

## Supplementary Information

### **Enantioselective synthesis of 3-substituted dihydrobenzofurans through iridium-catalyzed asymmetric intramolecular hydroarylation**

Kana Sakamoto and Takahiro Nishimura\*

*Department of Chemistry, Graduate School of Science, Osaka City University, Sumiyoshi, Osaka 558-8585, Japan*

#### Contents of Supplementary Information:

1. General	S-2
2. Materials	S-2
3. Preparation of compounds <b>1a</b> , <b>1b</b> , <b>1k–1n</b> , and <b>1w</b>	S-2
4. Preparation of <b>1c–j</b>	S-3
5. Preparation of <b>1o–r</b> , <b>1t</b> , and <b>1u</b>	S-4
6. Preparation of <b>1s</b>	S-4
7. Preparation of <b>1v</b>	S-5
8. Preparation of <b>1l–d</b>	S-6
9. Characterization of compounds <b>1</b>	S-8
10. General procedure for Table 1	S-15
11. Procedure for Scheme 3	S-15
12. Transformation of <b>2b</b> into <b>4</b>	S-16
13. Procedures for Scheme 5	S-17
14. Procedures for Scheme 6	S-18
15. General procedure for Table 2	S-19
16. Procedures for Scheme 8	S-19
17. Procedures for Schemes 9 and 10	S-20
18. Characterization of products <b>2</b>	S-21
19. References	S-31
20. <sup>1</sup> H and <sup>13</sup> C NMR spectra and chiral HPLC charts	S-32

## 1. General

All anaerobic and moisture-sensitive manipulations were carried out with standard Schlenk techniques under nitrogen. NMR spectra were recorded on a JEOL JNM ECA-400 or a Bruker Avance III HD 400 spectrometer (400 MHz for  $^1\text{H}$  NMR, 100 MHz for  $^{13}\text{C}$  NMR, 376 MHz for  $^{19}\text{F}$  NMR). Chemical shifts are reported in  $\delta$  (ppm) referenced to the residual peaks of  $\text{CDCl}_3$  ( $\delta$  7.26) for  $^1\text{H}$  NMR and  $\text{CDCl}_3$  ( $\delta$  77.00) for  $^{13}\text{C}$  NMR. The following abbreviations are used; s, singlet; d, doublet; t, triplet; q, quartet; quint, quintet; sext, sextet; sept, septet; m, multiplet; bs, broad singlet. High-resolution mass spectra were obtained with a JEOL AccuTOF LC-plus JMS-T100LP spectrometer. Optical rotations are measured on JASCO P-2200 polarimeter. Preparative thin-layer chromatography was performed with Silica Gel 70 PF254 (Wako). Alumina (active 200) for column chromatography was purchased from Nacalai Tesque.

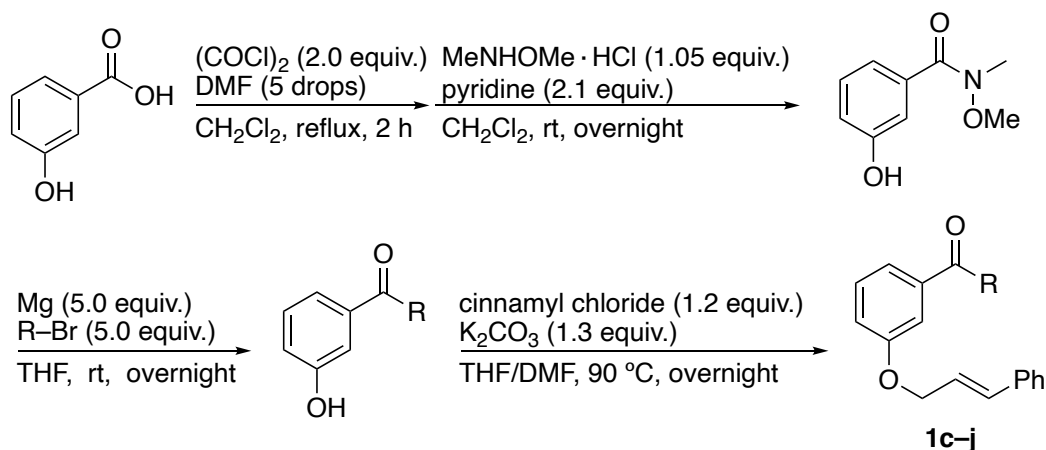
## 2. Material

Dehydrated solvents were purchased and used after deoxygenated by bubbling  $\text{N}_2$ . Iridium complex  $[\text{IrCl}(\text{cod})]_2$  was prepared according to the reported procedure.<sup>1</sup>  $\text{NaBAR}_4^{\text{F}}$  was prepared according to the reported procedure.<sup>2</sup> Ligands (*R*)-binap, (*S*)-segphos, (*R*)-difluorphos, (*R*)-MeO-biphep, (*S,S*)-chiraphos, (*S,S*)-QuinoxP\*, and dppf were purchased from commercial suppliers and used as received. The corresponding racemic products were prepared by using racemic binap as a ligand.

## 3. Preparation of compounds 1a, 1b, 1k–1n, and 1w

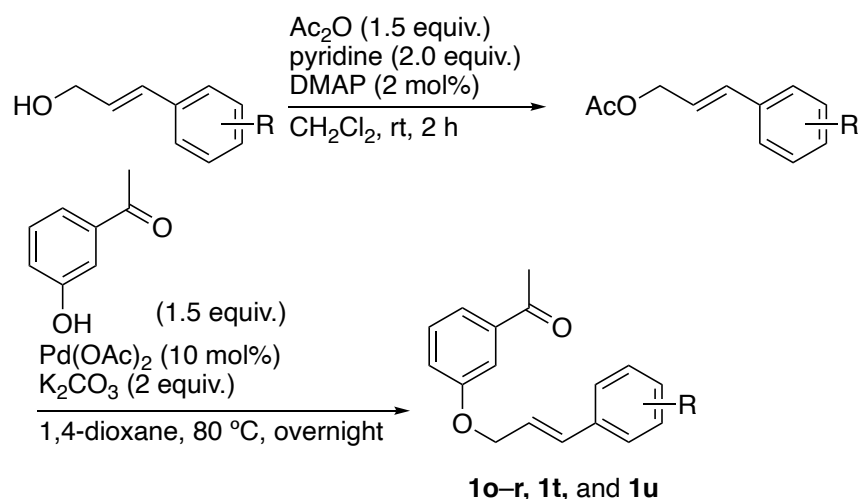
Compound **1a** (CAS: 58621-54-8) was prepared according to the reported procedure.<sup>3</sup> Compound **1b** (CAS: 1870882-97-5), **1k–1n** were prepared by the reaction of cinnamyl chloride with the corresponding *m*-hydroxy aromatic ketones or a 3-aminoacetophenone derivative according to the reported procedure.<sup>4</sup> **1w** (CAS: 1002607-98-8) was prepared by the reaction of 4-chlorocinnamoyl chloride with *m*-hydroxyacetophenone according to the reported procedure.<sup>5</sup>

#### 4. Preparation of 1c-j



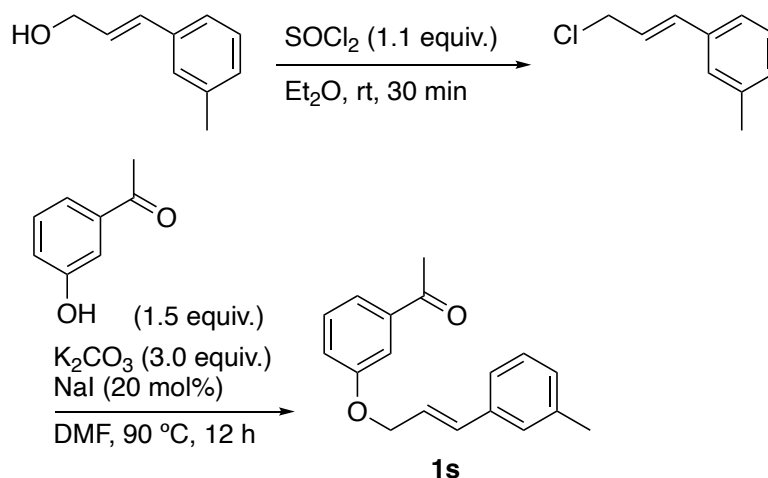
Oxalyl chloride (0.31 mL, 12 mmol) was slowly added to a solution of *m*-hydroxybenzoic acid (1.38 g, 10 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (30 mL) with 5 drops of DMF at 0 °C under N<sub>2</sub>, and the mixture was refluxed at 55 °C for 2 h. CH<sub>2</sub>Cl<sub>2</sub> and excess oxalyl chloride were removed under vacuum, and MeNHOMe·HCl (1.02 g, 10.5 mmol) and pyridine (1.7 mL, 21.0 mmol) were added to the residue in CH<sub>2</sub>Cl<sub>2</sub> (30 mL) at 0 °C. The resulting mixture was stirred at room temperature overnight. 1 N HCl<sub>aq</sub> was added to the mixture, and the resulting mixture was extracted with CH<sub>2</sub>Cl<sub>2</sub>. The organic layer was washed with brine, dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated on a rotary evaporator. The residue was subjected to column chromatography on silica gel eluted with EtOAc/hexane (1:1) to give *m*-hydroxy-*N*-methoxy-*N*-methylbenzamide (1.31 g, 7.22 mmol, 72%). To a flame-dried round bottom flask were added Mg (121.5 mg, 5.0 mmol) and THF (0.5 mL) under N<sub>2</sub>. A solution of an aryl or alkyl bromide (5.0 mmol) in THF (9.5 mL) was slowly added to the flask, and the resulting mixture was stirred for 1 h. *m*-Hydroxy-*N*-methoxy-*N*-methylbenzamide (181 mg, 1.0 mmol) in THF (2.0 mL) was slowly added to the mixture at 0 °C, and the resulting mixture was stirred overnight. The reaction was quenched with 2 N HCl<sub>aq</sub>, and the resulting mixture was extracted with EtOAc. The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated on a rotary evaporator. The residue was subjected to column chromatography on silica gel eluted with EtOAc/hexane to give the corresponding *m*-hydroxy aromatic ketones. Cinnamyl chloride (183 mg, 1.2 mmol) and K<sub>2</sub>CO<sub>3</sub> (180 mg, 1.3 mmol) was added to a solution of the *m*-hydroxy aromatic ketone (1.0 mmol) in THF (5.0 mL) and DMF (5.0 mL), and the resulting mixture was stirred at 90 °C overnight. Water was added to the mixture, and the resulting mixture was extracted with EtOAc. The organic layer was washed with 1 N NaOH<sub>aq</sub>, water, and brine, dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated on a rotary evaporator. The residue was subjected to column chromatography on silica gel with EtOAc/hexane to give 1c-j.

## 5. Preparation of 1o–r, 1t, and 1u



To a mixture of substituted cinnamyl alcohol (5.0 mmol), pyridine (0.81 mL, 10 mmol), and *N,N*-dimethyl-4-aninopyridine (DMAP, 12 mg, 0.10 mmol) in CH<sub>2</sub>Cl<sub>2</sub> was added Ac<sub>2</sub>O (0.71 mL, 7.5 mmol) at 0 °C, and the resulting mixture was stirred at room temperature for 2 h. The mixture was passed through a short column of silica gel with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator. Pd(OAc)<sub>2</sub> (45 mg, 0.20 mmol) and K<sub>2</sub>CO<sub>3</sub> (553 mg, 4.0 mmol) were added to a solution of the crude mixture in 1,4-dioxane (4 mL) under N<sub>2</sub>, and the resulting mixture was stirred at 80 °C overnight. The mixture was passed through a short column of alumina with EtOAc/hexane (1:4) as an eluent. The residue was subjected to column chromatography on silica gel eluted with EtOAc/hexane to give the corresponding ketones **1o–r, 1t, and 1u**.

## 6. Preparation of 1s

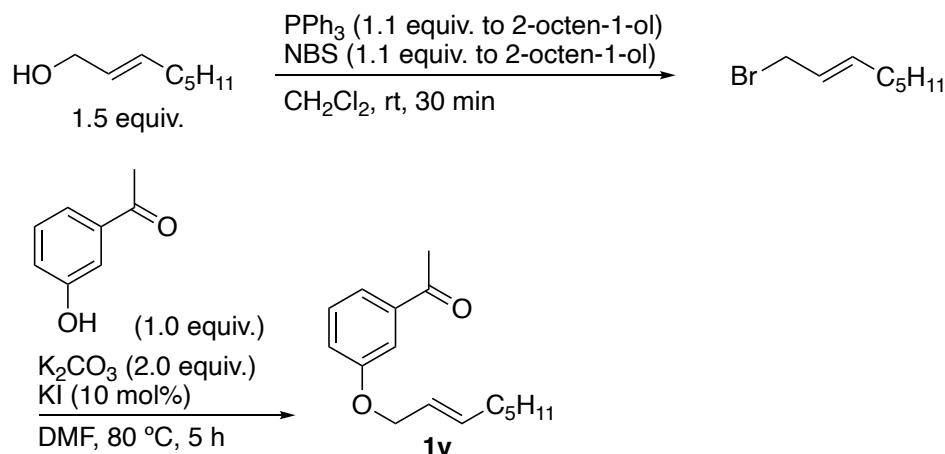


To a solution of 3-methylcinnamyl alcohol (741 mg, 5.0 mmol) in Et<sub>2</sub>O (20 mL) was slowly added SOCl<sub>2</sub> (399 μL, 5.5 mmol) at 0 °C, and the resulting mixture was stirred at room temperature for 30 min. Et<sub>2</sub>O was removed on a rotary evaporator, and *m*-hydroxyacetophenone



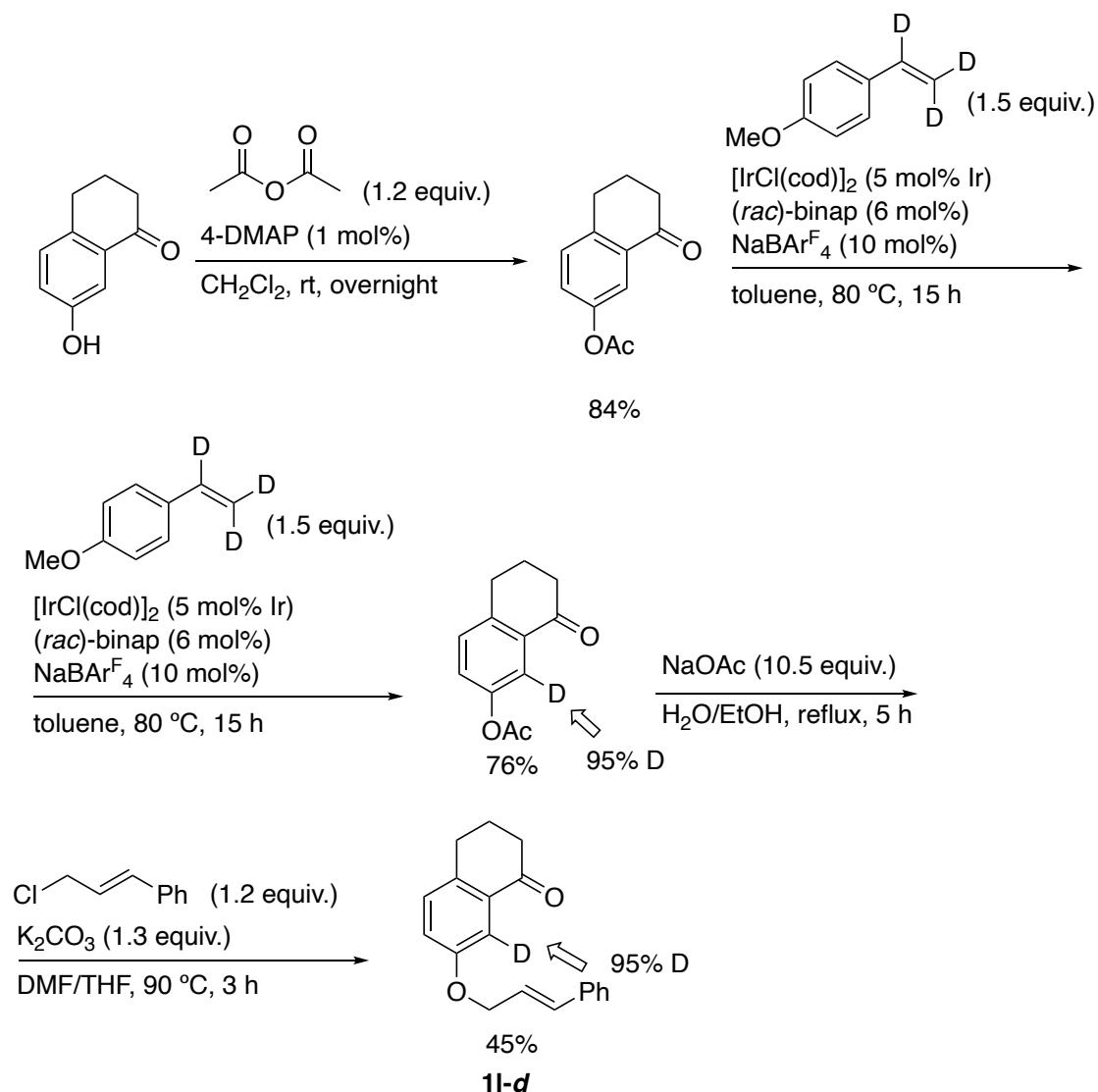
(1.02 g, 7.5 mmol),  $K_2CO_3$  (2.07 g, 15 mmol), and NaI (150 mg, 1.0 mmol) were added to a solution of the crude mixture in DMF (5 mL). The mixture was heated to 90 °C and stirred overnight. Water was added to the mixture and the resulting mixture was extracted with  $Et_2O$ . The organic layer was washed with 1 N NaOHaq, water, and brine, dried over  $Na_2SO_4$ , and concentrated on a rotary evaporator. The residue was subjected to column chromatography on silica gel with EtOAc/hexane (1:10) to give **1s** (628 mg, 2.36 mmol, 47% yield).

## 7. Preparation of **1v**



To a mixture of *trans*-2-octen-1-ol (385 mg, 3.0 mmol) and  $PPh_3$  (866 mg, 3.3 mmol) in  $CH_2Cl_2$  (10 mL) was added *N*-bromosuccinimide (NBS, 587  $\mu$ L, 3.3 mmol) at  $-20$  °C, and the resulting mixture was stirred at  $-20$  °C for 30 min and at room temperature for 30 min. The mixture was passed through a short column of silica gel with pentane as an eluent, and the solvent was removed on a rotary evaporator. *m*-Hydroxyacetophenone (272 mg, 2.0 mmol),  $K_2CO_3$  (553 mg, 4.0 mmol), and KI (33 mg, 0.2 mmol) were added to a solution of the crude mixture in DMF (4 mL), and the resulting mixture was stirred at 80 °C for 5 h. Water was added to the mixture and the resulting mixture was extracted with  $Et_2O$ . The organic layer was washed with 1 N NaOHaq, water, and brine, dried over  $Na_2SO_4$ , and concentrated on a rotary evaporator. The residue was subjected to column chromatography on silica gel with EtOAc/hexane (1:10) to give **1v** (398 mg, 1.6 mmol, 81% yield).

## 8. Preparation of 11-d



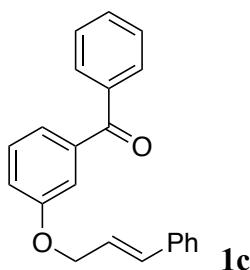
To a mixture of 7-hydroxy-1-tetralone (162 mg, 1.0 mmol) and 4-DMAP (4-dimethylaminopyridine, 1.2 mg, 0.01 mmol) in  $\text{CH}_2\text{Cl}_2$  (3 mL) was added acetic anhydride (92  $\mu\text{L}$ , 1.2 mmol), and the resulting mixture was stirred at room temperature overnight. Water was added to the mixture at 0 °C and the resulting mixture was extracted with  $\text{CH}_2\text{Cl}_2$ . The organic layer was dried over  $\text{Na}_2\text{SO}_4$ , and concentrated on a rotary evaporator. The residue was passed through a short column of silica gel with hexane/EtOAc (1:1) as an eluent, and the solvent was removed on a rotary evaporator to give 7-acetoxy-1-tetralone (172 mg, 0.84 mmol, 84% yield).

7-Acetoxy-1-tetralone (172 mg, 0.84 mmol) and deuterated 4-methoxystyrene<sup>6</sup> were added to the mixture of  $[\text{IrCl}(\text{cod})]_2$  (14.5 mg, 0.021 mmol, 5 mol% of Ir), (*rac*)-binap (31.5 mg, 0.051 mmol, 6 mol%), and  $\text{NaBARF}_4$  (78.2 mg calculated as the dihydrate, 0.085 mmol, 10 mol%) in toluene (1.7 mL) under  $\text{N}_2$ , and the resulting mixture was stirred at 80 °C for 15 h. The solvent was removed on a rotary evaporator and the residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give deuterated 7-acetoxy-1-tetralone (82% D, 160 mg, 0.78

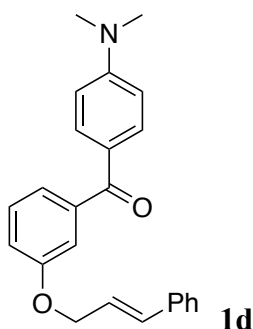
mmol, 93% yield). The resulting deuterated 7-acetoxy-1-tetralone (160 mg, 0.78 mmol) was treated again with deuterated 4-methoxystyrene under the same reaction conditions to give deuterated 7-acetoxy-1-tetralone with 95% deuterium at the *ortho*-position (139 mg, 0.67 mmol, 87% yield).

A mixture of deuterated 7-acetoxy-1-tetralone (139 mg, 0.67 mmol) and NaOAc (580 mg, 7.0 mmol) in EtOH (17 mL) and H<sub>2</sub>O (1.6 mL) was refluxed at 90 °C for 5 h. 1 N NaOH<sub>aq</sub> was added to the mixture and the aqueous layer was washed with EtOAc. The aqueous layer was acidified with 2 N HCl<sub>aq</sub> and the mixture was extracted with EtOAc. The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated on a rotary evaporator. The residue was added to a mixture of K<sub>2</sub>CO<sub>3</sub> (120 mg, 0.87 mmol) and cinnamyl chloride (122 mg, 0.80 mmol) in DMF (3.4 mL) and THF (3.4 mL), and the resulting mixture was stirred at 90 °C for 3 h. The solvent was removed on a rotary evaporator and the residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **11-d** (92 mg, 0.45 mmol, 45% yield over 2 steps).

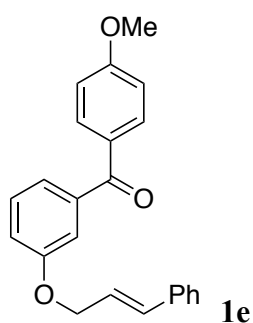
## 9. Characterization of compounds 1



**Compound 1c** (pale yellow solid, 52% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  4.74 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.41 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.73 (d,  $J = 16.0$  Hz, 1H), 7.19 (dt,  $J = 7.2, 2.0$  Hz, 1H), 7.22–7.31 (m, 1H), 7.33 (t,  $J = 7.6$  Hz, 2H), 7.35–7.45 (m, 5H), 7.46 (d,  $J = 7.6$  Hz, 2H), 7.57 (t,  $J = 7.2$  Hz, 1H), 7.80 (dd,  $J = 8.0, 1.2$  Hz, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  68.8, 115.4, 119.6, 123.0, 123.9, 126.6, 128.0, 128.2, 128.6, 129.3, 130.0, 132.4, 133.3, 136.3, 137.5, 138.9, 158.5, 196.4. HRMS (DART) calcd for  $\text{C}_{22}\text{H}_{19}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  315.1385, found 315.1400.

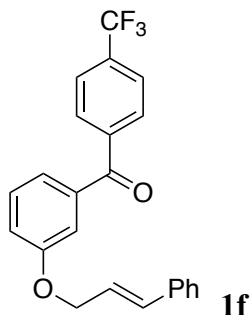


**Compound 1d** (pale yellow solid, 70 % yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  3.06 (s, 6H), 4.75 (dd,  $J = 5.8, 1.4$  Hz, 2H), 6.42 (dt,  $J = 16.0, 5.8$  Hz, 1H), 6.60 (dd,  $J = 9.2, 2.4$  Hz, 2H), 6.74 (d,  $J = 16.0$  Hz, 1H), 7.14 (ddd,  $J = 8.2, 2.8, 1.2$  Hz, 1H), 7.19–7.43 (m, 6H), 7.43 (d,  $J = 7.2$  Hz, 2H), 7.81 (d,  $J = 8.8$  Hz, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  40.1, 68.7, 110.6, 115.0, 118.3, 122.2, 124.1, 124.8, 126.6, 127.9, 128.6, 129.1, 132.7, 133.1, 136.3, 140.6, 153.1, 158.2, 194.7. HRMS (DART) calcd for  $\text{C}_{24}\text{H}_{24}\text{N}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  358.1807, found 358.1797.

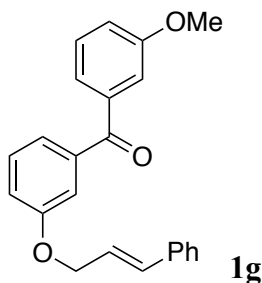


**Compound 1e** (pale yellow solid, 37% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  3.87 (s, 3H), 4.76 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.42 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.74 (d,  $J = 16.0$  Hz, 1H), 6.93 (d,  $J = 6.8$  Hz,

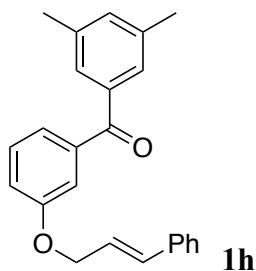
2H), 7.17 (ddd,  $J = 8.0, 2.8, 1.2$  Hz, 1H), 7.23–7.30 (m, 1H), 7.30–7.44 (m, 7H), 7.83 (d,  $J = 7.2$  Hz, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  55.5, 68.8, 113.5, 115.2, 119.1, 122.6, 124.0, 126.6, 128.0, 128.6, 129.3, 130.1, 132.6, 133.3, 136.3, 139.6, 158.4, 163.2, 195.2. HRMS (DART) calcd for  $\text{C}_{23}\text{H}_{21}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  345.1491, found 345.1487.



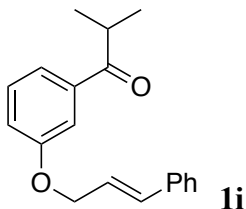
**Compound 1f** (pale yellow solid, 69% yield).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  4.77 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.41 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.74 (d,  $J = 16.0$  Hz, 1H), 7.20–7.31 (m, 2H), 7.30–7.39 (m, 3H), 7.38–7.46 (m, 4H), 7.71 (d,  $J = 8.0$  Hz, 2H), 7.88 (d,  $J = 8.0$  Hz, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  68.8, 115.3, 120.2, 123.0, 123.6 (q,  $J_{\text{C-F}} = 271$  Hz), 123.7, 125.2 (q,  $J_{\text{C-F}} = 3$  Hz), 126.5, 128.0, 128.6, 129.6, 130.1, 133.6 (q,  $J_{\text{C-F}} = 26$  Hz), 133.8, 136.1, 137.9, 140.6, 158.6, 195.2;  $^{19}\text{F}$  NMR ( $\text{CDCl}_3$ )  $\delta$  -63.0. HRMS (DART) calcd for  $\text{C}_{23}\text{H}_{18}\text{F}_3\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  383.1259, found 383.1265.



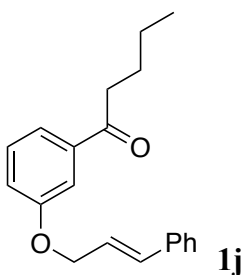
**Compound 1g** (colorless oil, 85% yield).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  3.82 (s, 3H), 4.72 (d,  $J = 6.0$  Hz, 2H), 6.39 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.72 (d,  $J = 16.0$  Hz, 1H), 7.07–7.14 (m, 1H), 7.14–7.21 (m, 1H), 7.21–7.28 (m, 1H), 7.28–7.36 (m, 4H), 7.32–7.44 (m, 6H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  55.4, 68.7, 114.2, 115.2, 118.8, 119.5, 122.8, 122.9, 123.8, 126.5, 127.9, 128.5, 129.1, 129.2, 133.3, 136.2, 138.76, 138.81, 158.4, 159.5, 196.1. HRMS (DART) calcd for  $\text{C}_{23}\text{H}_{21}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  345.1491, found 345.1589.



**Compound 1h** (pale yellow solid, 84% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.36 (s, 6H), 4.74 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.42 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.74 (d,  $J = 16.0$  Hz, 1H), 7.18 (ddd,  $J = 7.6, 2.6, 1.8$  Hz, 1H), 7.21 (bs, 1H), 7.23–7.28 (m, 1H), 7.29–7.44 (m, 9H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  21.1, 68.7, 115.1, 119.3, 122.9, 123.8, 126.5, 127.7, 127.9, 128.5, 129.1, 133.2, 134.0, 136.2, 137.6, 137.8, 139.1, 158.4, 196.7. HRMS (DART) calcd for  $\text{C}_{24}\text{H}_{23}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  343.1698, found 343.1690.

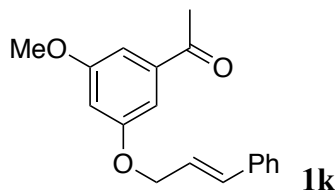


**Compound 1i** (colorless oil, 33% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  1.22 (d,  $J = 6.8$  Hz, 6H), 3.53 (sept,  $J = 6.8$  Hz, 1H), 4.75 (dd,  $J = 5.6, 1.6$  Hz, 2H), 6.42 (dt,  $J = 16.0, 5.6$  Hz, 1H), 6.75 (d,  $J = 16.0$  Hz, 1H), 7.15 (dd,  $J = 8.0, 2.4$  Hz, 1H), 7.23–7.30 (m, 1H), 7.33 (t,  $J = 7.6$  Hz, 2H), 7.38 (t,  $J = 8.0$  Hz, 1H), 7.41 (d,  $J = 6.8$  Hz, 2H), 7.51 (d,  $J = 6.4$  Hz, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  19.2, 35.5, 68.7, 113.7, 119.8, 121.0, 123.9, 126.6, 128.0, 128.6, 129.6, 133.4, 136.3, 137.6, 158.8, 204.2. HRMS (ESI) calcd for  $\text{C}_{19}\text{H}_{20}\text{Na}_1\text{O}_2$  ( $\text{M}+\text{Na}$ ) $^+$  303.1361, found 303.1368.

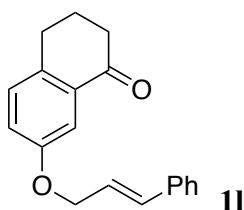


**Compound 1j** (colorless oil, 73% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  0.95 (t,  $J = 7.6$  Hz, 3H), 1.41 (sext,  $J = 7.6$  Hz, 2H), 1.74 (quint,  $J = 7.6$  Hz, 2H), 2.96 (t,  $J = 7.6$  Hz, 2H), 4.76 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.42 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.76 (d,  $J = 16.0$  Hz, 1H), 7.16 (ddd,  $J = 8.2, 2.6, 0.8$  Hz, 1H), 7.27 (t,  $J = 7.4$  Hz, 1H), 7.33 (t,  $J = 7.4$  Hz, 2H), 7.38 (d,  $J = 7.6$  Hz, 1H), 7.42 (d,  $J = 7.2$  Hz, 2H), 7.53–7.58 (m, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  13.9, 22.5, 26.5, 38.4, 68.8, 113.4, 120.0, 120.9,

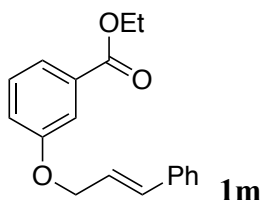
123.9, 126.6, 128.0, 128.6, 129.6, 133.4, 136.3, 138.5, 158.8, 200.3. HRMS (ESI) calcd for  $C_{20}H_{22}Na_1O_2 (M+Na)^+$  317.1518, found 317.1511.



**Compound 1k** (pale yellow solid, 78% yield).  $^1H$  NMR ( $CDCl_3$ )  $\delta$  2.58 (s, 3H), 3.84 (s, 3H), 4.73 (dd,  $J = 6.0, 1.6$  Hz, 2H), 6.41 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.70–6.74 (m, 1H), 6.75 (d,  $J = 16.0$  Hz, 1H), 7.09–7.12 (m, 1H), 7.13–7.18 (m, 1H), 7.23–7.30 (m, 1H), 7.34 (t,  $J = 7.2$  Hz, 2H), 7.42 (d,  $J = 7.2$  Hz, 2H);  $^{13}C$  NMR ( $CDCl_3$ )  $\delta$  26.7, 55.6, 68.9, 106.0, 106.3, 107.0, 123.7, 126.6, 128.0, 128.6, 133.5, 136.2, 139.0, 159.8, 160.8, 197.7. HRMS (DART) calcd for  $C_{18}H_{19}O_3 (M+H)^+$  283.1334, found 283.1326.

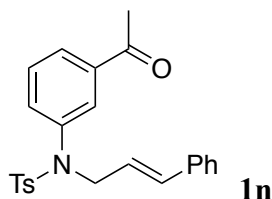


**Compound 1l** (pale yellow solid, 87% yield).  $^1H$  NMR ( $CDCl_3$ )  $\delta$  2.12 (quint,  $J = 6.4$  Hz, 2H), 2.64 (t,  $J = 6.4$  Hz, 2H), 2.91 (t,  $J = 6.4$  Hz, 2H), 4.74 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.41 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.74 (d,  $J = 16.0$  Hz, 1H), 7.11 (dd,  $J = 8.4, 2.8$  Hz, 1H), 7.18 (d,  $J = 8.4$  Hz, 1H), 7.22–7.29 (m, 1H), 7.33 (t,  $J = 7.2$  Hz, 2H), 7.41 (d,  $J = 7.2$  Hz, 2H), 7.57 (d,  $J = 2.8$  Hz, 1H);  $^{13}C$  NMR ( $CDCl_3$ )  $\delta$  23.5, 28.9, 39.0, 68.8, 110.2, 122.3, 124.0, 126.6, 127.9, 128.6, 130.0, 133.3, 133.4, 136.4, 137.3, 157.3, 198.3. HRMS (DART) calcd for  $C_{19}H_{19}O_2 (M+H)^+$  279.1385, found 279.1378.

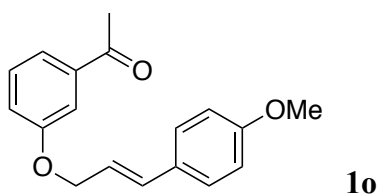


**Compound 1m** (colorless oil, 80% yield).  $^1H$  NMR ( $CDCl_3$ )  $\delta$  1.40 (t,  $J = 7.0$  Hz, 3H), 4.38 (q,  $J = 7.0$  Hz, 2H), 4.75 (dd,  $J = 5.8, 1.0$  Hz, 2H), 6.42 (dt,  $J = 16.0, 5.8$  Hz, 1H), 6.76 (d,  $J = 16.0$  Hz, 1H), 7.15 (ddd,  $J = 8.0, 2.4, 1.2$  Hz, 1H), 7.24–7.30 (m, 1H), 7.32 (d,  $J = 7.2$  Hz, 1H), 7.36 (t,  $J = 8.0$  Hz, 2H), 7.42 (d,  $J = 7.2$  Hz, 2H), 7.60–7.67 (m, 1H), 7.66 (d,  $J = 7.2$  Hz, 1H);  $^{13}C$  NMR

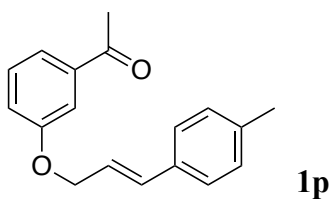
(CDCl<sub>3</sub>)  $\delta$  14.3, 61.1, 68.8, 115.0, 120.0, 122.1, 124.0, 126.6, 128.0, 128.6, 129.4, 131.8, 133.3, 136.3, 158.5, 166.4. HRMS (ESI) calcd for C<sub>18</sub>H<sub>18</sub>Na<sub>1</sub>O<sub>3</sub> (M+Na)<sup>+</sup> 305.1154, found 305.1160.



**Compound 1n** (pale yellow solid, 11% yield). <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  2.44 (s, 3H), 2.53 (s, 3H), 4.35 (dd, *J* = 6.6, 1.0 Hz, 2H), 6.07 (dt, *J* = 16.0, 6.6 Hz, 1H), 6.37 (d, *J* = 16.0 Hz, 1H), 7.17–7.31 (m, 8H), 7.33–7.38 (m, 1H), 7.40 (t, *J* = 7.4 Hz, 1H), 7.50 (d, *J* = 8.0 Hz, 2H), 7.59–7.63 (m, 1H), 7.84 (d, *J* = 8.0 Hz, 1H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  21.5, 26.6, 53.0, 123.6, 126.4, 127.6, 127.7, 127.9, 128.1, 128.5, 129.2, 129.6, 133.7, 134.3, 135.2, 136.1, 137.8, 139.8, 143.8, 197.0. HRMS (ESI) calcd for C<sub>24</sub>H<sub>24</sub>N<sub>1</sub>Na<sub>1</sub>O<sub>3</sub>S<sub>1</sub> (M+H)<sup>+</sup> 429.1375, found 429.1386.

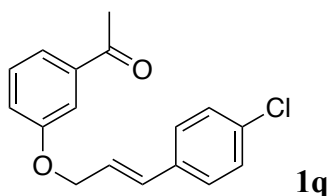


**Compound 1o** (pale yellow solid, 74% yield). <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  2.60 (s, 3H), 3.81 (s, 3H), 4.73 (dd, *J* = 6.2, 1.2 Hz, 2H), 6.28 (dt, *J* = 16.0, 6.2 Hz, 1H), 6.69 (d, *J* = 16.0 Hz, 1H), 6.86 (d, *J* = 8.8 Hz, 2H), 7.16 (dd, *J* = 7.8, 2.8 Hz, 1H), 7.32–7.42 (m, 3H), 7.51–7.58 (m, 2H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  26.5, 55.0, 68.7, 113.2, 113.8, 120.0, 121.0, 121.3, 127.6, 128.8, 129.4, 132.9, 138.2, 158.6, 159.3, 197.6. HRMS (DART) calcd for C<sub>18</sub>H<sub>19</sub>O<sub>3</sub> (M+H)<sup>+</sup> 283.1334, found 283.1324.

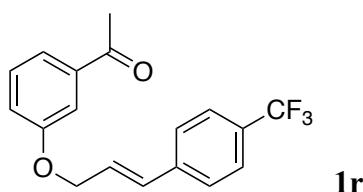


**Compound 1p** (pale yellow solid, 69% yield). <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  2.35 (s, 3H), 2.60 (s, 3H), 4.74 (dd, *J* = 6.0, 1.2 Hz, 2H), 6.37 (dt, *J* = 16.0, 6.0 Hz, 1H), 6.72 (d, *J* = 16.0 Hz, 1H), 7.14 (d, *J* = 8.0 Hz, 2H), 7.18 (d, *J* = 1.6 Hz, 1H), 7.32 (d, *J* = 8.0 Hz, 2H), 7.38 (t, *J* = 8.0 Hz, 1H), 7.52–7.59 (m, 2H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  21.0, 26.5, 68.7, 113.2, 120.0, 121.0, 122.6, 126.3, 129.1, 129.4, 133.2, 133.3, 137.7, 138.2, 158.6, 197.6. HRMS (DART) calcd for C<sub>18</sub>H<sub>19</sub>O<sub>2</sub> (M+H)<sup>+</sup> 267.1385, found 267.1389.

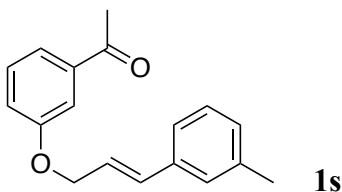




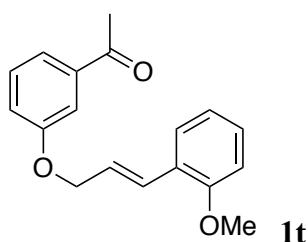
**Compound 1q** (pale yellow solid, 29% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.60 (s, 3H), 4.75 (dd,  $J = 5.4, 1.4$  Hz, 2H), 6.39 (dt,  $J = 16.0, 5.4$  Hz, 1H), 6.71 (d,  $J = 16.0$  Hz, 1H), 7.16 (ddd,  $J = 8.4, 2.8, 0.8$  Hz, 1H), 7.26–7.39 (m, 3H), 7.39 (t,  $J = 8.0$  Hz, 2H), 7.52–7.60 (m, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  26.6, 68.4, 113.2, 120.1, 121.3, 124.5, 127.7, 128.7, 129.6, 131.8, 133.5, 134.7, 138.4, 158.6, 197.7. HRMS (DART) calcd for  $\text{C}_{17}\text{H}_{16}^{35}\text{Cl}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  287.0839,  $\text{C}_{17}\text{H}_{16}^{37}\text{Cl}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  289.0809, found 287.0839.



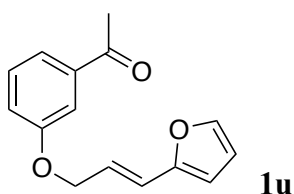
**Compound 1r** (pale yellow solid, 54% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.61 (s, 3H), 4.78 (dd,  $J = 5.6, 2.0$  Hz, 2H), 6.51 (dt,  $J = 16.0, 5.6$  Hz, 1H), 6.79 (d,  $J = 16.0$  Hz, 1H), 7.17 (ddd,  $J = 8.3, 2.8, 0.8$  Hz, 1H), 7.40 (t,  $J = 8.0$  Hz, 1H), 7.51 (d,  $J = 8.0$  Hz, 2H), 7.53–7.62 (m, 4H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  26.5, 68.1, 113.1, 120.0, 121.4, 125.4 (q,  $J_{\text{C-H}} = 4$  Hz), 126.6, 126.7 (q,  $J_{\text{C-H}} = 271$  Hz), 129.5 (q,  $J_{\text{C-H}} = 31$  Hz), 129.6, 131.3, 138.4, 139.7, 158.5, 197.7;  $^{19}\text{F NMR}$  ( $\text{CDCl}_3$ )  $\delta$  -62.5. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{16}\text{F}_3\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  321.1102, found 321.1106.



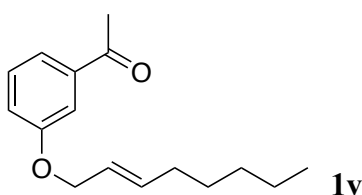
**Compound 1s** (pale yellow solid, 47% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.35 (s, 3H), 2.60 (s, 3H), 4.75 (dd,  $J = 6.0, 1.2$  Hz, 2H), 6.41 (dt,  $J = 16.0, 6.0$  Hz, 1H), 6.72 (d,  $J = 16.0$  Hz, 1H), 7.05–7.12 (m, 1H), 7.17 (ddd,  $J = 8.4, 2.6, 1.4$  Hz, 1H), 7.19–7.27 (m, 3H), 7.39 (t,  $J = 8.2$  Hz, 1H), 7.52–7.59 (m, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  21.2, 26.5, 68.6, 113.2, 120.0, 121.1, 123.5, 123.6, 127.2, 128.3, 128.6, 129.5, 133.3, 136.0, 138.0, 138.3, 158.6, 197.7. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  267.1385, found 267.1385.



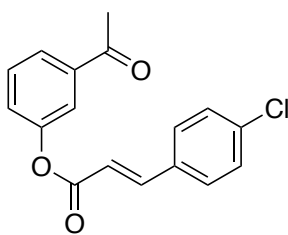
**Compound 1t** (pale yellow oil, 64% yield).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.60 (s, 3H), 3.86 (s, 3H), 4.76 (dd,  $J = 5.8, 1.4$  Hz, 2H), 6.44 (dt,  $J = 16.0, 5.8$  Hz, 1H), 6.88 (d,  $J = 16.0$  Hz, 1H), 6.94 (t,  $J = 7.6$  Hz, 1H), 7.08 (d,  $J = 16.0$  Hz, 1H), 7.14–7.20 (m, 1H), 7.21–7.29 (m, 1H), 7.38 (t,  $J = 8.0$  Hz, 1H), 7.46 (dd,  $J = 7.6, 2.0$  Hz, 1H), 7.52–7.58 (m, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  26.6, 55.3, 69.2, 110.7, 113.5, 120.1, 120.5, 121.0, 124.4, 125.1, 127.0, 128.5, 129.0, 129.5, 138.3, 156.7, 158.8, 197.8. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  283.1334, found 283.1337.



**Compound 1u** (pale yellow solid, 43% yield).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.60 (s, 3H), 4.73 (dd,  $J = 6.4, 1.2$  Hz, 2H), 6.28 (d,  $J = 3.2$  Hz, 1H), 6.34 (dt,  $J = 16.0, 6.4$  Hz, 1H), 6.35–6.42 (m, 1H), 6.56 (d,  $J = 16.0$  Hz, 1H), 7.16 (ddd,  $J = 8.0, 2.8, 1.2$  Hz, 1H), 7.36 (d,  $J = 2.0$  Hz, 1H), 7.39 (d,  $J = 8.0$  Hz, 1H), 7.51–7.59 (m, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  26.5, 67.9, 108.5, 111.2, 113.2, 119.9, 120.9, 121.1, 122.2, 129.4, 138.2, 142.1, 151.7, 158.5, 197.6. HRMS (DART) calcd for  $\text{C}_{15}\text{H}_{15}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  243.1021, found 243.1029.



**Compound 1v** (colorless oil, 81% yield).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  0.87 (t,  $J = 7.0$  Hz, 3H), 1.19–1.49 (m, 6H), 2.07 (q,  $J = 7.0$  Hz, 2H), 2.57 (s, 3H), 4.51 (d,  $J = 5.6$  Hz, 2H), 5.68 (dt,  $J = 15.6, 5.6$  Hz, 1H), 5.85 (dt,  $J = 15.6, 7.0$  Hz, 1H), 7.10 (ddd,  $J = 8.4, 2.8, 0.8$  Hz, 1H), 7.34 (t,  $J = 8.0$  Hz, 1H), 7.44–7.52 (m, 1H), 7.51 (d,  $J = 7.6$  Hz, 1H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  14.0, 22.4, 26.6, 28.5, 31.3, 32.2, 68.9, 113.3, 120.2, 121.0, 124.1, 129.4, 136.2, 138.3, 158.8, 197.8. HRMS (DART) calcd for  $\text{C}_{16}\text{H}_{23}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  247.1698, found 247.1708.



**1w**

**Compound 1w** (pale yellow solid, 67% yield).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.62 (s, 3H), 6.61 (d,  $J = 21.6$  Hz, 1H), 7.35–7.45 (m, 1H), 7.41 (d,  $J = 11.2$  Hz, 2H), 7.45–7.56 (m, 1H), 7.53 (d,  $J = 11.2$  Hz, 2H), 7.72–7.89 (m, 1H), 7.78–7.90 (m, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  26.7, 117.4, 121.5, 125.8, 126.4, 129.3, 129.5, 129.7, 132.5, 136.9, 138.6, 145.6, 150.9, 164.9, 197.0. HRMS (ESI) calcd for  $\text{C}_{17}\text{H}_{13}^{35}\text{Cl}_1\text{Na}_1\text{O}_3$  ( $\text{M}+\text{Na}$ ) $^+$  323.0451,  $\text{C}_{17}\text{H}_{13}^{37}\text{Cl}_1\text{Na}_1\text{O}_3$  ( $\text{M}+\text{Na}$ ) $^+$  325.0421, found 323.0454.

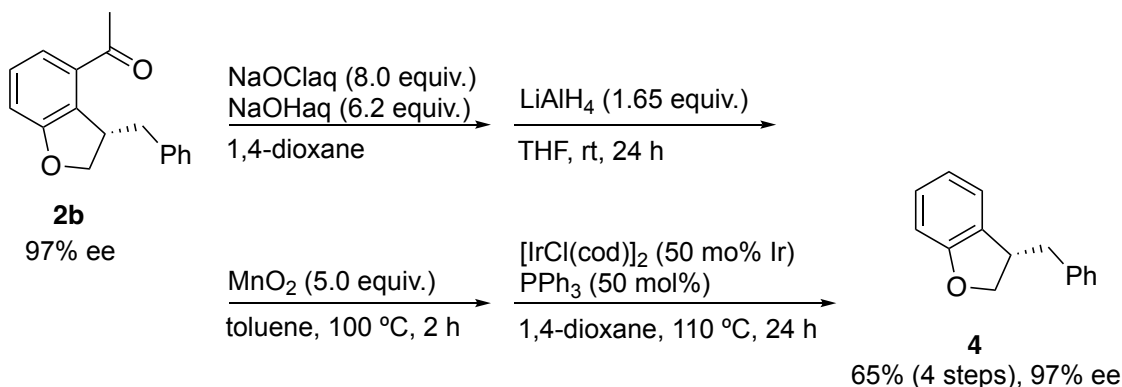
### 10. General procedure for Table 1

A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir), ligand (0.0060 mmol, 6 mol%), and  $\text{NaBAR}^{\text{F}}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under  $\text{N}_2$ . Then, **1b** (25.2 mg, 0.10 mmol) was added to the tube, and the mixture was stirred at 80 °C for 18 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The yields of the product were determined by  $^1\text{H NMR}$  analysis using benzyl phenyl ether as an internal standard. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2b**. The ee was measured by HPLC analysis with a chiral stationary phase column: Chiralcel OJ-H

### 11. Procedure for Scheme 3

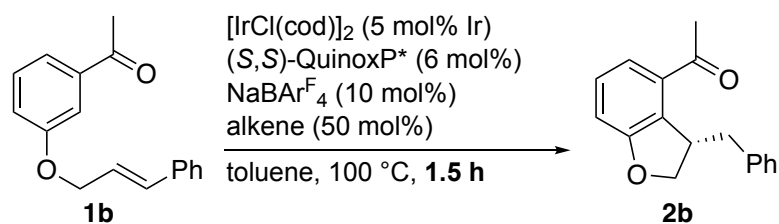
A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (*S,S*)-QuinoxP\* (2.0 mg, 0.0060 mmol, 6 mol%) or (*S*)-difluorophos (4.1 mg, 0.0060 mmol, 6 mol%), and  $\text{NaBAR}^{\text{F}}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under  $\text{N}_2$ . Then, **1** (0.10 mmol) was added to the tube, and the mixture was stirred at 100 °C for 18 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2**. The ee was measured by HPLC analysis with a chiral stationary phase column.

## 12. Transformation of **2b** into **4b**

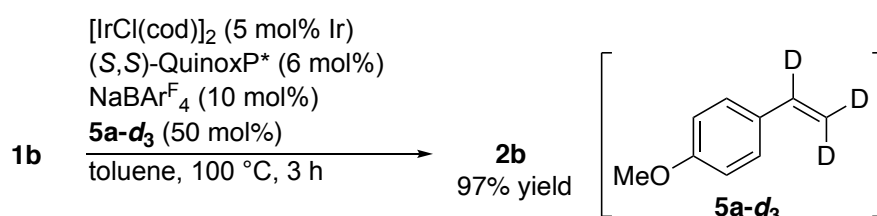


To a stirred solution of **2b** (68.7 mg, 0.27 mmol, 97% ee) in 1,4-dioxane (0.4 mL) was added dropwise a mixture of sodium hypochlorite (1.8 mL, 5% Cl in water) and 1 N NaOHaq at room temperature under N<sub>2</sub>.<sup>7</sup> After completion of the addition, the yellow solution was stirred at 75 °C for 3 h and at room temperature overnight. The mixture was washed with Et<sub>2</sub>O, and the aqueous layer was acidified with 2 N HClaq. The mixture was extracted with Et<sub>2</sub>O three times, and then the combined organic layer was washed with saturated Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> and brine, dried over Na<sub>2</sub>SO<sub>4</sub>, filtered, and concentrated on a rotary evaporator. Lithium aluminum hydride (170 mg, 0.45 mmol) was slowly added to a solution of the crude mixture (70.0 mg) in THF (0.7 mL), and the mixture was stirred at room temperature for 24 h. Et<sub>2</sub>O (0.9 mL) and 1 N NaOHaq (0.6 mL) were added to the mixture, and the resulting mixture was stirred at room temperature for 30 min. H<sub>2</sub>O was added to the mixture and the resulting mixture was extracted with Et<sub>2</sub>O. The organic layer was washed with brine, dried over Na<sub>2</sub>SO<sub>4</sub>, filtered, and concentrated on a rotary evaporator. MnO<sub>2</sub> (119.5 mg, 1.37 mmol) was added to the crude mixture in toluene (0.3 mL), and the resulting mixture was stirred at 100 °C for 2 h. The mixture was filtered through a pad of celite with Et<sub>2</sub>O, and the filtrate was concentrated on a rotary evaporator. To the residue in 1,4-dioxane (0.3 mL) were added PPh<sub>3</sub> (36 mg, 0.14 mmol) and [IrCl(cod)]<sub>2</sub> (46.2 mg, 0.14 mmol) under N<sub>2</sub>, and the mixture was stirred at 100 °C for 24 h.<sup>8</sup> The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **4** in 65% yield (CAS: 72374-36-8: 37.4 mg, 0.18 mmol, 97% ee). The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 98:2, flow 0.5 mL/min, 254 nm, t<sub>1</sub> = 21.8 min (minor), t<sub>2</sub> = 22.5 min (major)]: [α]<sup>25</sup><sub>D</sub> +37.4 (c 0.37, CHCl<sub>3</sub>) for 97% ee (*S*); lit. [α]<sup>20</sup><sub>D</sub> +41.3 (c = 0.75, CHCl<sub>3</sub>) for 86% ee (*S*)-**4**. <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 2.88 (dd, *J* = 14.0, 9.0 Hz, 1H), 3.09 (dd, *J* = 14.0, 6.4 Hz, 1H), 3.71–3.82 (m, 1H), 4.31 (dd, *J* = 8.8, 5.8 Hz, 1H), 4.55 (t, *J* = 8.8 Hz, 1H), 6.83 (d, *J* = 8.0 Hz, 1H), 6.84 (t, *J* = 7.2 Hz, 1H), 7.00 (d, *J* = 7.2 Hz, 1H), 7.16 (t, *J* = 7.2 Hz, 1H), 7.21 (d, *J* = 7.2 Hz, 2H), 7.27 (t, *J* = 7.2 Hz, 1H), 7.28–7.39 (m, 2H).

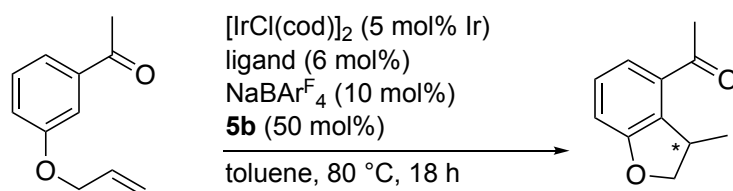
### 13. Procedures for Scheme 5



A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (*S,S*)-QuinoxP\* (2.0 mg, 0.0060 mmol, 6 mol%),  $\text{NaBARF}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%), **1b** (0.10 mmol), and alkene **5** (0.0050 mmol, 50 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at 100 °C for 1.5 h under  $\text{N}_2$ . The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2b**. The ee was measured by HPLC analysis with a chiral stationary phase column: Chiralcel OJ-H.



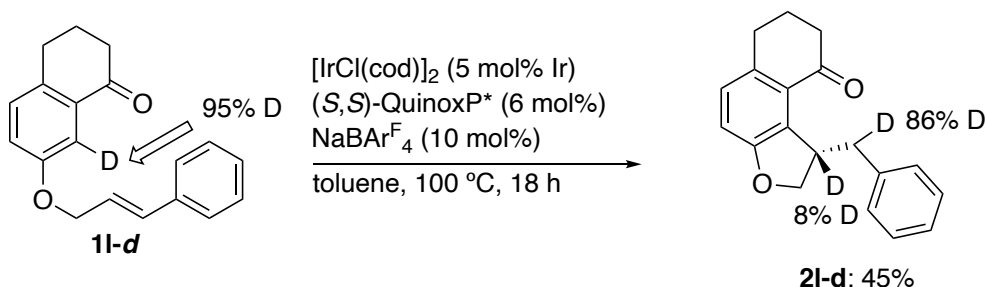
A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (*S,S*)-QuinoxP\* (2.0 mg, 0.0060 mmol, 6 mol%),  $\text{NaBARF}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%), **1b** (0.10 mmol), and **5a-d<sub>3</sub>** (0.0050 mmol, 50 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at 100 °C for 3 h under  $\text{N}_2$ . The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2b** (24.5 mg).



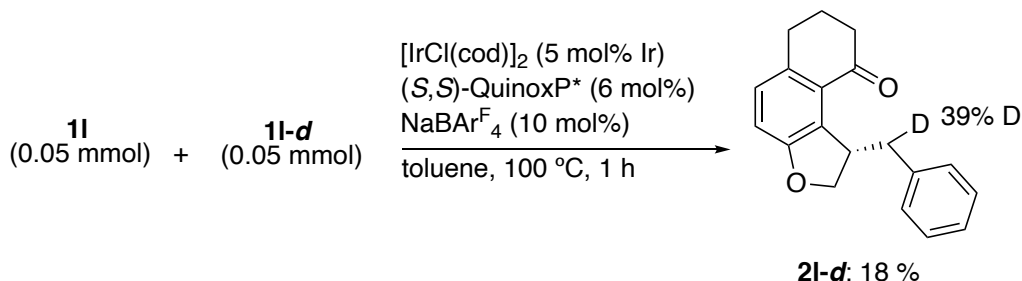
A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir), ligand (0.0060 mmol, 6 mol%), and  $\text{NaBARF}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under  $\text{N}_2$ . Then, **1a** (17.5 mg, 0.10 mmol) and 4-methoxystyrene (**5a**) (6.8 mg, 0.050 mmol, 50 mol%) were added to the tube, and the mixture was stirred at 80 °C for 18 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The

residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2a**. The ee was measured by HPLC analysis with a chiral stationary phase column: Chiralcel OJ-H.

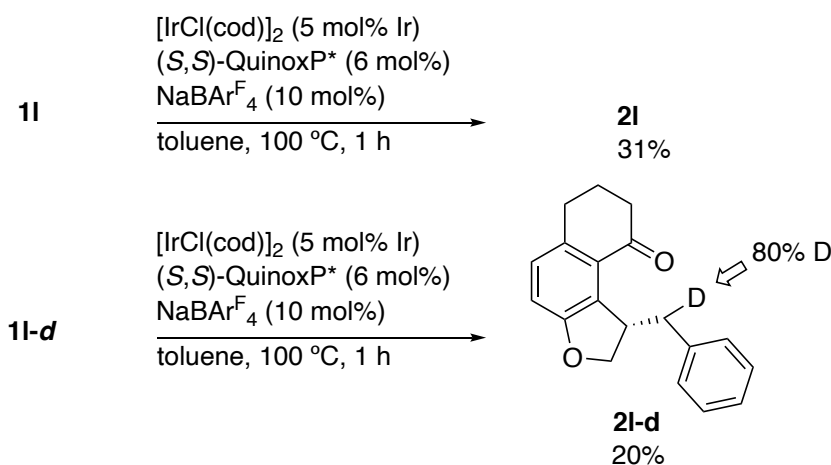
#### 14. Procedures for Scheme 6



A mixture of [IrCl(cod)]<sub>2</sub> (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (S,S)-QuinoxP\* (2.0 mg, 0.0060 mmol, 6 mol%), and NaBARF<sub>4</sub> (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under N<sub>2</sub>. Then, **1l-d** (27.9 mg, 0.10 mmol) was added to the tube, and the mixture was stirred at 100 °C for 18 h. The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2l-d** (12.6 mg, 45%). A deuterium content was determined by <sup>1</sup>H NMR. <sup>2</sup>H NMR (CHCl<sub>3</sub>) was also measured to determine the position of deuterium incorporation.



A mixture of [IrCl(cod)]<sub>2</sub> (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (S,S)-QuinoxP\* (2.0 mg, 0.0060 mmol, 6 mol%), and NaBARF<sub>4</sub> (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under N<sub>2</sub>. Then, **1l** (13.9 mg, 0.050 mmol) and **1l-d** (14.0 mg, 0.050 mmol) were added to the tube, and the mixture was stirred at 100 °C for 1 h. The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2l-d** (6.4 mg, 18%). A deuterium content was determined by <sup>1</sup>H NMR.



A mixture of  $[\text{IrCl}(\text{cod})]_2$  (1.7 mg, 0.0025 mmol, 5 mol% of Ir),  $(\text{S,S})\text{-QuinoxP}^*$  (2.0 mg, 0.0060 mmol, 6 mol%), and  $\text{NaBAR}^{\text{F}}_4$  (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk under  $\text{N}_2$  was stirred at room temperature for 10 min under  $\text{N}_2$ . Then,  $\mathbf{11}$  or  $\mathbf{11-d}$  (0.10 mmol) was added to the tube, and the mixture was stirred at 100 °C for 1 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The yields of the products were determined by  $^1\text{H}$  NMR analysis using benzyl phenyl ether as an internal standard.

### 15. General procedure for Table 2

A mixture of  $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$  (1.0 mg, 0.0010 mmol, 1 mol% of Pd), ligand (0.0012 mmol, 1.2 mol%) in toluene (0.4 mL) in a Schlenk tube was stirred at room temperature for 10 min under  $\text{N}_2$ . Then, 3-acetylphenyl cinnamyl carbonate (51.5 mg, 0.22 mmol) was added to the tube, and the mixture was stirred at 40 °C for 3 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator. The yields of the product were determined by  $^1\text{H}$  NMR analysis using benzyl phenyl ether as an internal standard.

### 16. Procedures for Scheme 8

Scheme 8a:  $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$  (1.0 mg, 0.0010 mmol, 1 mol% of Pd) and  $\mathbf{L1}$  (1.0 mg, 0.0012 mmol, 1.2 mol%) in a Schlenk tube was added toluene (0.2 mL) under  $\text{N}_2$ , and the mixture was stirred at room temperature for 10 min. Separately, a solution of  $[\text{IrCl}(\text{cod})]_2$  (3.4 mg, 0.0050 mmol, 5 mol% of Ir),  $(\text{S,S})\text{-QuinoxP}^*$  (0.012 mmol, 6 mol%), and  $\text{NaBAR}^{\text{F}}_4$  (18.4 mg calculated as the dihydrate, 0.020 mmol, 10 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under  $\text{N}_2$ . Then, the solution of the Ir catalyst and 3-acetylphenyl cinnamyl carbonate ( $\mathbf{6}$ ) (51.5 mg, 0.22 mmol) were added to the tube of the Pd catalyst, and the mixture was stirred at room temperature for 30 min and then at 100 °C for 18 h. The mixture was passed through a short column of alumina with  $\text{CH}_2\text{Cl}_2$  as an eluent, and the solvent was removed on a rotary evaporator.

Scheme 8b: Pd<sub>2</sub>(dba)<sub>3</sub>·CHCl<sub>3</sub> (1.0 mg, 0.0010 mmol, 1 mol% of Pd) and **L1** (1.0 mg, 0.0012 mmol, 1.2 mol%) in a Schlenk tube was added toluene (0.20 mL) under N<sub>2</sub>, and the mixture was stirred at room temperature for 10 min. Separately, a solution of [IrCl(cod)]<sub>2</sub> (3.4 mg, 0.0050 mmol, 5 mol% of Ir) and (*S,S*)-QuinoxP\* (0.012 mmol, 6 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under N<sub>2</sub>. Then, the solution of the Ir catalyst and 3-acetylphenyl cinnamyl carbonate (**6**) (51.5 mg, 0.22 mmol) were added to the tube of the Pd catalyst, and the mixture was stirred at room temperature for 30 min. To the mixture was added NaBAR<sup>F</sup><sub>4</sub> (18.4 mg calculated as the dihydrate, 0.020 mmol, 10 mol%), and the resulting mixture was stirred at 100 °C for 14 h. The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator.

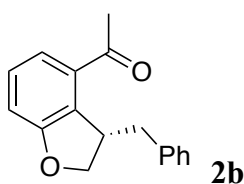
Scheme 8c: A mixture of Pd<sub>2</sub>(dba)<sub>3</sub>·CHCl<sub>3</sub> (1.0 mg, 0.0010 mmol, 1 mol% of Pd) and **L1** (1.0 mg, 0.0012 mmol, 1.2 mol%) in toluene (0.4 mL) in a Schlenk tube was stirred at room temperature for 10 min under N<sub>2</sub>. Then, 3-acetylphenyl cinnamyl carbonate (**6**) (51.5 mg, 0.22 mmol) was added to the tube, and the mixture was stirred at room temperature for 30 min. To the mixture were added [IrCl(cod)]<sub>2</sub> (3.4 mg, 0.0050 mmol, 5 mol% of Ir), (*S,S*)-QuinoxP\* (0.012 mmol, 6 mol%), and NaBAR<sup>F</sup><sub>4</sub> (18.4 mg calculated as the dihydrate, 0.020 mmol, 10 mol%), and the resulting mixture was stirred at 100 °C for 16 h. The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator. The yield of the product was determined by <sup>1</sup>H NMR analysis using benzyl phenyl ether as an internal standard. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2b**. The ee was measured by HPLC analysis with a chiral stationary phase column: Chiralcel OJ-H.

## 17. Procedures for Schemes 9 and 10

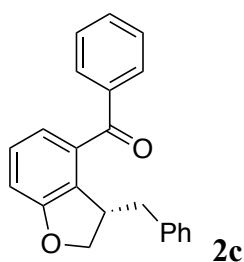
A mixture of Pd<sub>2</sub>(dba)<sub>3</sub>·CHCl<sub>3</sub> (0.5 mg, 0.0005 mmol, 1 mol% of Pd) and **L1** (0.5 mg, 0.0006 mmol, 1.2 mol%) in toluene (0.2 mL) in a Schlenk tube was stirred at room temperature for 10 min under N<sub>2</sub>. Then, *m*-hydroxyacetophenones **6** (0.10 mmol) and *t*-butyl cinnamyl carbonates **7** (0.11 mmol) were added to the tube, and the mixture was stirred at 40 °C for 1 h. To the mixture were added [IrCl(cod)]<sub>2</sub> (1.7 mg, 0.0025 mmol, 5 mol% of Ir), (*S,S*)-QuinoxP\* (0.006 mmol, 6 mol%), and NaBAR<sup>F</sup><sub>4</sub> (9.2 mg calculated as the dihydrate, 0.010 mmol, 10 mol%), and the resulting mixture was stirred at 100 °C for 18 h. The mixture was passed through a short column of alumina with CH<sub>2</sub>Cl<sub>2</sub> as an eluent, and the solvent was removed on a rotary evaporator. The residue was subjected to preparative TLC on silica gel eluted with EtOAc/hexane (1:10) to give **2**. The ee was measured by HPLC analysis with a chiral stationary phase column.



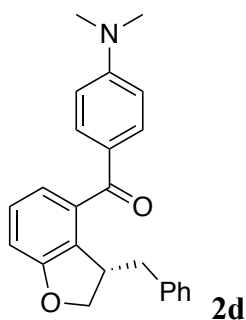
## 18. Characterization of products 2



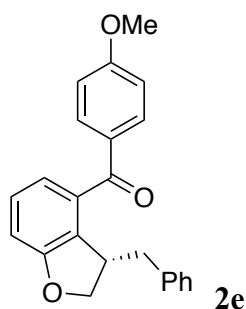
**Compound 2b** (Table 1, entry 7: pale yellow solid, 21.6 mg, 85% yield, 97% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 20.3 min (minor),  $t_2$  = 22.4 min (major)]:  $[\alpha]^{25}_D -33$  ( $c$  0.70,  $\text{CHCl}_3$ ) for 97% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.49 (dd,  $J$  = 13.6, 10.4 Hz, 1H), 2.64 (s, 3H), 3.09 (dd,  $J$  = 13.6, 3.2 Hz, 1H), 4.14–4.22 (m, 1H), 4.25–4.32 (m, 1H), 4.46 (dd,  $J$  = 9.0, 2.2 Hz, 1H), 7.01 (d,  $J$  = 8.0 Hz, 1H), 7.19–7.27 (m, 1H), 7.27 (t,  $J$  = 8.0 Hz, 1H), 7.29–7.35 (m, 4H), 7.44 (dd,  $J$  = 8.0, 1.2 Hz, 1H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  28.0, 39.5, 44.5, 75.7, 114.3, 122.4, 126.2, 128.5, 128.6, 129.3, 132.1, 133.6, 140.0, 160.8, 199.0. HRMS (DART) calcd for  $\text{C}_{17}\text{H}_{17}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  253.1229, found 253.1234.



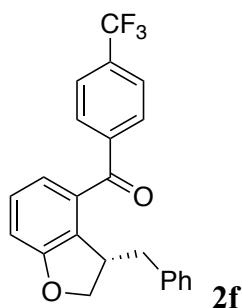
**Compound 2c** (Scheme 3: colorless oil, 21.1 mg, 67% yield, 96% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 26.4 min (minor),  $t_2$  = 35.0 min (major)]:  $[\alpha]^{25}_D -127$  ( $c$  0.35,  $\text{CHCl}_3$ ) for 96% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.58 (dd,  $J$  = 13.6, 11.0 Hz, 1H), 3.02 (dd,  $J$  = 13.6, 3.8 Hz, 1H), 4.01–4.12 (m, 1H), 4.36–4.46 (m, 2H), 7.01 (d,  $J$  = 7.6 Hz, 1H), 7.07–7.15 (m, 3H), 7.17 (t,  $J$  = 7.4 Hz, 1H), 7.20–7.29 (m, 3H), 7.51 (t,  $J$  = 7.6 Hz, 2H), 7.59–7.66 (m, 1H), 7.85 (dd,  $J$  = 8.4, 1.6 Hz, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  40.5, 43.4, 75.8, 113.2, 123.1, 126.3, 128.0, 128.36, 128.44, 129.0, 130.0, 131.7, 132.8, 134.5, 137.9, 139.2, 160.6, 197.0. HRMS (DART) calcd for  $\text{C}_{22}\text{H}_{19}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  315.1385, found 315.1386.



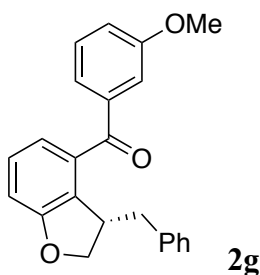
**Compound 2d** (Scheme 3: yellow solid, 28.7 mg, 80% yield, 86% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralpak AD-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 53.0 min (major),  $t_2$  = 57.7 min (minor)]:  $[\alpha]^{25}_D$  -68 ( $c$  1.14,  $\text{CHCl}_3$ ) for 86% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.57 (dd,  $J$  = 13.6, 11.0 Hz, 1H), 3.03 (dd,  $J$  = 13.6, 3.6 Hz, 1H), 3.13 (s, 6H), 3.99–4.10 (m, 1H), 4.32–4.50 (m, 2H), 6.73 (d,  $J$  = 9.0 Hz, 2H), 6.95 (d,  $J$  = 8.0 Hz, 1H), 7.07 (d,  $J$  = 7.6 Hz, 1H), 7.10 (d,  $J$  = 7.2 Hz, 2H), 7.14–7.32 (m, 4H), 7.87 (d,  $J$  = 9.0 Hz, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  40.1, 40.5, 43.1, 75.7, 110.7, 111.7, 121.7, 125.2, 126.2, 127.8, 128.4, 129.0, 130.4, 132.6, 136.4, 139.3, 153.4, 160.4, 195.0. HRMS (DART) calcd for  $\text{C}_{24}\text{H}_{24}\text{N}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  358.1807, found 358.1807.



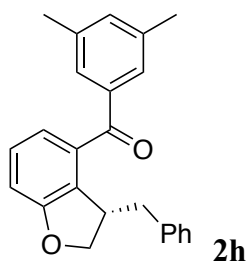
**Compound 2e** (Scheme 3: colorless oil, 34.5 mg, >99% yield, 82% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralpak AD-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 29.7 min (major),  $t_2$  = 32.2 min (minor)]:  $[\alpha]^{25}_D$  -102 ( $c$  0.73,  $\text{CHCl}_3$ ) for 82% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.56 (dd,  $J$  = 14.0, 10.6 Hz, 1H), 2.99 (dd,  $J$  = 14.0, 3.6 Hz, 1H), 3.90 (s, 3H), 3.98–4.09 (m, 1H), 4.36–4.45 (m, 2H), 6.95–7.01 (m, 3H), 7.05 (dd,  $J$  = 7.8, 1.0 Hz, 1H), 7.09 (dd,  $J$  = 7.6, 1.6 Hz, 2H), 7.12–7.29 (m, 1H), 7.19–7.27 (m, 3H), 7.86 (d,  $J$  = 8.8 Hz, 2H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  40.6, 43.2, 55.5, 75.8, 112.6, 113.6, 122.3, 126.3, 128.0, 128.4, 129.0, 130.5, 131.1, 132.5, 135.3, 139.2, 160.6, 163.5, 195.6. HRMS (DART) calcd for  $\text{C}_{23}\text{H}_{21}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  345.1491, found 345.1498.



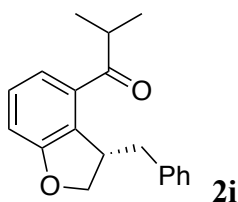
**Compound 2f** (Scheme 3: pale yellow solid, 31.3 mg, 82% yield, 98% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 16.2 min (minor),  $t_2$  = 17.7 min (major)]:  $[\alpha]^{25}_D$  -166 ( $c$  0.68,  $\text{CHCl}_3$ ) for 98% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.62 (dd,  $J$  = 13.6, 10.4 Hz, 1H), 3.04 (dd,  $J$  = 13.6, 4.2 Hz, 1H), 4.08–4.18 (m, 1H), 4.40–4.47 (m, 1H), 4.48 (dd,  $J$  = 9.2, 3.6 Hz, 1H), 7.06 (dd,  $J$  = 7.0, 2.6 Hz, 2H), 7.13–7.21 (m, 3H), 7.21–7.30 (m, 3H), 7.78 (d,  $J$  = 8.0 Hz, 2H), 7.92 (d,  $J$  = 8.4 Hz, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  40.5, 43.5, 76.0, 114.0, 123.4, 123.6 (q,  $J_{\text{C-F}}$  = 271 Hz), 125.5 (q,  $J_{\text{C-F}}$  = 4 Hz), 126.4, 128.2, 128.5, 129.1, 130.1, 132.2, 133.5, 133.9 (q,  $J_{\text{C-F}}$  = 33 Hz), 139.0, 141.0, 160.9, 195.7;  $^{19}\text{F}$  NMR ( $\text{CDCl}_3$ )  $\delta$  -63.0. HRMS (ESI) calcd for  $\text{C}_{23}\text{H}_{17}\text{F}_3\text{Na}_1\text{O}_2$  ( $\text{M}+\text{Na}$ ) $^+$  405.1078, found 405.1092.



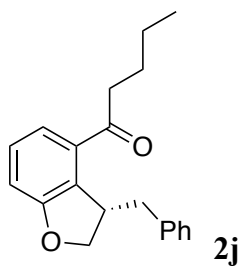
**Compound 2g** (Scheme 3: pale yellow oil, 26.6 mg, 77% yield, 96% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 29.7 min (minor),  $t_2$  = 46.7 min (major)]:  $[\alpha]^{25}_D$  -119 ( $c$  0.79,  $\text{CHCl}_3$ ) for 96% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.58 (dd,  $J$  = 13.2, 10.8 Hz, 1H), 3.03 (dd,  $J$  = 13.2, 3.6 Hz, 1H), 3.88 (s, 3H), 4.02–4.14 (m, 1H), 4.40–4.47 (m, 2H), 7.00 (d,  $J$  = 7.6 Hz, 1H), 7.10 (dd,  $J$  = 7.2, 0.8 Hz, 1H), 7.14 (dd,  $J$  = 7.6, 1.6 Hz, 2H), 7.13–7.29 (m, 5H), 7.35–7.43 (m, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  40.5, 43.4, 55.5, 75.8, 113.2, 114.0, 119.2, 122.9, 123.0, 126.3, 128.0, 128.4, 129.0, 129.3, 131.6, 134.5, 139.22, 139.24, 159.6, 160.6, 196.7. HRMS (DART) calcd for  $\text{C}_{23}\text{H}_{21}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  345.1491, found 345.1493.



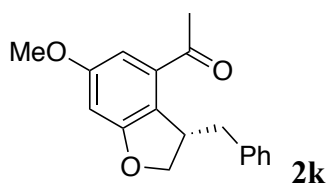
**Compound 2h** (Scheme 3: pale yellow oil, 32.1 mg, 94% yield, 96% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 17.2 min (minor),  $t_2$  = 23.7 min (major)]:  $[\alpha]^{25}_D$  -126 ( $c$  1.16,  $\text{CHCl}_3$ ) for 96% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.39 (s, 6H), 2.58 (dd,  $J$  = 13.6, 11.0 Hz, 1H), 3.04 (dd,  $J$  = 13.6, 3.4 Hz, 1H), 4.03–4.13 (m, 1H), 4.36–4.47 (m, 2H), 7.00 (d,  $J$  = 7.6 Hz, 1H), 7.09 (d,  $J$  = 7.6 Hz, 1H), 7.14 (d,  $J$  = 8.0 Hz, 2H), 7.15–7.30 (m, 5H), 7.45 (s, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  21.2, 40.5, 43.4, 75.8, 113.0, 123.1, 126.3, 127.7, 127.9, 128.4, 129.0, 131.6, 134.4, 134.8, 138.0, 138.1, 139.3, 160.6, 197.4. HRMS (DART) calcd for  $\text{C}_{24}\text{H}_{23}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  343.1698, found 343.1686.



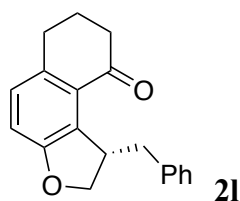
**Compound 2i** (Scheme 3: pale yellow solid, 25.2 mg, 90% yield, 90% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 10.9 min (major),  $t_2$  = 12.5 min (minor)]:  $[\alpha]^{25}_D$  -44 ( $c$  0.49,  $\text{CHCl}_3$ ) for 90% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  1.24 (d,  $J$  = 6.8 Hz, 3H), 1.26 (d,  $J$  = 6.8 Hz, 3H), 2.47 (dd,  $J$  = 13.3, 10.8 Hz, 1H), 3.06 (dd,  $J$  = 13.3, 3.0 Hz, 1H), 3.61 (sept,  $J$  = 6.8 Hz, 1H), 4.19–4.28 (m, 1H), 4.26–4.34 (m, 1H), 4.44 (dd,  $J$  = 8.4, 2.2 Hz, 1H), 6.99 (d,  $J$  = 7.6 Hz, 1H), 7.19–7.28 (m, 1H), 7.27 (t, 7.6 Hz, 1 H) 7.28–7.36 (m, 4H), 7.44 (d,  $J$  = 7.6 Hz, 1H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  18.9, 19.4, 36.2, 39.6, 44.3, 75.5, 113.9, 121.3, 126.2, 128.4, 128.5, 129.2, 132.5, 132.9, 139.8, 161.0, 205.6. HRMS (DART) calcd for  $\text{C}_{19}\text{H}_{21}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  281.1542, found 281.1543.



**Compound 2j** (Scheme 3: colorless oil, 24.6 mg, 84% yield, 96% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralpak AD-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 9.3 min (major),  $t_2$  = 10.4 min (minor)]:  $[\alpha]^{25}_D -34$  ( $c$  0.61,  $\text{CHCl}_3$ ) for 96% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  0.99 (t,  $J$  = 7.2 Hz, 3H), 1.45 (sext,  $J$  = 7.2 Hz, 2H), 1.76 (quint,  $J$  = 7.2 Hz, 2H), 2.50 (dd,  $J$  = 13.2, 10.4 Hz, 1H), 3.00 (sext,  $J$  = 7.2 Hz, 2H), 3.09 (dd,  $J$  = 13.2, 3.4 Hz, 1H), 4.18–4.28 (m, 1H), 4.25–4.34 (m, 1H), 4.46 (dd,  $J$  = 8.8, 1.6 Hz, 1H), 7.01 (d,  $J$  = 8.0 Hz, 1H), 7.20–7.28 (m, 1H), 7.27 (t,  $J$  = 8.0 Hz, 1H), 7.29–7.37 (m, 4H), 7.46 (d,  $J$  = 8.0 Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  14.0, 22.5, 26.6, 39.5, 39.6, 44.4, 75.6, 114.0, 121.6, 126.2, 128.4, 129.3, 132.1, 133.7, 139.9, 160.9, 201.5. HRMS (DART) calcd for  $\text{C}_{20}\text{H}_{23}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  295.1698, found 295.1693.

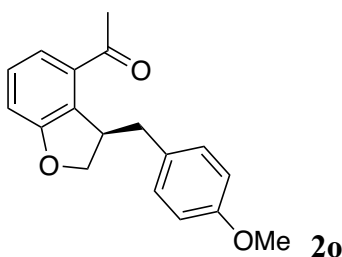


**Compound 2k** (Scheme 3: pale yellow solid, 25.1 mg, 89% yield, 96% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OD-H, hexane/2-propanol = 19:1, flow 0.8 mL/min, 254 nm,  $t_1$  = 9.7 min (major),  $t_2$  = 12.2 min (minor)]:  $[\alpha]^{25}_D -23$  ( $c$  1.26,  $\text{CHCl}_3$ ) for 99% (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.47 (dd,  $J$  = 13.4, 10.4 Hz, 1H), 2.60 (s, 3H), 3.05 (dd,  $J$  = 13.4, 3.2 Hz, 1H), 3.84 (s, 3H), 4.04–4.13 (m, 1H), 4.26–4.34 (m, 1H), 4.45 (dd,  $J$  = 8.8, 2.0 Hz, 1H), 6.60 (d,  $J$  = 2.0 Hz, 1H), 6.96 (d,  $J$  = 2.0 Hz, 1H), 7.19–7.26 (m, 1H), 7.27–7.35 (m, 4H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  27.9, 39.8, 44.0, 55.7, 76.4, 100.2, 108.6, 124.0, 126.2, 128.4, 129.2, 133.7, 140.0, 160.3, 162.1, 198.8. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  283.1334, found 283.1323.

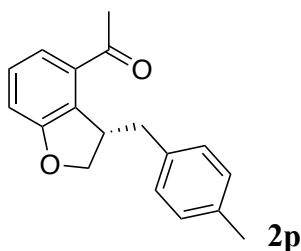


**Compound 2l** (Scheme 3: pale yellow solid, 26.4 mg, 95% yield, 98% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC

[Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 28.7 min (minor),  $t_2$  = 31.3 min (major)]:  $[\alpha]^{25}_D$  -46 ( $c$  1.32,  $\text{CHCl}_3$ ) for 96% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.08–2.21 (m, 2H), 2.45 (dd,  $J$  = 13.2, 10.4 Hz, 1H), 2.67 (dd,  $J$  = 7.8, 5.8 Hz, 2H), 2.87–3.02 (m, 2H), 3.12 (dd,  $J$  = 13.2, 2.8 Hz, 1H), 4.15–4.23 (m, 1H), 4.22–4.30 (m, 1H), 4.46 (dd,  $J$  = 8.6, 1.8 Hz, 1H), 6.95 (d,  $J$  = 8.2 Hz, 1H), 7.09 (d,  $J$  = 8.2 Hz, 1H), 7.19–7.26 (m, 1H), 7.32 (t,  $J$  = 7.6 Hz, 2H), 7.37 (d,  $J$  = 6.8 Hz, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  23.6, 29.6, 39.3, 40.2, 45.1, 75.8, 114.8, 126.2, 128.4, 128.8, 129.0, 129.3, 132.0, 137.3, 140.2, 159.0, 199.3. HRMS (DART) calcd for  $\text{C}_{19}\text{H}_{19}\text{O}_2$  ( $\text{M}+\text{H}$ )<sup>+</sup> 279.1385, found 279.1383.

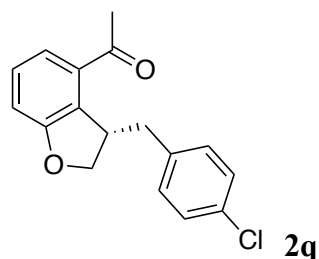


**Compound 2o** (Scheme 3: colorless oil, 17.7 mg, 63% yield, 85% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralpak IA, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 14.1 min (major),  $t_2$  = 15.9 min (minor)]:  $[\alpha]^{25}_D$  +33 ( $c$  0.96,  $\text{CHCl}_3$ ) for 85% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.43 (dd,  $J$  = 13.8, 10.6 Hz, 1H), 2.63 (s, 3H), 3.01 (dd,  $J$  = 13.8, 3.2 Hz, 1H), 3.80 (s, 3H), 4.09–4.17 (m, 1H), 4.26–4.32 (m, 1H), 4.45 (dd,  $J$  = 8.3, 2.2 Hz, 1H), 6.86 (d,  $J$  = 8.8 Hz, 2H), 7.01 (d,  $J$  = 8.0 Hz, 1H), 7.24 (d,  $J$  = 8.8 Hz, 2H), 7.26 (t,  $J$  = 8.0 Hz, 1H), 7.44 (dd,  $J$  = 8.0, 0.8 Hz, 1H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  28.0, 38.7, 44.7, 55.2, 75.7, 113.8, 114.3, 122.3, 128.5, 130.2, 132.0, 132.1, 133.6, 158.1, 160.8, 199.0. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_3$  ( $\text{M}+\text{H}$ )<sup>+</sup> 283.1334, found 283.1331.

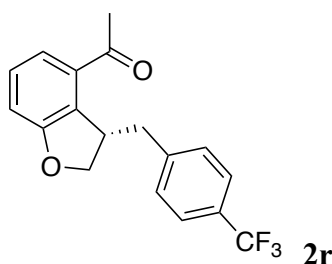


**Compound 2p** (Scheme 3: pale yellow solid, 23.6 mg, 89% yield, 98% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 21.5 min (minor),  $t_2$  = 26.6 min (major)]:  $[\alpha]^{25}_D$  -36 ( $c$  0.98,  $\text{CHCl}_3$ ) for 98% ee (*S*).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  2.34 (s, 3H), 2.45 (dd,  $J$  = 13.4, 10.6 Hz, 1H), 2.64 (s, 3H), 3.05 (dd,  $J$  = 13.4, 3.0 Hz, 1H), 4.12–4.20 (m, 1H), 4.29 (t,  $J$  = 8.0 Hz, 1H), 4.46 (dd,  $J$  = 9.0, 2.2 Hz, 1H), 7.01 (d,  $J$  = 7.8 Hz, 1H), 7.13 (d,  $J$  = 8.0 Hz, 2H), 7.22 (d,  $J$  = 8.0 Hz, 2H), 7.27 (t,  $J$  = 7.8 Hz, 1H), 7.44 (d,  $J$  = 7.8 Hz, 1H);  $^{13}\text{C}$

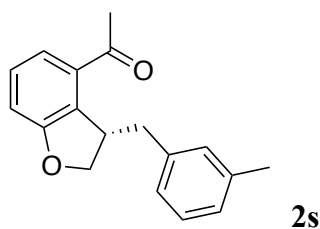
NMR (CDCl<sub>3</sub>)  $\delta$  21.0, 28.0, 39.1, 44.6, 75.7, 114.3, 122.3, 128.5, 129.1, 132.2, 133.6, 135.7, 136.8, 160.8, 199.0. HRMS (DART) calcd for C<sub>18</sub>H<sub>19</sub>O<sub>2</sub> (M+H)<sup>+</sup> 267.1385, found 267.1385.



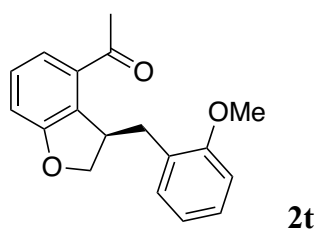
**Compound 2q** (Scheme 3: pale yellow solid, 25.5 mg, 89% yield, 94% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 16.7 min (minor),  $t_2$  = 19.3 min (major)]:  $[\alpha]_D^{25}$  -27 ( $c$  1.33, CHCl<sub>3</sub>) for 94% ee (*S*). <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  2.47 (dd,  $J$  = 13.3, 10.6 Hz, 1H), 2.63 (s, 3H), 3.03 (dd,  $J$  = 13.3, 3.2 Hz, 1H), 4.08–4.17 (m, 1H), 4.24–4.32 (m, 1H), 4.30 (dd,  $J$  = 9.2, 2.4 Hz, 1H), 7.00 (d,  $J$  = 8.4 Hz, 1H), 7.20–7.30 (m, 5H), 7.44 (d,  $J$  = 7.2 Hz, 1H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  27.9, 38.8, 44.5, 75.5, 114.5, 122.5, 128.5, 128.7, 130.6, 131.7, 132.1, 133.5, 138.4, 160.8, 199.0. HRMS (DART) calcd for C<sub>17</sub>H<sub>16</sub><sup>35</sup>ClO<sub>2</sub> (M+H)<sup>+</sup> 287.0839, C<sub>17</sub>H<sub>16</sub><sup>37</sup>ClO<sub>2</sub> (M+H)<sup>+</sup> 289.0809, found 287.0842.



**Compound 2r** (Scheme 3: pale yellow solid, 21.6 mg, 67% yield, 89% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 20.7 min (minor),  $t_2$  = 24.2 min (major)]:  $[\alpha]_D^{25}$  -14 ( $c$  0.58, CHCl<sub>3</sub>) for 89% ee (*S*). <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  2.57 (dd,  $J$  = 13.2, 10.4 Hz, 1H), 2.64 (s, 3H), 3.14 (dd,  $J$  = 13.2, 2.8 Hz, 1H), 4.14–4.22 (m, 1H), 4.25–4.33 (m, 1H), 4.41 (dd,  $J$  = 8.8, 2.0 Hz, 1H), 7.24 (d,  $J$  = 7.8 Hz, 1H), 7.29 (t,  $J$  = 7.8 Hz, 1H), 7.44 (d,  $J$  = 8.0 Hz, 2H), 7.46 (dd,  $J$  = 7.8, 0.8 Hz, 1H), 7.57 (d,  $J$  = 8.0 Hz, 2H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  27.9, 39.3, 44.4, 75.5, 114.5, 122.6, 124.3 (q,  $J_{C-F}$  = 271 Hz), 125.3 (q,  $J_{C-F}$  = 4 Hz), 128.6 (q,  $J_{C-F}$  = 32 Hz), 128.9, 129.5, 131.5, 133.5, 144.1, 160.8, 199.0; <sup>19</sup>F NMR (CDCl<sub>3</sub>)  $\delta$  -62.3. HRMS (DART) calcd for C<sub>18</sub>H<sub>16</sub>F<sub>3</sub>O<sub>2</sub> (M+H)<sup>+</sup> 321.1102, found 321.1101.

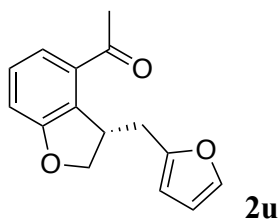


**Compound 2s** (Scheme 3: pale yellow solid, 21.2 mg, 80% yield, 97% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 23.1 min (minor),  $t_2$  = 24.3 min (major)]:  $[\alpha]^{25}_D -27$  ( $c$  0.69,  $\text{CHCl}_3$ ) for 97% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.36 (s, 3H), 2.42 (dd,  $J$  = 13.2, 10.8 Hz, 1H), 2.65 (s, 3H), 3.06 (dd,  $J$  = 13.2, 3.5 Hz, 1H), 4.12–4.21 (m, 1H), 4.24–4.32 (m, 1H), 4.46 (dd,  $J$  = 8.8, 2.0 Hz, 1H), 7.02 (d,  $J$  = 7.6 Hz, 1H), 7.05 (d,  $J$  = 8.0 Hz, 1H), 7.13 (d,  $J$  = 7.6 Hz, 1H), 7.16 (s, 1H), 7.18–7.25 (m, 1H), 7.28 (t,  $J$  = 7.6 Hz, 1H), 7.45 (d,  $J$  = 7.2 Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  21.4, 28.0, 39.4, 44.5, 75.6, 114.3, 122.4, 126.3, 127.0, 128.3, 128.5, 130.0, 132.2, 133.6, 138.1, 140.0, 160.8, 199.0. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  267.1385, found 267.1390.

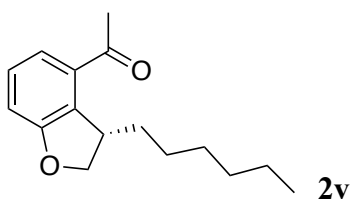


**Compound 2t** (Scheme 3: pale yellow oil, 22.9 mg, 81% yield, 93% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralpak AD-H, hexane/2-propanol = 98:2, flow 0.5 mL/min, 254 nm,  $t_1$  = 19.5 min (major),  $t_2$  = 23.8 min (minor)]:  $[\alpha]^{25}_D +17$  ( $c$  0.71,  $\text{CHCl}_3$ ) for 93% ee (*R*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.61 (s, 3H), 2.81 (dd,  $J$  = 13.6, 9.6 Hz, 1H), 2.91 (dd,  $J$  = 13.6, 4.2 Hz, 1H), 3.88 (s, 3H), 4.24–4.39 (m, 2H), 4.53 (dd,  $J$  = 8.2, 1.8 Hz, 1H), 6.89 (d,  $J$  = 8.4 Hz, 1H), 6.93 (td,  $J$  = 7.4, 1.0 Hz, 1H), 7.03 (d,  $J$  = 8.0 Hz, 1H), 7.20–7.28 (m, 2H), 7.28 (d,  $J$  = 6.8 Hz, 1H), 7.40 (dd,  $J$  = 7.6, 1.0 Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  28.1, 33.7, 43.1, 55.2, 76.2, 110.3, 114.0, 120.4, 121.9, 127.5, 128.0, 128.3, 131.0, 132.0, 134.4, 157.7, 160.8, 199.1. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  283.1334, found 283.1331.

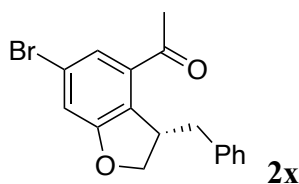




**Compound 2u** (Scheme 3: pale yellow solid, 15.1 mg, 62% yield, 85% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 23.5 min (minor),  $t_2$  = 24.8 min (major)]:  $[\alpha]^{25}_D -100$  ( $c$  1.12,  $\text{CHCl}_3$ ) for 85% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.61 (s, 3H), 2.68 (dd,  $J$  = 15.0, 9.8 Hz, 1H), 3.04 (dd,  $J$  = 15.0, 3.4 Hz, 1H), 4.19–4.27 (m, 1H), 4.42 (t,  $J$  = 8.4 Hz, 1H), 4.45 (dd,  $J$  = 8.8, 2.4 Hz, 1H), 6.01 (d,  $J$  = 3.0 Hz, 1H), 6.27 (dd,  $J$  = 3.0, 1.4 Hz, 1H), 6.99 (d,  $J$  = 8.0 Hz, 1H), 7.22–7.29 (m, 1H), 7.33 (d,  $J$  = 1.4 Hz, 1H), 7.41 (d,  $J$  = 7.6 Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  27.9, 31.9, 41.9, 76.1, 106.4, 110.1, 114.2, 122.2, 128.7, 131.0, 133.9, 141.5, 153.7, 160.9, 198.9. HRMS (ESI) calcd for  $\text{C}_{15}\text{H}_{14}\text{Na}_1\text{O}_3$  ( $\text{M}+\text{Na}$ ) $^+$  265.0841, found 265.0843.

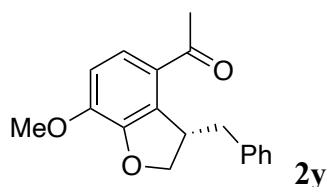


**Compound 2v** (Scheme 3: colorless oil, 17.9 mg, 73% yield, 56% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1$  = 8.4 min (major),  $t_2$  = 8.8 min (minor)]:  $[\alpha]^{25}_D +26$  ( $c$  0.79,  $\text{CHCl}_3$ ) for 56% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  0.86 (t,  $J$  = 6.8 Hz, 3H), 1.18–1.68 (m, 10H), 2.30 (s, 3H), 3.84–3.93 (m, 1H), 4.40–4.51 (m, 2H), 6.97 (d,  $J$  = 7.6 Hz, 1H), 7.21 (t,  $J$  = 7.6 Hz, 1H), 7.37 (d,  $J$  = 7.6 Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  14.1, 22.6, 27.3, 28.1, 29.2, 31.8, 34.0, 42.4, 76.6, 113.9, 122.1, 128.1, 132.6, 133.9, 160.7, 199.0. HRMS (DART) calcd for  $\text{C}_{16}\text{H}_{23}\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  247.1698, found 247.1690.



**Compound 2x** (Scheme 10: pale yellow oil, 21.3 mg, 99% yield, 83% ee). A solution of EtOAc/hexane (1:10) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OD-H, hexane/2-propanol = 98:2, flow 0.5 mL/min, 254 nm,  $t_1$  = 13.2 min (major),  $t_2$  =

14.2 min (minor):  $[\alpha]^{25}_{\text{D}} -36$  (*c* 0.69,  $\text{CHCl}_3$ ) for 83% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.45 (dd,  $J = 13.4, 10.2$  Hz, 1H), 2.58 (s, 3H), 3.02 (dd,  $J = 13.4, 3.4$  Hz, 1H), 4.05–4.17 (m, 1H), 4.25–4.35 (m, 1H), 4.44 (dd,  $J = 9.0, 2.2$  Hz, 1H), 7.12 (d,  $J = 1.8$  Hz, 1H), 7.17–7.34 (m, 5H), 7.51 (d,  $J = 1.8$  Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  27.9, 39.5, 44.0, 76.4, 117.5, 121.4, 125.0, 126.4, 128.5, 129.2, 131.5, 134.5, 139.4, 161.9, 197.7. HRMS (DART) calcd for  $\text{C}_{17}\text{H}_{16}^{79}\text{Br}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  331.0334,  $\text{C}_{17}\text{H}_{16}^{81}\text{Br}_1\text{O}_2$  ( $\text{M}+\text{H}$ ) $^+$  333.0313, found 331.0331.

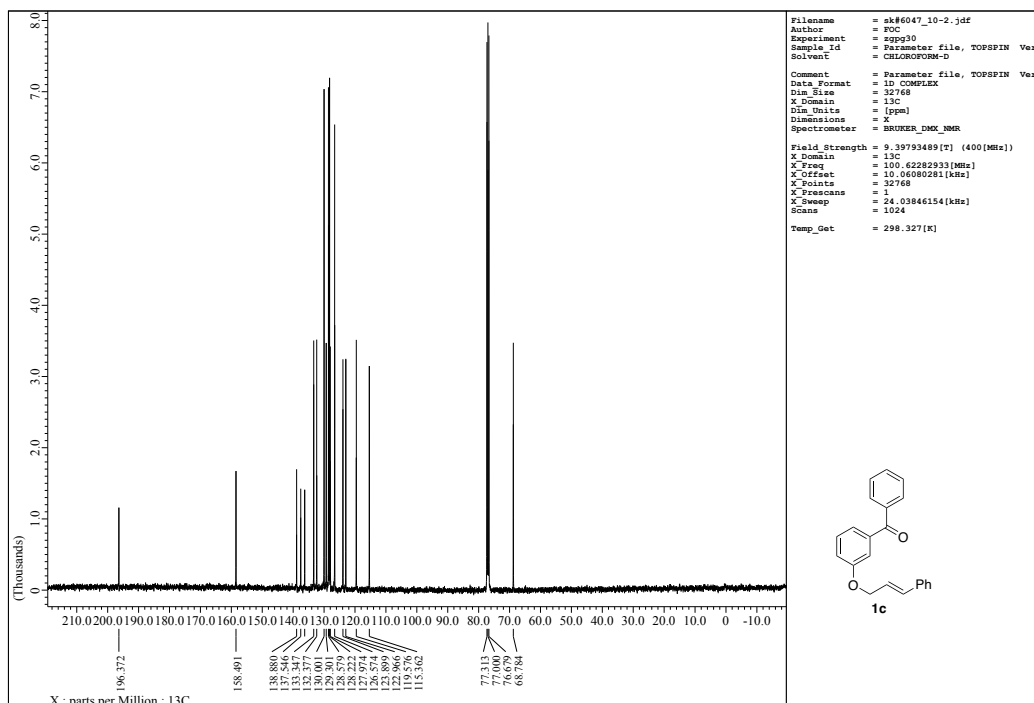
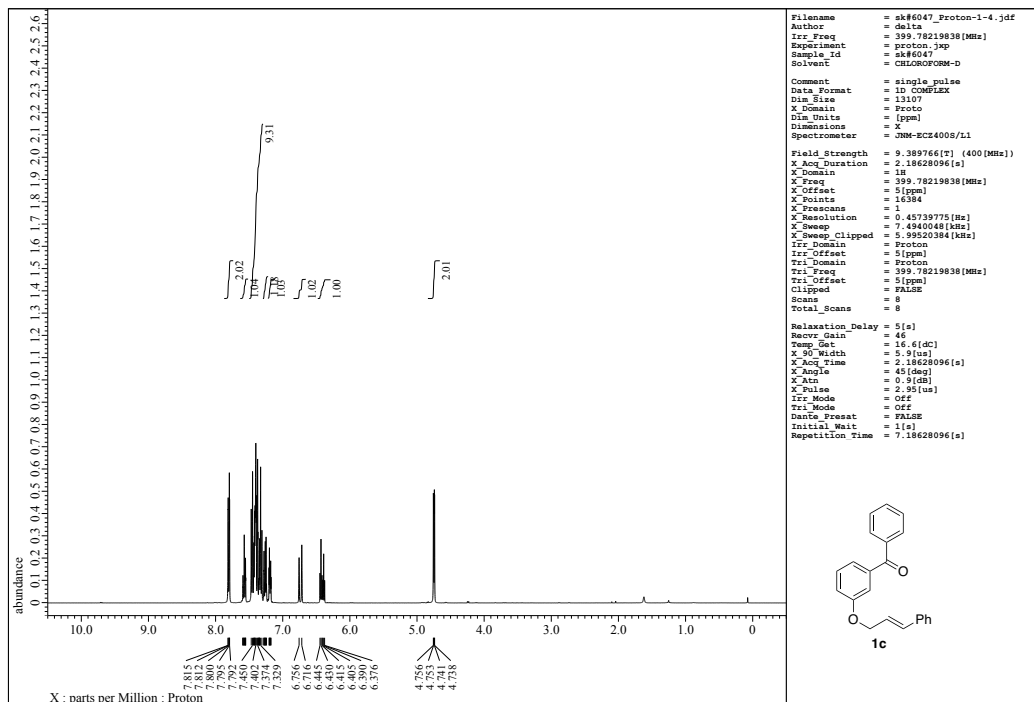


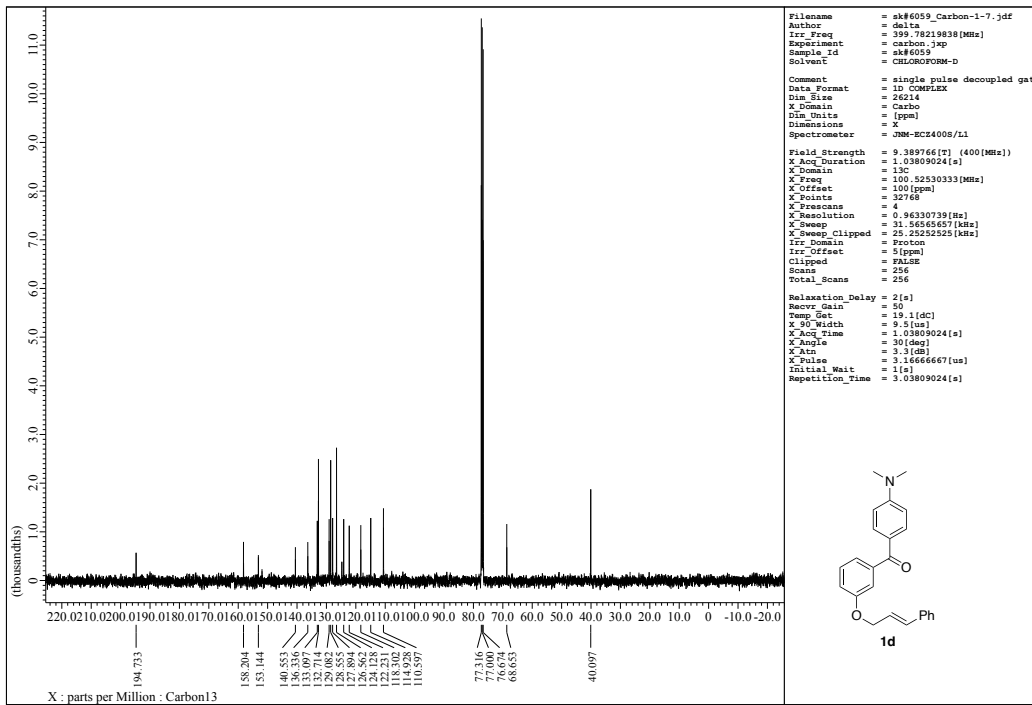
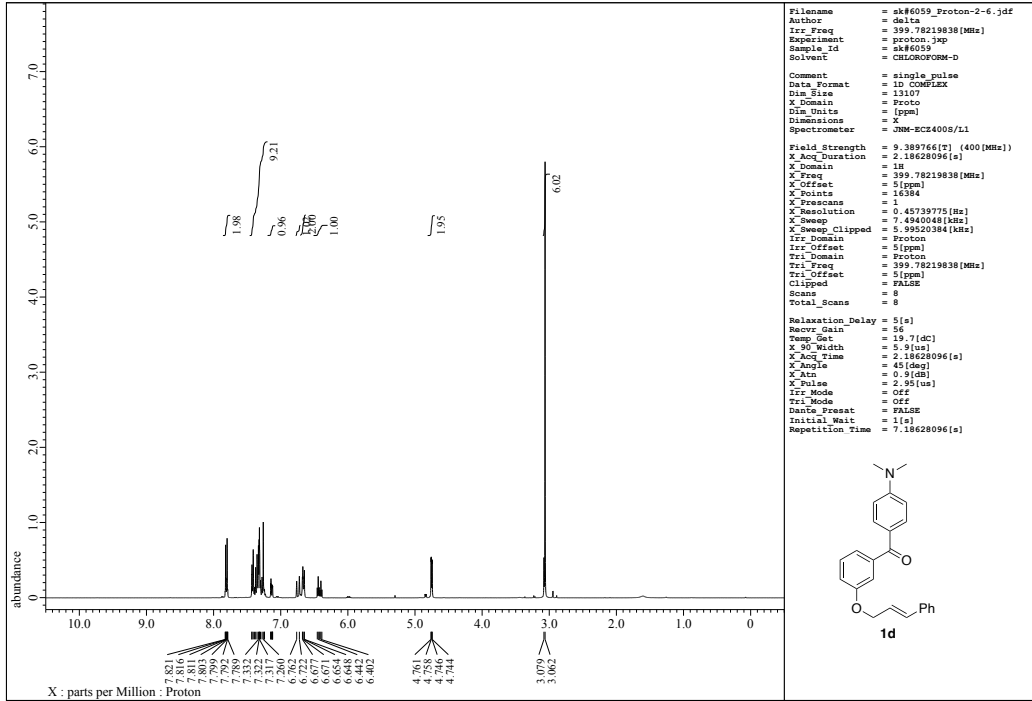
**Compound 2y** (Scheme 10: pale yellow oil, 26.3 mg, 93% yield, 81% ee). A solution of EtOAc/hexane (1:5) was used as an eluent for preparative TLC. The ee was measured by HPLC [Chiralcel OJ-H, hexane/2-propanol = 19:1, flow 0.5 mL/min, 254 nm,  $t_1 = 41.8$  min (major),  $t_2 = 56.6$  min (minor)]:  $[\alpha]^{25}_{\text{D}} -48$  (*c* 0.69,  $\text{CHCl}_3$ ) for 81% ee (*S*).  $^1\text{H NMR}$  ( $\text{CDCl}_3$ )  $\delta$  2.46 (dd,  $J = 13.2, 11.2$  Hz, 1H), 2.60 (s, 3H), 3.11 (dd,  $J = 13.2, 2.8$  Hz, 1H), 3.95 (s, 3H), 4.16–4.25 (m, 1H), 2.49–4.37 (m, 1H), 4.53 (dd,  $J = 8.6, 1.8$  Hz, 1H), 6.82 (d,  $J = 8.6$  Hz, 1H), 7.22 (tt,  $J = 6.8, 1.6$  Hz, 1H), 7.28–7.38 (m, 4H), 7.49 (d,  $J = 8.6$  Hz, 1H);  $^{13}\text{C NMR}$  ( $\text{CDCl}_3$ )  $\delta$  27.5, 39.3, 45.5, 56.0, 76.3, 110.2, 124.8, 126.2, 126.7, 128.5, 129.2, 133.4, 140.0, 148.6, 148.6, 197.5. HRMS (DART) calcd for  $\text{C}_{18}\text{H}_{19}\text{O}_3$  ( $\text{M}+\text{H}$ ) $^+$  283.1334, found 283.1326.

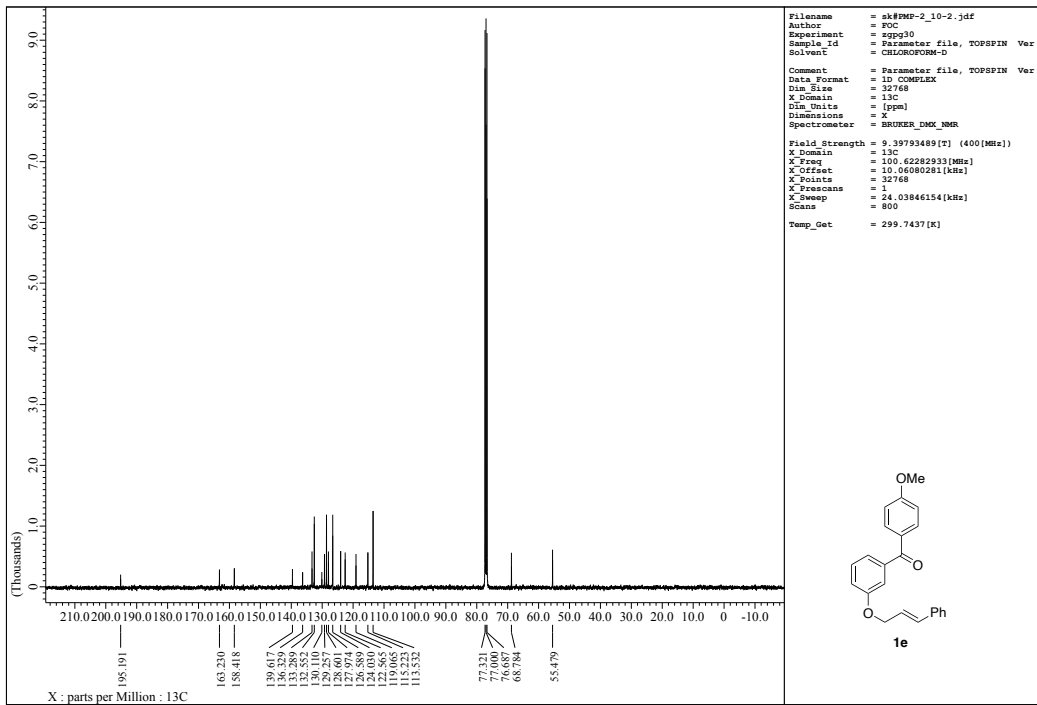
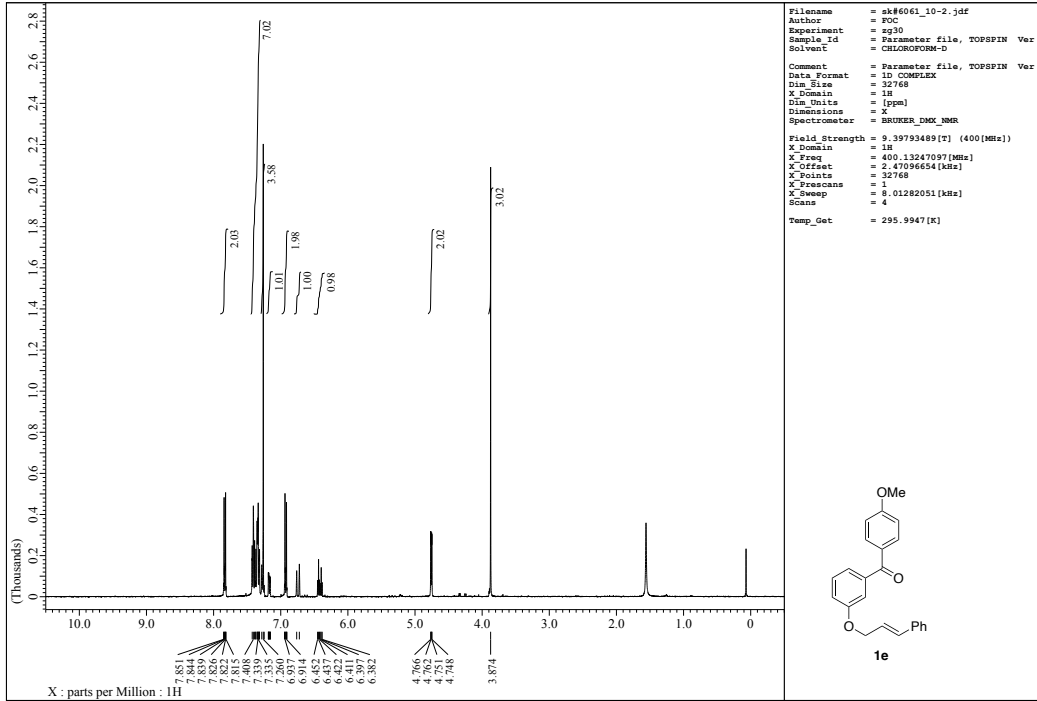
## 19. References

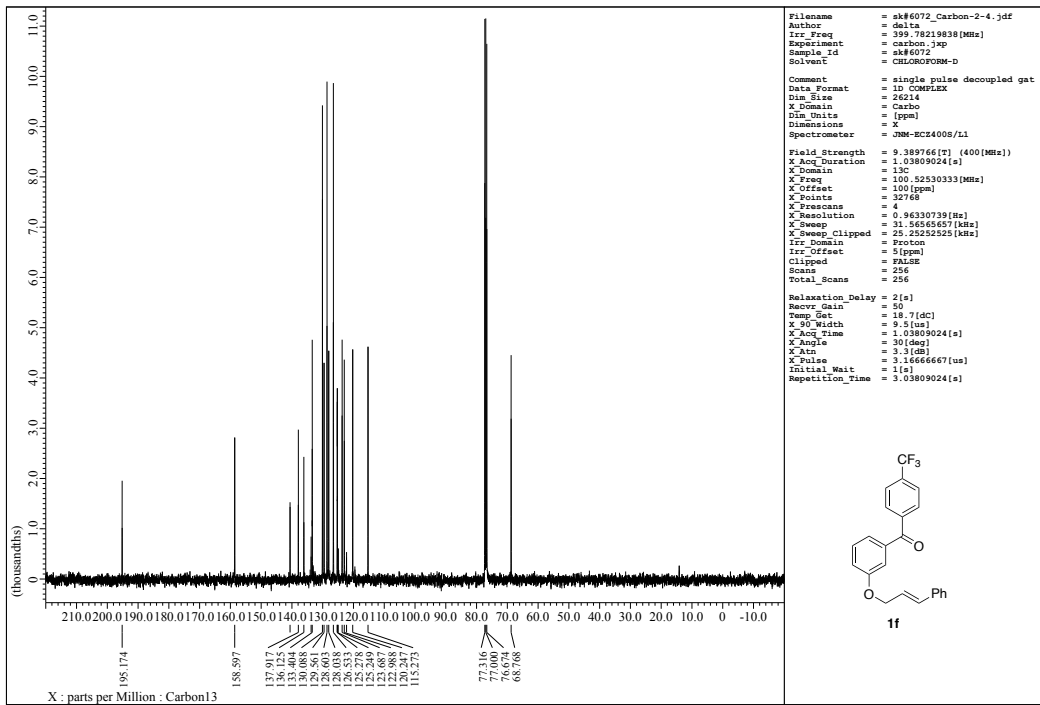
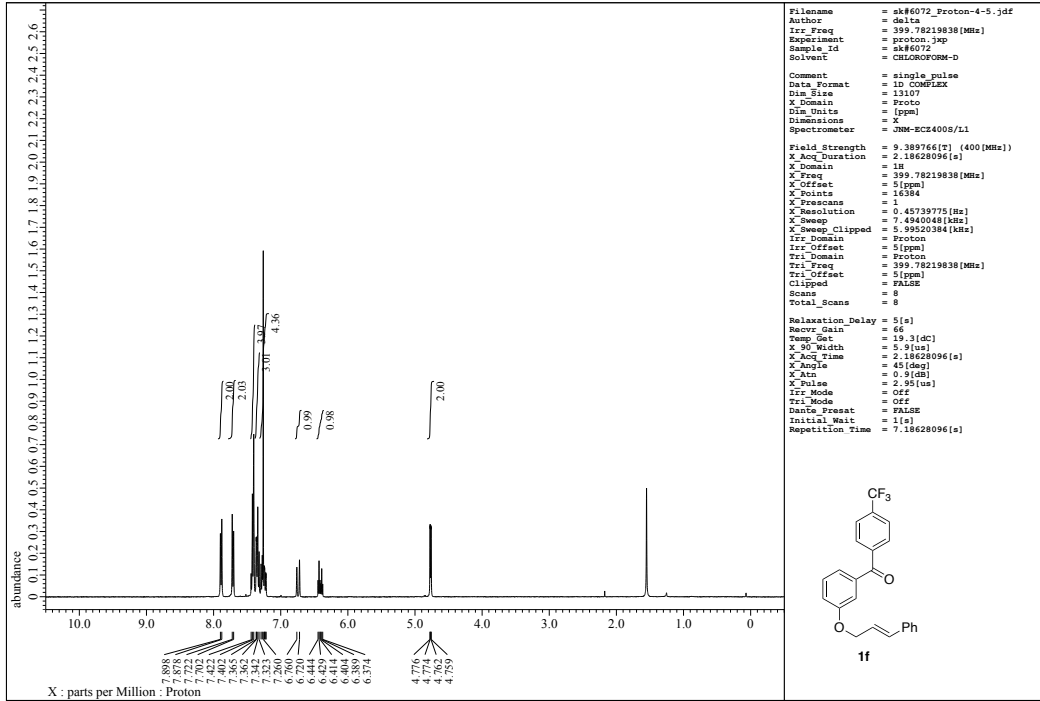
- (1) J. L. Herde, J. C. Lambert and C. V. Senoff, *Inorg. Synth.*, 1974, **15**, 18–20.
- (2) M. Brookhart, B. Grant and A. F. Volpe, Jr., *Organometallics*, 1992, **11**, 3920–3922.
- (3) D. F. Vargas, E. L. Karghi and T. S. Kaufman, *Eur. J. Org. Chem.*, 2018, 5605–5614.
- (4) T. Mino, H. Shinda, T. Kaneda, Y. Kasahara, M. Sakamoto and T. Fujita, *Tetrahedron Lett.*, 2009, **50**, 5358–5360.
- (5) T. H. Fife, T. J. Przystas and M. P. Pujaril, *J. Am. Chem. Soc.*, 1988, **110**, 8157–8163.
- (6) M. Hatano, T. Nishimura and H. Yorimitsu, *Org. Lett.*, 2016, **18**, 3674–3677.
- (7) T. H. West, D. M. Walden, J. E. Taylor, A. C. Brueckner, R. C. Johnston, P. H.-Y. Cheong, G. C. Lloyd-Jones and A. D. Smith, *J. Am. Chem. Soc.*, 2017, **139**, 4366–4375.
- (8) T. Iwai, T. Fujihara and Y. Tsuji, *Chem. Commun.*, 2008, 6215–6217.

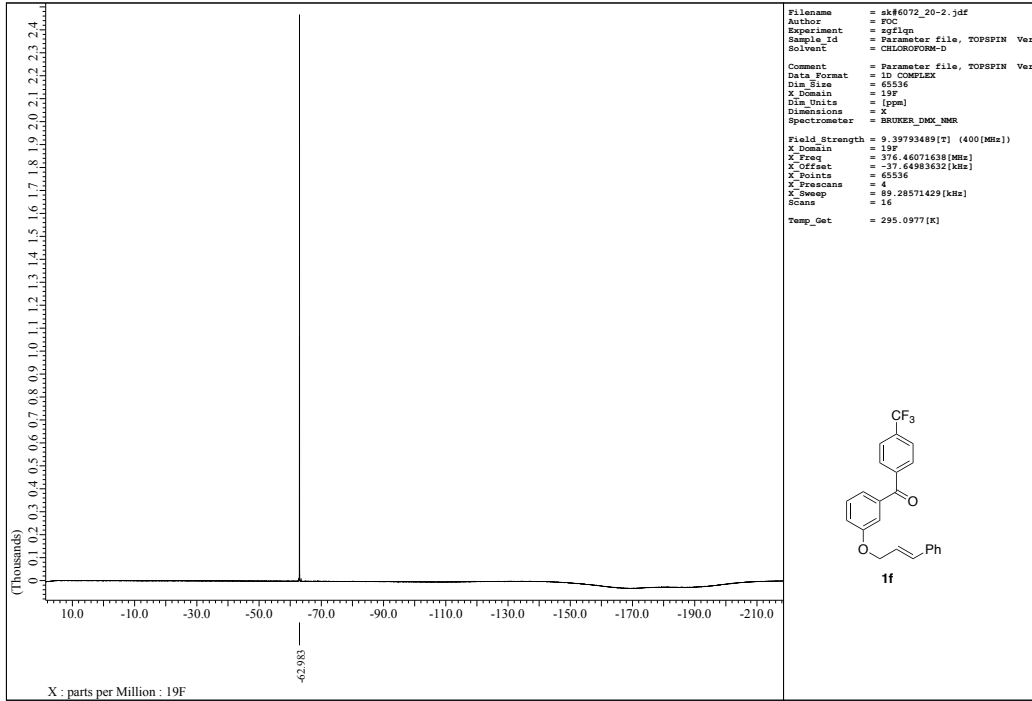
## 20. <sup>1</sup>H and <sup>13</sup>C NMR spectra and chiral HPLC charts



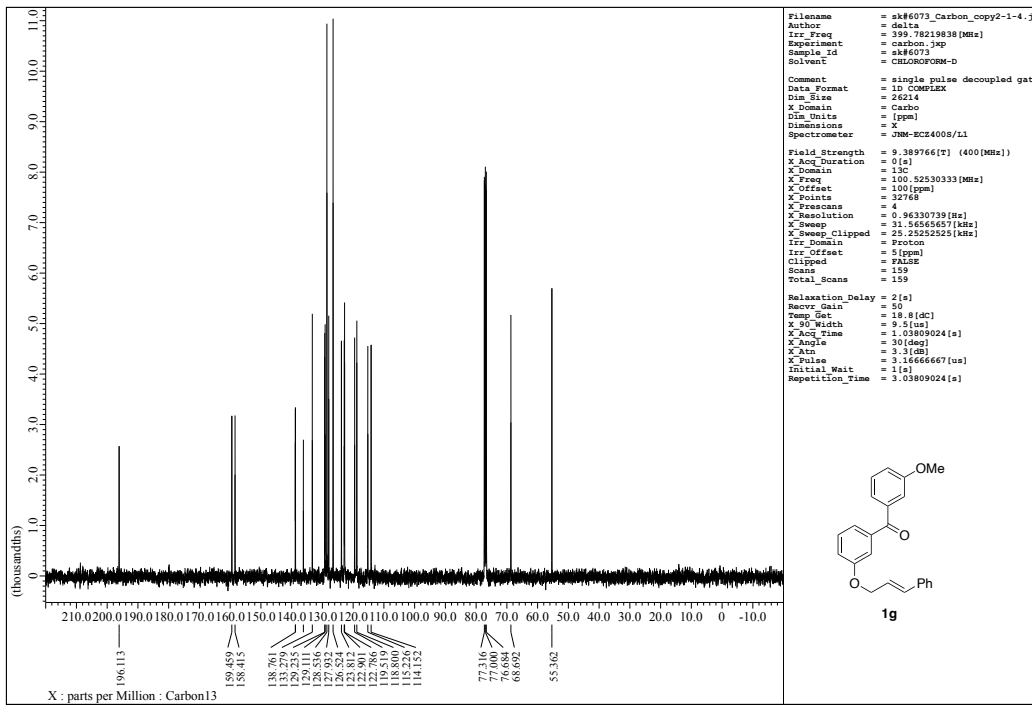
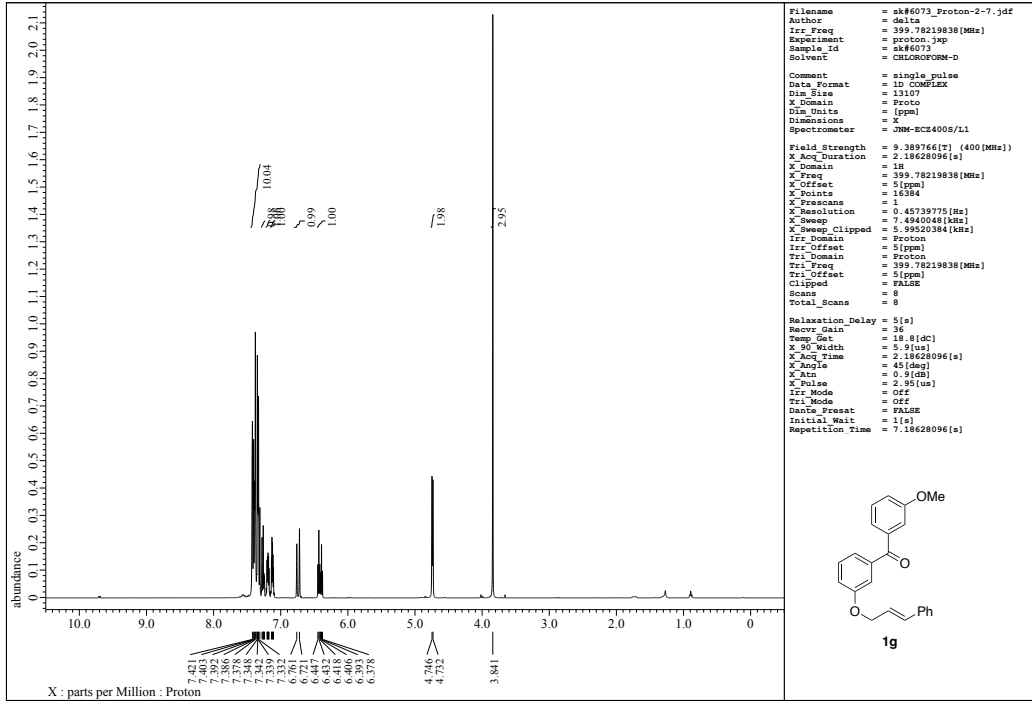


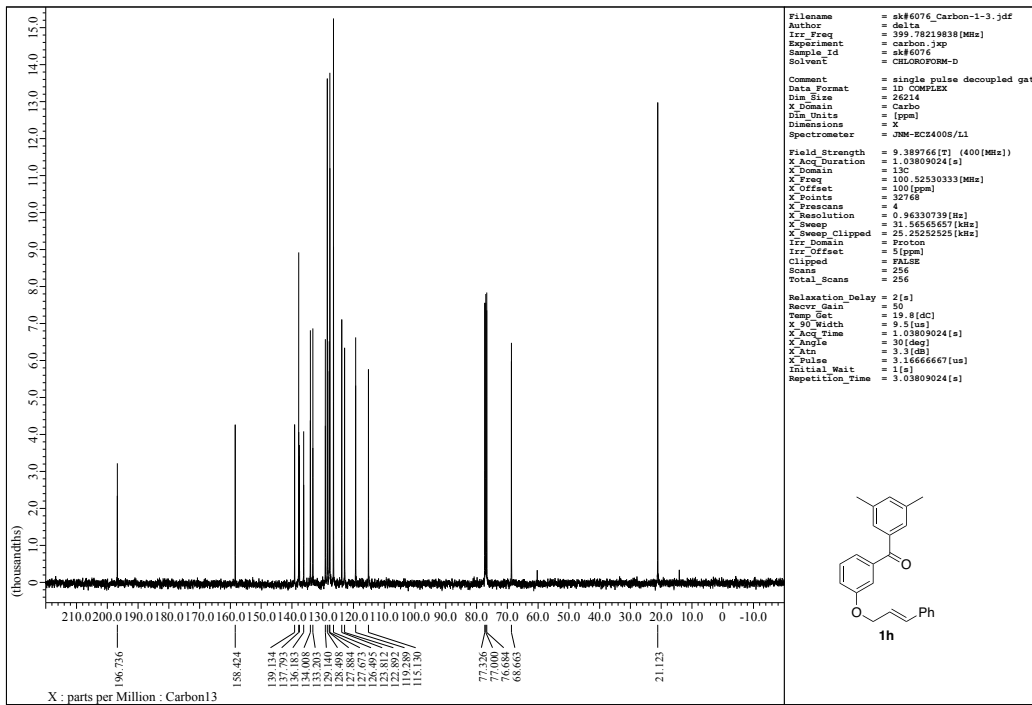
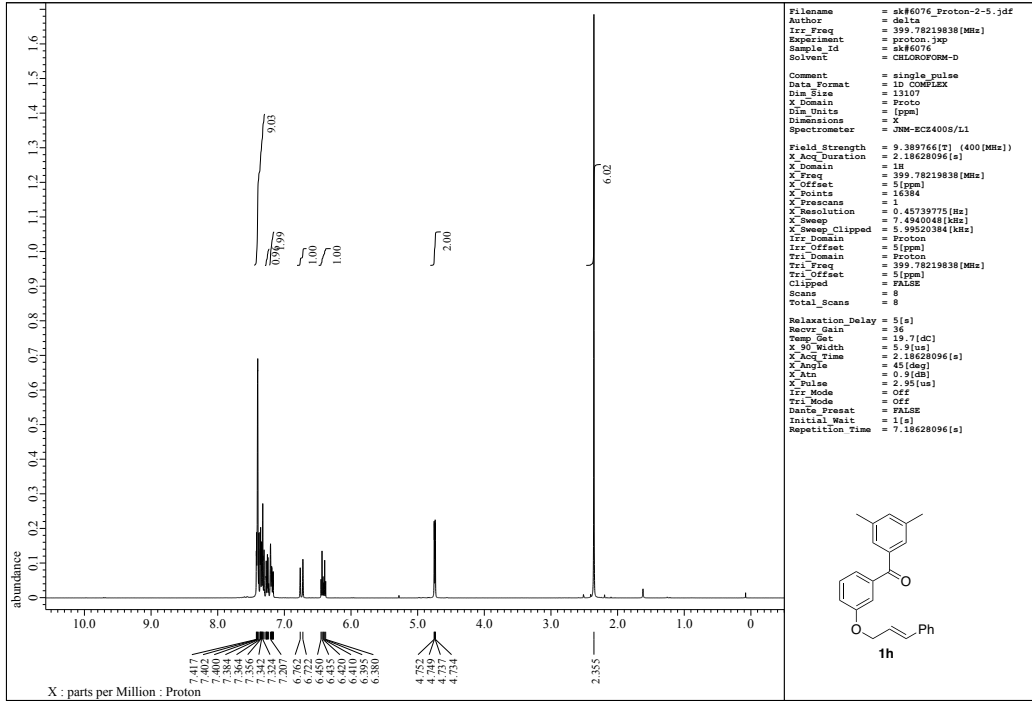


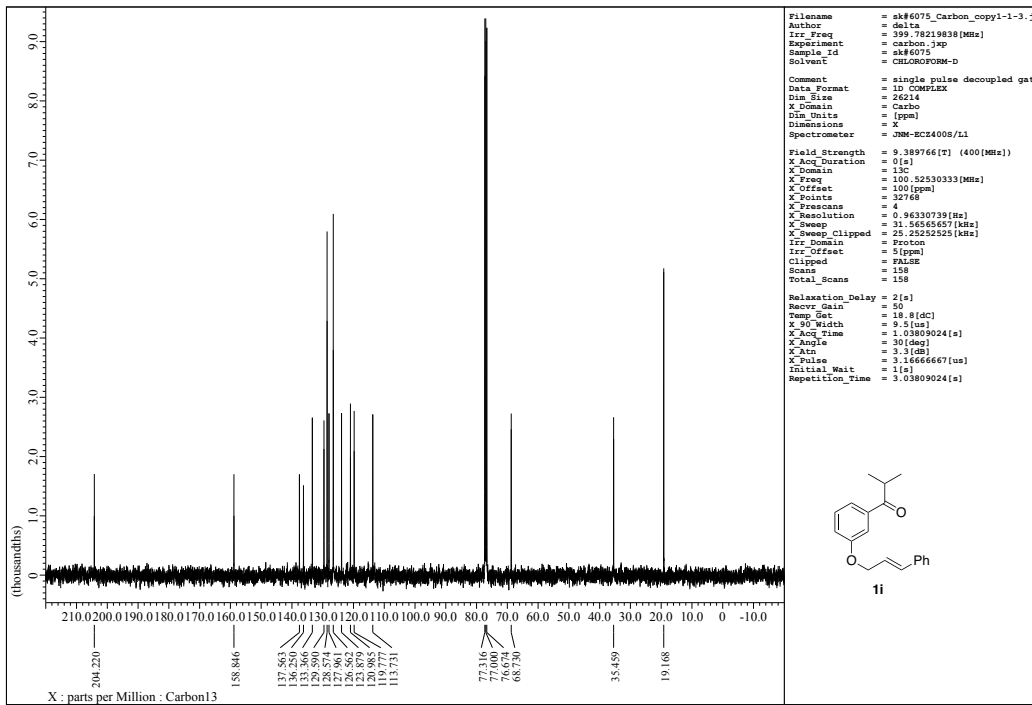
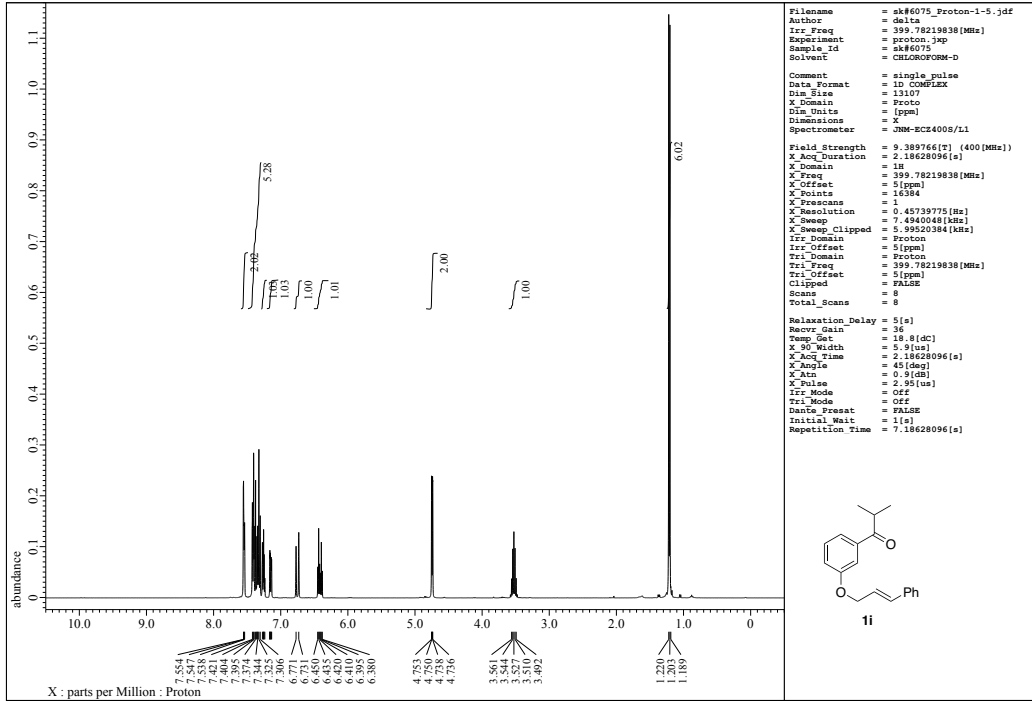


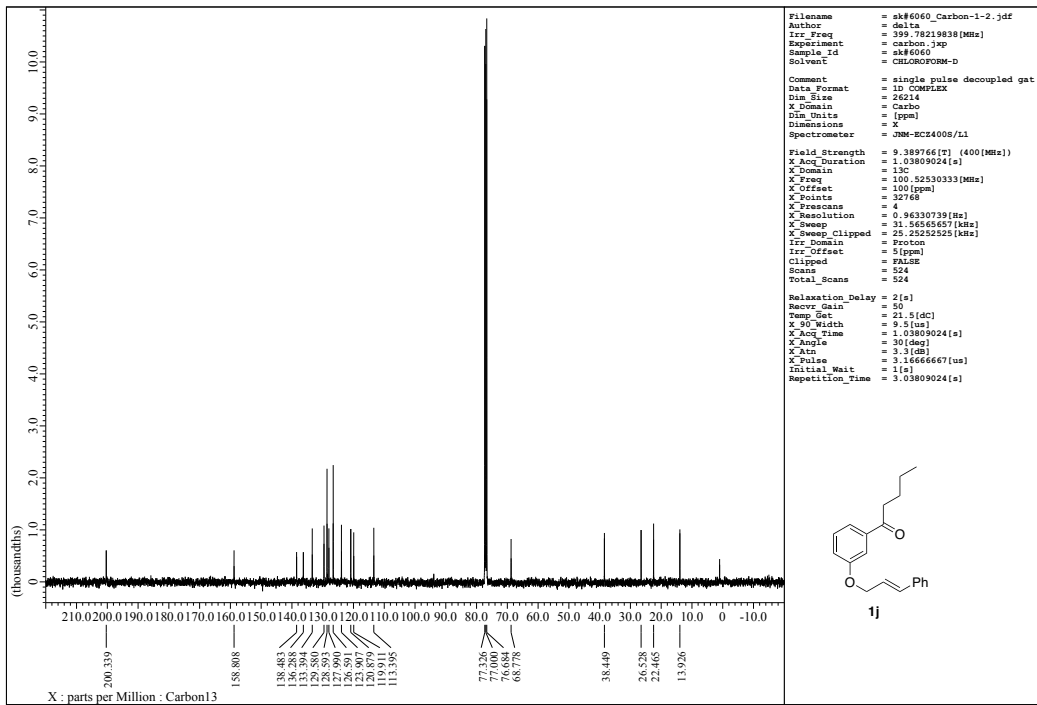
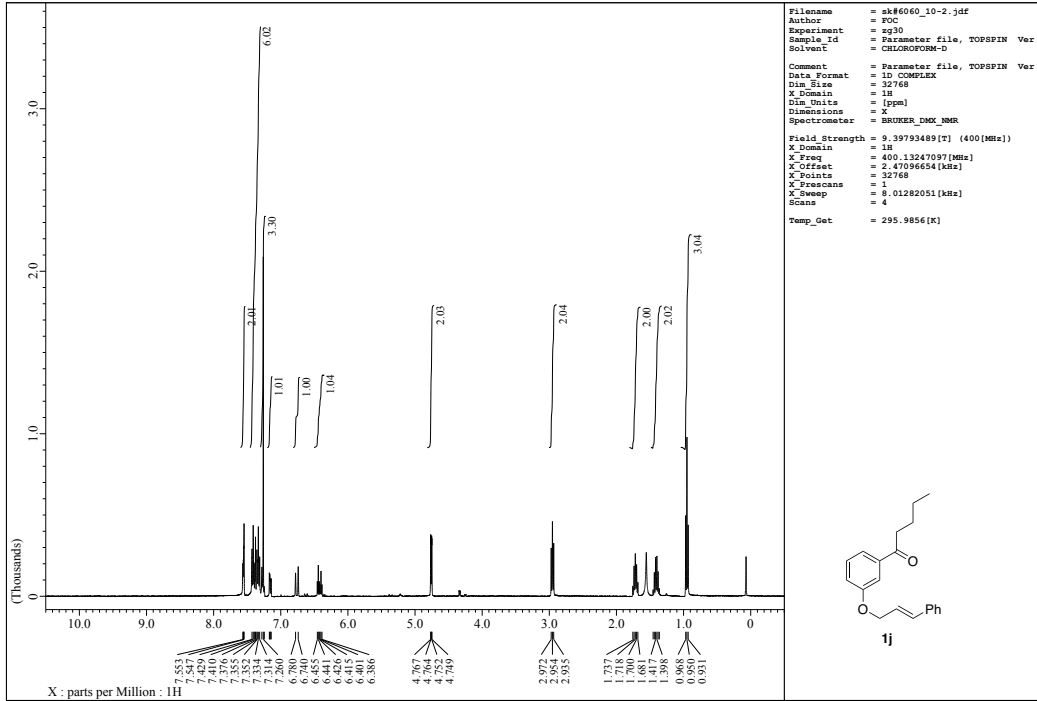


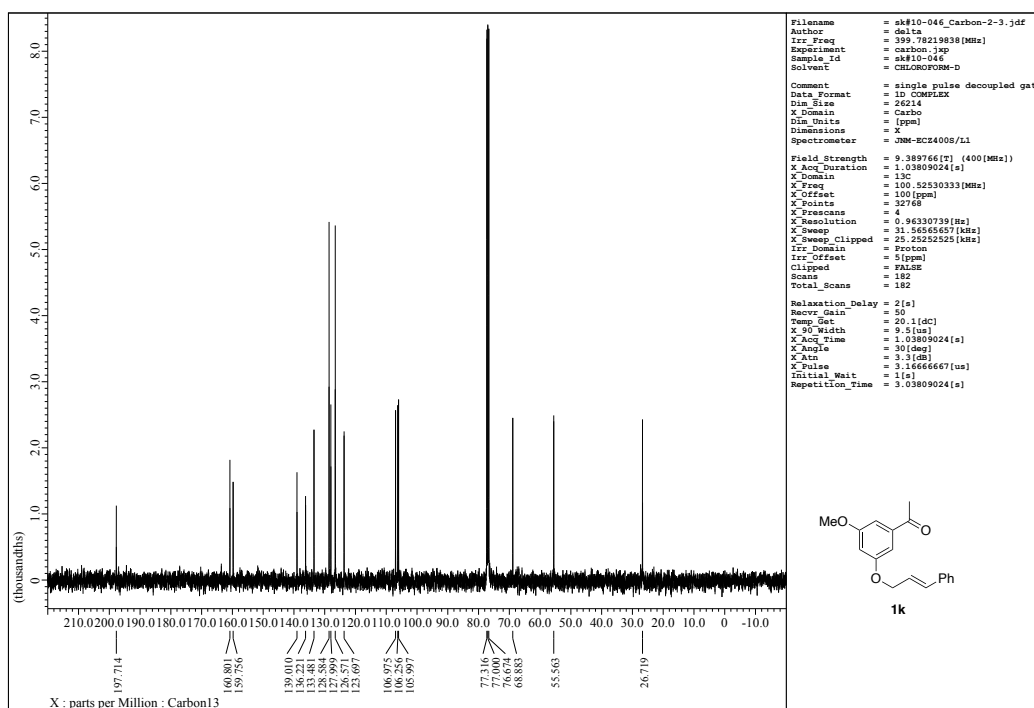
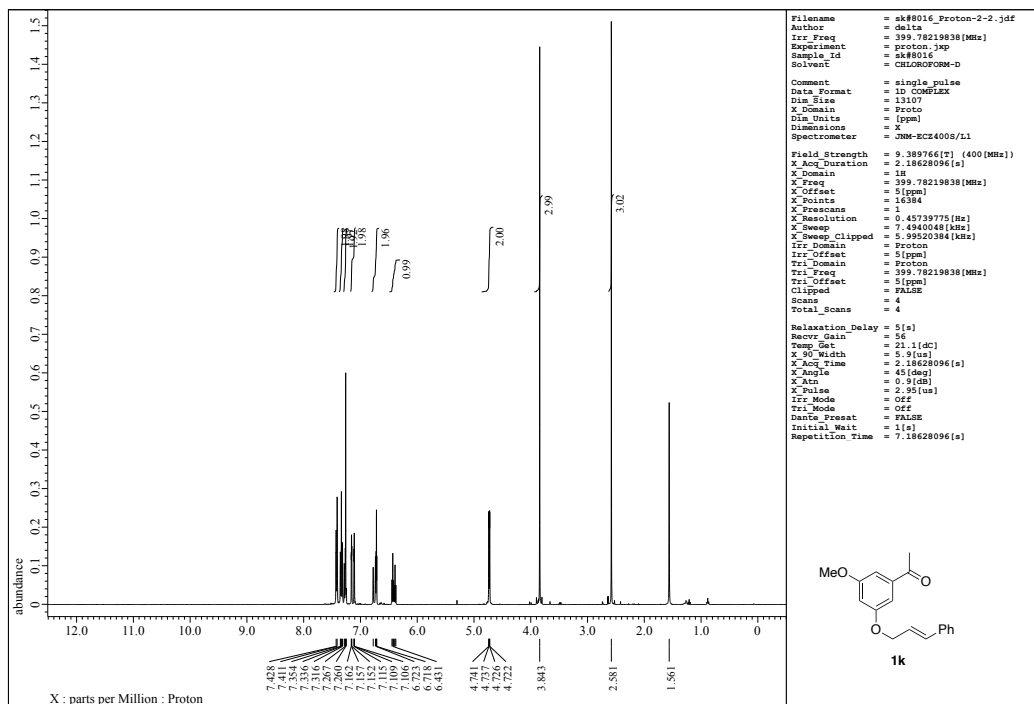


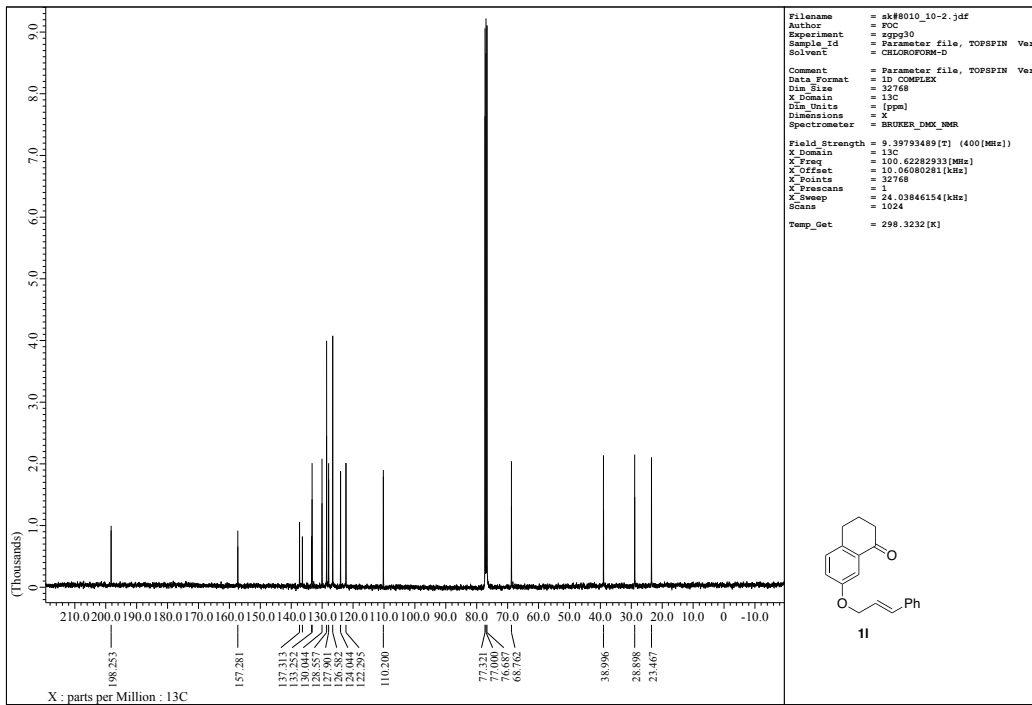
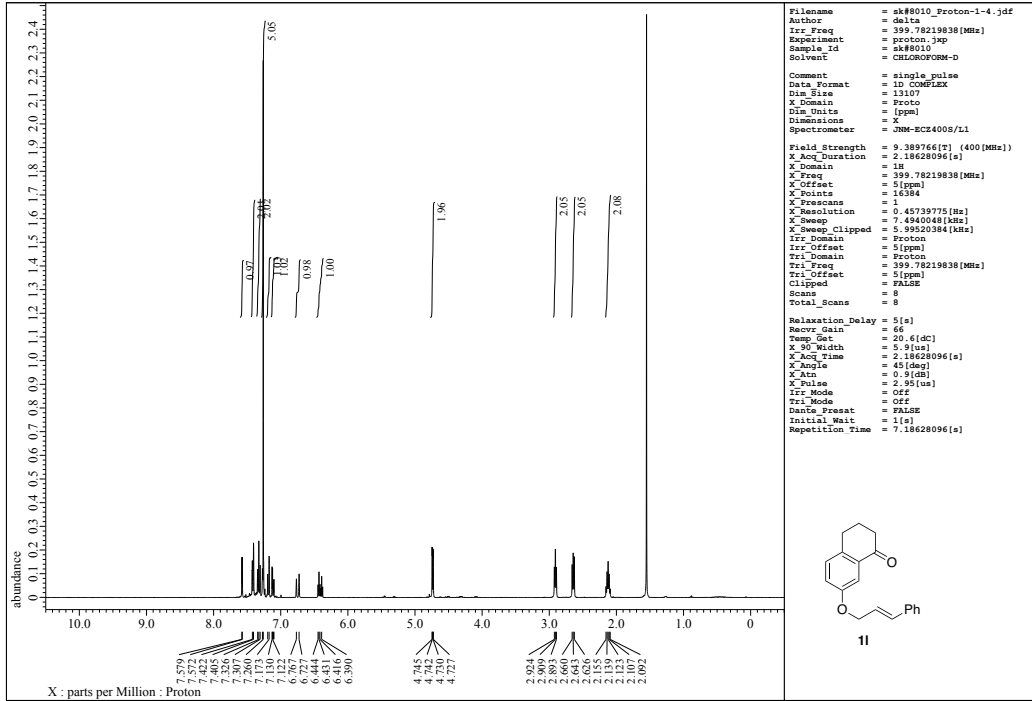


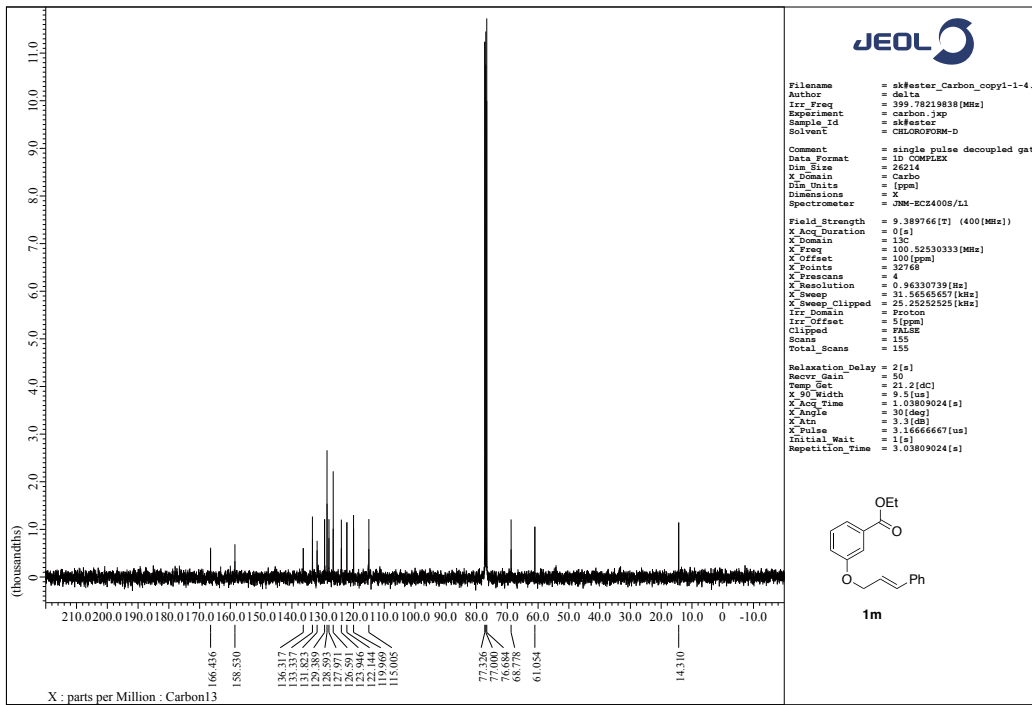
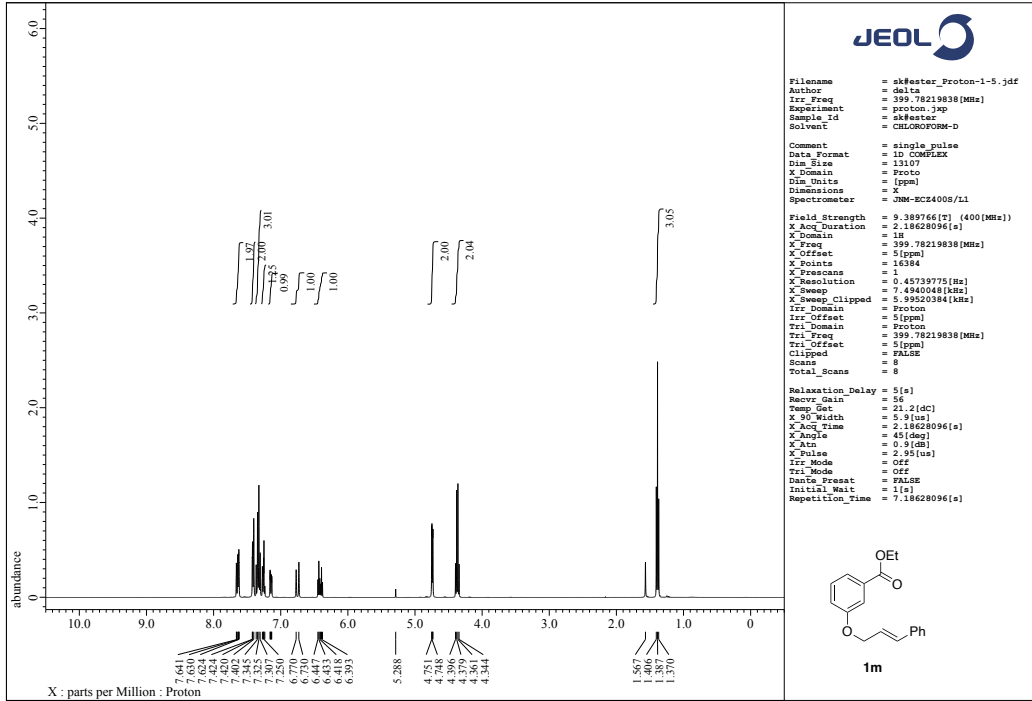


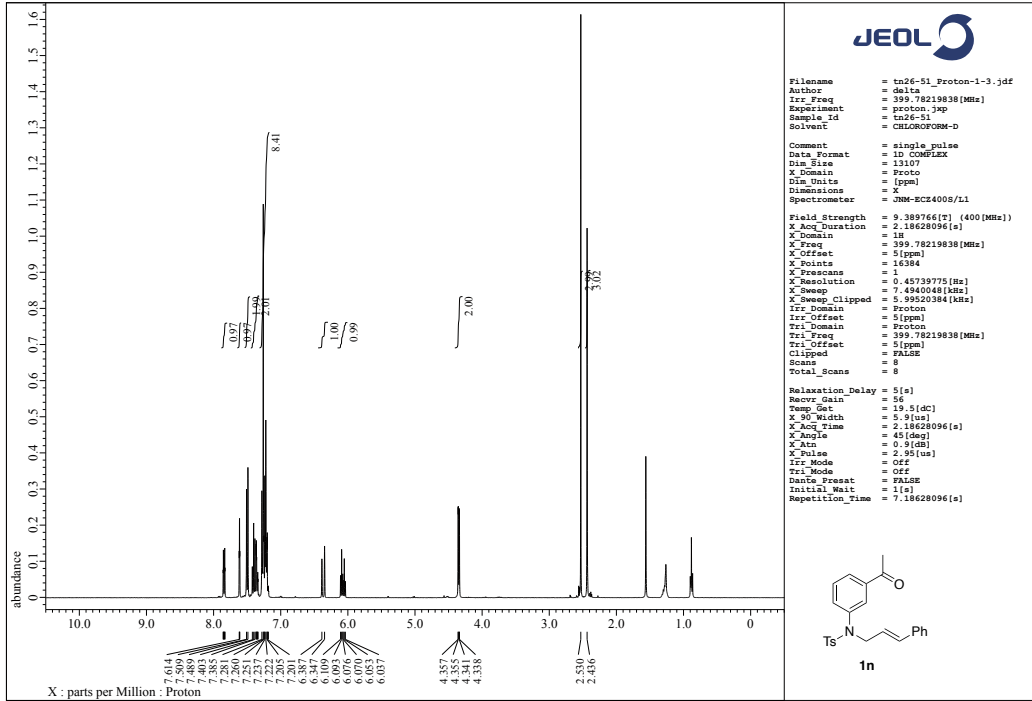












**JEOL**

```

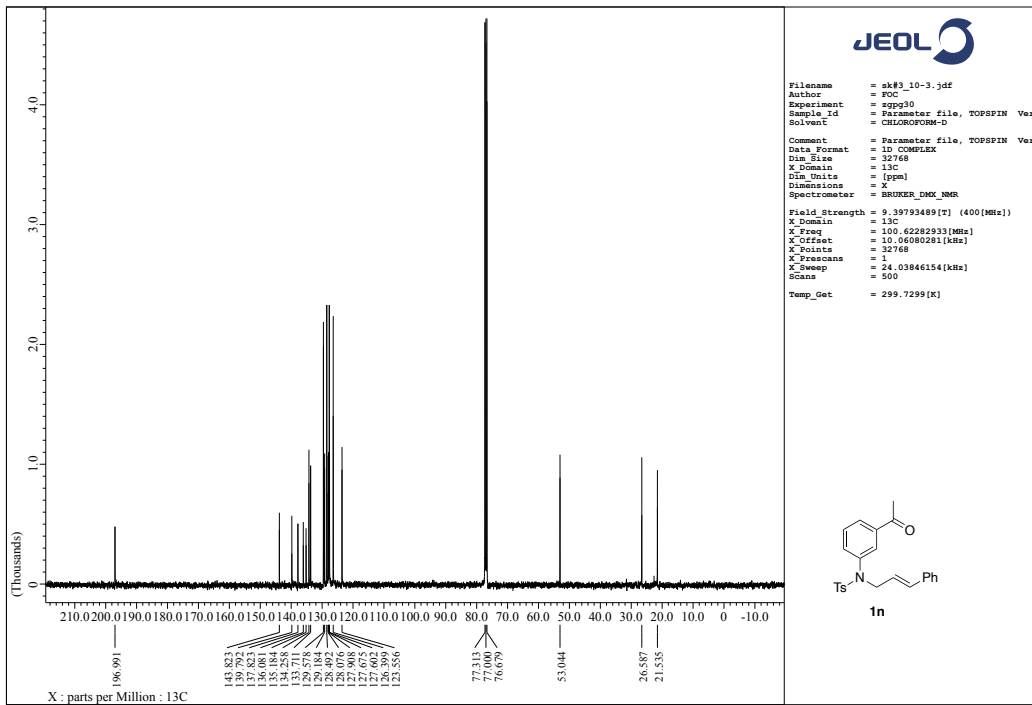
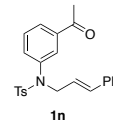
Filename = tn26-51_Proton-1-3.jdf
Author = delta
Experiment = proton_jmp
Sample Id = tn26-51
Solvent = CHLOROFORM-D

Comment = single_pulse
Data Format = 1D COMPLEX
Dim Size = 13107
X_Domain = Proto
Dim Units = [ppm]
Dimensions = X
Spectrometer = JNM-EZ400S/L1

Field Strength = 9.389766[T] (400[MHz])
X_Acq_Duration = 2.18628096[s]
X_Domain = 18
X_Freq = 399.78219838[MHz]
X_Offset = 5[ppm]
X_Points = 14384
X_Prescans = 1
X_Resolution = 0.45739775[Hz]
X_Sweep = 7.4940048[kHz]
X_Sweep_Clippped = 5.99520364[kHz]
Irr_Domain = Proton
Irr_Offset = 5[ppm]
Tri_Domain = Proton
Tri_Freq = 399.78219838[MHz]
Tri_Offset = 5[ppm]
Clipped = FALSE
Scans = 8
Total_Scans = 8

Relaxation_Delay = 5[s]
Recvr_Gain = 56
Temp_Get = 19.5[dc]
X_90_Width = 5.9[us]
X_Acq_Time = 2.18628096[s]
X_Angle = 45[deg]
X_Atn = 0.9[db]
X_Pulse = 2.8[us]
Irr_Mode = Off
Tri_Mode = Off
Data_Preset = FALSE
Initial_Wait = 1[s]
Repetition_Time = 7.18628096[s]

```



**JEOL**

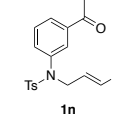
```

Filename = sk#3_10-3.jdf
Author = FOC
Experiment = zgpg30
Sample Id = Parameter file, TOPSPIN Ver
Solvent = CHLOROFORM-D

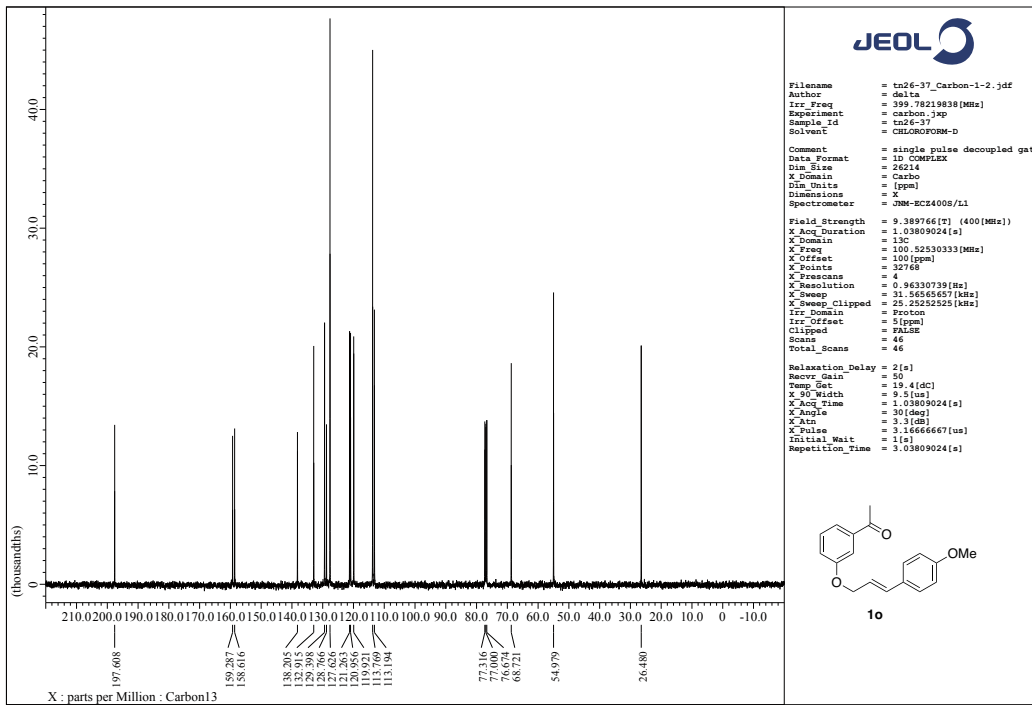
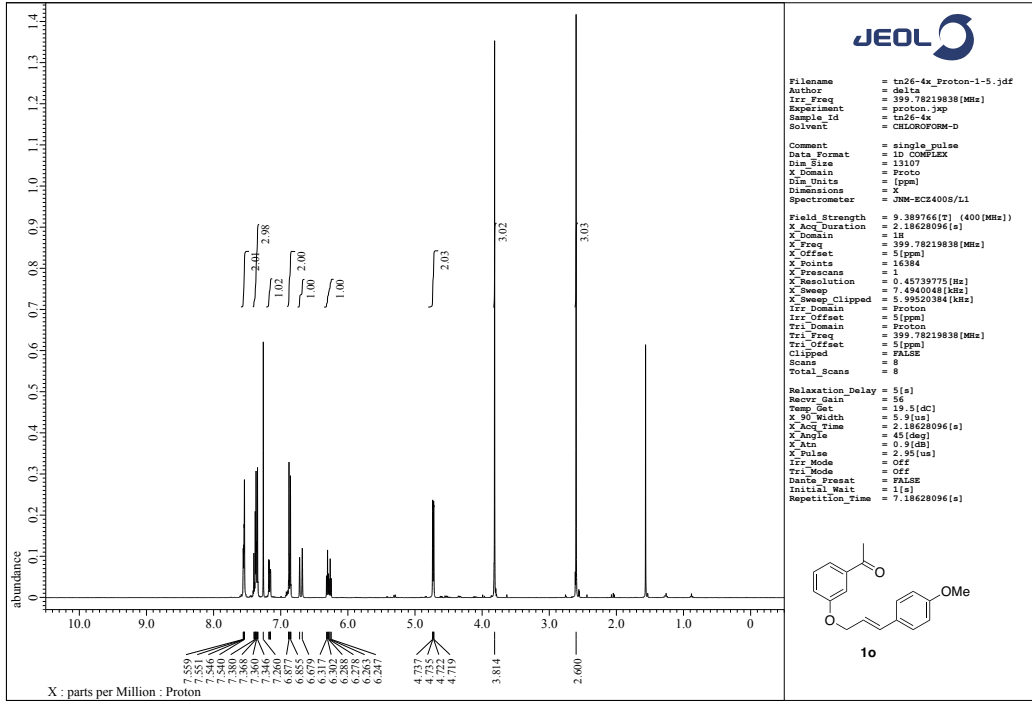
Comment = Parameter file, TOPSPIN Ver
Data Format = 1D COMPLEX
Dim Size = 32768
X_Domain = 13C
Dim Units = [ppm]
Dimensions = X
Spectrometer = BRUKER DMX_MMR

Field Strength = 9.39793489[T] (400[MHz])
X_Domain = 13C
X_Freq = 100.62282933[MHz]
X_Offset = 10.06080281[kHz]
X_Points = 32768
X_Prescans = 1
X_Sweep = 24.03846154[kHz]
X_Sweep = 500
Temp_Get = 299.7299[K]

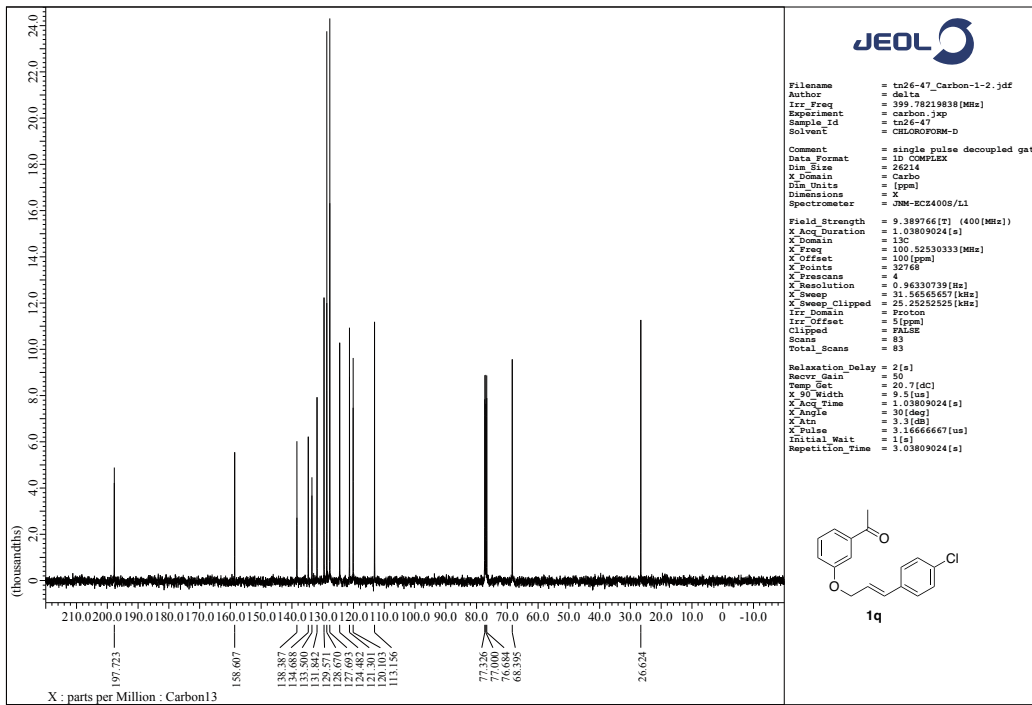
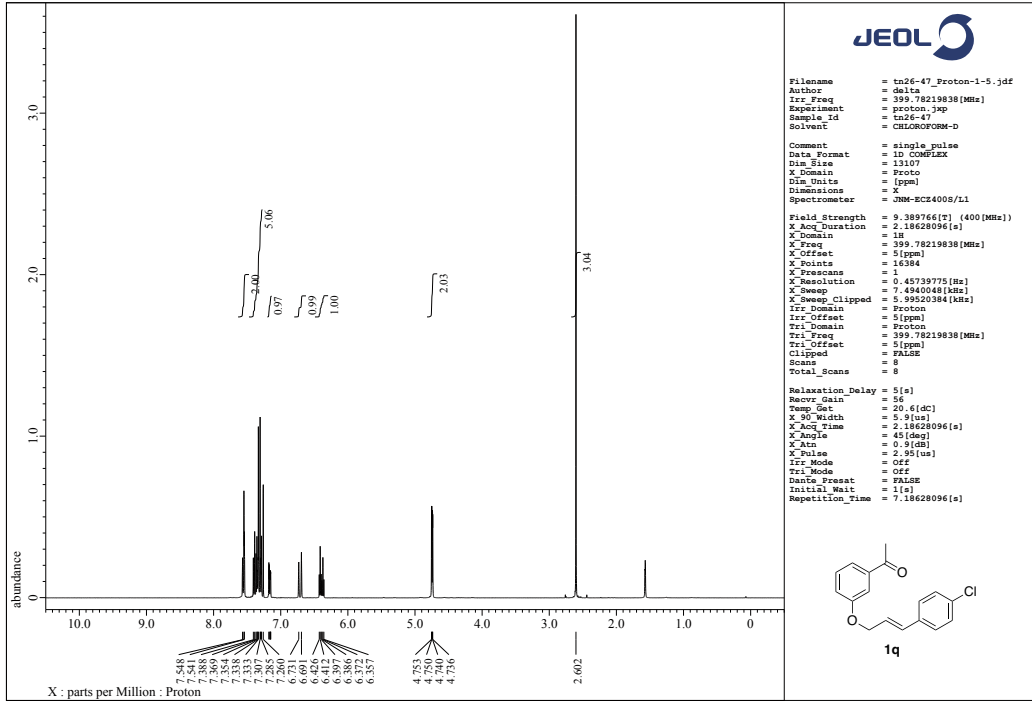
```

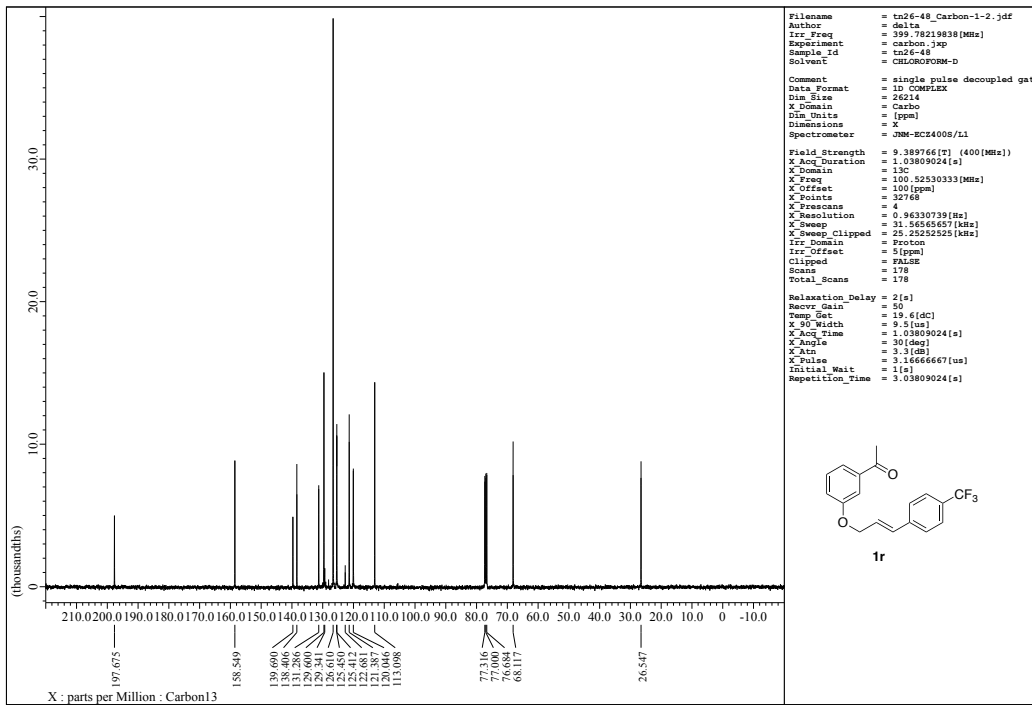
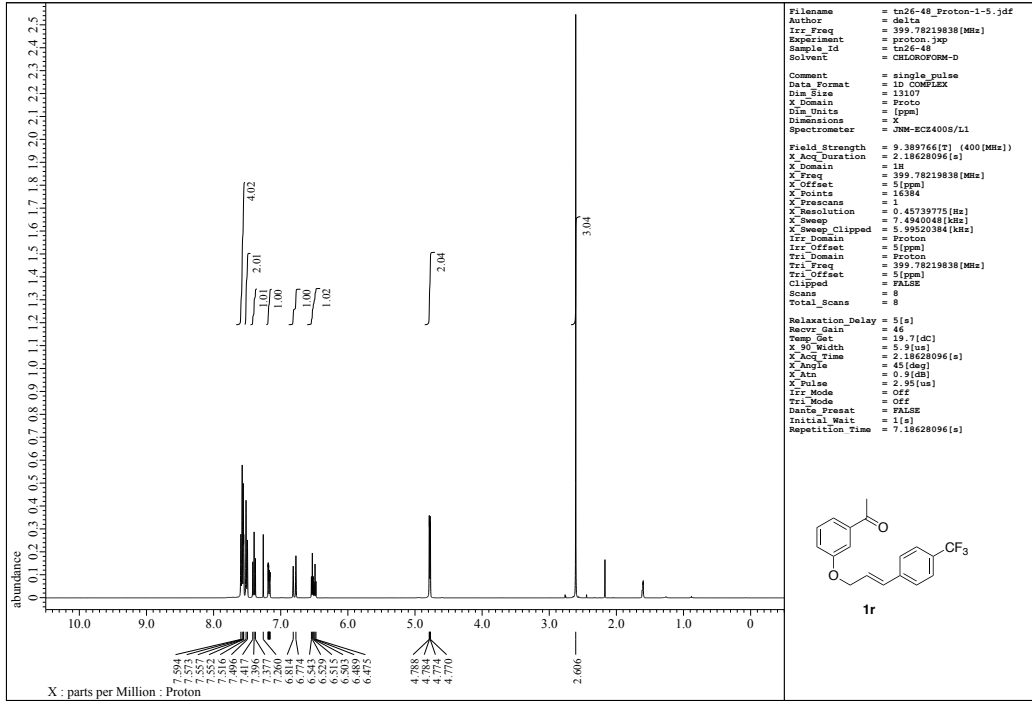


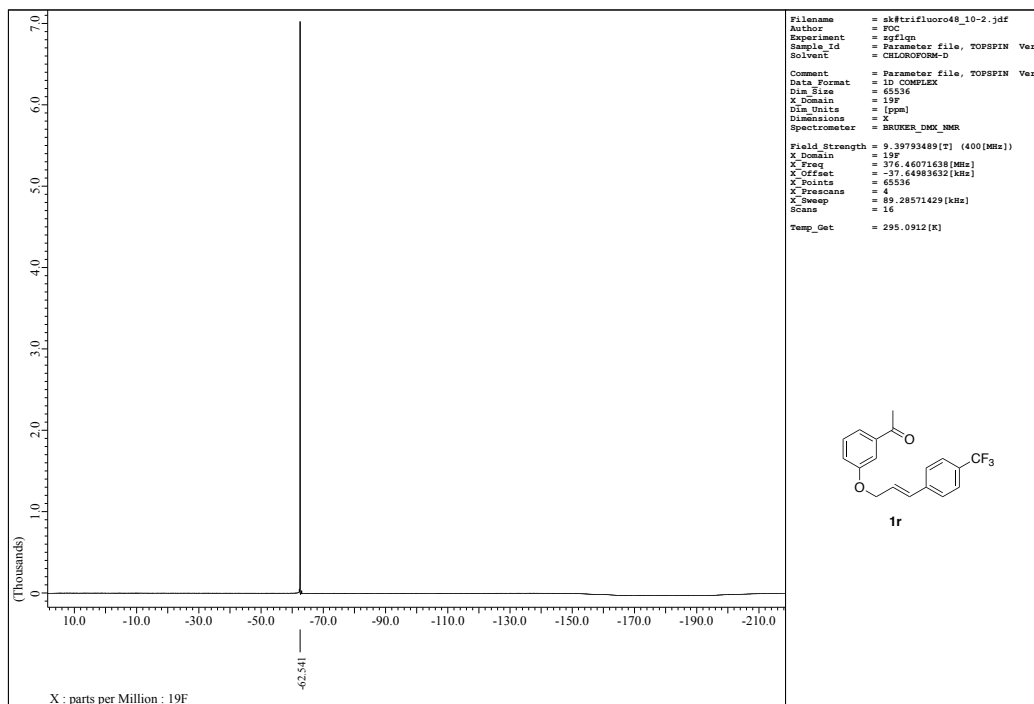


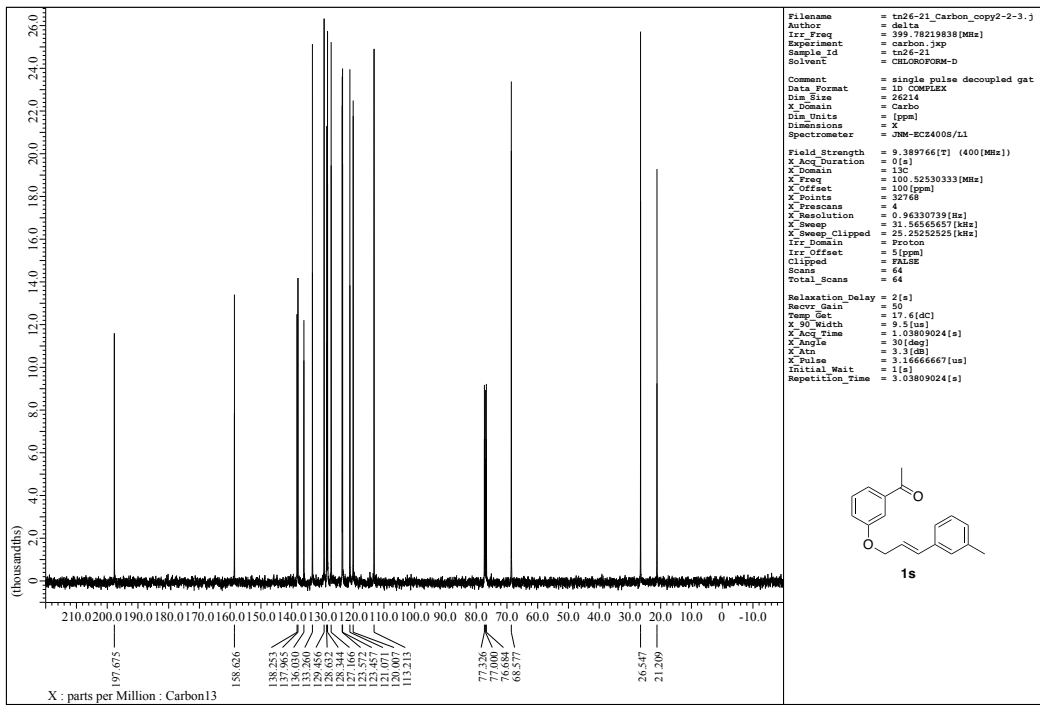
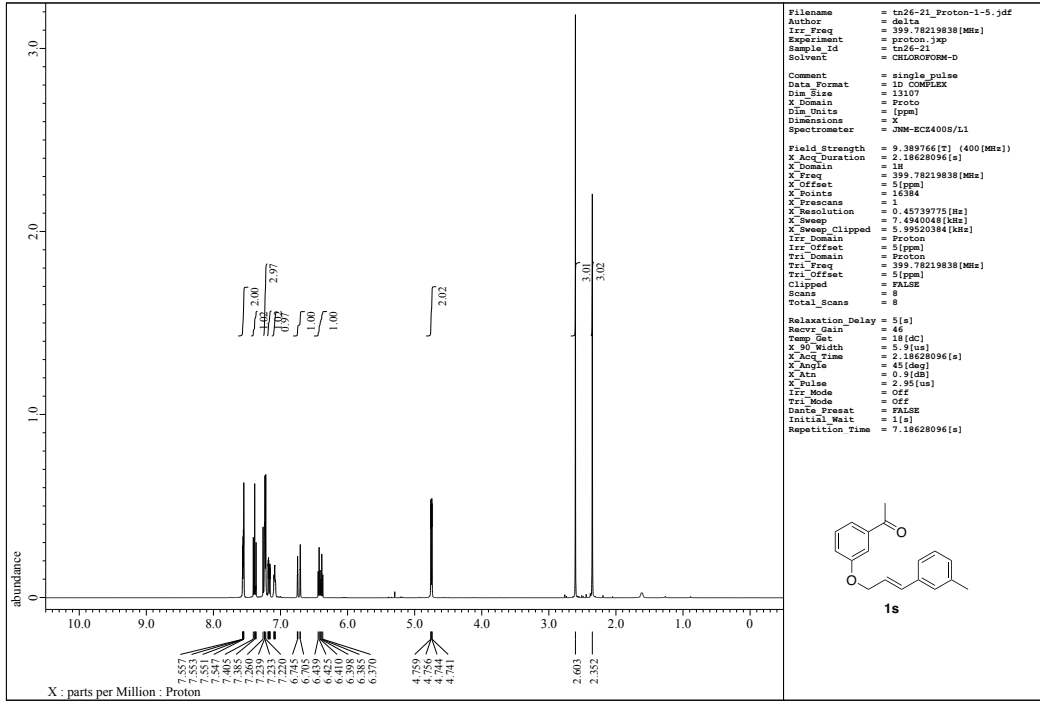




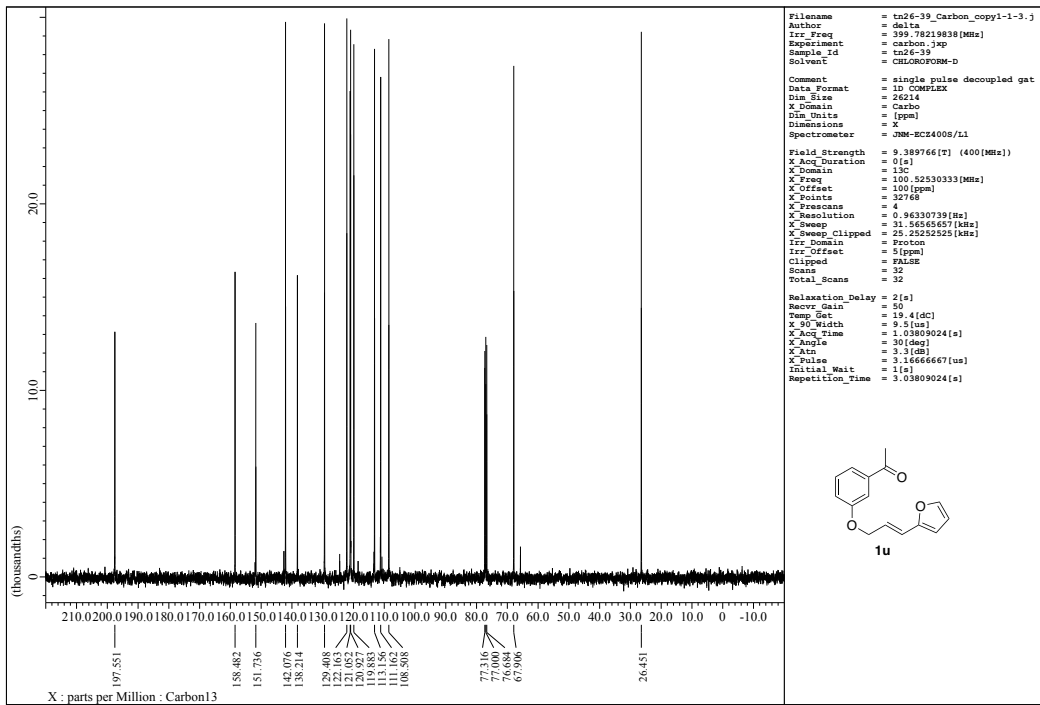
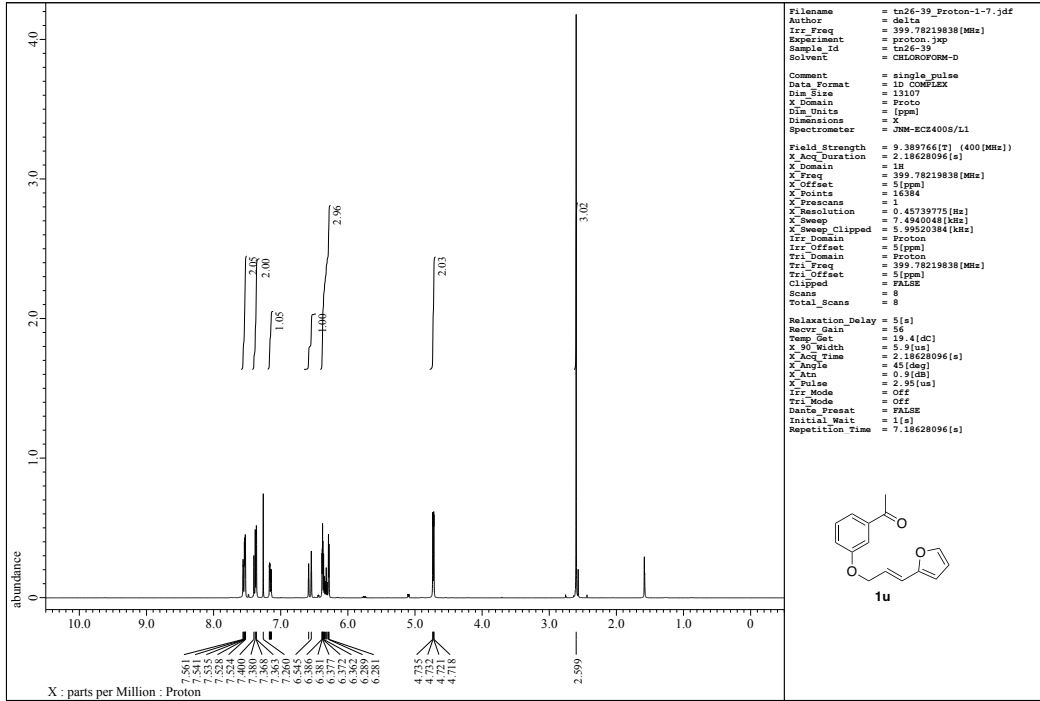




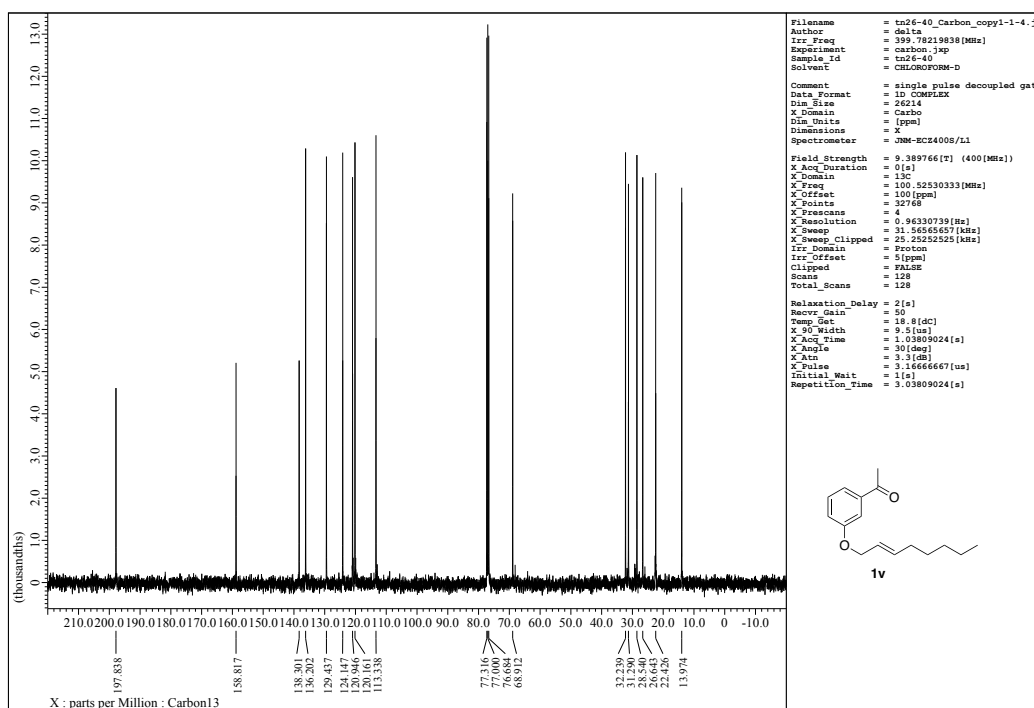
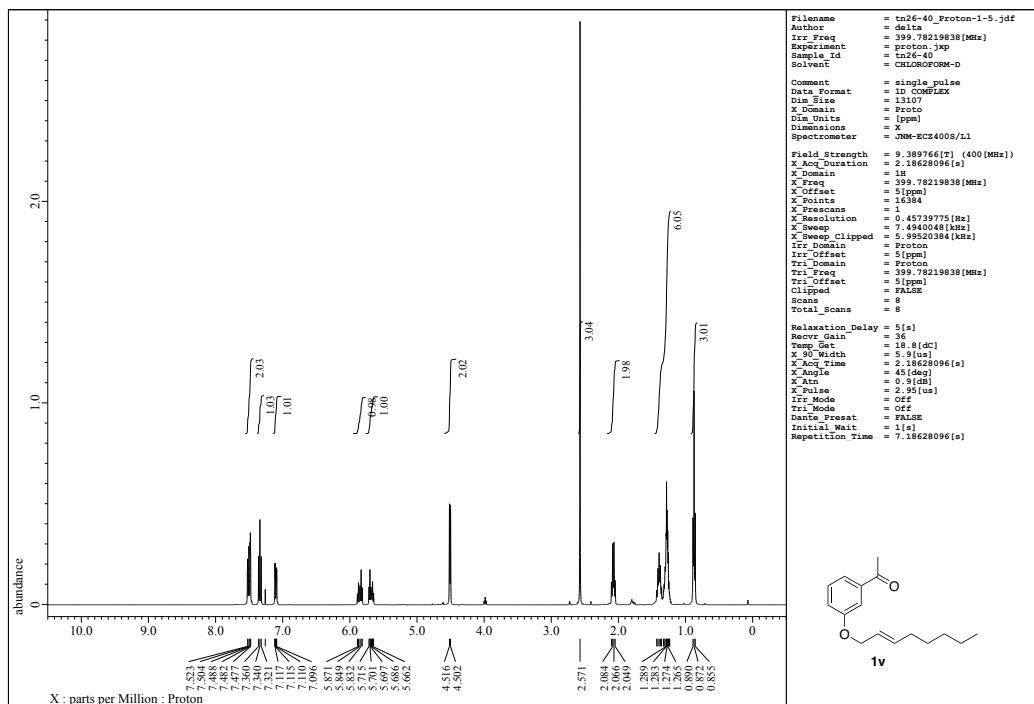


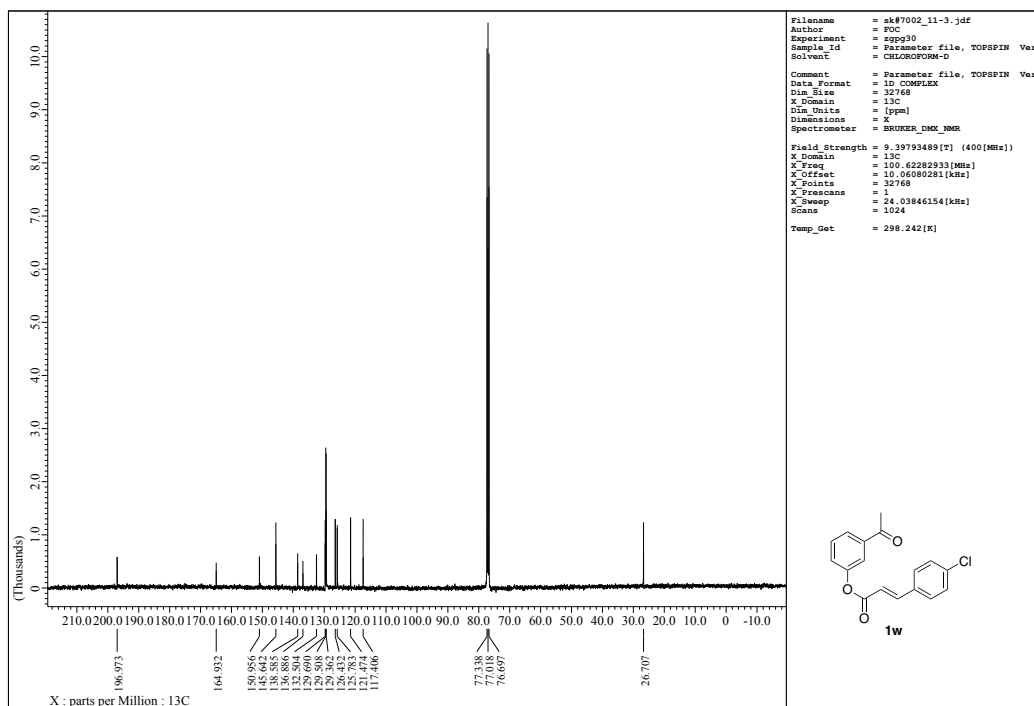
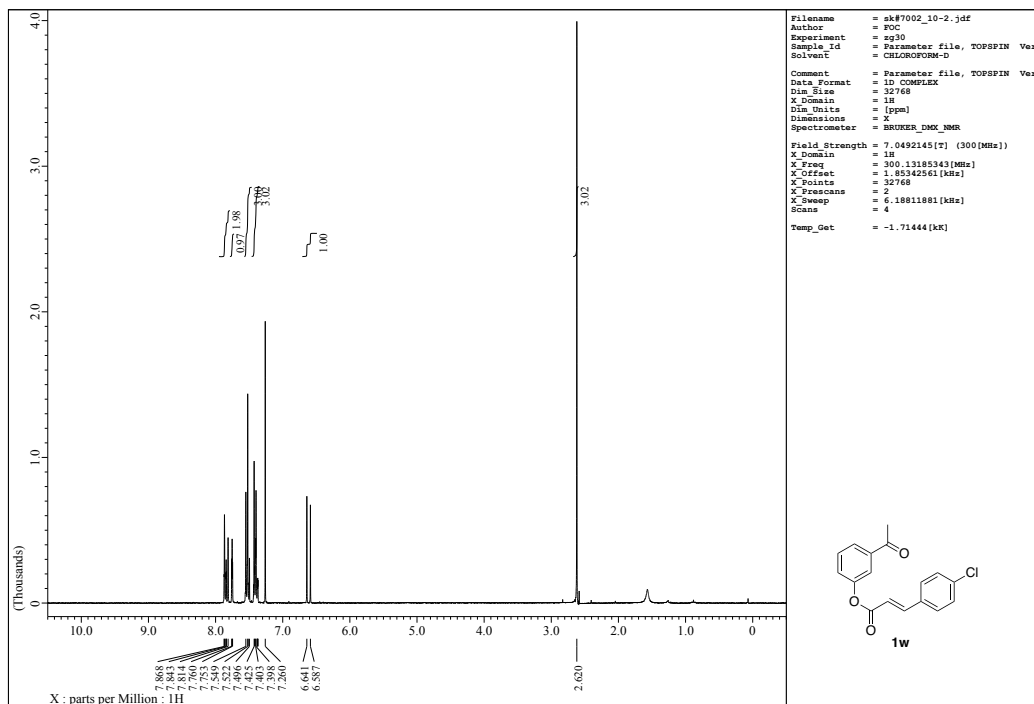


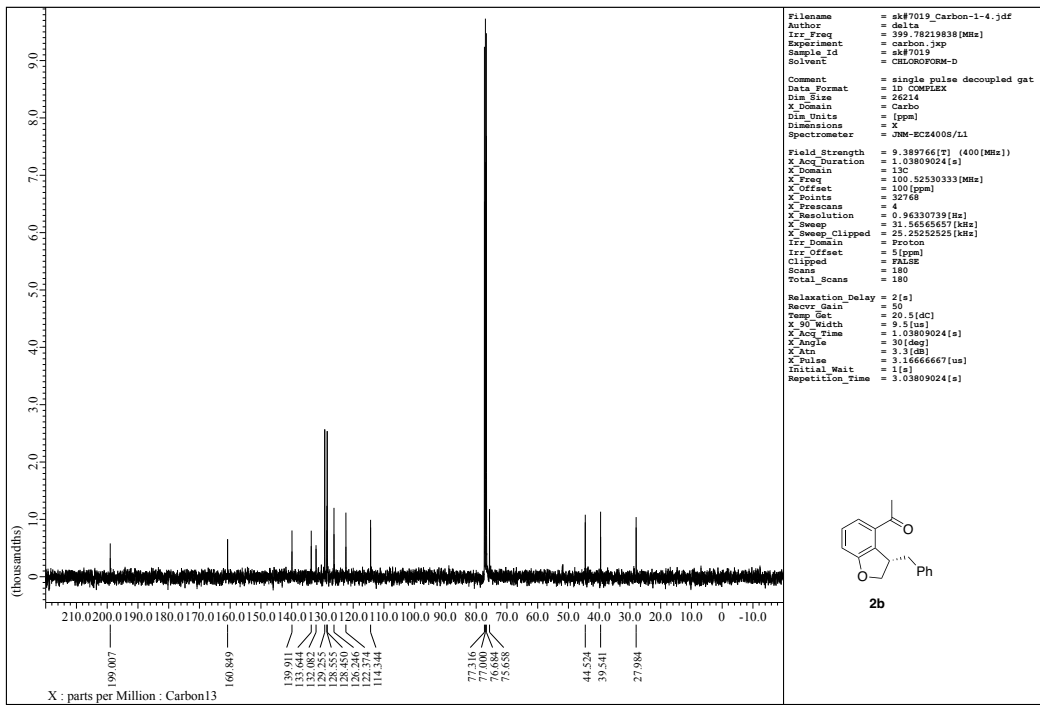
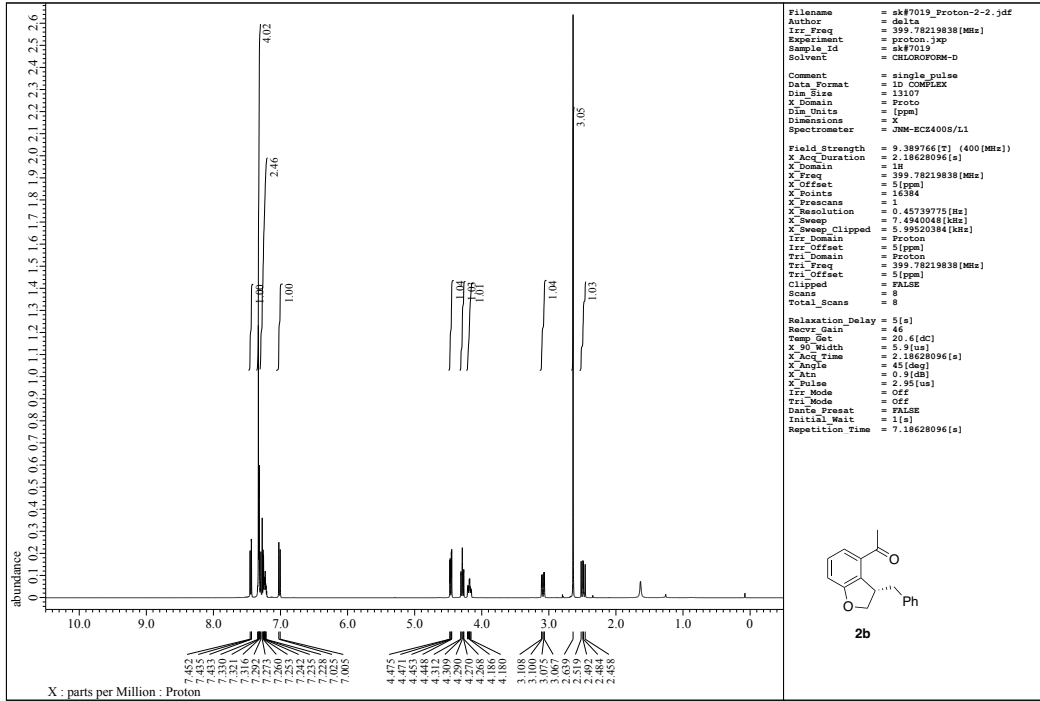


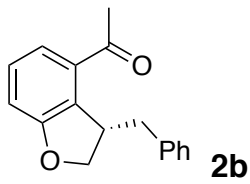




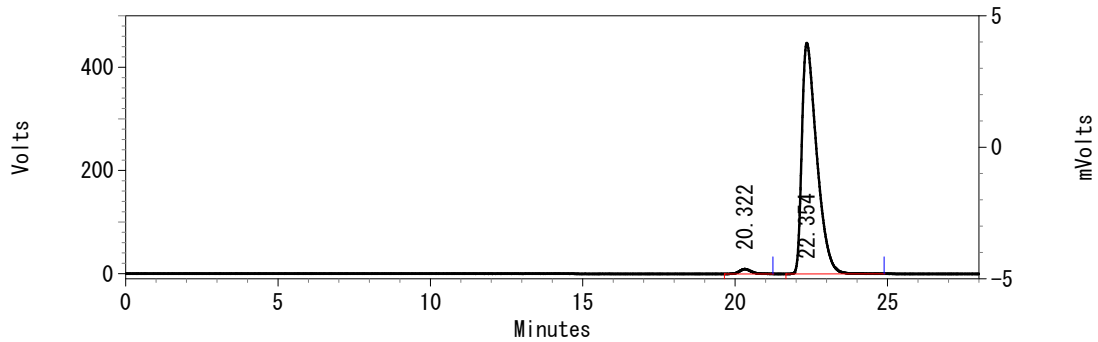








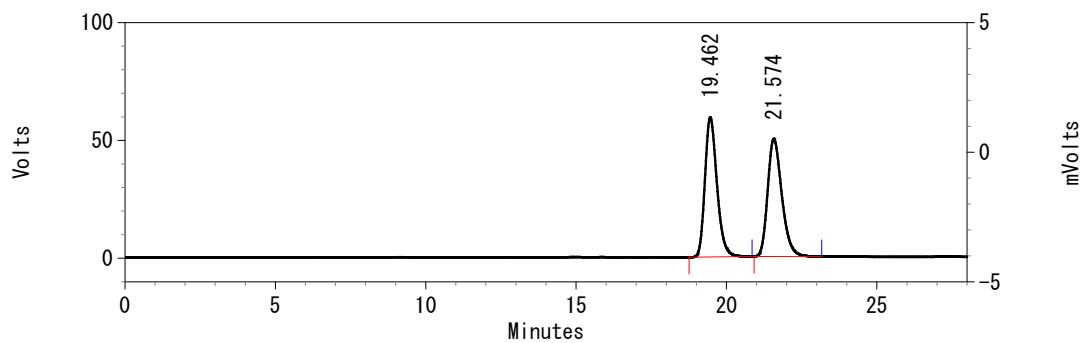
(Table 1, entry 7)



**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	20.322	242235	1.572	9321
2	22.354	15165838	98.428	447757

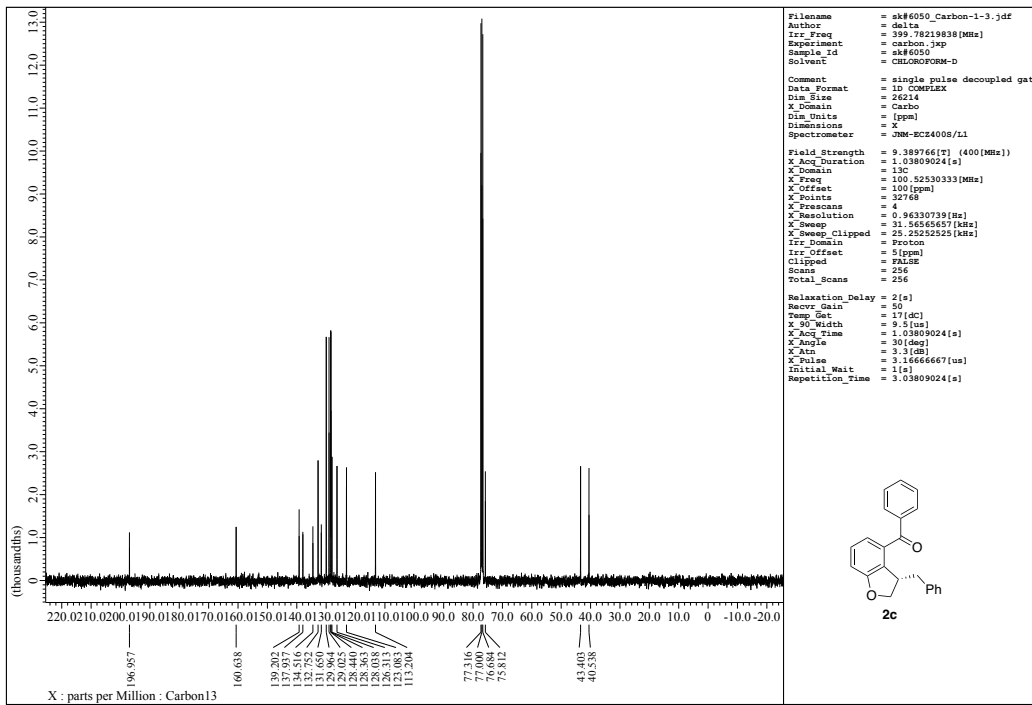
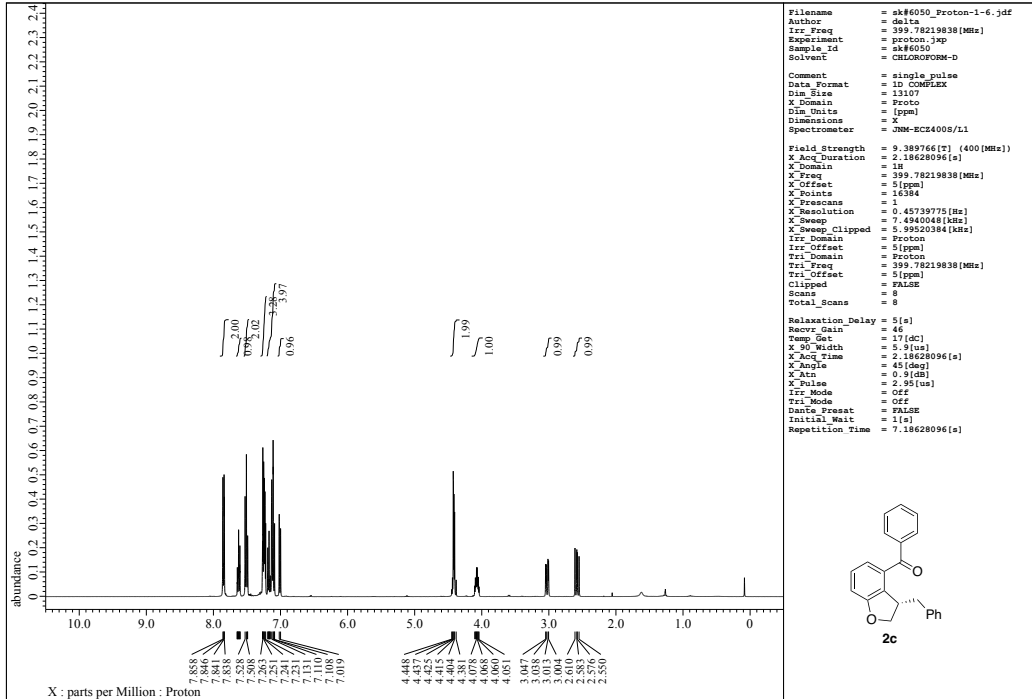
Totals		15408073	100.000	457078
--------	--	----------	---------	--------

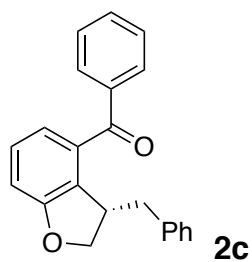


**UV Results**

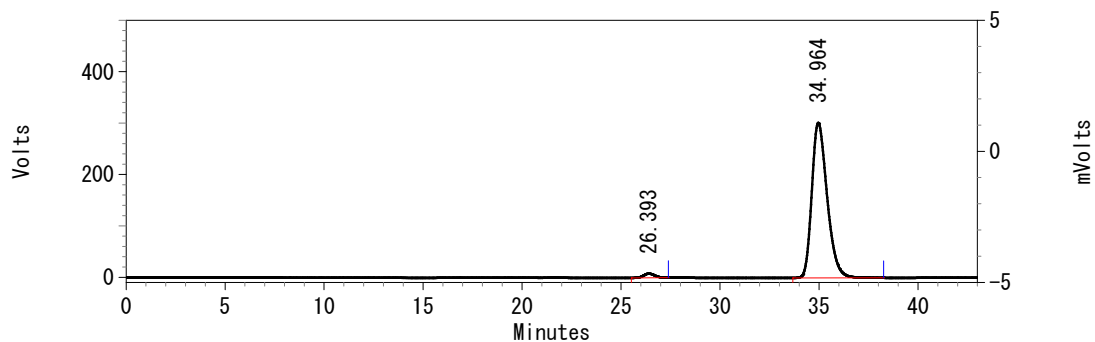
Pk #	Retention Time	Area	Area Percent	Height
1	19.462	1648846	50.155	59270
2	21.574	1638680	49.845	49975

Totals		3287526	100.000	109245
--------	--	---------	---------	--------



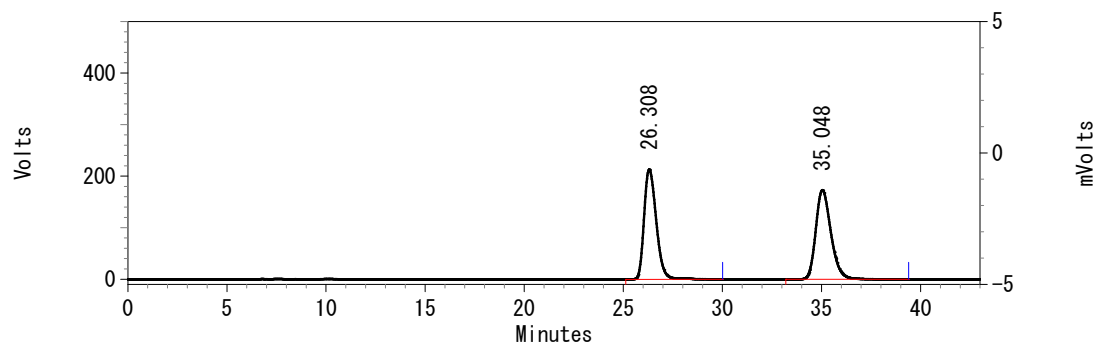


(Scheme 3)



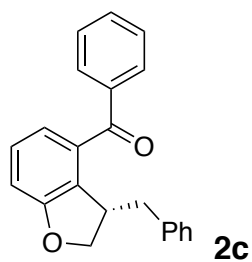
**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	26.393	326078	1.969	8289
2	34.964	16235344	98.031	301696
Totals		16561422	100.000	309985

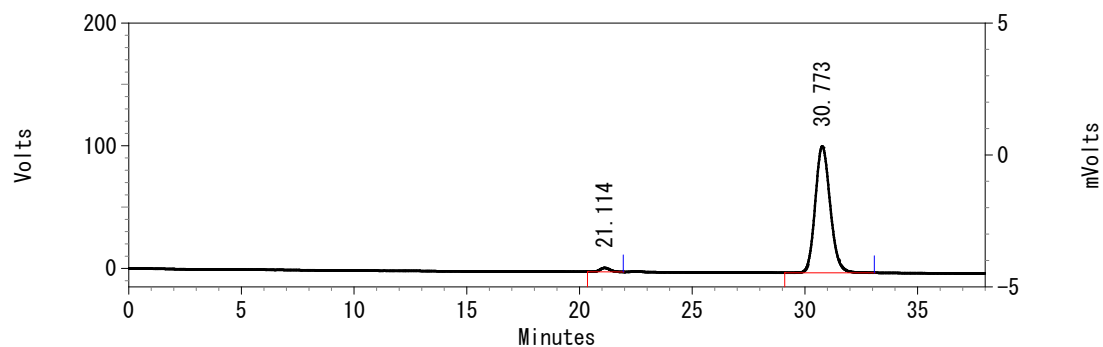


**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	26.308	9121919	49.771	213204
2	35.048	9205948	50.229	173179
Totals		18327867	100.000	386383

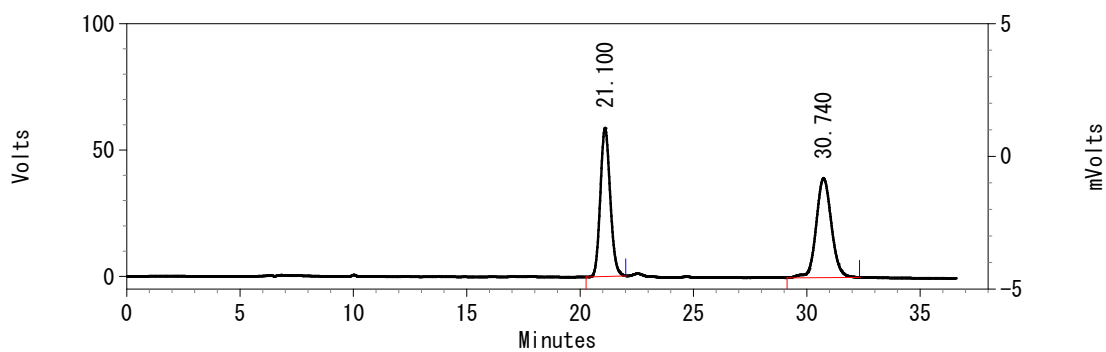


(Scheme 10)



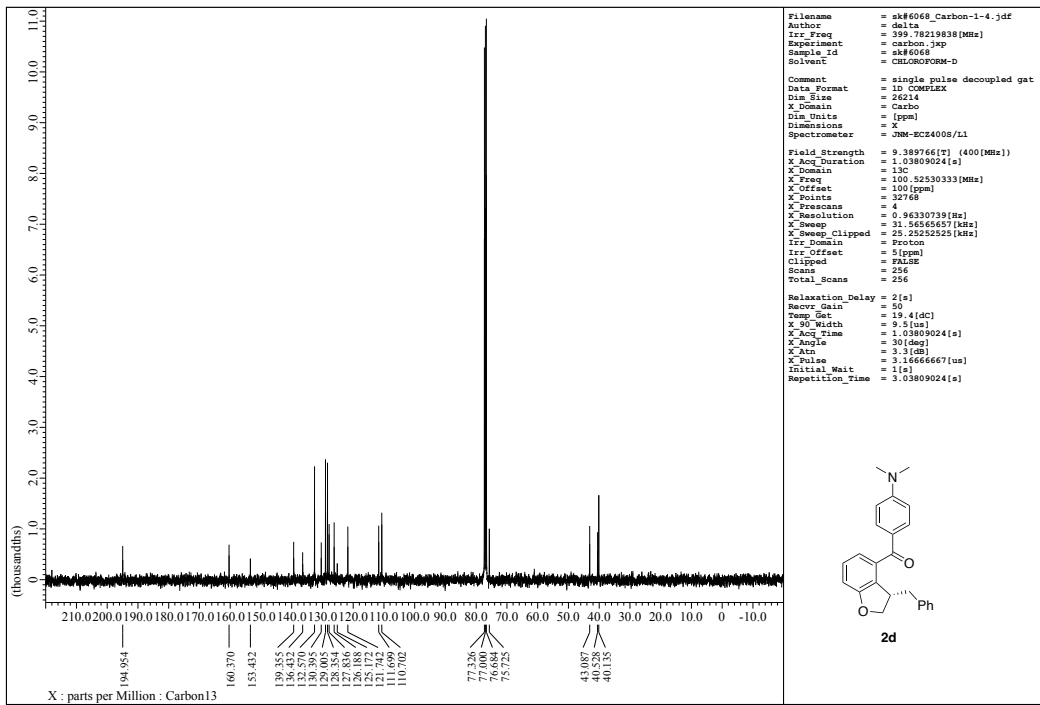
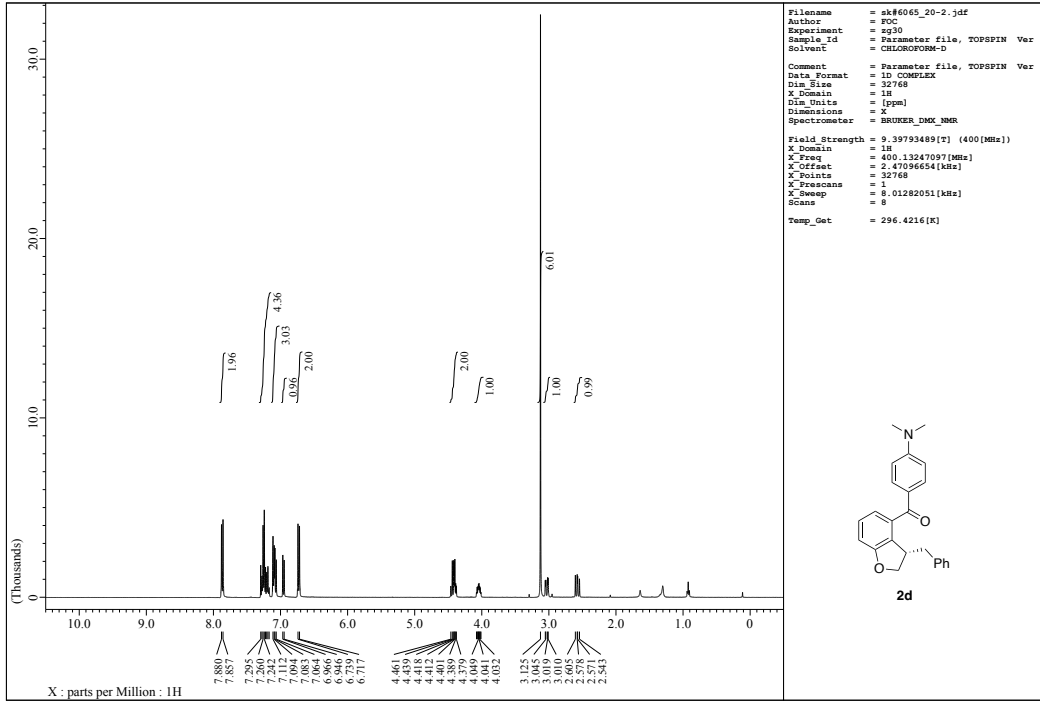
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	21.114	99905	2.057	3277
2	30.773	4756851	97.943	103170
Totals		4856756	100.000	106447

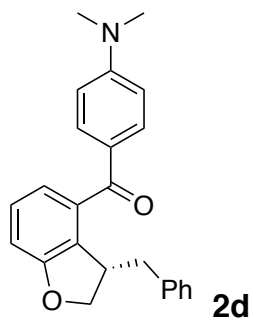


**UV Results**

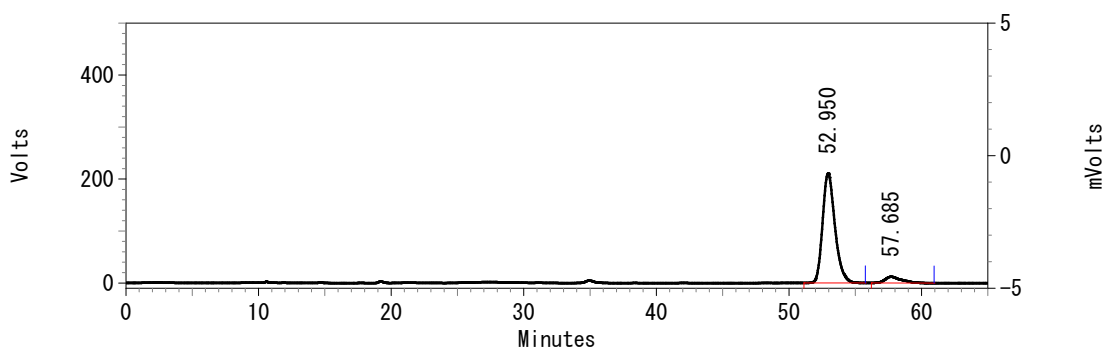
Pk #	Retention Time	Area	Area Percent	Height
1	21.100	1777129	49.183	58785
2	30.740	1836163	50.817	39341
Totals		3613292	100.000	98126





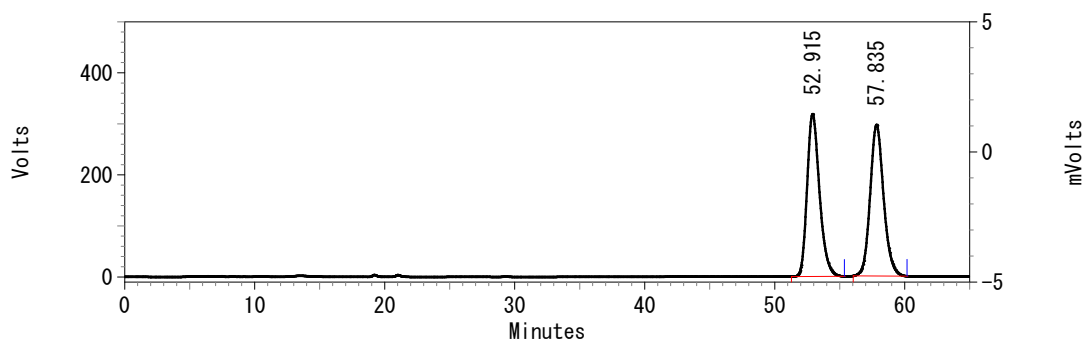


(Scheme 3)



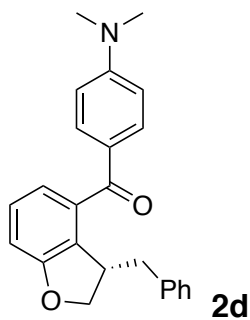
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	52.950	13664750	92.964	210935
2	57.685	1034167	7.036	12042
Totals		14698917	100.000	222977

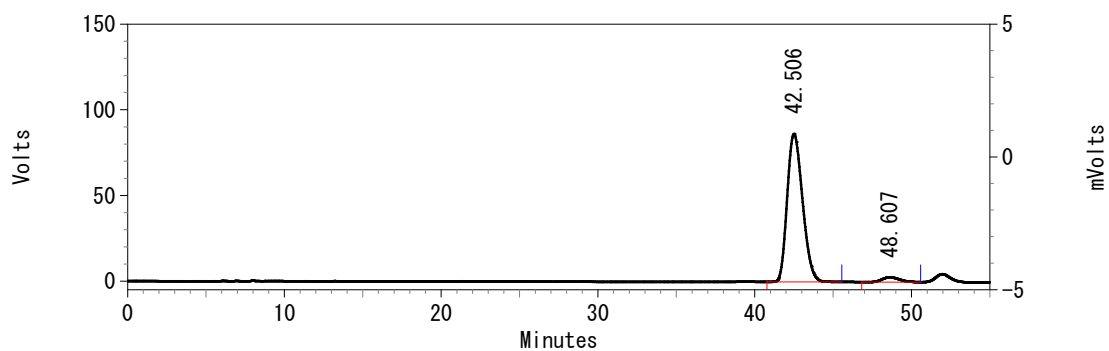


**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	52.915	21095755	49.684	318333
2	57.835	21363823	50.316	296389
Totals		42459578	100.000	614722

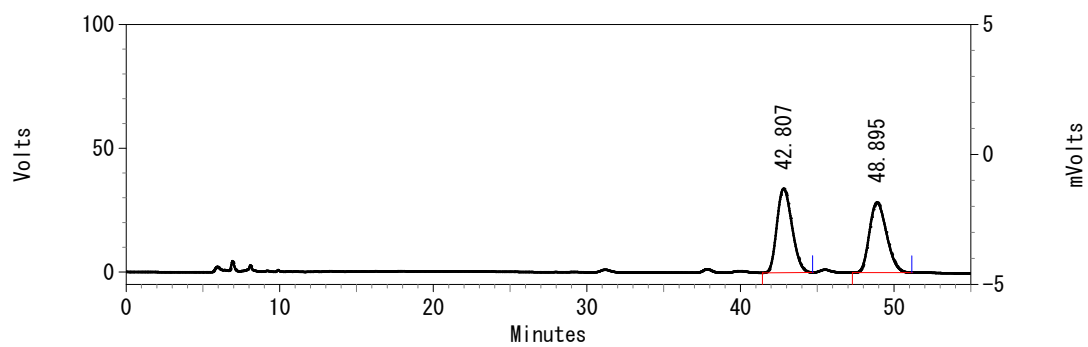


(Scheme 10)



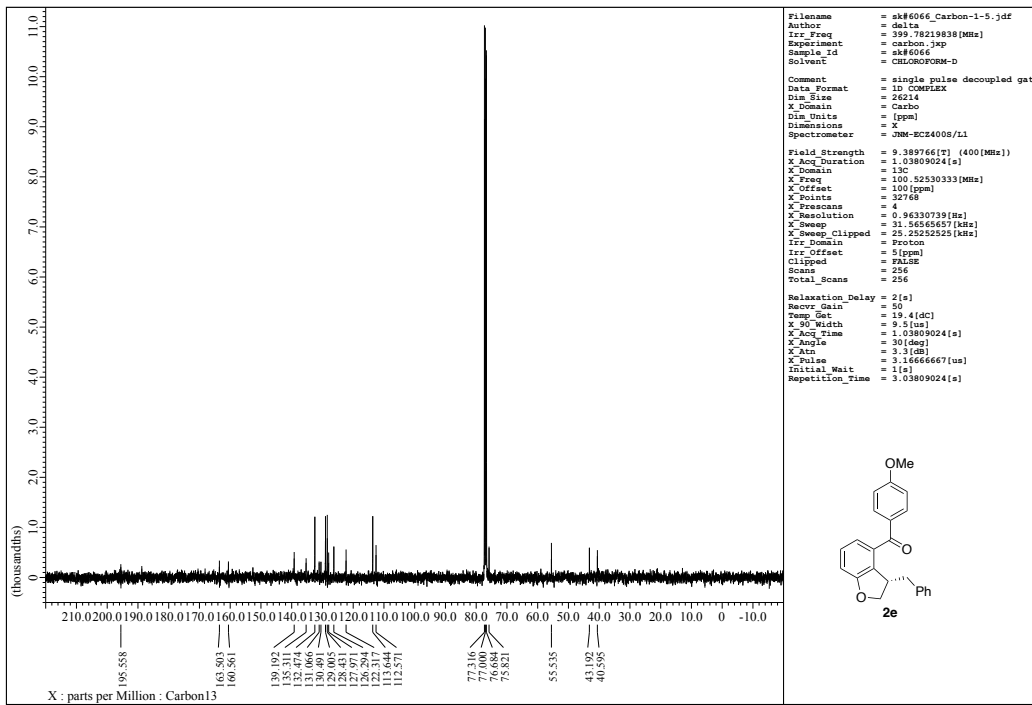
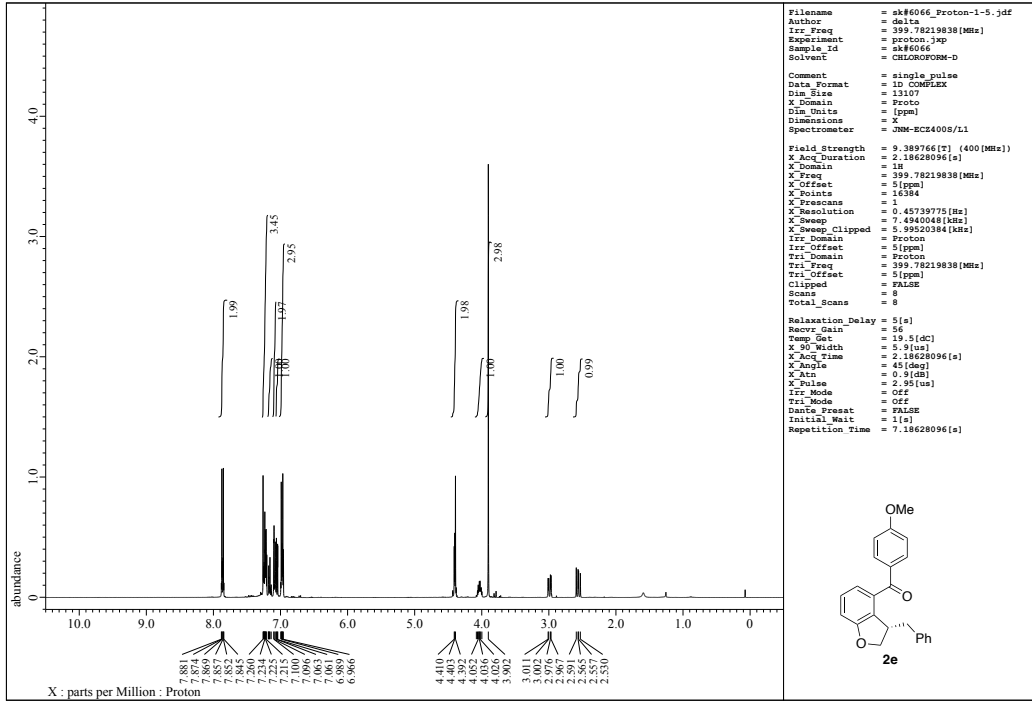
**UV Results**

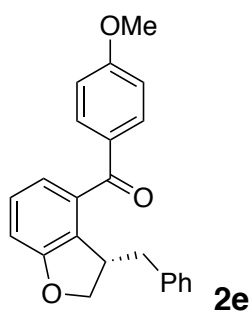
Pk #	Retention Time	Area	Area Percent	Height
1	42.506	5874474	96.511	86346
2	48.607	212352	3.489	2794
Totals		6086826	100.000	89140



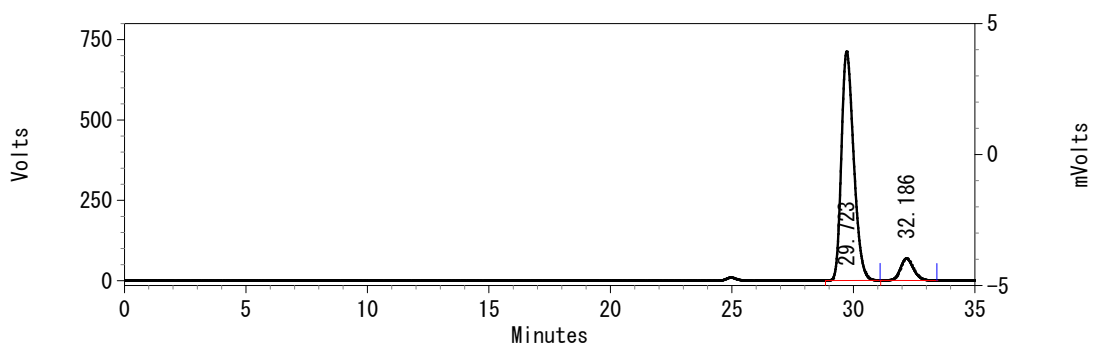
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	42.807	2319382	51.320	33938
2	48.895	2200040	48.680	28337
Totals		4519422	100.000	62275



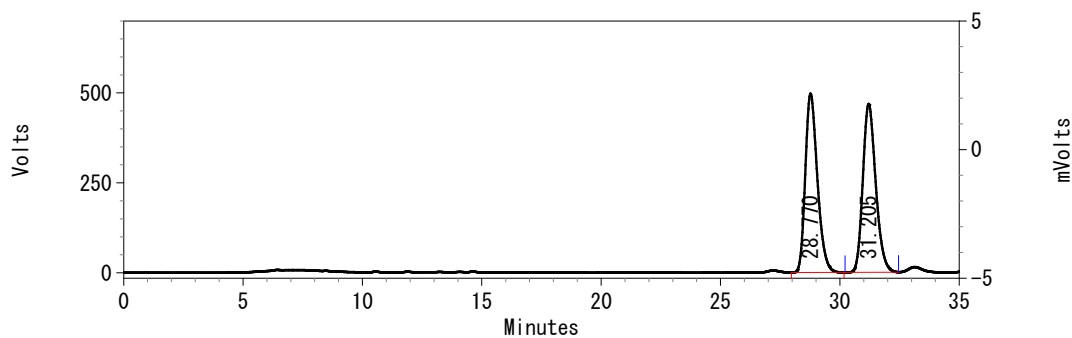


(Scheme 3)



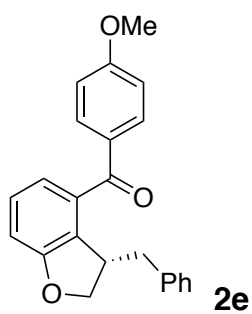
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	29.723	25013634	90.754	712364
2	32.186	2548428	9.246	68337
Totals		27562062	100.000	780701

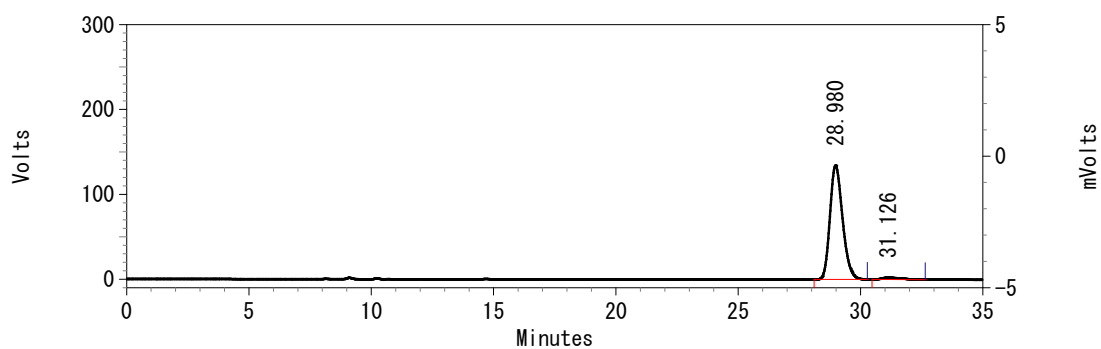


**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	28.770	17469439	49.877	497156
2	31.205	17555906	50.123	467809
Totals		35025345	100.000	964965

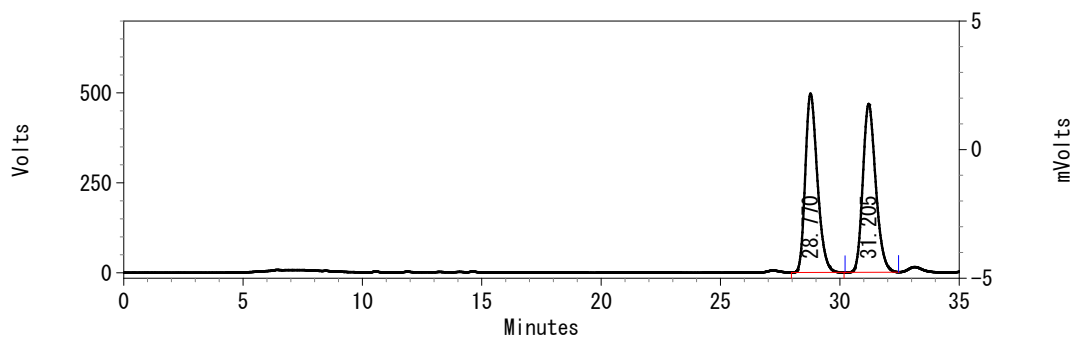


(Scheme 10)



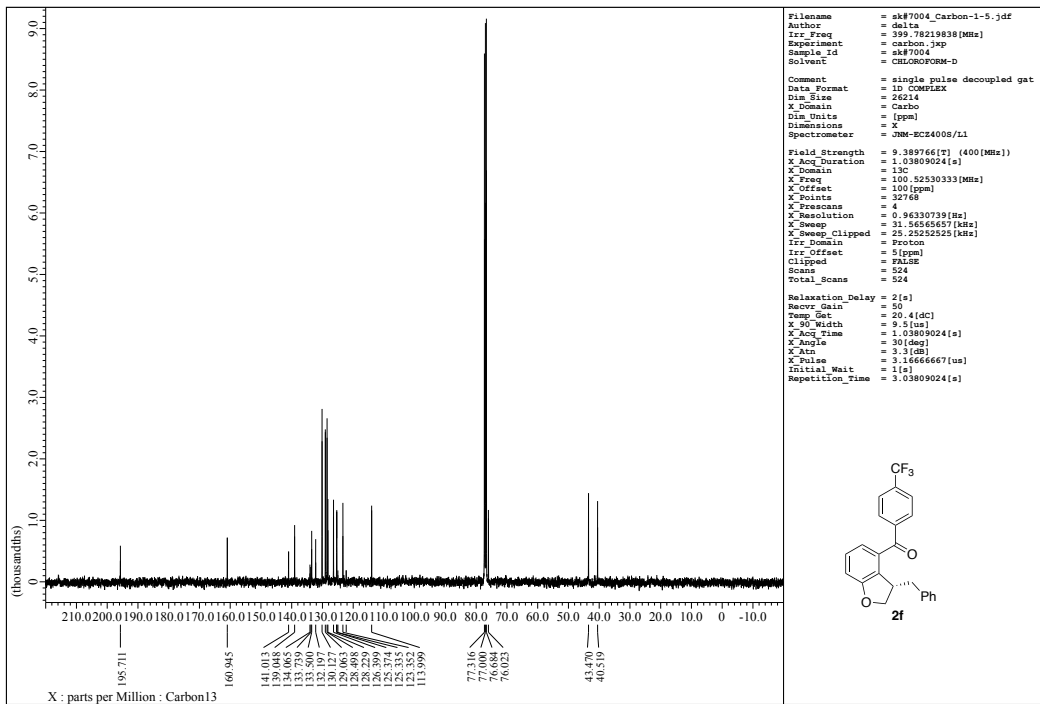
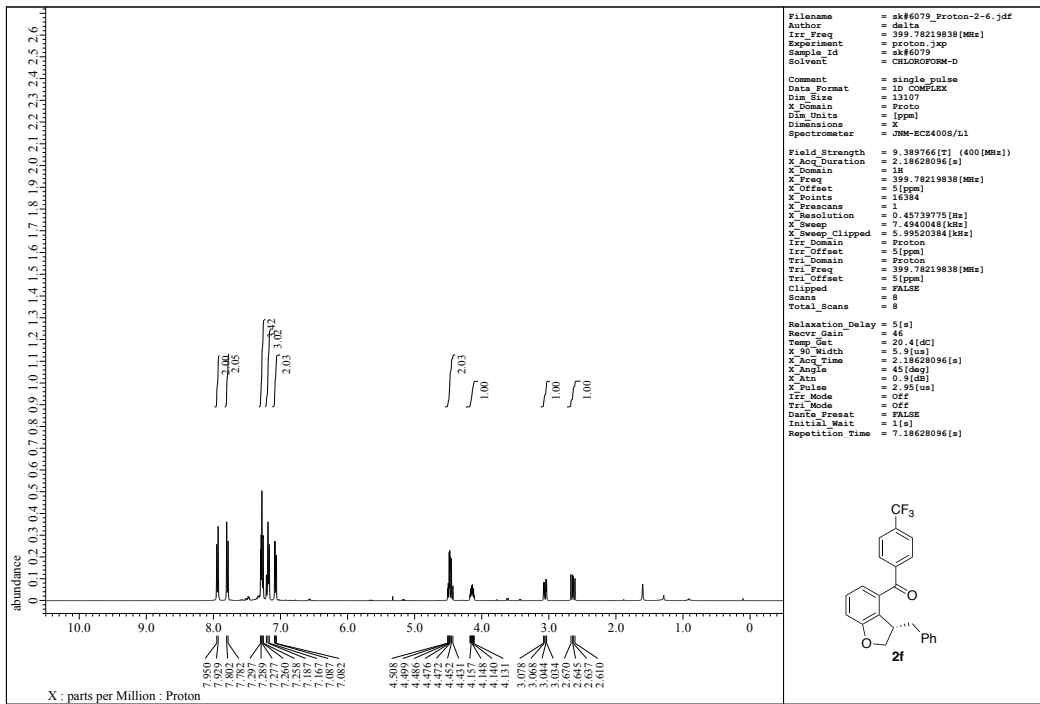
**UV Results**

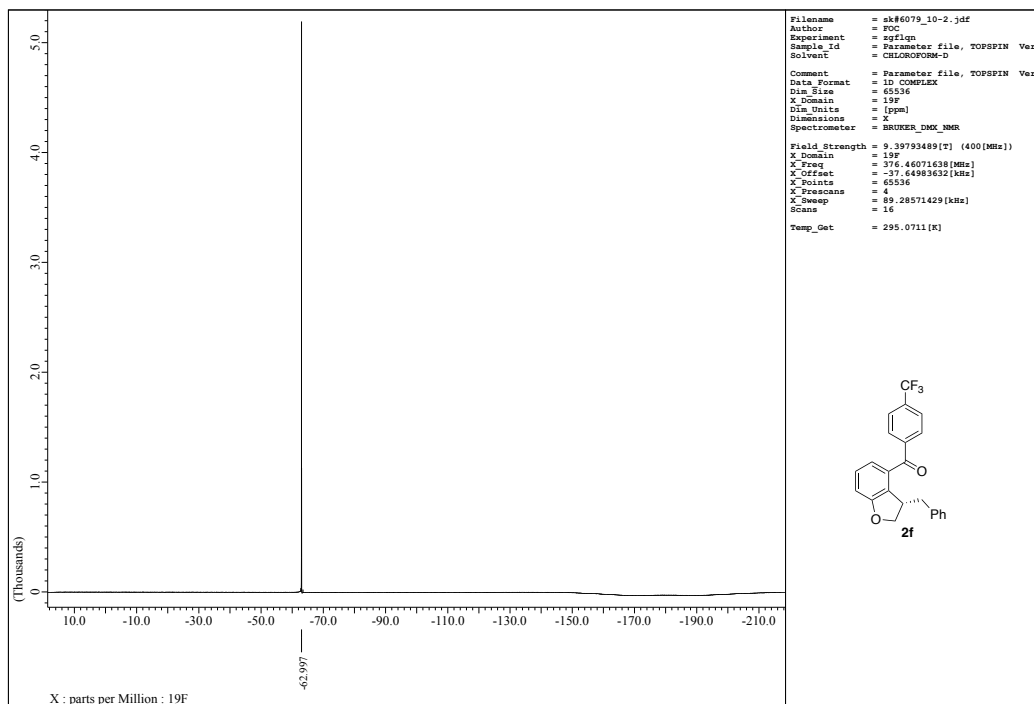
Pk #	Retention Time	Area	Area Percent	Height
1	28.980	4807698	97.594	134248
2	31.126	118525	2.406	2254
Totals		4926223	100.000	136502

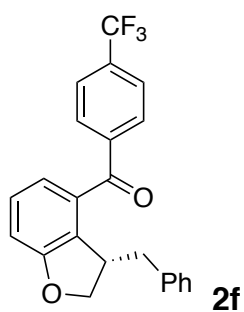


**UV Results**

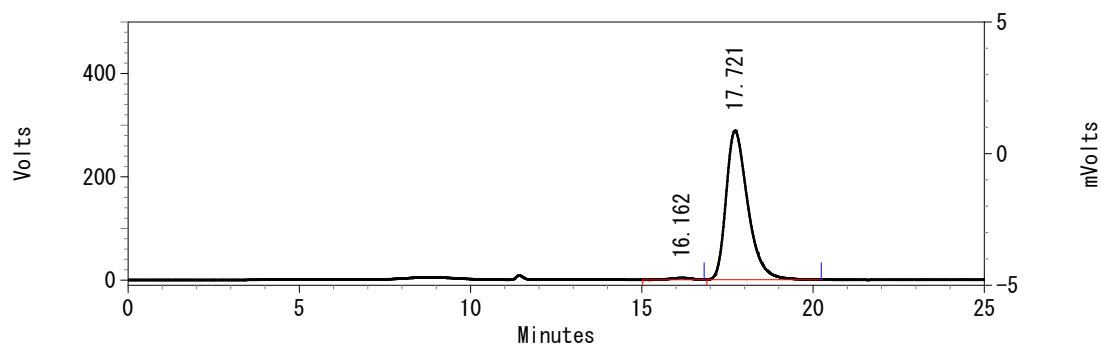
Pk #	Retention Time	Area	Area Percent	Height
1	28.770	17469439	49.877	497156
2	31.205	17555906	50.123	467809
Totals		35025345	100.000	964965





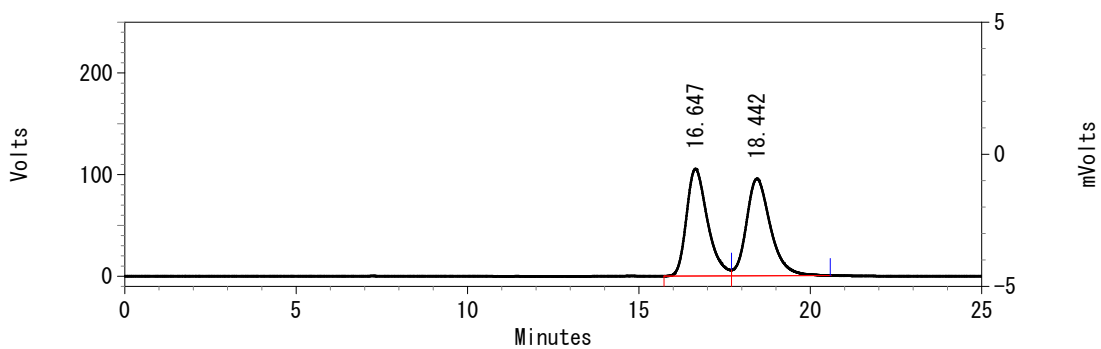


(Scheme 3)



**UV Results**

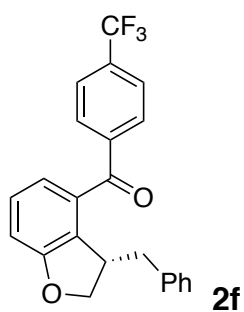
Pk #	Retention Time	Area	Area Percent	Height
1	16.162	148865	1.159	3552
2	17.721	12694607	98.841	288450
Totals		12843472	100.000	292002



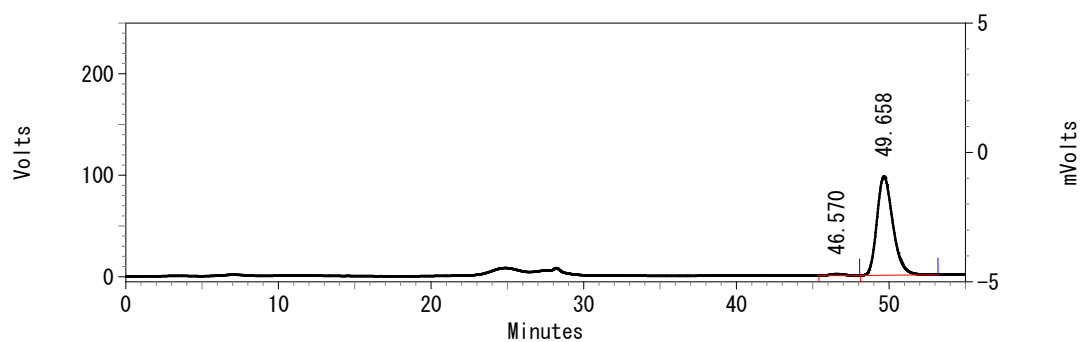
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	16.647	4495791	49.184	105366
2	18.442	4644904	50.816	95516
Totals		9140695	100.000	200882



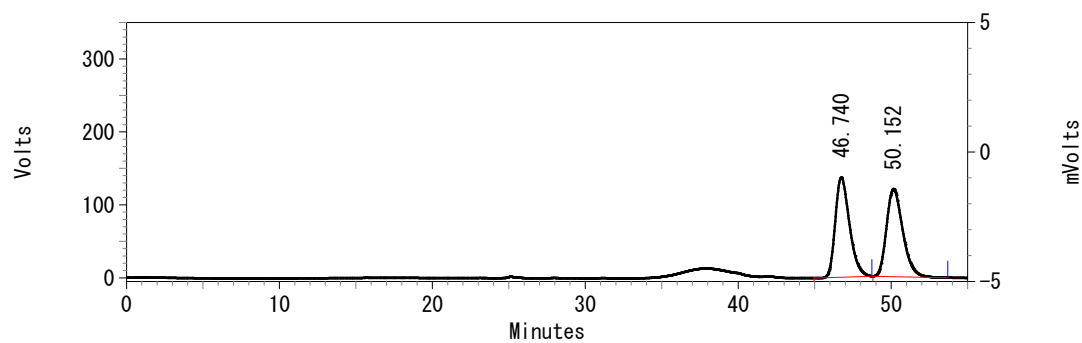


(Scheme 10)



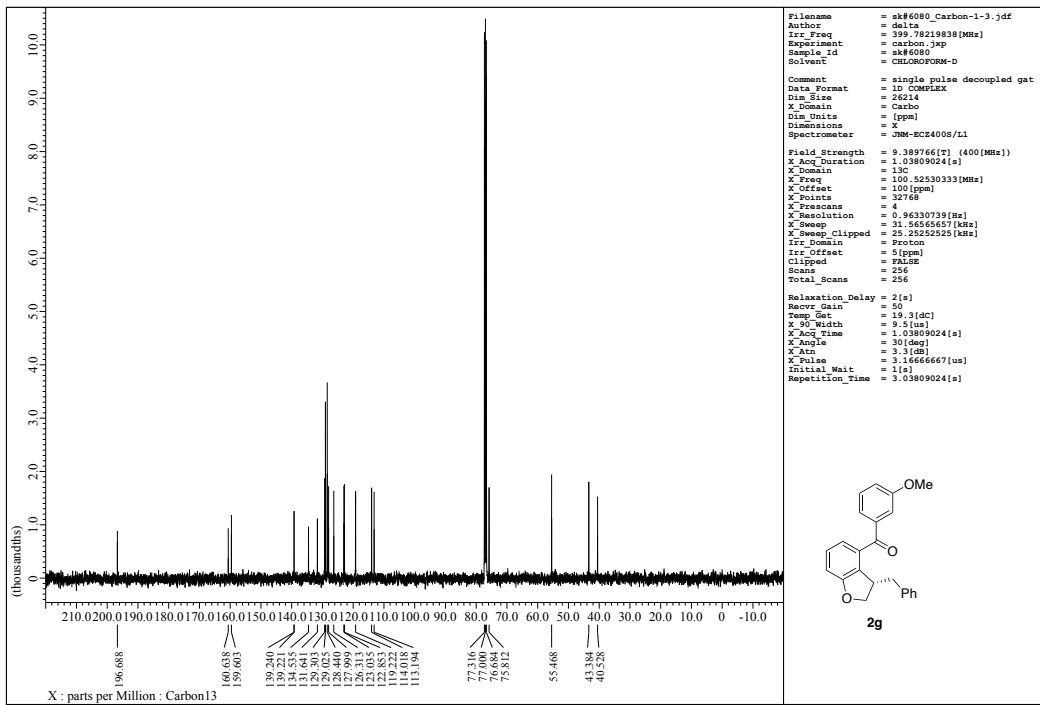
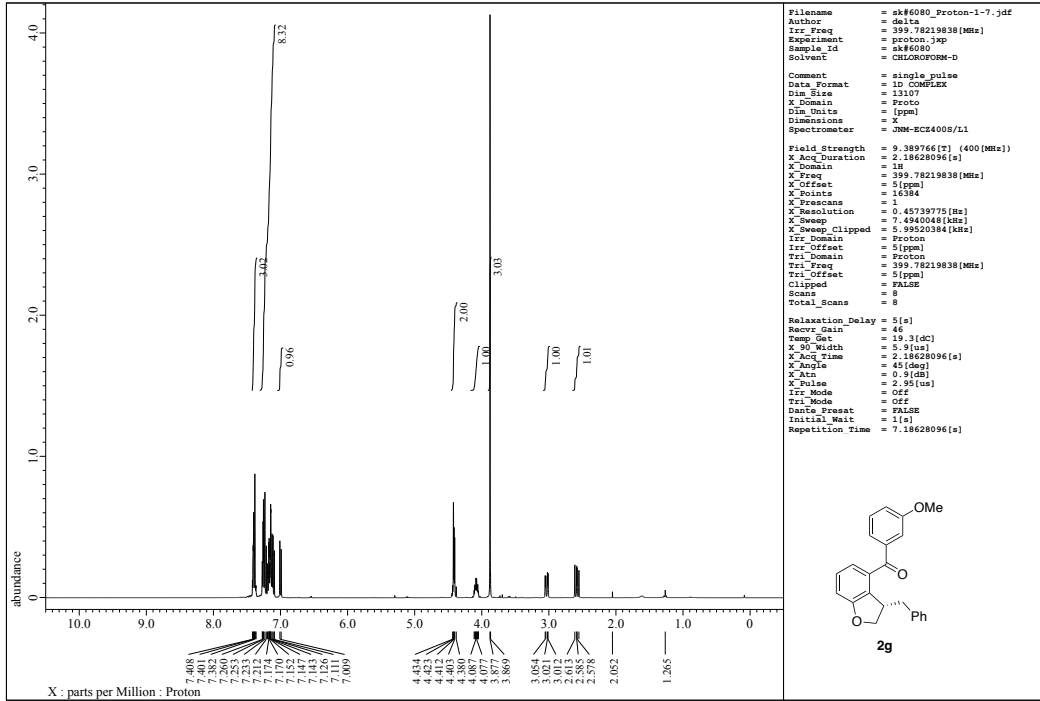
**UV Results**

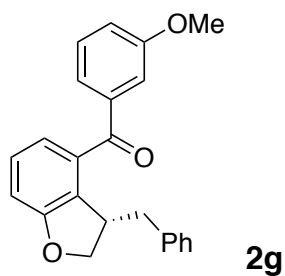
PK #	Retention Time	Area	Area Percent	Height
1	46.570	97308	1.358	1559
2	49.658	7068042	98.642	97512
Totals		7165350	100.000	99071



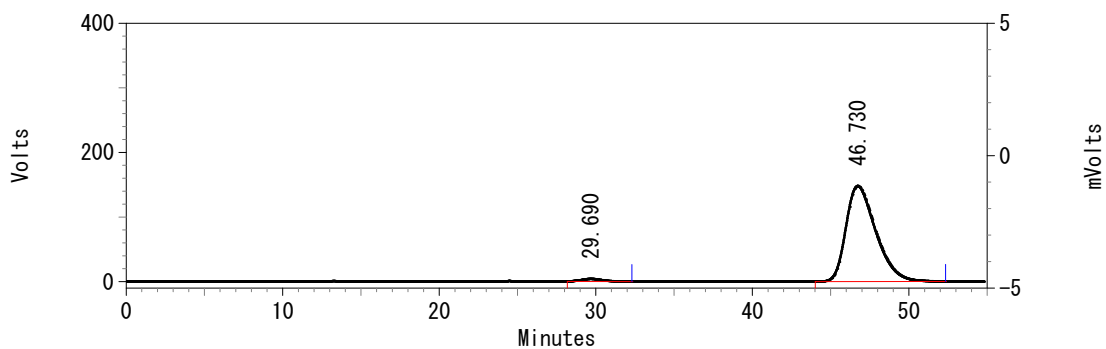
**UV Results**

PK #	Retention Time	Area	Area Percent	Height
1	46.740	8830029	49.832	136714
2	50.152	8889675	50.168	120267
Totals		17719704	100.000	256981



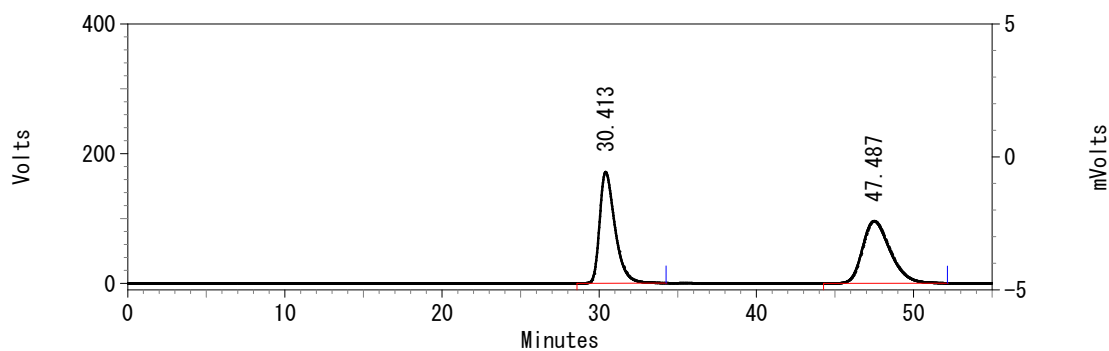


(Scheme 3)



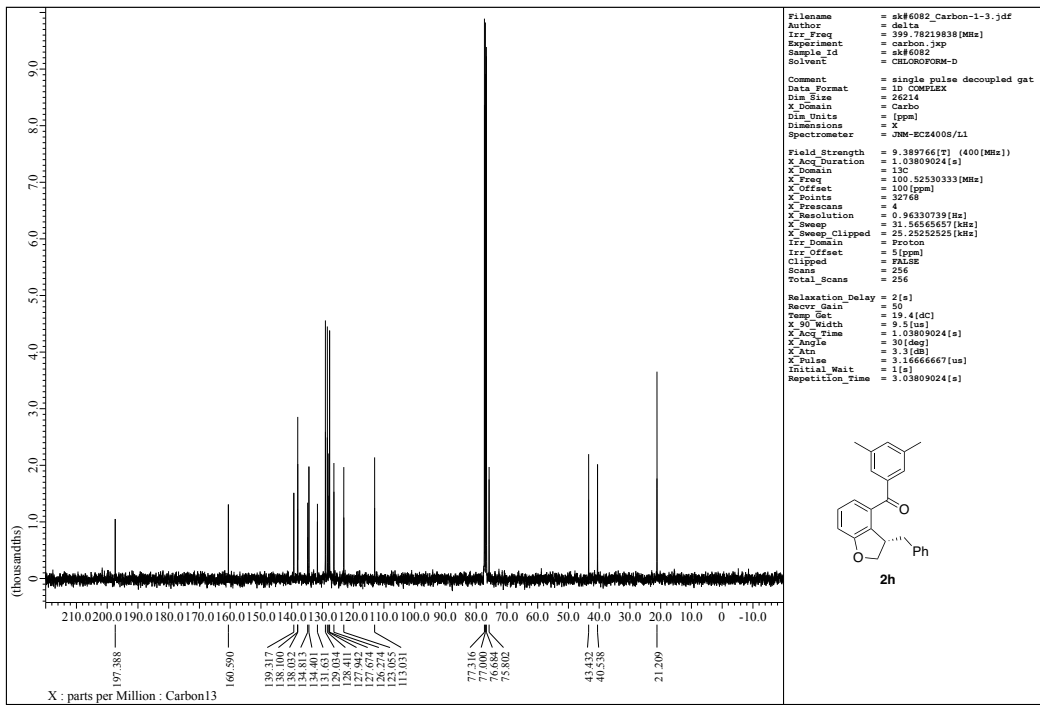
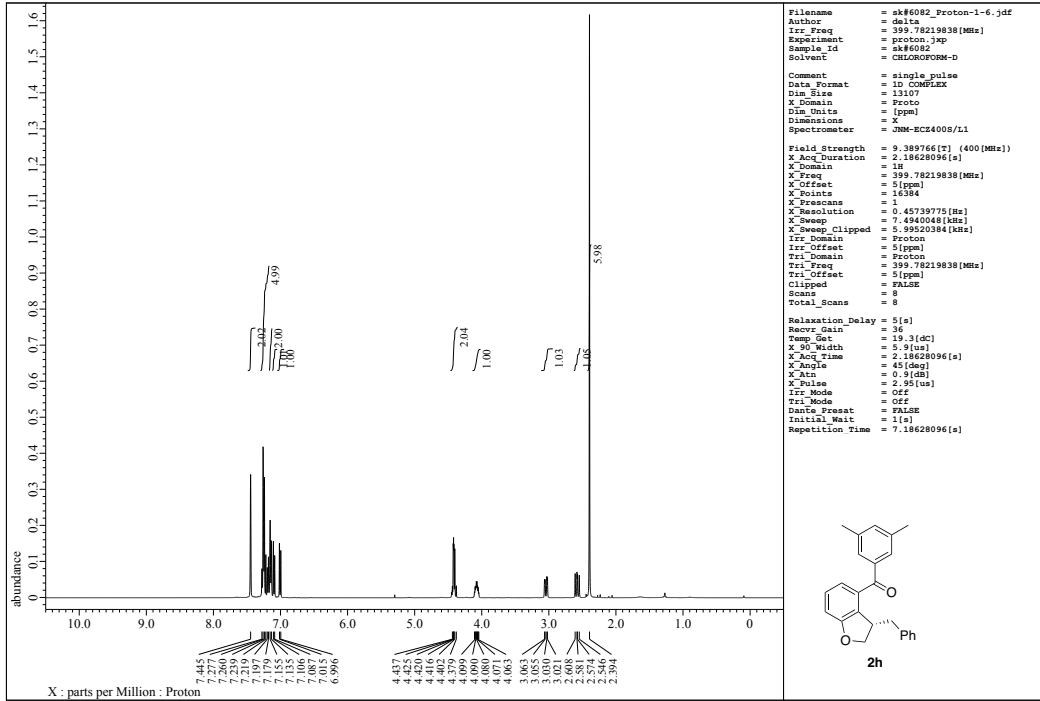
**UV Results**

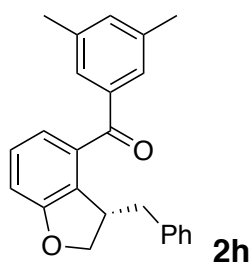
Pk #	Retention Time	Area	Area Percent	Height
1	29.690	381944	1.913	4084
2	46.730	19580072	98.087	148012
Totals		19962016	100.000	152096



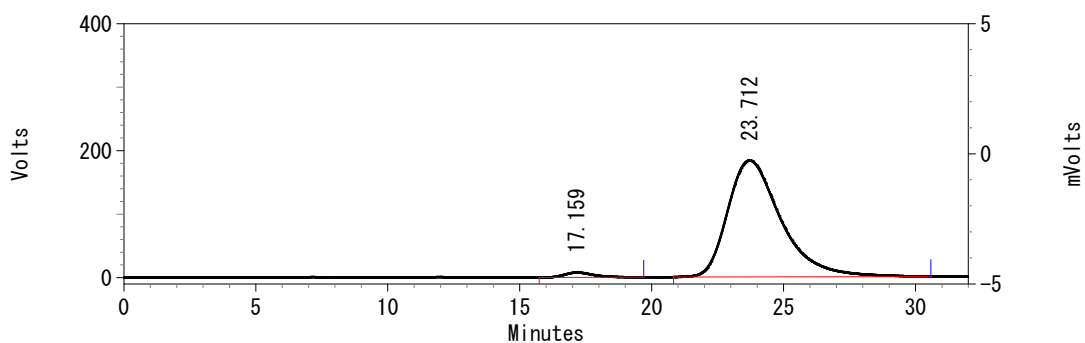
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	30.413	11647490	49.942	171650
2	47.487	11674486	50.058	95828
Totals		23321976	100.000	267478





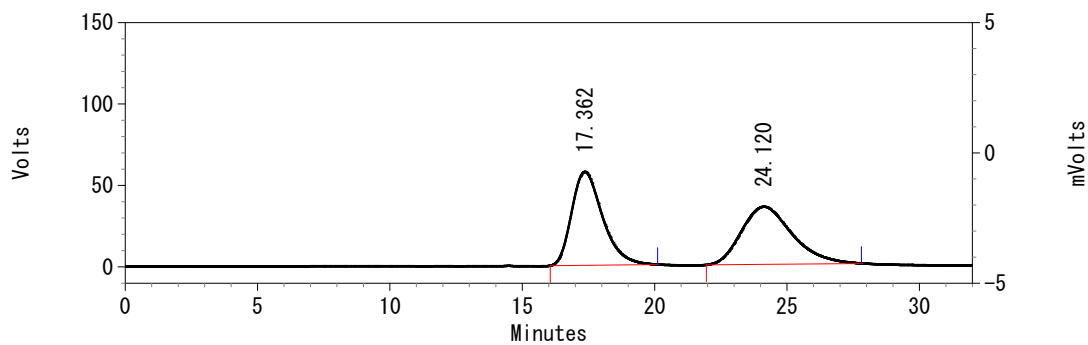
(Scheme 3)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	17.159	576157	2.185	7636
2	23.712	25794626	97.815	183519

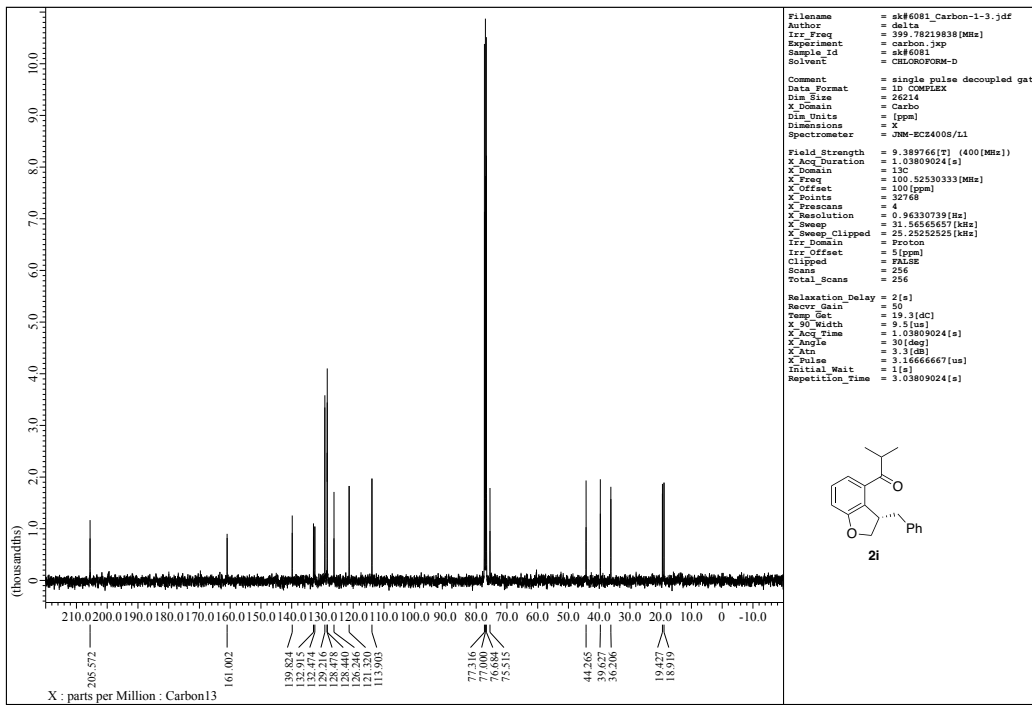
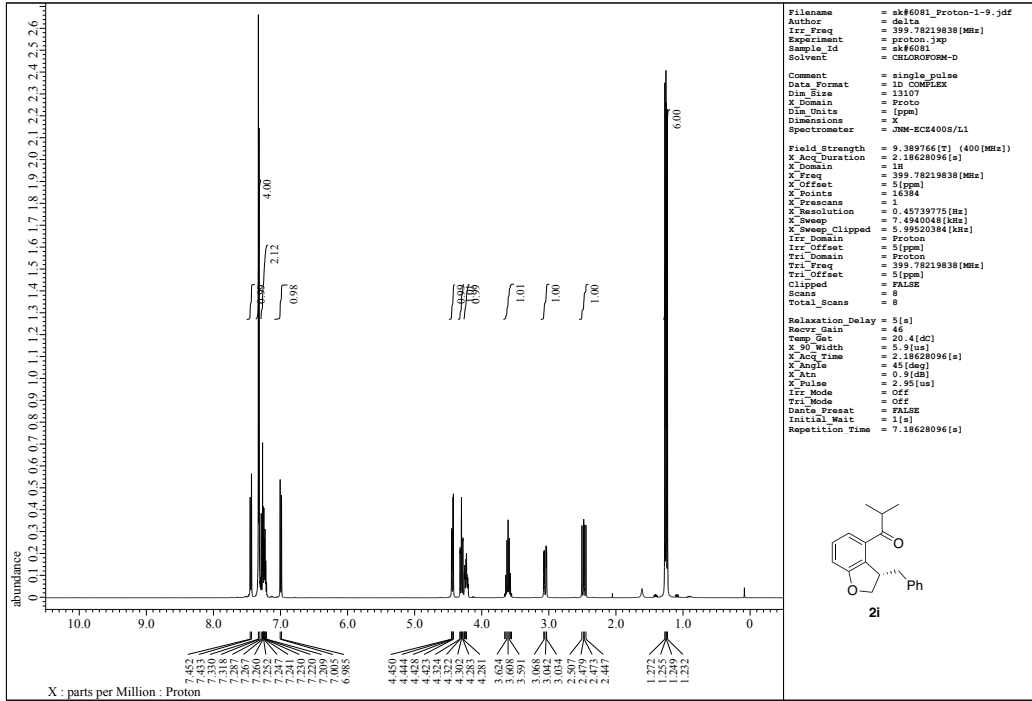
Totals		26370783	100.000	191155
--------	--	----------	---------	--------

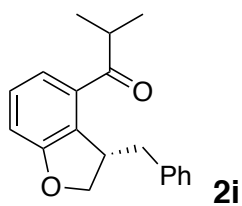


**UV Results**

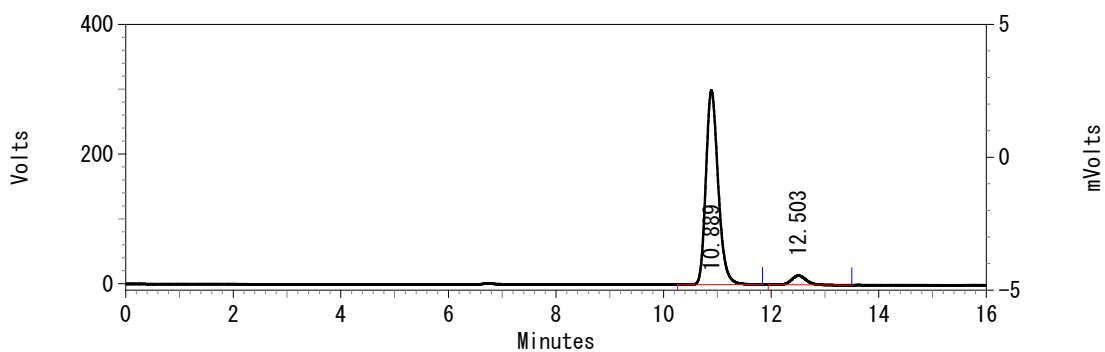
Pk #	Retention Time	Area	Area Percent	Height
1	17.362	4658084	49.643	57351
2	24.120	4725141	50.357	35396

Totals		9383225	100.000	92747
--------	--	---------	---------	-------



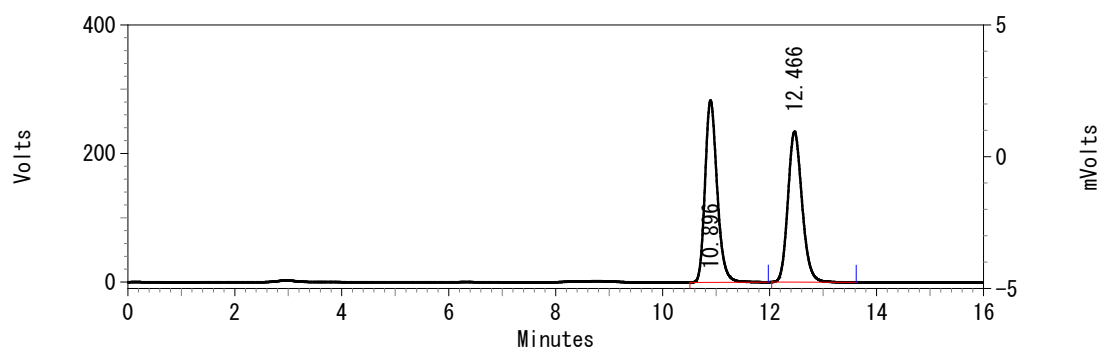


(Scheme 3)



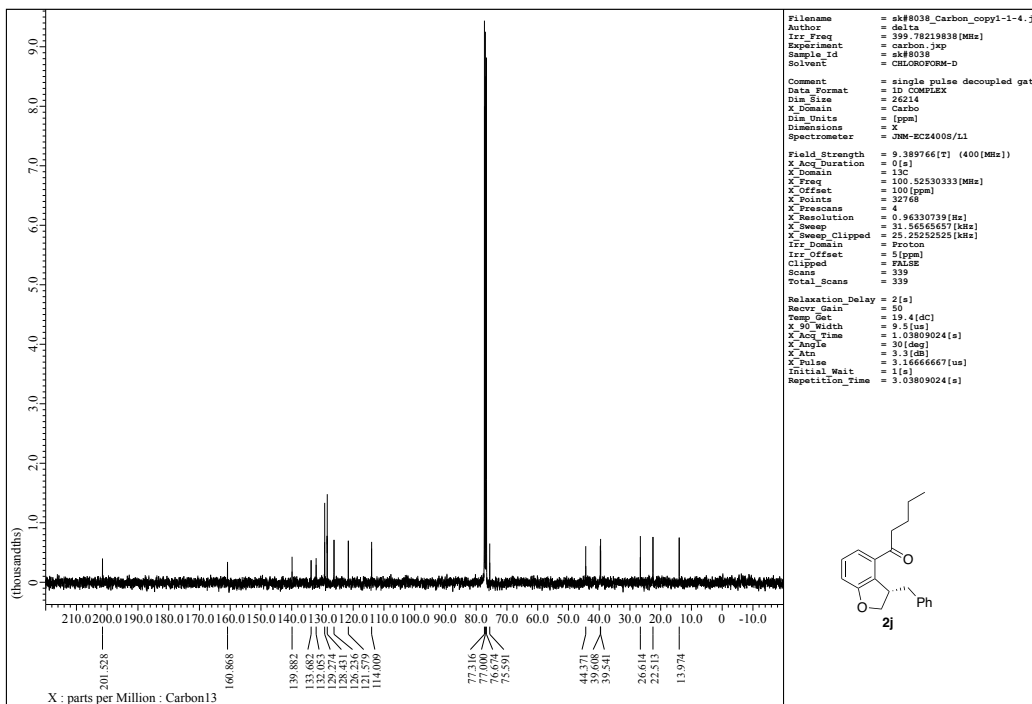
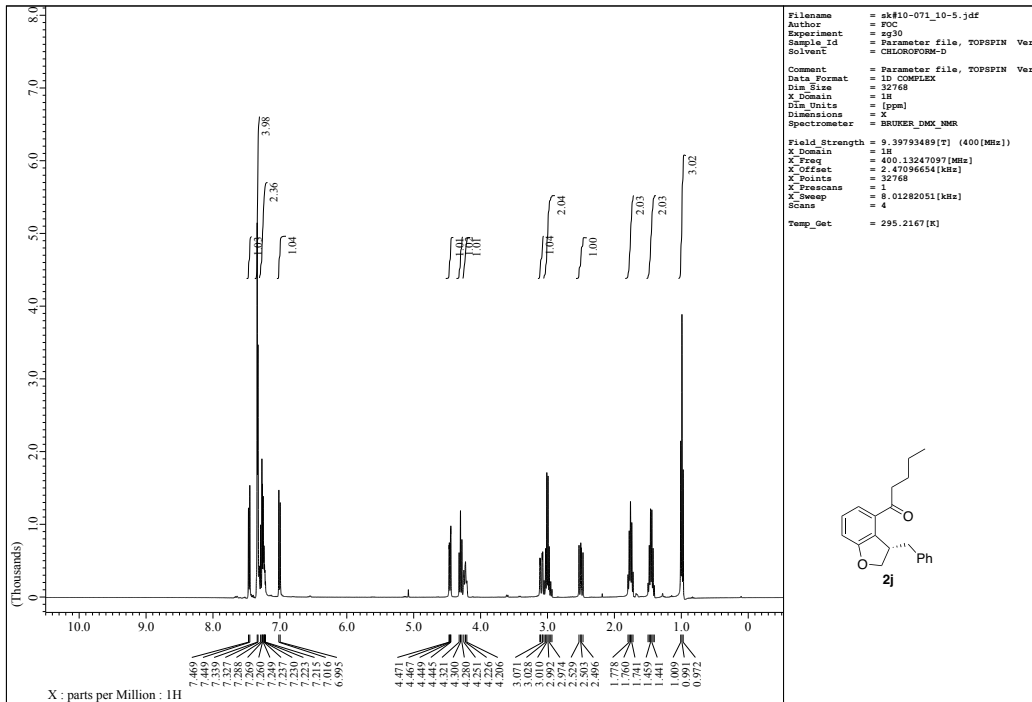
**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	10.889	4747362	94.869	299785
2	12.503	256739	5.131	14090
Totals		5004101	100.000	313875

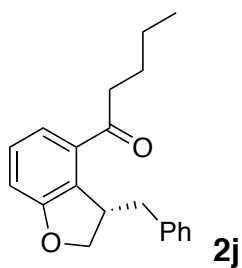


**UV-970 Results**

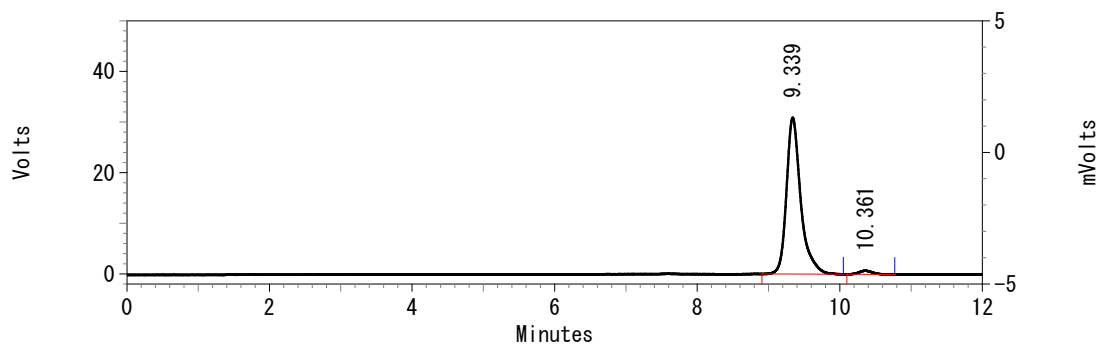
Pk #	Retention Time	Area	Area Percent	Height
1	10.896	4437963	50.802	283043
2	12.466	4297760	49.198	234032
Totals		8735723	100.000	517075







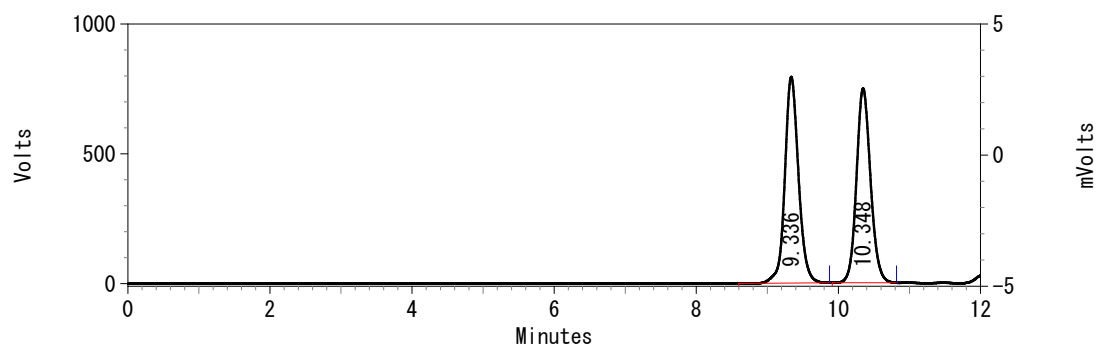
(Scheme 3)



**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	9.339	429817	97.856	30884
2	10.361	9415	2.144	709

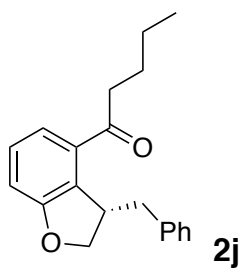
Totals		439232	100.000	31593
--------	--	--------	---------	-------



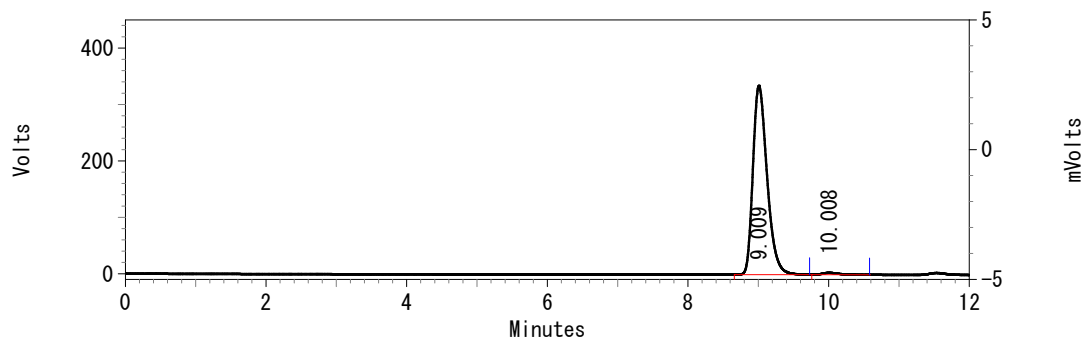
**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	9.336	10621377	50.738	794060
2	10.348	10312510	49.262	748874

Totals		20933887	100.000	1542934
--------	--	----------	---------	---------

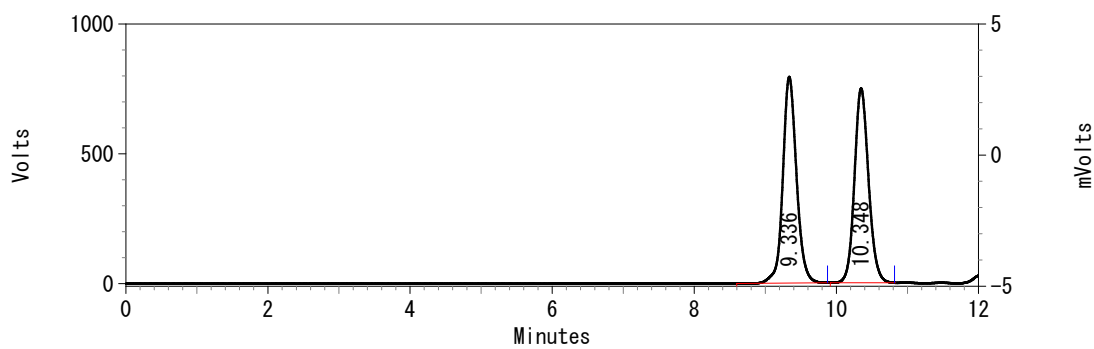


(Scheme 10)



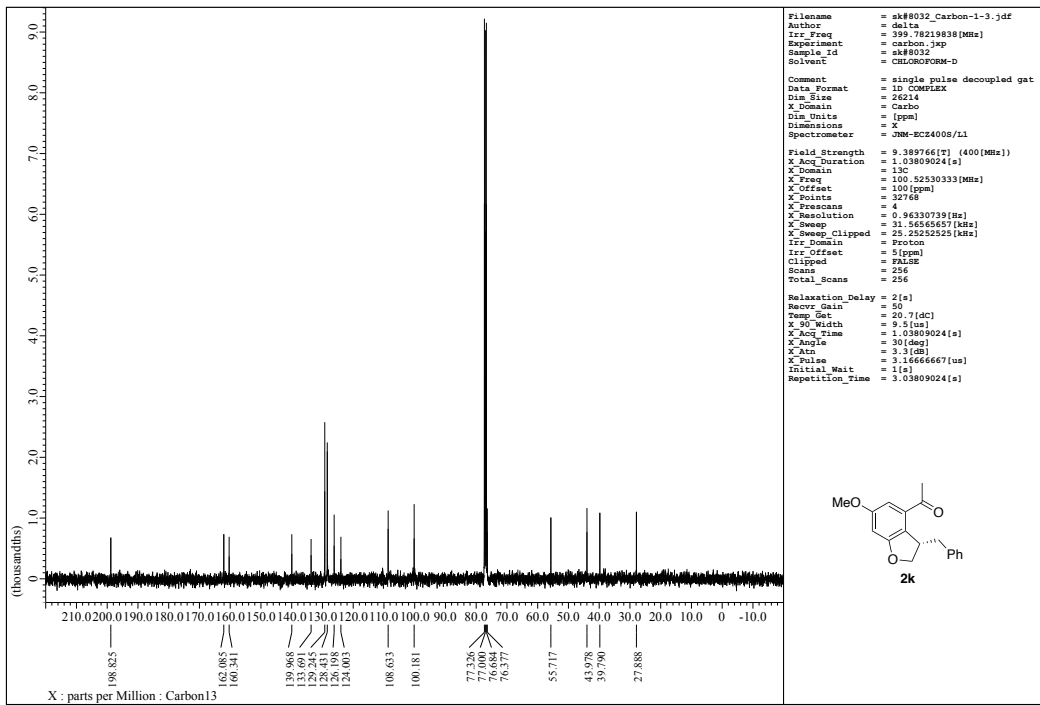
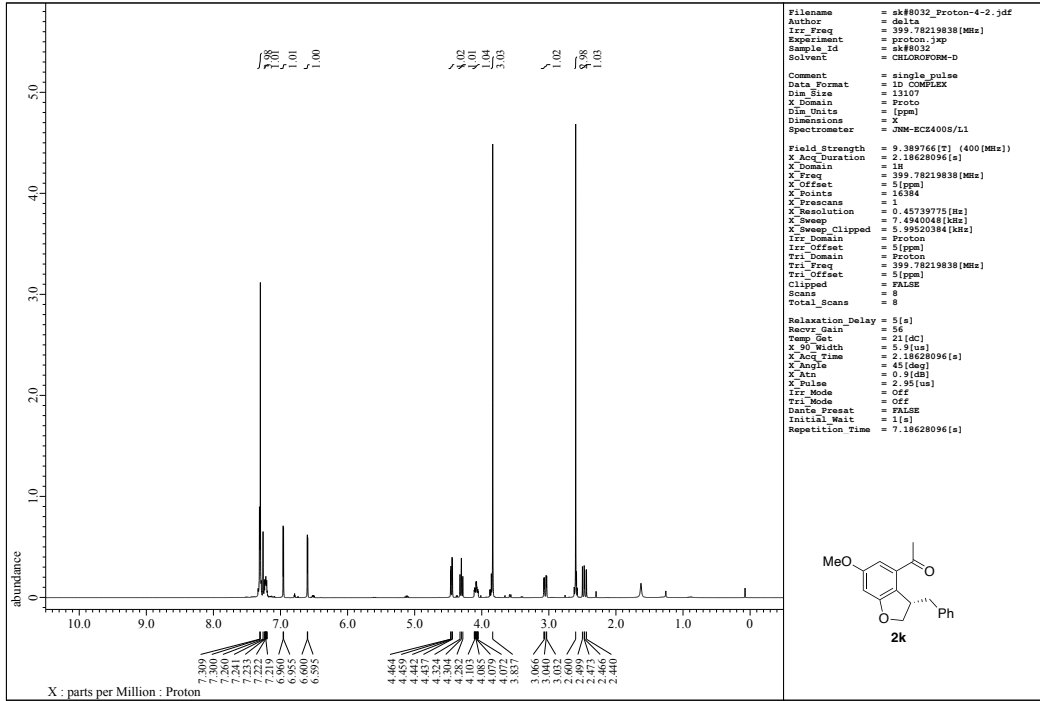
**UV Results**

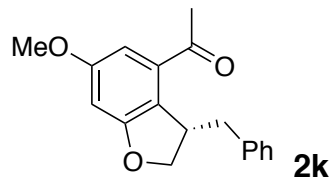
Pk #	Retention Time	Area	Area Percent	Height
1	9.009	4678830	98.944	334709
2	10.008	49928	1.056	3354
Totals		4728758	100.000	338063



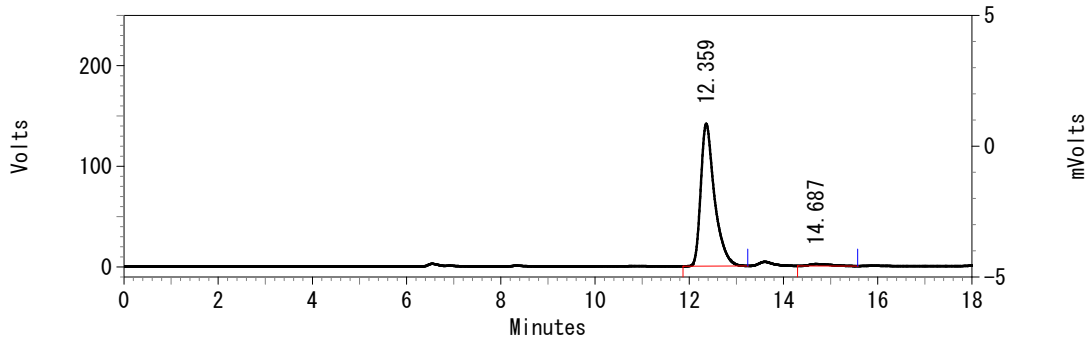
**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	9.336	10621377	50.738	794060
2	10.348	10312510	49.262	748874
Totals		20933887	100.000	1542934





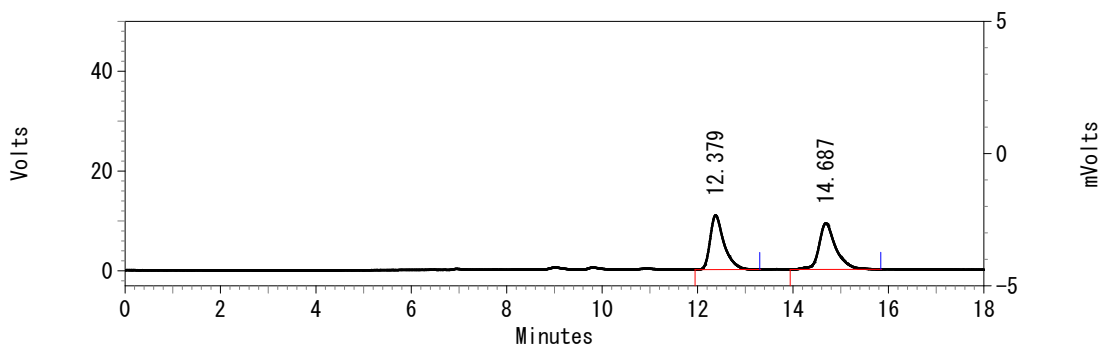
(Scheme 3)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	12.359	2860590	98.197	141531
2	14.687	52527	1.803	1877

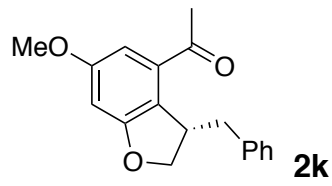
Totals		2913117	100.000	143408
--------	--	---------	---------	--------



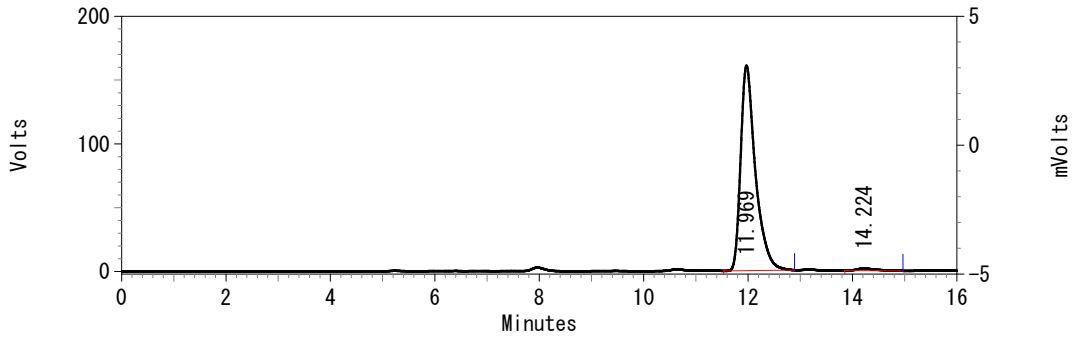
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	12.379	219191	49.350	10872
2	14.687	224966	50.650	9251

Totals		444157	100.000	20123
--------	--	--------	---------	-------



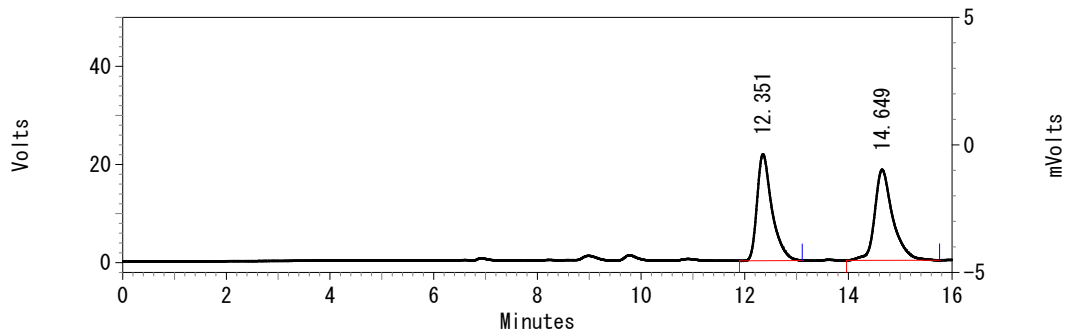
(Scheme 10)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	11.969	3156159	98.763	160597
2	14.224	39541	1.237	1692

Totals		3195700	100.000	162289
--------	--	---------	---------	--------

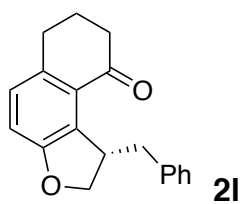


**UV Results**

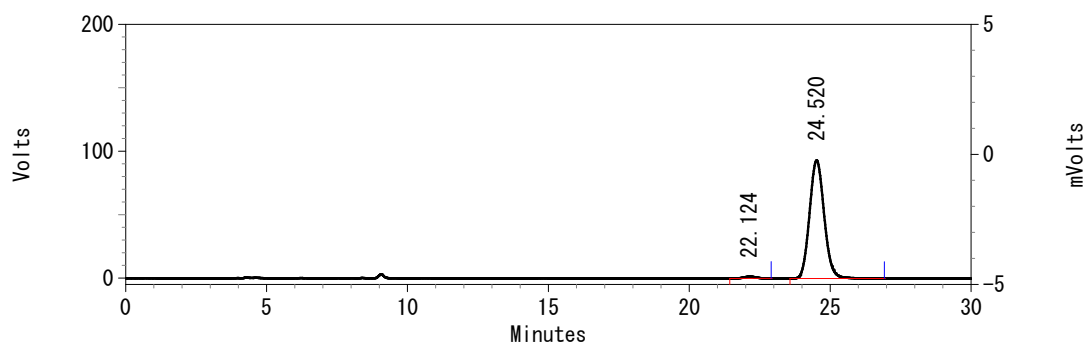
Pk #	Retention Time	Area	Area Percent	Height
1	12.351	433155	49.238	21733
2	14.649	446553	50.762	18488

Totals		879708	100.000	40221
--------	--	--------	---------	-------





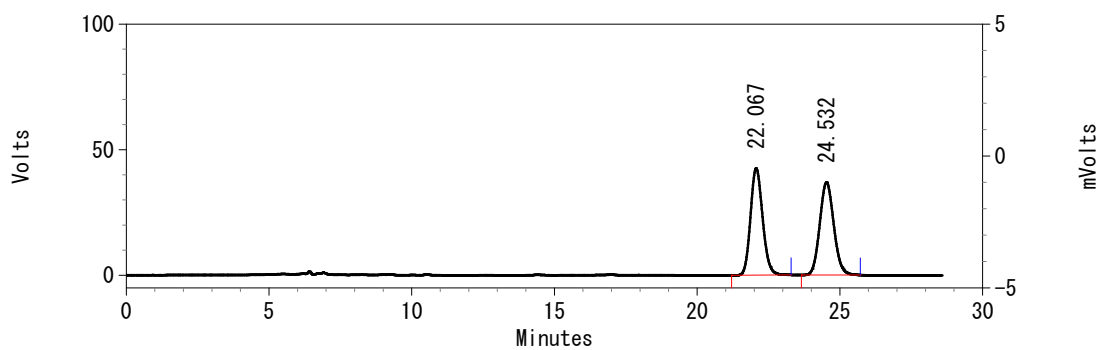
(Scheme 3)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	22.124	40110	1.182	1377
2	24.520	3353730	98.818	93045

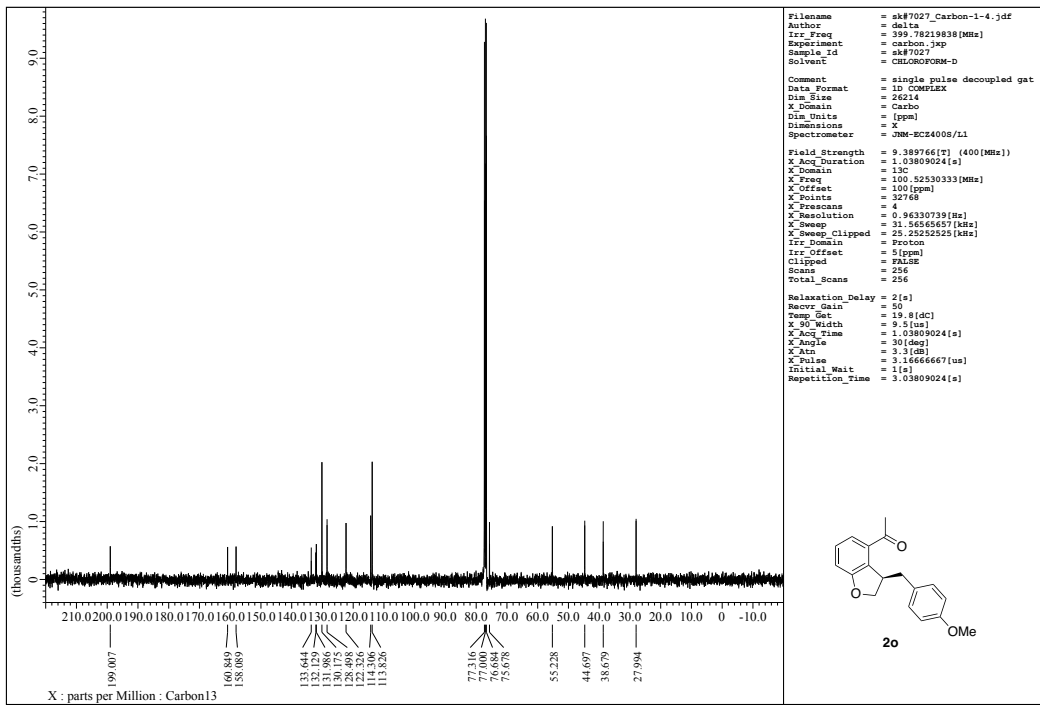
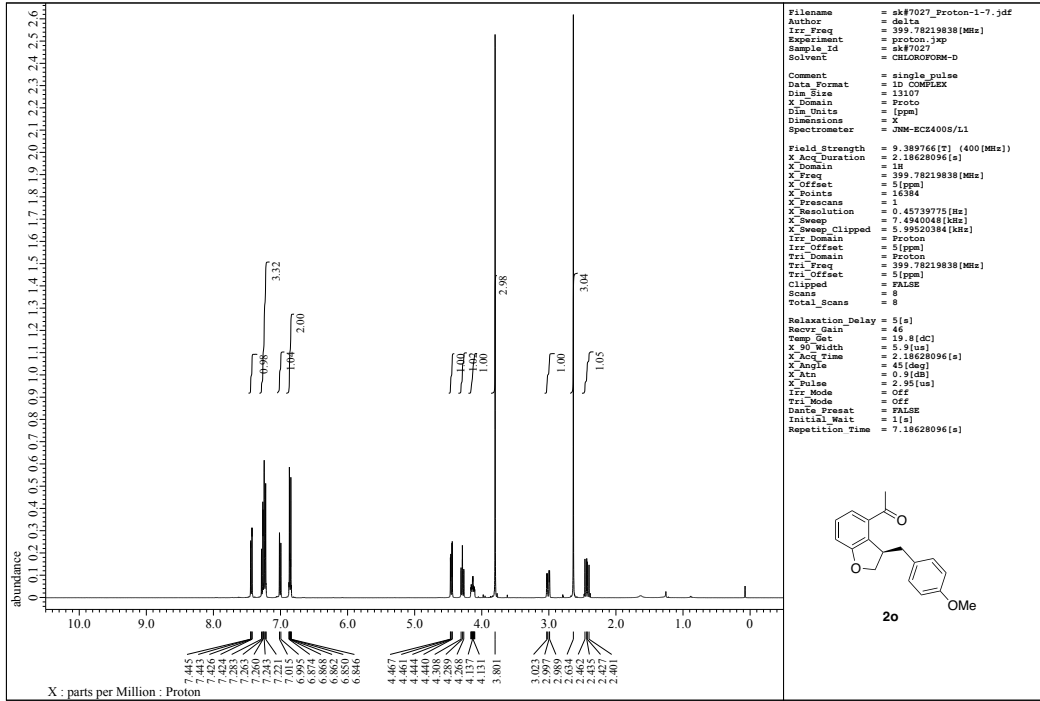
Totals		3393840	100.000	94422
--------	--	---------	---------	-------



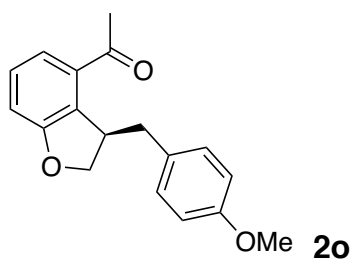
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	22.067	1255236	49.909	42615
2	24.532	1259823	50.091	36901

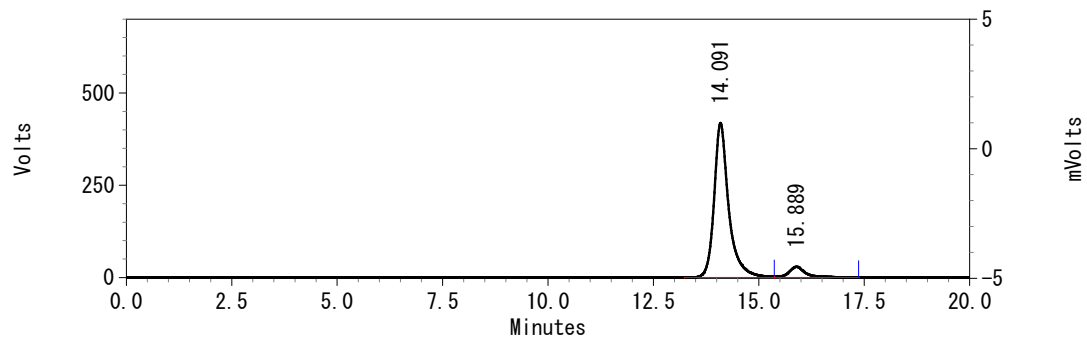
Totals		2515059	100.000	79516
--------	--	---------	---------	-------





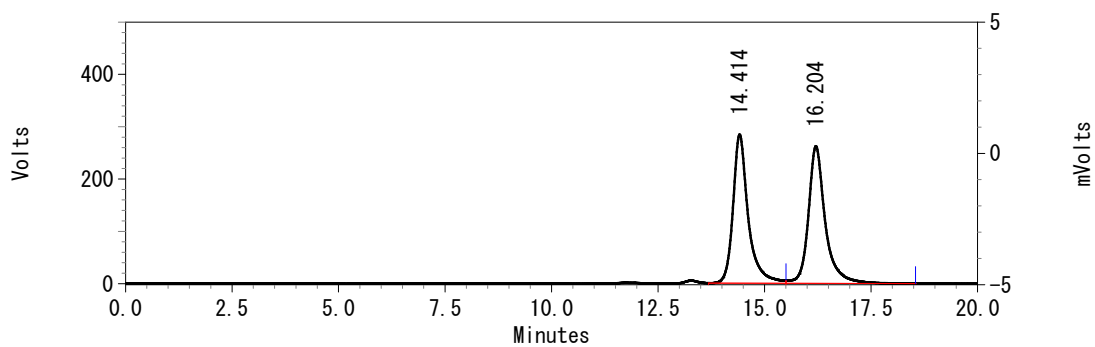


(Scheme 3)



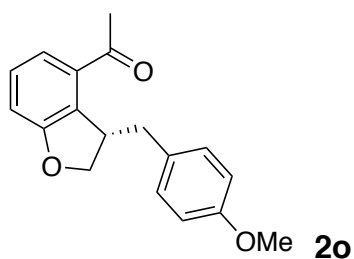
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	14.091	10069190	92.625	418629
2	15.889	801769	7.375	29035
Totals		10870959	100.000	447664

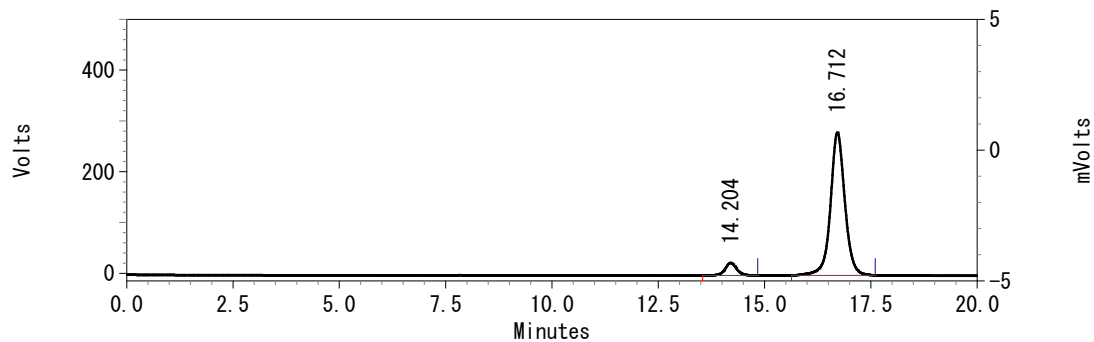


**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	14.414	7056671	49.462	284308
2	16.204	7210077	50.538	262324
Totals		14266748	100.000	546632



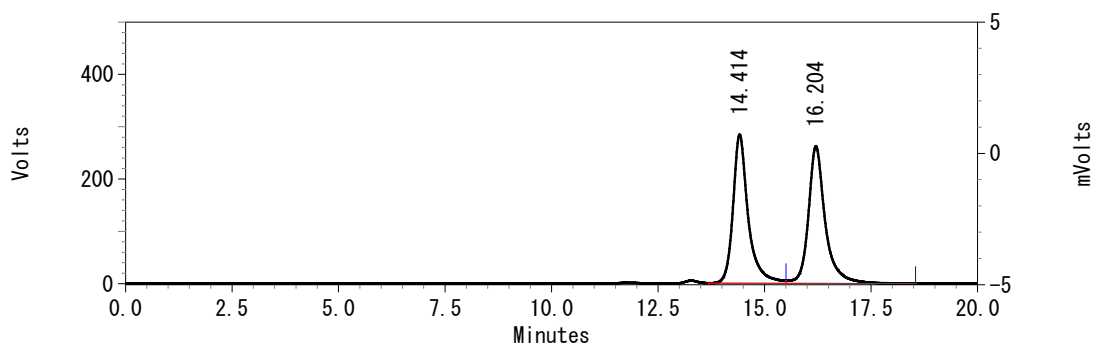
(Scheme 10)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	14.204	475678	6.689	24801
2	16.712	6635694	93.311	281192

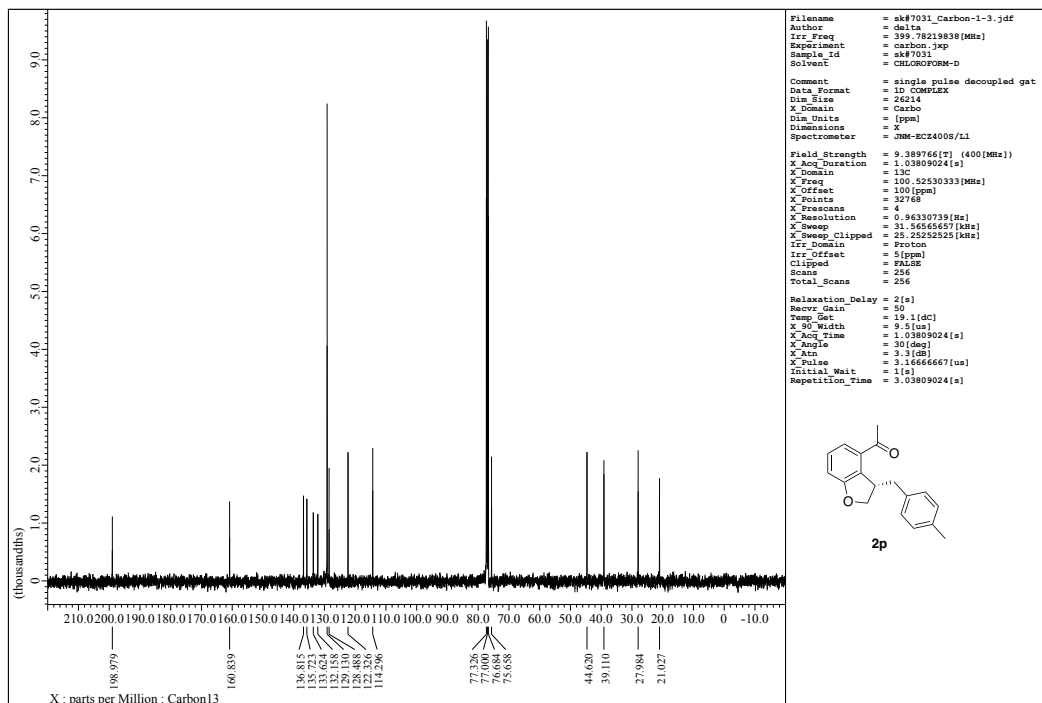
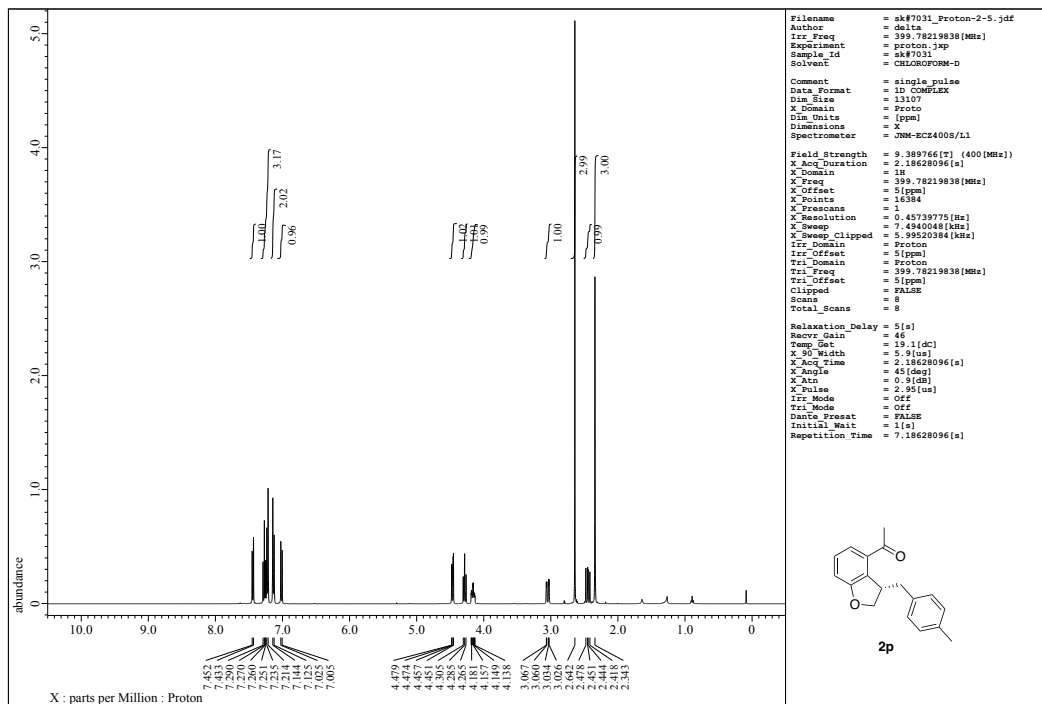
Totals		7111372	100.000	305993
--------	--	---------	---------	--------

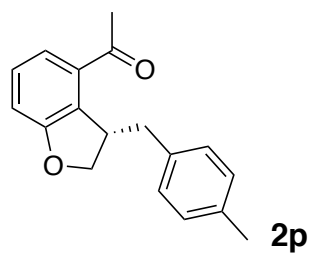


**UV Results**

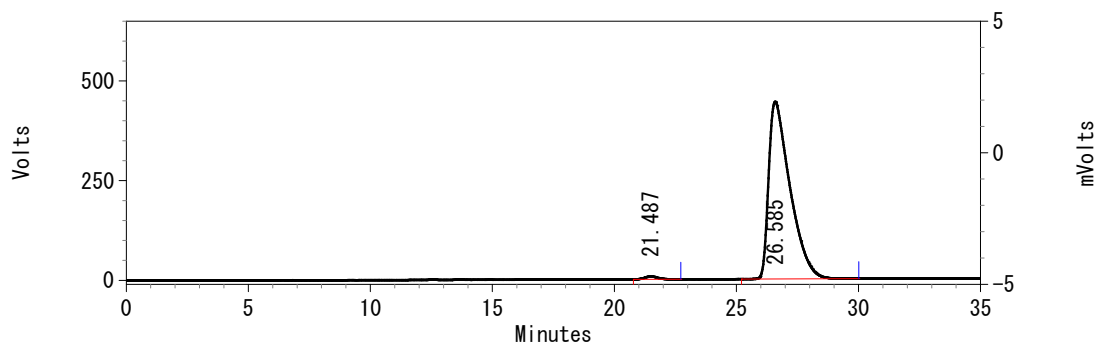
Pk #	Retention Time	Area	Area Percent	Height
1	14.414	7056671	49.462	284308
2	16.204	7210077	50.538	262324

Totals		14266748	100.000	546632
--------	--	----------	---------	--------



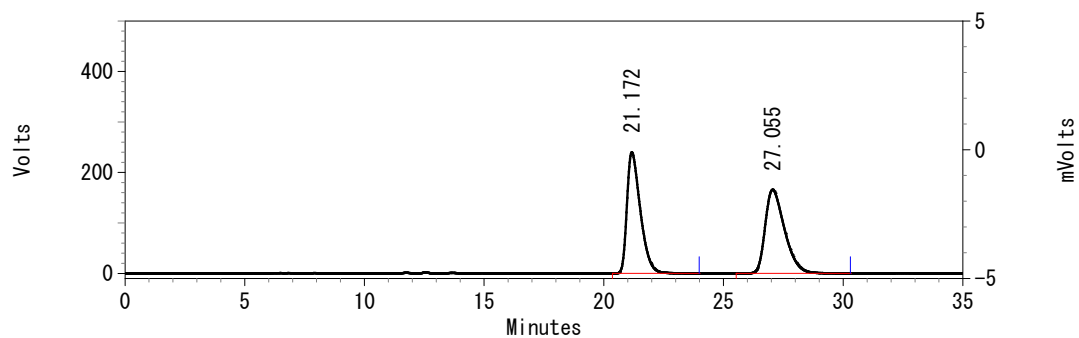


(Scheme 3)



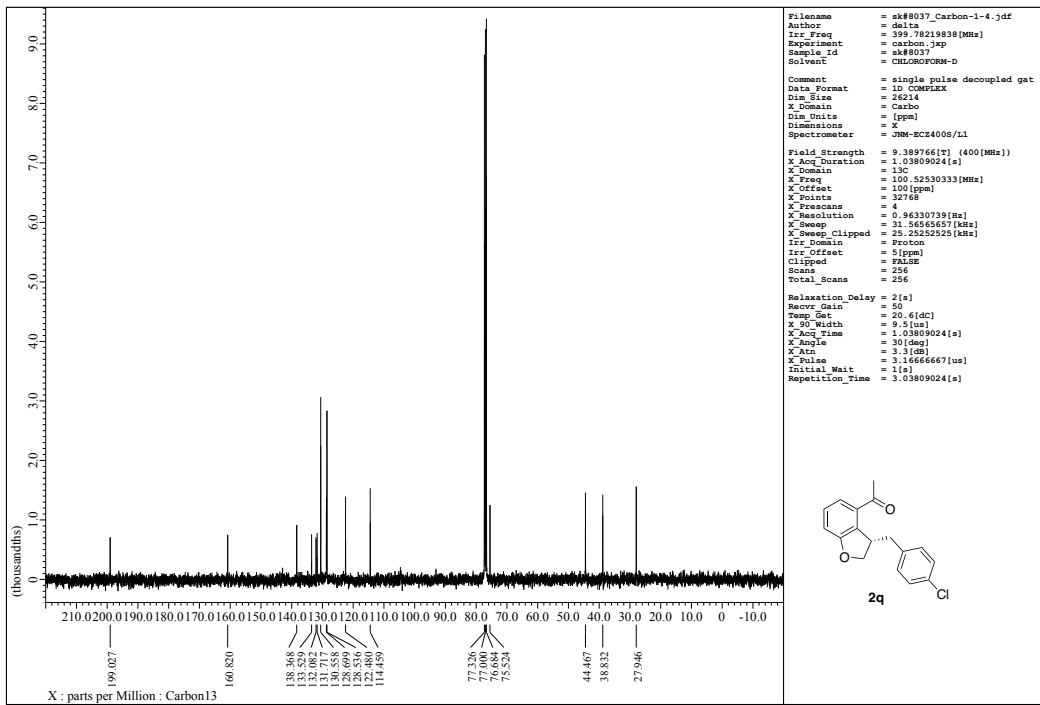
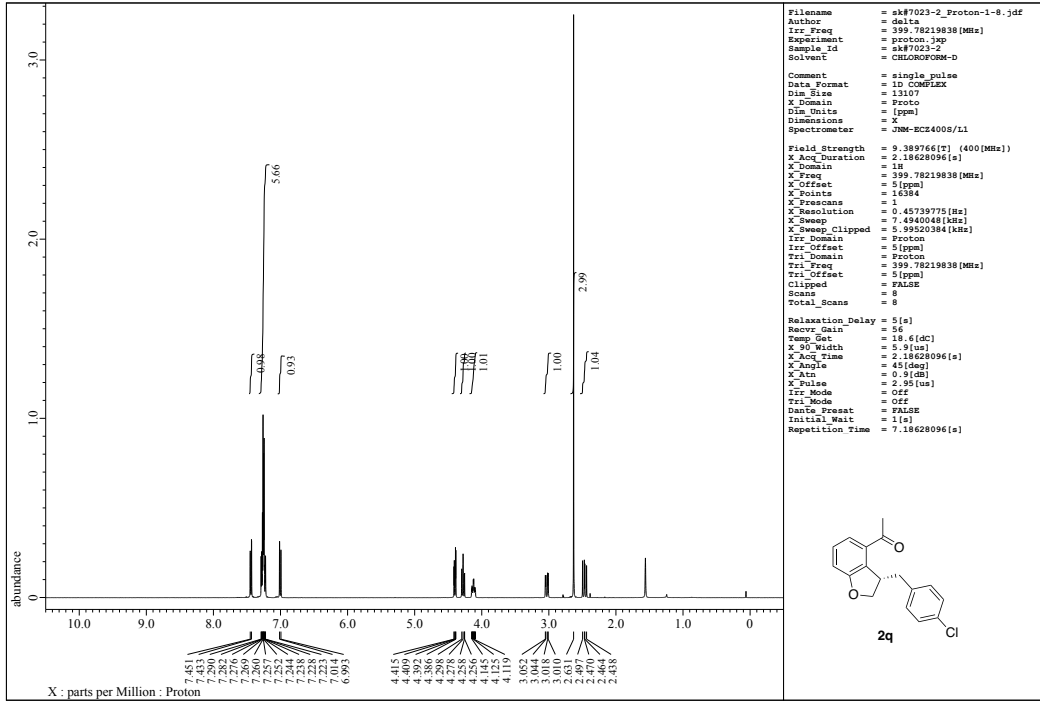
**UV Results**

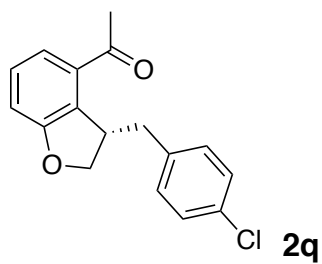
Pk #	Retention Time	Area	Area Percent	Height
1	21.487	266836	0.979	7264
2	26.585	26996289	99.021	444525
Totals		27263125	100.000	451789



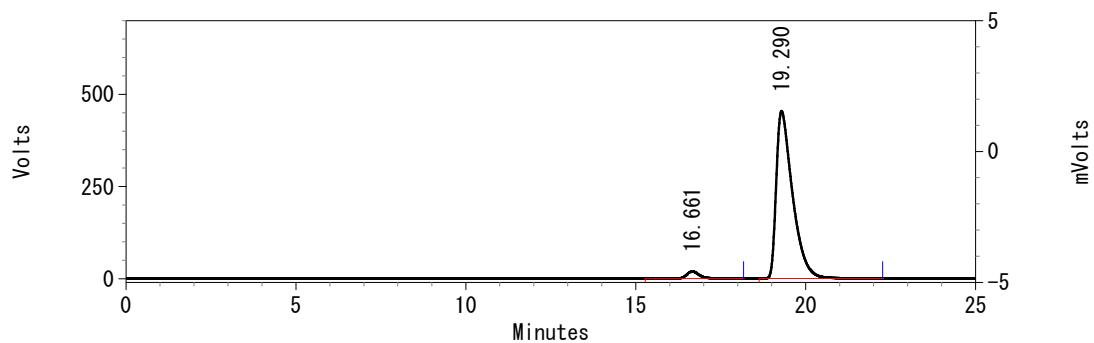
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	21.172	9316071	50.014	240052
2	27.055	9310784	49.986	165843
Totals		18626855	100.000	405895





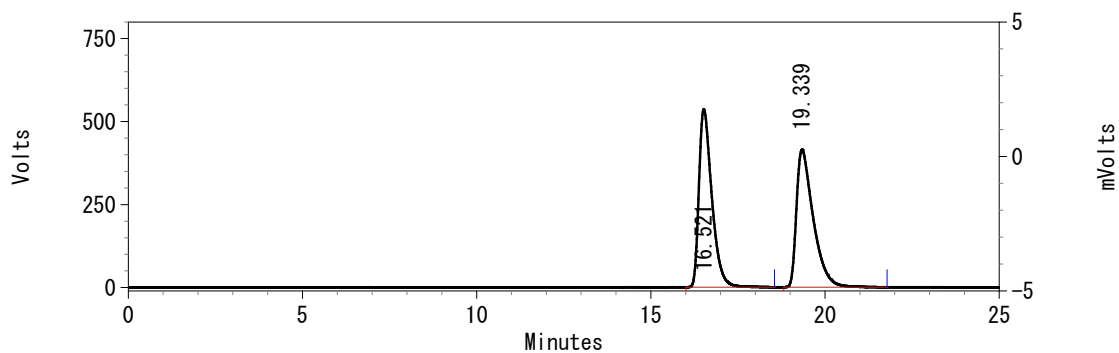
(Scheme 3)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	16.661	484837	3.111	19093
2	19.290	15098542	96.889	454181

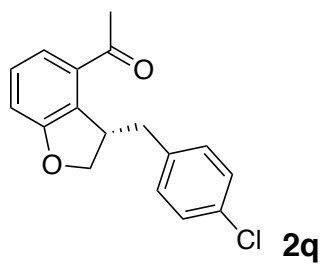
Totals		15583379	100.000	473274
--------	--	----------	---------	--------



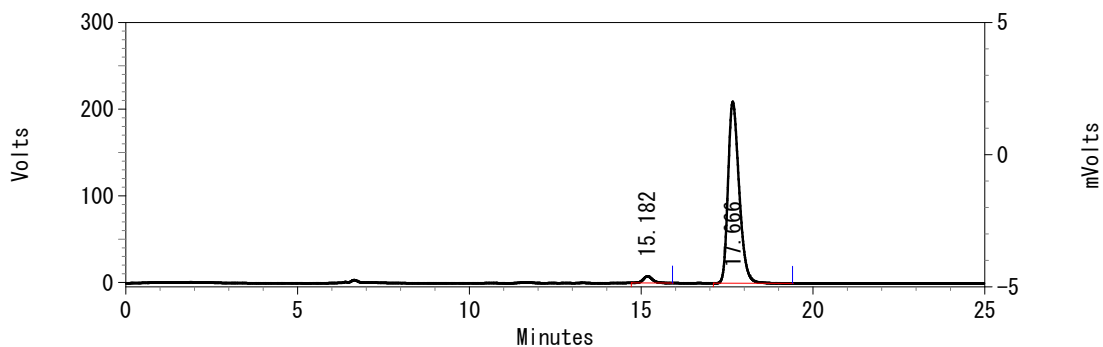
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	16.521	13789777	49.962	536355
2	19.339	13810607	50.038	414284

Totals		27600384	100.000	950639
--------	--	----------	---------	--------



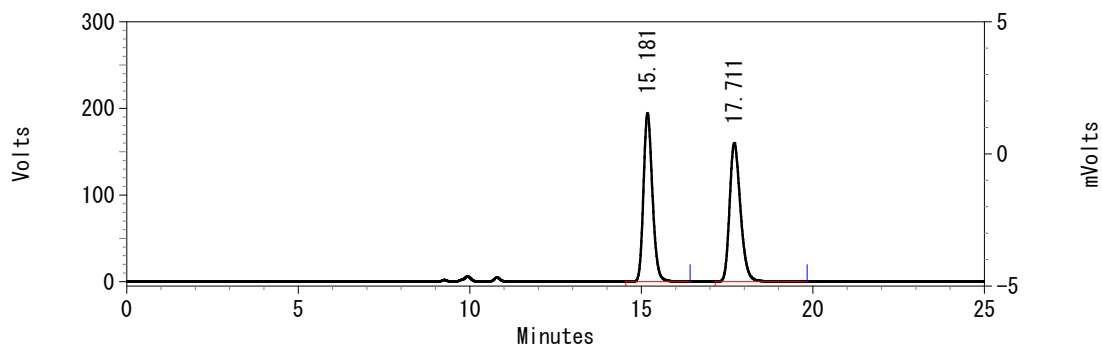
(Scheme 10)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	15.182	143541	2.967	7603
2	17.666	4694530	97.033	209446

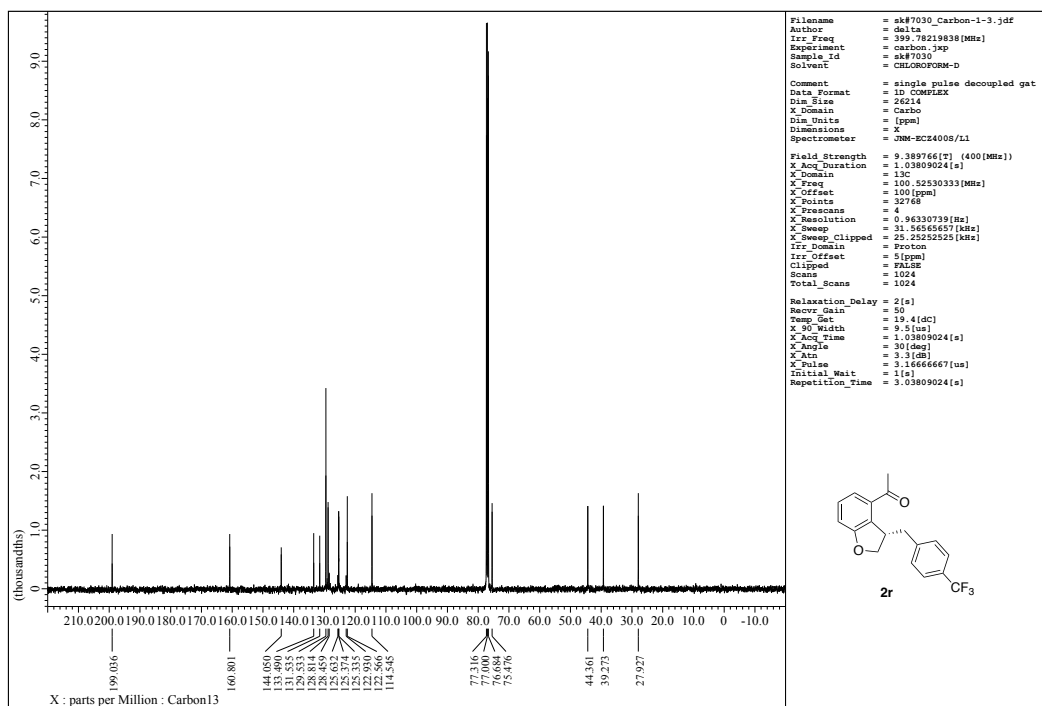
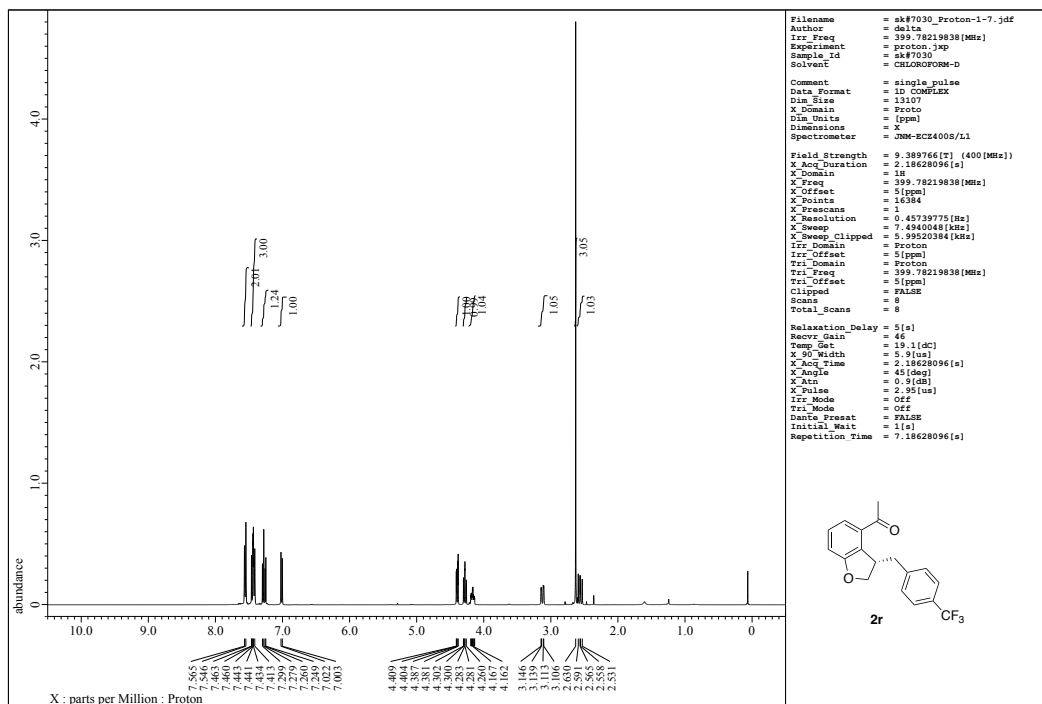
Totals		4838071	100.000	217049
--------	--	---------	---------	--------



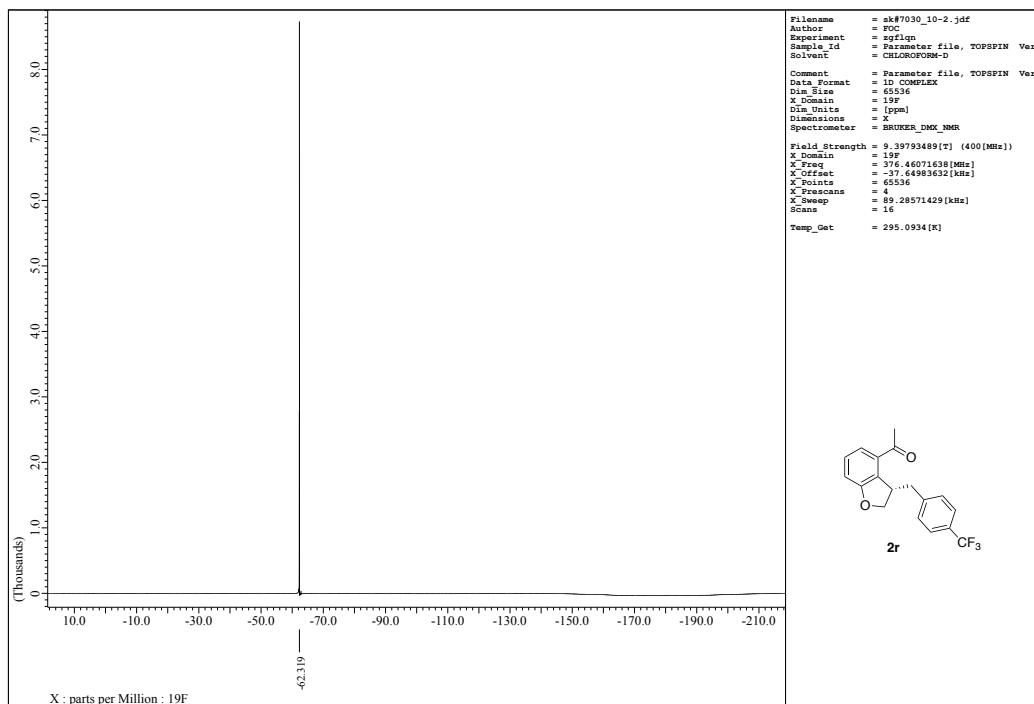
**UV Results**

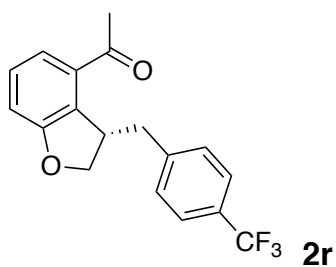
Pk #	Retention Time	Area	Area Percent	Height
1	15.181	3519584	49.903	194419
2	17.711	3533249	50.097	159882

Totals		7052833	100.000	354301
--------	--	---------	---------	--------

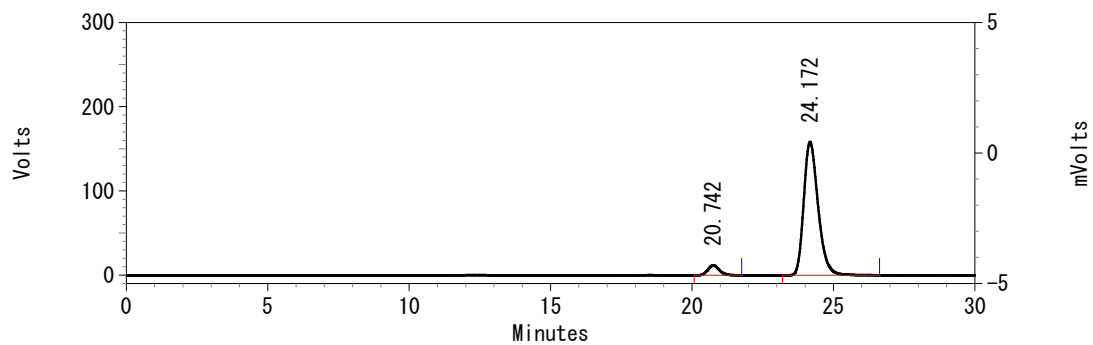








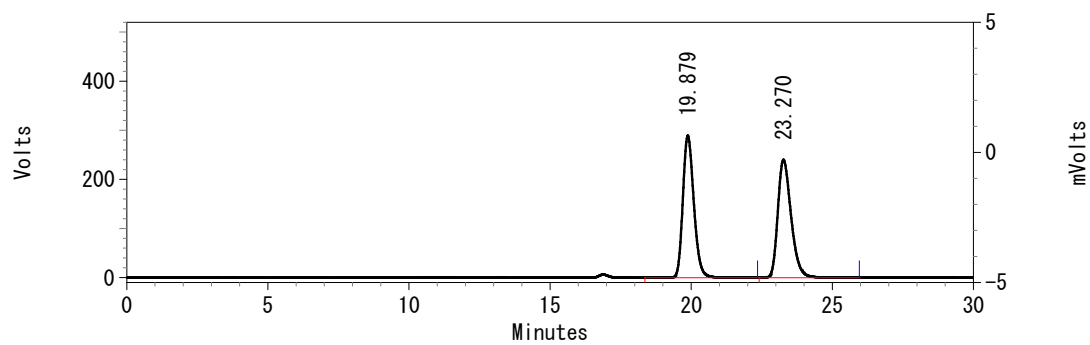
(Scheme 3)



**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	20.742	333375	5.632	11832
2	24.172	5585909	94.368	158443

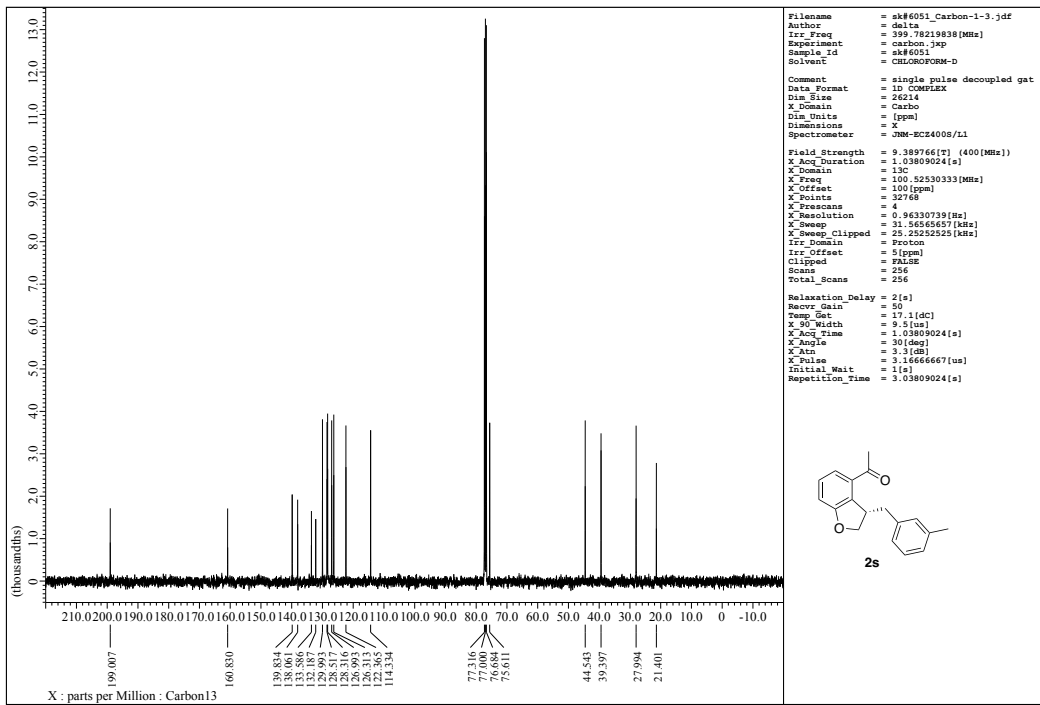
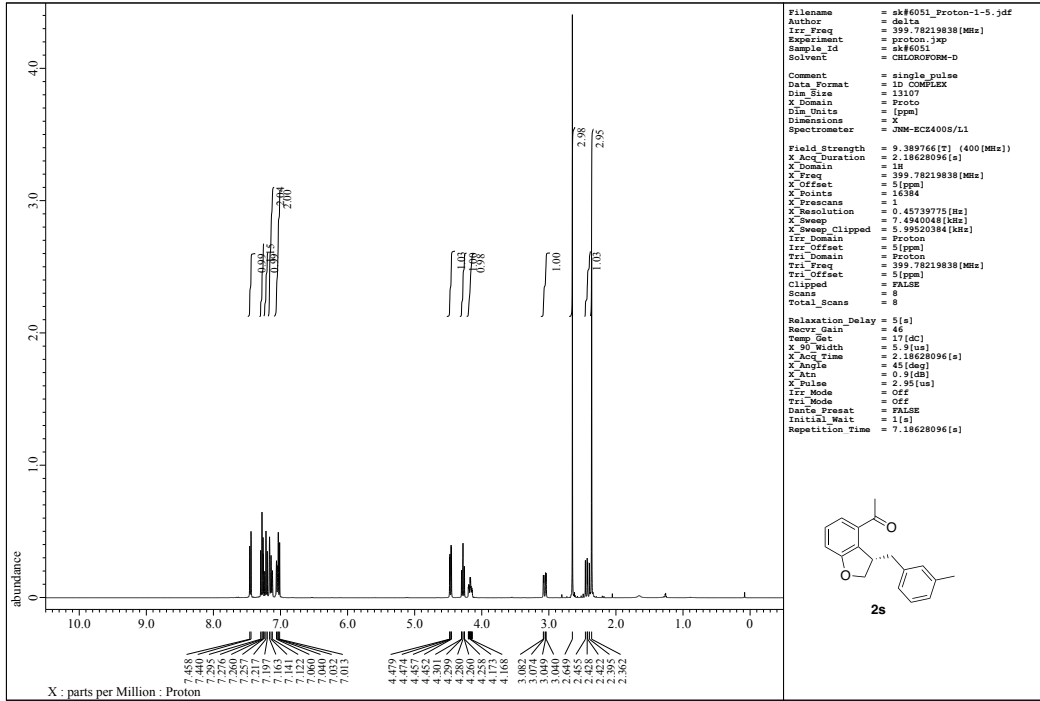
Totals		5919284	100.000	170275
--------	--	---------	---------	--------

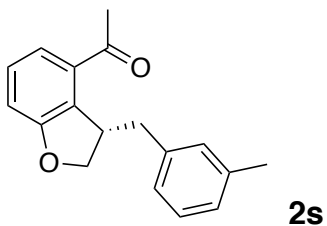


**UV-970 Results**

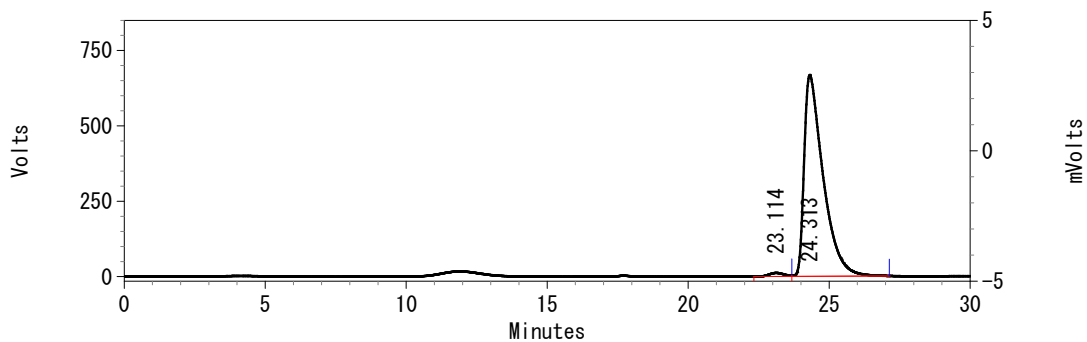
Pk #	Retention Time	Area	Area Percent	Height
1	19.879	7822832	49.888	289468
2	23.270	7858098	50.112	240266

Totals		15680930	100.000	529734
--------	--	----------	---------	--------



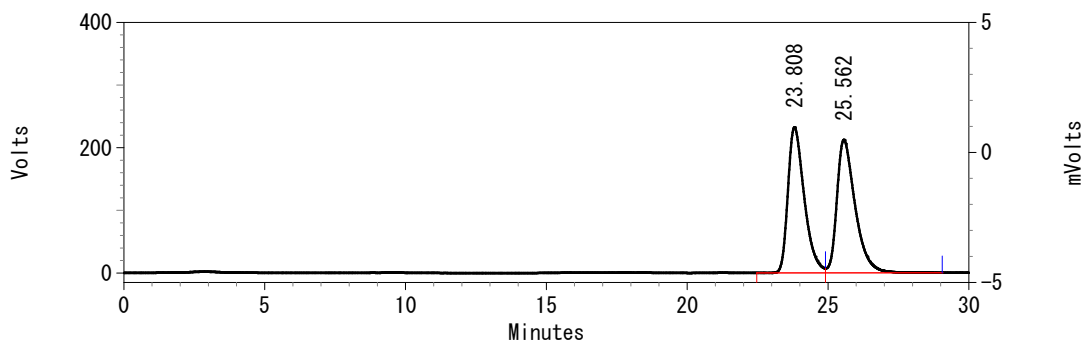


(Scheme 3)



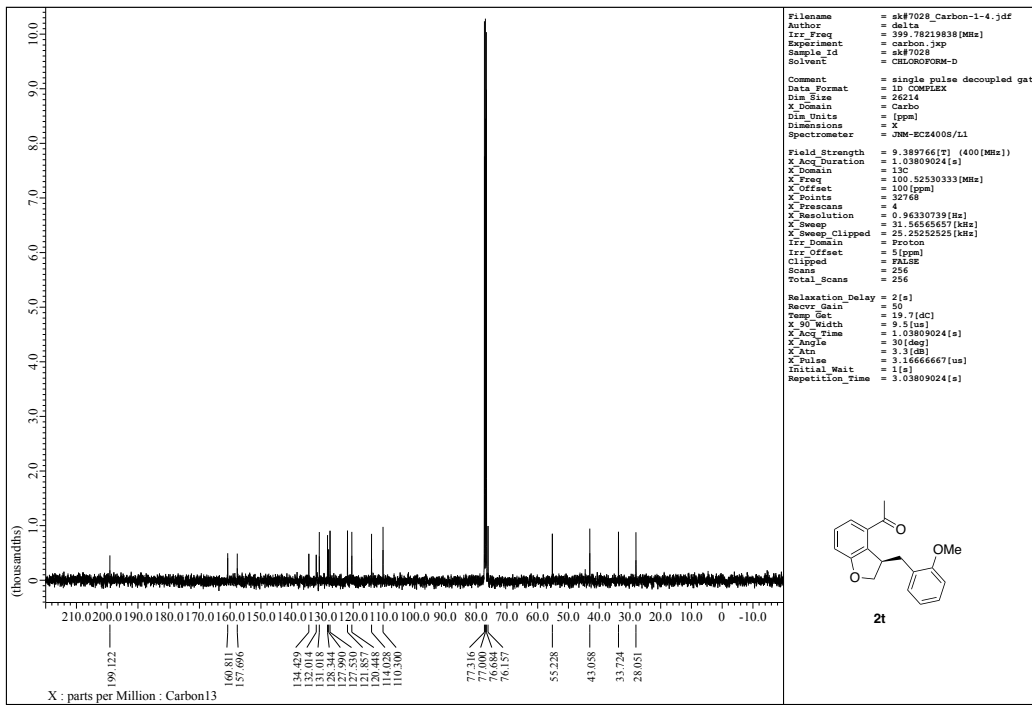
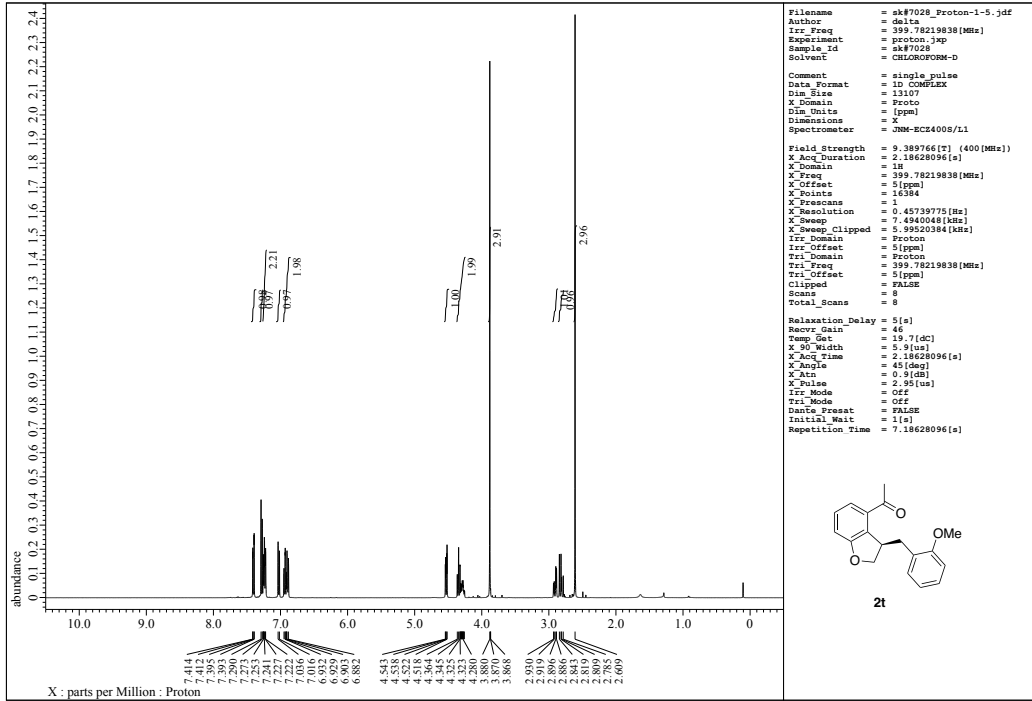
**UV Results**

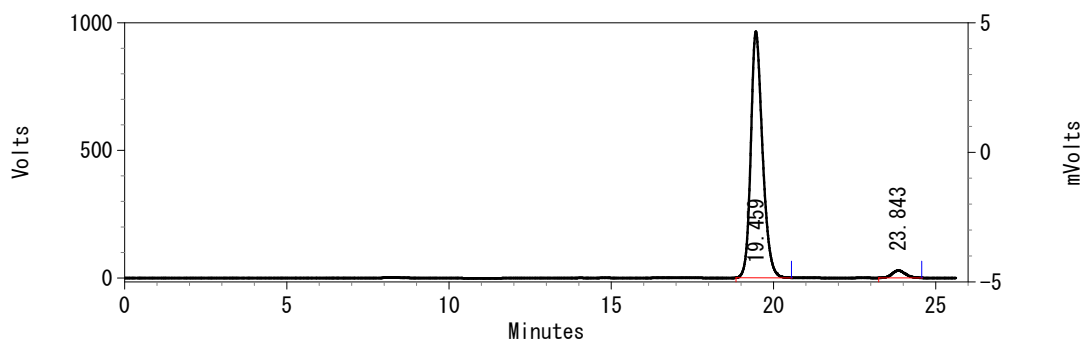
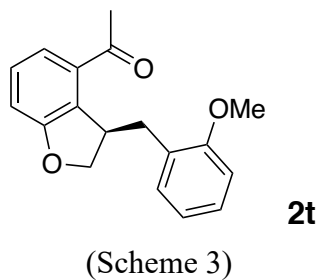
Pk #	Retention Time	Area	Area Percent	Height
1	23.114	441230	1.393	11865
2	24.313	31223949	98.607	667666
Totals		31665179	100.000	679531



**UV Results**

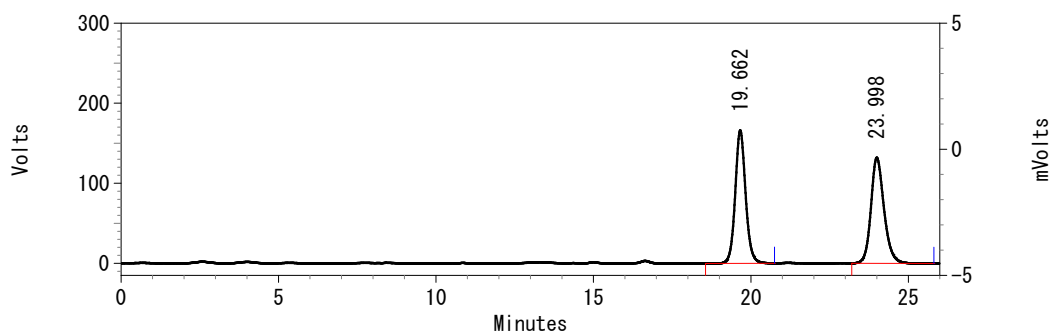
Pk #	Retention Time	Area	Area Percent	Height
1	23.808	9362515	49.402	232537
2	25.562	9589191	50.598	212411
Totals		18951706	100.000	444948





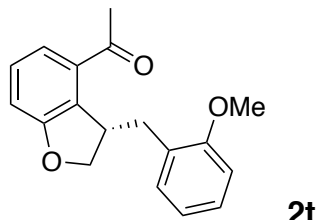
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	19.459	24188573	96.648	964630
2	23.843	838882	3.352	29062
Totals		25027455	100.000	993692

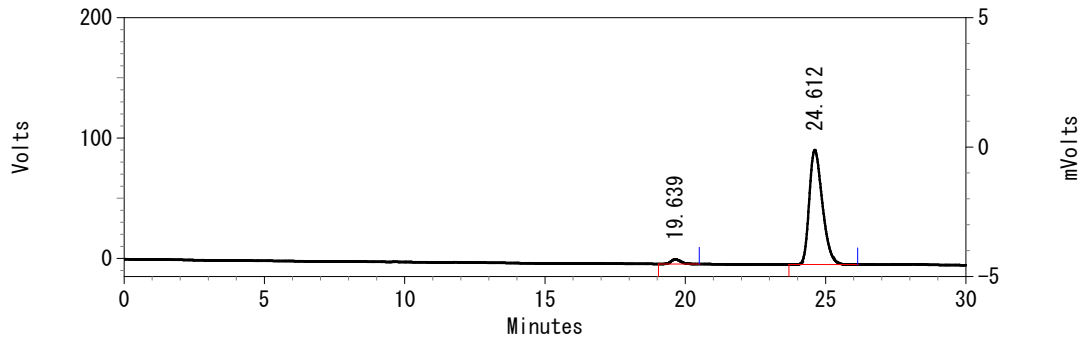


**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	19.662	3809943	49.994	166187
2	23.998	3810916	50.006	132125
Totals		7620859	100.000	298312

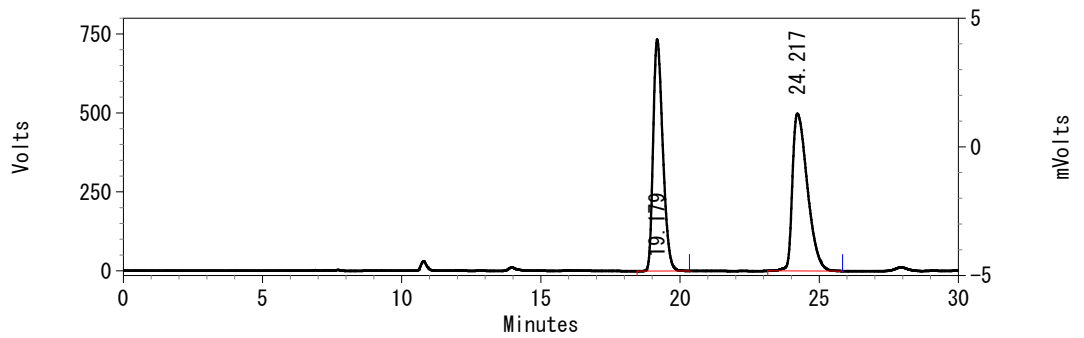


(Scheme 10)



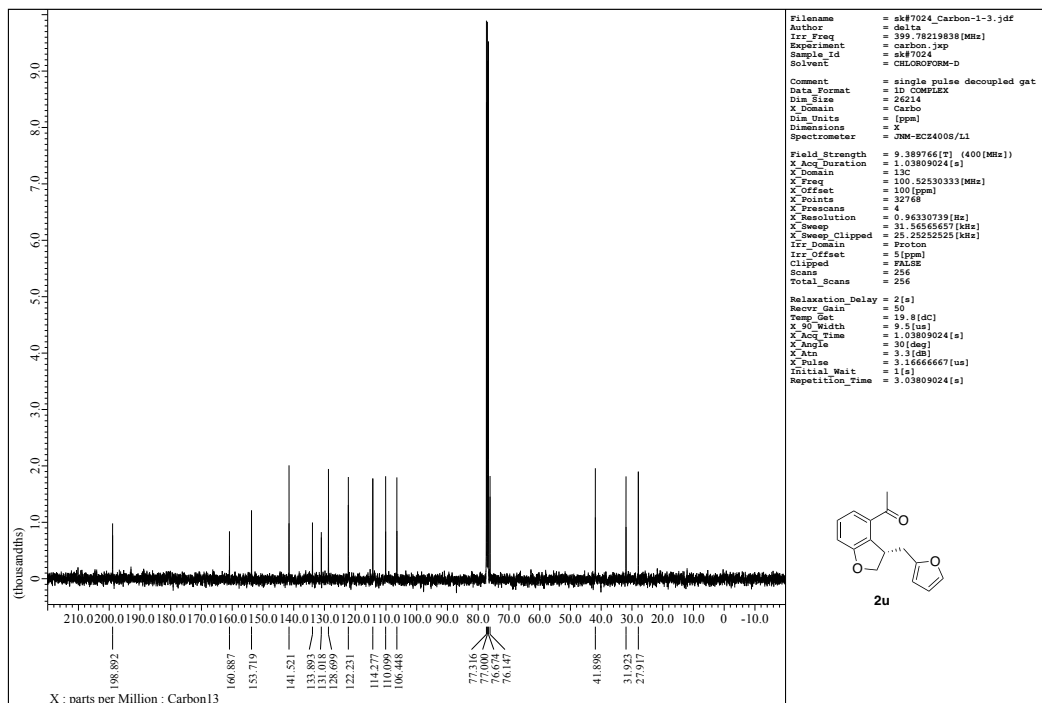
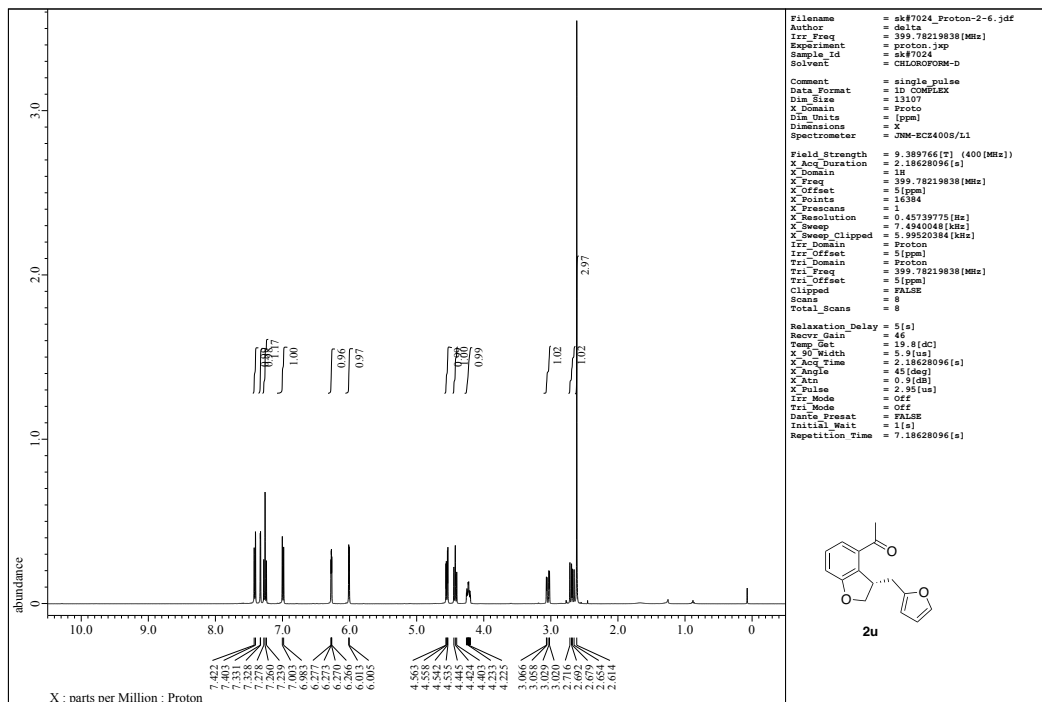
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	19.639	93087	2.921	3871
2	24.612	3093808	97.079	95077
Totals		3186895	100.000	98948

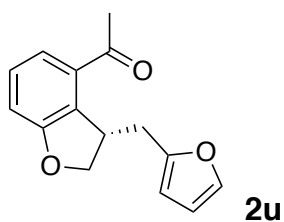


**UV Results**

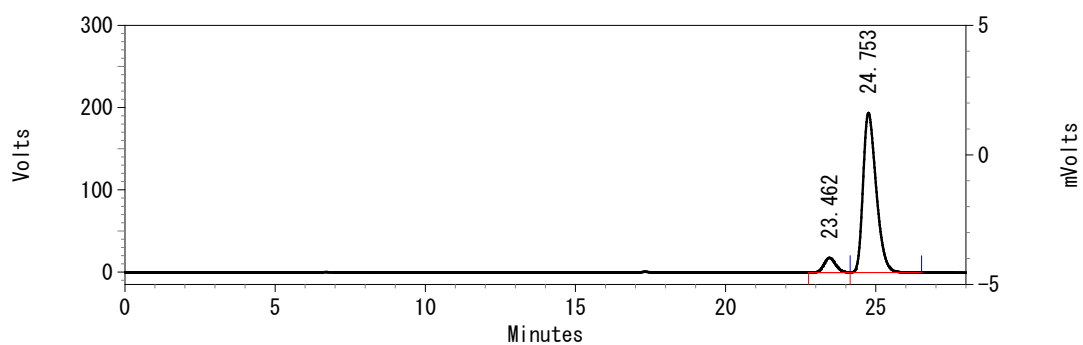
Pk #	Retention Time	Area	Area Percent	Height
1	19.179	17652635	48.634	733686
2	24.217	18644391	51.366	498123
Totals		36297026	100.000	1231809





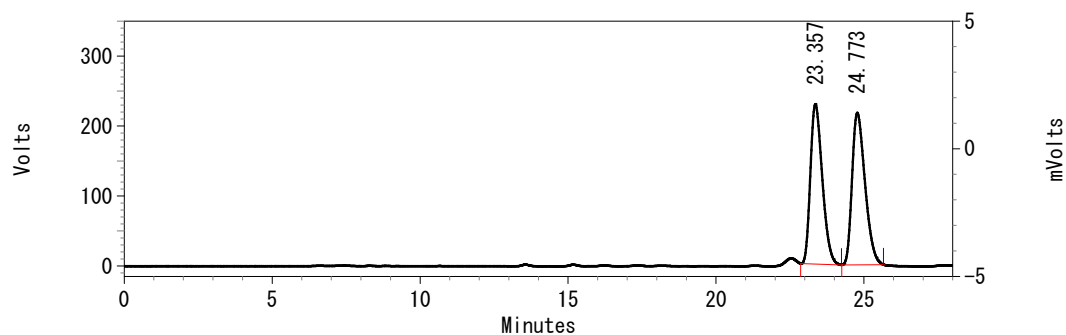


(Scheme 3)



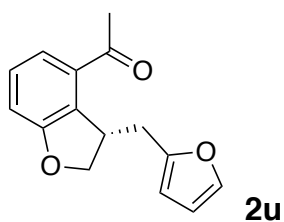
**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	23.462	488177	7.645	17885
2	24.753	5897678	92.355	194061
Totals		6385855	100.000	211946

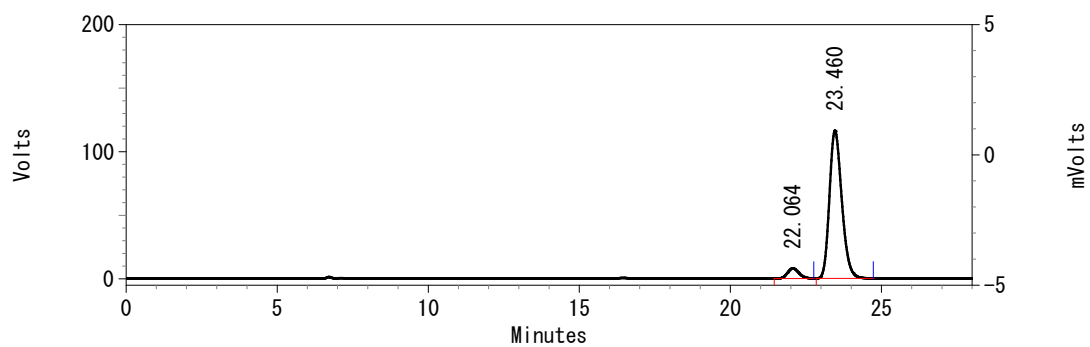


**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	23.357	6389183	49.125	228595
2	24.773	6616891	50.875	217309
Totals		13006074	100.000	445904



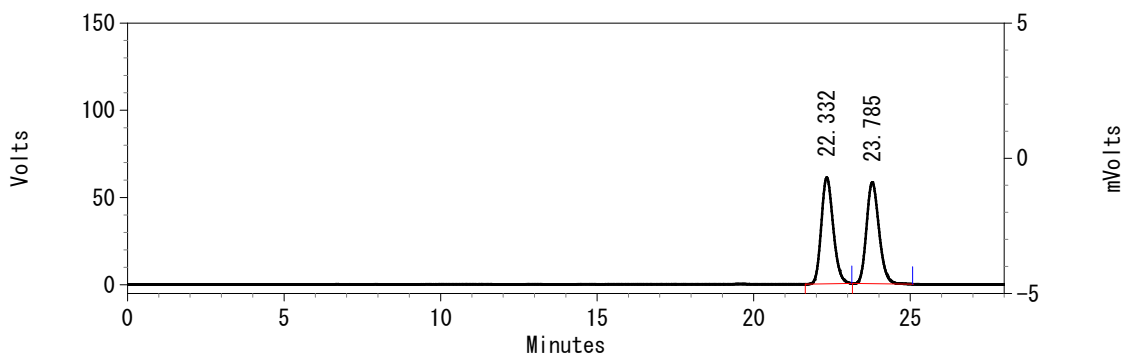
(Scheme 10)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	22.064	211831	6.028	8070
2	23.460	3302311	93.972	116348

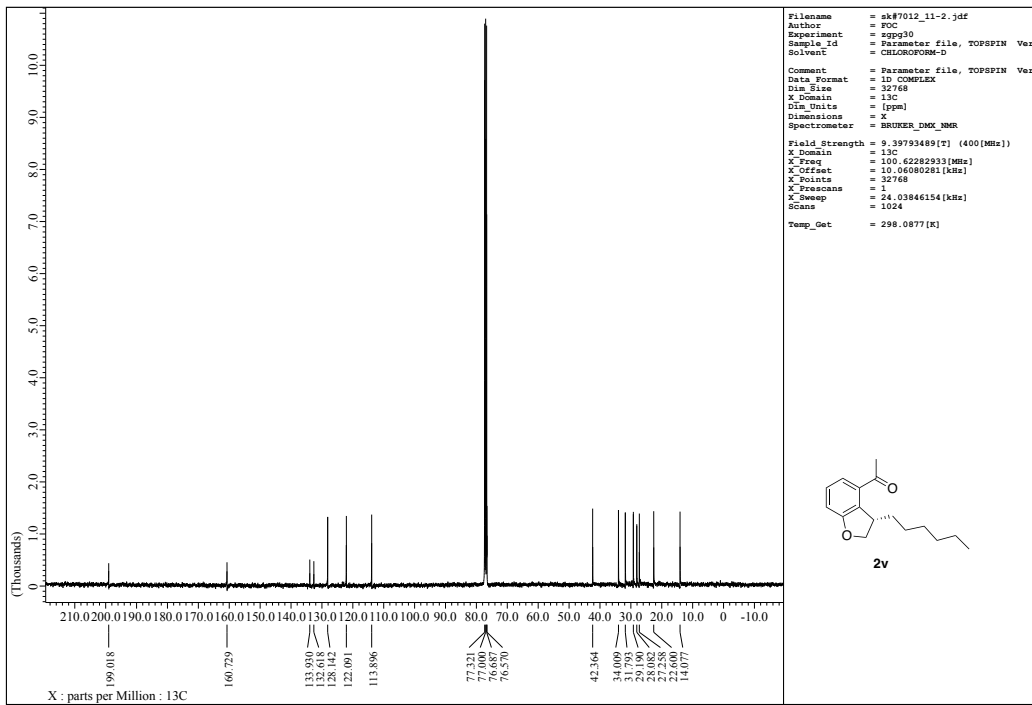
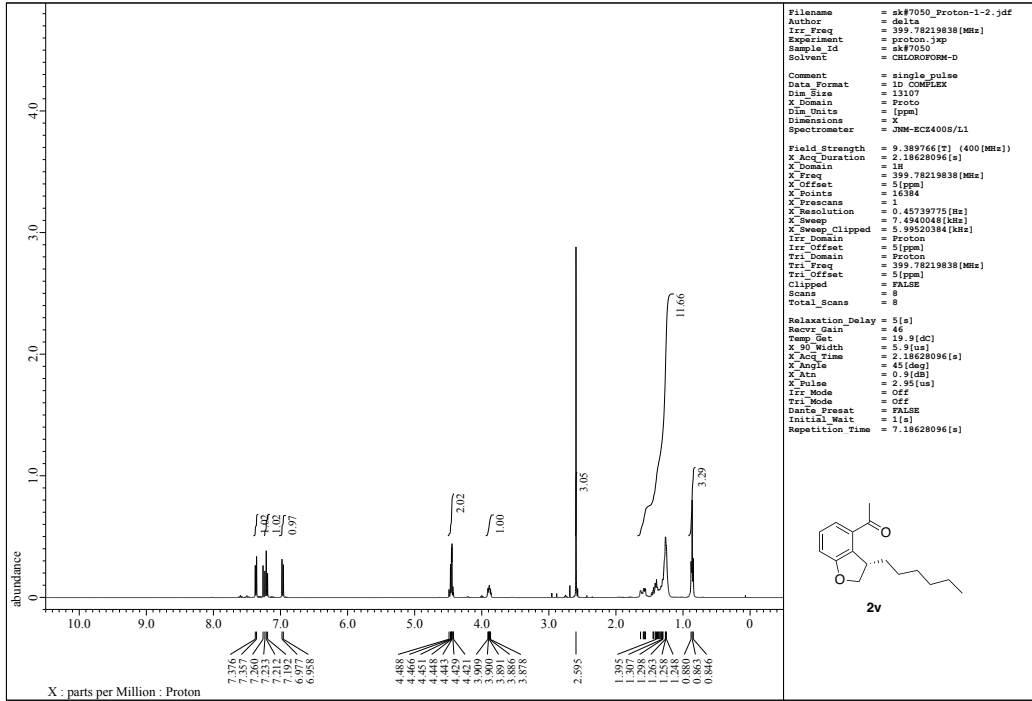
Totals		3514142	100.000	124418
--------	--	---------	---------	--------

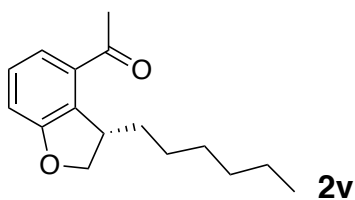


**UV Results**

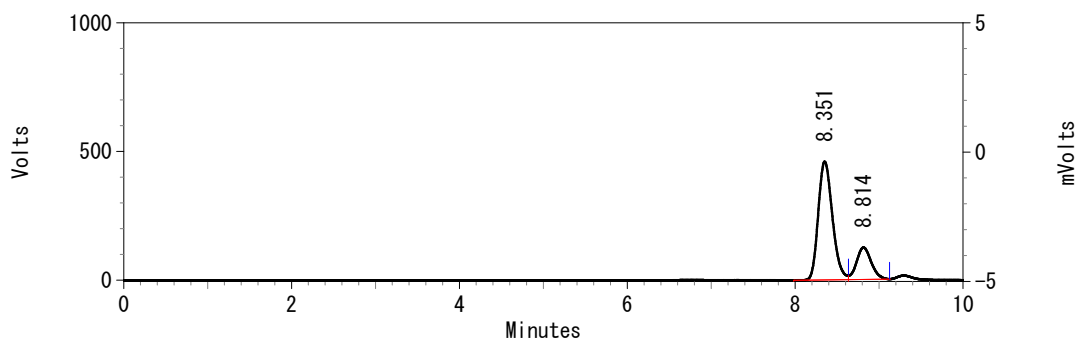
Pk #	Retention Time	Area	Area Percent	Height
1	22.332	1610855	49.940	61035
2	23.785	1614727	50.060	58165

Totals		3225582	100.000	119200
--------	--	---------	---------	--------





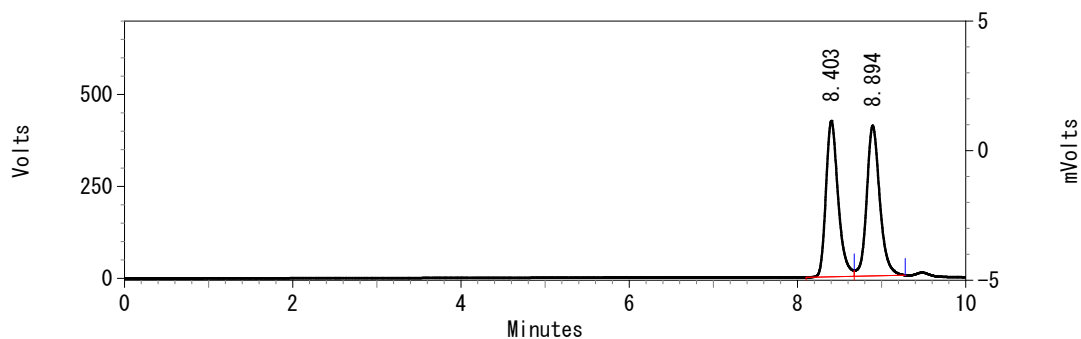
(Scheme 3)



**UV-970 Results**

Pk #	Retention Time	Area	Area Percent	Height
1	8.351	5377585	78.104	459298
2	8.814	1507587	21.896	123896

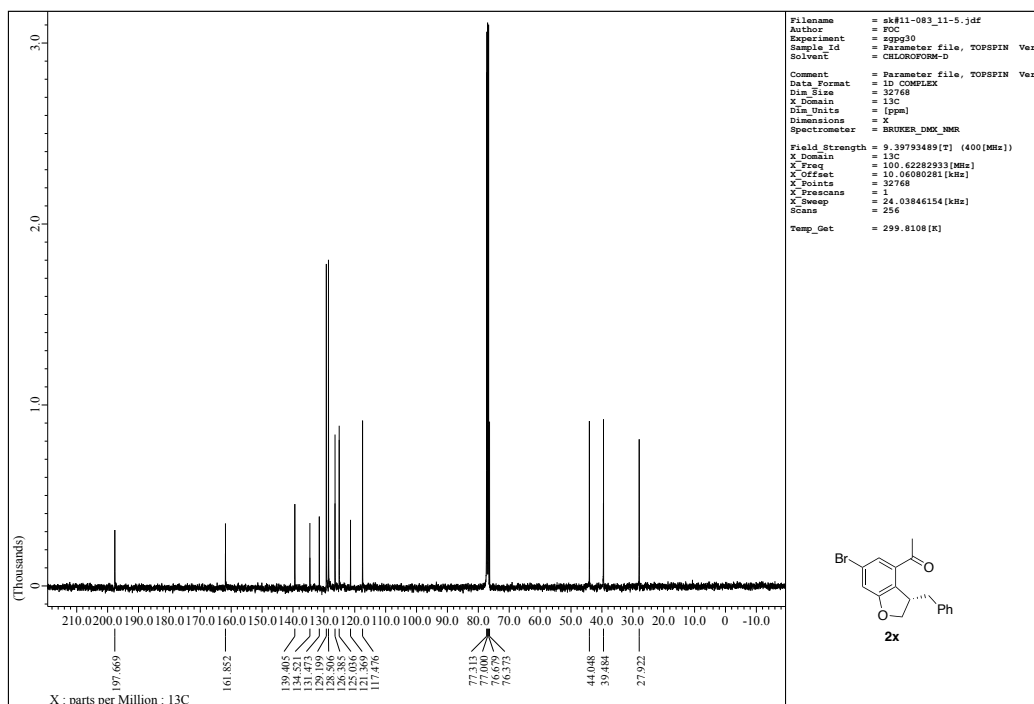
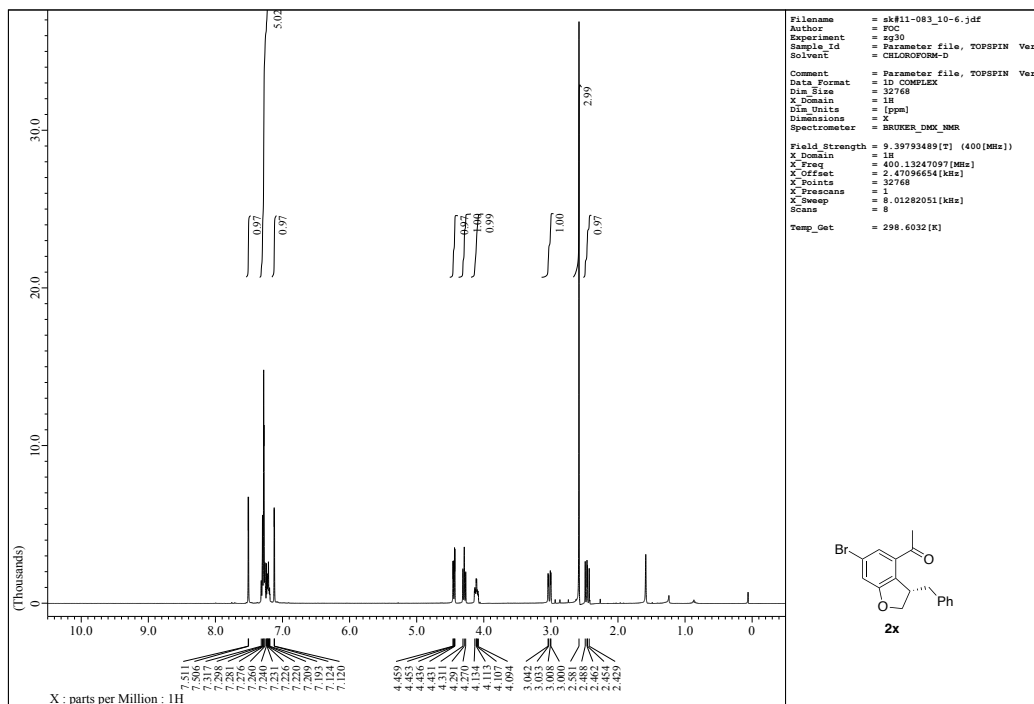
Totals		6885172	100.000	583194
--------	--	---------	---------	--------

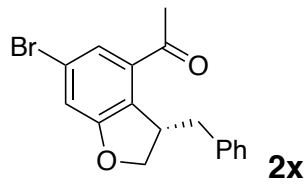


**UV Results**

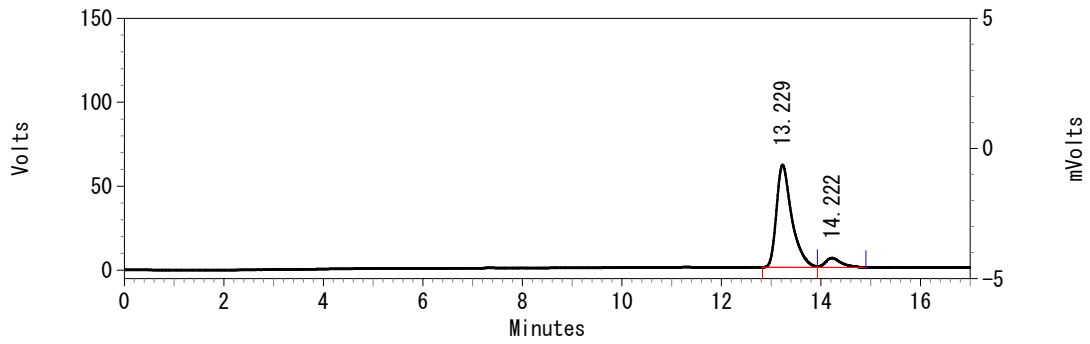
Pk #	Retention Time	Area	Area Percent	Height
1	8.403	4259015	49.115	423968
2	8.894	4412431	50.885	408815

Totals		8671446	100.000	832783
--------	--	---------	---------	--------



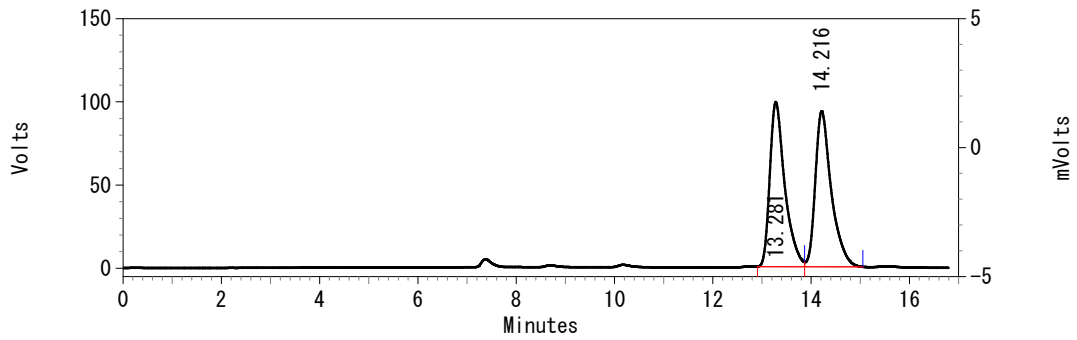


(Scheme 10)



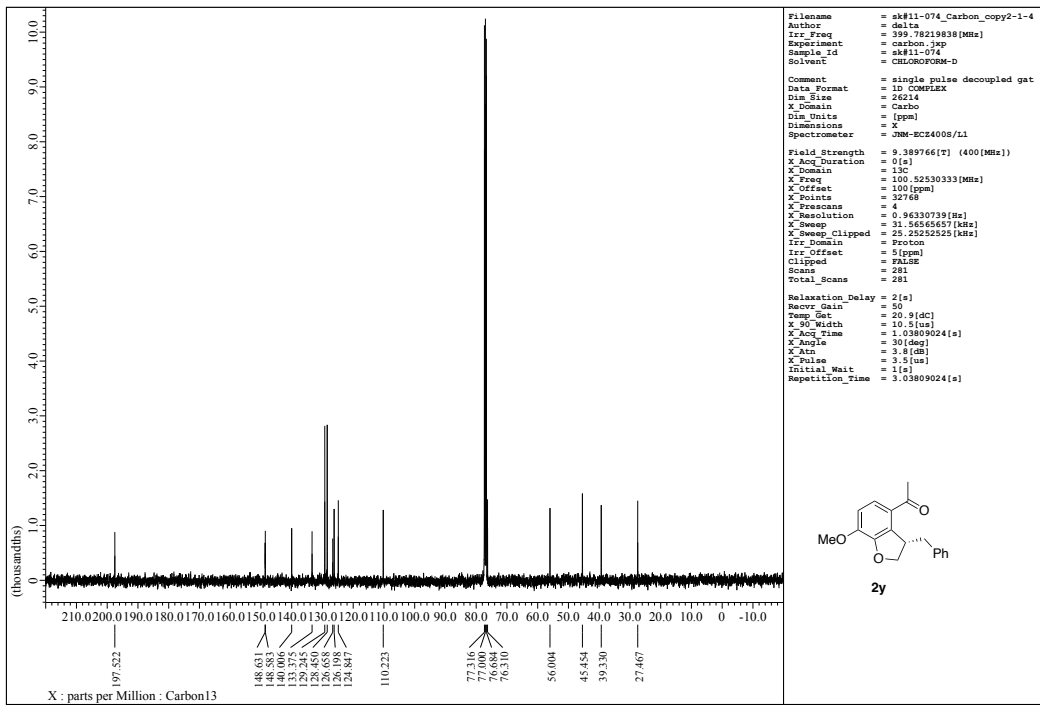
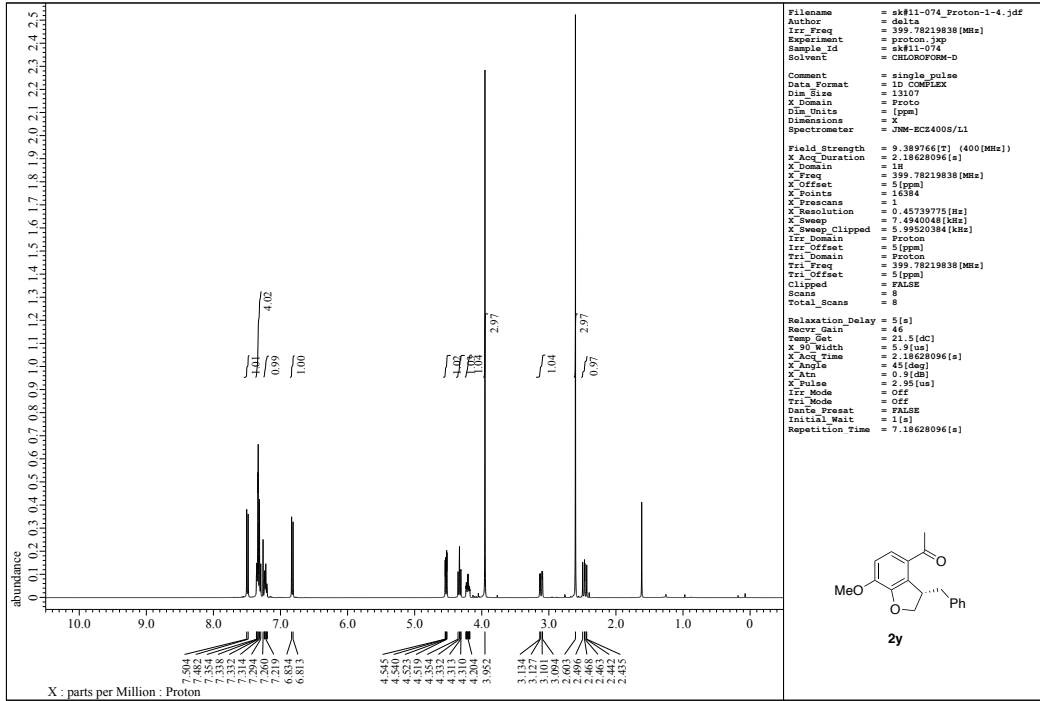
**UV Results**

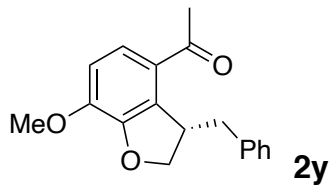
Pk #	Retention Time	Area	Area Percent	Height
1	13.229	1302953	91.263	61010
2	14.222	124731	8.737	5578
Totals		1427684	100.000	66588



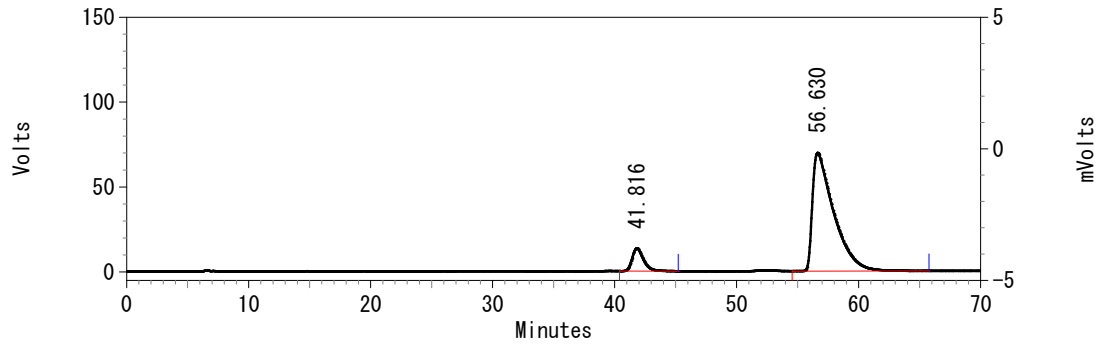
**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	13.281	2096377	49.728	98991
2	14.216	2119332	50.272	93533
Totals		4215709	100.000	192524





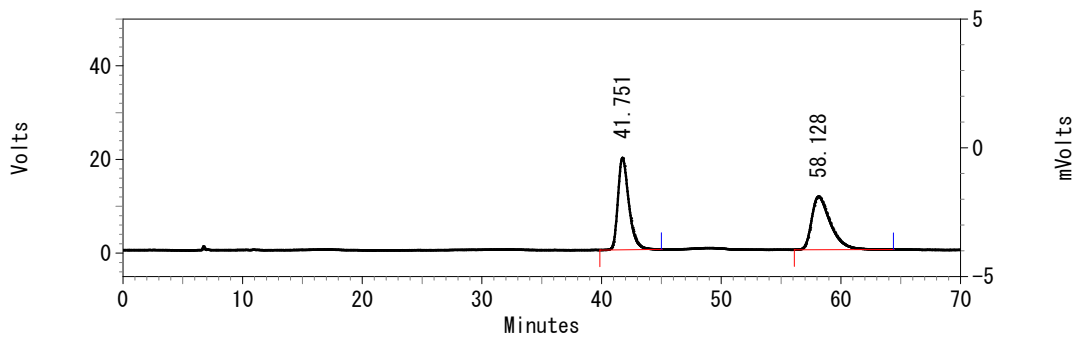
(Scheme 10)



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	41.816	858958	9.255	13433
2	56.630	8422550	90.745	69658

Totals		9281508	100.000	83091
--------	--	---------	---------	-------



**UV Results**

Pk #	Retention Time	Area	Area Percent	Height
1	41.751	1244152	50.226	19644
2	58.128	1232974	49.774	11337

Totals		2477126	100.000	30981
--------	--	---------	---------	-------



