Electronic Supplementary Material (ESI) for RSC Advances.

Synthesis of functionalized γ-lactones via a three-component cascade reaction catalyzed by consecutive N-heterocyclic carbene systems

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Supporting Information

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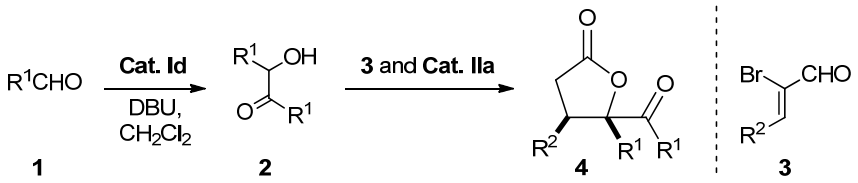
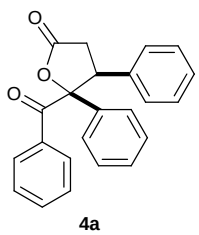
1. General methods

NMR data was obtained for ^{1}H at 400 MHz, and for ^{13}C at 100 MHz. Chemical shifts were reported in ppm from tetramethylsilane with the solvent resonance as the internal standard in $CDCl_3$ solution. ESI HRMS was performed on a Waters SYNAPT G2. Column chromatography was performed on silica gel (200-300 mesh) using an eluent of ethyl acetate and petroleum ether. TLC was performed on glass-backed silica plates; products were visualized using UV light and I_2. Melting points were determined on a Mel-Temp apparatus and were not corrected. All chemicals were used from Adamas-beta without purification unless otherwise noted.

2. General procedure for the synthesis of γ-lactone 4



The reaction was carried out with precatalyst **Id** (0.1 mmol), DBU (0.3 mmol) and aldehyde **1** (1.6 mmol) in CH_2Cl_2 (2.0 mL) at 50 ^{o}C for a specified reaction time until the sufficient acyloin **2** was generated (monitored by TLC), after which precatalyst **IIa** (0.1 mmol) and 2-bromoenal **3** (0.4 mmol) were added in-situ. The reaction mixture was stirred until the reaction completed. Then the reaction mixture was concentrated and the residue was purified by flash chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) to give γ-lactone **4**.

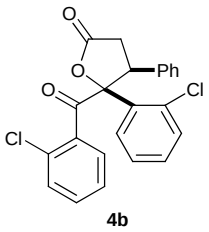


4a

4a was obtained as a white solid in 64% yield for two steps after flash chromatography. The dr value was calculated to be 90:10 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 139-140 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.90 (d, J = 7.6 Hz, 2H), 7.46-7.43 (m, 1H), 7.32-7.26 (m, 2H), 7.11-7.07 (m, 8H), 6.94 (s, 2H), 4.88 (t, J = 5.6 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.8 Hz, 1H), 2.88 (dd, J_1 = 18.0 Hz, J_2 = 3.2 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.29, 175.24, 137.31, 135.33, 133.59, 133.42, 130.95, 128.79, 128.45, 128.27, 128.19, 128.07, 127.26, 124.68,

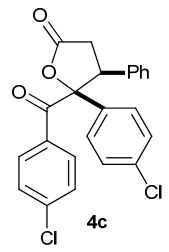
95.07, 47.94, 35.53 ppm; ESI HRMS: calcd. For $C_{23}H_{18}O_3$+Na 365.1154, found 365.1151.

For the minor diastereomer of **4a**, ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.81 (d, *J* = 7.6 Hz, 2H), 7.60 (d, *J* = 7.2 Hz, 2H), 7.47-7.40 (m, 4H), 7.30-7.24 (m, 5H), 7.18-7.17 (m, 2H), 4.17 (d, *J* = 7.6 Hz, 1H), 2.87 (dd, J_1 = 17.6 Hz, J_2 = 8.0 Hz, 1H), 2.58 (d, *J* = 17.2 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 197.48, 175.65, 140.13, 138.46, 136.14, 132.84, 129.40, 129.17, 128.97, 128.93, 128.01, 127.57, 127.49, 125.27, 95.85, 53.94, 36.43 ppm; ESI HRMS: calcd. For $C_{23}H_{18}O_3$+Na 365.1154, found 365.1156.



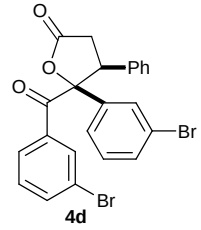
4b

4b was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 95:5 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 144-145 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.57 (d, *J* = 7.2 Hz, 1H), 7.39 (d, *J* = 7.6 Hz, 1H), 7.26-7.21 (m, 1H), 7.12-6.93 (m, 10H), 5.05 (d, *J* = 8.8 Hz, 1H), 3.62 (dd, J_1 = 18.0 Hz, J_2 = 9.2 Hz, 1H), 2.71 (d, *J* = 18.0 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.46, 175.25, 139.28, 134.30, 134.02, 133.48, 131.81, 131.11, 130.70, 129.80, 129.70, 129.32, 128.21, 127.93, 127.38, 126.77, 125.48, 94.29, 45.32, 37.97 ppm; ESI HRMS: calcd. For $C_{23}H_{16}Cl_2O_3$+Na 433.0374, found 433.0370.



4c

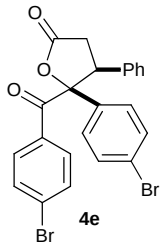
4c was obtained as a white solid in 68% yield for two steps after flash chromatography. The dr value was calculated to be 88:15 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 114-115 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.84 (d, *J* = 8.4 Hz, 2H), 7.31-7.29 (m, 2H), 7.11-7.09 (m, 5H), 6.98-6.93 (m, 4H), 4.85 (dd, J_1 = 8.0 Hz, J_2 = 5.6 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.87 (dd, J_1 = 18.0 Hz, J_2 = 5.6 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.84, 174.65, 140.29, 136.89, 134.49, 133.76, 132.27, 131.61, 128.79, 128.76, 128.63, 128.35, 127.62, 126.07, 94.48, 47.75, 35.38 ppm; ESI HRMS: calcd. For $C_{23}H_{16}Cl_2O_3$+Na 433.0374, found 433.0371.



4d

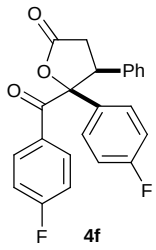
4d was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 126-127 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.08 (s, 1H), 7.79 (d, *J* = 8.0 Hz, 1H), 7.60-7.56 (m, 1H), 7.25-7.23 (m, 1H),

7.20-7.16 (m, 2H), 7.11 (m, 3H), 7.00-6.91 (m, 4H), 4.84 (t, J = 6.8 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.88 (dd, J_1 = 18.0 Hz, J_2 = 5.2 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.60, 174.52, 137.25, 136.73, 136.55, 135.04, 133.47, 131.57, 130.07, 129.94, 129.60, 128.59, 128.32, 127.78, 127.70, 123.26, 122.92, 122.68, 94.20, 47.94, 35.24 ppm; ESI HRMS: calcd. For $C_{23}H_{16}Br_2O_3$+Na 520.9364, found 520.9367.



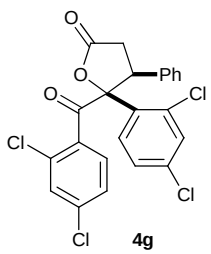
4e

4e was obtained as a white solid in 70% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 143-144 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.76 (d, J = 8.4 Hz, 2H), 7.47 (d, J = 8.0 Hz, 2H), 7.26-7.24 (m, 3H), 7.11 (s, 3H), 6.91-6.89 (m, 3H), 4.84 (t, J = 6.4 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.87 (dd, J_1 = 18.0 Hz, J_2 = 5.2 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.85, 174.58, 136.83, 134.26, 132.31, 132.01, 131.78, 131.74, 129.19, 128.62, 128.36, 127.64, 126.34, 122.68, 94.50, 47.70, 35.37 ppm; ESI HRMS: calcd. For $C_{23}H_{16}Br_2O_3$+Na 520.9364, found 520.9366.



4f

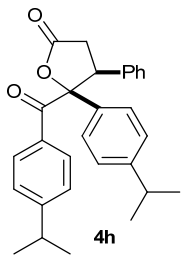
4f was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 87:13 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 127-128 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.95 (s, 2H), 7.10 (br s, 3H), 7.01-7.00 (m, 4H), 6.92 (m, 2H), 6.83-6.79 (m, 2H), 4.86 (t, J = 6.0 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.88 (dd, J_1 = 18.0 Hz, J_2 = 4.8 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.59, 174.82, 165.77 (d, J_{CF} = 255 Hz), 162.41 (d, J_{CF} = 247 Hz), 137.10, 133.78 (d, J_{CF} = 9 Hz), 131.14 (d, J_{CF} = 4 Hz), 129.72 (d, J_{CF} = 3 Hz), 128.65, 128.27, 127.50, 126.54 (d, J_{CF} = 9 Hz), 115.72 (d, J_{CF} = 3 Hz), 115.50 (d, J_{CF} = 2 Hz), 94.57, 47.81, 35.38 ppm; ESI HRMS: calcd. For $C_{23}H_{16}F_2O_3$+Na 401.0965, found 401.0968.



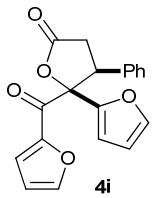
4g

4g was obtained as a white solid in 70% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 148-149 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.49 (d, J = 8.4 Hz, 1H), 7.43 (s, 1H), 7.19-7.17 (m, 1H), 7.07-6.97 (m, 8H), 4.98 (d, J = 8.8 Hz, 1H), 3.61 (dd, J_1 = 18.0 Hz, J_2 = 9.2 Hz, 1H), 2.82 (d, J = 18.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 192.09, 174.73, 138.86, 137.85, 135.08, 134.85,

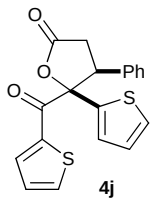
132.83, 132.17, 131.36, 131.33, 130.30, 129.68, 128.73, 128.46, 127.75, 127.25, 126.03, 93.71, 45.39, 37.76 ppm; ESI HRMS: calcd. For $C_{23}H_{14}Cl_4O_3$+Na 500.9595, found 500.9597.



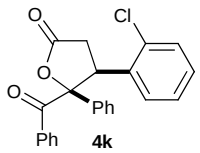
4h was obtained as a white solid in 54% yield for two steps after flash chromatography. The dr value was calculated to be 86:14 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 131-132 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.86 (d, *J* = 8.4 Hz, 2H), 7.17-7.15 (m, 2H), 7.04-7.03 (m, 3H), 6.96-6.88 (m, 6H), 4.82 (dd, J_1 = 8.4 Hz, J_2 = 6.4 Hz, 1H), 2.99 (dd, J_1 = 18.0 Hz, J_2 = 8.8 Hz, 1H), 2.90-2.83 (m, 2H), 2.77-2.71 (m, 1H), 1.20 (d, *J* = 2.0 Hz, 3H), 1.18 (d, *J* = 1.6 Hz, 3H), 1.11 (d, *J* = 3.2 Hz, 3H), 1.10 (d, *J* = 3.2 Hz, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.06, 175.47, 154.91, 148.99, 137.40, 132.71, 131.44, 131.32, 128.85, 127.86, 127.06, 126.39, 124.57, 95.20, 48.04, 35.40, 34.24, 33.60, 23.78, 23.77, 23.53, 23.47 ppm; ESI HRMS: calcd. For $C_{29}H_{30}O_3$+Na 449.2093, found 449.2090.



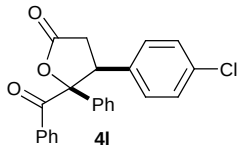
4i was obtained as a white solid in 72% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 126-127 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.65 (s, 1H), 7.32 (br s, 1H), 7.18 (br s, 4H), 7.09 (br s, 2H), 6.49 (s, 1H), 6.15 (d, *J* = 8.8 Hz, 2H), 4.70 (t, *J* = 8.4 Hz, 1H), 3.11-2.97 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 181.03, 174.27, 149.14, 148.16, 147.95, 143.20, 136.25, 128.29, 128.24, 127.66, 123.13, 112.56, 110.58, 109.38, 89.67, 46.69, 34.42 ppm; ESI HRMS: calcd. For $C_{19}H_{14}O_5$+Na 345.0739, found 345.0743.



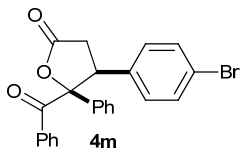
4j was obtained as a white solid in 71% yield for two steps after flash chromatography. The dr value was calculated to be 75:25 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 90-91 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.98 (d, *J* = 3.6 Hz, 1H), 7.66 (d, *J* = 4.8 Hz, 1H), 7.16-7.05 (m, 7H), 6.75-6.72 (m, 1H), 6.60-6.59 (m, 1H), 4.75 (t, *J* = 7.2 Hz, 1H), 3.06-2.93 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 187.83, 174.24, 139.34, 138.10, 136.77, 136.63, 135.76, 128.70, 128.61, 128.18, 127.67, 127.10, 126.17, 126.09, 93.47, 48.18, 34.96 ppm; ESI HRMS: calcd. For $C_{19}H_{14}O_3S_2$+Na 377.0282, found 377.0280.



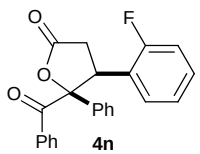
4k was obtained as a white solid in 60% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 101-103 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.93 (d, *J* = 7.6 Hz, 2H), 7.48-7.44 (m, 1H), 7.34-7.26 (m, 5H), 7.12-7.03 (m, 5H), 7.00-6.97 (m, 1H), 5.72 (d, *J* = 8.8 Hz, 1H), 3.15 (dd, J_1 = 18.0 Hz, J_2 = 9.2 Hz, 1H), 2.75 (d, *J* = 18.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.80, 175.42, 136.79, 134.83, 134.20, 133.48, 133.29, 131.04, 129.50, 128.57, 128.54, 128.31, 128.24, 128.20, 126.92, 124.67, 95.86, 43.24, 36.73 ppm; ESI HRMS: calcd. For $C_{23}H_{17}ClO_3$+Na 399.0764, found 399.0760.



4l was obtained as a white solid in 61% yield for two steps after flash chromatography. The dr value was calculated to be 86:14 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 123-124 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 8.0 Hz, 2H), 7.47-7.43 (m, 1H), 7.32-7.29 (m, 2H), 7.15 (br s, 3H), 7.06-7.04 (m, 4H), 6.86 (d, *J* = 7.6 Hz, 2H), 4.85 (t, *J* = 7.6 Hz, 1H), 3.01 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.82 (dd, J_1 = 18.0 Hz, J_2 = 6.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.03, 173.71, 134.67, 134.01, 132.50, 132.41, 132.18, 129.91, 129.10, 127.65, 127.46, 127.26, 127.17, 123.58, 93.64, 46.37, 34.28 ppm; ESI HRMS: calcd. For $C_{23}H_{17}ClO_3$+Na 399.0764, found 399.0767.

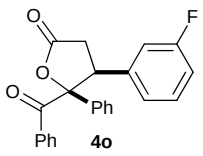


4m was obtained as a white solid in 66% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 149-150 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 8.0 Hz, 2H), 7.46-7.43 (m, 1H), 7.32-7.28 (m, 2H), 7.21-7.15 (m, 5H), 7.04 (br s, 2H), 6.80 (d, *J* = 8.0 Hz, 2H), 4.83 (t, *J* = 7.6 Hz, 1H), 3.01 (dd, J_1 = 18.0 Hz, J_2 = 8.8 Hz, 1H), 2.81 (dd, J_1 = 18.0 Hz, J_2 = 6.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.04, 174.70, 136.23, 135.02, 133.53, 133.44, 131.16, 130.94, 130.49, 128.70, 128.52, 128.30, 124.62, 121.37, 94.59, 47.48, 35.26 ppm; ESI HRMS: calcd. For $C_{123}H_{17}BrO_3$+Na 443.0259, found 443.0262.



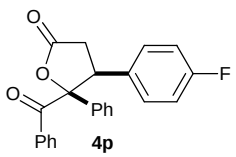
4n was obtained as a white solid in 57% yield for two steps after flash chromatography. The dr value was calculated to be 90:10 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 112-114 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.93 (d, *J* = 7.6 Hz, 2H), 7.47-7.44 (m, 1H), 7.33-7.30 (m, 2H), 7.23-7.21 (m, 2H), 7.13-7.00 (m,

5H), 6.93-6.90 (m, 1H), 6.75-6.70 (m, 1H), 5.28 (dd, J_1 = 9.2 Hz, J_2 = 1.6 Hz, 1H), 3.09 (dd, J_1 = 18.0 Hz, J_2 = 8.8 Hz, 1H), 2.85 (dd, J_1 = 18.0 Hz, J_2 = 2.0 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.87, 175.19, 160.44 (d, J_{CF} = 245 Hz), 135.29, 133.47, 133.34, 131.04, 129.88 (d, J_{CF} = 4 Hz), 129.24 (d, J_{CF} = 9 Hz), 128.38, 128.29, 128.21, 125.80 (d, J_{CF} = 13 Hz), 124.38, 123.97 (d, J_{CF} = 4 Hz), 115.38 (d, J_{CF} = 23 Hz), 95.34, 42.16, 35.45 ppm; ESI HRMS: calcd. For $C_{23}H_{17}FO_3$+Na 383.1059, found 383.1063.



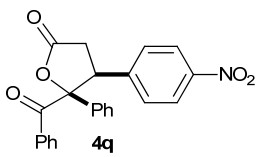
4o

4o was obtained as a white solid in 61% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 129-130 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.90 (d, J = 8.0 Hz, 2H), 7.47-7.43 (m, 1H), 7.33-7.29 (m, 2H), 7.15-7.14 (m, 3H), 7.07-7.02 (m, 3H), 6.79-6.73 (m, 2H), 6.65 (d, J = 10.0 Hz, 1H), 4.88 (t, J = 7.2 Hz, 1H), 3.03 (dd, J_1 = 18.0 Hz, J_2 = 8.8 Hz, 1H), 2.86 (dd, J_1 = 18.0 Hz, J_2 = 6.0 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.96, 174.70, 162.36 (d, J_{CF} = 244 Hz), 139.85 (d, J_{CF} = 7 Hz), 135.05, 133.53, 133.42, 130.97, 129.52, 128.62, 128.45, 128.30, 125.17, 124.57, 115.93 (d, J_{CF} = 21 Hz), 114.25 (d, J_{CF} = 21 Hz), 94.76, 47.59, 35.27 ppm; ESI HRMS: calcd. For $C_{23}H_{17}FO_3$+Na 383.1059, found 383.1056.



4p

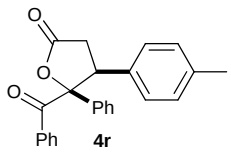
4p was obtained as a white solid in 68% yield for two steps after flash chromatography. The dr value was calculated to be 82:18 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 120-122 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.89 (d, J = 8.0 Hz, 2H), 7.47-7.43 (m, 1H), 7.33-7.29 (m, 2H), 7.15-7.14 (m, 3H), 7.04-7.03 (m, 2H), 6.91-6.88 (m, 2H), 6.79-6.75 (m, 2H), 4.88-4.85 (m, 1H), 3.02 (dd, J_1 = 17.6 Hz, J_2=8.4 Hz, 1H), 2.83 (dd, J_1 = 18.0 Hz, J_2 = 6.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.16, 174.92, 161.85 (d, J_{CF} = 245 Hz), 135.17, 133.52, 133.46, 132.93 (d, J_{CF} = 3 Hz), 130.95, 130.37 (d, J_{CF} = 8 Hz), 128.63, 128.40, 128.30, 124.60, 114.96 (d, J_{CF} = 21 Hz), 94.77, 47.25, 35.43; ESI HRMS: calcd. For $C_{23}H_{17}FO_3$+Na 383.1059, found 383.1060.



4q

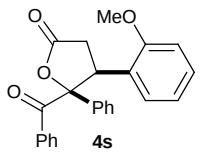
4q was obtained as a white solid in 63% yield for two steps after flash chromatography. The dr value was calculated to be 84:16 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 158-160 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.94 (d, J = 8.8 Hz, 2H), 7.90 (d, J= 7.6 Hz, 2H), 7.49-7.46 (m, 1H), 7.35-7.31 (m, 2H),

7.16-7.11 (m, 5H), 7.04-7.03 (m, 2H), 5.02-4.99 (m, 1H), 3.09 (dd, J_1 = 18.0 Hz, J_2 = 8.4 Hz, 1H), 2.89 (dd, J_1 = 18.0 Hz, J_2 = 6.4 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.64, 174.08, 146.97, 144.81, 134.69, 133.78, 133.11, 131.00, 129.81, 128.93, 128.87, 128.39, 124.46, 123.16, 94.42, 47.70, 35.10 ppm; ESI HRMS: calcd. For $C_{23}H_{17}NO_5$+Na 410.1004, found 410.1009.



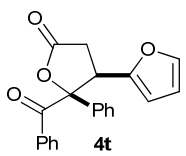
4r

4r was obtained as a white solid in 54% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 99-100 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.90 (d, J = 7.6 Hz, 2H), 7.45-7.41 (m, 1H), 7.31-7.27 (m, 2H), 7.12-7.11 (m, 3H), 7.07-7.06 (m, 2H), 6.87 (d, J = 8.0 Hz, 2H), 6.81 (d, J = 8.0 Hz, 2H), 4.83 (t, J = 7.2 Hz, 1H), 2.99 (dd, J_1 = 17.6 Hz, J_2 = 8.4 Hz, 1H), 2.84 (dd, J_1 = 18.0 Hz, J_2 = 6.0 Hz, 1H), 2.19 (s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.40, 175.32, 136.91, 135.38, 134.15, 133.78, 133.36, 130.92, 128.74, 128.66, 128.44, 128.25, 128.17, 124.76, 95.06, 47.68, 35.64, 20.96 ppm; ESI HRMS: calcd. For $C_{24}H_{20}O_3$+Na 379.1310, found 379.1315.



4s

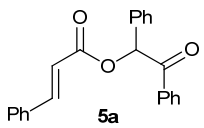
4s was obtained as a white solid in 50% yield for two steps after flash chromatography. The dr value was calculated to be 87:13 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 89-90 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.94 (d, J = 7.6 Hz, 2H), 7.46-7.42 (m, 1H), 7.32-7.29 (m, 2H), 7.23-7.21 (m, 2H), 7.07-7.00 (m, 5H), 6.74-6.70 (m, 1H), 6.50-6.48 (m, 1H), 5.22 (d, J = 9.6 Hz, 1H), 3.64 (s, 3H), 2.98 (dd, J_1 = 18.0 Hz, J_2 = 10.0 Hz, 1H), 2.83 (dd, J_1 = 17.6 Hz, J_2 = 1.2 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.59, 176.22, 156.91, 135.81, 133.70, 133.22, 131.03, 130.88, 128.72, 128.19, 127.73, 127.69, 127.09, 124.57, 120.14, 110.11, 95.68, 54.29, 44.66, 35.39 ppm; ESI HRMS: calcd. For $C_{24}H_{20}O_4$+Na 395.1259, found 395.1263.



4t

4t was obtained as a white solid in 35% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by ^{1}H NMR analysis of the crude reaction mixture. m.p. 102-104 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.91 (d, J = 6.4 Hz, 2H), 7.46 (br s, 1H), 7.32-7.26 (m, 3H), 7.19 (br s, 5H), 7.07 (br s, 1H), 6.08 (s, 1H), 6.01 (s, 1H), 4.94 (br s, 1H), 2.94 (br s, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.64, 174.49, 150.44, 142.14, 135.45, 133.57, 133.24, 131.01, 128.56, 128.34, 128.31, 124.03, 110.17, 108.94,

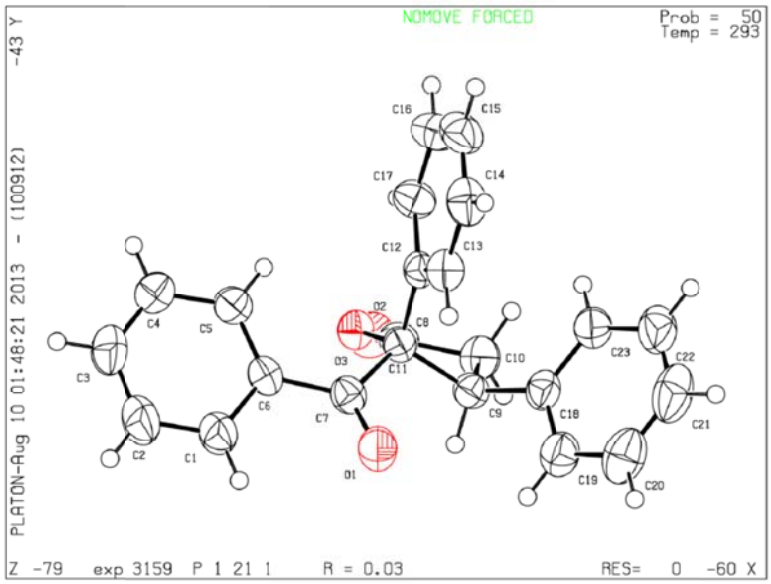
94.14, 42.59, 33.26 ppm; ESI HRMS: calcd. For $C_{21}H_{16}O_4$+Na 355.0946, found 355.0943.

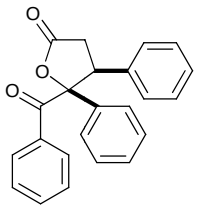


5a

5a was obtained as a white solid in 87% yield for two steps after flash chromatography. m.p. 104-106 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.98 (d, *J* = 7.2 Hz, 2H), 7.78 (d, *J* = 16.0 Hz, 1H), 7.52 (br s, 5H), 7.43-7.38 (m, 7H), 7.25 (s, 1H), 7.01(s, 1H), 6.60 (d, *J* = 16.0 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 193.83, 166.32, 146.21, 134.71, 134.27, 133.78, 133.52, 130.53, 129.37, 129.19, 128.91, 128.88, 128.78, 128.68, 128.28, 117.14, 77.65 ppm; ESI HRMS: calcd. For $C_{23}H_{18}O_3$+Na 365.1154, found 365.1151.

3. Crystal data of 4a

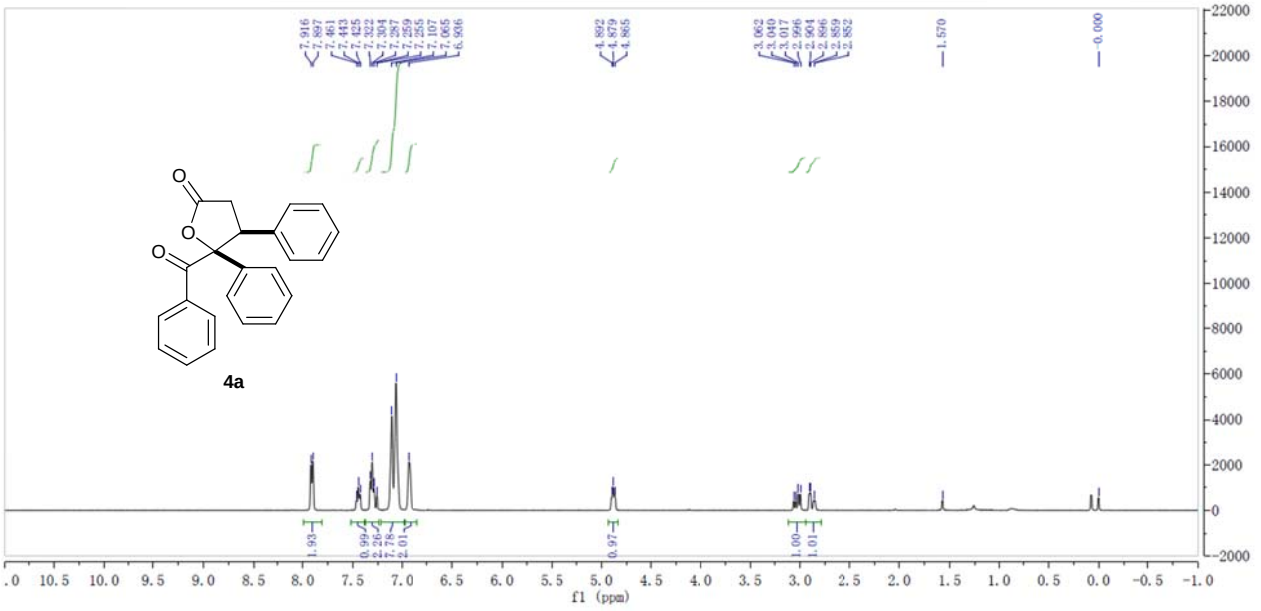


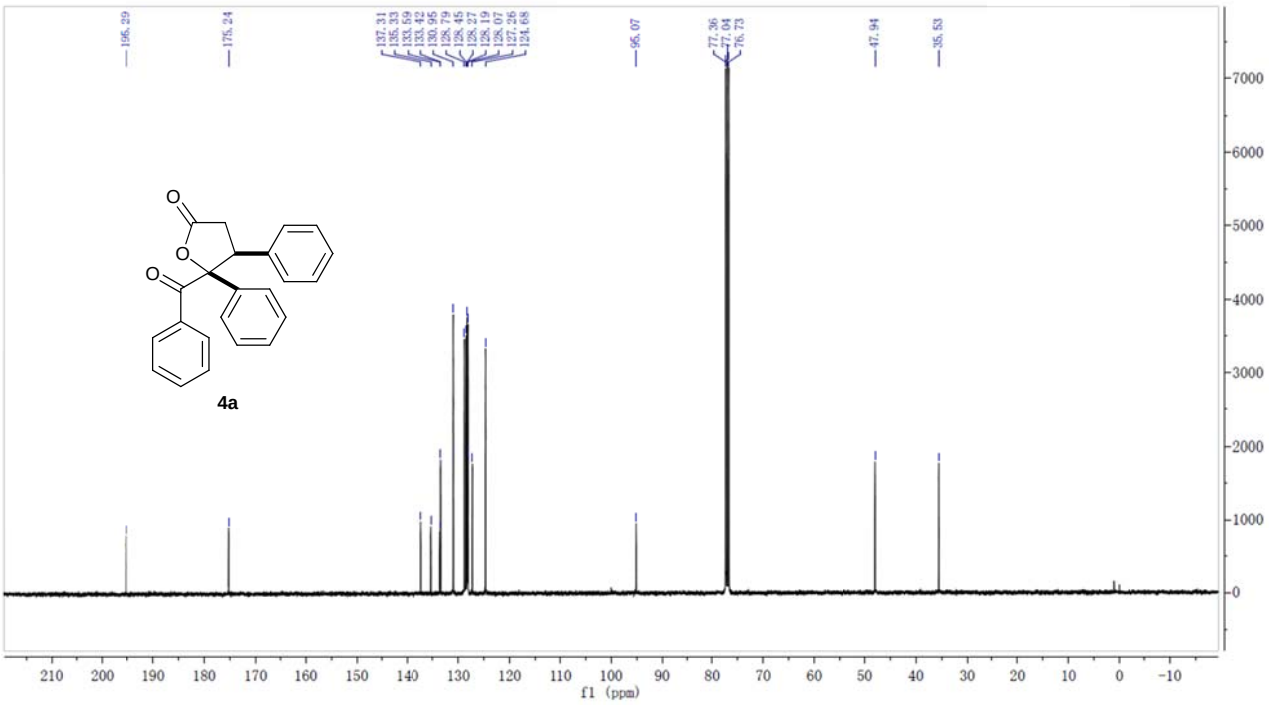


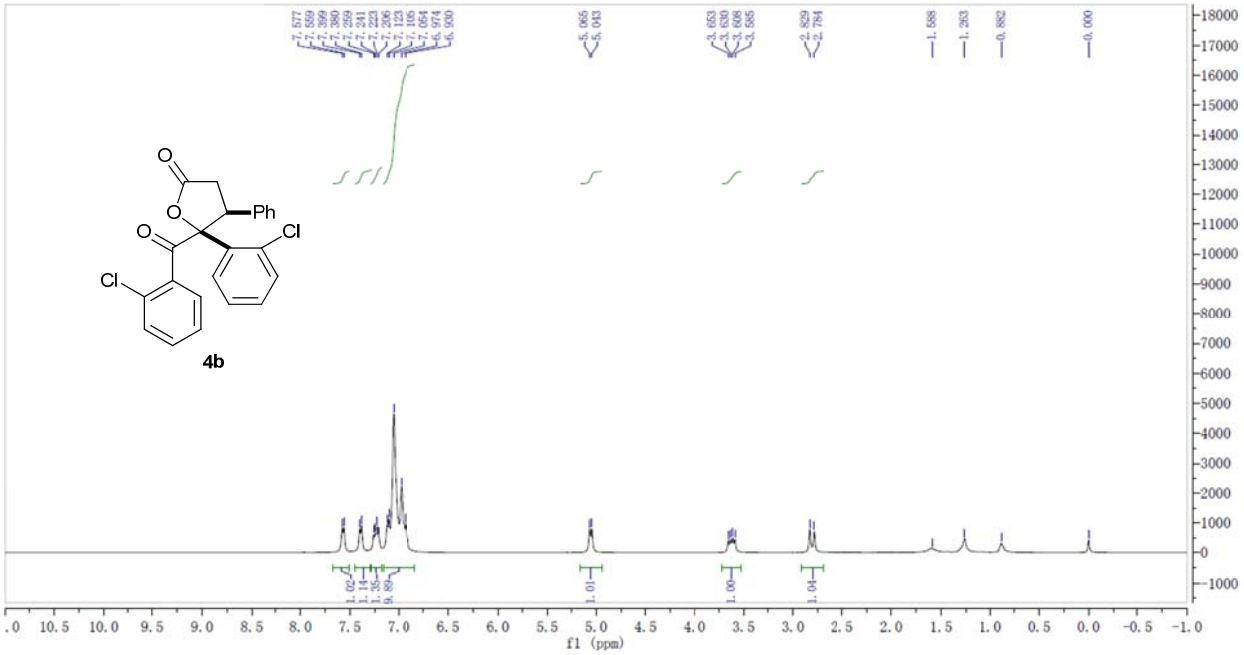
4a

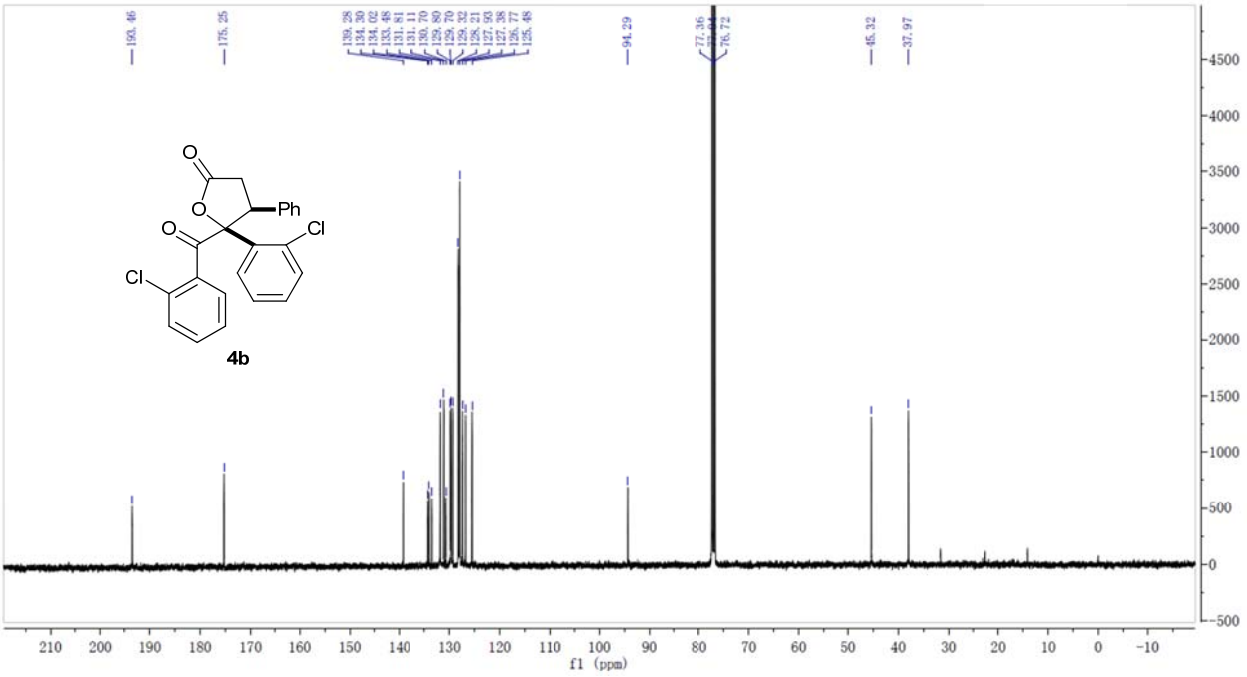
Empirical formula	$C_{23}H_{18}O_3$
Formula weight	342.37
Temperature/K	293(2)
Crystal system	monoclinic
Space group	$P2_1$
a/Å	6.7969(3)
b/Å	14.0639(6)
c/Å	9.4194(4)
α/°	90.00
β/°	96.811(5)
γ/°	90.00
Volume/Å^3	894.05(7)
Z	2
ρ_{calc}mg/mm^3	1.272
m/mm^{-1}	0.669
F(000)	360.0
Crystal size/mm^3	0.3 × 0.3 × 0.02
2Θ range for data collection	9.46 to 134.48°
Index ranges	$-5 \le h \le 8$, $-16 \le k \le 14$, $-11 \le l \le 11$
Reflections collected	5229
Independent reflections	2737[R(int) = 0.0221]
Data/restraints/parameters	2737/1/236
Goodness-of-fit on F^2	1.096
Final R indexes [I>=2σ (I)]	$R_1 = 0.0317$, $wR_2 = 0.0877$
Final R indexes [all data]	$R_1 = 0.0333$, $wR_2 = 0.0894$
Largest diff. peak/hole / e Å^{-3}	0.15/-0.13

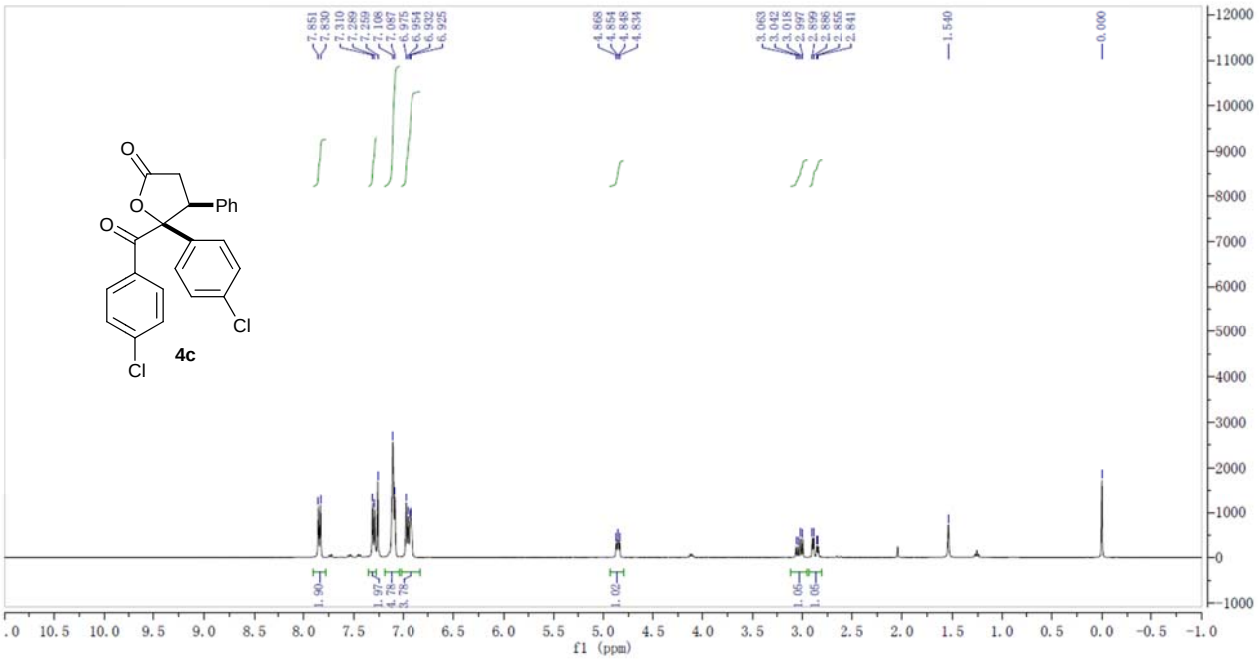
4. NMR spectra






4b
f1 (ppm)


4b
f1 (ppm)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7.108
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6.932
6.925
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4.854
4.848
4.834
3.063
3.042
3.018
2.997
2.899
2.886
2.855
2.841
1.540
0.000
1.90
1.97
4.78
3.78
1.02
1.05
1.05
f1 (ppm)
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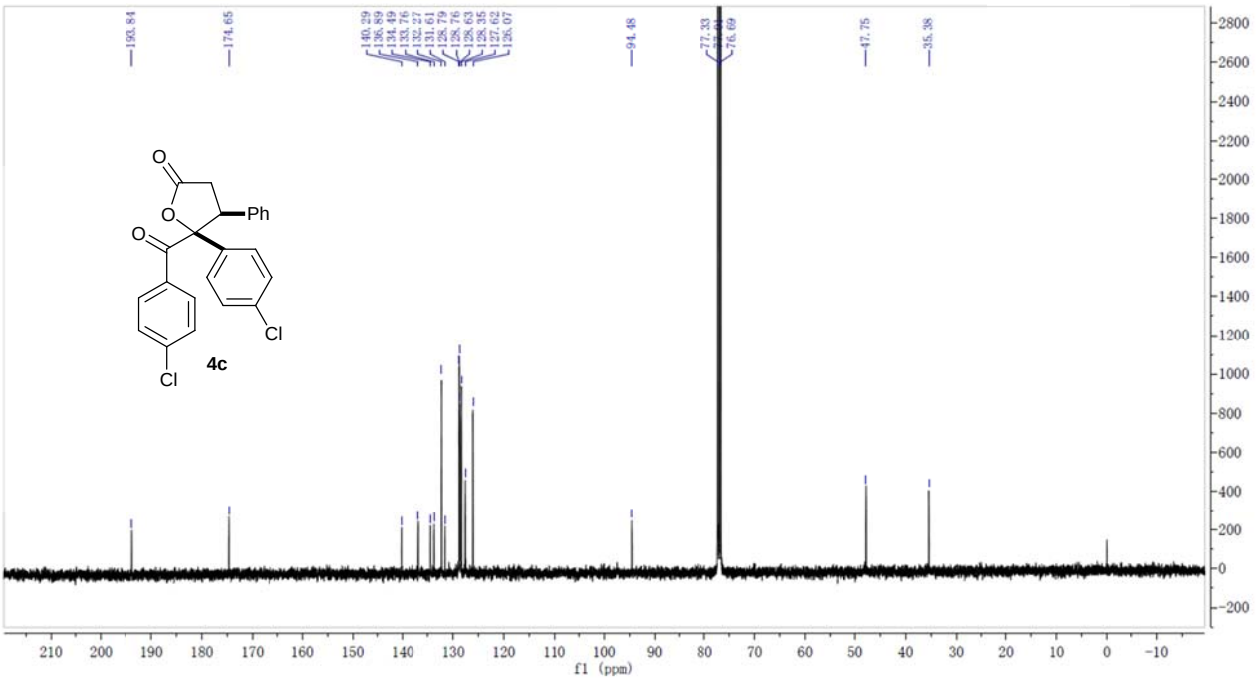
O
O
Ph
Cl
Cl
4c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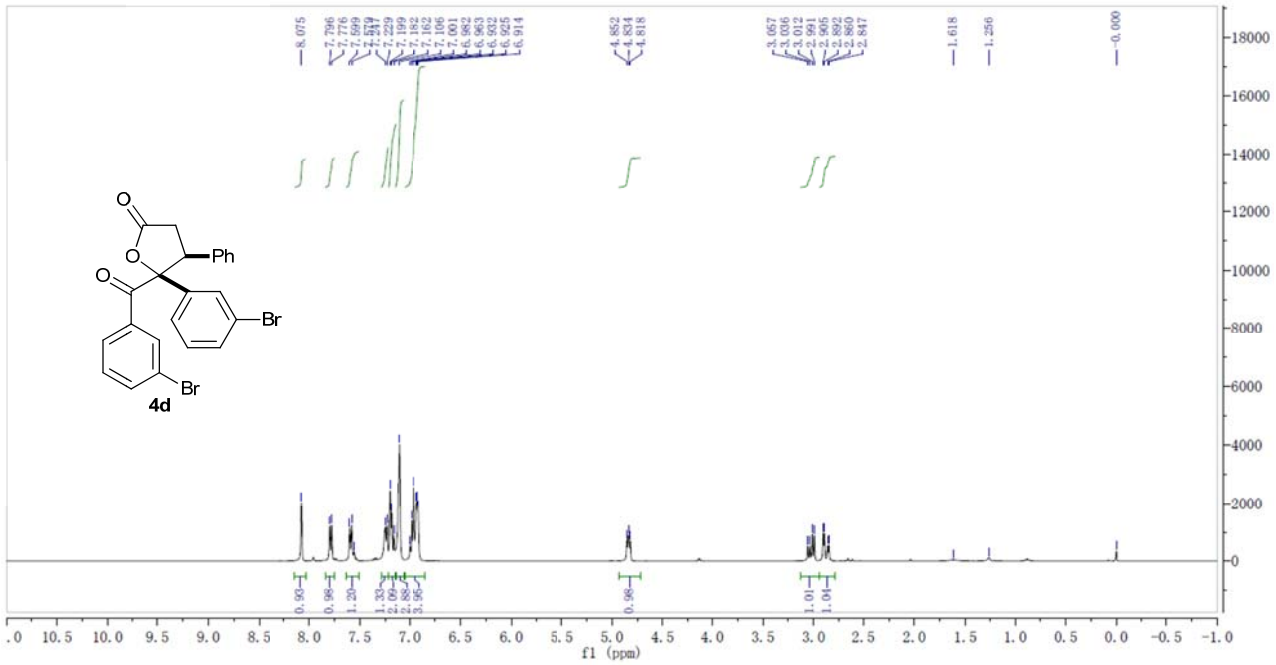
136.89
134.49
133.76
132.27
131.61
129.79
129.76
128.63
128.35
127.62
126.07
94.48
77.33
77.04
76.69
47.75
35.38
f1 (ppm)
O
O
O
Ph
Cl
Cl
4c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7.776
7.699
7.579
7.547
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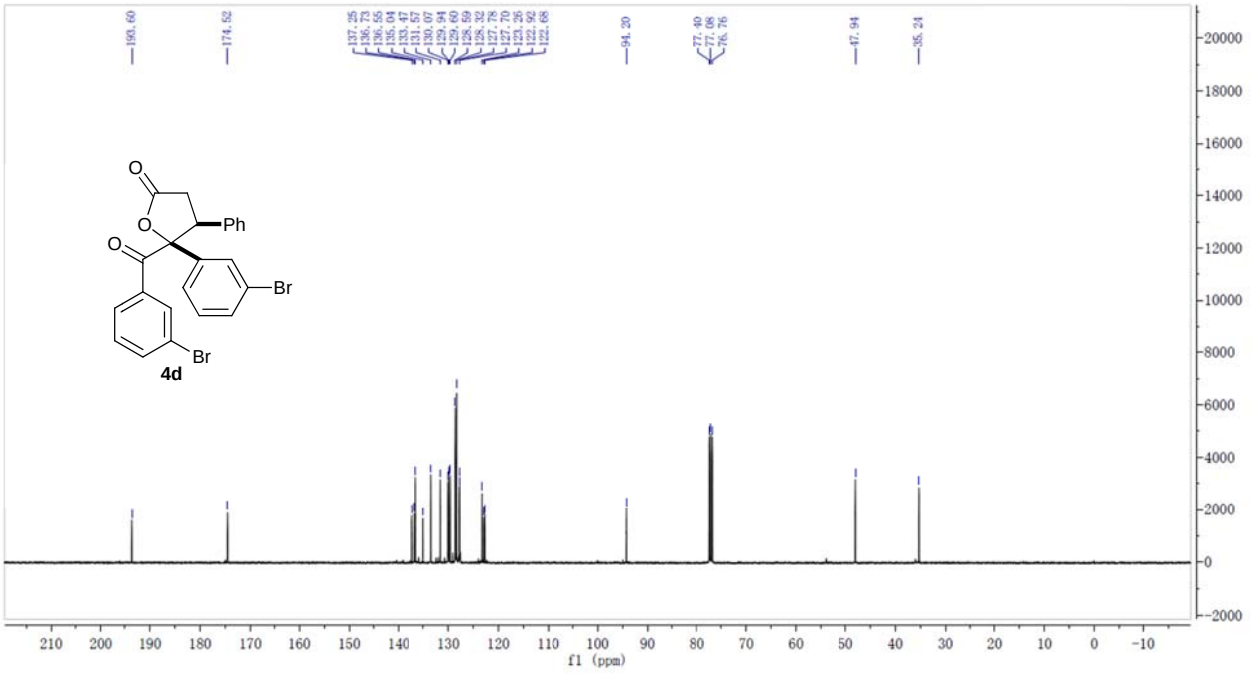
7.199
7.182
7.162
7.106
7.001
6.982
6.963
6.932
6.925
6.914
4.852
4.834
4.818
3.057
3.036
3.012
2.991
2.905
2.892
2.860
2.847
1.618
1.256
0.000
O
O
Ph
Br
Br
4d
0.93
0.98
1.20
1.33
2.09
2.88
3.95
0.98
1.01
1.04
f1 (ppm)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136.73
136.55
135.04
133.47
131.57
130.07
129.94
129.60
128.59
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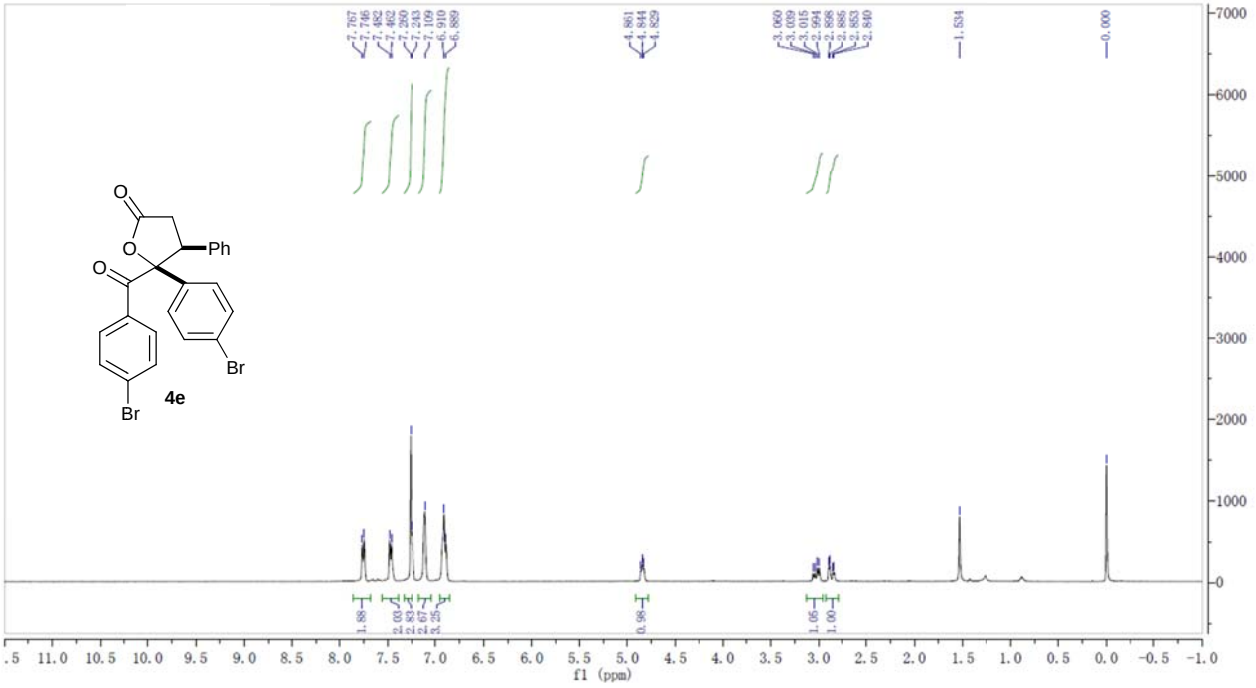
127.78
127.70
123.26
122.92
122.68
94.20
77.49
77.08
76.76
47.94
35.24
O
O
Ph
Br
Br
4d
f1 (ppm)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7.260
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7.109
6.910
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4.861
4.844
4.829
3.060
3.039
3.015
2.994
2.888
2.885
2.853
2.840
1.534
0.000
O
O
O
Ph
Br
Br
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2.03
2.83
2.67
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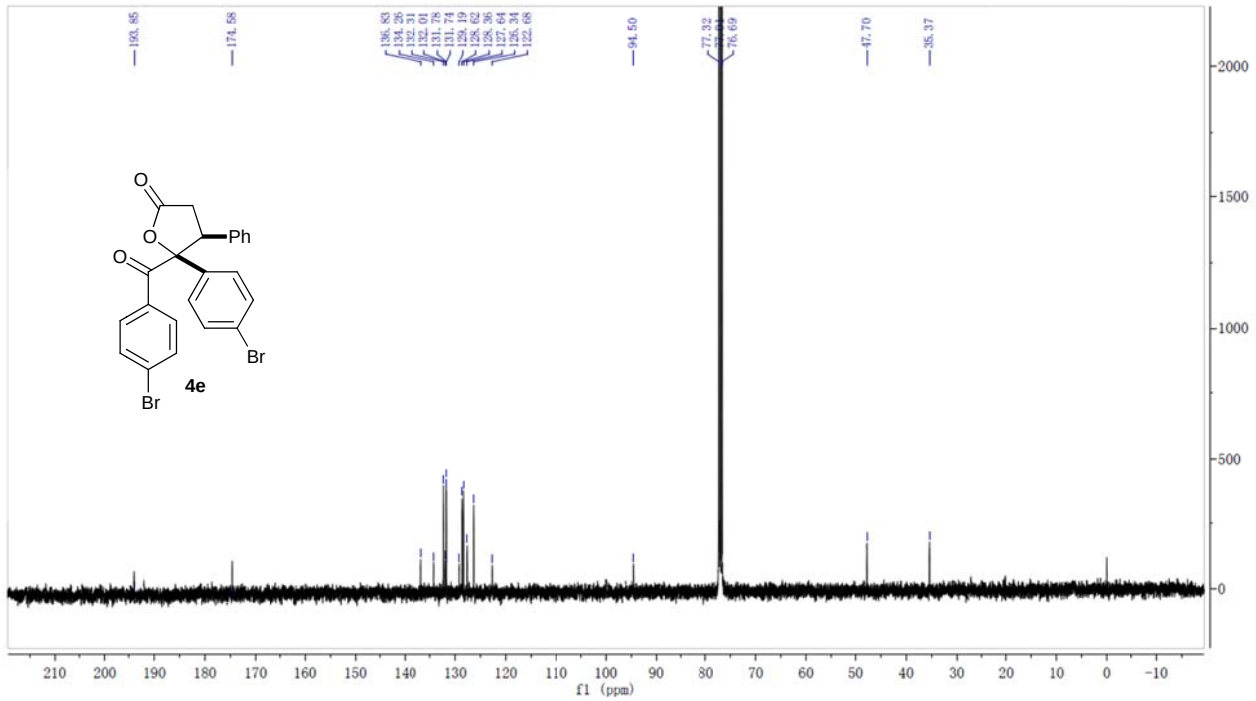
0.98
1.05
1.00
f1 (ppm)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132.01
131.78
131.74
129.19
128.62
128.36
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125.34
122.68
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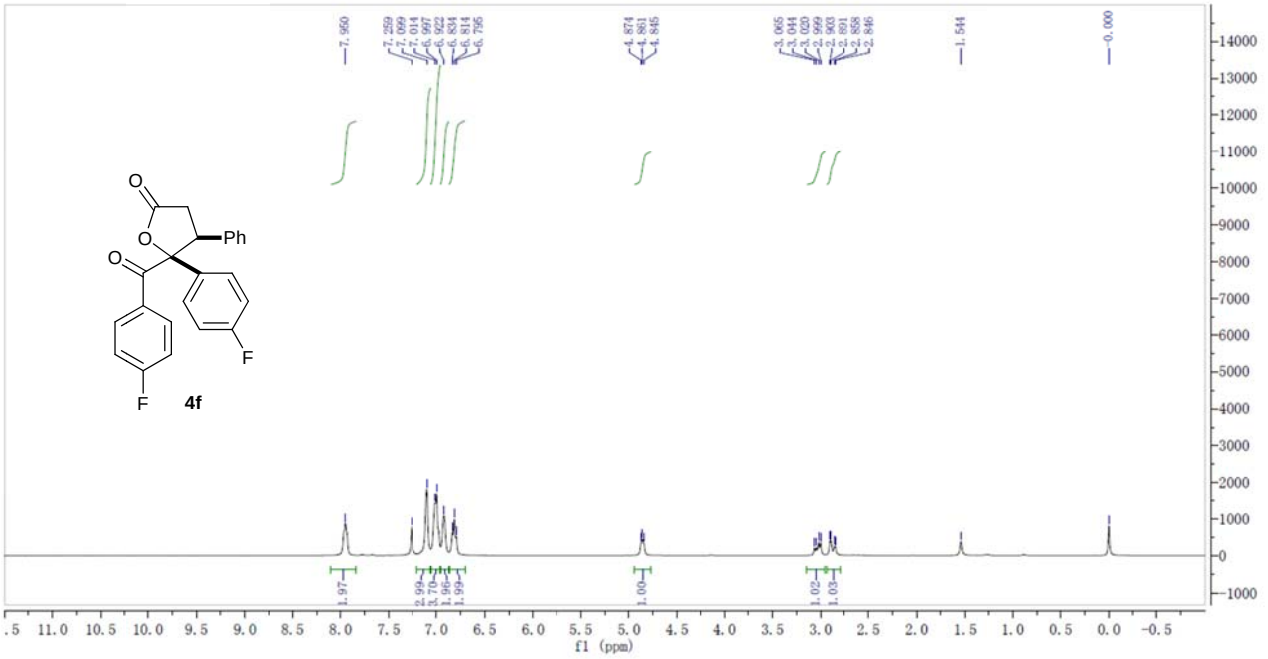
77.32
76.69
47.70
35.37
O
O
O
Ph
Br
Br
4e
f1 (ppm)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6.997
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6.834
6.814
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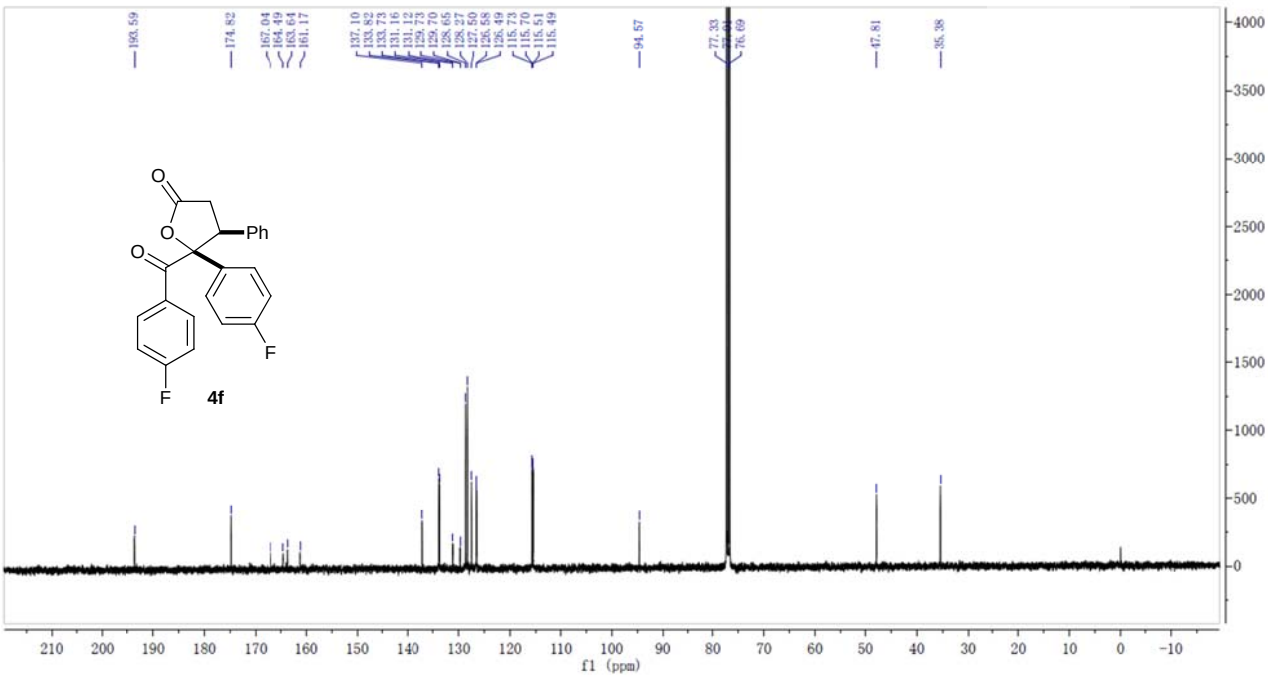
4.874
4.861
4.845
3.065
3.044
3.030
2.999
2.969
2.903
2.891
2.858
2.846
1.544
0.000
1.97
2.99
3.70
1.96
1.99
1.00
1.02
1.03
f1 (ppm)
O
O
O
Ph
F
F
4f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164.49
163.64
161.17
137.10
133.82
133.73
131.16
131.12
129.73
129.70
128.65
128.27
127.50
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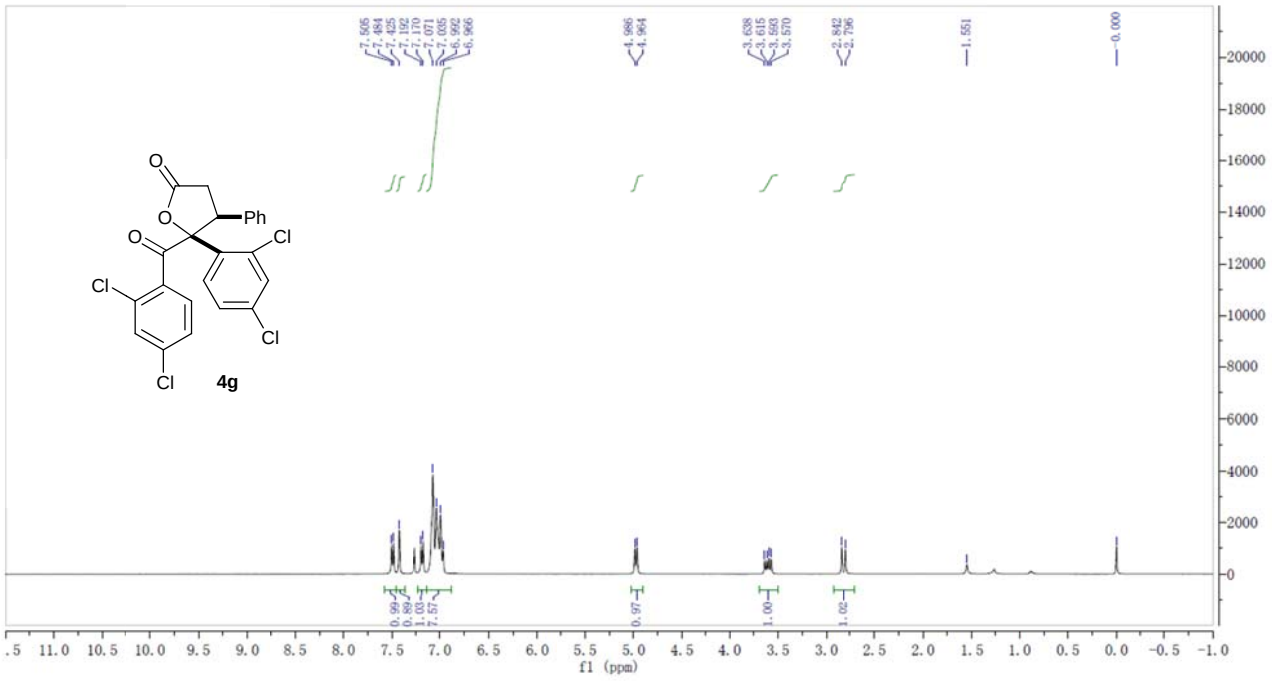
115.70
115.51
115.49
94.57
77.33
77.01
76.69
47.81
35.38
f1 (ppm)
O
O
O
Ph
F
F
4f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6.992
6.966
4.986
4.964
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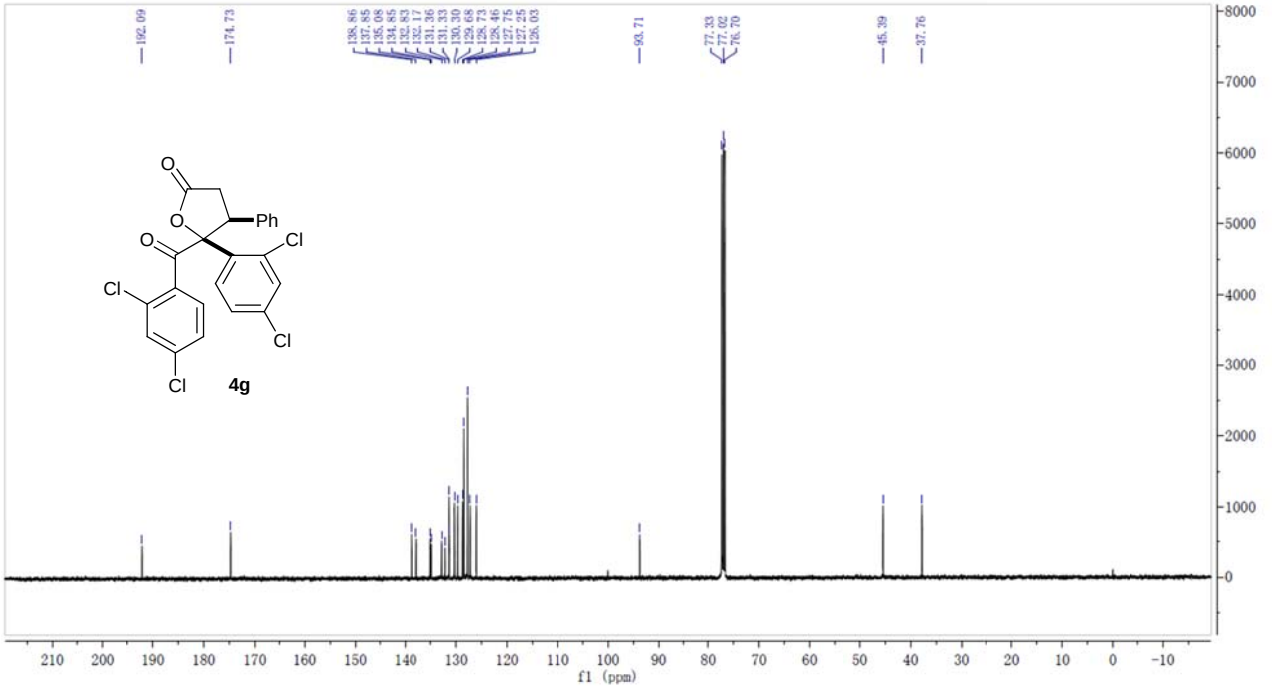
3.615
3.593
3.570
2.842
2.796
1.551
0.000
O
O
O
Ph
Cl
Cl
Cl
Cl
4g
0.99
0.89
1.03
7.57
0.97
1.00
1.02
f1 (ppm)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135.08
134.85
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132.17
131.36
131.33
130.30
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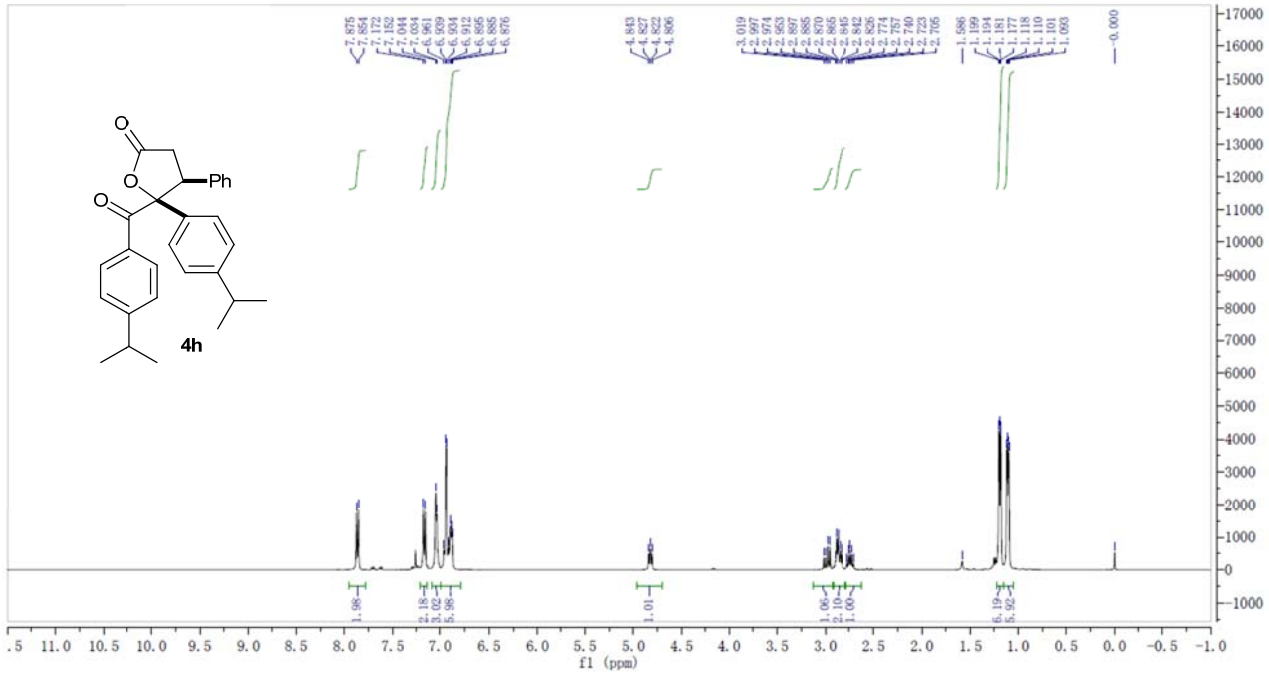
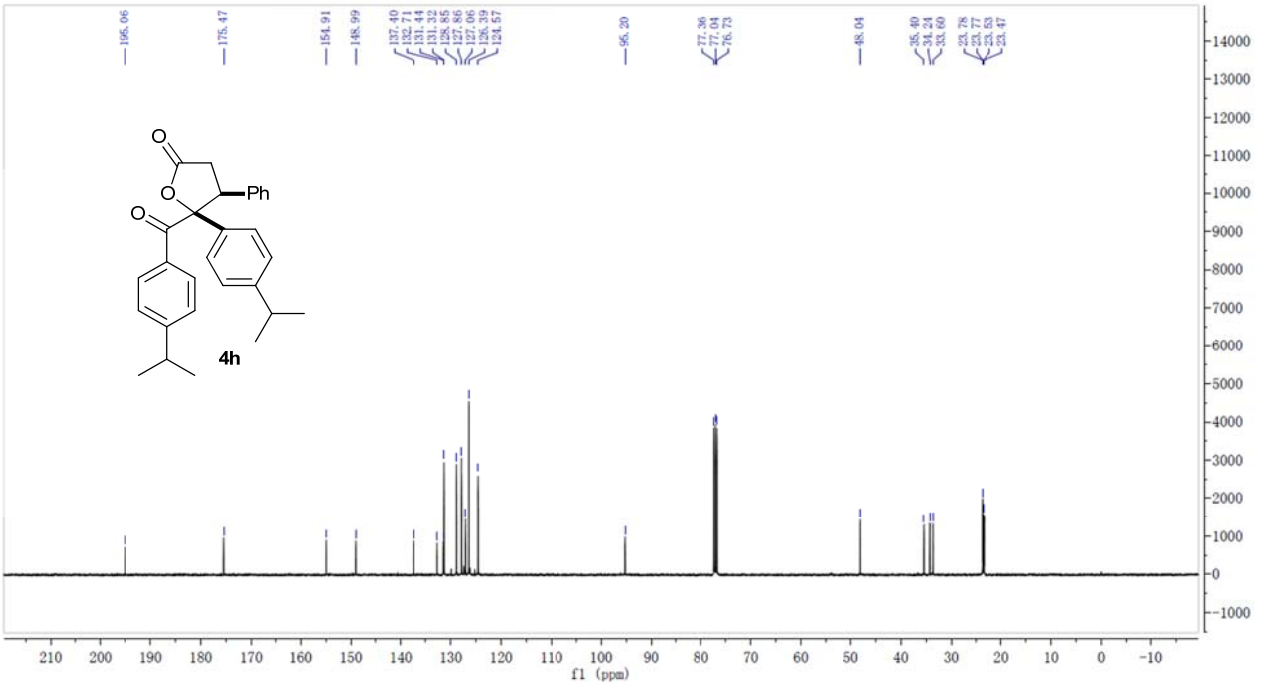
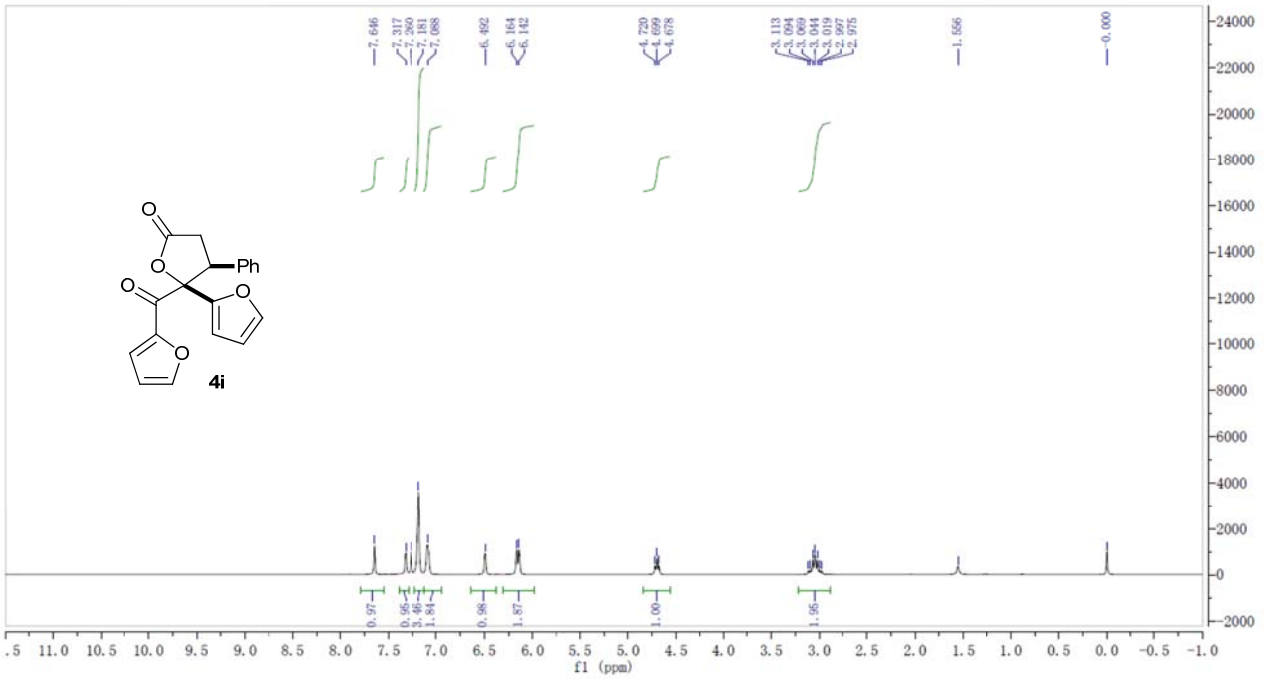
128.73
128.46
127.75
127.25
126.03
93.71
77.33
77.02
76.70
45.39
37.76
O
O
O
Ph
Cl
Cl
Cl
Cl
4g
f1 (ppm)


Ph
4h
f1 (ppm)


Ph
4h
f1 (ppm)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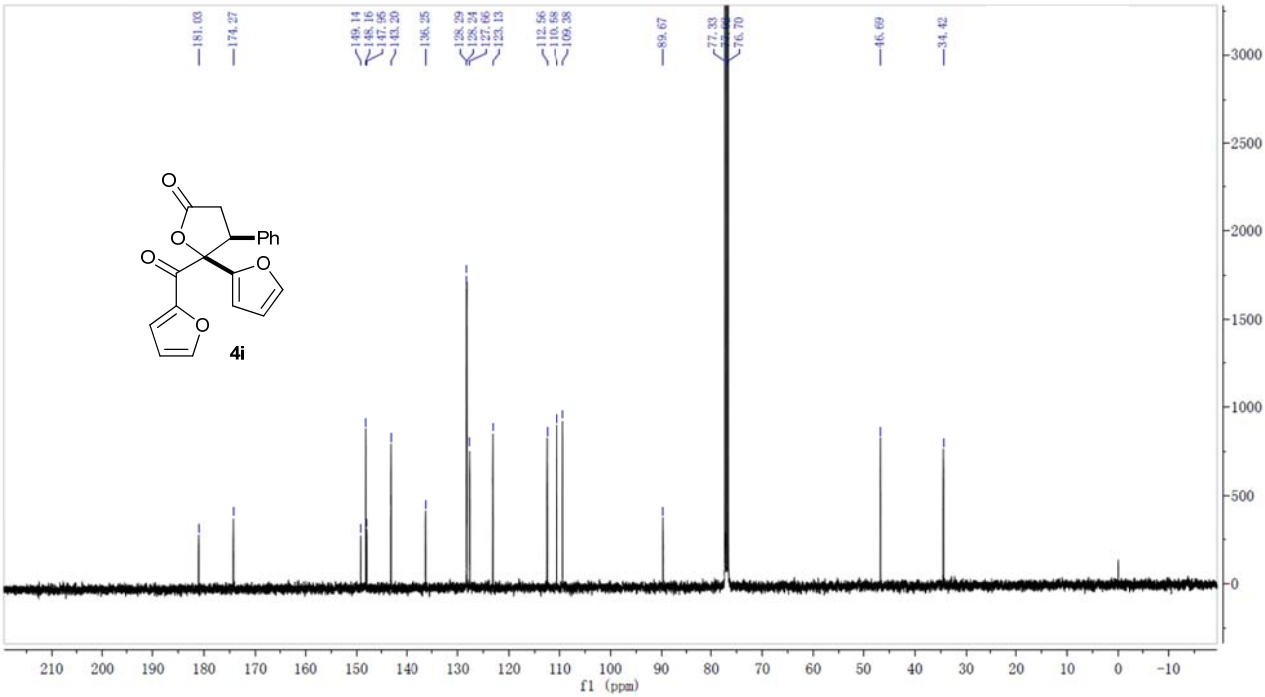
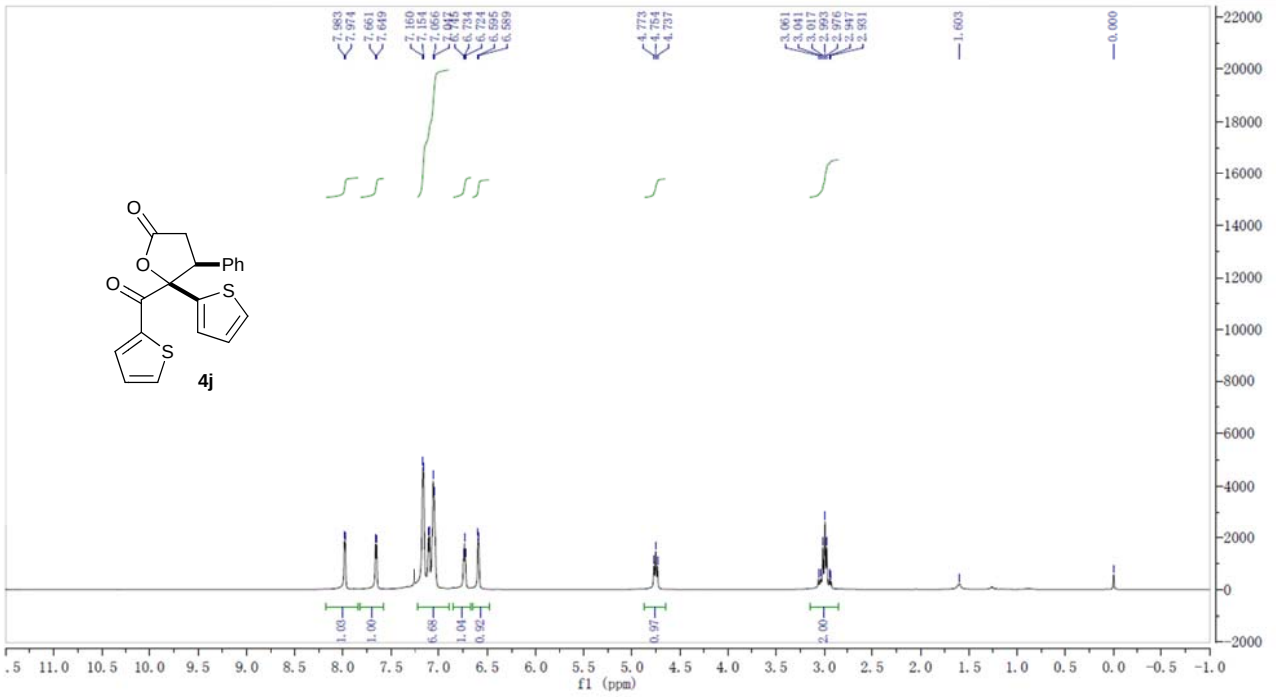
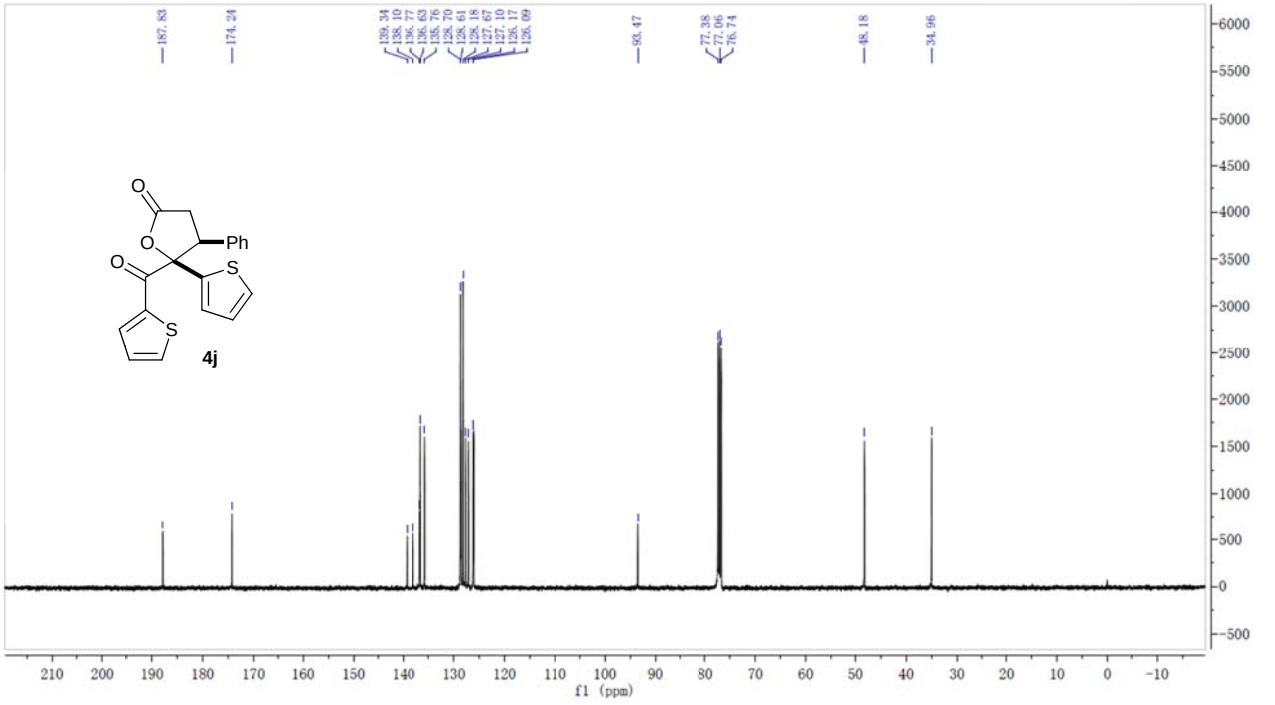
3.069
3.044
3.019
2.997
2.975
1.566
0.000
Ph
O
4i
0.97
0.95
3.46
1.84
0.98
1.87
1.00
1.95
f1 (ppm)


181.03
174.27
149.14
148.16
147.95
143.20
126.25
128.29
128.24
127.66
123.13
112.56
110.58
109.38
89.67
77.33
76.70
46.69
34.42
Ph
O
4i
f1 (ppm)


7.983
7.974
7.661
7.649
7.160
7.154
7.066
6.734
6.724
6.595
6.589
4.773
4.754
4.737
3.061
3.041
3.017
2.993
2.976
2.957
2.931
1.603
0.000
1.03
1.00
6.68
1.04
0.92
0.97
2.00
f1 (ppm)

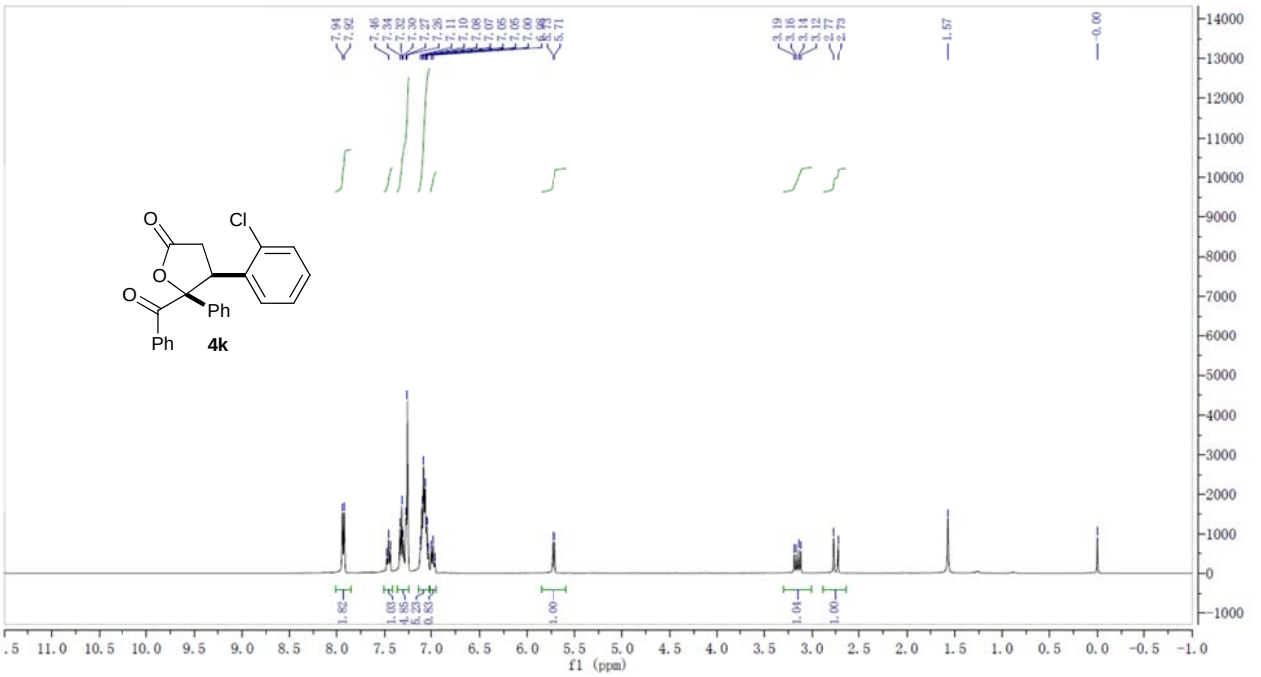
O
O
Ph
O
S
S

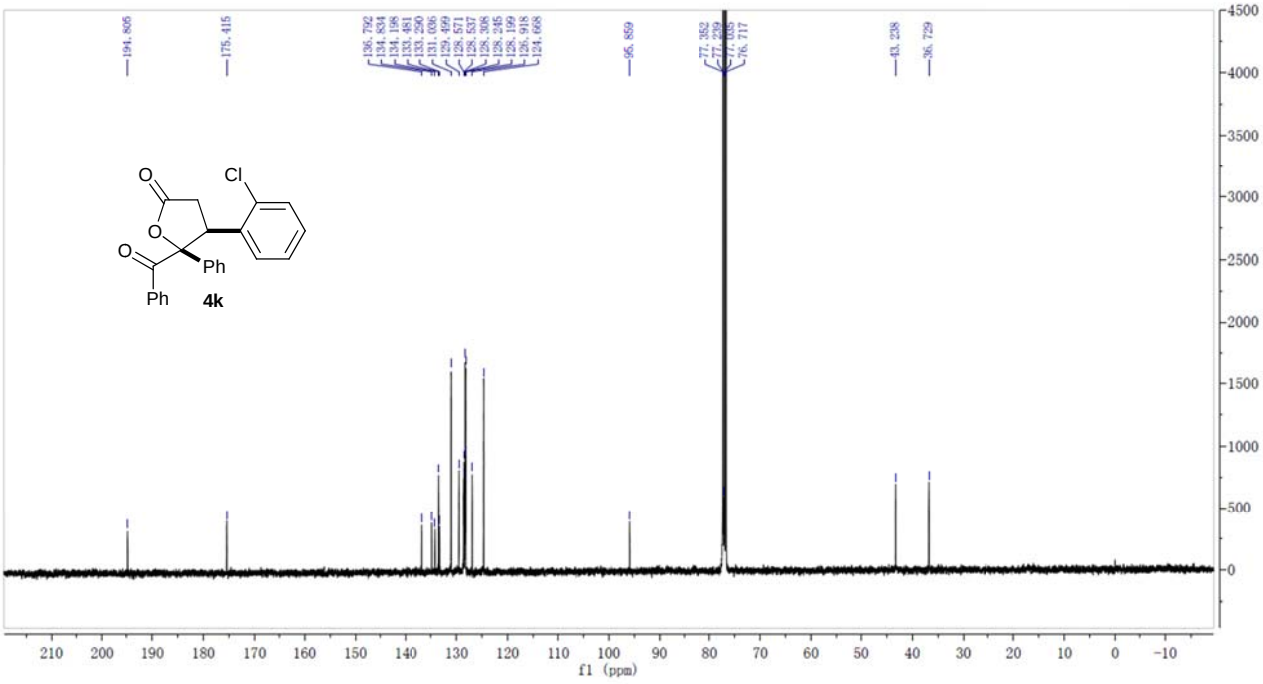
4j


187.83
174.24
139.34
138.10
136.77
136.63
135.76
128.70
128.61
128.18
127.67
127.10
126.17
126.09
93.47
77.38
77.06
76.74
48.18
34.96
f1 (ppm)

O
O
Ph
O
S
S

4j


7.94
7.92
7.46
7.34
7.32
7.30
7.27
7.26
7.11
7.10
7.08
7.07
7.05
7.00
5.71
3.19
3.16
3.14
3.12
2.77
2.73
1.57
0.00
1.82
1.03
4.85
5.23
0.83
1.00
1.04
1.00
f1 (ppm)
O
O
O
Cl
Ph
Ph
4k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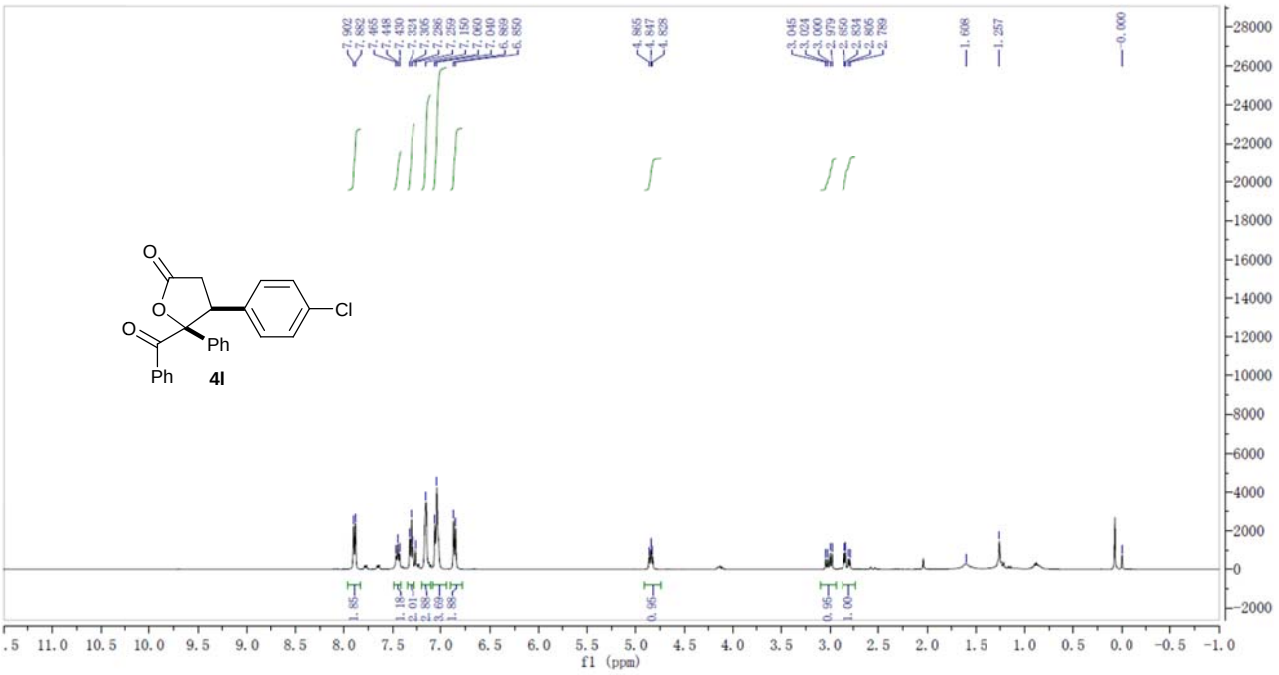
175.415
136.792
134.834
134.198
133.481
133.290
131.036
129.499
128.571
128.537
128.306
128.245
128.169
126.918
124.668
95.859
77.352
77.239
77.035
76.717
43.238
36.729
f1 (ppm)
O
O
O
Cl
Ph
Ph
4k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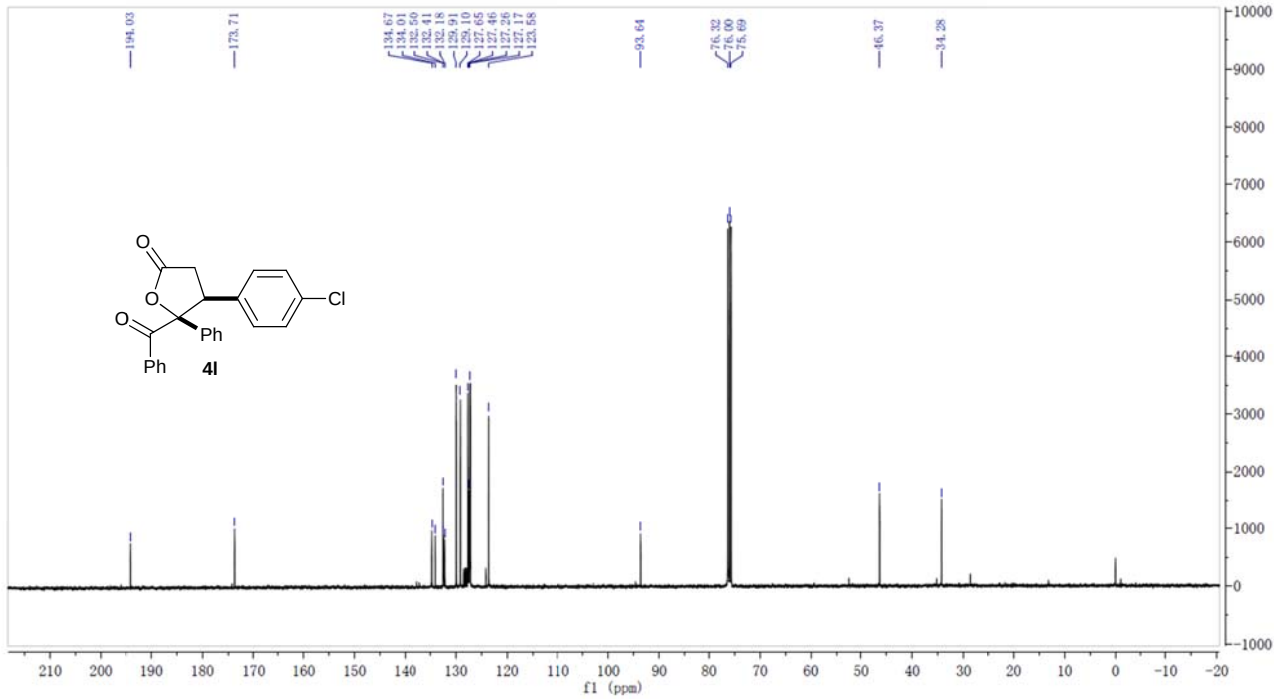
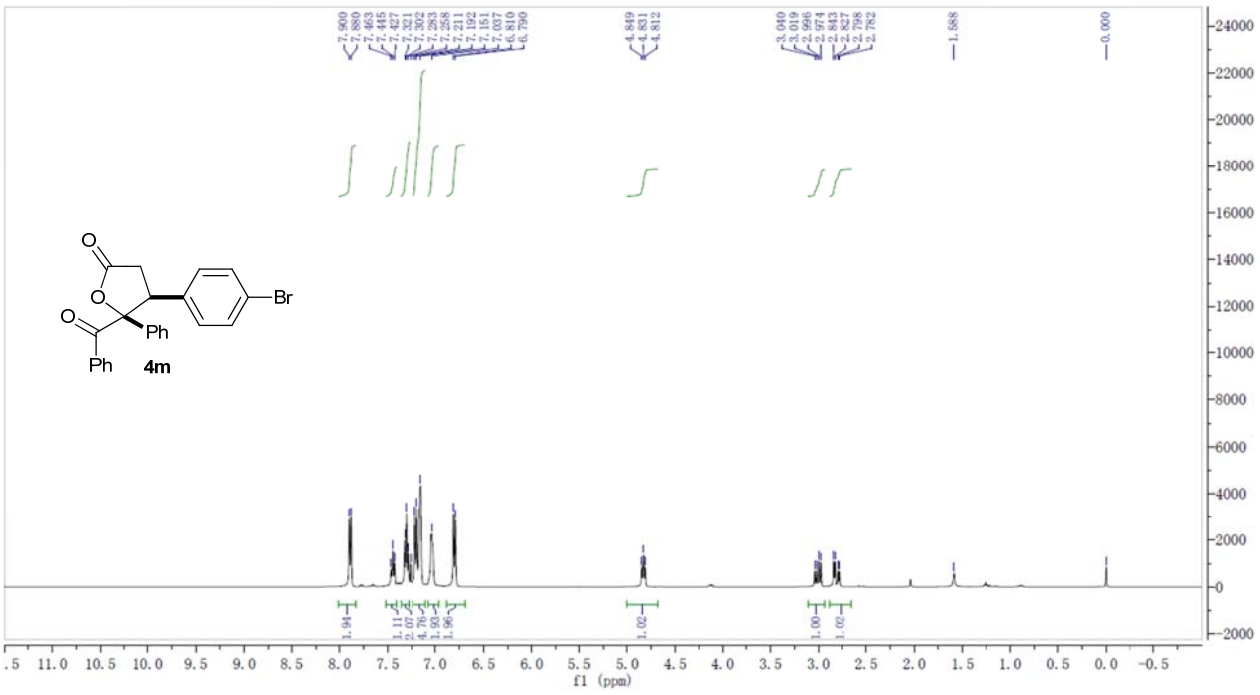
7.882
7.465
7.446
7.330
7.324
7.306
7.286
7.259
7.150
7.060
7.040
6.869
6.850
4.865
4.847
4.828
3.045
3.024
3.000
2.979
2.850
2.834
2.805
2.789
1.608
1.257
0.000
O
O
O
Cl
Ph
Ph
4l
1.85
1.18
1.01
2.88
3.69
1.88
0.95
0.95
1.00
f1 (ppm)


194.03
173.71
134.67
134.01
132.60
132.41
132.18
129.91
129.10
127.65
127.46
127.26
127.17
123.58
93.64
76.32
76.00
75.69
46.37
34.28
O
O
O
Cl
Ph
Ph
4l
f1 (ppm)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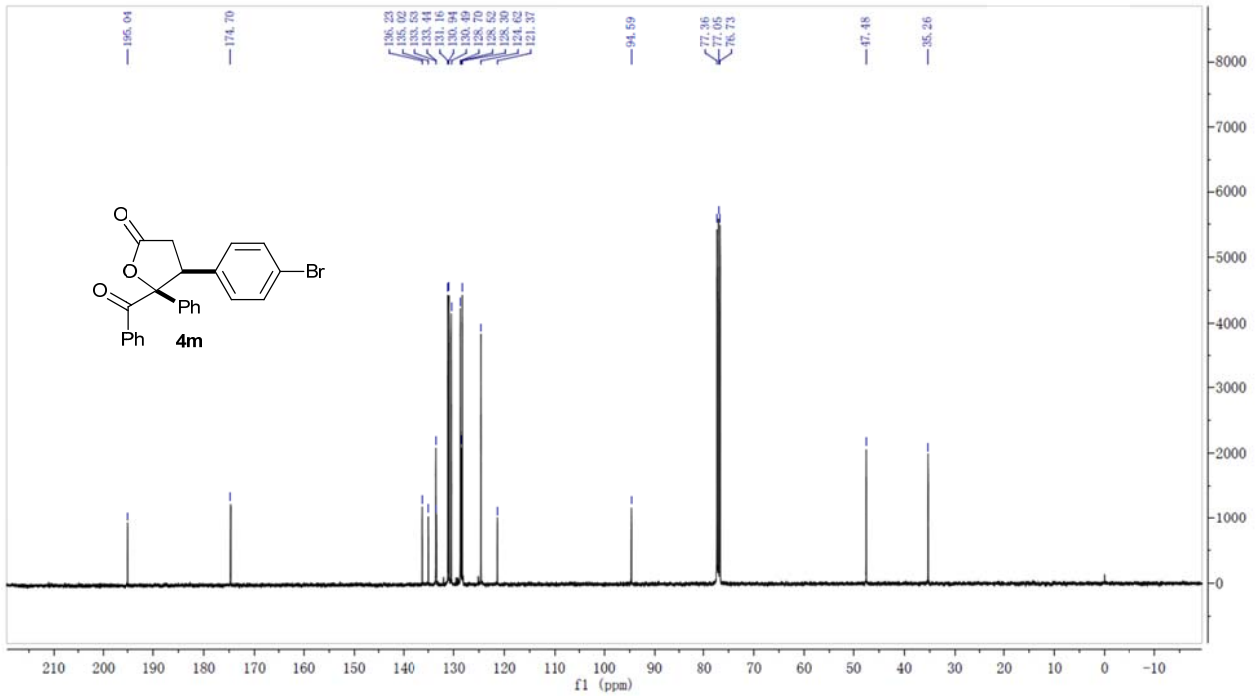
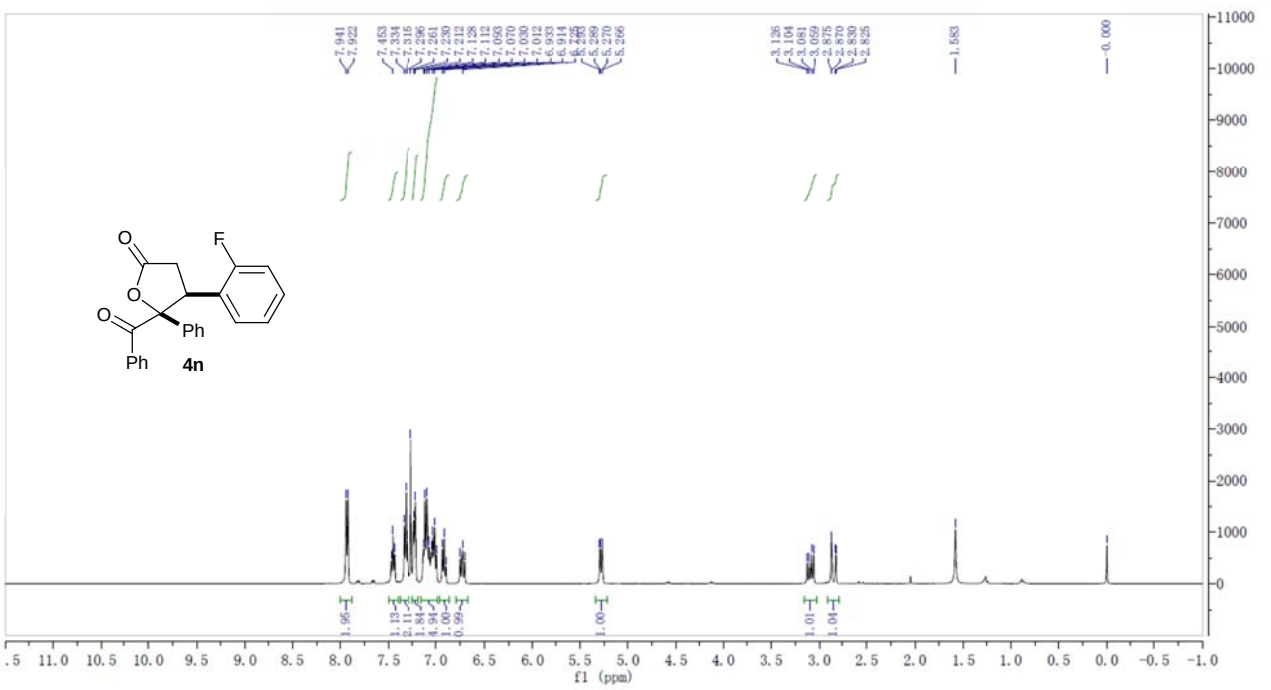
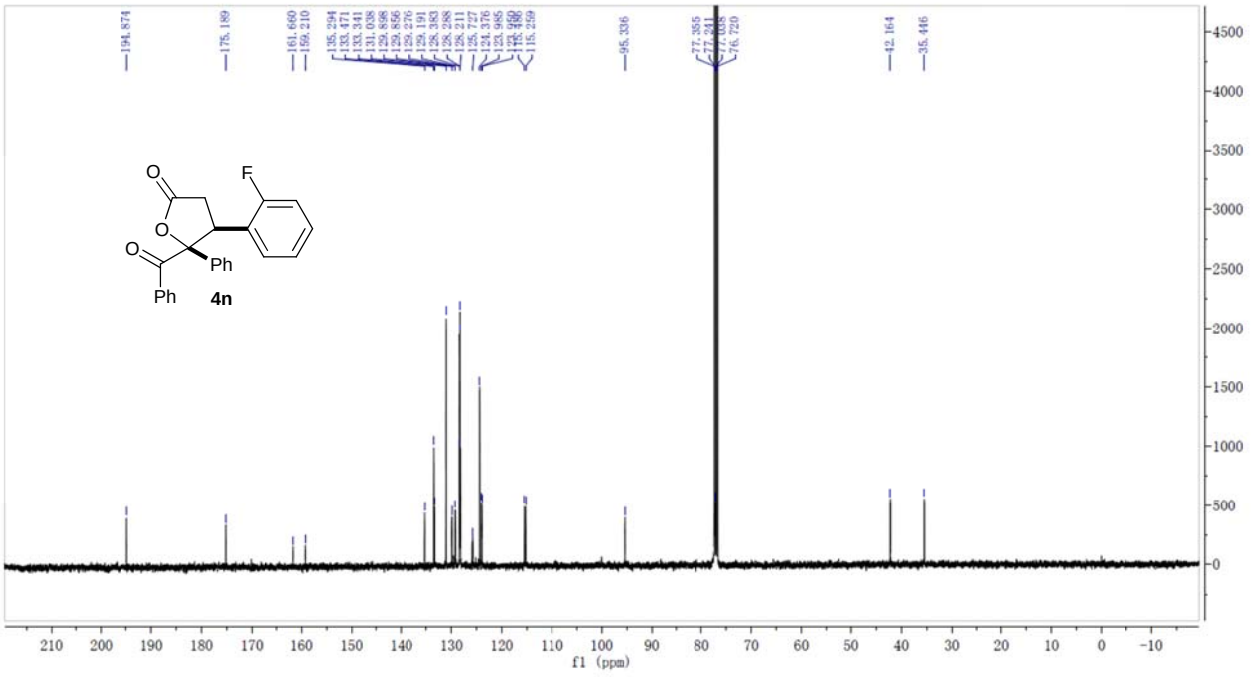
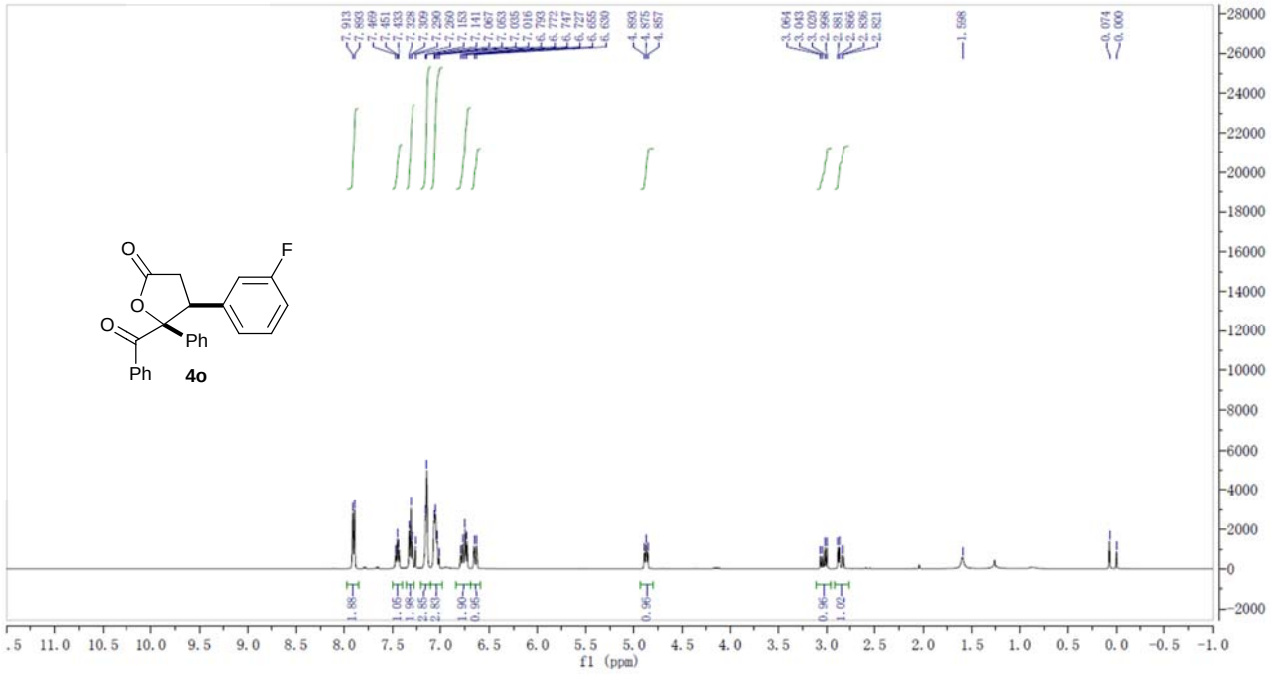
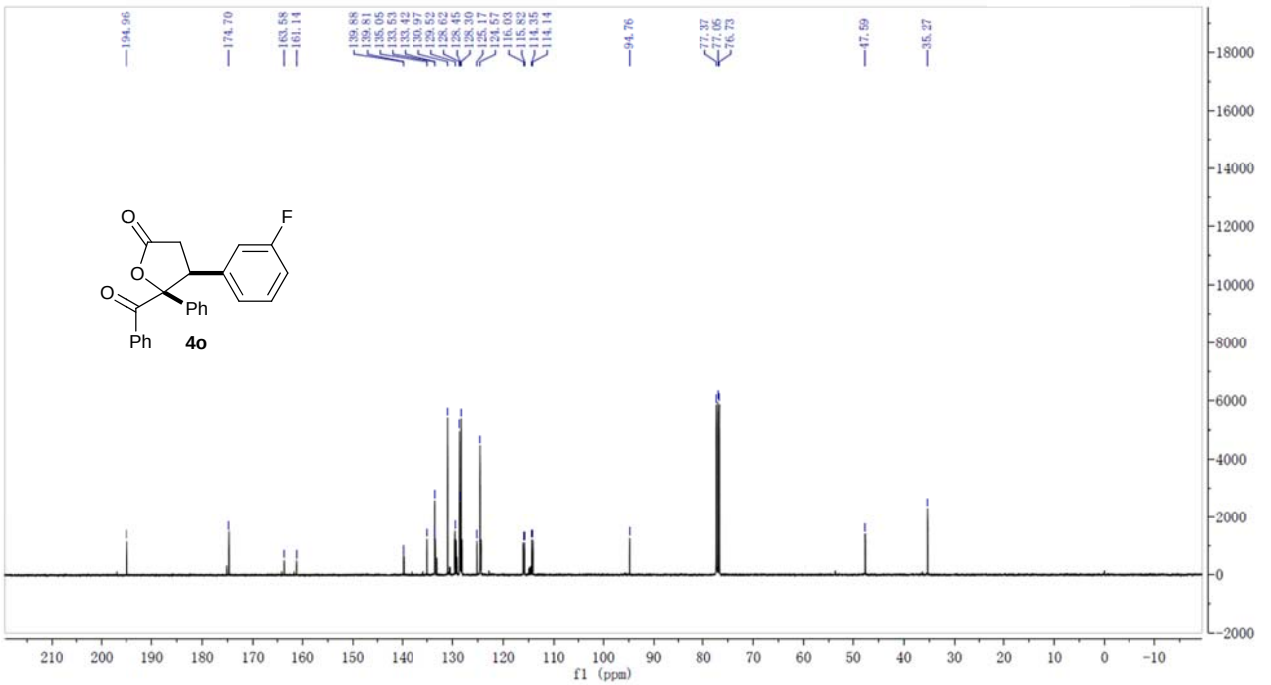
7.880
7.463
7.445
7.427
7.321
7.302
7.283
7.258
7.211
7.192
7.151
7.007
6.810
6.790
4.849
4.831
4.812
3.040
3.019
2.996
2.974
2.843
2.827
2.798
2.782
1.588
0.000
Br
O
O
Ph
Ph
4m
1.94
1.11
2.07
4.76
1.90
1.96
1.02
1.00
1.02
f1 (ppm)

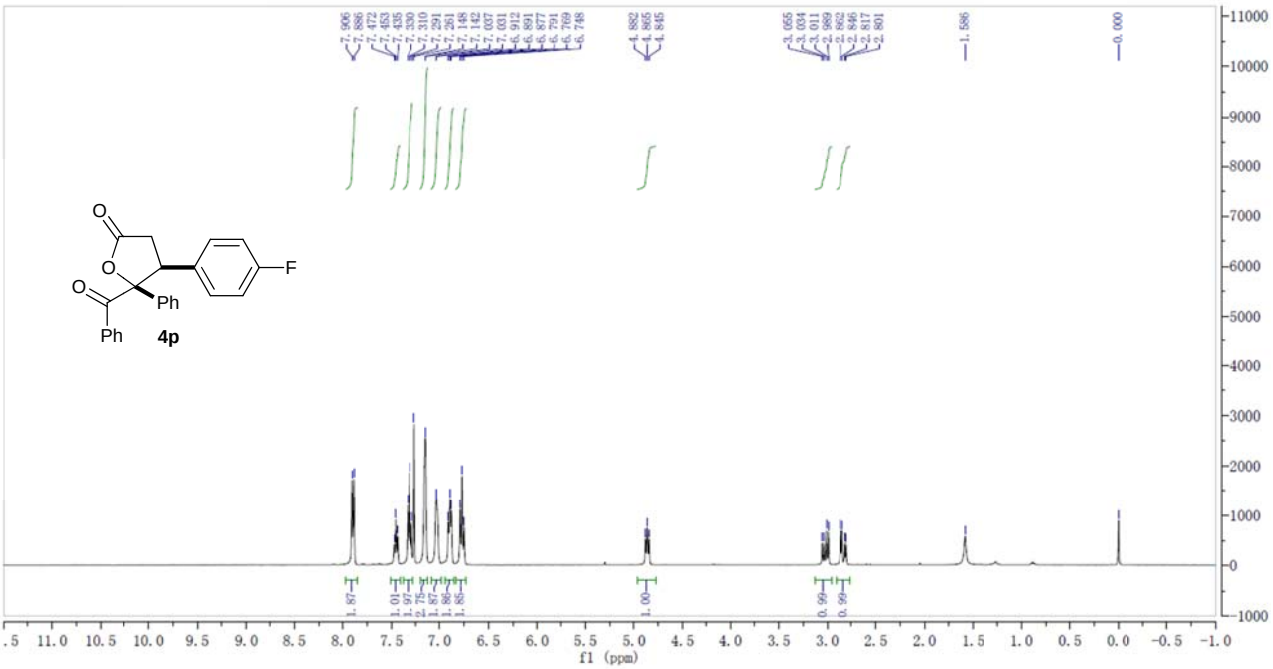

195.04
174.70
136.23
135.02
133.53
133.44
131.16
130.94
130.49
128.70
128.52
128.30
124.62
121.37
94.59
77.36
77.05
76.73
47.48
35.26
Br
O
O
Ph
Ph
4m
f1 (ppm)

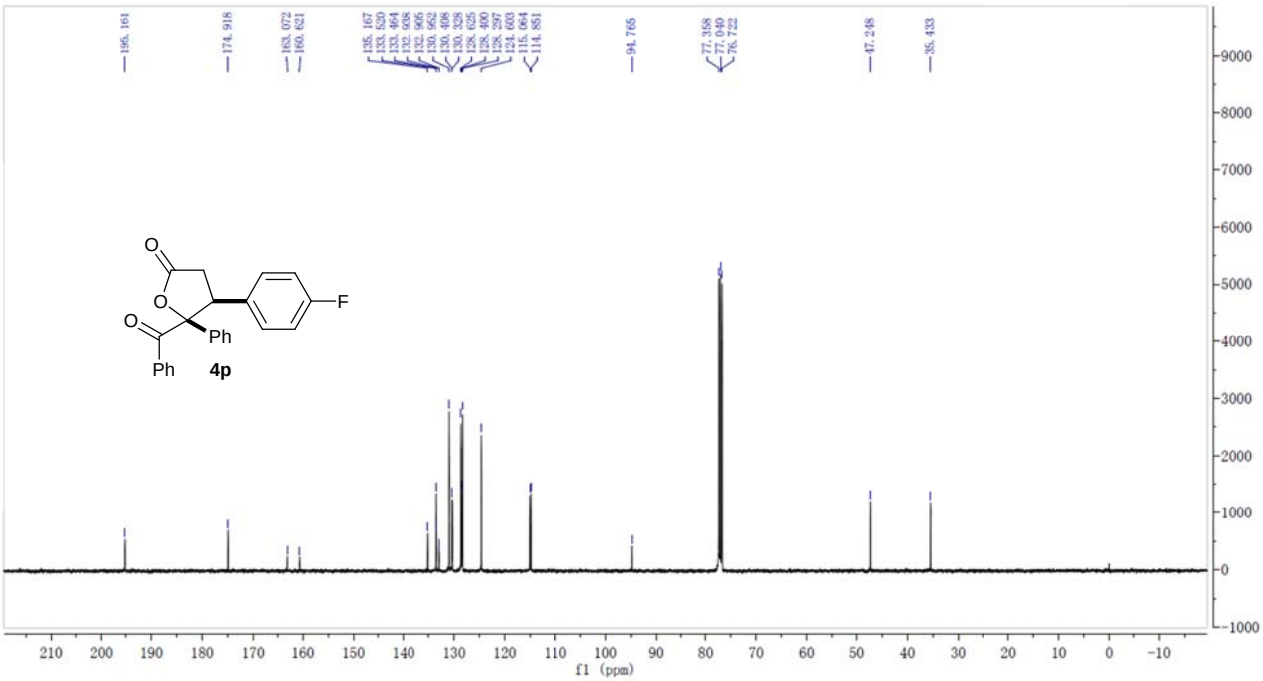

F
O
O
O
Ph
Ph
4n
f1 (ppm)

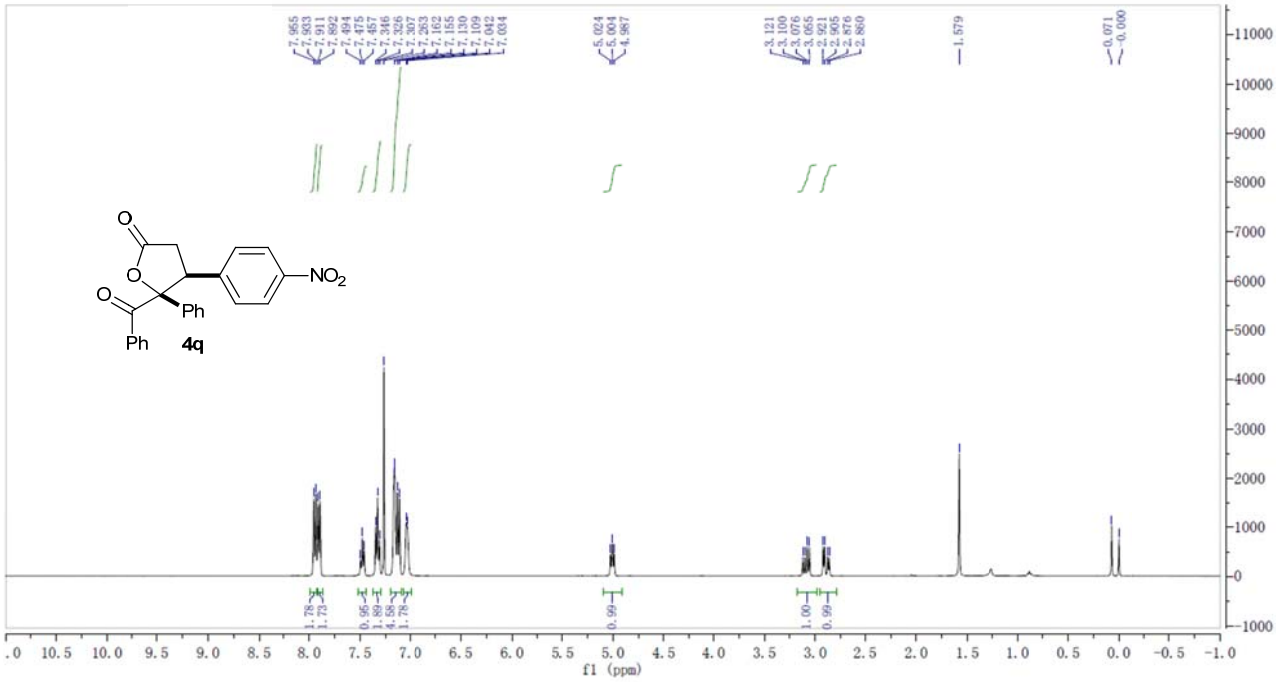

F
O
O
O
Ph
Ph
4n
f1 (ppm)


O
O
O
F
Ph
Ph
4o
f1 (ppm)


O
O
O
F
Ph
Ph
4o
f1 (ppm)


O
O
O
Ph
Ph
F
4p
f1 (ppm)


O
O
O
Ph
Ph
F
4p
f1 (ppm)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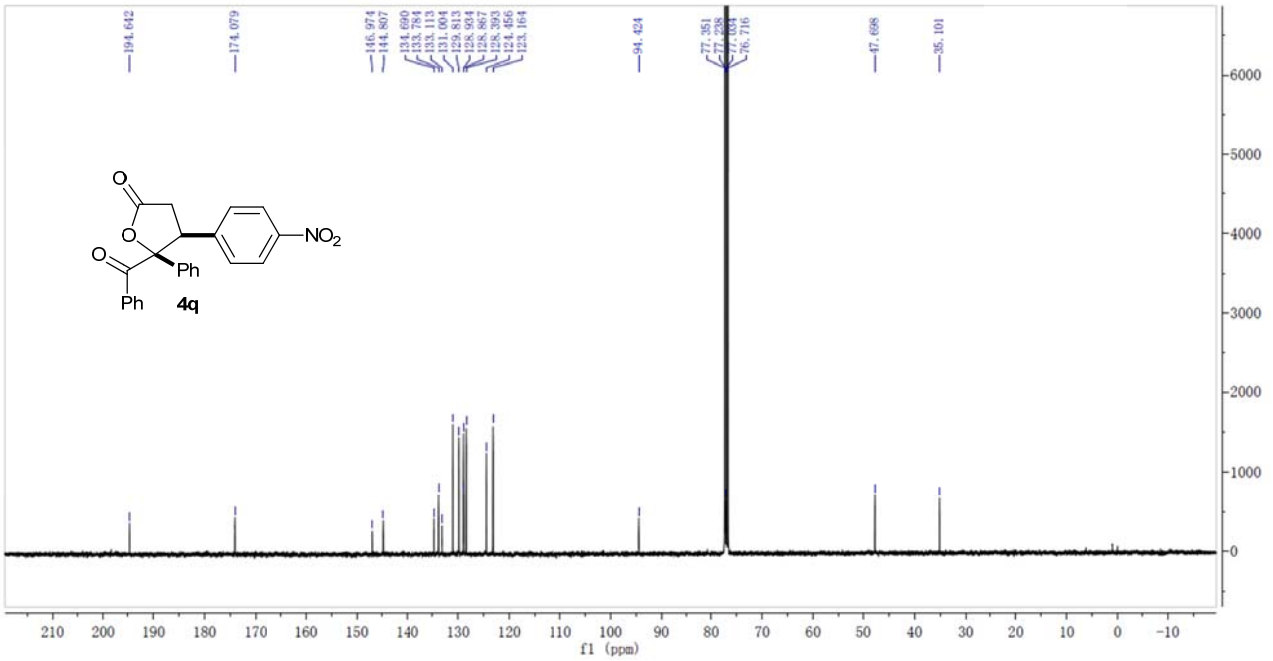
7.933
7.911
7.892
7.474
7.455
7.346
7.326
7.307
7.283
7.162
7.155
7.130
7.109
7.042
7.034
5.024
5.004
4.987
3.121
3.100
3.076
3.055
2.911
2.905
2.876
2.869
1.579
0.071
0.000
O
O
O
Ph
Ph
NO2
4q
1.78
1.73
0.96
1.89
4.58
1.78
0.99
1.00
0.99
f1 (ppm)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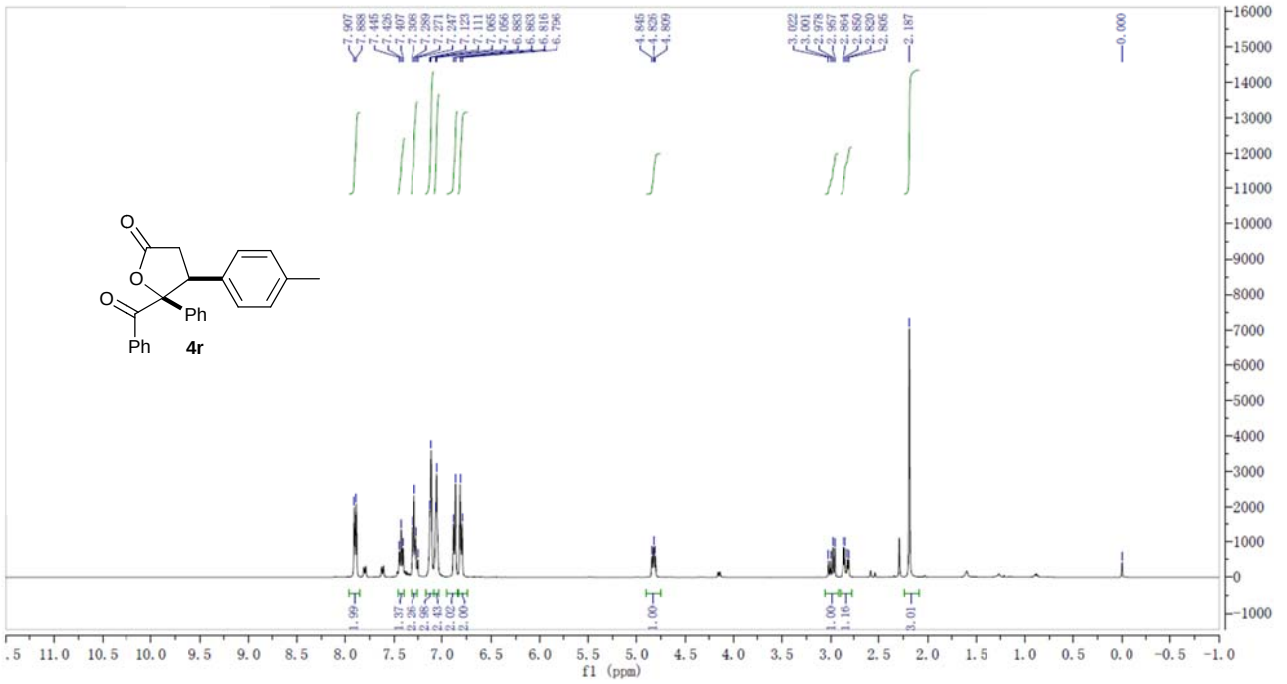
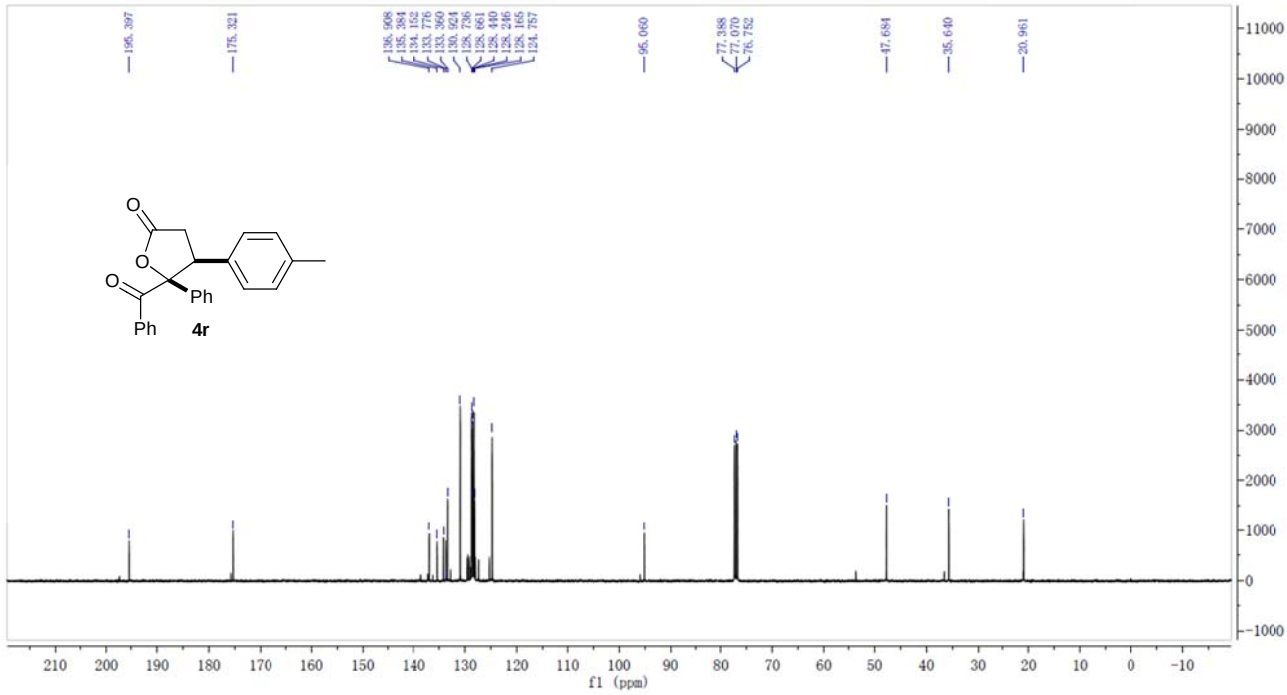
174.079
146.974
144.807
134.690
133.784
133.113
131.004
129.813
128.934
128.867
128.383
124.466
123.164
94.424
77.351
77.039
76.716
47.698
35.101
O
O
O
Ph
Ph
NO2
4q
f1 (ppm)


7.907
7.888
7.445
7.426
7.407
7.396
7.289
7.271
7.247
7.123
7.111
7.065
7.056
6.883
6.863
6.816
6.796
4.845
4.826
4.809
3.022
3.001
2.978
2.957
2.894
2.850
2.820
2.805
2.187
0.000
O
O
O
Ph
Ph
4r
f1 (ppm)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130.924
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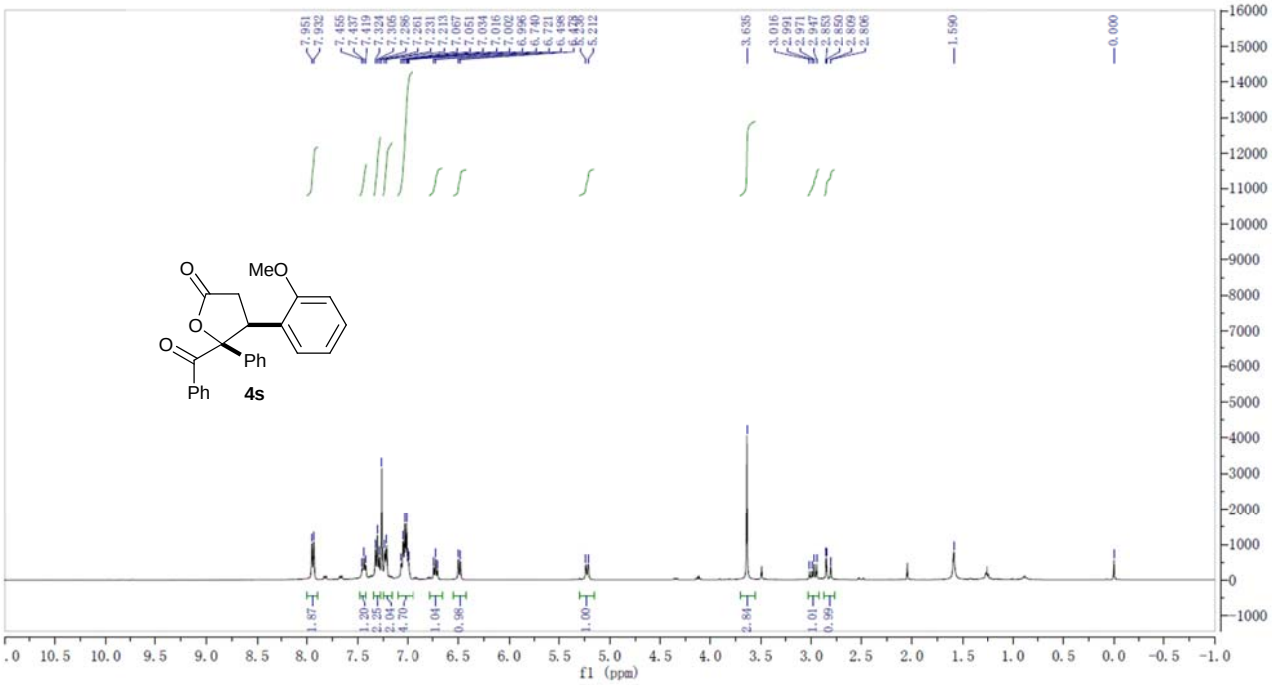
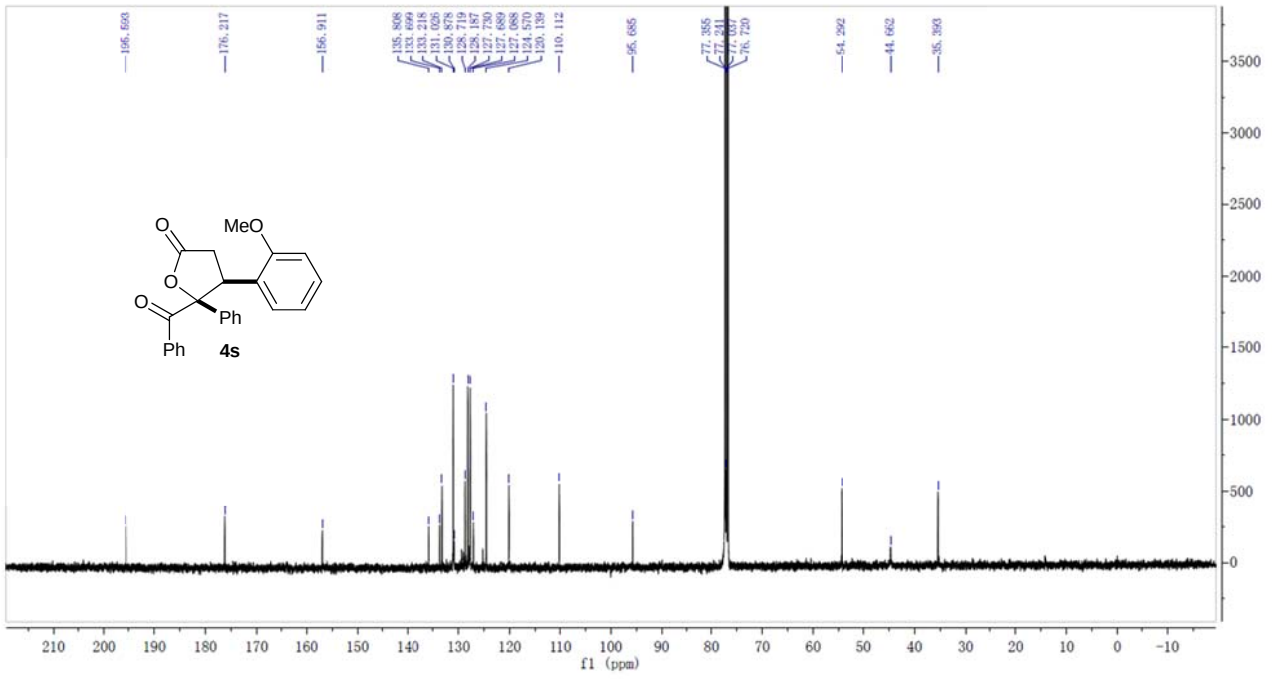
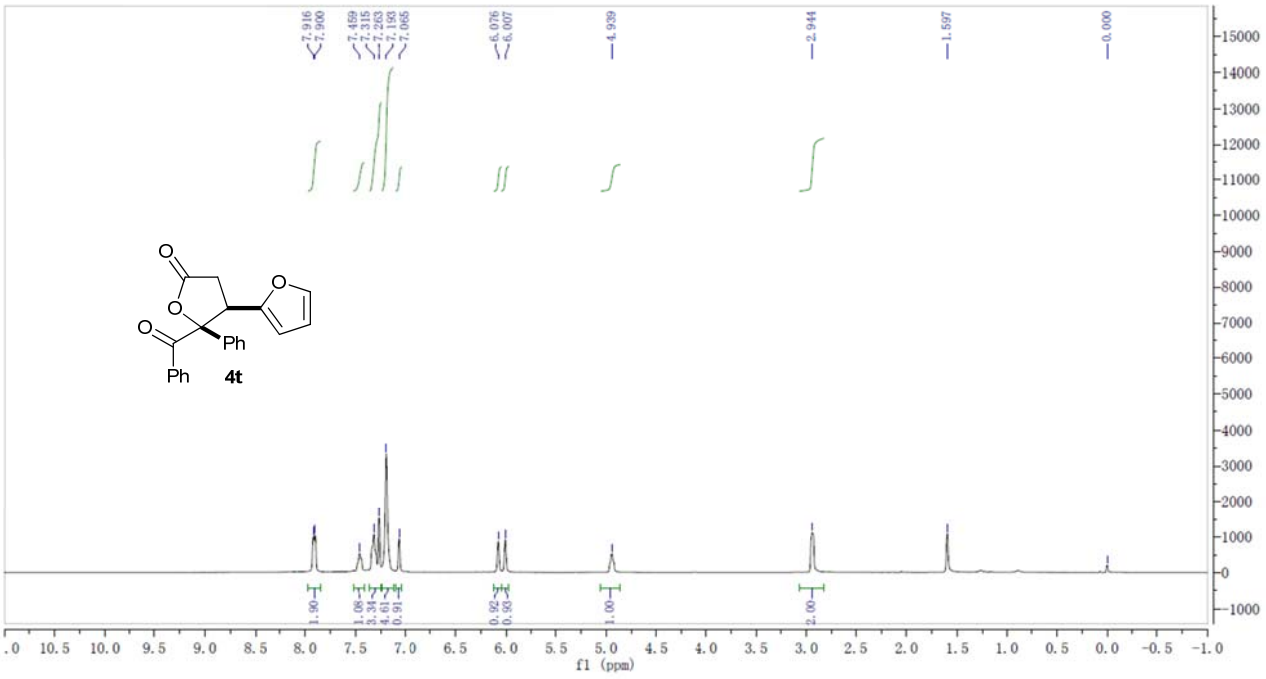
128.661
128.440
128.246
128.165
124.757
95.060
77.388
77.070
76.752
47.684
35.640
20.961
O
O
O
Ph
Ph
4r
f1 (ppm)


MeO
O
O
O
Ph
Ph
4s
f1 (ppm)


MeO
O
O
O
Ph
Ph
4s
f1 (ppm)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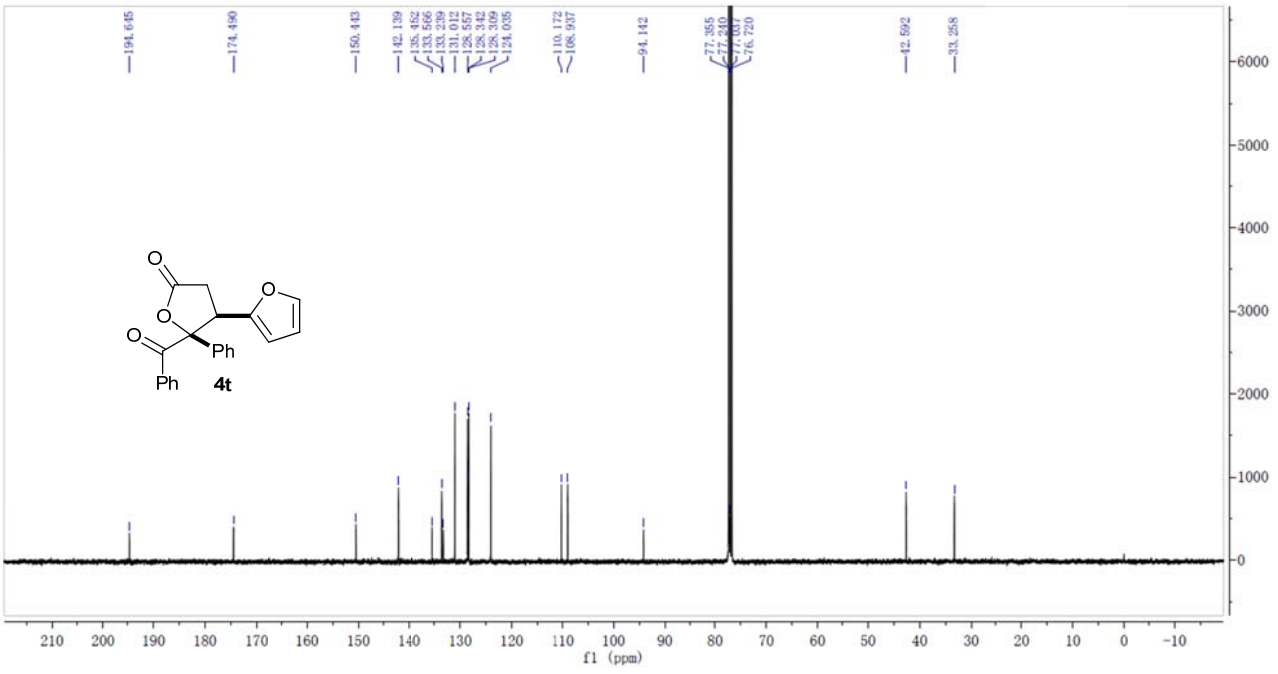
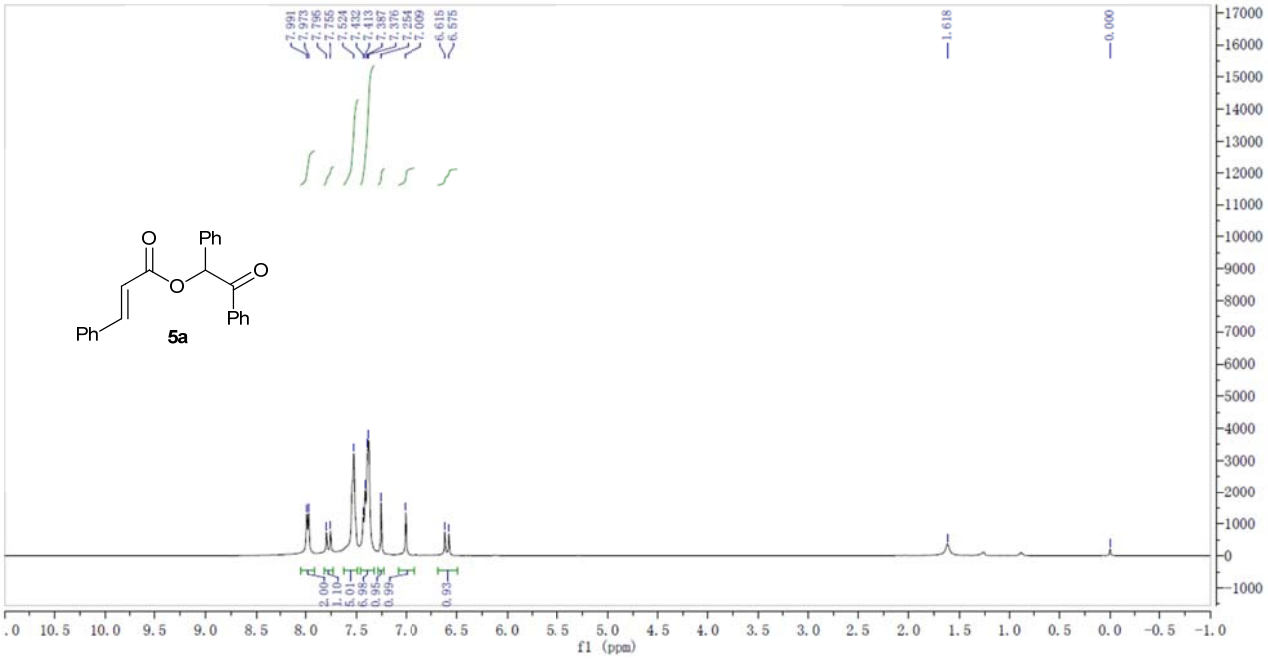
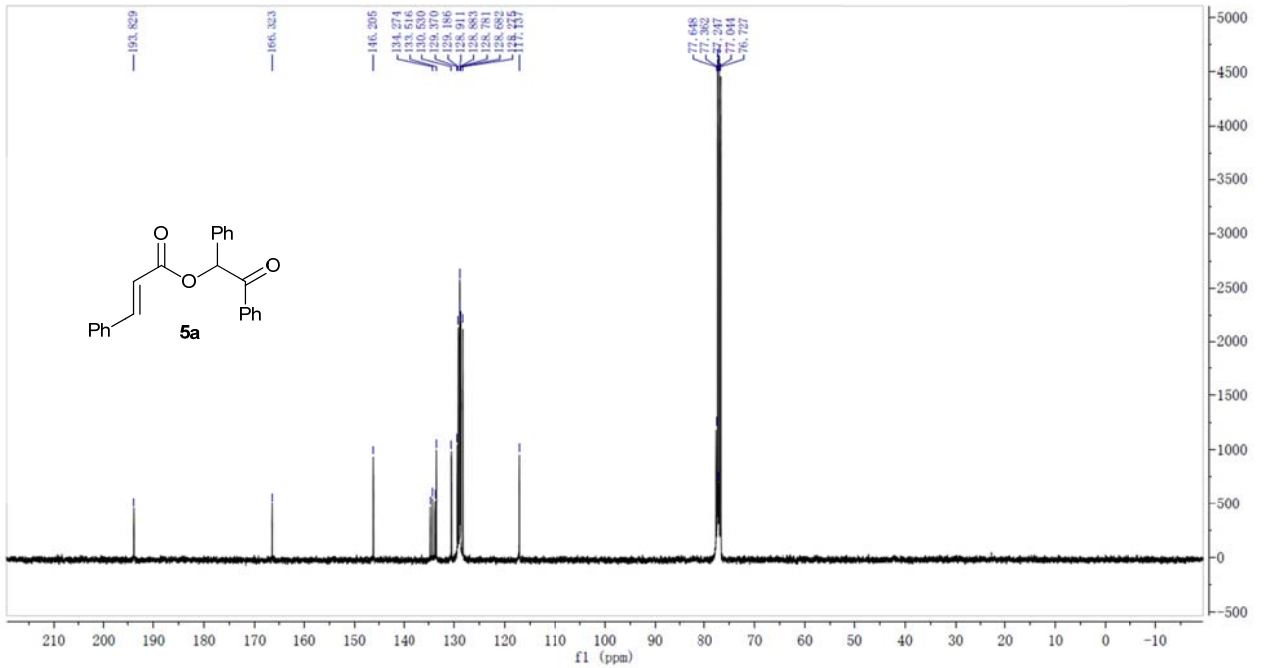
7.315
7.263
7.193
7.065
6.076
6.007
4.939
2.944
1.597
0.000
Ph
Ph
4t
f1 (ppm)


194.645
174.490
150.443
142.139
135.452
133.566
133.239
131.612
131.057
128.342
128.309
124.035
110.172
106.937
94.142
77.355
77.240
77.037
76.720
42.692
33.258
Ph
Ph
4t
f1 (ppm)


7.991
7.973
7.795
7.785
7.554
7.432
7.413
7.387
7.376
7.254
7.009
6.615
6.575
1.618
0.000
Ph
O
O
Ph
O
Ph
5a
2.00
1.10
5.01
6.98
0.95
0.99
0.93
f1 (ppm)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166.323
146.205
134.274
133.516
130.530
129.370
129.186
128.911
128.883
128.781
128.682
77.648
77.362
77.247
77.044
76.727
Ph
O
O
Ph
O
Ph
5a
f1 (ppm)