti-3fa** and **syn-3fa** (107 mg, 0.47 mmol, 93% yield, *anti/syn* = 5.0 : 1). Colorless oil; IR (neat)  $\nu$  3031, 2919, 1756, 1715, 1602, 1496, 1163, 1454, 767, 703  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  for **anti-3fa** 2.06 (3H, s), 2.90 (1H, dd,  $J$  = 17.5, 8.1 Hz), 3.03 (1H, dd,  $J$  = 17.5, 5.3 Hz), 3.41-3.48 (1H, m), 5.15 (1H, dt,  $J$  = 7.5, 1.9 Hz), 6.09 (1H, dd,  $J$  = 5.7, 1.9

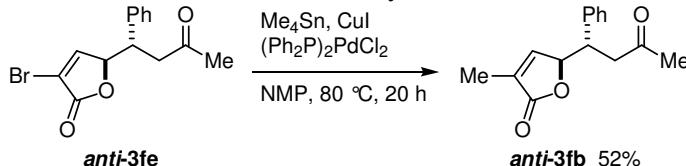
Hz), 7.09-7.35 (6H, m), for *syn*-3fa 2.17 (3H, s), 2.86-2.96 (1H, m), 3.23 (1H, dd,  $J$  = 18.2, 8.3 Hz), 3.69-3.76 (1H, m), 5.34 (1H, quin,  $J$  = 1.9 Hz), 7.09-7.35 (6H, m);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  for *anti*-3fa 30.5, 44.3, 45.0, 85.7, 122.0, 127.8, 128.1, 129.0, 139.4, 155.4, 172.6, 205.8, for *syn*-3fa 30.5, 42.7, 44.8, 84.2, 122.2, 127.7, 128.3, 128.7, 137.0, 155.1, 172.8, 206.5; MS (ESI-TOF)  $m/z$  253 [M+Na] $^+$ ; HRMS calcd for  $\text{C}_{14}\text{H}_{14}\text{NaO}_3$  [M+Na] $^+$ , 253.0841; found, 253.0821. Anal. Calcd for  $\text{C}_{14}\text{H}_{14}\text{O}_3$ : C, 73.08; H, 6.13. Found: C, 72.80; H, 6.21.

**(*R*\*)-3-Methyl-5-[(*S*\*)-3-oxo-1-phenylbutyl]furan-2(5*H*)-one (*anti*-3fb) and (*S*\*)-3-methyl-5-[(*S*\*)-3-oxo-1-phenylbutyl]furan-2(5*H*)-one (*syn*-3fb)**



According to the synthetic procedure for **3fa**, 1,4-adduct **3fb** was obtained in 87% yield (*anti*-3fb, 88.2 mg, 0.36 mmol; *syn*-3fb, 0.07 mmol, 18.0 mg) by the reaction of **2f** (73 mg, 0.50 mmol) with *tert*-butyl(dimethyl)[(3-methylfuran-2-yl)oxy]silane (127 mg, 0.60 mmol) in the presence of carbon acid **1** (2.9 mg, 5.0  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at -78  $^{\circ}\text{C}$  for 2 h. For *anti*-3fb Colorless crystals; Mp. 60.1-61.0  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3030, 3006, 1752, 1711, 1498, 1456, 1163, 768, 703  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.86 (3H, brs), 2.03 (3H, s), 2.87 (1H, dd,  $J$  = 17.4, 8.4 Hz), 2.99 (1H, dd,  $J$  = 17.4, 5.0 Hz), 3.30-3.41 (1H, m), 4.98 (1H, dt,  $J$  = 7.6, 1.6 Hz), 6.77 (1H, brs), 7.15-7.28 (3H, m), 7.28-7.36 (2H, m);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  10.6, 30.5, 44.6, 45.2, 83.4, 127.6, 128.0, 128.9, 130.5, 139.6, 147.7, 173.7, 205.9; MS (ESI-TOF)  $m/z$  245 [M+H] $^+$ ; HRMS calcd for  $\text{C}_{15}\text{H}_{17}\text{O}_3$  [M+H] $^+$ , 245.1178; found, 245.1189. For *syn*-3fb Colorless oil; IR (neat)  $\nu$  3031, 1757, 1714, 1496, 1454, 1162, 763, 703  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.67 (3H, brs), 2.14 (3H, s), 2.89 (1H, dd,  $J$  = 18.0, 6.2 Hz), 3.16 (1H, dd,  $J$  = 18.0, 7.9 Hz), 3.68 (1H, ddd,  $J$  = 7.9, 6.2, 3.4 Hz), 5.15 (1H, dt,  $J$  = 3.4, 1.7 Hz), 6.82-6.88 (1H, m), 7.07-7.14 (2H, m), 7.15-7.28 (3H, m);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  10.4, 30.5, 42.9, 44.6, 82.0, 127.5, 128.3, 128.6, 130.8, 137.3, 147.3, 173.9, 206.6; MS (ESI-TOF)  $m/z$  245 [M+H] $^+$ ; HRMS calcd for  $\text{C}_{15}\text{H}_{17}\text{O}_3$  [M+H] $^+$ , 245.1178; found, 245.1188.

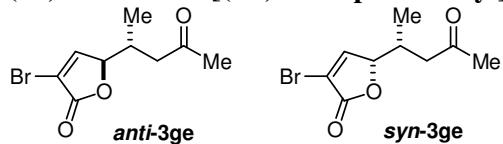
To determine the stereochemistry of **3fb**, we conducted the following methylation reaction.



To a solution of (*R*\*)-3-bromo-5-[(*S*\*)-3-oxo-1-phenylbutyl]furan-2(5*H*)-one **anti**-3fe (88 mg, 0.29 mmol) in *N*-methyl-2-pyrrolidone (NMP, 2.0 mL),  $(\text{Ph}_2\text{P})_2\text{PdCl}_2$  (30 mg, 0.04 mmol), CuI (34 mg, 0.17 mmol) and  $\text{Me}_4\text{Sn}$  (0.16 mL, 1.2 mmol) were added. After being stirred for 20 h at 80  $^{\circ}\text{C}$ , the resultant mixture was quenched with  $\text{H}_2\text{O}$  (10 mL), extracted with EtOAc (10 mL x 3) and dried over anhydrous  $\text{MgSO}_4$ . After the concentration of this organic layer under reduced pressure, the residue was purified by column chromatography on silica gel (hexane/EtOAc = 2 : 1) to give (*R*\*)-3-methyl-5-[(*S*\*)-3-oxo-1-phenylbutyl]furan-2(5*H*)-one **anti**-3fb in 52% yield (35.0 mg, 0.15 mmol) without the formation of *syn*-3fb.

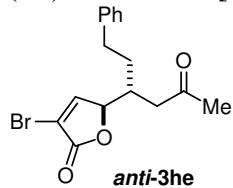
**(R\*)-3-Bromo-5-[(R\*)-4-oxopentan-2-yl]furan-2(5H)-one (*anti*-3ge) and**

**(S\*)-3-bromo-5-[(R\*)-4-oxopentan-2-yl]furan-2(5H)-one (*syn*-3ge)**



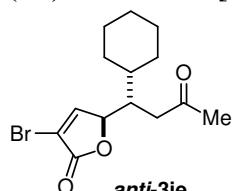
According to the synthetic procedure for **3fa**, an inseparable mixture of **anti**-3ge and **syn**-3ge was obtained in 76% yield (94 mg, 0.38 mmol, *anti/syn* = 12 : 1) by the reaction of  $\alpha,\beta$ -enone **2g** (42 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (1.4 mg, 2.5  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. Colorless oil; IR (neat)  $\nu$  3088, 2970, 1770, 1713, 1607, 1369, 1160, 981  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  for **anti**-3ge 1.04 (3H, m), 2.09 (3H, m), 2.33 (1H, ddd,  $J$  = 16.7, 6.7, 2.6 Hz), 2.38-2.58 (2H, m), 4.89 (1H, dt,  $J$  = 5.4, 2.0 Hz), 7.49 (1H, brd,  $J$  = 2.0 Hz), for **syn**-3ge 0.80 (3H, dd,  $J$  = 6.9, 3.5 Hz), 2.13 (3H, d,  $J$  = 3.9 Hz), 2.38-2.58 (2H, m), 2.59 (1H, ddd,  $J$  = 17.7, 6.9, 4.6 Hz), 5.12-5.30 (1H, m), 7.47 (1H, d,  $J$  = 1.6 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  for **anti**-3ge 16.4, 29.6, 32.1, 44.5, 85.7, 113.2, 151.9, 168.0, 206.4, for **syn**-3ge 13.4, 30.4, 31.1, 45.9, 84.7, 113.2, 151.9, 168.3, 206.7; MS (ESI-TOF)  $m/z$  269 [ $\text{M}+\text{Na}$ ] $^+$ , 271 [ $\text{M}+2+\text{Na}$ ] $^+$ ; HRMS calcd for  $\text{C}_9\text{H}_{11}\text{BrNaO}_3$  [ $\text{M}+\text{Na}$ ] $^+$ , 268.9789; found, 268.9792; Anal. Calcd for  $\text{C}_9\text{H}_{11}\text{BrO}_3$ : C, 43.75; H, 4.49. Found: C, 43.62; H, 4.59.

**(R\*)-3-Bromo-5-[(R\*)-5-oxo-1-phenylhexan-3-yl]furan-2(5H)-one (*anti*-3he)**



According to the synthetic procedure for **3fa**, 1,4-adduct **anti**-3he was obtained in 91% yield (153 mg, 0.45 mmol) by the reaction of  $\alpha,\beta$ -enone **2c** (87 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (1.4 mg, 2.5  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. Colorless oil; IR (neat)  $\nu$  3086, 3026, 1772, 1713, 1604, 1496, 1454, 1155, 984, 752, 704  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.61-1.72 (1H, m), 1.72-1.86 (1H, m), 2.01 (3H, s), 2.22-2.36 (2H, m), 2.41-2.51 (1H, m), 2.54-2.68 (2H, m), 5.01 (1H, dd,  $J$  = 3.8, 1.7 Hz), 7.06-7.16 (3H, m), 7.17-7.25 (2H, m), 7.33 (1H, d,  $J$  = 1.7 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  30.4, 33.0, 33.3, 35.9, 41.6, 84.0, 112.8, 126.2, 128.2, 128.6, 140.8, 152.5, 168.2, 206.7; MS (ESI-TOF)  $m/z$  337 [ $\text{M}+\text{H}$ ] $^+$ , 339 [ $\text{M}+2+\text{H}$ ] $^+$ ; HRMS calcd for  $\text{C}_{16}\text{H}_{18}\text{BrO}_3$  [ $\text{M}+\text{H}$ ] $^+$ , 337.0439; found, 337.0449; Anal. Calcd for  $\text{C}_{16}\text{H}_{17}\text{BrO}_3$ : C, 56.99; H, 5.08. Found: C, 56.89; H, 5.06.

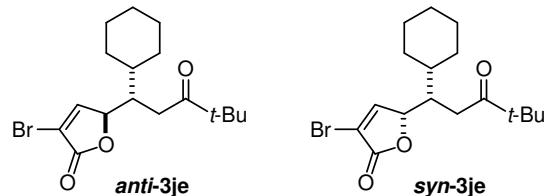
**(R\*)-3-Bromo-5-[(S\*)-1-cyclohexyl-3-oxobutyl]furan-2(5H)-one (*anti*-3ie)**



According to the synthetic procedure for **3fa**, 1,4-adduct **anti**-3ie was obtained in 93% yield (146 mg, 0.47 mmol) by the reaction of  $\alpha,\beta$ -enone **2i** (76 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60

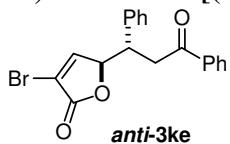
mmol) in the presence of carbon acid **1** (0.71 mg, 1.3  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78$   $^{\circ}\text{C}$  for 2 h. The stereochemistry of *anti*-**3ie** was determined by an X-ray crystallographic analysis. Colorless crystals; Mp. 105.0-105.3  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3102, 2930, 2847, 1758, 1716, 1607, 992  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.91-1.27 (5H, m), 1.36-1.48 (1H, m), 1.58-1.82 (5H, m), 2.06 (3H, s), 2.17 (1H, dd,  $J$  = 18.1, 7.0 Hz), 2.33, (1H, dd,  $J$  = 18.1, 4.1 Hz), 2.34-2.41 (1H, m), 5.16 (1H, brs), 7.37 (1H, d,  $J$  = 1.5 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  26.1, 26.3, 30.3, 30.6, 30.8, 39.1, 40.0, 40.8, 83.1, 112.1, 153.8, 168.4, 207.1; MS (ESI-TOF)  $m/z$  337 [M+Na] $^+$ , 339 [M+2+Na] $^+$ ; HRMS calcd for  $\text{C}_{14}\text{H}_{19}\text{BrNaO}_3$  [M+Na] $^+$ , 337.0415; found, 337.0405; Anal. Calcd for  $\text{C}_{14}\text{H}_{19}\text{BrO}_3$ ; C, 53.35; H, 6.08. Found: C, 53.20; H, 6.19.

**(R\*)-3-Bromo-5-[(S\*)-1-cyclohexyl-4,4-dimethyl-3-oxopentyl]furan-2(5H)-one (*anti*-**3je**) and (S\*)-3-bromo- 5-[(S\*)-1-cyclohexyl-4,4-dimethyl-3-oxopentyl]furan-2(5H)-one (*syn*-**3je**)**



According to the synthetic procedure for **3fa**, 1,4-adduct **3je** was obtained in 66% yield (*anti*-**3je**, 106 mg, 0.30 mmol; *syn*-**3je**, 12 mg, 0.04 mmol) by the reaction of  $\alpha,\beta$ -enone **2j** (97 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (2.8 mg, 5.0  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-24$   $^{\circ}\text{C}$  for 2 h. The stereochemistry of **3je** was determined by an X-ray crystallographic analysis of *anti*-**3je**. For *anti*-**3je** Colorless crystals; Mp. 108.8-109.3  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3113, 2928, 1764, 1700, 1609, 988  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.50-1.29 (5H, m), 1.07 (9H, s), 1.36-1.48 (1H, m), 1.60-1.85 (5H, m), 2.33 (2H, d,  $J$  = 5.6 Hz), 2.42-2.49 (1H, m), 5.19 (1H, t,  $J$  = 1.6 Hz), 7.37 (1H, d,  $J$  = 1.6 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  26.2, 26.4, 26.5, 26.6, 30.6, 31.1, 32.3, 40.1, 40.6, 44.3, 83.2, 111.7, 154.2, 168.7, 214.6; MS (ESI-TOF)  $m/z$  357 [M+H] $^+$ , 359 [M+2+H] $^+$ ; HRMS calcd for  $\text{C}_{17}\text{H}_{26}\text{BrO}_3$  [M+H] $^+$ , 357.1065; found, 357.1059; Anal. Calcd for  $\text{C}_{17}\text{H}_{25}\text{BrO}_3$ ; C, 57.15; H, 7.05. Found: C, 57.11; H, 7.00. For *syn*-**3je** Colorless crystals; Mp. 64.5-65.0  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3120, 2923, 2852, 1766, 1697, 1612, 1000  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.94-1.32 (5H, m), 1.16 (9H, s), 1.38-1.48 (1H, m), 1.51-1.78 (5H, m), 2.37-2.44 (1H, m), 2.52 (1H, dd,  $J$  = 18.4, 4.4 Hz), 2.65 (1H, dd,  $J$  = 18.4, 7.8 Hz), 5.08 (1H, dd,  $J$  = 5.0, 1.7 Hz), 7.49 (1H, d,  $J$  = 1.7 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  26.3, 26.5, 26.58, 26.63, 30.1, 31.8, 33.5, 38.3, 41.3, 44.6, 84.4, 112.9, 152.6, 168.4, 214.5; MS (ESI-TOF)  $m/z$  357 [M+H] $^+$ , 359 [M+2+H] $^+$ ; HRMS calcd for  $\text{C}_{17}\text{H}_{26}\text{BrO}_3$  [M+H] $^+$ , 357.1065; found, 357.1073.

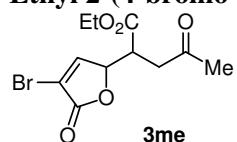
**(R\*)-3-Bromo-5-[(S\*)-3-oxo-1,3-diphenylpropyl]furan-2(5H)-one (*anti*-**3ke**)**



According to the procedure of **3fa**, the reaction of  $\alpha,\beta$ -enone **2k** (97 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (2.8 mg, 5.0  $\mu$ mol) was conducted at  $-78$   $^{\circ}\text{C}$

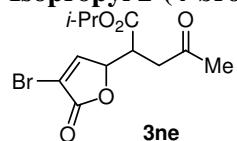
for 2 h. After extractive work up, the resultant mixture was treated with triflic acid in  $\text{CH}_2\text{Cl}_2$  at  $-78^\circ\text{C}$  for 1 h. Then, this reaction mixture was quenched with  $\text{H}_2\text{O}$  (50 mL), extracted with  $\text{CH}_2\text{Cl}_2$  (40 mL), dried over  $\text{MgSO}_4$  and concentrated. The resulting residue was purified by column chromatography on silica gel (hexane/EtOAc = 4 : 1) to give 1,4-adduct **anti-3ke** in 95% yield (176 mg, 0.48 mmol, *anti/syn* = >30 : 1). Colorless crystals; Mp. 34.0-34.6  $^\circ\text{C}$ ; IR (KBr)  $\nu$  3087, 2914, 1774, 1685, 1598, 1496, 1449, 993, 752, 727, 700  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  3.42 (1H, dd,  $J$  = 17.6, 8.0 Hz), 3.50 (1H, dd,  $J$  = 17.6, 5.2 Hz), 3.66 (1H, td,  $J$  = 7.8, 5.2 Hz), 5.15 (1H, dd,  $J$  = 7.8, 1.6 Hz), 7.18-7.31 (6H, m), 7.32-7.40 (2H, m), 7.47 (1H, t,  $J$  = 7.4 Hz), 7.82 (2H, d,  $J$  = 7.4 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  39.9, 44.4, 85.0, 113.5, 127.8, 127.9, 128.1, 128.6, 129.0, 133.3, 136.5, 138.8, 152.0, 167.9, 197.0; MS (ESI-TOF)  $m/z$  371 [ $\text{M}+\text{H}]^+$ , 373 [ $\text{M}+2+\text{H}]^+$ ; HRMS calcd for  $\text{C}_{19}\text{H}_{16}\text{BrO}_3$  [ $\text{M}+\text{H}]^+$ , 371.0283; found, 371.0277; Anal. Calcd for  $\text{C}_{19}\text{H}_{15}\text{BrO}_3$ : C, 61.47; H, 4.07. Found: C, 61.50; H, 4.20.

#### Ethyl 2-(4-bromo-5-oxo-2,5-dihydrofuran-2-yl)-4-oxopentanoate (3me)



According to the synthetic procedure for **3fa**, 1,4-adduct **3me** was obtained in 96% yield (**3me-major**, 124 mg, 0.41 mmol; **3me-minor**, 22 mg, 0.07 mmol) by the reaction of  $\alpha,\beta$ -enone **2m** (71 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (1.4 mg, 2.5  $\mu\text{mol}$ ) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. For **3me-major** Colorless oil; IR (neat)  $\nu$  3093, 2983, 1779, 1721, 1608, 1370, 1188, 1163, 984  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.26 (3H, t,  $J$  = 7.1 Hz), 2.14 (3H, s), 2.60 (1H, dd,  $J$  = 18.3, 4.9 Hz), 3.02 (1H, dd,  $J$  = 18.3, 6.8 Hz), 3.14-3.21 (1H, m), 4.19 (2H, q,  $J$  = 7.1 Hz), 5.39 (1H, dd,  $J$  = 6.2, 1.8 Hz), 7.61 (1H, d,  $J$  = 1.8 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  14.0, 29.9, 39.1, 43.0, 61.8, 81.1, 113.8, 151.6, 167.4, 169.4, 205.3; MS (ESI-TOF)  $m/z$  327 [ $\text{M}+\text{Na}]^+$ , 329 [ $\text{M}+2+\text{Na}]^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{13}\text{BrNaO}_5$  [ $\text{M}+\text{Na}]^+$ , 326.9844; found, 326.9849; Anal. Calcd for  $\text{C}_{11}\text{H}_{13}\text{BrO}_5$ : C, 43.30; H, 4.29. Found: C, 43.22; H, 4.35. For **3me-minor** Colorless oil; IR (neat)  $\nu$  3094, 2983, 1776, 1720, 1608, 1371, 1162, 1026, 985  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.24 (3H, t,  $J$  = 7.1 Hz), 2.18 (3H, s), 2.68 (1H, dd,  $J$  = 18.3, 5.3 Hz), 2.89 (1H, dd,  $J$  = 18.3, 7.6 Hz), 3.43-3.55 (1H, m), 4.06-4.24 (2H, m), 5.28 (1H, dd,  $J$  = 4.2, 1.7 Hz), 7.54 (1H, d,  $J$  = 1.7 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  14.1, 29.9, 39.5, 42.6, 61.7, 80.8, 113.4, 151.1, 167.5, 169.6, 205.2; MS (ESI-TOF)  $m/z$  305 [ $\text{M}+\text{H}]^+$ , 307 [ $\text{M}+2+\text{H}]^+$ ; HRMS calcd for  $\text{C}_{11}\text{H}_{13}\text{BrO}_5$  [ $\text{M}+\text{H}]^+$ , 305.0025; found, 305.0021.

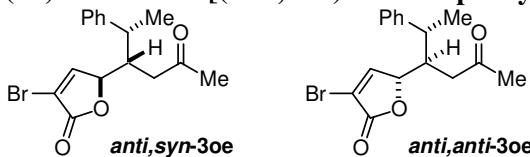
#### Isopropyl 2-(4-bromo-5-oxo-2,5-dihydrofuran-2-yl)-4-oxopentanoate (3ne)



According to the synthetic procedure for **3fa**, 1,4-adduct **3ne** was obtained in 80% yield (**3ne-major**, 111 mg, 0.35 mmol; **3ne-minor**, 17 mg, 0.05 mmol) by the reaction of  $\alpha,\beta$ -enone **2n** (78 mg, 0.50 mmol) with (3-bromofuran-2-yloxy)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (2.8 mg, 5.0  $\mu\text{mol}$ ) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. For **3ne-major** Colorless oil; IR (neat)  $\nu$  3092, 2982, 1780, 1721, 1608, 1374, 1107, 984  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.248 (3H, d,  $J$  = 6.3 Hz), 1.252 (3H, d,  $J$  = 6.3 Hz), 2.18

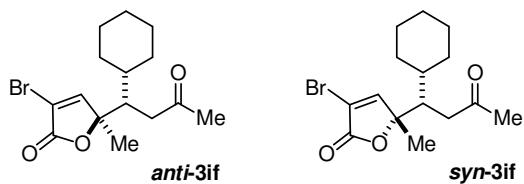
(3H, s), 2.60 (1H, dd,  $J$  = 18.2, 4.9 Hz), 3.03 (1H, dd,  $J$  = 18.2, 6.9 Hz), 3.05-3.14 (1H, m), 5.06 (1H, septet,  $J$  = 6.3 Hz), 5.38 (1H, dd,  $J$  = 6.2, 1.7 Hz), 7.61 (1H, d,  $J$  = 1.7 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  21.5, 29.9, 39.1, 43.1, 69.5, 81.3, 113.6, 151.7, 167.5, 169.4, 205.3; MS (ESI-TOF)  $m/z$  341 [M+Na] $^+$ , 343 [M+2+Na] $^+$ ; HRMS calcd for  $\text{C}_{12}\text{H}_{15}\text{BrNaO}_5$  [M+Na] $^+$ , 341.0001; found, 340.9983; Anal. Calcd for  $\text{C}_{12}\text{H}_{15}\text{BrO}_5$ : C, 45.16; H, 4.74. Found: C, 45.45; H, 4.97. For **3ne-minor** Colorless oil; IR (neat)  $\nu$  3095, 2982, 1779, 1721, 1609, 1375, 1166, 1107, 984  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.21 (3H, d,  $J$  = 6.3 Hz), 1.22 (3H, d,  $J$  = 6.3 Hz), 2.18 (3H, s), 2.68 (1H, dd,  $J$  = 18.3, 5.5 Hz), 2.91 (1H, dd,  $J$  = 18.3, 7.6 Hz), 3.40-3.45 (1H, m), 5.00 (1H, septet,  $J$  = 6.3 Hz), 5.26 (1H, dd,  $J$  = 4.0, 1.7 Hz), 7.54 (1H, d,  $J$  = 1.7 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  21.66 and 21.73, 30.0, 39.8, 42.9, 69.5, 81.0, 113.4, 151.3, 167.6, 169.0, 205.3; MS (ESI-TOF)  $m/z$  341 [M+Na] $^+$ , 343 [M+2+Na] $^+$ ; HRMS calcd for  $\text{C}_{12}\text{H}_{15}\text{BrNaO}_5$  [M+Na] $^+$ , 341.0001; found, 340.9997.

**(R\*)-3-Bromo-5-[(2R\*,3S\*)-5-oxo-2-phenylhexan-3-yl]furan-2(5H)-one (*anti,syn*-3oe) and (S\*)-3-bromo-5-[(2R\*,3R\*)-5-oxo-2-phenylhexan-3-yl]furan-2(5H)-one (*anti,anti*-3oe)**



According to the synthetic procedure for **3fa**, 1,4-adduct **3oe** was obtained in 91% yield (**anti,syn**-3oe 109 mg, 0.33 mmol; **anti,anti**-3oe 44 mg, 0.13 mmol) by the reaction of **2o** (87 mg, 0.50 mmol) with (3-bromofuran-2-yl)triethylsilane (166 mg, 0.60 mmol) in the presence of carbon acid **1** (0.71 mg, 1.3  $\mu\text{mol}$ ) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78$   $^{\circ}\text{C}$  for 2 h. The stereochemistry of **3oe** was determined by an X-ray crystallographic analysis of **anti,anti**-3oe. For **anti,syn**-3oe Colorless crystals; Mp. 86.8-87.1  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3102, 3032, 1758, 1713, 1606, 1454, 1424, 1168, 1032, 982, 768, 701  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.25 (3H, d,  $J$  = 6.9 Hz), 2.13 (3H, s), 2.25 (1H, dd,  $J$  = 18.8, 7.0 Hz), 2.50 (1H, dd,  $J$  = 18.8, 3.7 Hz), 2.72-2.80 (1H, m), 2.82 (1H, d of quintet,  $J$  = 10.7, 6.9 Hz), 4.71 (1H, t,  $J$  = 1.7 Hz), 7.18 (1H, d,  $J$  = 1.7 Hz), 7.21-7.36 (5H, m);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  20.0, 30.4, 39.2, 41.5, 42.3, 83.2, 111.9, 127.0, 127.6, 128.9, 144.3, 153.7, 168.4, 207.0; MS (ESI-TOF)  $m/z$  359 [M+Na] $^+$ , 361 [M+2+Na] $^+$ ; HRMS calcd for  $\text{C}_{16}\text{H}_{17}\text{BrNaO}_3$  [M+Na] $^+$ , 359.0259; found, 359.0253; Anal. Calcd for  $\text{C}_{16}\text{H}_{17}\text{BrO}_3$ : C, 56.99; H, 5.08. Found: C, 56.97; H, 5.14. For **anti,anti**-3oe Colorless crystals; Mp. 69.8-70.0  $^{\circ}\text{C}$ ; IR (KBr)  $\nu$  3111, 3027, 2966, 1771, 1710, 1605, 1492, 1454, 1164, 1056, 982, 765, 703  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  1.41 (3H, d,  $J$  = 6.9 Hz), 1.85 (3H, s), 2.12 (2H, d,  $J$  = 5.7 Hz), 2.80-2.88 (1H, m), 2.88-2.98 (1H, m), 5.30 (1H, brs), 7.17 (2H, d,  $J$  = 7.3 Hz), 7.30 (1H, t,  $J$  = 7.3 Hz), 7.37 (1H, d,  $J$  = 1.6 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  19.5, 30.3, 39.9, 41.3, 41.7, 82.1, 112.2, 126.9, 127.6, 128.9, 144.5, 153.7, 168.5, 207.2; MS (ESI-TOF)  $m/z$  359 [M+Na] $^+$ , 361 [M+2+Na] $^+$ ; HRMS calcd for  $\text{C}_{16}\text{H}_{17}\text{BrNaO}_3$  [M+Na] $^+$ , 359.0259; found, 359.0243.

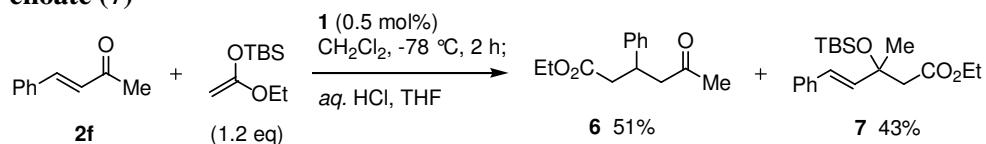
**(R\*)-3-Bromo-5-[(S\*)-1-cyclohexyl-3-oxobutyl]-5-methylfuran-2(5H)-one (*anti*-3if) and (S\*)-3-bromo-5- [(S\*)-1-cyclohexyl-3-oxobutyl]-5-methylfuran-2(5H)-one (*syn*-3if)**



According to the synthetic procedure for **3fa**, 1,4-adduct **3if** was obtained in 97% yield (**anti-3if**, 139 mg, 0.43 mmol; **syn-3if**, 21 mg, 0.06 mmol) by the reaction of  $\alpha,\beta$ -enone **2i** (76 mg, 0.50 mmol) with (3-bromo-5-methylfuran-2-yloxy)triethylsilane (175 mg, 0.60 mmol) in the presence of carbon acid **1** (0.71 mg, 1.3  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. The stereochemistry of **3if** was determined by an X-ray crystallographic analysis of **anti-3if**. For **anti-3if** Colorless crystals; Mp. 79.0-79.6  $^\circ\text{C}$ ; IR (KBr)  $\nu$  3103, 2997, 2920, 2852, 1775, 1703, 1612, 992  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.83 (1H, qd,  $J$  = 13.1, 3.4 Hz), 0.95-1.08 (1H, m), 1.17 (1H, qt,  $J$  = 12.9, 3.4 Hz), 1.27 (1H, qt,  $J$  = 12.9, 3.4 Hz), 1.43 (1H, d,  $J$  = 12.8 Hz), 1.48 (3H, s), 1.58-1.80 (3H, m), 1.61 (1H, d,  $J$  = 12.8 Hz), 1.85 (1H, d,  $J$  = 13.1 Hz), 2.05 (3H, s), 2.14 (1H, dd,  $J$  = 18.7, 8.2 Hz), 2.30 (1H, dd,  $J$  = 18.7, 3.0 Hz), 2.36 (1H, dt,  $J$  = 8.2, 3.0 Hz), 7.27 (1H, brs);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  22.2, 26.1, 26.2, 26.7, 28.2, 30.3, 32.7, 37.4, 38.6, 43.9, 90.9, 110.8, 158.8, 168.0, 207.4; MS (ESI-TOF)  $m/z$  329 [ $\text{M}+\text{H}]^+$ , 331 [ $\text{M}+2+\text{H}]^+$ ; HRMS calcd for  $\text{C}_{15}\text{H}_{22}\text{BrO}_3$  [ $\text{M}+\text{H}]^+$ , 329.0752; found, 329.0772; Anal. Calcd for  $\text{C}_{15}\text{H}_{21}\text{BrO}_3$ : C, 54.72; H, 6.43. Found: C, 54.73; H, 6.40. For **syn-3if** Colorless crystals; Mp. 78.8-79.3  $^\circ\text{C}$ ; IR (KBr)  $\nu$  3087, 2928, 2852, 1766, 1716, 1607, 988  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.84-1.31 (5H, m), 1.35-1.47 (2H, m), 1.41 (3H, s), 1.47-1.59 (1H, m), 1.69 (1H, brd,  $J$  = 12.6 Hz), 1.67-1.76 (2H, m), 2.19 (3H, s), 2.41 (1H, dd,  $J$  = 18.3, 4.9 Hz), 2.47 (1H, dd,  $J$  = 18.3, 6.0 Hz), 2.53-2.59 (1H, m), 7.39 (1H, brs);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  24.5, 26.1, 26.4, 26.8, 28.8, 30.1, 32.9, 39.2, 39.8, 45.2, 91.7, 112.0, 156.5, 167.6, 206.7; MS (ESI-TOF)  $m/z$  329 [ $\text{M}+\text{H}]^+$ , 331 [ $\text{M}+2+\text{H}]^+$ ; HRMS calcd for  $\text{C}_{15}\text{H}_{22}\text{BrO}_3$  [ $\text{M}+\text{H}]^+$ , 329.0752; found, 329.0768; Anal. Calcd for  $\text{C}_{15}\text{H}_{21}\text{BrO}_3$ : C, 54.72; H, 6.43. Found: C, 54.54; H, 6.36.

### 3.3. Reaction of benzalacetone (**2f**) with acyclic ketene silyl acetal

**Ethyl 5-oxo-3-phenylhexanoate (6) and ethyl (E)-3-(*tert*-butyldimethylsilyloxy)-3-methyl-5-phenylpent-4-enoate (7)**

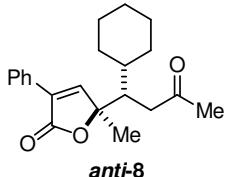


According to the synthetic procedure for **3fa**, 1,4-adduct **6** and 1,2-adduct **7** were obtained in 51% yield (60 mg, 0.26 mmol) and 43% yield (75 mg, 0.22 mmol), respectively, by the reaction of **2f** (73 mg, 0.50 mmol) with *tert*-butyl(1-ethoxyvinyloxy)dimethylsilane (151 mg, 0.75 mmol) in the presence of carbon acid **1** (0.71 mg, 1.3  $\mu$ mol) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at  $-78^\circ\text{C}$  for 2 h. The structure of 1,4-adduct **6** was confirmed by comparison to the reported spectrum data.<sup>17</sup> For 1,2-adduct **7** Colorless oil; IR (neat)  $\nu$  3026, 2956, 2930, 2895, 2856, 1736, 1495, 1472, 971, 775, 693  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  0.09 (3H, s), 0.10, (3H, s), 0.91 (9H, s), 1.23 (3H, t,  $J$  = 7.1 Hz), 1.60 (3H, s), 2.60 (1H, d,  $J$  = 13.4 Hz), 2.64 (1H, d,  $J$  = 13.4 Hz), 4.10 (2H, q,  $J$  = 7.1 Hz), 6.42 (1H, d,  $J$  = 16.1 Hz), 6.55 (1H, d,  $J$  = 16.1 Hz), 7.21 (1H, t,  $J$  = 7.3 Hz), 7.32 (2H, t,  $J$  = 7.3 Hz), 7.39 (2H, d,  $J$  = 7.3 Hz);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  -2.2 and -2.1, 14.2, 18.2, 25.8, 27.4, 49.4, 60.2, 74.0, 126.5, 127.45, 127.47, 128.6, 136.1, 137.0, 170.5; MS (ESI-TOF)  $m/z$  371 [ $\text{M}+\text{Na}]^+$ ; HRMS calcd for  $\text{C}_{20}\text{H}_{32}\text{BrNaO}_3\text{Si}$  [ $\text{M}+\text{Na}]^+$ ,

371.2018; found, 371.2009; Anal. Calcd for  $C_{20}H_{32}O_3Si$ : C, 68.92; H, 9.25. Found: C, 68.64; H, 9.26.

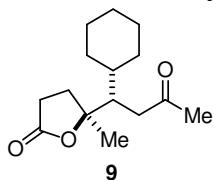
#### 4. Some transformations of $\alpha$ -bromo- $\gamma$ -butenolides

##### (*R*<sup>\*</sup>)-5-[(*S*<sup>\*</sup>)-1-Cyclohexyl-3-oxobutyl]-5-methyl-3-phenylfuran-2(5*H*)-one (*anti*-8)



To a solution of *anti*-3if (33 mg, 0.10 mmol) and  $(Ph_3P)_4Pd$  (6 mg, 3.5  $\mu$ mol) in a mixed solvent of 1,2-dimethoxyethane-EtOH (5 : 1, 0.6 mL), phenylboronic acid (12 mg, 0.10 mmol) and 2.0 M aqueous solution of  $Na_2CO_3$  (0.4 mL, 0.80 mmol) were added at room temperature. After being refluxed for 1 h, the reaction mixture was quenched with  $H_2O$  (10 mL) and extracted with EtOAc (10 mL x 3). The combined organic layer was washed with brine (10 mL), dried over anhydrous  $MgSO_4$  and evaporated. The obtained residue was purified by column chromatography on silica gel (hexane/EtOAc = 5 : 1) to give coupling product *anti*-8 in 95% yield (31 mg, 0.10 mmol). Colorless crystals; Mp. 129.5-131.1 °C; IR (KBr)  $\nu$  3109, 3073, 2993, 2925, 2854, 1746, 1708, 1495, 1451, 1415, 795, 693  $cm^{-1}$ ; <sup>1</sup>H NMR (400 MHz,  $CDCl_3$ )  $\delta$  0.90 (1H, qd,  $J$  = 12.6, 3.4 Hz), 1.01-1.16 (1H, m), 1.24 (1H, qt,  $J$  = 13.0, 3.5 Hz), 1.34 (1H, qt,  $J$  = 13.0, 3.5 Hz), 1.51 (1H, brd,  $J$  = 12.6 Hz), 1.56 (3H, s), 1.67 (1H, brd,  $J$  = 12.6 Hz), 1.76 (2H, brd,  $J$  = 12.6 Hz), 1.81-1.93 (1H, m), 1.95 (3H, s), 2.02 (1H, d,  $J$  = 13.5 Hz), 2.25 (1H, dd,  $J$  = 18.7, 8.0 Hz), 2.33 (1H, dd,  $J$  = 18.7, 3.3 Hz), 2.47 (1H, dt,  $J$  = 8.0, 3.3 Hz), 7.32-7.42 (4H, m), 7.75 (1H, d,  $J$  = 1.5 Hz), 7.77 (1H, d,  $J$  = 1.9 Hz); <sup>13</sup>C NMR (100 MHz,  $CDCl_3$ )  $\delta$  22.6, 26.3, 26.4, 26.9, 28.3, 30.5, 32.9, 37.6, 38.8, 44.1, 87.8, 126.9, 128.7, 129.1, 129.2, 154.5, 171.5, 208.0; MS (ESI-TOF)  $m/z$  327 [M+H]<sup>+</sup>; HRMS calcd for  $C_{21}H_{26}O_3$  [M+H]<sup>+</sup>, 327.1936; found, 327.1945; Anal. Calcd for  $C_{21}H_{26}O_3$ : C, 77.27; H, 8.03. Found: C, 77.10; H, 7.94.

##### (*S*<sup>\*</sup>)-5-[(*S*<sup>\*</sup>)-1-Cyclohexyl-3-oxobutyl]-5-methylfuran-2(3*H*)-one (9)



In the presence of 10% palladium on carbon (10 mg, 0.01 mmol), a solution of *anti*-3if (33 mg, 0.10 mmol) in EtOH (2.5 mL) was stirred at room temperature for 3 h under  $H_2$  atmosphere. The resultant mixture was filtrated through celite pad. The filtrate was evaporated and purified by column chromatography on silica gel (hexane/EtOAc = 1 : 1) to give  $\gamma$ -butanolide 9 in 99% yield (25.0 mg, 0.099 mmol). Colorless crystals; Mp. 70.5-71.5 °C; IR (KBr)  $\nu$  2963, 2922, 2853, 1758, 1712  $cm^{-1}$ ; <sup>1</sup>H NMR (400 MHz,  $CDCl_3$ )  $\delta$  0.82-1.02 (1H, m), 1.01-1.33 (4H, m), 1.35 (3H, s), 1.36-1.49 (1H, m), 1.50-1.60 (1H, m), 1.61-1.79 (4H, m), 1.94-2.15 (2H, m), 2.19 (3H, s), 2.28-2.36 (1H, m), 2.42-2.65 (4H, m); <sup>13</sup>C NMR (100 MHz,  $CDCl_3$ )  $\delta$  23.1, 26.2, 26.5, 27.0, 28.5, 29.2, 30.2, 33.4, 33.8, 38.3, 40.4, 46.8, 89.1, 176.2, 207.7; MS (ESI-TOF)  $m/z$  253 [M+H]<sup>+</sup>; HRMS calcd for  $C_{15}H_{25}O_3$  [M+H]<sup>+</sup>, 253.1804; found, 253.1800.

## 5. Gas-phase acidity measurement

The gas-phase acidity measurements were performed on an Extrel FTMS 2001 Fourier transform mass spectrometer. Most of the experimental techniques used for the measurements of the equilibrium constants of the reversible proton-transfer reactions are the same as the procedures reported previously.<sup>18</sup> Methyl nitrite as a chemical ionization reagent was not necessary for such strong acids. Electron impact of ionization produced the corresponding anions. The following schemes describe the sequence of reactions which occur in a typical experiment where AH and A<sub>o</sub>H are the measured acid and the reference acid, respectively.



An experiment is initiated by a 5 ms pulse of a low-energy electron beam (0.3~0.5 eV) through the ICR cell. The partial pressures of the acids were maintained at lower than  $4 \times 10^{-7}$  Torr. The proton-transfer equilibrium (eq. 3) was achieved within 20~100 s of initiation of the reaction (depending on the pressure of neutrals). The equilibrium constant and free energy change for the reaction were evaluated by using the expression (eq. 4).

$$K = \frac{I(A^-) p(A_oH)}{I(A_o^-) p(AH)} \quad (4)$$
$$\Delta G_A = -RT \ln K$$

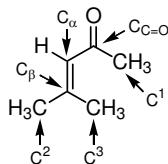
The relative abundances of ions A<sup>-</sup> and A<sub>o</sub><sup>-</sup> were determined by the relative intensities of ICR mass spectra signals when the equilibrium attained. The pressures of the neutral reactants were measured by means of a Bayard-Alpert type ionization gauge applying appropriate correction factors to correct the gauge reading for the different ionization cross sections of various compounds.<sup>19</sup> The blank pressure was kept at less than 10<sup>-9</sup> Torr. Each experiment was performed at several ratios of the partial pressures and at different overall pressures. The proton-transfer reactions were examined by ion-eject experiments. Equilibrium constants measured in this way can be used to calculate  $\Delta G_{acid}$  at 300 K (eq. 4). The average uncertainty is  $\pm 0.2$  kcal/mol. The gas-phase acidity values for the reference compounds were taken from the literature.<sup>20,21</sup> Gas-phase acidity value (295.7 kcal/mol) of Tf<sub>2</sub>CHCH<sub>2</sub>CHTf<sub>2</sub> was determined based on following free energy changes; 3 kcal/mol stronger than (F<sub>3</sub>C)<sub>5</sub>C<sub>6</sub>OH (299.0),<sup>20</sup> 2.0 stronger than *m*-FC<sub>6</sub>H<sub>4</sub>CHTf<sub>2</sub> (298.1),<sup>21</sup> 0.6 stronger than *m*-CF<sub>3</sub>C<sub>6</sub>H<sub>4</sub>CHTf<sub>2</sub> (296.4),<sup>21</sup> 0.2 stronger than *p*-CF<sub>3</sub>C<sub>6</sub>H<sub>4</sub>CHTf<sub>2</sub> (295.9),<sup>21</sup> 0.8 weaker than 3,5-(CF<sub>3</sub>)<sub>2</sub>C<sub>6</sub>H<sub>3</sub>CHTf<sub>2</sub> (294.9),<sup>21</sup> where values in the parentheses are gas-phase acidities of the indicated reference acids.

## 6. NMR studies for mixtures of **2a** and Brønsted acids

<sup>1</sup>H and <sup>13</sup>C NMR spectra of mixtures of **2a** (0.375 mmol) and Brønsted acid (0.375 mmol) in CDCl<sub>3</sub> (0.75 mL) were taken on a 400 MHz spectrometer at room temperature, and chemical shifts were reported in parts per million (ppm) using CHCl<sub>3</sub> (7.26 ppm) in CDCl<sub>3</sub> for <sup>1</sup>H NMR, and CDCl<sub>3</sub> (77.01 ppm) for <sup>13</sup>C NMR as an internal

standard, respectively. Results are summarized in Tables S1 and S2.

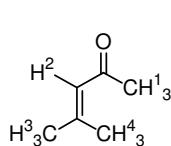
**Table S1.** Chemical shifts of **2a** in the presence of Brønsted acids in  $^{13}\text{C}$  NMR (100 MHz)



Brønsted acid	Chemical shifts (ppm)											
	$\text{C}_{\text{C=O}}$	$\Delta\text{C}_{\text{C=O}}$	$\text{C}_\alpha$	$\Delta\text{C}_\alpha$	$\text{C}_\beta$	$\Delta\text{C}_\beta$	$\text{C}^1$	$\Delta\text{C}^1$	$\text{C}^2$	$\Delta\text{C}^2$	$\text{C}^3$	$\Delta\text{C}^3$
none	198.7	-	124.3	-	155.0	-	31.7	-	27.6	-	20.6	-
TfOH	210.6	+11.9	122.8	-1.5	186.8	+31.8	31.0	-0.7	28.3	+0.7	25.3	+4.7
Tf <sub>2</sub> CHCH <sub>2</sub> CHTf <sub>2</sub>	199.3	+0.6	124.2	-0.1	155.5	+0.5	31.5	-0.2	27.5	-0.1	20.5	-0.1
Tf <sub>2</sub> CH <sub>2</sub>	199.0	+0.3	124.2	-0.1	155.5	+0.5	31.5	-0.2	27.5	-0.1	20.5	-0.1

Conditions: **2a** (0.375 mmol) and Brønsted acids (0.375 mmol) in  $\text{CDCl}_3$  (0.75 mL) at room temperature.

**Table S2.** Chemical shifts of **2a** in the presence of Brønsted acids in  $^1\text{H}$  NMR (400 MHz)

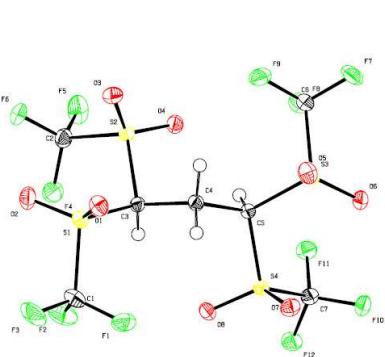


Brønsted acid	Chemical shifts (ppm)							
	$\text{H}^1$	$\Delta\text{H}^1$	$\text{H}^2$	$\Delta\text{H}^2$	$\text{H}^3$	$\Delta\text{H}^3$	$\text{H}^4$	$\Delta\text{H}^4$
none	2.15	-	6.08	-	2.13	-	1.87	-
TfOH	2.69	+0.54	6.56	+0.48	2.45	+0.32	2.29	+0.42
Tf <sub>2</sub> CH <sub>2</sub>	2.12	-0.03	6.06	-0.02	2.09	-0.04	1.85	-0.02
Tf <sub>2</sub> CHCH <sub>2</sub> CHTf <sub>2</sub>	2.12	-0.03	6.06	-0.02	2.08	-0.05	1.85	-0.02

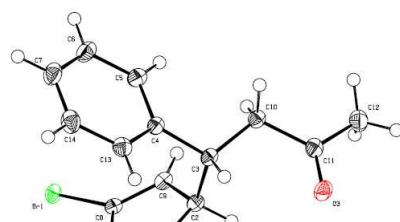
Conditions: **2a** (0.375 mmol) and Brønsted acids (0.375 mmol) in  $\text{CDCl}_3$  (0.75 mL) at room temperature.

## 7. X-ray crystallographic data of **1**, **anti-3fe**, **anti-3ie**, **anti-3je**, **anti,anti-3oe**, and **anti-3if**

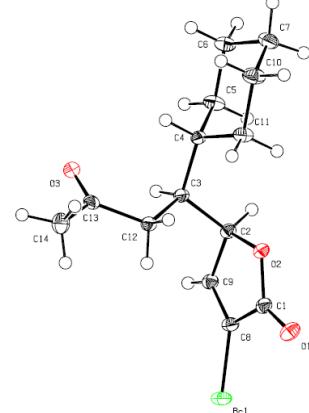
Crystallographic data for the X-ray crystal structure analysis of **1**, **anti-3fe**, **anti-3ie**, **anti-3je**, **anti,anti-3oe**, and **anti-3if** have been deposited with Cambridge Crystallographic Data Center (CCDC) as supplementary publication Nos. CCDC 674990 (**1**), 739547 (**anti-3fe**), 739352 (**anti-3ie**), 739353 (**anti-3je**), 739351 (**anti,anti-3oe**) and 739354 (**anti-3if**). These data can be obtained free of charge from the CCDC via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).



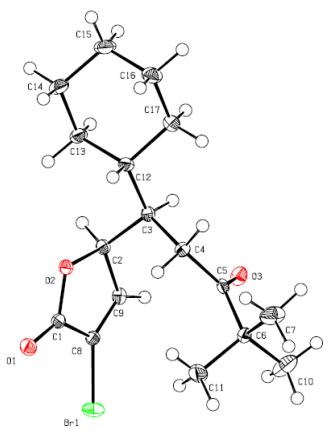
X-ray structure of **1**



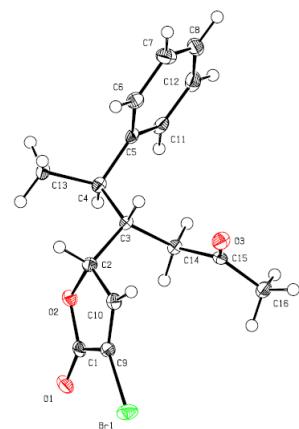
X-ray structure of **anti-3fe**



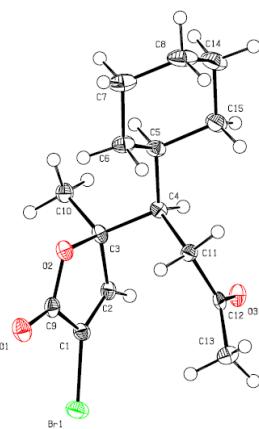
X-ray structure of **anti-3ie**



X-ray structure of **anti-3je**



X-ray structure of **anti,anti-3oe**



X-ray structure of **anti-3if**

**Table S3.** Crystal data and structure refinement for **1**.

Empirical formula	$C_7H_4F_{12}O_8S_4$
Formula weight	572.34
Temperature	100 K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	P2(1)/c
Unit cell dimensions	$a = 9.9367(9)$ Å
	$\alpha = 90^\circ$ .

	$b = 16.5820(15) \text{ \AA}$	$\beta = 103.5850(10)^\circ$
	$c = 10.9892(10) \text{ \AA}$	$\gamma = 90^\circ$
Volume	$1760.0(3) \text{ \AA}^3$	
Z	4	
Density (calculated)	$2.160 \text{ Mg/m}^3$	
Absorption coefficient	$0.702 \text{ mm}^{-1}$	
F(000)	1128	
Crystal size	$0.22 \times 0.16 \times 0.05 \text{ mm}^3$	
Theta range for data collection	2.11 to 27.48°	
Index ranges	$-12 \leq h \leq 10, -21 \leq k \leq 20, -9 \leq l \leq 14$	
Reflections collected	9655	
Independent reflections	3932 [ $R(\text{int}) = 0.0237$ ]	
Completeness to theta = 27.48°	97.4 %	
Absorption correction	Empirical	
Max. and min. transmission	0.9657 and 0.8609	
Refinement method	Full-matrix least-squares on $F^2$	
Data / restraints / parameters	3932 / 0 / 280	
Goodness-of-fit on $F^2$	1.021	
Final R indices [ $I > 2\sigma(I)$ ]	$R_1 = 0.0284, wR_2 = 0.0621$	
R indices (all data)	$R_1 = 0.0384, wR_2 = 0.0666$	
Largest diff. peak and hole	0.421 and -0.400 e.Å <sup>-3</sup>	

**Table S4.** Crystal data and structure refinement for **anti-3fe**.

Empirical formula	$C_{14}H_{13}BrO_3$	
Formula weight	309.15	
Temperature	90 K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P -1	
Unit cell dimensions	$a = 6.2196(16) \text{ \AA}$	$\alpha = 73.247(2)^\circ$
	$b = 10.038(3) \text{ \AA}$	$\beta = 85.069(3)^\circ$
	$c = 10.899(3) \text{ \AA}$	$\gamma = 89.251(3)^\circ$
Volume	$649.1(3) \text{ \AA}^3$	
Z	2	
Density (calculated)	$1.582 \text{ Mg/m}^3$	
Absorption coefficient	$3.164 \text{ mm}^{-1}$	
F(000)	312	
Crystal size	$0.23 \times 0.08 \times 0.03 \text{ mm}^3$	

Theta range for data collection	1.96 to 27.69°.
Index ranges	-8<=h<=8, -12<=k<=12, -13<=l<=14
Reflections collected	6933
Independent reflections	2937 [R(int) = 0.0521]
Completeness to theta = 27.69°	96.8 %
Absorption correction	Empirical
Max. and min. transmission	0.9111 and 0.5298
Refinement method	Full-matrix least-squares on $F^2$
Data / restraints / parameters	2937 / 0 / 164
Goodness-of-fit on $F^2$	1.104
Final R indices [I>2sigma(I)]	R1 = 0.0370, wR2 = 0.1106
R indices (all data)	R1 = 0.0383, wR2 = 0.1117
Largest diff. peak and hole	0.862 and -1.490 e. $\text{\AA}^{-3}$

**Table S5.** Crystal data and structure refinement for compound *anti*-3ie.

Empirical formula	$\text{C}_{14}\text{H}_{19}\text{BrO}_3$		
Formula weight	315.20		
Temperature	90 K		
Wavelength	0.71073 $\text{\AA}$		
Crystal system	Monoclinic		
Space group	P 21/n		
Unit cell dimensions	$a = 6.2821(12) \text{\AA}$	$\alpha = 90^\circ$ .	
	$b = 15.603(3) \text{\AA}$	$\beta = 101.736(2)^\circ$ .	
	$c = 14.722(3) \text{\AA}$	$\gamma = 90^\circ$ .	
Volume	$1412.9(5) \text{\AA}^3$		
Z	4		
Density (calculated)	1.482 Mg/m <sup>3</sup>		
Absorption coefficient	2.908 mm <sup>-1</sup>		
F(000)	648		
Crystal size	$0.49 \times 0.37 \times 0.33 \text{ mm}^3$		
Theta range for data collection	1.92 to 27.51°.		
Index ranges	-8<=h<=8, -20<=k<=20, -18<=l<=10		
Reflections collected	7760		
Independent reflections	3188 [R(int) = 0.0285]		
Completeness to theta = 27.51°	98.3 %		
Absorption correction	Empirical		
Max. and min. transmission	0.4471 and 0.3300		
Refinement method	Full-matrix least-squares on $F^2$		

Data / restraints / parameters	3188 / 0 / 164
Goodness-of-fit on $F^2$	1.051
Final R indices [ $I > 2\sigma(I)$ ]	$R_1 = 0.0270$ , $wR_2 = 0.0707$
R indices (all data)	$R_1 = 0.0318$ , $wR_2 = 0.0729$
Largest diff. peak and hole	0.783 and -0.583 e. $\text{\AA}^{-3}$

**Table S6.** Crystal data and structure refinement for compound ***anti*-3je**.

Empirical formula	$\text{C}_{17}\text{H}_{25}\text{BrO}_3$
Formula weight	357.28
Temperature	90 K
Wavelength	0.71073 $\text{\AA}$
Crystal system	Monoclinic
Space group	$P 21/c$
Unit cell dimensions	$a = 9.477(3) \text{\AA}$ $\alpha = 90^\circ$ . $b = 10.226(3) \text{\AA}$ $\beta = 93.780(3)^\circ$ . $c = 17.617(5) \text{\AA}$ $\gamma = 90^\circ$ .
Volume	1703.6(9) $\text{\AA}^3$
Z	4
Density (calculated)	1.393 $\text{Mg/m}^3$
Absorption coefficient	2.420 $\text{mm}^{-1}$
F(000)	744
Crystal size	0.23 x 0.23 x 0.04 $\text{mm}^3$
Theta range for data collection	2.15 to 27.69 $^\circ$ .
Index ranges	-12 $\leq h \leq 12$ , -6 $\leq k \leq 13$ , -22 $\leq l \leq 21$
Reflections collected	9346
Independent reflections	3894 [ $R(\text{int}) = 0.0542$ ]
Completeness to theta = 27.69 $^\circ$	97.4 %
Absorption correction	Numerical
Max. and min. transmission	0.9094 and 0.6060
Refinement method	Full-matrix least-squares on $F^2$
Data / restraints / parameters	3894 / 0 / 193
Goodness-of-fit on $F^2$	1.021
Final R indices [ $I > 2\sigma(I)$ ]	$R_1 = 0.0362$ , $wR_2 = 0.0964$
R indices (all data)	$R_1 = 0.0470$ , $wR_2 = 0.1023$
Largest diff. peak and hole	0.545 and -0.398 e. $\text{\AA}^{-3}$

**Table S7.** Crystal data and structure refinement for compound ***anti,anti*-3oe**.

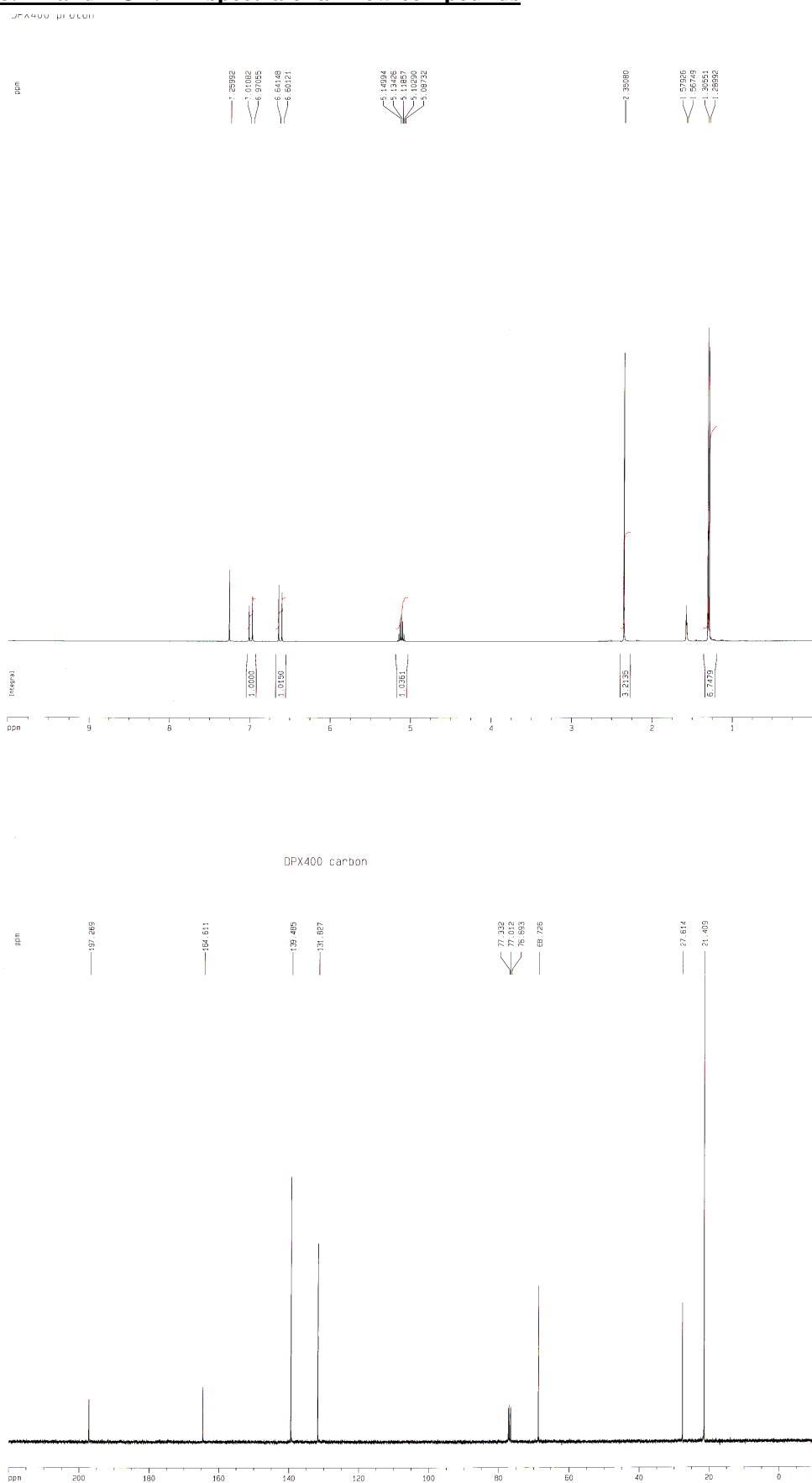
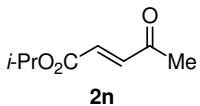
Empirical formula	$C_{16}H_{17}BrO_3$		
Formula weight	337.21		
Temperature	90 K		
Wavelength	0.71073 Å		
Crystal system	Orthorhombic		
Space group	P b c n		
Unit cell dimensions	$a = 21.609(4)$ Å	$\alpha = 90^\circ$ .	
	$b = 8.9577(16)$ Å	$\beta = 90^\circ$ .	
	$c = 15.245(3)$ Å	$\gamma = 90^\circ$ .	
Volume	$2951.0(9)$ Å <sup>3</sup>		
Z	8		
Density (calculated)	1.518 Mg/m <sup>3</sup>		
Absorption coefficient	2.790 mm <sup>-1</sup>		
F(000)	1376		
Crystal size	0.23 x 0.19 x 0.16 mm <sup>3</sup>		
Theta range for data collection	1.88 to 27.58°.		
Index ranges	-28≤h≤18, -11≤k≤11, -15≤l≤19		
Reflections collected	15617		
Independent reflections	3397 [R(int) = 0.0554]		
Completeness to theta = 27.58°	99.5 %		
Absorption correction	Numerical		
Max. and min. transmission	0.6638 and 0.5662		
Refinement method	Full-matrix least-squares on F <sup>2</sup>		
Data / restraints / parameters	3397 / 0 / 183		
Goodness-of-fit on F <sup>2</sup>	1.027		
Final R indices [I>2sigma(I)]	R1 = 0.0303, wR2 = 0.0759		
R indices (all data)	R1 = 0.0398, wR2 = 0.0811		
Largest diff. peak and hole	0.634 and -0.491 e.Å <sup>-3</sup>		

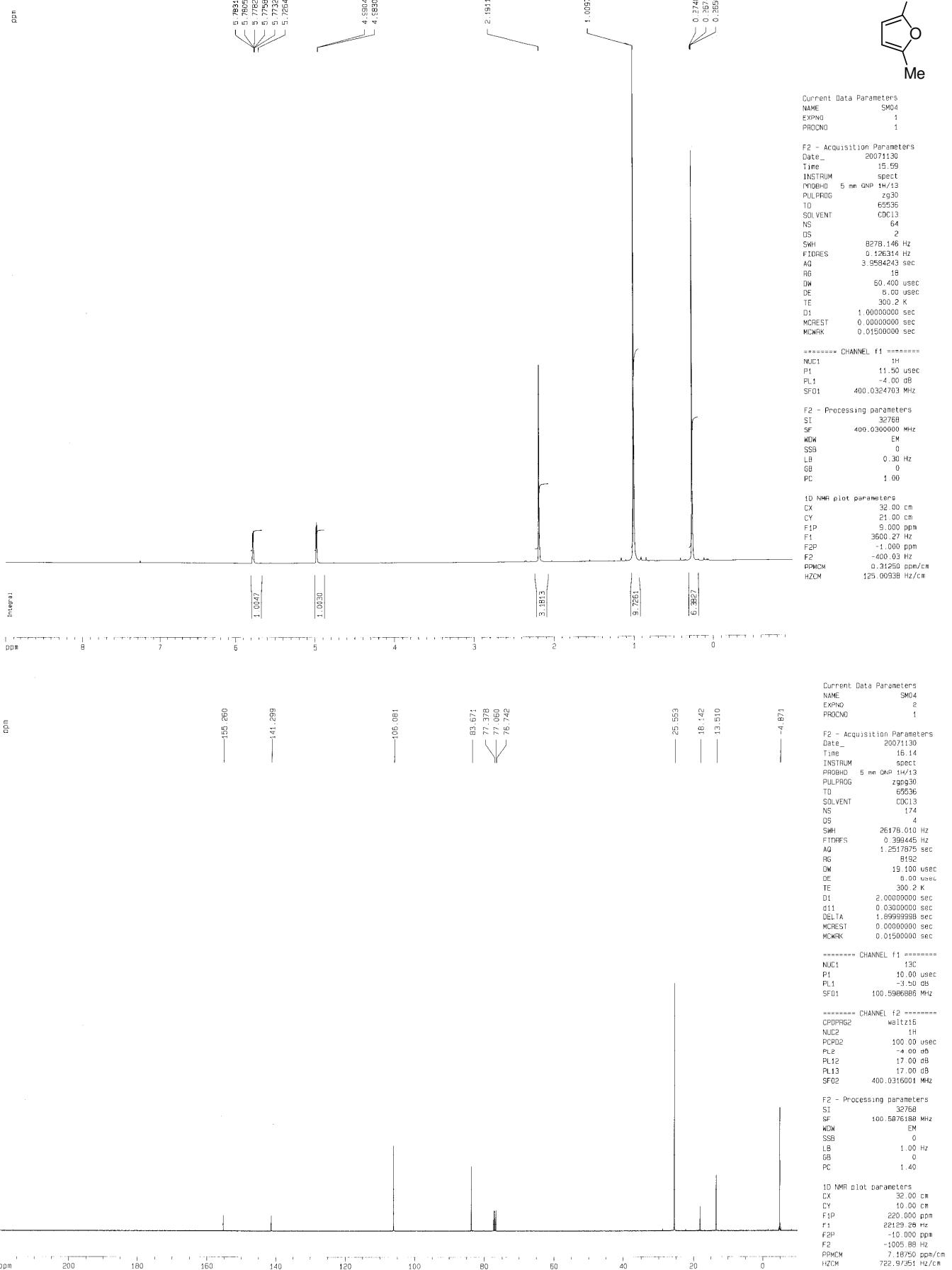
**Table S8.** Crystal data and structure refinement for compound **anti-3if**.

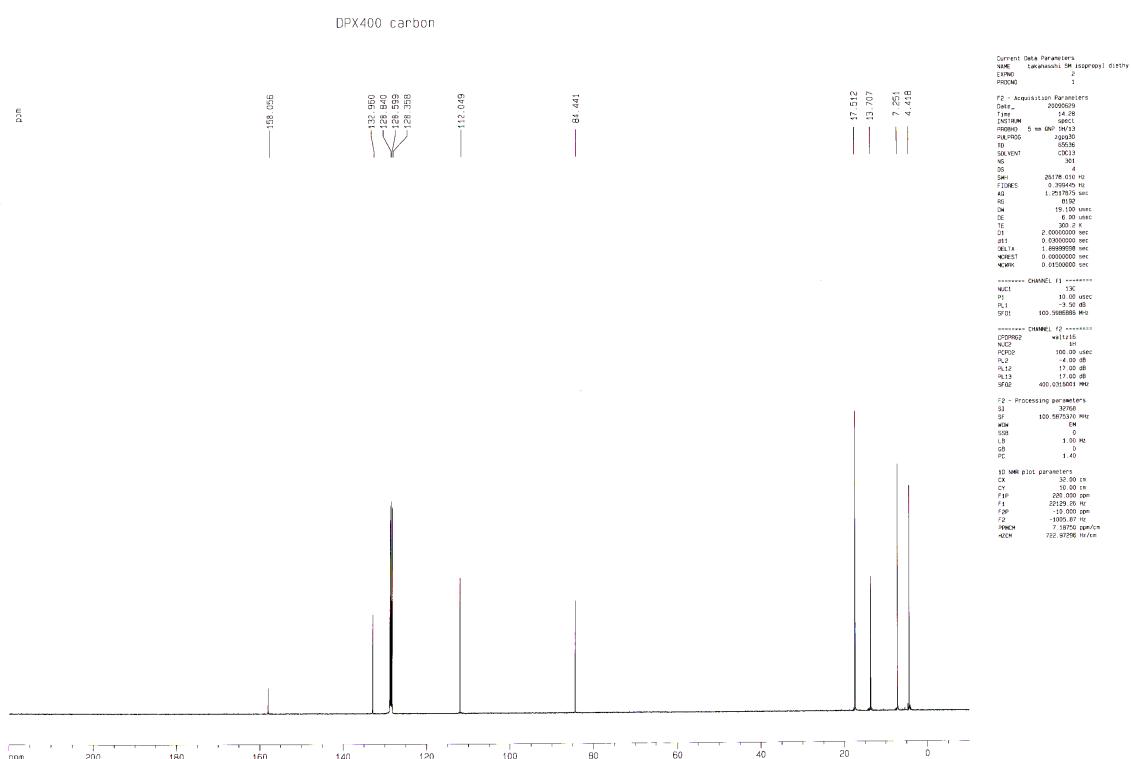
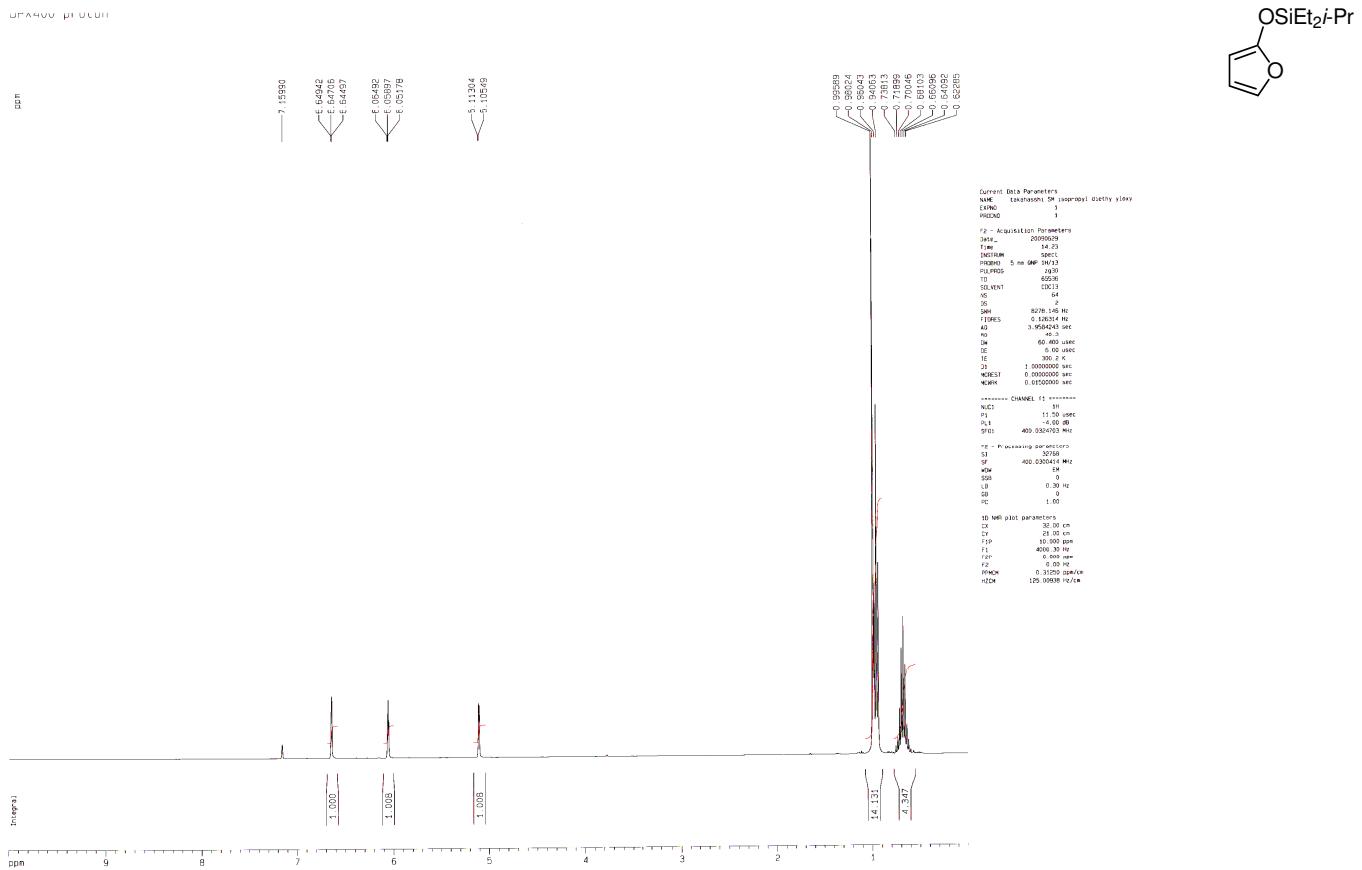
Empirical formula	$C_{15}H_{21}BrO_3$		
Formula weight	329.23		
Temperature	90 K		
Wavelength	0.71073 Å		
Crystal system	Orthorhombic		
Space group	P c a 21		
Unit cell dimensions	$a = 20.354(6)$ Å	$\alpha = 90^\circ$ .	
	$b = 10.517(3)$ Å	$\beta = 90^\circ$ .	

	$c = 7.131(2) \text{ \AA}$	$\gamma = 90^\circ$ .
Volume	$1526.3(8) \text{ \AA}^3$	
Z	4	
Density (calculated)	$1.433 \text{ Mg/m}^3$	
Absorption coefficient	$2.695 \text{ mm}^{-1}$	
F(000)	680	
Crystal size	$0.28 \times 0.20 \times 0.05 \text{ mm}^3$	
Theta range for data collection	1.94 to $27.81^\circ$ .	
Index ranges	$-26 \leq h \leq 26, -13 \leq k \leq 13, -9 \leq l \leq 9$	
Reflections collected	16690	
Independent reflections	3579 [R(int) = 0.0386]	
Completeness to theta = $27.81^\circ$	99.4 %	
Absorption correction	Numerical	
Max. and min. transmission	0.8770 and 0.5191	
Refinement method	Full-matrix least-squares on $F^2$	
Data / restraints / parameters	3579 / 1 / 175	
Goodness-of-fit on $F^2$	1.036	
Final R indices [I>2sigma(I)]	$R_1 = 0.0259, wR_2 = 0.0625$	
R indices (all data)	$R_1 = 0.0306, wR_2 = 0.0646$	
Absolute structure parameter	0.364(7)	
Largest diff. peak and hole	0.698 and $-0.318 \text{ e.\AA}^{-3}$	

## 8. $^1\text{H}$ and $^{13}\text{C}$ NMR spectra of all new compounds



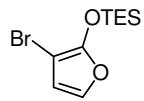




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6.26957

0.3481  
0.34612  
0.34510  
0.34515  
0.81950  
0.79356  
0.77359



Current Data Parameters  
NAME : takahashi SM  $\alpha$ -bromosilyloxy

EXPTID : 1  
PROCNO : 1

F2 - Acquisition Parameters

DATE : 20090609

TIME : 13:59

INSTRUM : spect

PROBHD : 5 mm QNP 1H/13

PULPROG : zg30

TD : 65536

SOLVENT : CDCl3

NS : 32

DS : 2

SWE : 6298.146 Hz

ETDRES : 0.126214 sec

TDZ : 3

RG : 101.6

DM : 0.00 sec

TE : 8.0 sec

TE2 : 30.2 sec

DI : 0.0000000 sec

MPCONT : 0.0000000 sec

SWWID : 0.0150000 sec

NUC1 : 1H

PC1 : 11.50 sec

PL1 : -2.00 dB

SW1 : 400.00000 Hz

DPG1 : 400.00000 Hz

PG1 : 1.00 sec

F2 - Processing parameters

SI : 32768

SF : 400.000000 Hz

WDW : EM

SSB : 0

LB : 0.30 Hz

SB : 0

PC : 1.00

1D NMR plot parameters

DX : 0.0000000 Hz

DY : 0.00 cm

FI1P : 10,000 cps

FI1 : 4000.00

FI2P : 0.0000 cps

FI2 : 0.00 Hz

PRINCH : 0.31750 cps/cm

RCOM : 125.00000 Hz/cm



ppm

## DPX400 carbon

ppm

153.495  
132.137  
114.056

9.525  
6.756  
6.561  
6.436  
6.310  
6.181  
6.040  
6.021  
5.200  
4.905  
4.609

0.3481  
0.34612  
0.34510  
0.81950  
0.79356  
0.77359

Current Data Parameters  
NAME : takahashi SM  $\alpha$ -bromosilyloxy

EXPTID : 2

PROCNO : 1

F2 - Acquisition Parameters

DATE : 20090609

TIME : 14:22

INSTRUM : spect

PROBHD : 5 mm QNP 1H/13

TD : 65536

SOLVENT : CDCl3

NS : 32

DS : 4

SWE : 6298.146 Hz

ETDRES : 0.399445 sec

TDZ : 1

RG : 8192

DM : 0.00 sec

TE : 8.0 sec

TE2 : 30.2 sec

DI : 0.0000000 sec

MPCONT : 0.0000000 sec

SWWID : 0.0150000 sec

NUC1 : 13C

PC1 : 10.00 sec

PL1 : -3.50 dB

SW1 : 100.50000 Hz

DPG1 : 100.50000 Hz

PG1 : 1.00 sec

F2 - Processing parameters

SI : 32768

SF : 100.5076230 Hz

WDW : EM

SSB : 0

LB : 1.00 Hz

SB : 0

PC : 1.40

1D NMR plot parameters

DX : 30.00 Hz

DY : 19.00 cm

FI1P : 229.400 cps

FI1 : 229.400

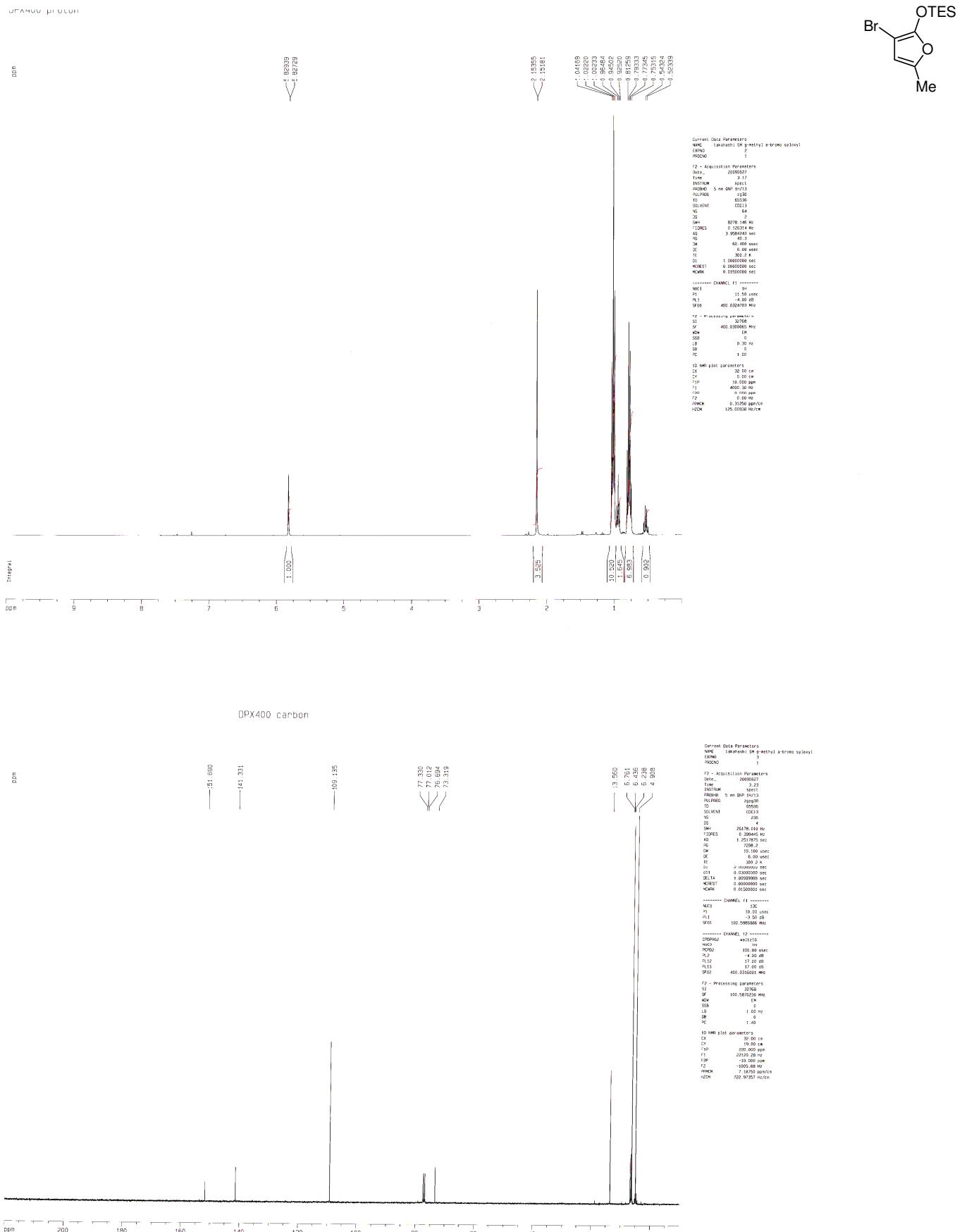
FI2P : -10.600 cps

FI2 : -105.69 Hz

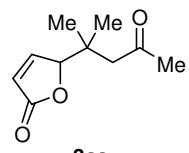
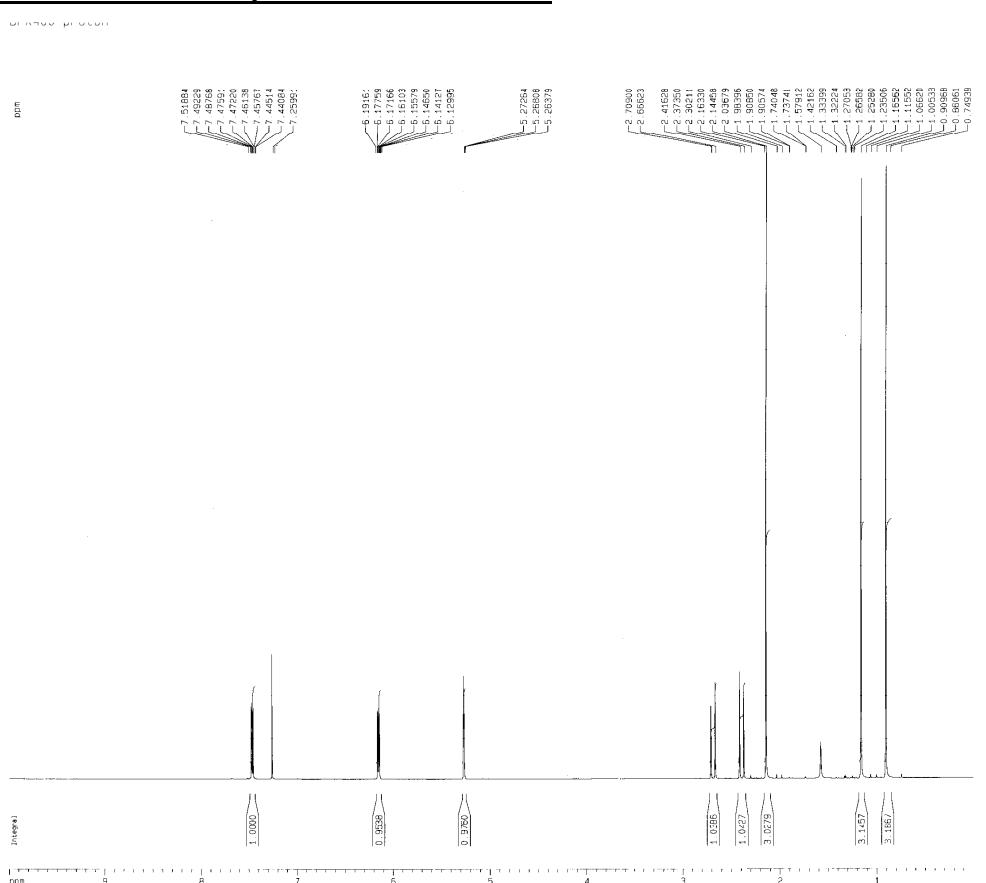
PRINCH : 7.18750 cps/cm

RCOM : 722.97357 Hz/cm

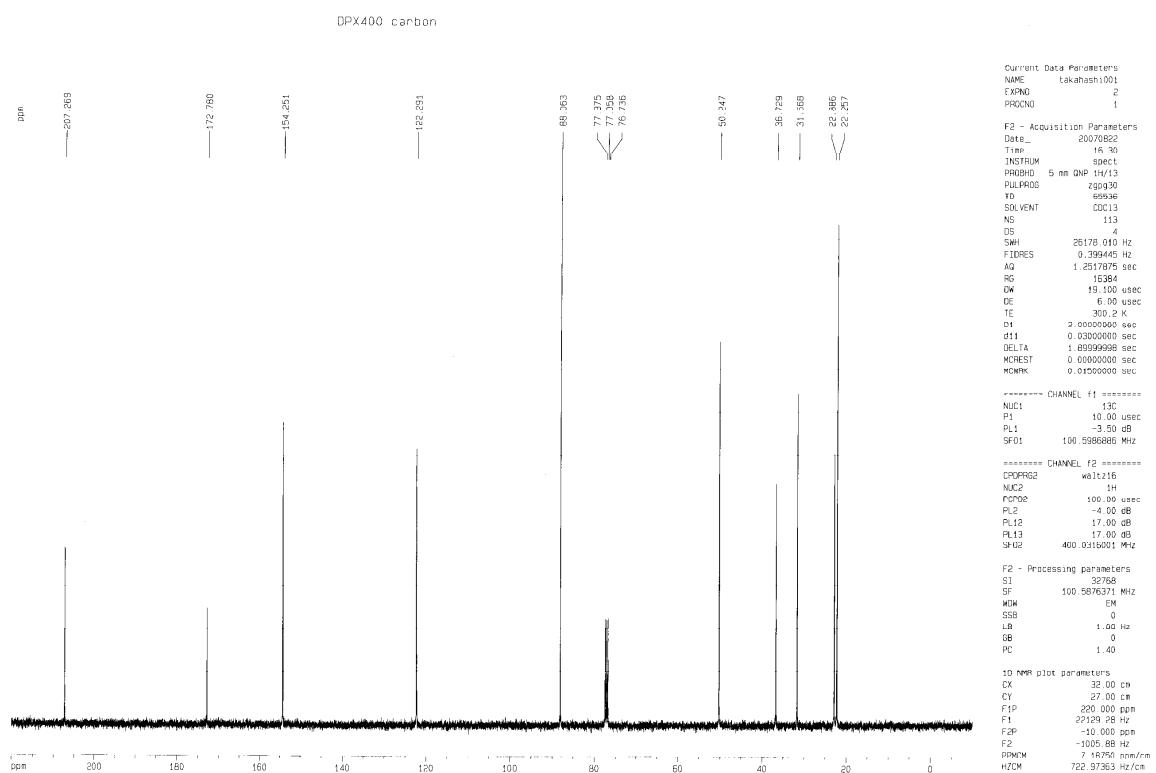
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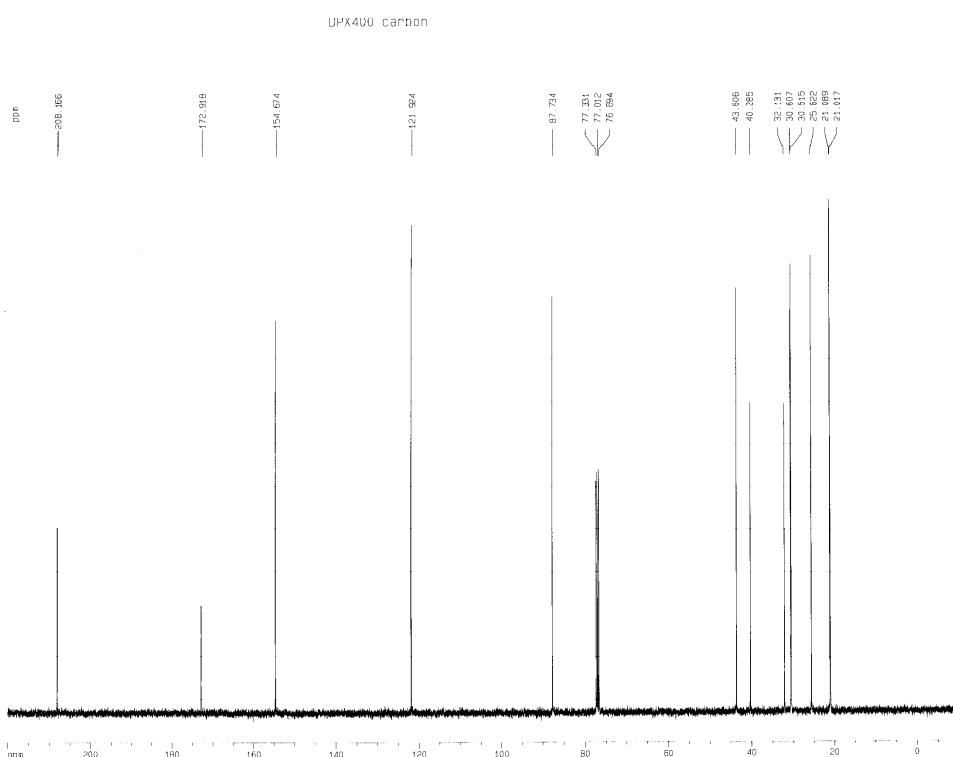
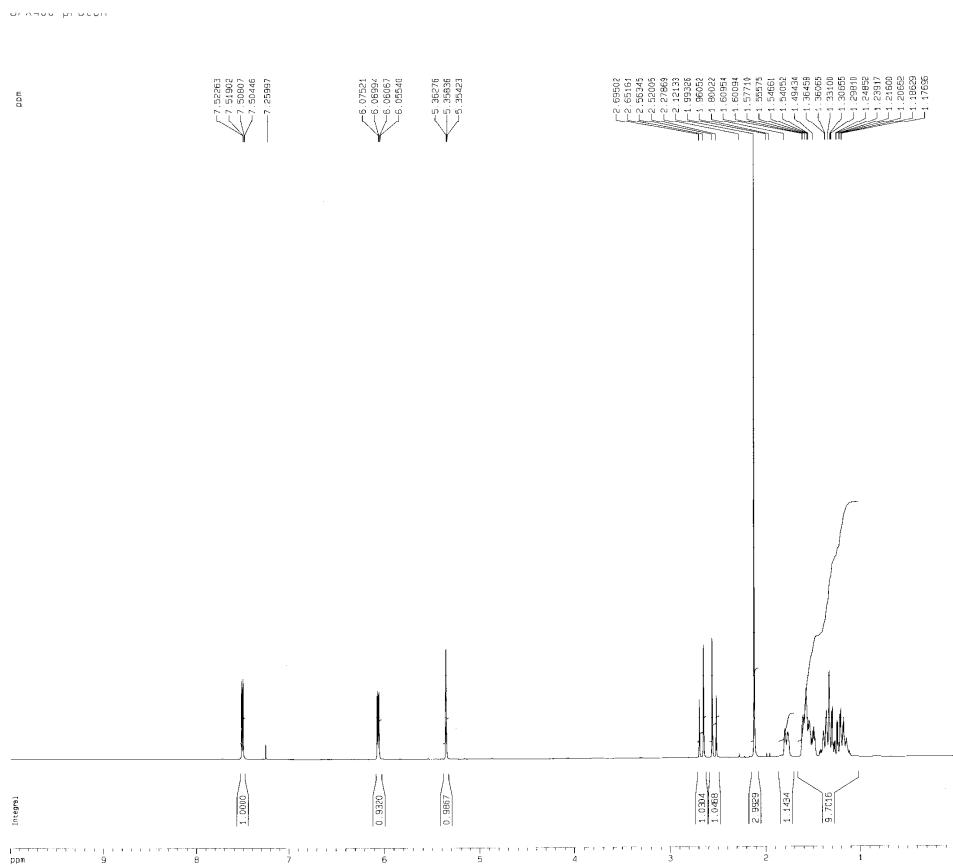


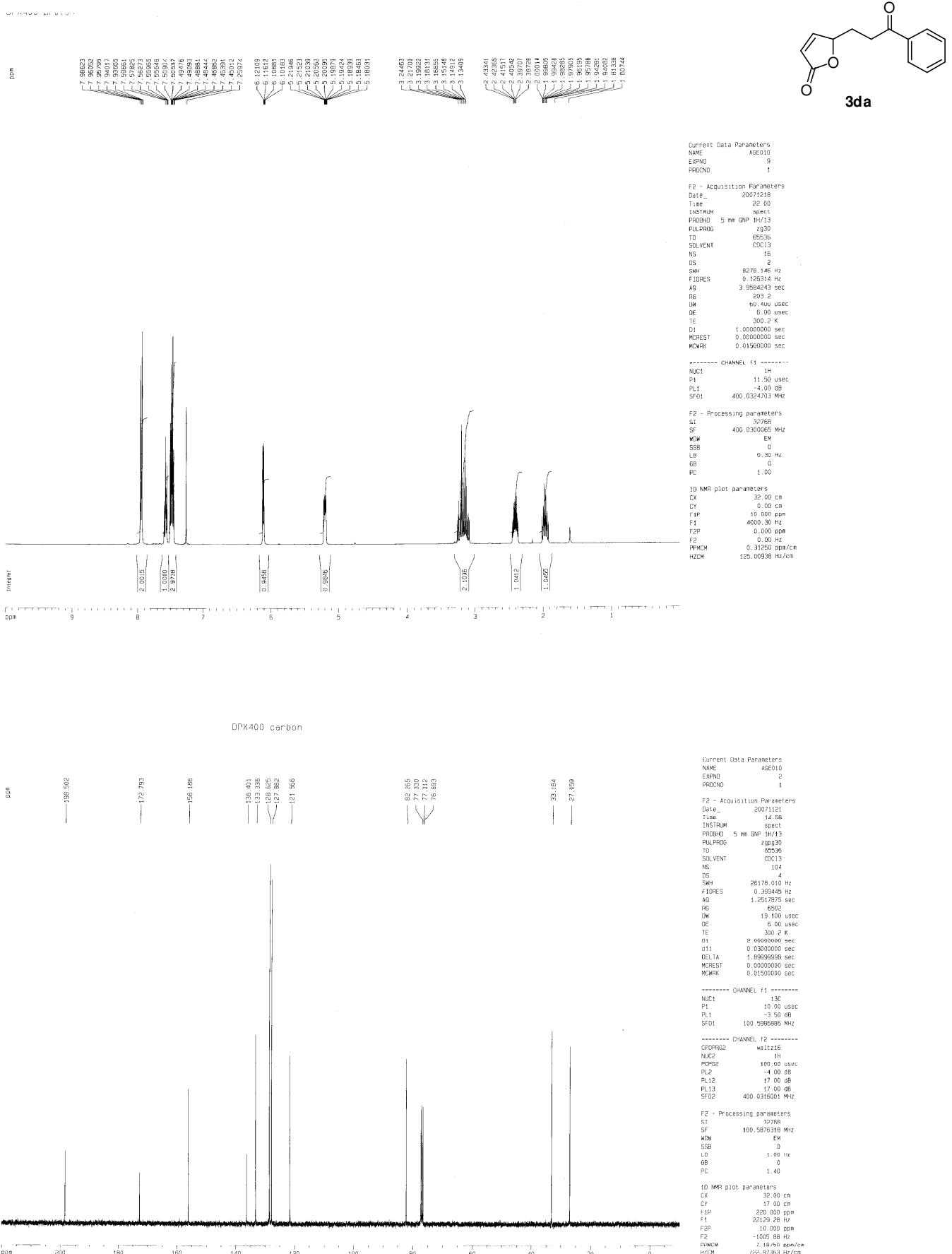
## 9. $^1\text{H}$ and $^{13}\text{C}$ NMR spectra of VMM adducts

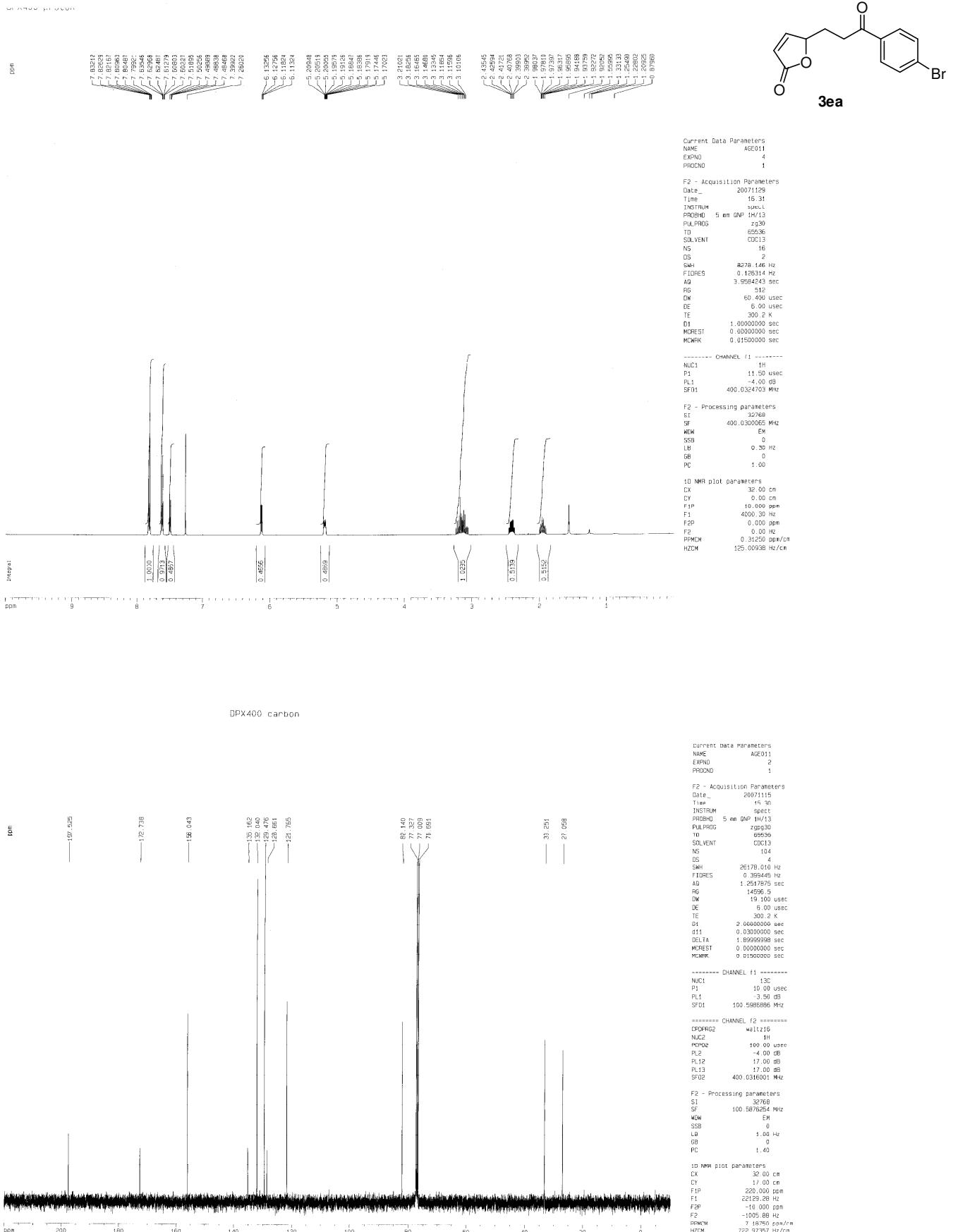


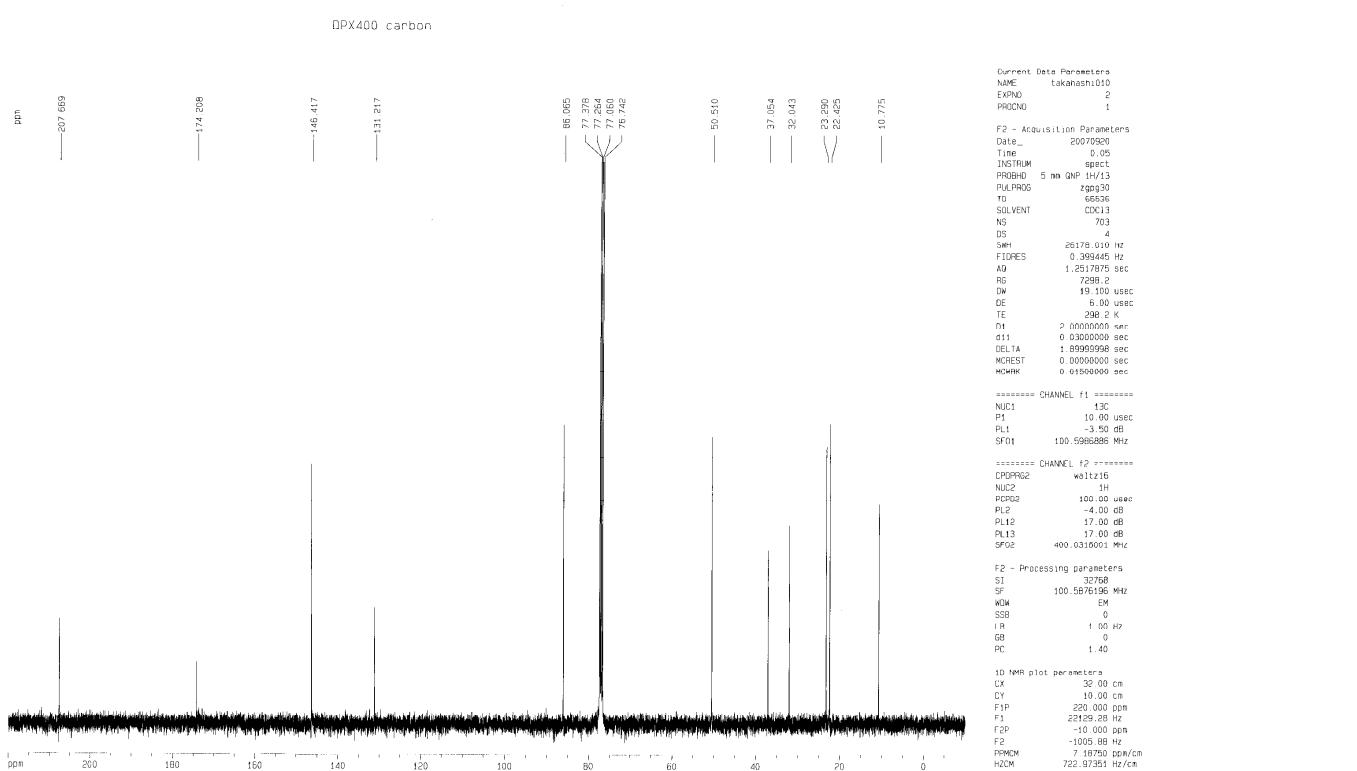
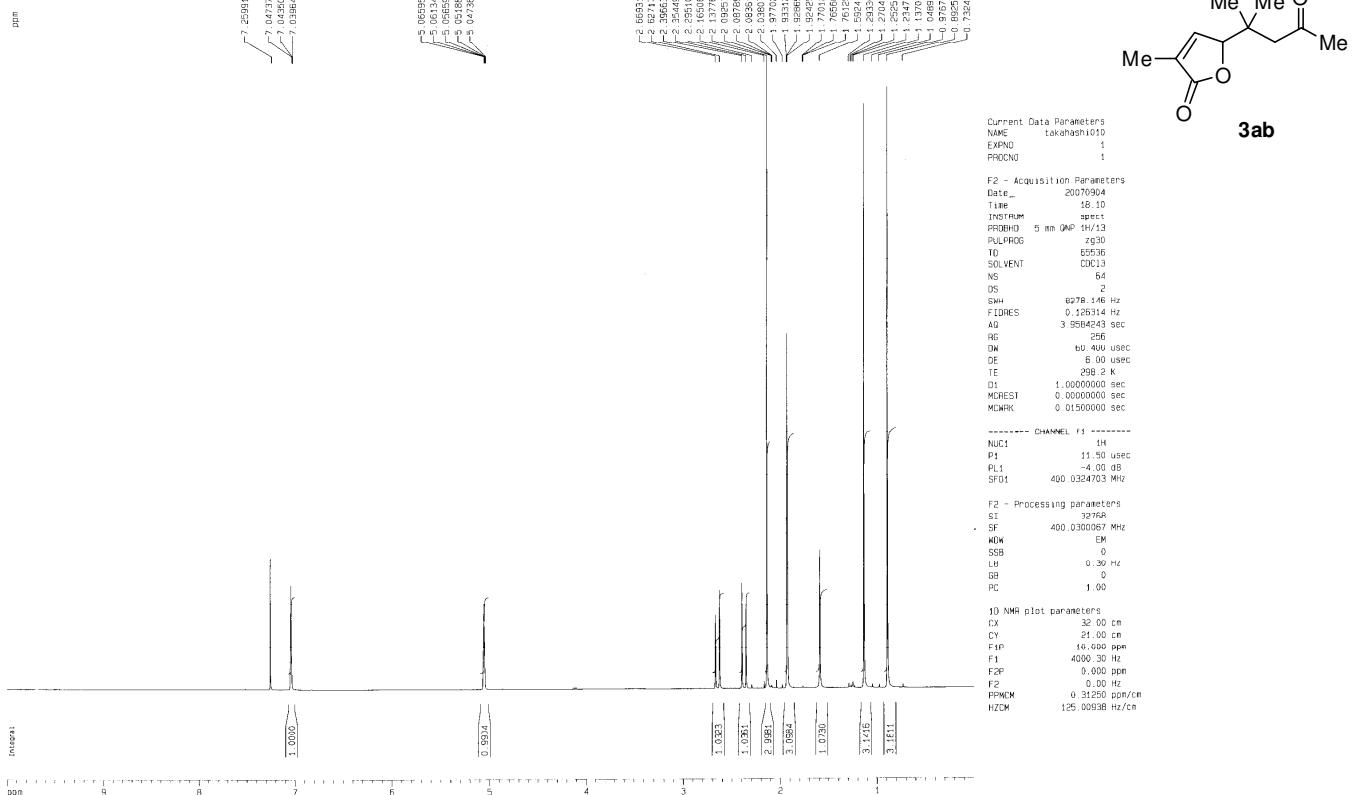
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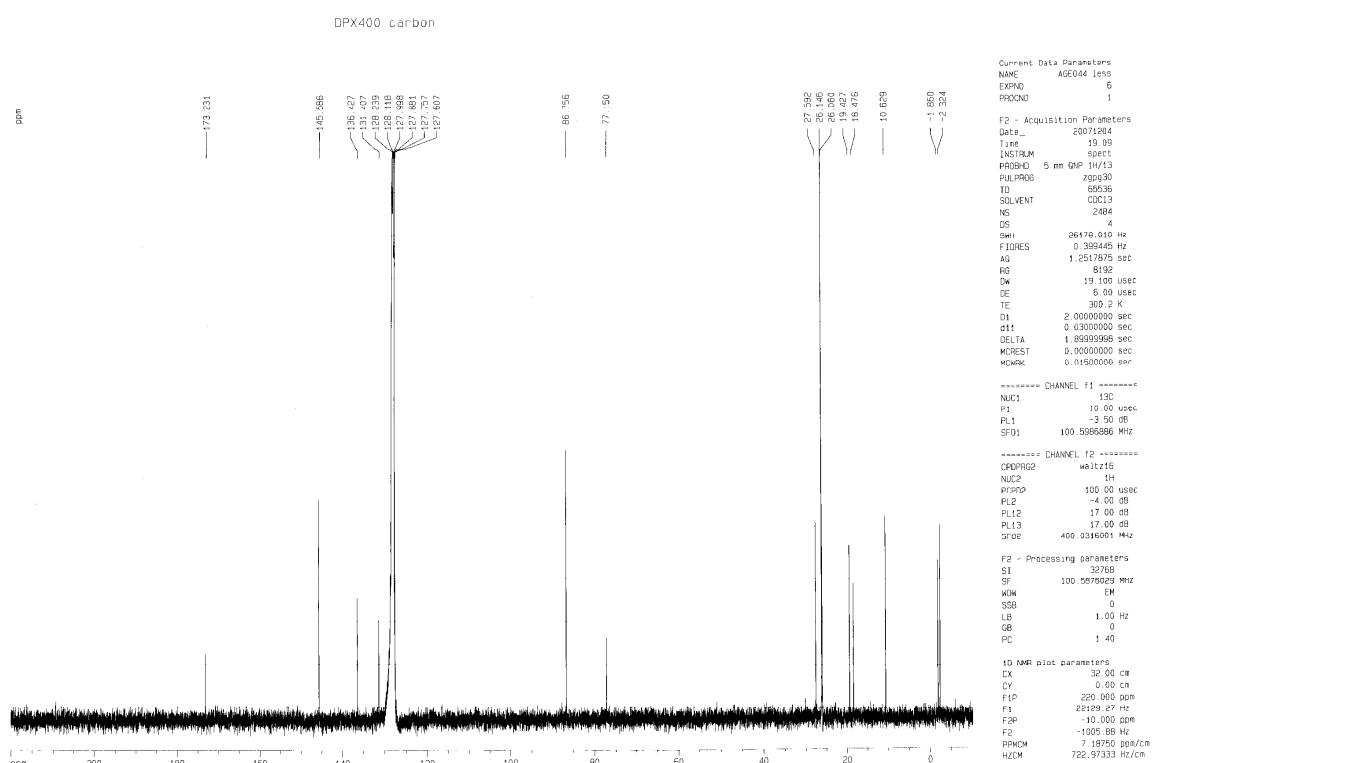
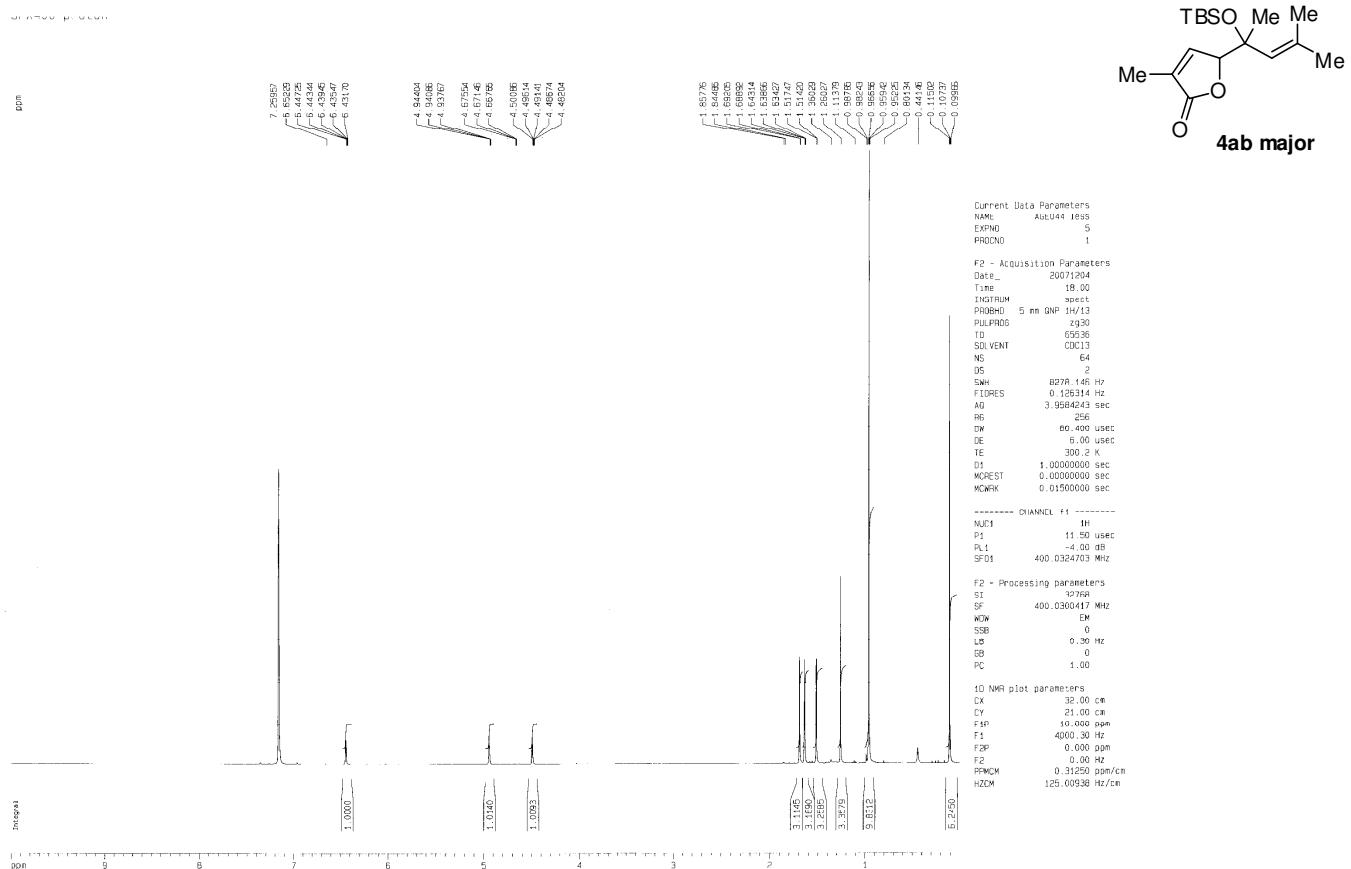


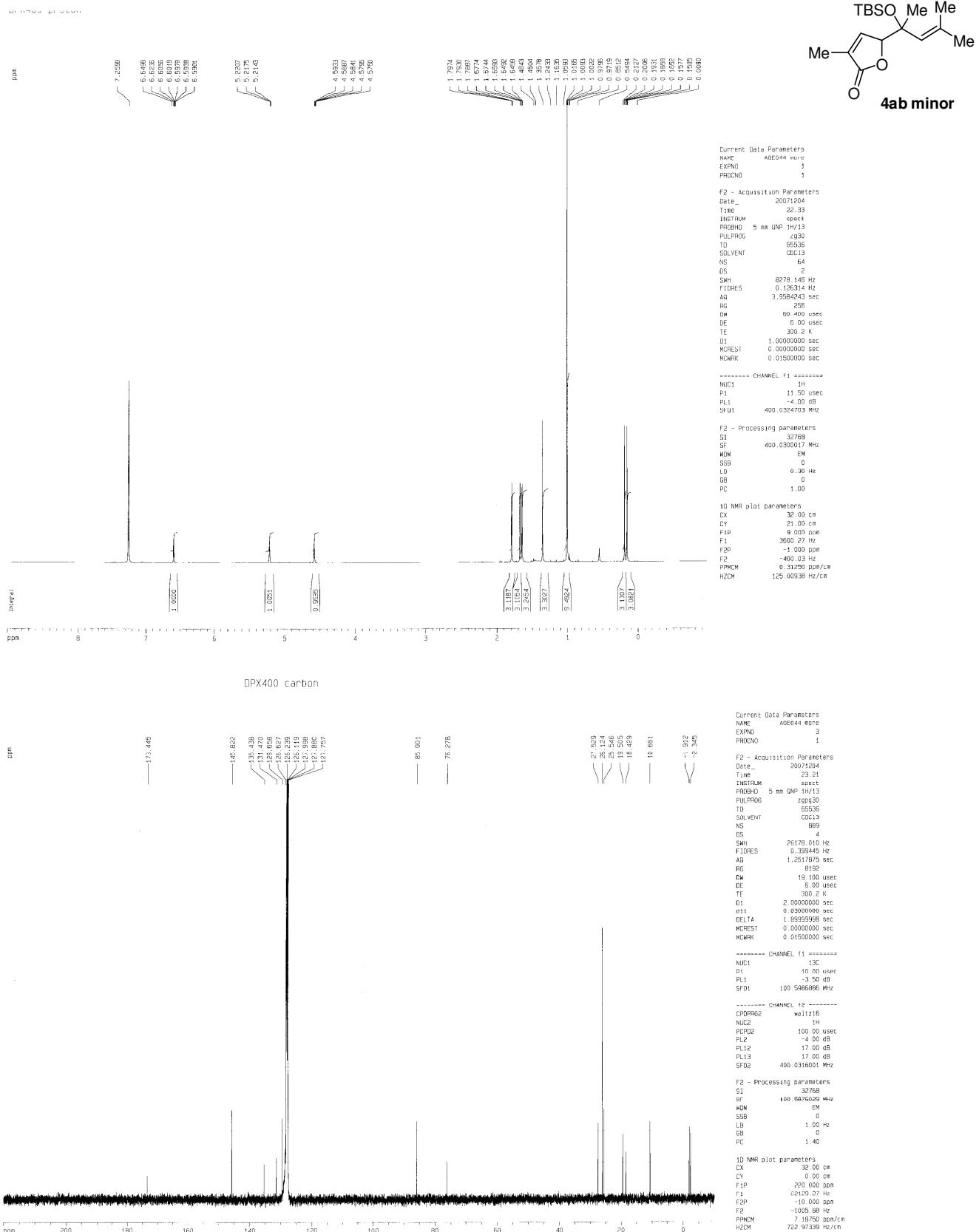


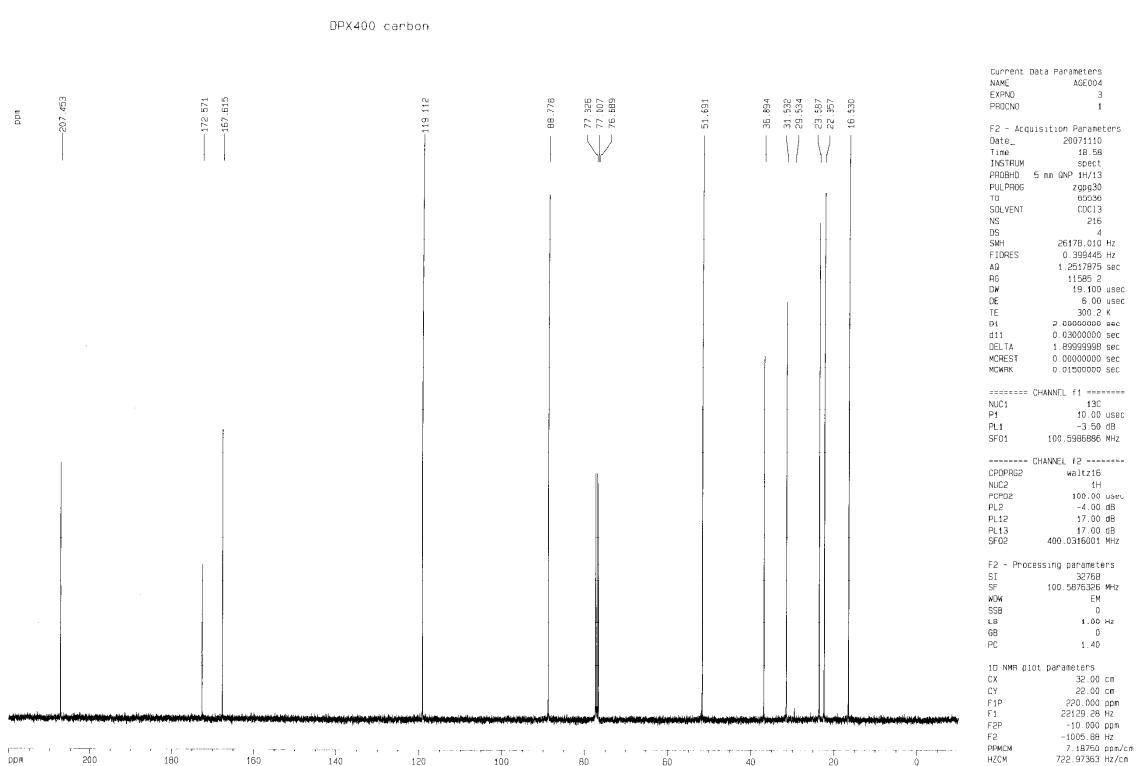
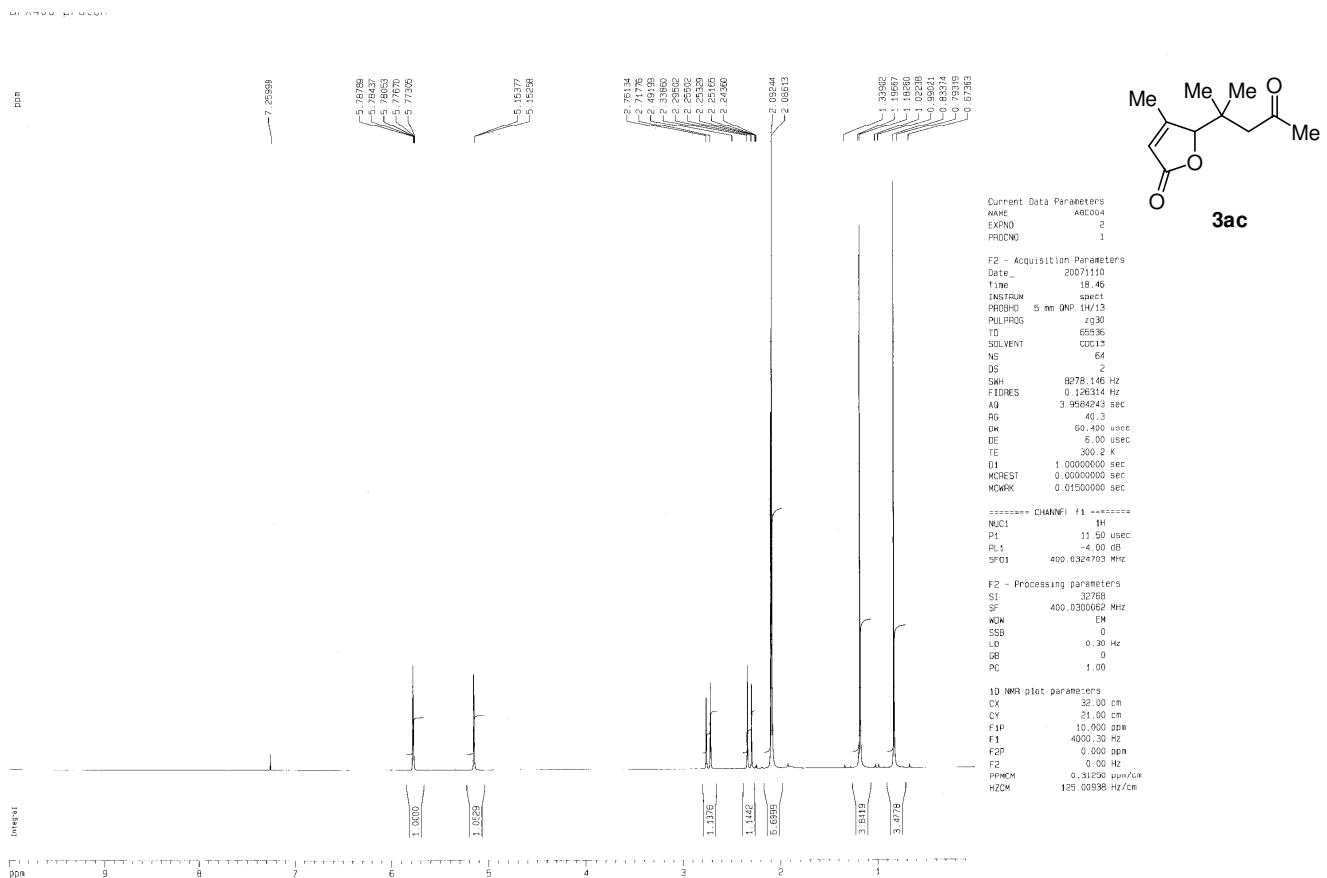


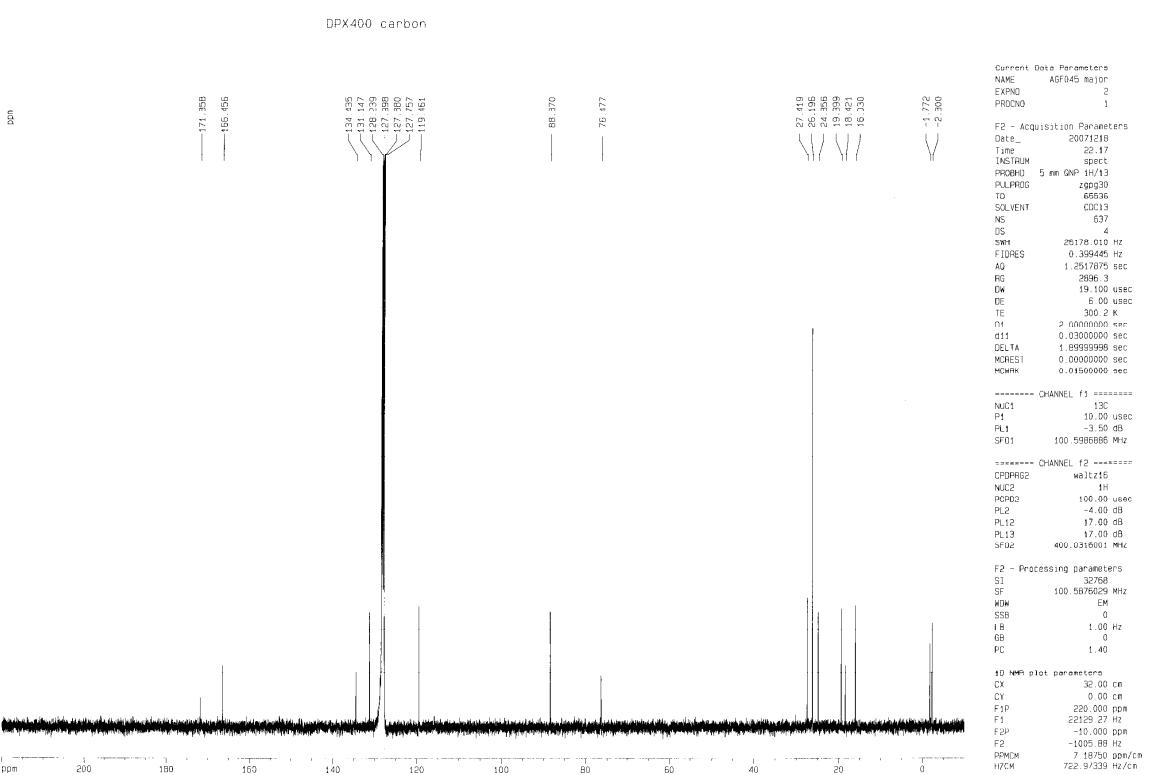
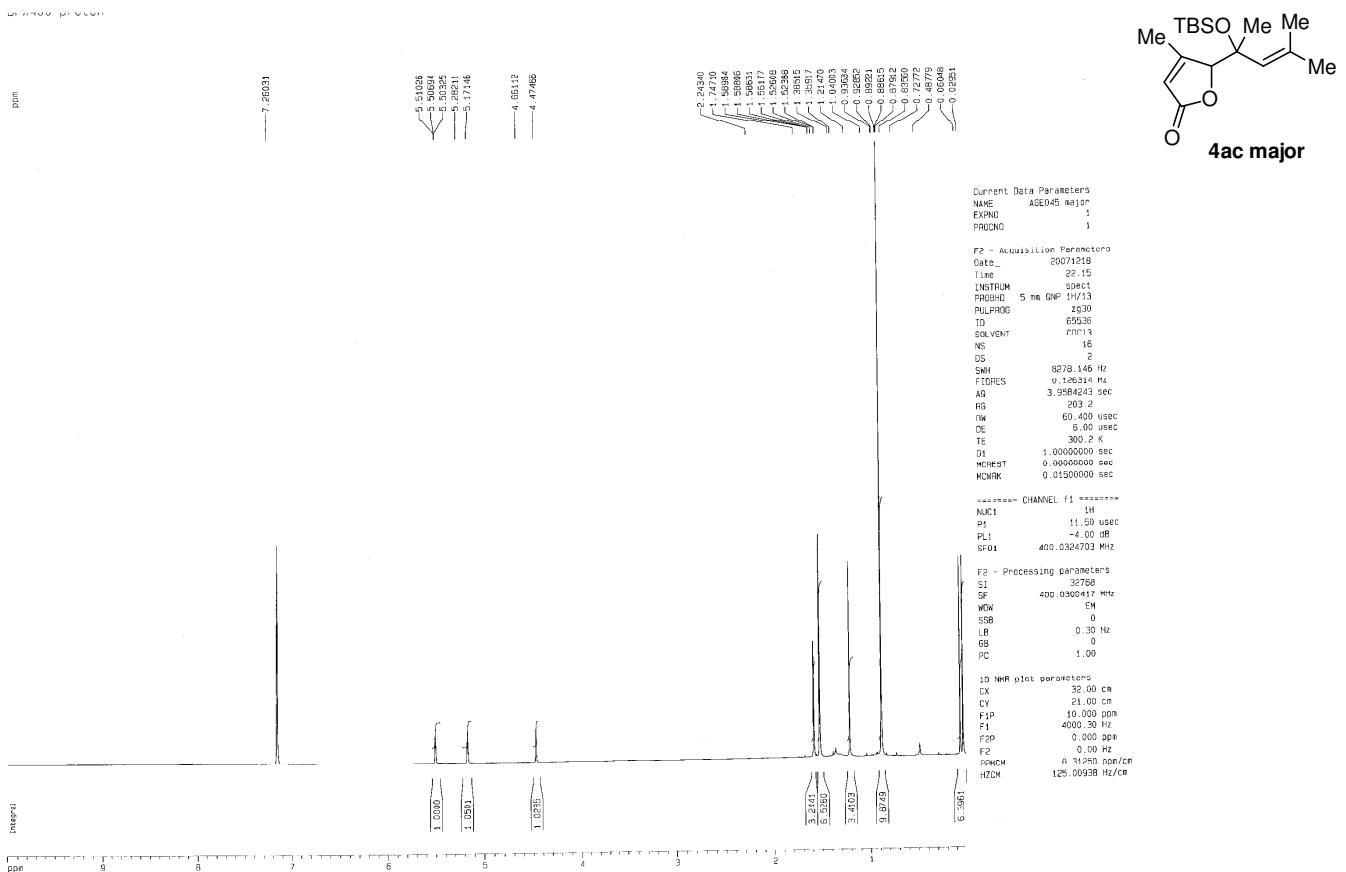


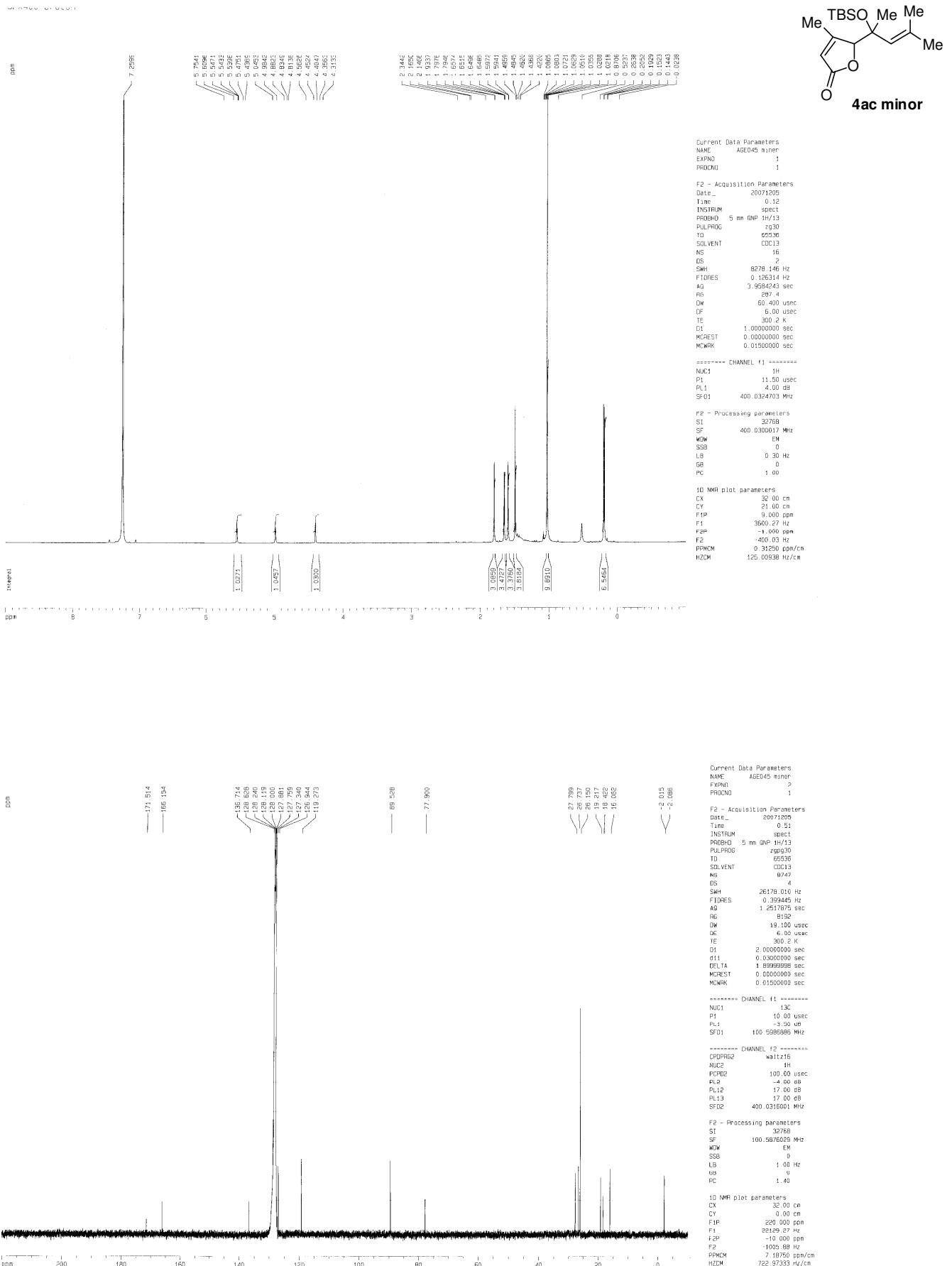


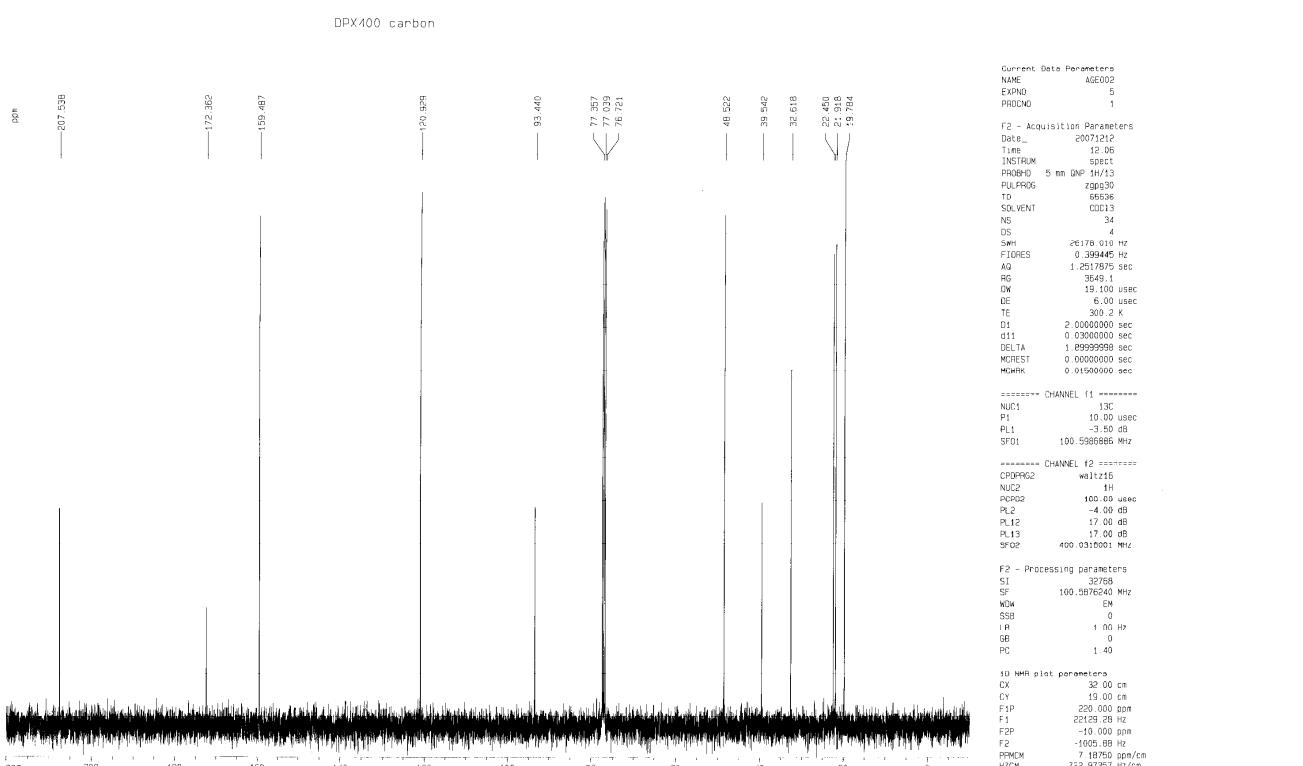
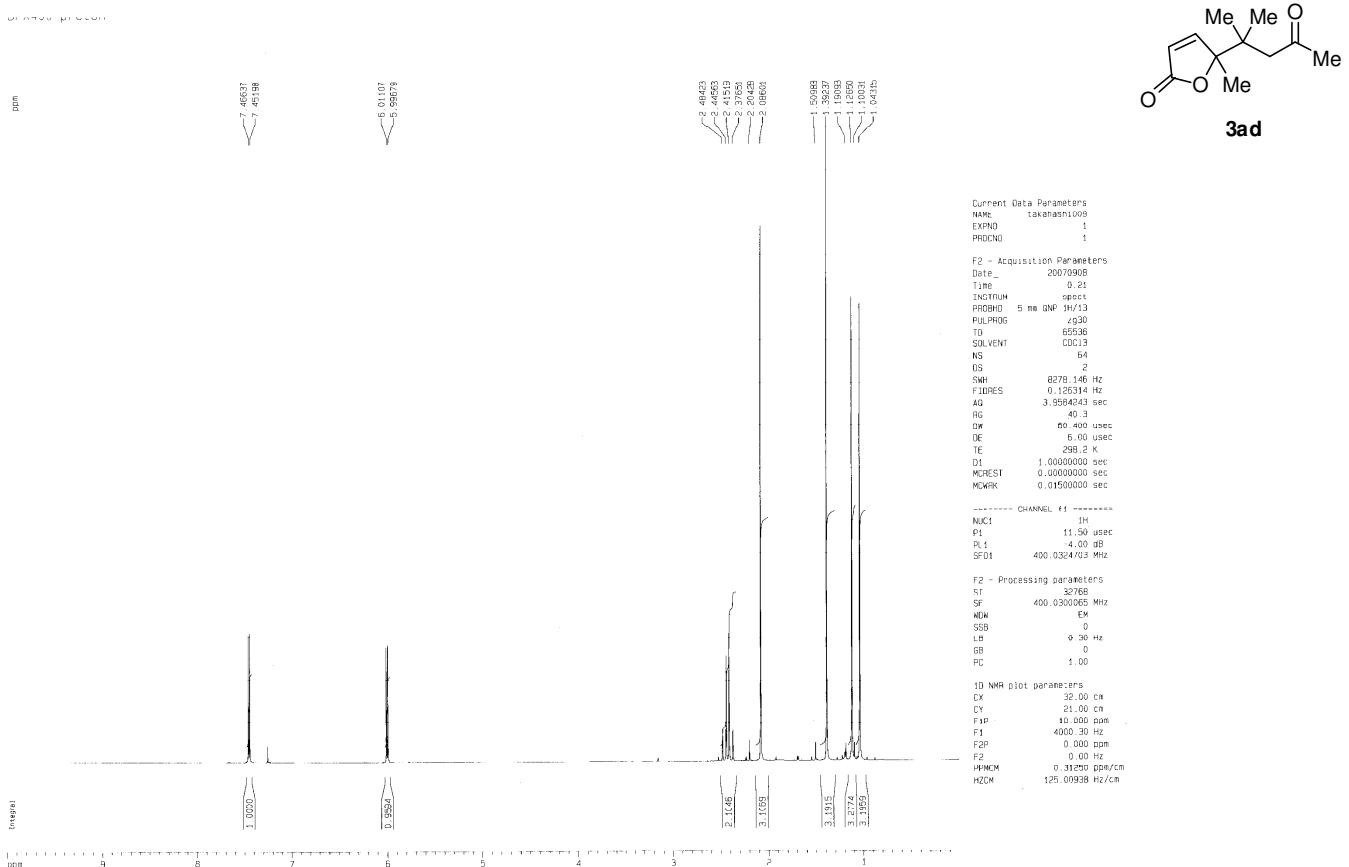




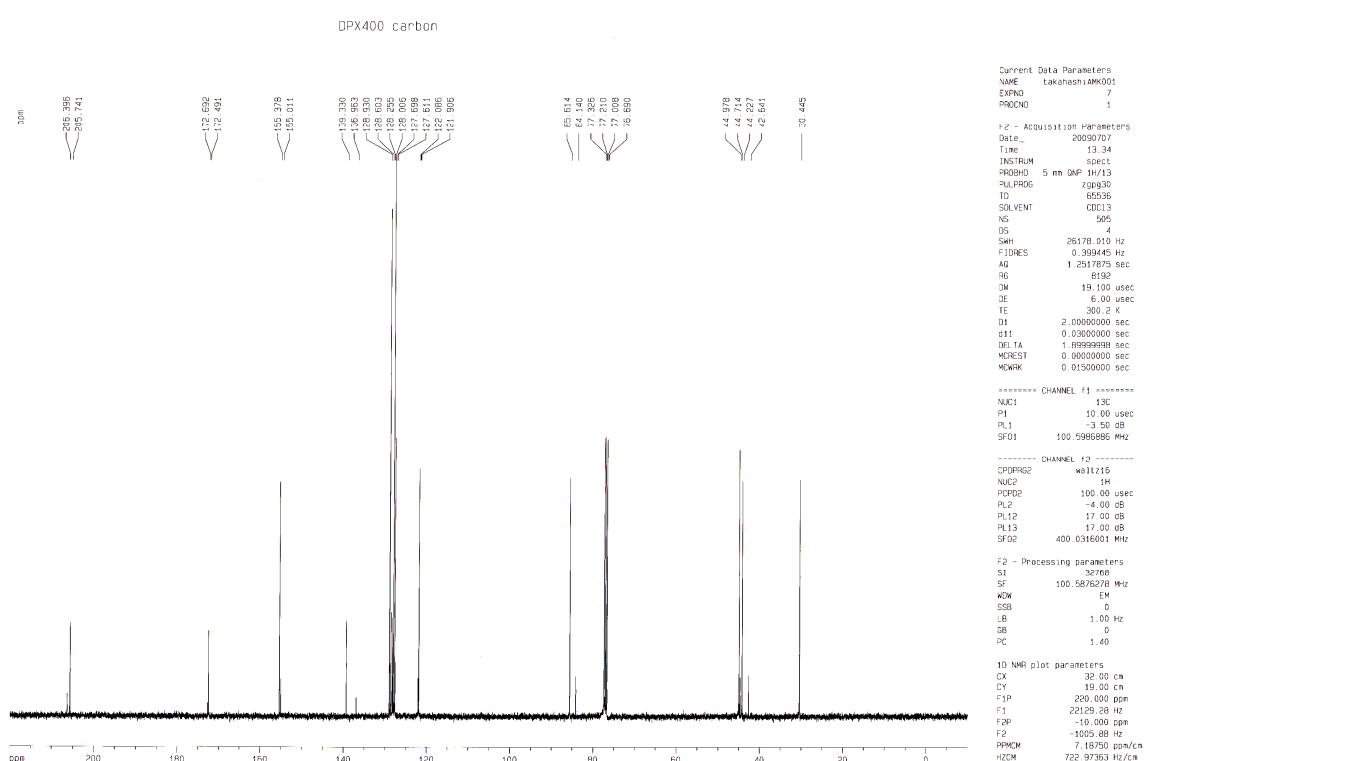
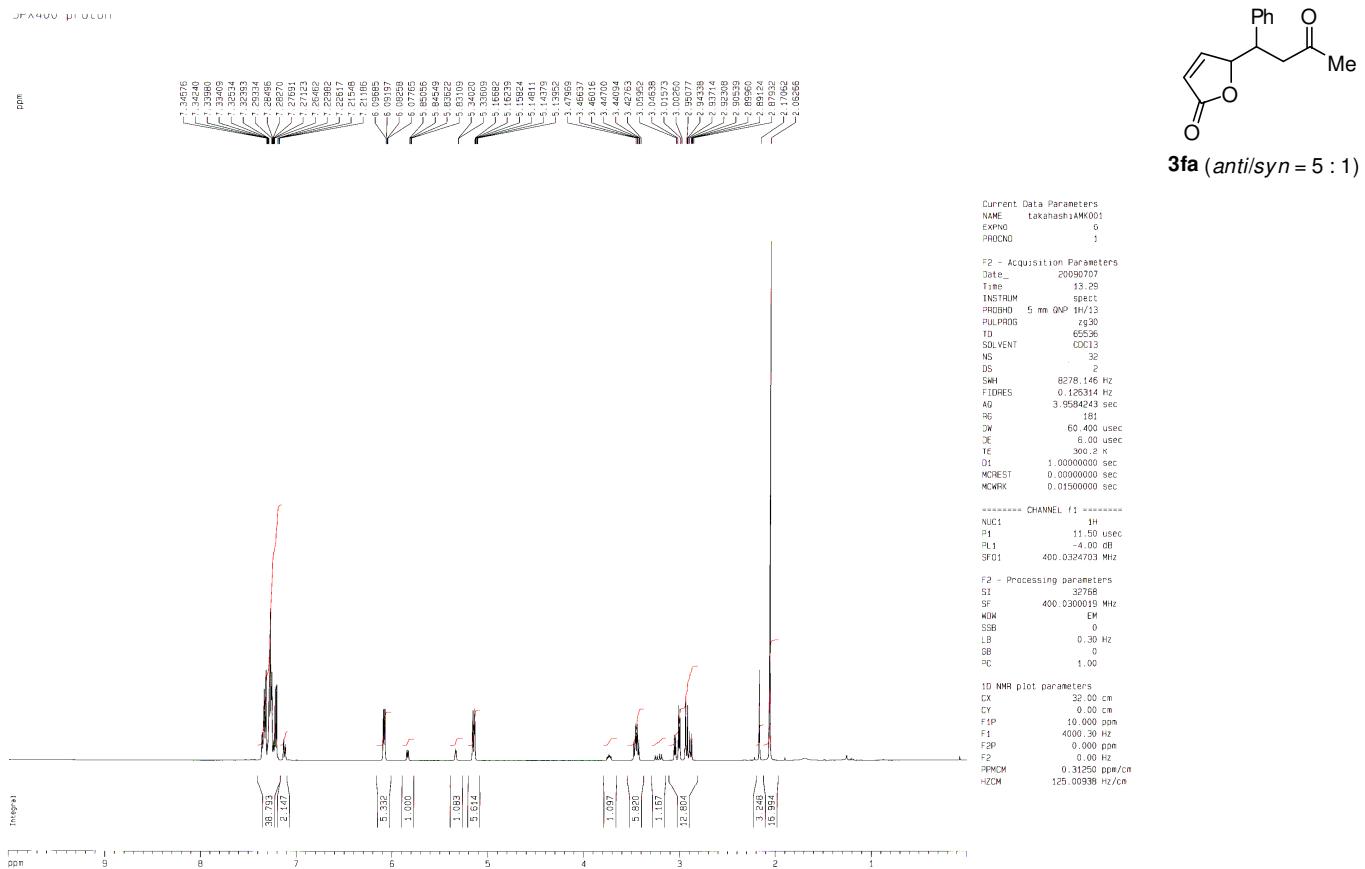


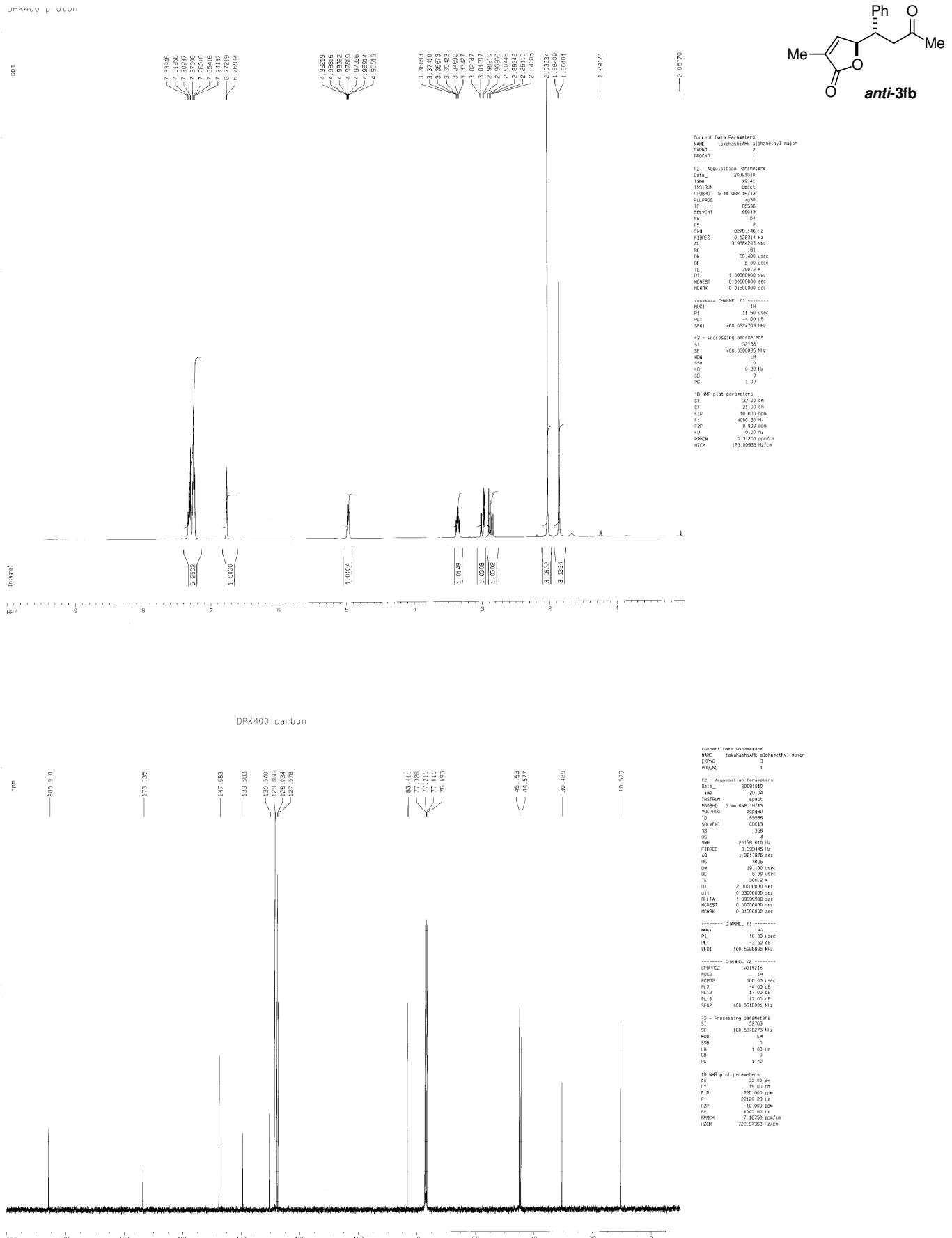


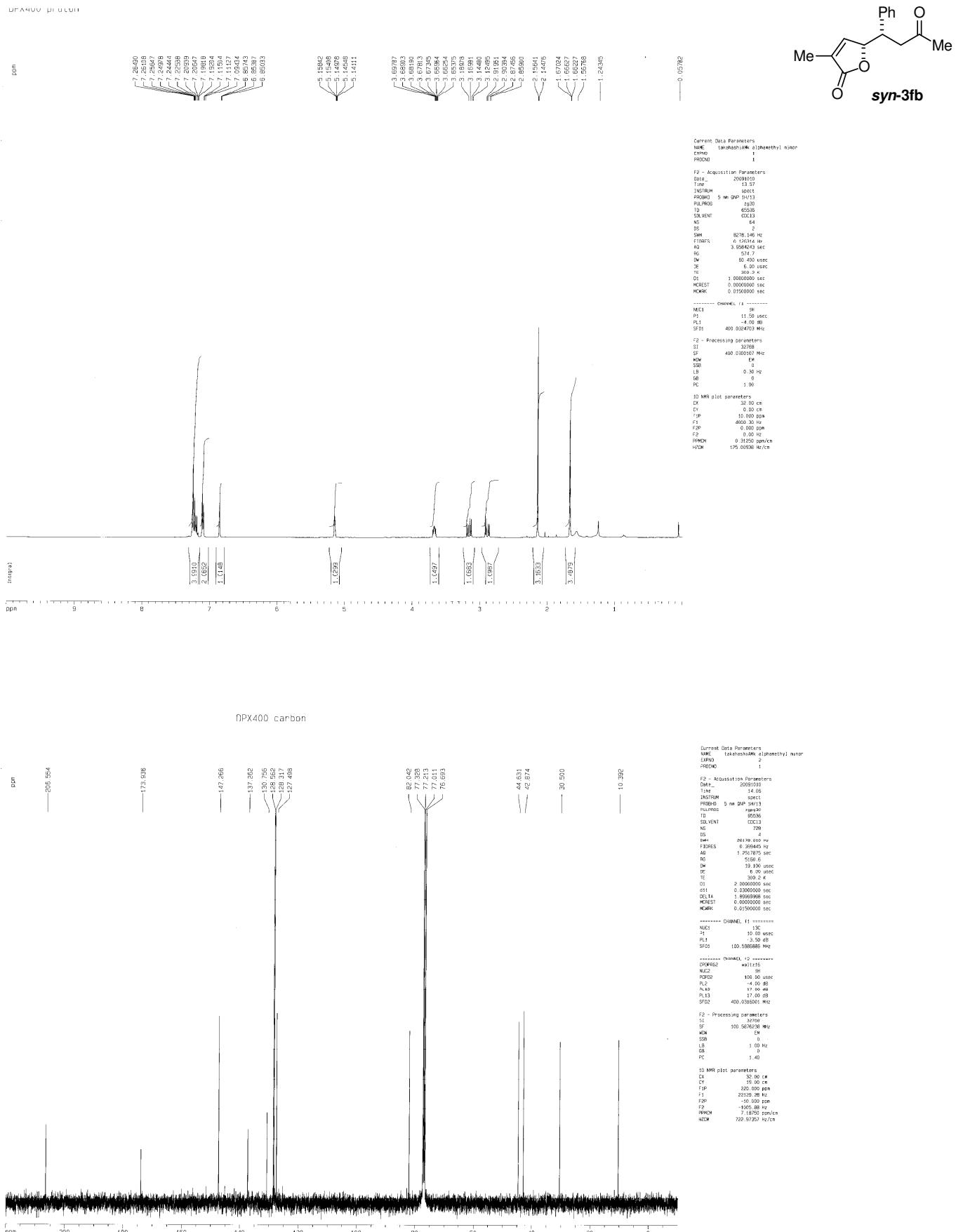




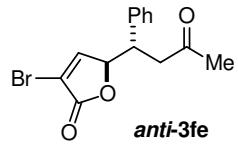
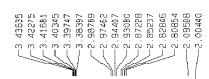
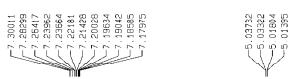








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EXPNO 1  
PROCNO 1

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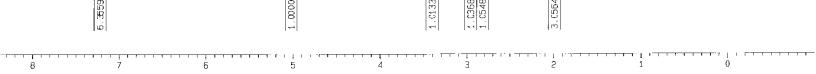
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SOLVENT CDCl3  
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DS 2  
SW1 8725.00 Hz  
T1 1.06314 sec  
AQ 3.9564243 sec  
RG 256  
DW 60.400 usec  
DE 6.00 usec  
TE 300.00  
D1 1.0000000 sec  
MIXT 0.0200000 sec  
NCWIR 0.01500000 sec

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PL1 -4.00 dB  
SFO1 400.0324703 MHz

F2 - Processing parameters  
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SF 400.0300000 MHz  
W0M EM  
SSB 0  
LB 0.30 Hz  
GB 0  
PC 1.00

1H NMR plot parameters  
CX 32.00 cm  
CY 21.00 cm  
F1P 10.000 ppm  
F1 4000.30 Hz  
F2P -1.000 ppm  
F2 -400.03 Hz  
P1WCH 0.33376 ppm/cm  
H2DM 137.51031 Hz/cm

ppm



DPX400 carbon

ppm

205.487

167.919

151.839

138.676

129.139

128.050

128.324

84.998

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77.051

76.744

14.932

14.251

30.551

Current Data Parameters  
NAME takahashiAM003  
EXPNO 4  
PROCNO 1

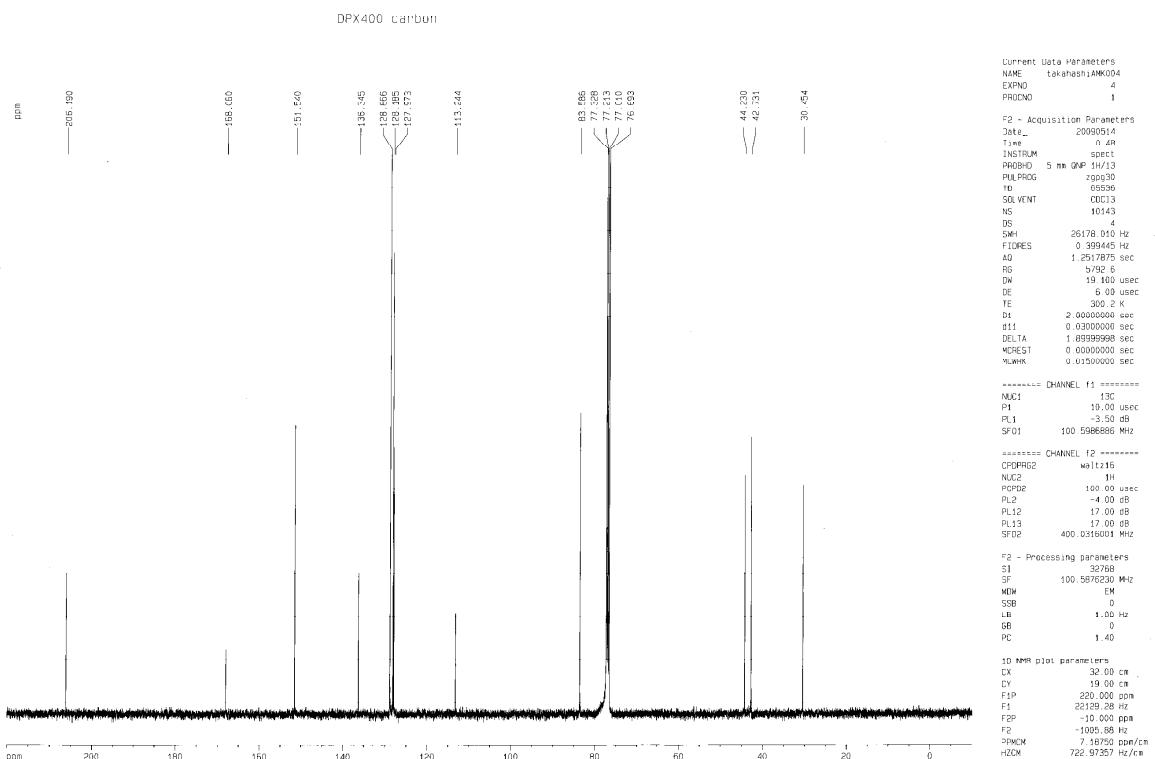
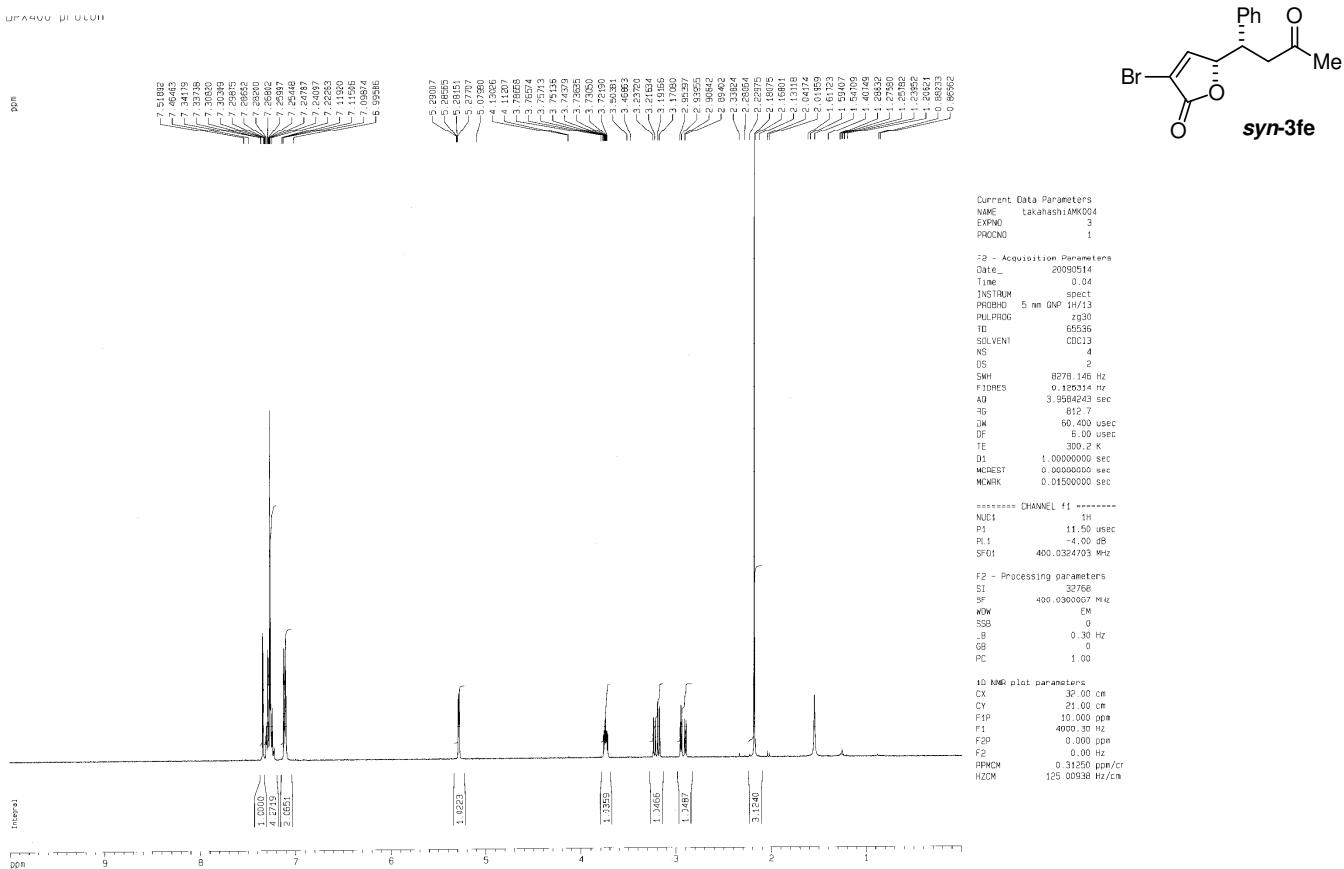
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DS 4  
SW1 26179.010 Hz  
T1 0.299454 sec  
AQ 1.2517875 sec  
RG 6502  
DW 19.00 usec  
DE 0.00 usec  
TE 300.2 K  
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DE11A 1.8999998 sec  
MIXT 0.0000000 sec  
NCWIR 0.01900000 sec

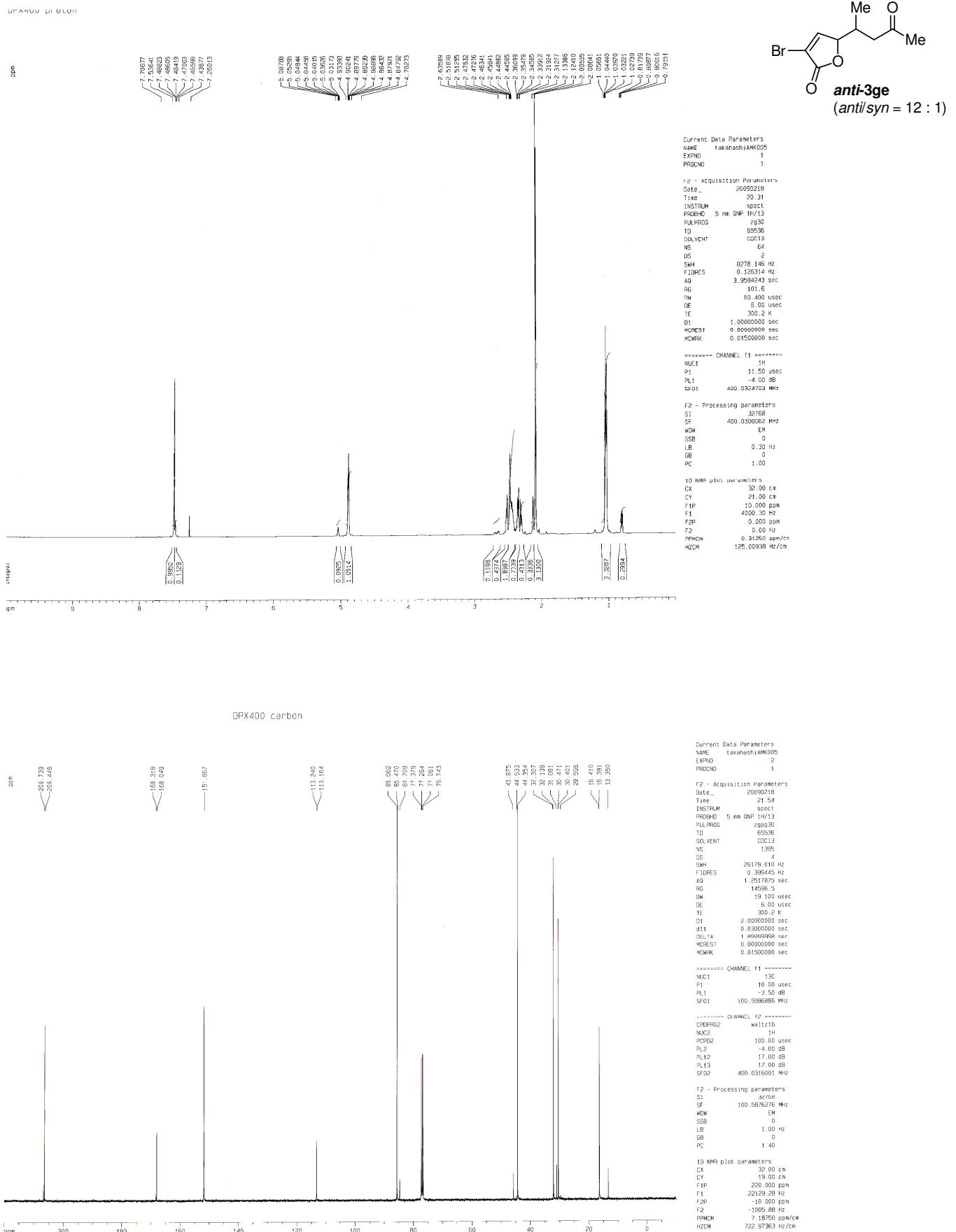
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PL1 -3.50 dB  
SFO1 100.5960000 MHz

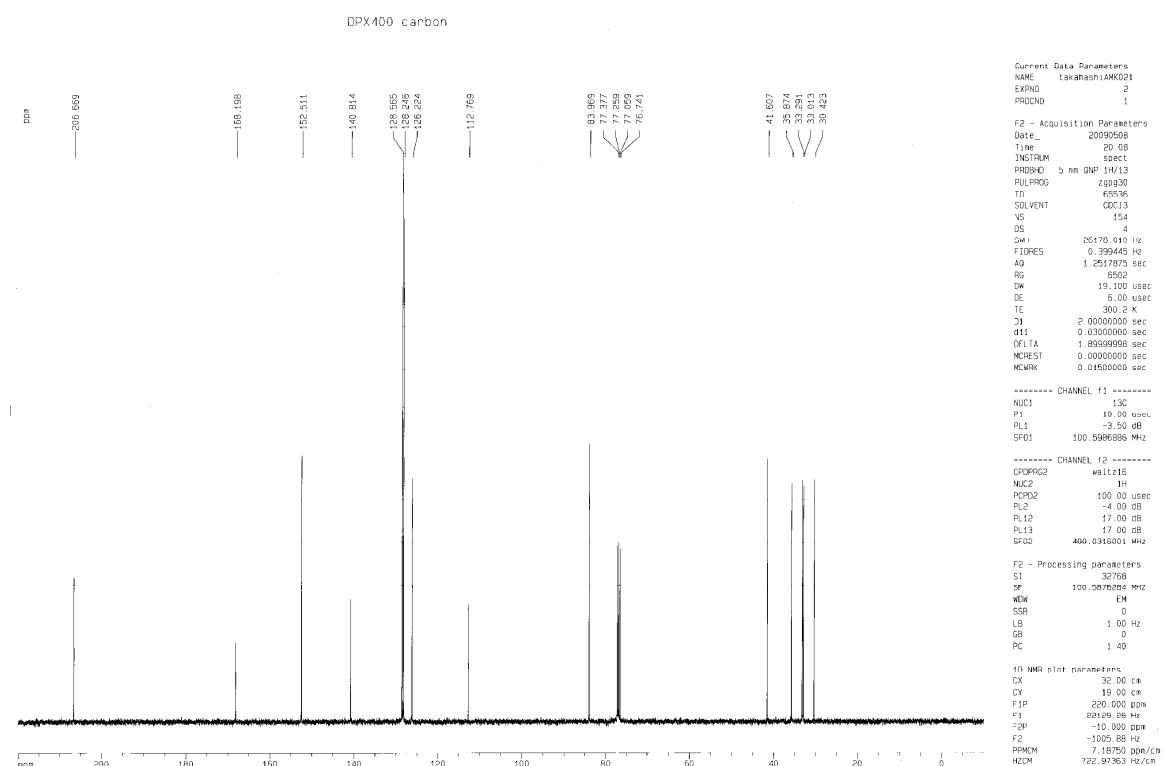
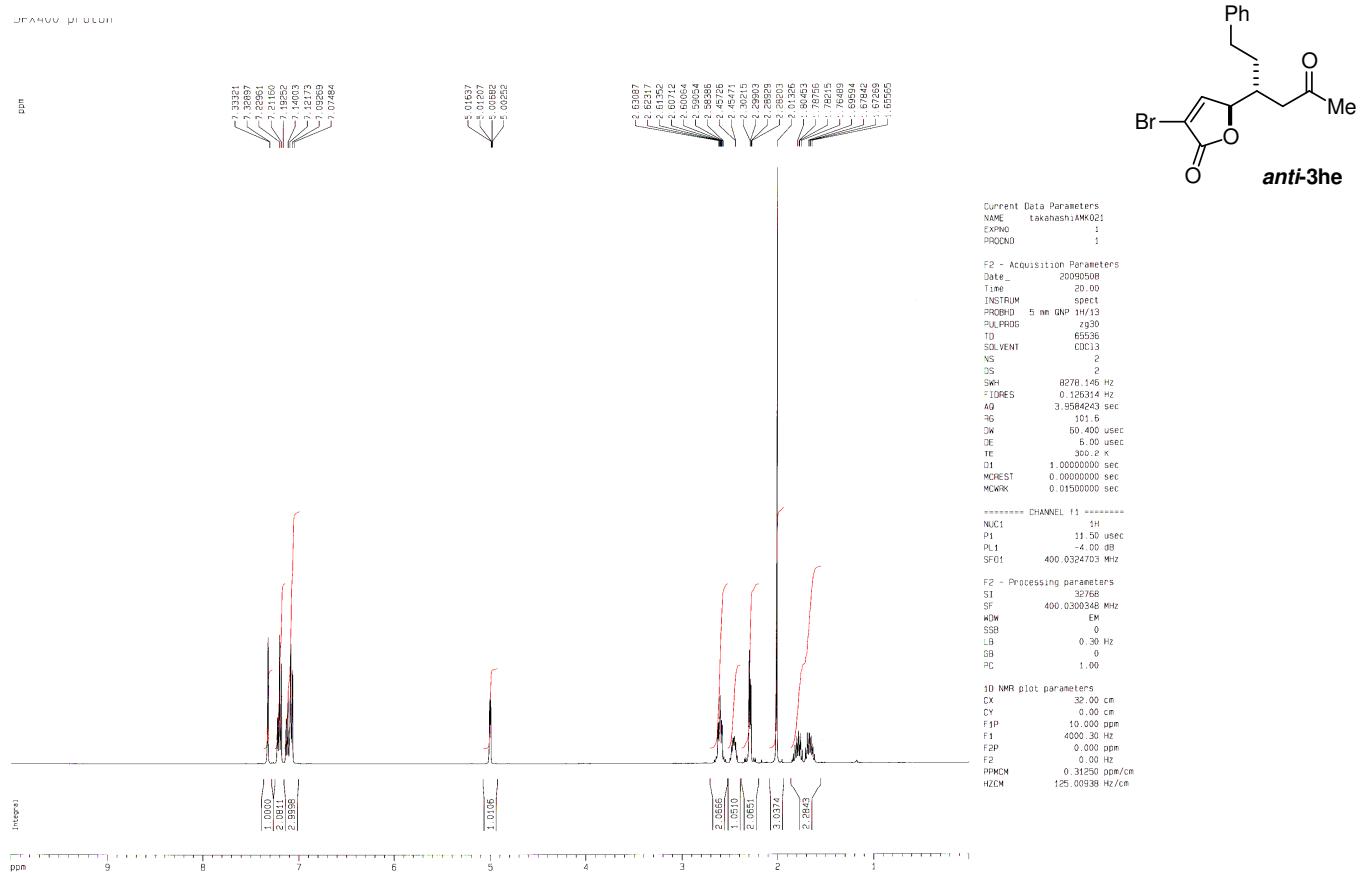
===== CHANNEL f2 =====  
DPDPROG waltz16  
NUC2 1H  
PDPD2 100.00 usec  
M1C -4.00 dB  
PL12 17.00 dB  
PL13 17.00 dB  
SFO2 400.0316001 MHz

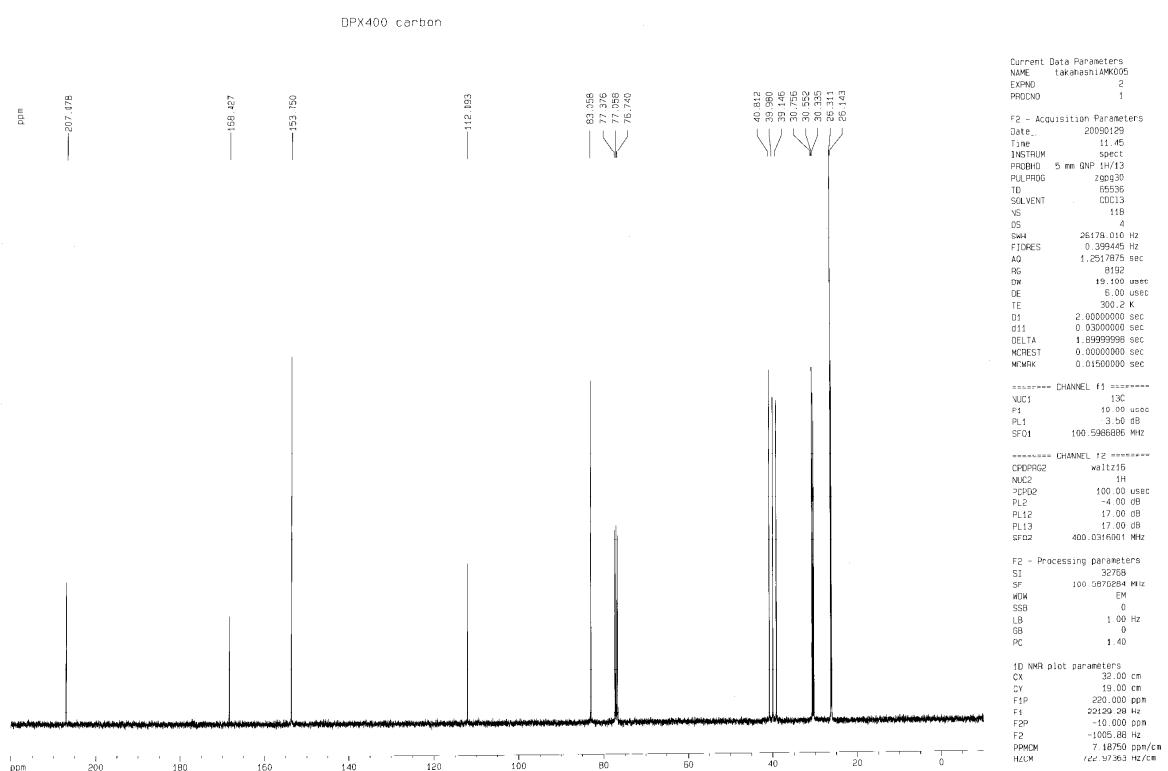
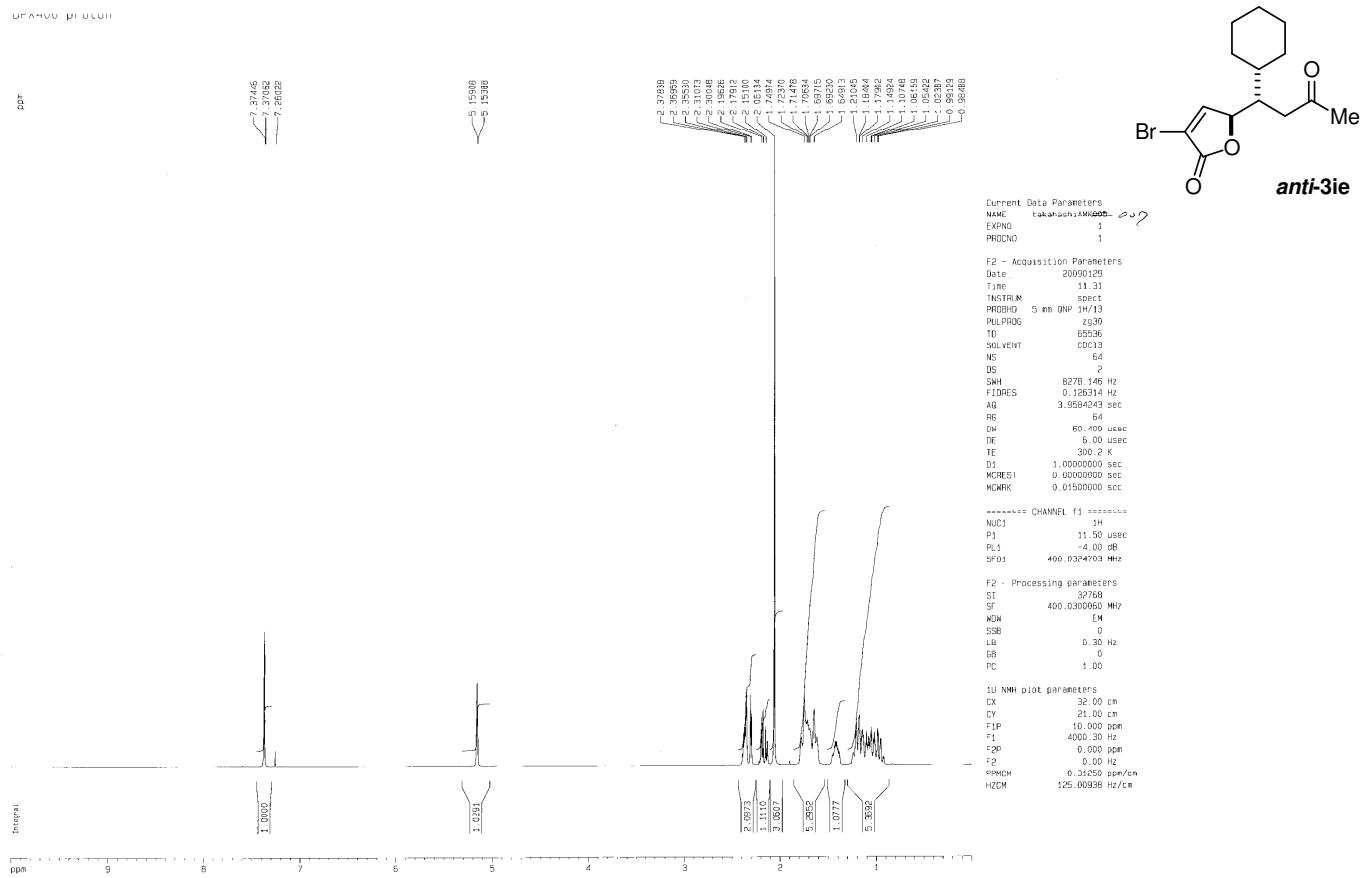
F2 - Processing parameters  
SI 32768  
SF 100.5876212 MHz  
W0M EM  
SSB 0  
LB 1.00 Hz  
GW 0  
RG 1.40

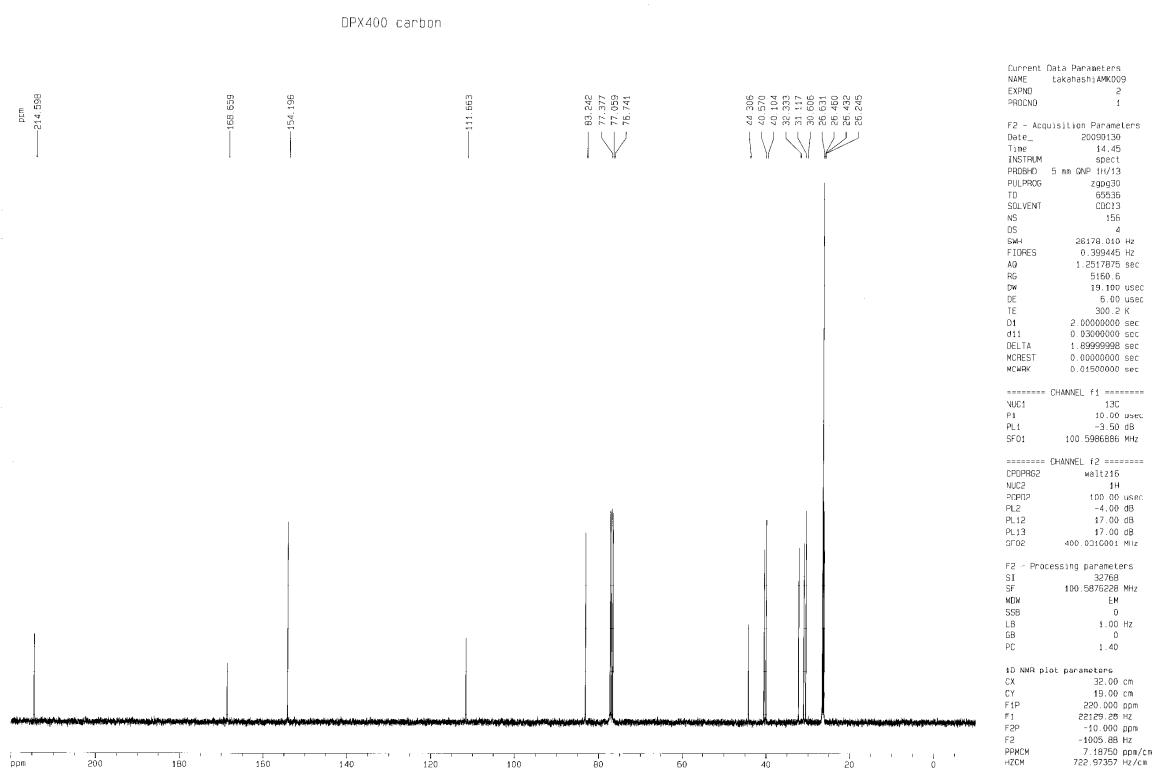
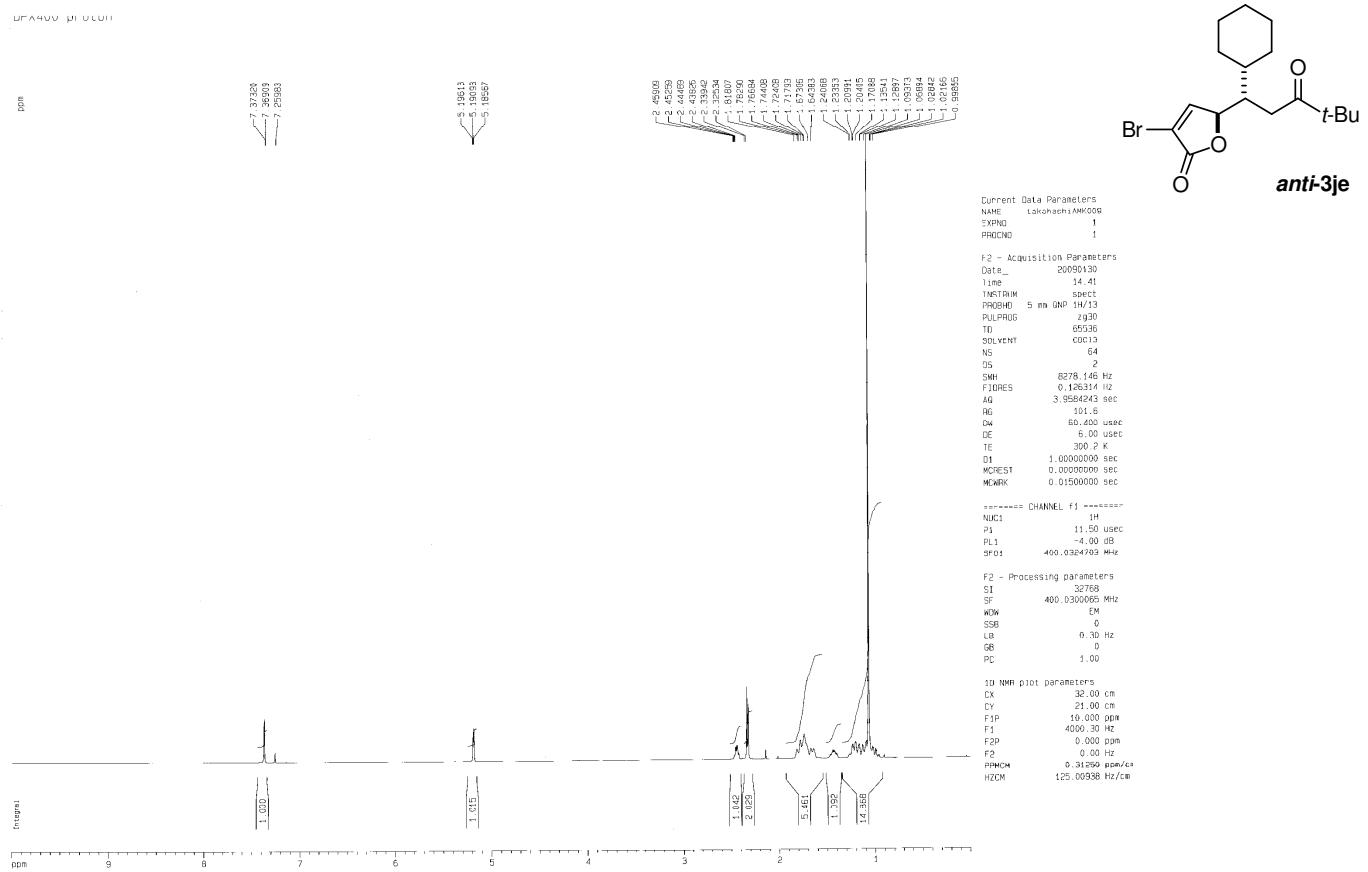
13C NMR plot parameters  
CX 32.00 cm  
CY 0.00 cm  
F1P 220.000 ppm  
F1 22129.28 Hz  
F2P -10.00 ppm  
F2 -105.88 Hz  
P1WCH 7.18750 ppm/cm  
H2DM 722.37207 Hz/cm



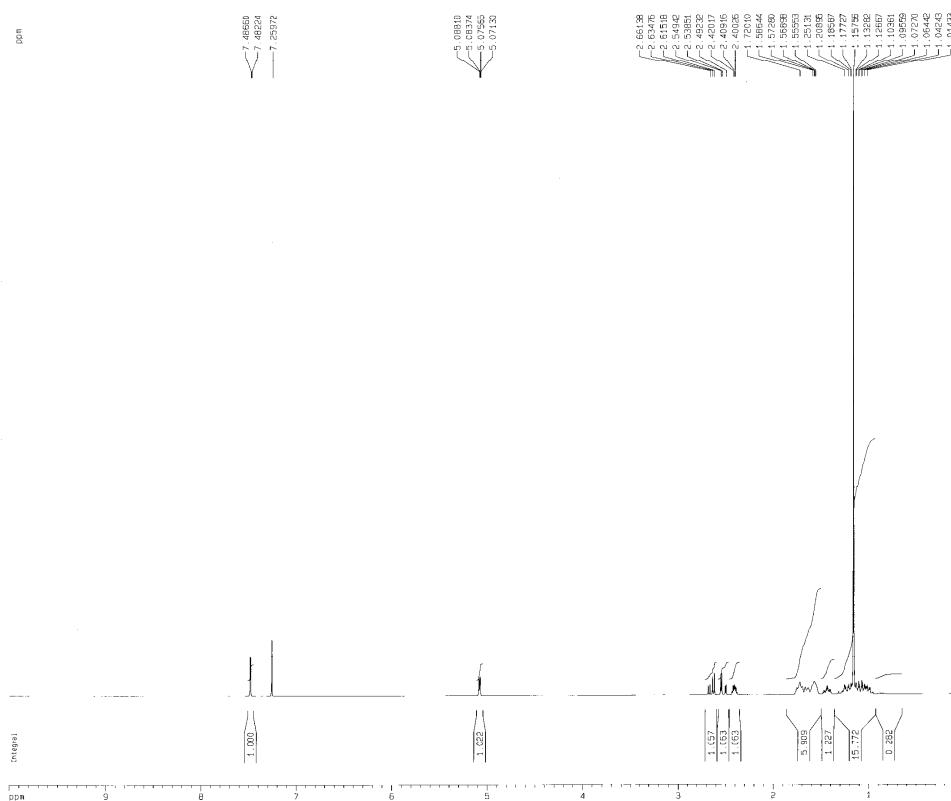




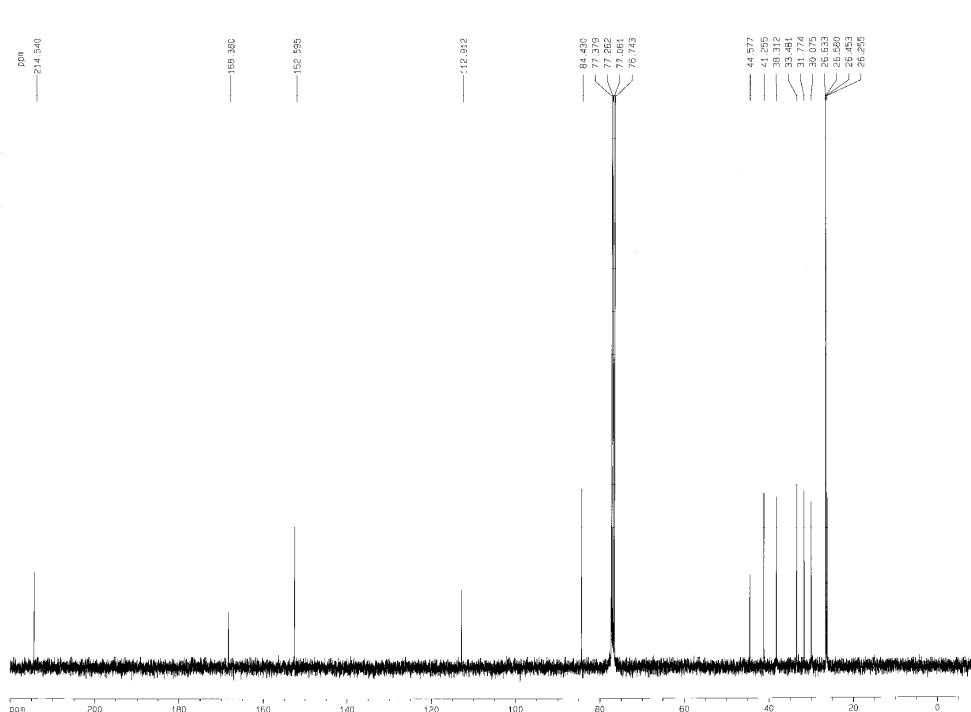


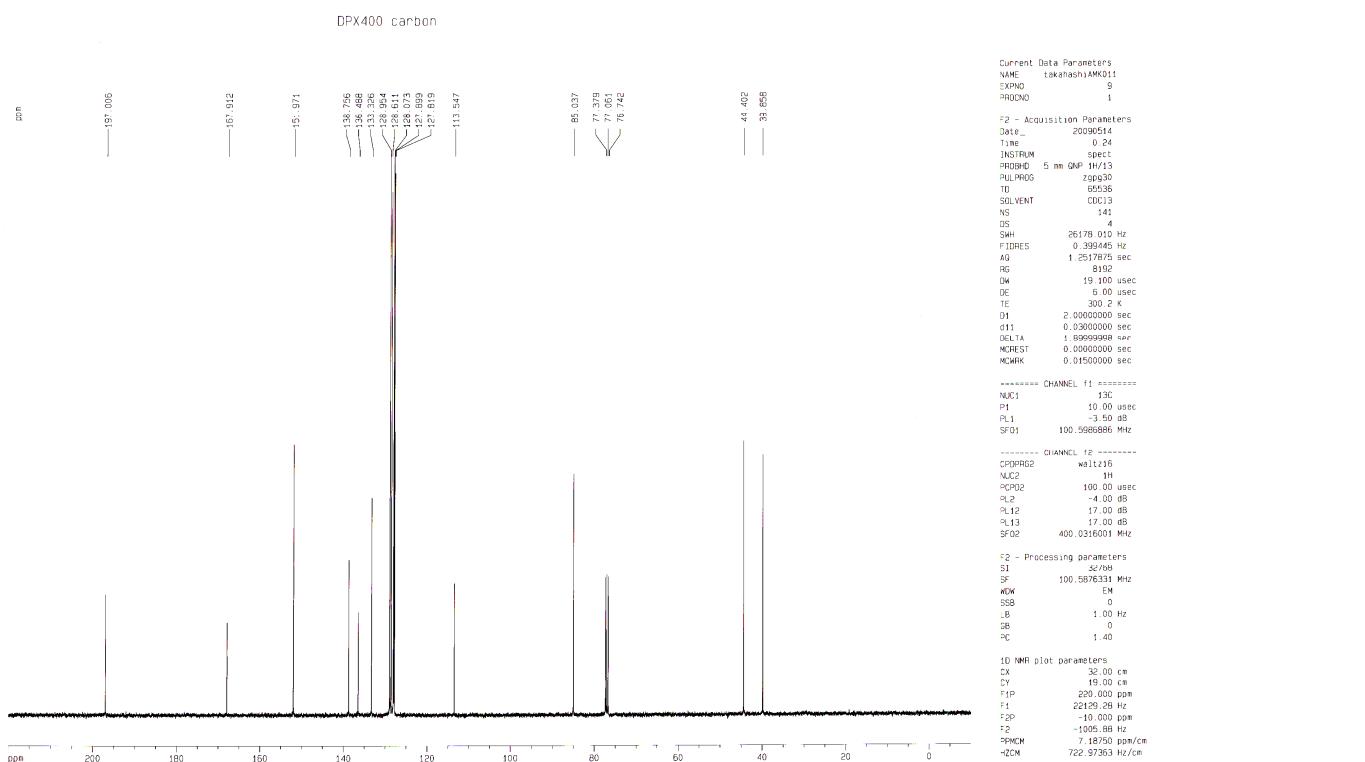
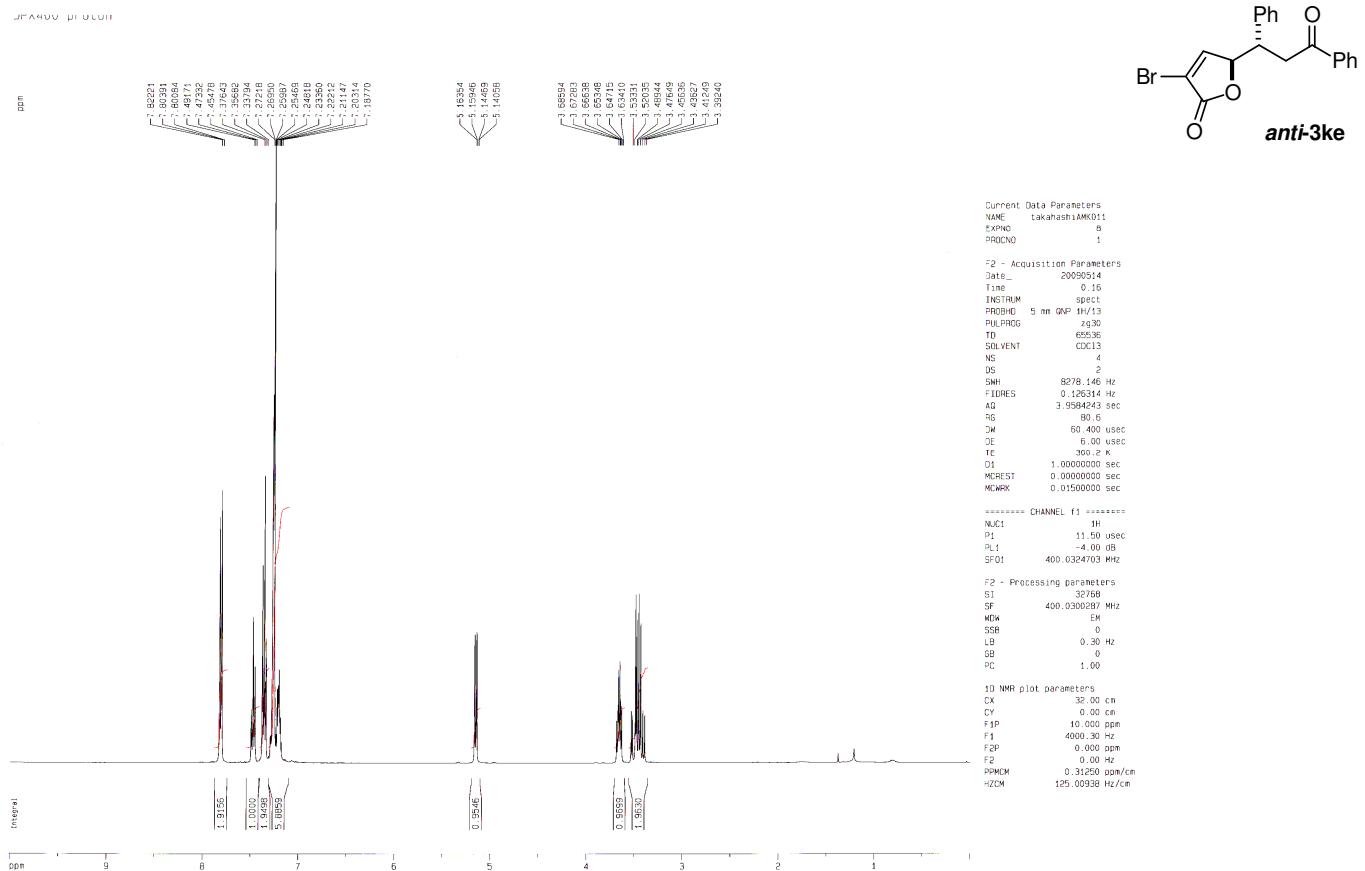


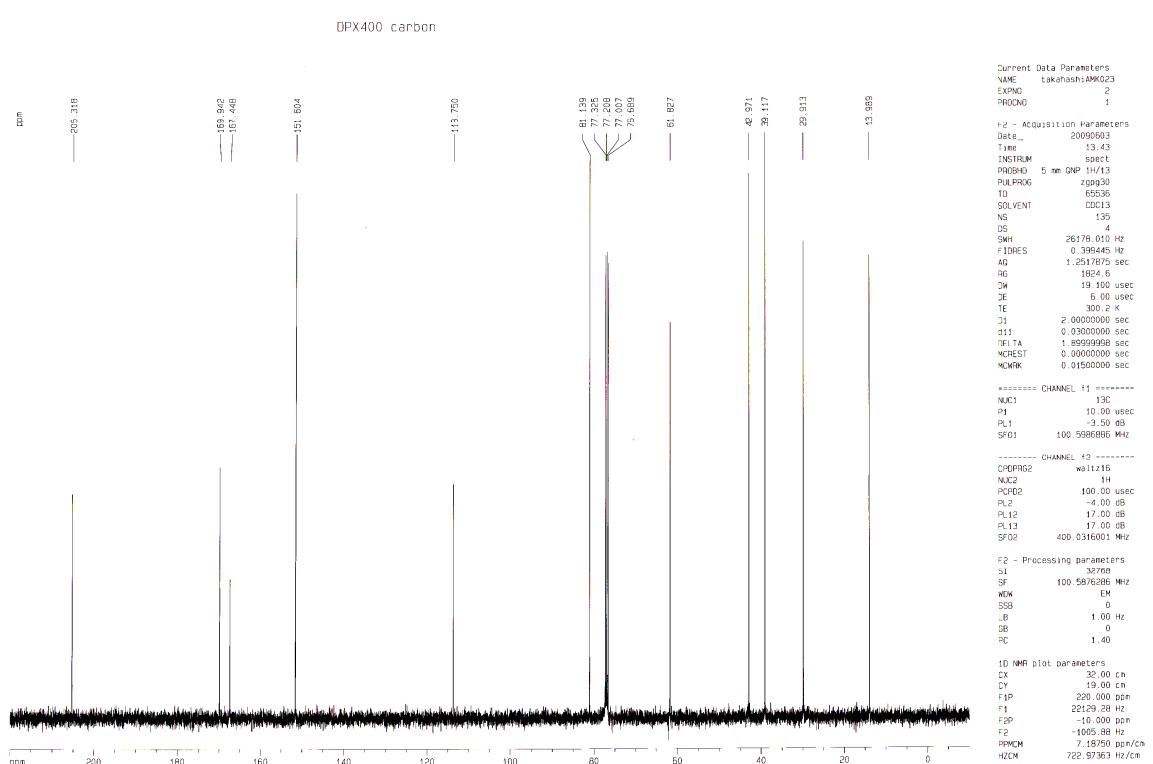
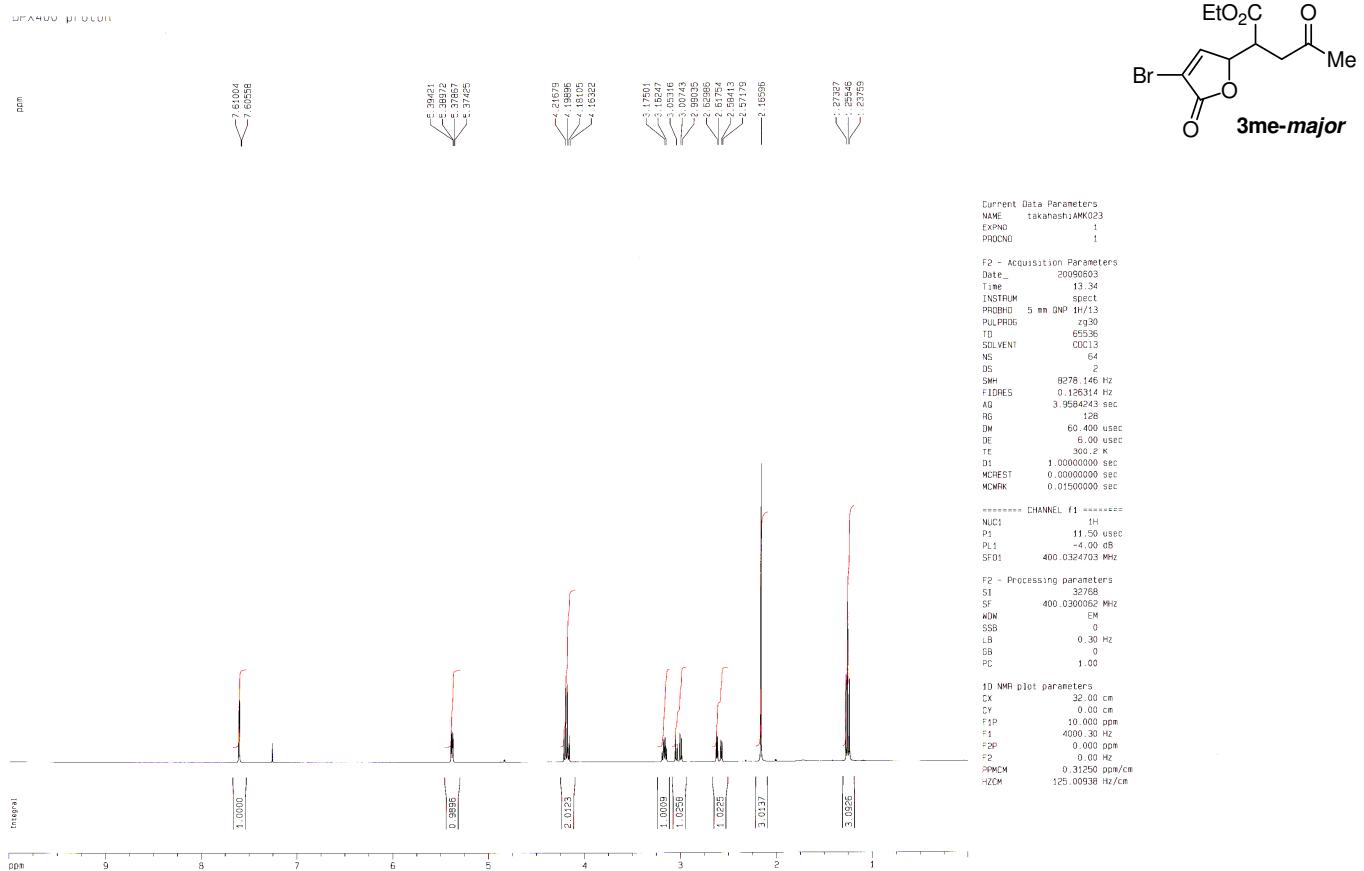
Data

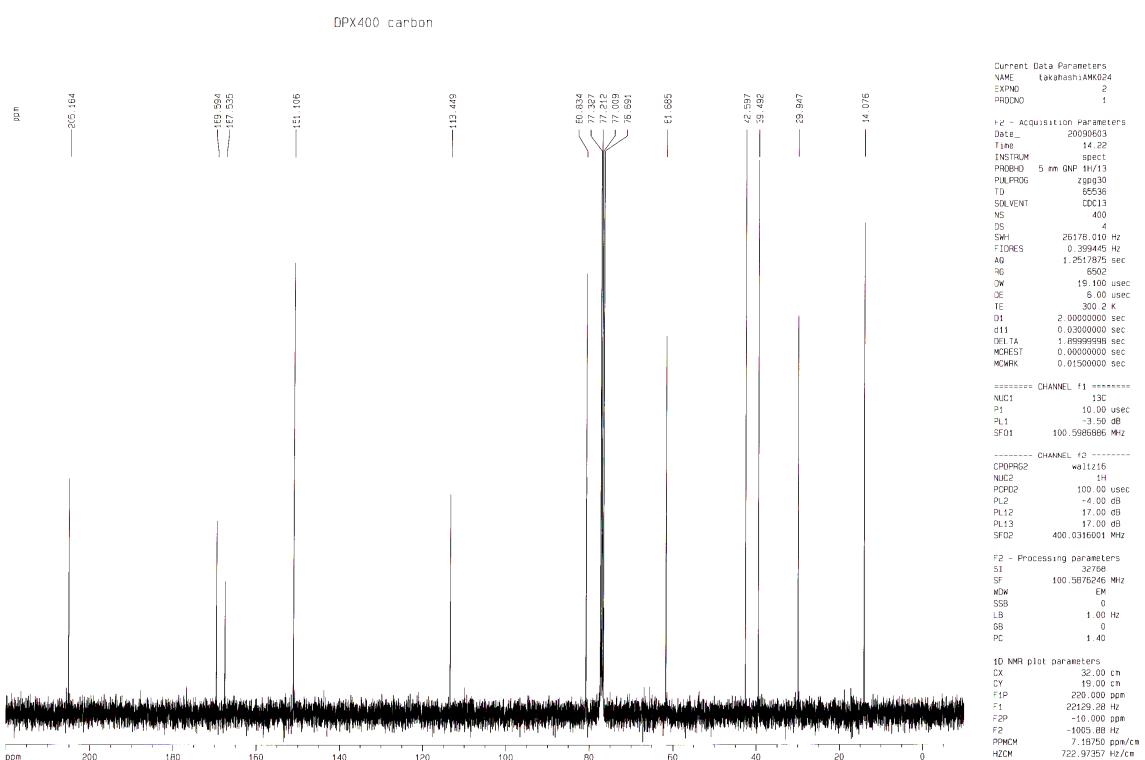
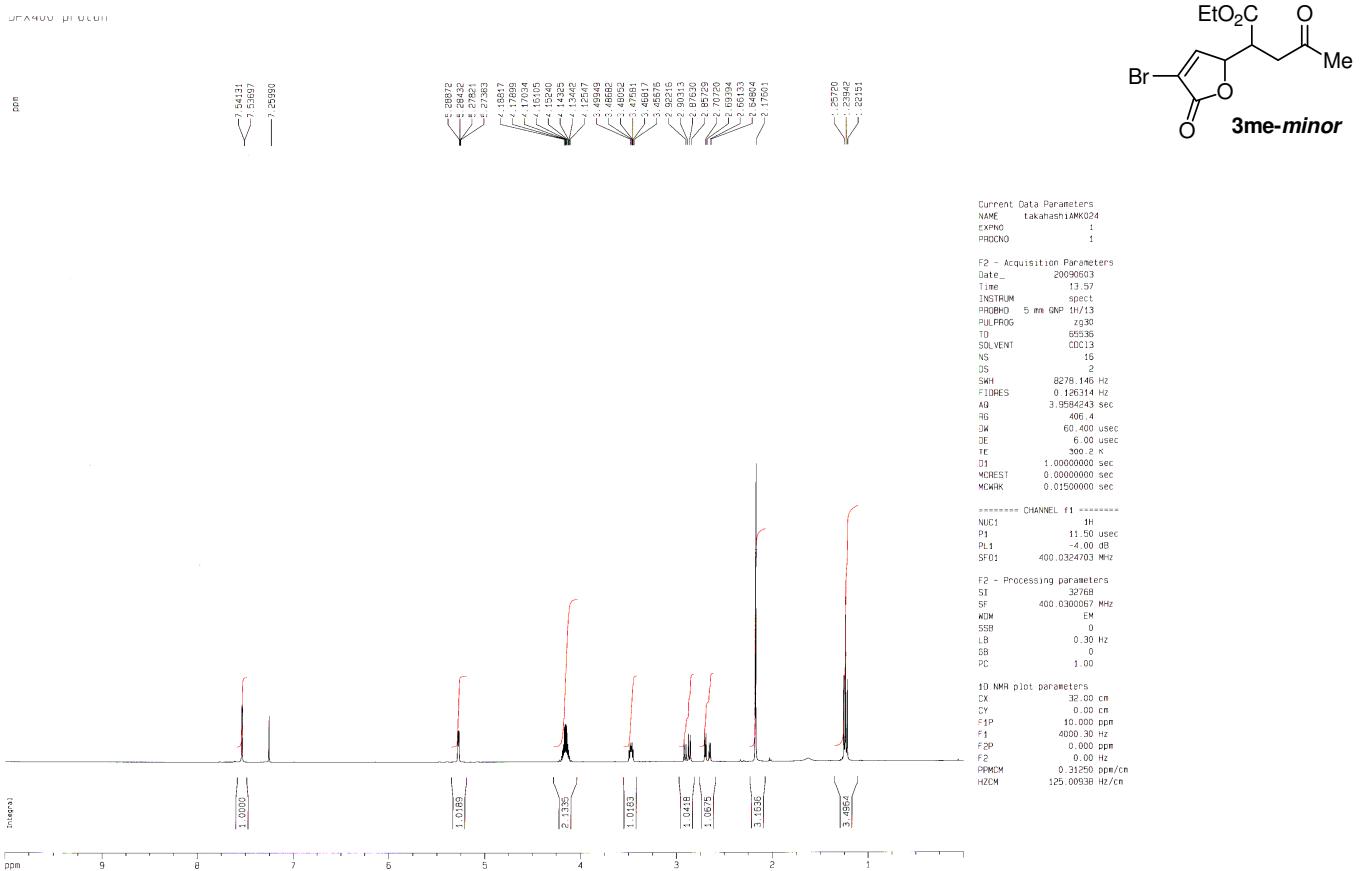


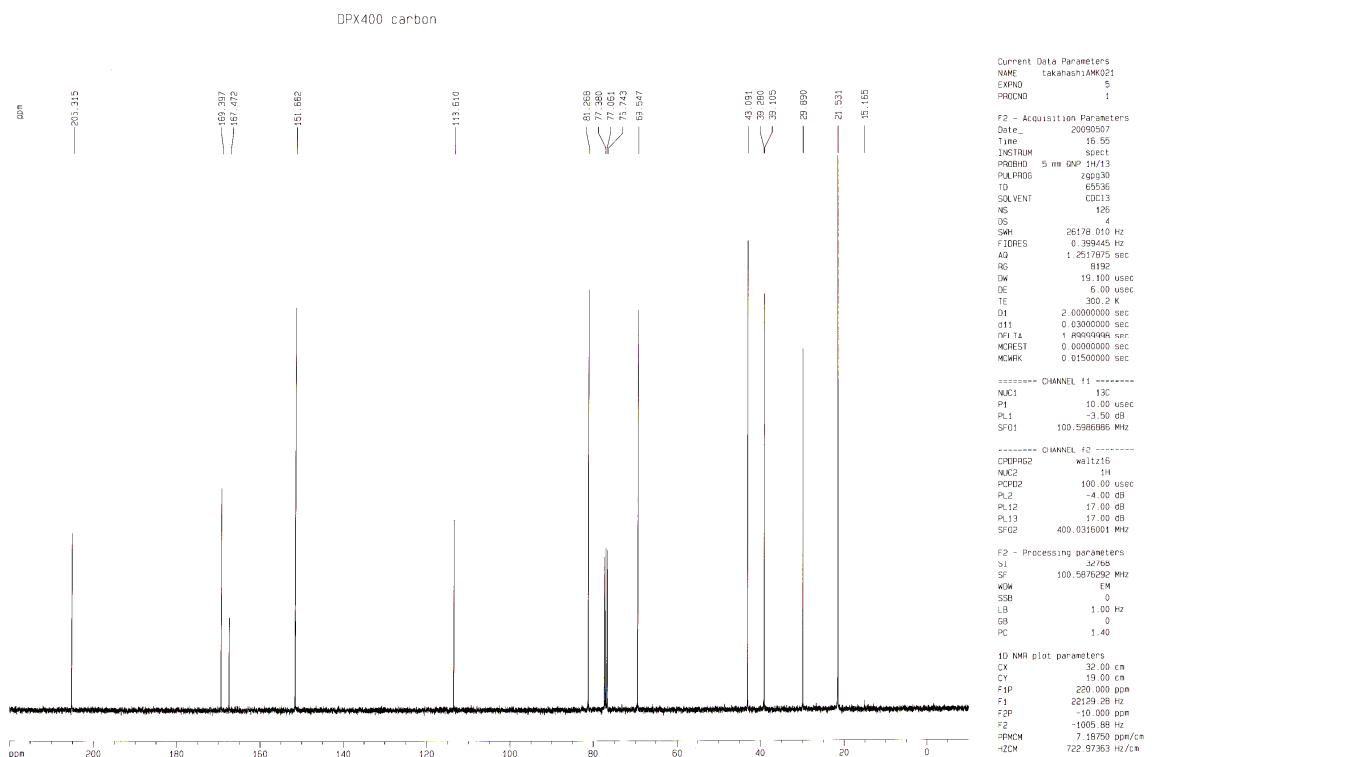
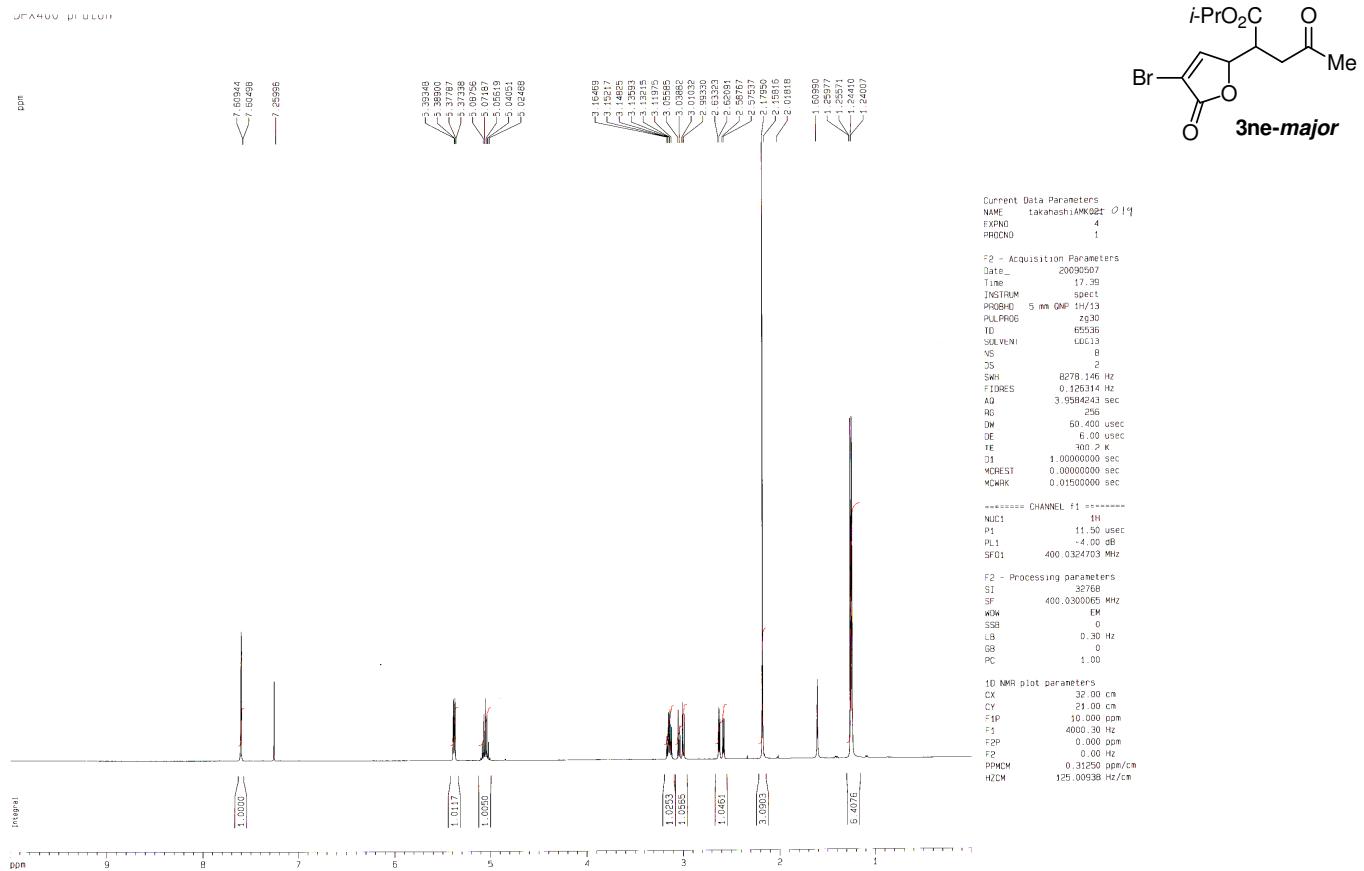
Data

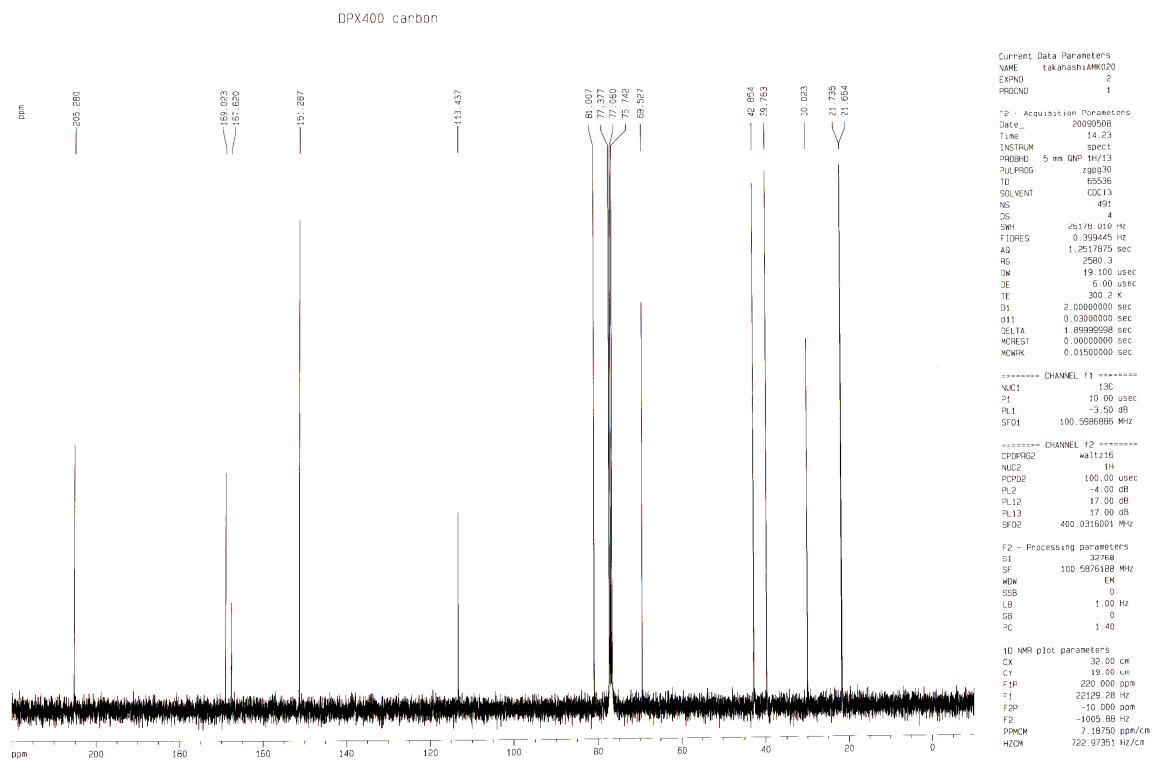
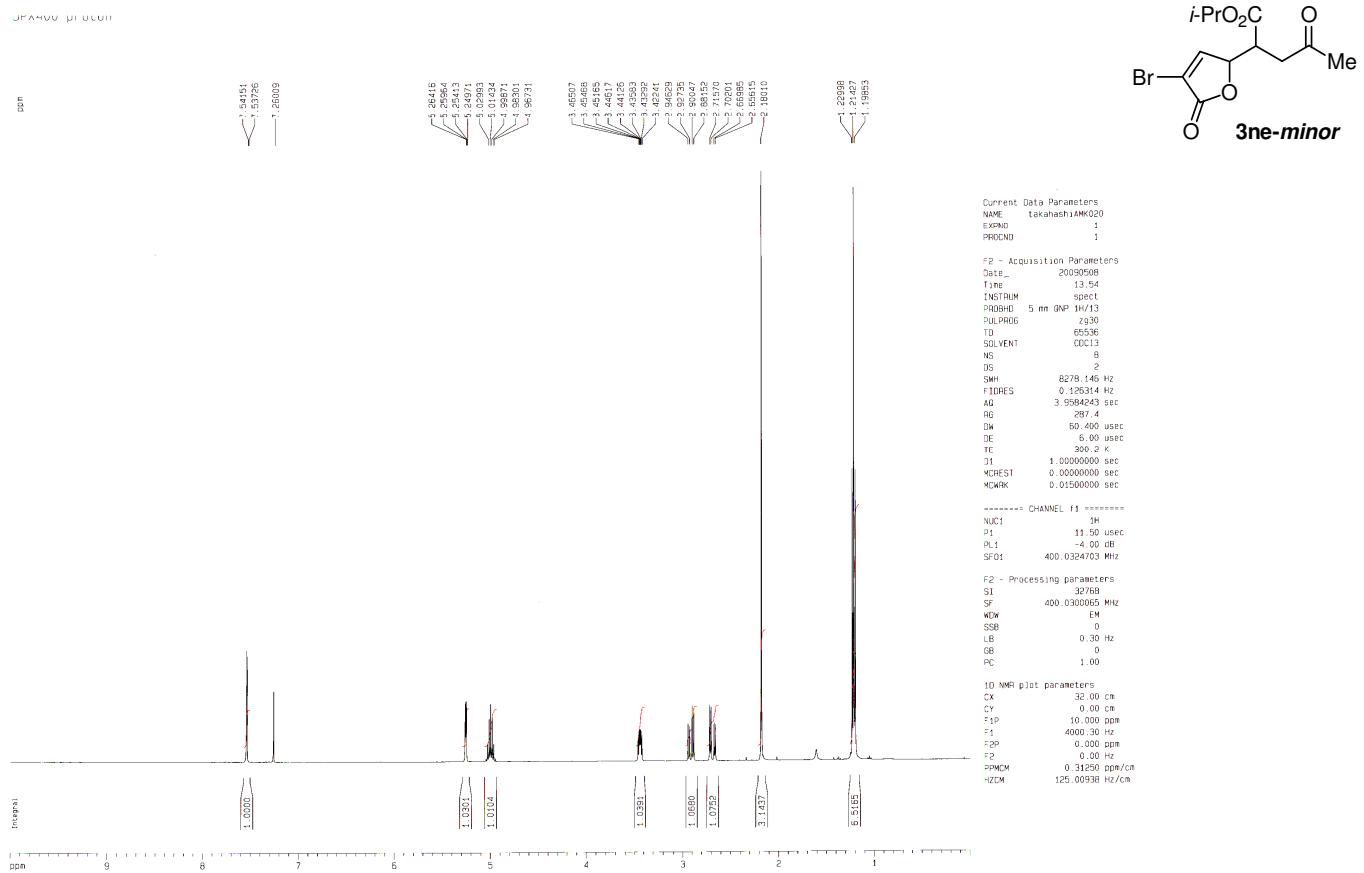




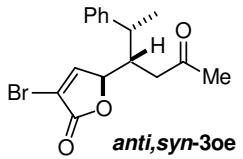
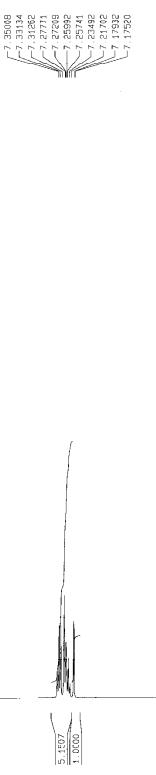








ppm



Current Data Parameters  
NAME: takahashiNMR-O-13  
EXPNO: 2  
PROCNO: 1

F2 - Acquisition Parameters

Date: 20090130

Time: 14:14

INSTRUM: spect

PROBHD: 5 mm QNP 1H/13

PULPROG: zgpg30

TD: 65536

SOLVENT: CDCl3

NS: 64

DS: 2

SWH: 8770.0 Hz

FIDRES: 0.128314 Hz

AQ: 3.958423 sec

RG: 101.6

DM: 60.000 usec

DE: 6.000 usec

TE: 300.2 sec

D1: 1.00000000 sec

MCREST: 0.00000000 sec

MCWRF: 0.01500000 sec

SF01: 400.0324703 MHz

F2 - Processing parameters

SI: 32768

SF: 400.0300000 MHz

WDW: FID

SSB: 0

LB: 0.30 Hz

GB: 0

PC: 1.00

1D NMR plot parameters

CX: 32.00 cm

CY: 0.00 cm

F1P: 10.000 ppm

F1: 4000.30 Hz

F2P: 0.0000 ppm

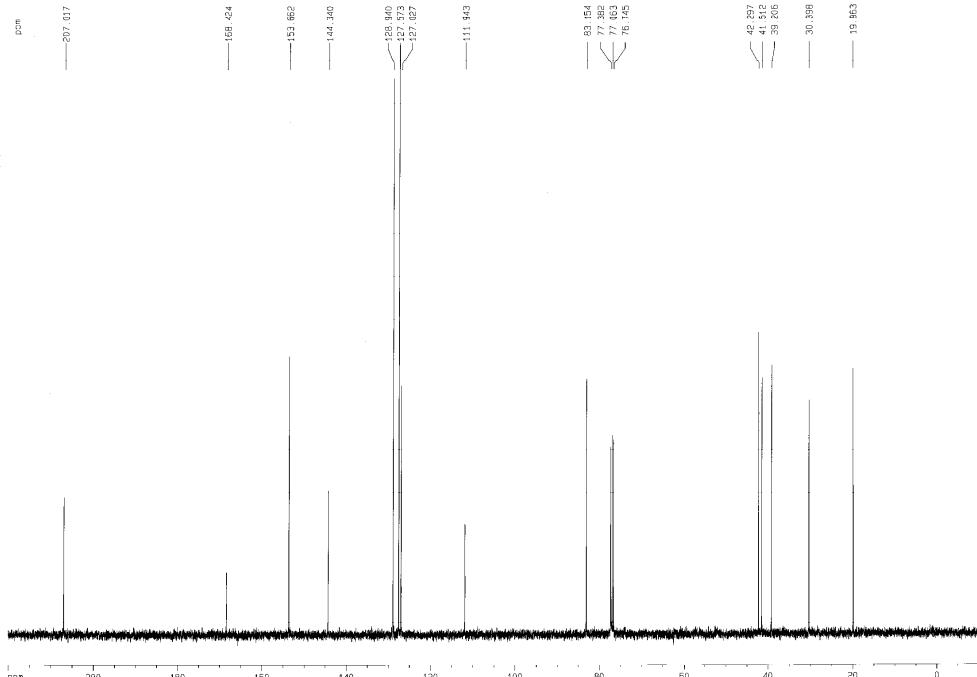
F3: 0.0000 ppm

RPMOM: 0.31826 ppm/cm

HZCM: 125.00538 Hz/cm

## DPX400 carbon

ppm



Current Data Parameters  
NAME: takahashiNMR-13  
EXPNO: 3  
PROCNO: 1

F2 - Acquisition Parameters

Date: 20090130

Time: 14:23

INSTRUM: spect

PROBHD: 5 mm QNP 1H/13

PULPROG: zgpg30

TD: 65536

SOLVENT: CDCl3

NS: 79

DS: 4

SWH: 26180.00 Hz

FIDRES: 0.39945 Hz

AQ: 1.2517875 sec

RG: 142.5

DE: 19.00 usec

TE: 300.2 K

D1: 2.0000000 sec

D11: 0.0300000 sec

DE1TA: 1.00000000 sec

MCREST: 0.01500000 sec

MCWRF: 0.01500000 sec

SF01: 100.5986885 MHz

F2 - Processing parameters

SI: 32768

SF: 100.5976525 MHz

WDW: FID

SSB: 0

LB: 1.00 Hz

GB: 0

PC: 1.40

1D NMR plot parameters

CX: 32.00 cm

CY: 19.00 cm

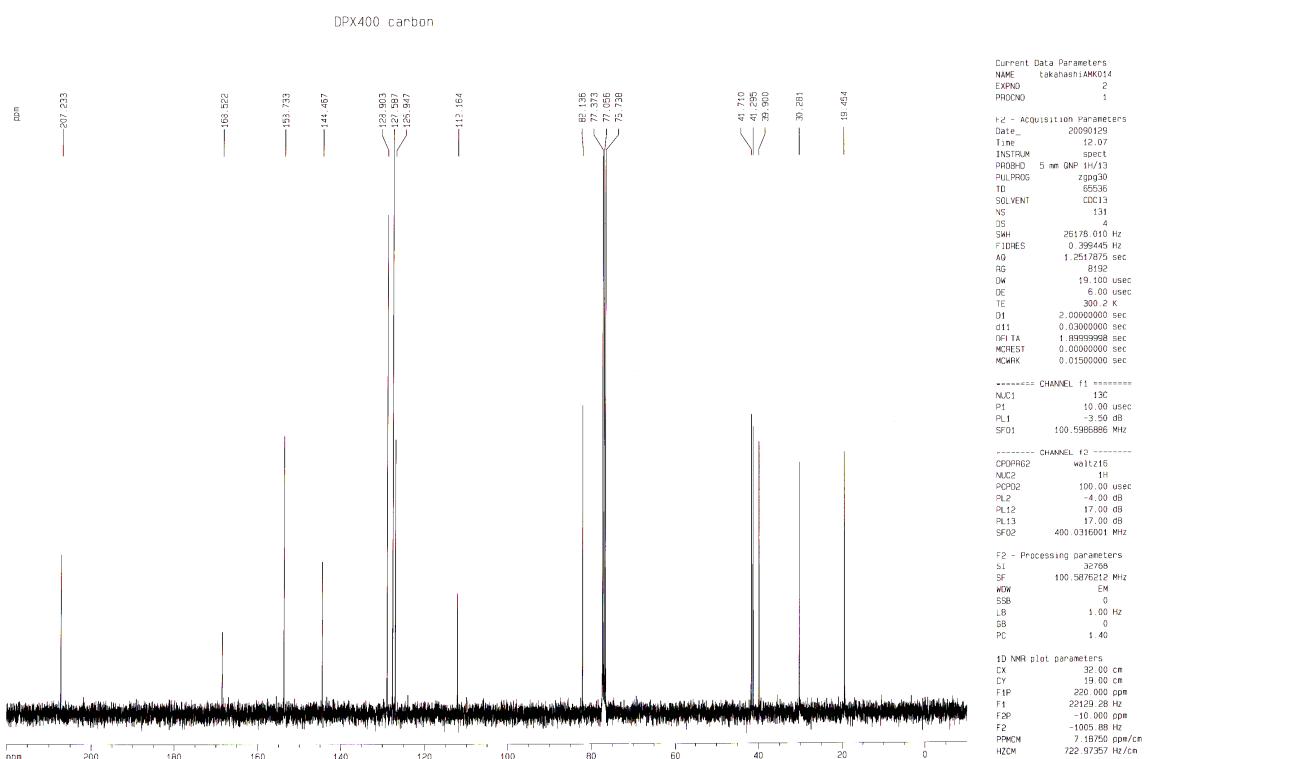
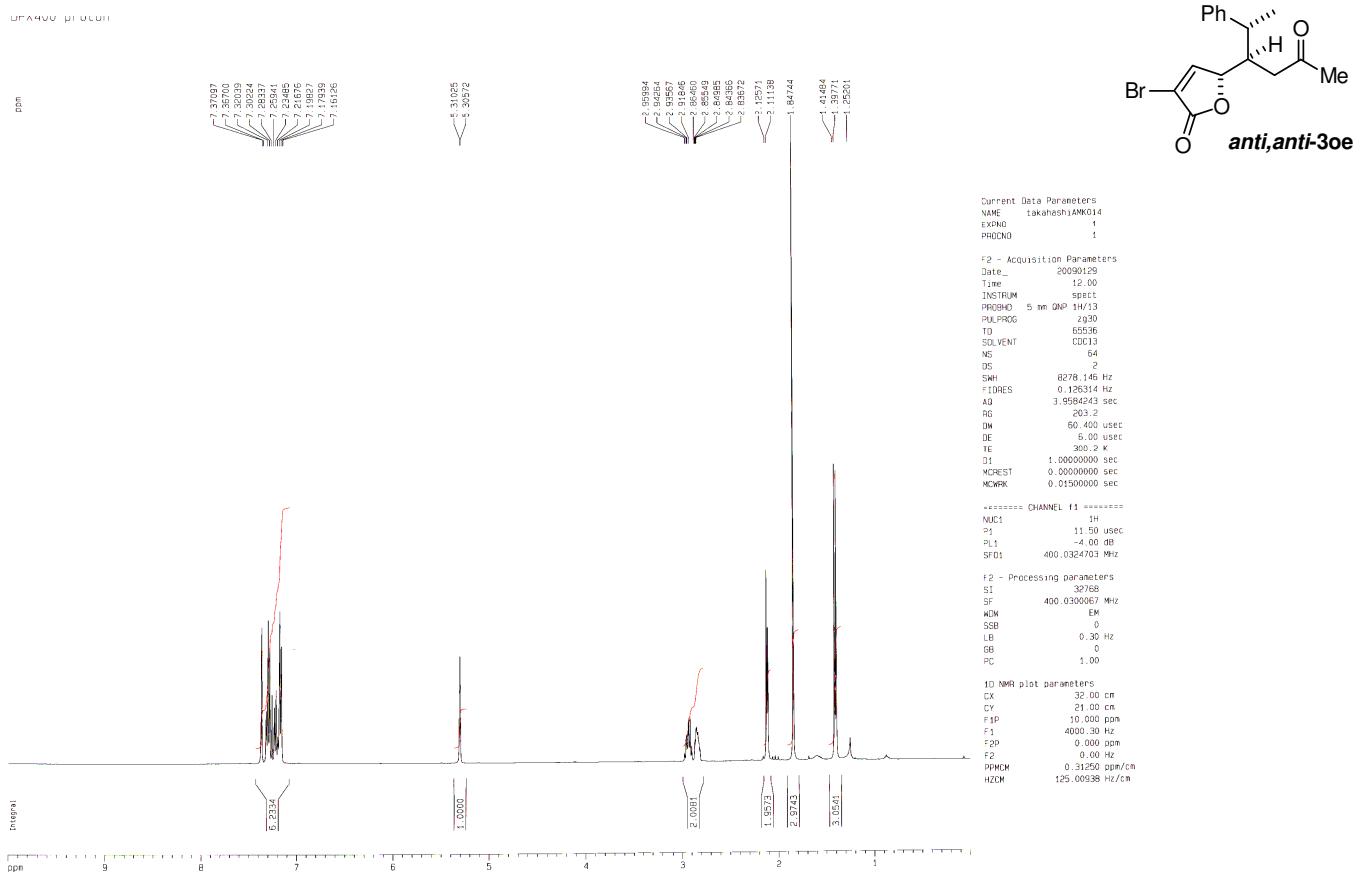
F1P: 220.000 ppm

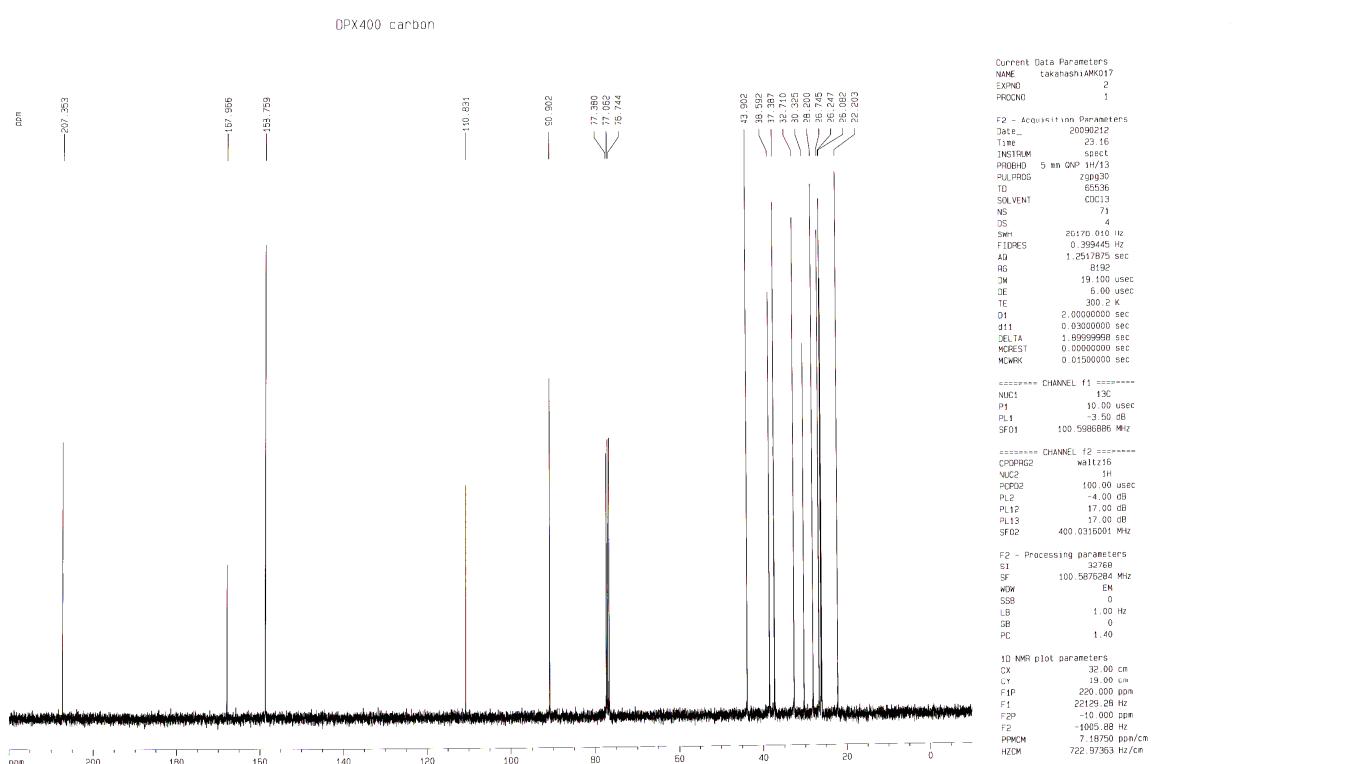
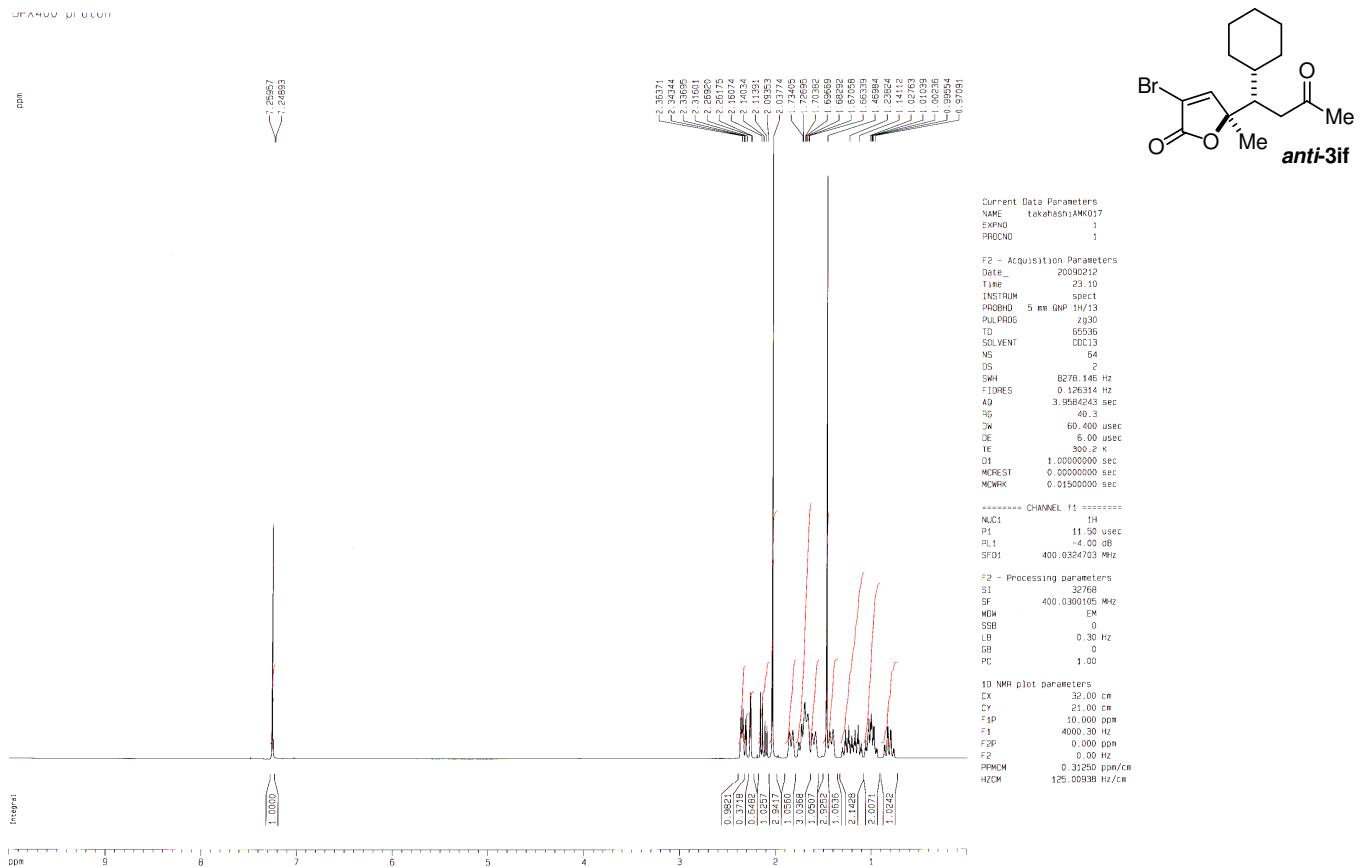
F1: 22129.28 Hz

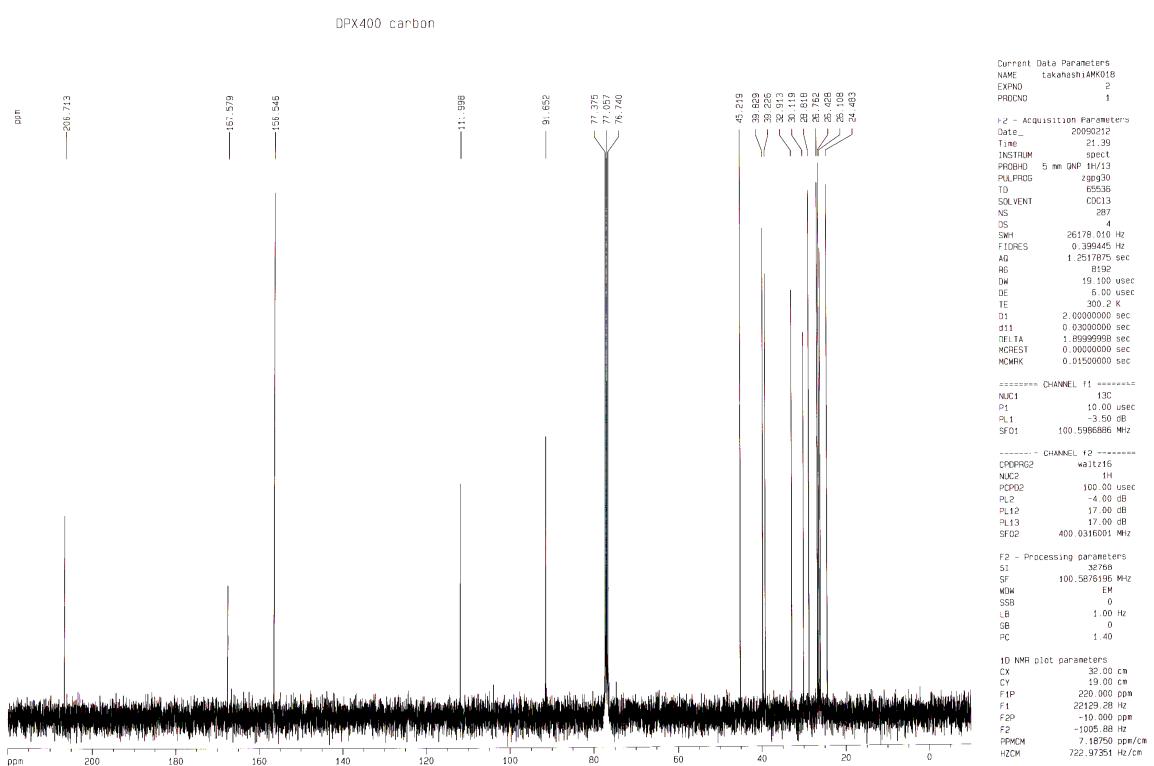
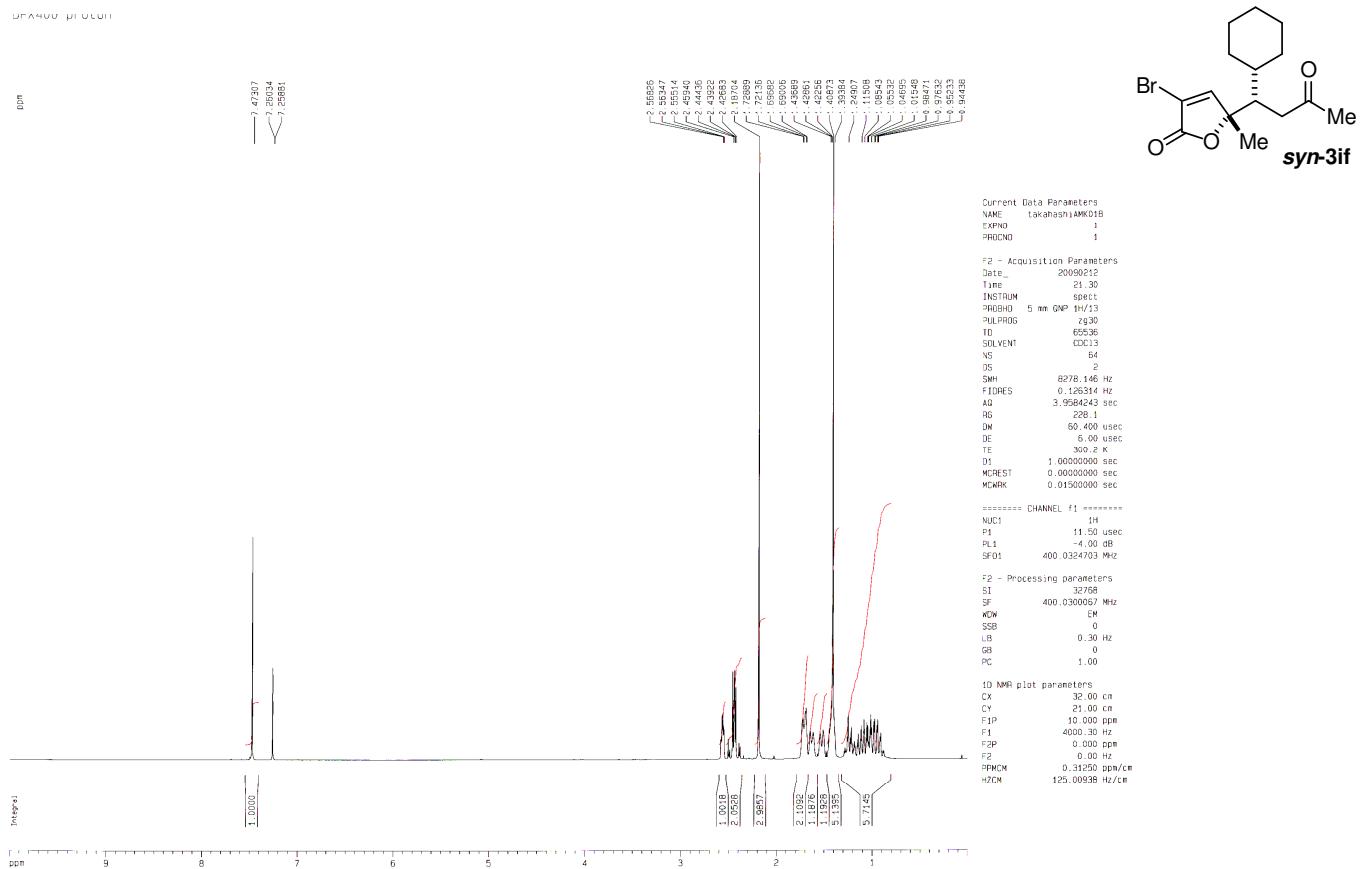
F2P: -105.88 ppm

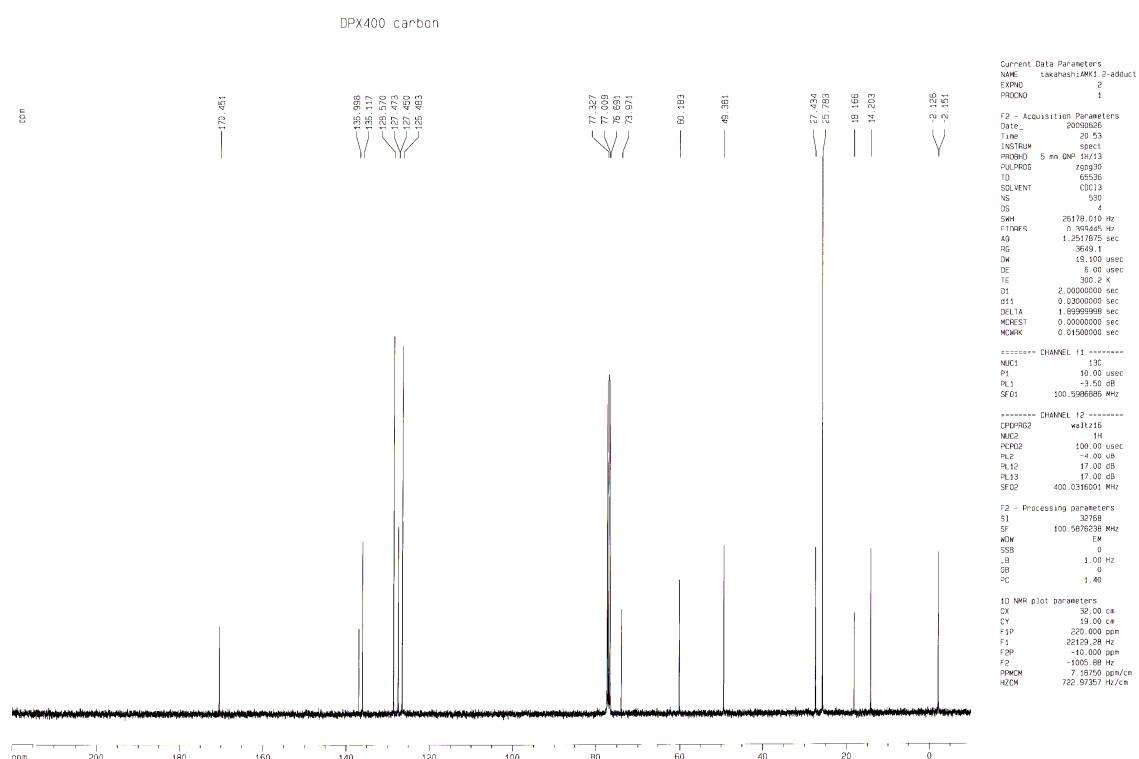
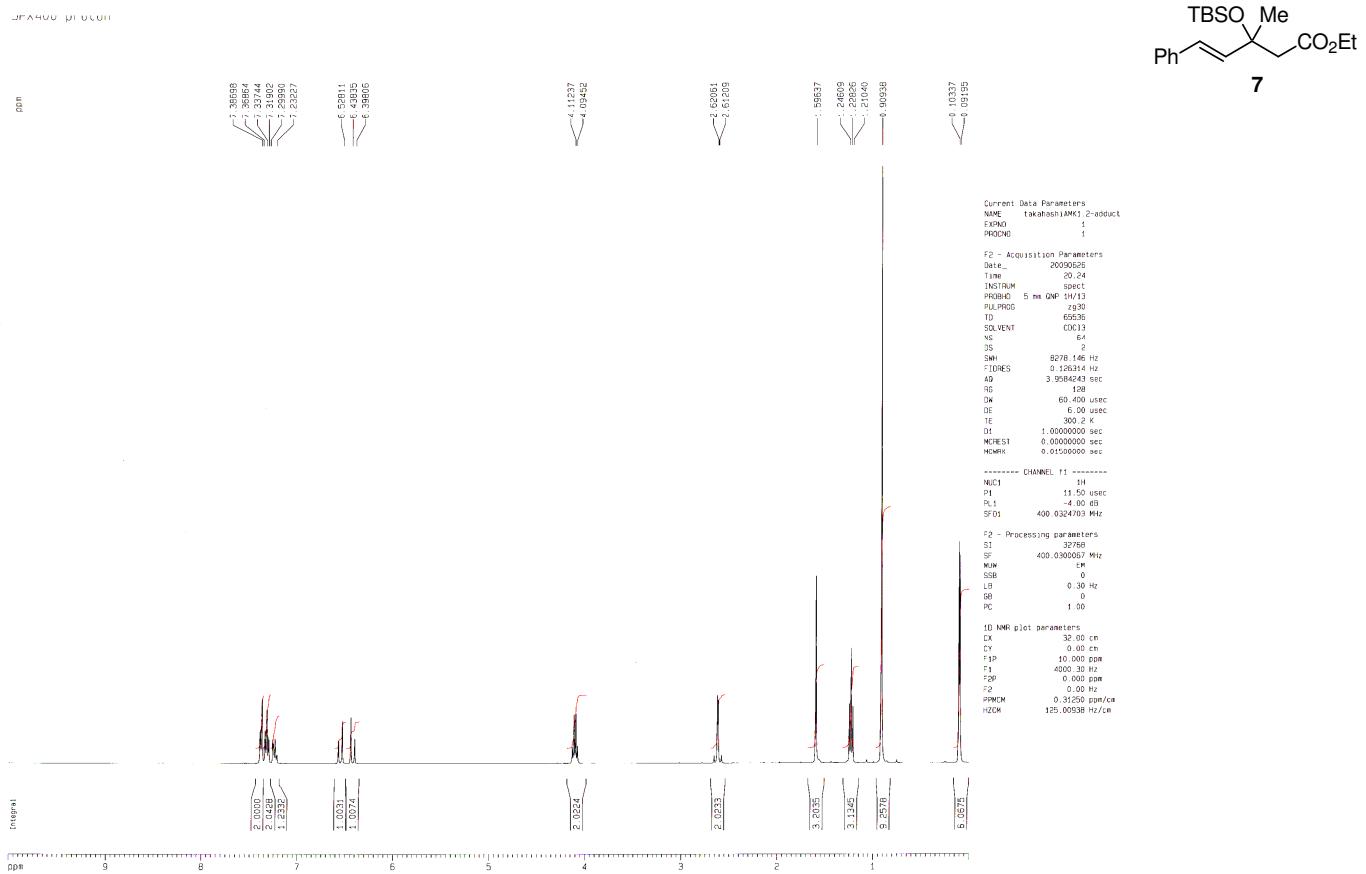
RPMOM: 7.18750 ppm/cm

HZCM: 722.97257 Hz/cm



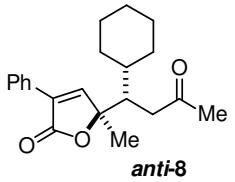
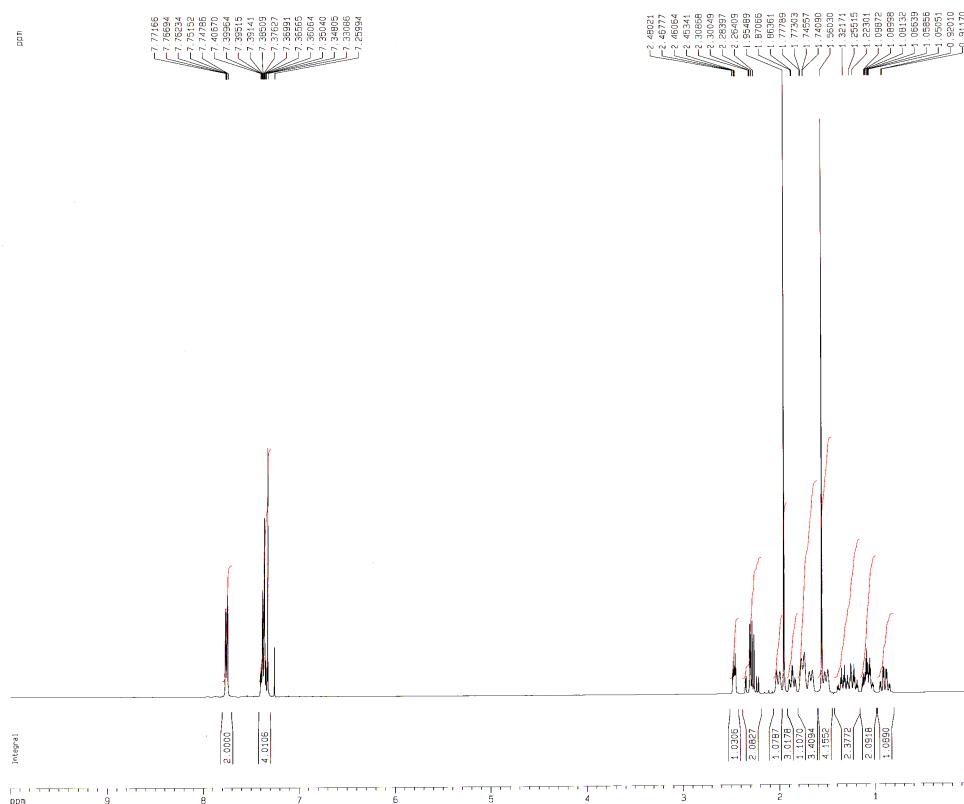






DPX400, 1H, 13C

ppm



Current Data Parameters  
NAME: TAKAHASHIANK017-2  
EXPNO: 1  
PROCNO: 1

F2 - Acquisition Parameters

Date: 20090425

Time: 11.31

INSTRUM: spect

PROBHD: 5 mm QNP 1H/13

PULPROG: zg30

TD: 65536

SOLVENT: CDCl3

NS: 10

DS: 2

SWH: 8278.140 Hz

ETR: 0.126314 Hz

AQ: 3.958423 sec

RG: 143.7

DW: 60.00 usec

DE: 6.00 usec

TE: 300.2 K

D1: 1.0000000 sec

MCRES1: 0.0000000 sec

MEMEK: 0.0150000 sec

NCMR: 1.00

\*\*\*\*\* CHANNEL f1 \*\*\*\*\*

NUC1: 1H

P1: 11.50 usec

PL1: -4.00 dB

SF01: 400.0324703 MHz

F2 - Processing parameters

SI: 32768

SF: 400.0300658 MHz

WDW: EM

SSB: 0

LB: 0.30 Hz

GB: 0

PC: 1.00

1D NMR plot parameters

CX: 30.00 cm

CY: 21.00 cm

F1P: 10,000 ppm

F1: 4000.30 Hz

F2P: 0.000 ppm

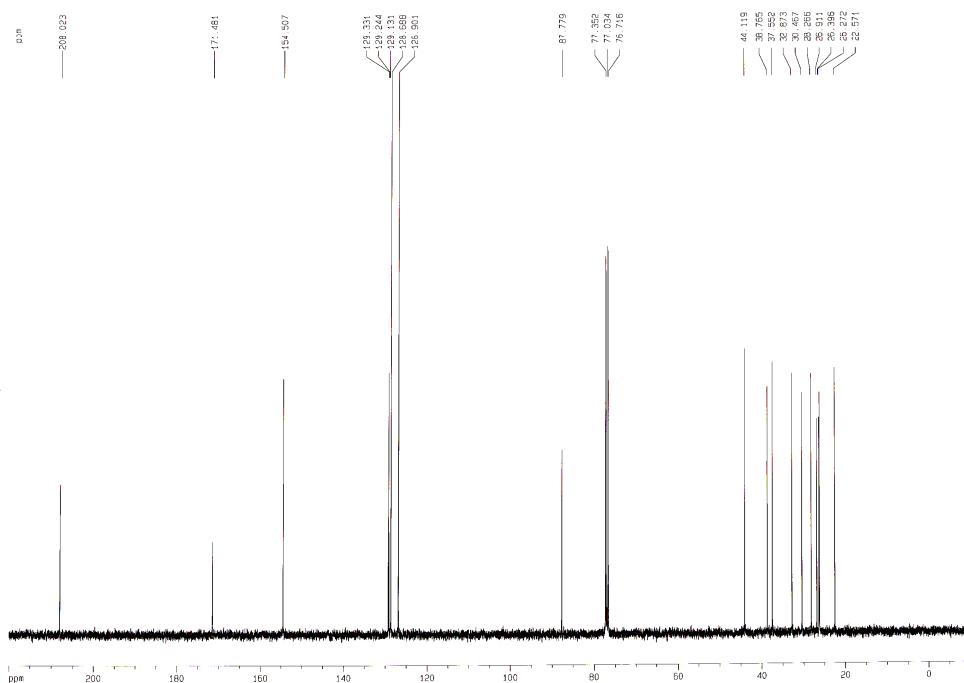
F2: 0.00 Hz

PMOD: 0.31250 ppm/cm

NZCM: 125.00938 kHz/cm

DPX400 carbon

ppm



Current Data Parameters  
NAME: TAKAHASHIANK017-2  
EXPNO: 2  
PROCNO: 1

F2 - Acquisition Parameters

Date: 20090425

Time: 11.35

INSTRUM: spect

PROBHD: 5 mm QNP 1H/13

PULPROG: zg30

TD: 65536

SOLVENT: CDCl3

NS: 223

DS: 4

SWH: 26178.000 Hz

ETR: 0.399495 Hz

AQ: 1.2517879 sec

RG: 4096

DW: 19.400 usec

DE: 6.00 usec

TE: 300.2 K

D1: 2.0000200 sec

D11: 0.0300000 sec

DELTA: 1.8999999 sec

MCRES1: 0.0000000 sec

MCWRK: 0.0150000 sec

\*\*\*\*\* CHANNEL f1 \*\*\*\*\*

NUC1: 13C

P1: 10.00 usec

PL1: -3.50 dB

SF01: 100.5098096 MHz

F2 - Processing parameters

SI: 32768

SF: 100.5076240 MHz

WDW: EM

SSB: 0

LB: 1.00 Hz

GB: 0

PC: 1.40

1D NMR plot parameters

CX: 32.00 cm

CY: 19.00 cm

F1P: 220,000 ppm

F1: 22129.28 Hz

F2P: -10,000 ppm

F2: -1005.88 Hz

PMOD: 7.16756 ppm/cm

NZCM: 722.97957 kHz/cm

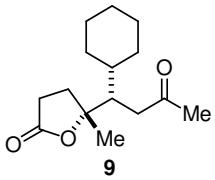
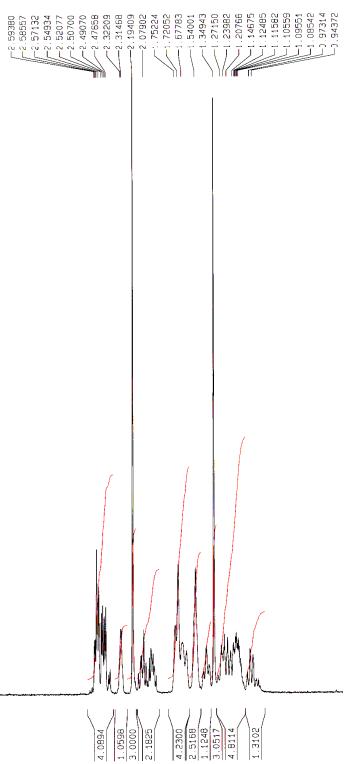
DPX400V PROTON

ppm

7.25951

Integral

ppm 8 7 6 5 4 3 2 1



Current Data Parameters  
NAME : takahashiAMK017-3  
EXPNO : 2  
PROCNO : 1

F2 - Acquisition Parameters  
Date : 20090626  
Time : 22:26  
INSTRUM : spect  
PROBHD : 5 mm QNP 1H/13  
PULPROG : zg30  
TD : 65536  
SOLVENT : CDCl3  
NS : 10  
DS : 2  
SWH : 8278.145 Hz  
ETRIM : 0.126314 Hz  
AQ : 3.9584243 sec  
RG : 724.1  
DW : 60.400 usec  
DE : 6.00 usec  
TE : 300.2 K  
D1 : 1.0000000 sec  
MESTEST : 0.0000000 sec  
MEWMK : 0.0150000 sec

\*\*\*\*\* CHANNEL F1 \*\*\*\*\*  
NUC1 : 1H  
P1 : 11.50 usec  
PL1 : -4.00 dB  
SF01 : 400.0324703 MHz  
F2 - Processing parameters  
SI : 32768  
SF : 400.0300026 MHz  
WDW : EM  
SSB : 0  
LB : 0.00 Hz  
GB : 0  
PC : 1.00

1D NMR plot parameters

CX : 32.00 cm

CY : 21.00 cm

CP : 10.000 ppm

F1 : 4000.30 Hz

F2 : 0.000 ppm

F2PPM : 0.31250 ppm/cm

NDIM : 325.00930 Hz/cm

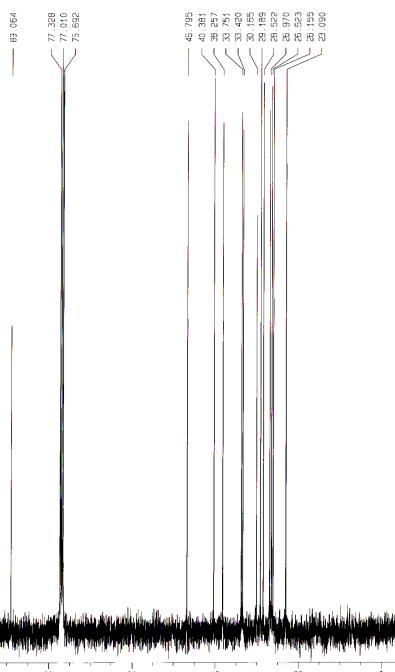
DPX400 carbon

ppm

207.587

175.165

ppm 200 180 160 140 120 100 80 60 40 20 0



## **10. References**

1. Taniguchi, M.; Kim, H.; Ra, D.; Schwartz, J. K.; Kirmaier, C.; Hindin, E.; Diers, J. R.; Prathapan, S.; Bocian, D. F.; Holten, D.; Lindsey, J. S. *J. Org. Chem.* **2002**, *67*, 7329–7342.
2. Bentley, K. W.; Ball, J. C. *J. Org. Chem.* **1958**, *23*, 1720–1725.
3. Pavlynchenko, A. I.; Purvaneckas, G.; Smirnova, N. I.; Titov, V. V. *Zh. Organiche. Khim.* **1986**, *22*, 1524–1529.
4. Arisawa, M.; Torisawa, Y.; Kawahara, M.; Yamanaka, M.; Nishida, A.; Nakagawa, M. *J. Org. Chem.* **1997**, *62*, 4327–4329.
5. Overend, W. G.; Turton, L. M.; Wiggins, L. F. *J. Chem. Soc.* **1950**, 3500–3505.
6. New, D. G.; Tesfai, Z.; Moeller, K. D. *J. Org. Chem.* **1996**, *61*, 1578–1598.
7. Lipshutz, B. H.; Ellsworth, E. L.; Dimock, S. H.; Smith, R. A. *J. Am. Chem. Soc.* **1990**, *112*, 4404–4410.
8. Ooi, T.; Ohara, D.; Tamura, M.; Maruoka, K. *J. Am. Chem. Soc.* **2004**, *126*, 6844–6845.
9. Clayton, H.; Kiyooka, S.; Blumenkopf, T. A. *J. Org. Chem.* **1984**, *49*, 4214–4223.
10. Rassu, G.; Zanardi, F.; Battistini, L.; Gaetani, E.; Casiraghi, G. *J. Med. Chem.* **1997**, *40*, 168–180.
11. Abe, M.; Torii, E.; Nojima, M. *J. Org. Chem.* **2000**, *65*, 3426–3431.
12. Asaoka, M.; Miyake, K.; Takei, H. *Chem. Lett.* **1977**, 167–170.
13. Wenzel, A. G.; Jacobsen, E. N. *J. Am. Chem. Soc.* **2002**, *124*, 12964–12965.
14. Boukouvalas, J.; Marion, O. *Synlett*, **2006**, 1511–1514.
15. Sorg, A.; Blank, F.; Brueckner, R. *Synlett*, **2005**, 1286–1290.
16. Asaoka, M.; Yanagida, N.; Sugimura, N.; Takei, H. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1061–1064.
17. Batra, S.; De, D.; Seth, M.; Bhaduri, A. P. *J. Chem. Res.* **1993**, *6*, 1228–1238.
18. Matsuoka, M.; Mustanir; Than, S.; Mishima, M. *Bull. Chem. Soc. Jpn.* **2005**, *78*, 147–153.
19. (a) Bartmess, J. E.; Georgiadis, R. M. *Vacuum*, **1983**, *33*, 149–153. (b) Miller, K. J. *J. Am. Chem. Soc.* **1990**, *112*, 8533–8541.
20. Leito, I.; Raamat, E.; Kütt, A.; Saame, J.; Kipper, K.; Koppel, I. A.; Koppel, I.; Zhang, M.; Mishima, M.; Yagupolskii, L. M.; Garlyauskayte, R. Yu.; Filatov, A. A. *J. Phys. Chem. A* **2009**, *113*, 8421–8424.
21. Zhang, M.; Mishima, M. *Abstract, 12th Kyushu International Symposium on Physical Organic Chemistry*, Fukuoka, **2009**.