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Highly Enantioselective Synthesis of Dihydrocoumarin-fused Dihydropyrans via a Phosphine-catalyzed [4+2] Annulation of Allenones with 3-Aroylcoumarins

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Supporting Information

A. General Information 2

B. Representative Procedure for Phosphine-mediated [4+2] Cyclization 2

C. Analytical Data and HPLC Chromatogram of [4+2] Cyclization Adducts 3

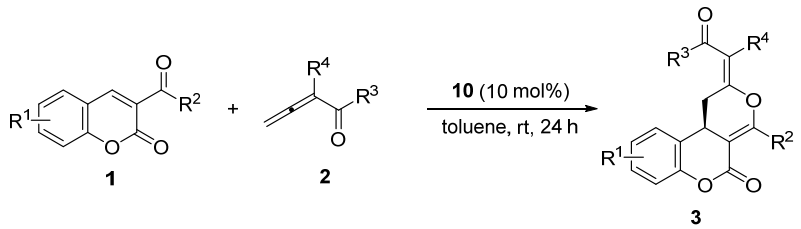
D. Determination of Absolute Configurations of Cyclization Adducts 20

E. NMR Spectra of the Cyclization Adducts 21

A.General Information

All the starting materials were obtained from commercial sources and were used without further purification unless otherwise stated. Toluene, THF and Et_2O were dried and distilled from sodium benzophenone prior to use. $CHCl_3$ and CH_2Cl_2 were distilled from CaH_2 prior to use. Dioxane was dried and distilled from Na prior to use. Optical rotations were measured using a Jasco DIP-1000 polarimeter. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX500 (500 MHz) spectrometer. Chemical shifts were reported in parts per million (ppm), and the residual solvent peak was used as an internal reference: proton (chloroform δ 7.26), carbon (chloroform δ 77.0). Multiplicity was indicated as follows: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), dd (doublet of doublet), br s (broad singlet). Coupling constants were reported in Hertz (Hz). All high resolution mass spectra were obtained on a Finnigan/MAT 95XL-T spectrometer. For thinlayer chromatography (TLC), Merck pre-coated TLC plates (Merck 60 F254) were used, and compounds were visualized with a UV light at 254 nm. Further visualization was achieved by staining with iodine, or ceric ammonium molybdate followed by heating on a hot plate. Flash chromatographic separations were performed on Merck 60 (0.040- 0.063 mm) mesh silica gel. Enantiomeric excesses were determined by HPLC analysis on achiral stationary phase. The coumaine-based compound **1**[1]and catalysts **4a**–**9**[2]were synthesized according to literature reported methods. Allenone **2** was synthesized via Wittig reaction from the corresponding triphenyl phosphonium ylied with ethenone.

B. Representavie Procedure For Phosphine-Mediated [4+2] Annulation of Allenones and 3-Aroylcoumarins



To a solution of3-aroylcoumarin **1** (0.1 mmol) in toluene (1 mL) was added allenone **2** (0.12 mmol),and the resulting mixture was stirred at room temperature for 24 h. At the end of the reaction, the solvent was removed *in vacuo* and the residue was purified by column chromatography on silica gel (hexane/EtOAc = 15:1 to 10:1) to afford the cyclization adducts **3** (83-94% yields, 76-94% ee's).

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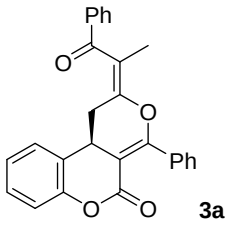
1 (*a*) Y. Wang, Z.-H.Yu, H.-F.Zheng and D.-Q. Shi, *Org. Biomol. Chem.*, **2012**, *10*, 7739; (*b*) T.-Y.Jian, X.-Y.Chen, L.-H. Sun and S. Ye, *Org. Biomol. Chem.*, **2013**, *11*, 158.

2 (*a*) X.Han, Y.Wang, F.Zhong and Y. Lu,*J. Am. Chem. Soc.***2011**, *133*, 1726; (*b*) F.Zhong,X.Han, Y.Wang and Y. Lu, *Chem. Sci.* **2012**, *3*, 1231; (*c*) F.Zhong, X.Han, Y.Wang and Y.Lu, *Angew. Chem., Int. Ed.***2011**,*50*, 7837; (*d*)F.Zhong, G.-Y.Chen, X.Han, W.Yao and Y.Lu, *Org.Lett.***2012**, *14*,3764; (*e*) W.Yao, X.Dou and Y.Lu, *J. Am. Chem. Soc.***2015**, *137*, 54.

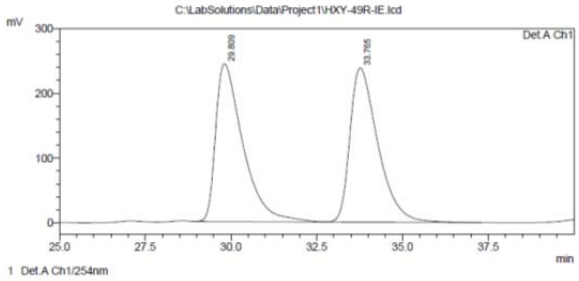
C. Analytical Data and HPLC Chromatogram of [4+2]CyclizationAdducts

(*R*,*E*)-2-(1-Oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3a**)



3a

89% yield, a white solid; $[\alpha]^{25}_{D}$ = -195.55 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97 – 7.89 (m, 2H), 7.65 (t, *J* = 7.4 Hz, 1H), 7.62 – 7.58 (m, 2H), 7.57 – 7.50 (m, 3H), 7.49 – 7.44 (m, 2H), 7.31 (d, *J* = 7.8 Hz, 1H), 7.14 – 7.07 (m, 2H), 7.01 (d, *J* = 7.7 Hz, 1H), 3.94 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.47 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.44 (ddd, *J* = 14.1Hz, 12.0Hz, 2.1 Hz, 1H), 2.18 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.63, 163.03, 162.33, 150.78, 150.16, 137.64, 133.58, 133.43, 130.72, 129.10, 128.96,129.82, 128.86, 128.26, 125.19, 124.59, 123.07, 118.46, 117.08, 100.19, 31.45, 27.33, 14.04; HRMS (APCI) m/z calcd for $C_{27}H_{21}O_4$ $[M+H]^+$ = 409.1434, found = 409.1436; the ee value was 91%, t_R (major) = 29.5 min, t_R (minor) = 33.7 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

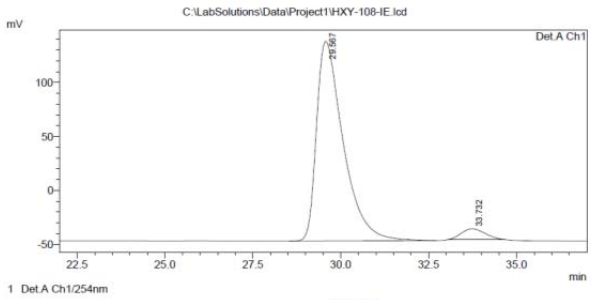


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	29.809	13471801	243720	49.955	50.568
2	33.765	13496341	238246	50.045	49.432
Total		26968142	481966	100.000	100.000

Racemic**3a**



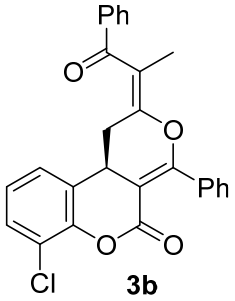
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	29.567	9761881	184825	95.294	94.812
2	33.732	482046	10114	4.706	5.188
Total		10243926	194940	100.000	100.000

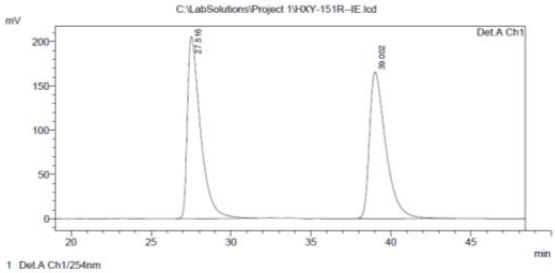
Enantiomerically enriched **3a**

(*R*,*E*)-7-Chloro-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3b**)



3b

91% yield, a white solid; $[\alpha]^{25}_{D}$ = -98.26 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, $CDCl_3$) δ 7.93 – 7.86 (m, 2H), 7.65 – 7.57 (m, 3H), 7.56 – 7.48 (m, 3H), 7.47 – 7.41 (m, 2H), 7.35 (d, *J* = 8.0 Hz, 1H), 7.01 (t, *J* = 7.9 Hz, 1H), 6.89 (dd, *J* = 7.8Hz, 1.1 Hz, 1H), 3.93 (dd, *J* = 11.8Hz, 5.7 Hz, 1H), 3.44 (dd, *J* = 14.1Hz, 5.8 Hz, 1H), 2.43 (ddd, *J* = 14.0Hz, 8.0Hz, 2.1 Hz, 1H), 2.15 (d, *J* = 2.0 Hz, 3H);^{13}C NMR (126 MHz, $CDCl_3$) δ 197.48, 163.65, 161.04, 149.70, 146.91, 137.51, 133.48, 133.25, 130.88, 129.65, 129.11, 129.02, 128.96, 128.28, 124.99, 124.65, 123.43, 122.14, 118.84, 99.26, 31.85, 29.70, 27.22, 14.07; HRMS (APCI) m/z calcd for $C_{27}H_{20}ClO_4$ $[M+H]^+$ =443.1045, found =443.1048; the ee value was 93%, t_R (major) = 27.1 min, t_R (minor) = 39.1 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

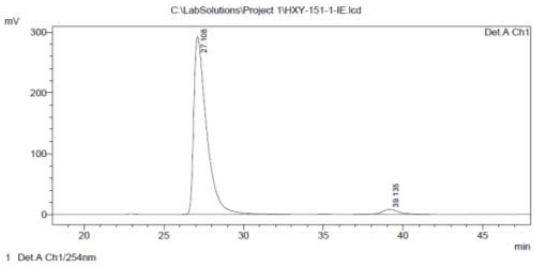


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	27.516	11681901	205258	49.938	55.416
2	39.002	11710914	165136	50.062	44.584
Total		23392815	370394	100.000	100.000

Racemic**3b**



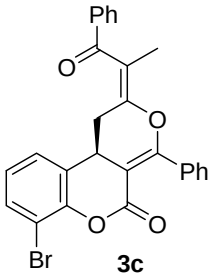
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	27.108	16305392	292116	96.590	97.324
2	39.135	575704	8031	3.410	2.676
Total		16881096	300147	100.000	100.000

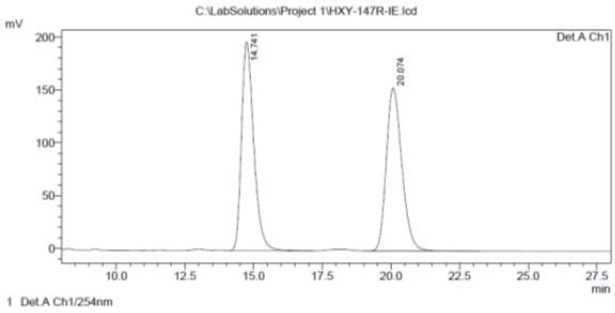
Enantiomerically enriched **3b**

(*R*,*E*)-7-Bromo-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3c**)



3c

92% yield, a white solid; $[\alpha]^{25}_{D}$ = -172.19 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, $CDCl_3$) δ 7.92 (d, *J* = 7.2 Hz, 2H), 7.63 (dt, *J* = 15.5Hz, 4.4 Hz, 3H), 7.58 – 7.50 (m, 4H), 7.47 (t, *J* = 7.4 Hz, 2H), 7.01 – 6.94 (m, 2H), 3.96 (dd, *J* = 11.8Hz, 5.7 Hz, 1H), 3.46 (dd, *J* = 14.1Hz, 5.8 Hz, 1H), 2.45 (ddd, *J* = 14.0Hz, 12.0Hz, 2.1 Hz, 1H), 2.18 (d, *J* = 1.9 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.51, 163.62, 161.13, 149.70, 147.93, 137.48, 133.50, 133.22, 132.73, 130.89, 129.12, 129.04, 128.97, 128.29, 125.17, 124.99, 124.21, 118.85, 111.00, 99.34, 31.91, 27.18, 14.10; HRMS (APCI) m/z calcd for $C_{27}H_{20}BrO_4$ $[M+H]^+$ = 487.0539, found = 487.0535; the ee value was 90%, t_R (major) = 14.7 min, t_R (minor) = 20.2 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

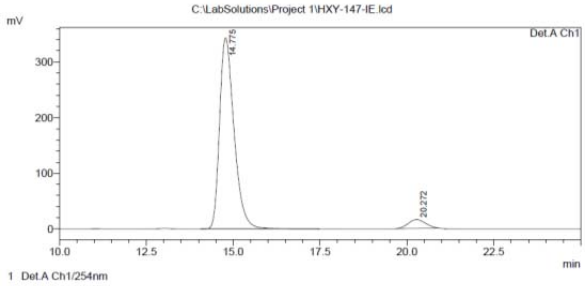


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.741	6111227	197182	50.107	56.122
2	20.074	6085172	154162	49.893	43.878
Total		12196399	351344	100.000	100.000

Racemic**3c**



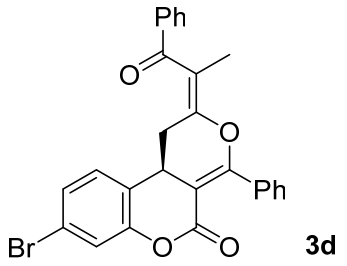
PeakTable

Detector A Ch1 254nm

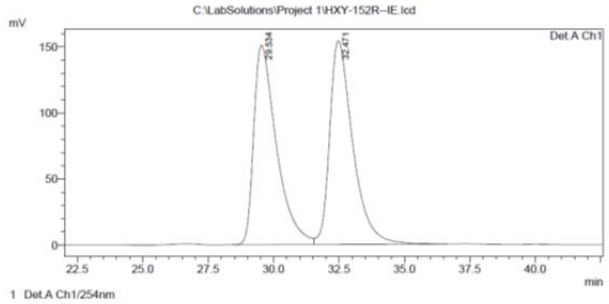
Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.775	9963178	343448	94.900	95.661
2	20.272	535392	15577	5.100	4.339
Total		10498570	359025	100.000	100.000

Enantiomerically enriched **3c**

(*R*,*E*)-8-Bromo-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3d**)



93% yield, awhite solid; $[\alpha]^{25}_{D}$ = -105.44 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, $CDCl_3$) δ 7.95 – 7.88 (m, 2H), 7.65 (ddd, *J* = 8.7Hz, 2.4Hz, 1.2 Hz, 1H), 7.62 – 7.50 (m, 5H), 7.49 – 7.43 (m, 2H), 7.27 – 7.20 (m, 2H), 6.88 (dd, *J* = 8.1Hz, 0.8 Hz, 1H), 3.87 (dd, *J* = 11.5Hz, 5.9 Hz, 1H), 3.45 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.41 (ddd, *J* = 14.1Hz, 12.0Hz, 2.2 Hz, 1H), 2.17 (d, *J* = 2.0 Hz, 3H);^{13}C NMR (126 MHz, $CDCl_3$) δ 197.46, 163.62, 160.54, 151.31, 149.73, 137.51, 133.48, 133.37, 130.84, 129.10, 128.96, 128.93, 128.29, 127.58, 126.52, 122.19, 121.74, 120.30, 118.78, 99.39, 31.29, 27.19, 14.05; HRMS (APCI) m/z calcd for $C_{27}H_{20}BrO_4$ $[M+H]^+$ = 487.0539, found = 487.0542; the ee value was 90%, t_R (major) = 29.1 min, t_R (minor) = 32.3 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

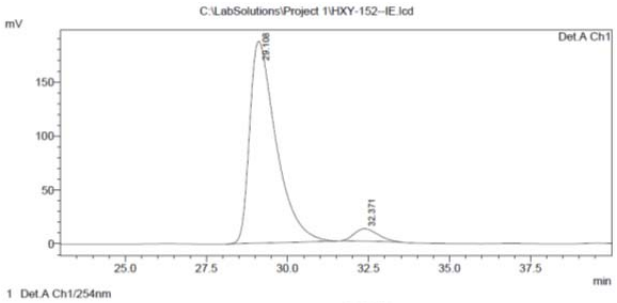


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	29.534	9129206	150985	49.035	49.483
2	32.471	9488699	154139	50.965	50.517
Total		18617905	305124	100.000	100.000

Racemic**3d**



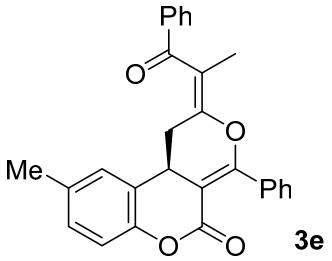
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	29.108	10651714	187164	94.784	94.169
2	32.371	586117	11589	5.216	5.831
Total		11237831	198753	100.000	100.000

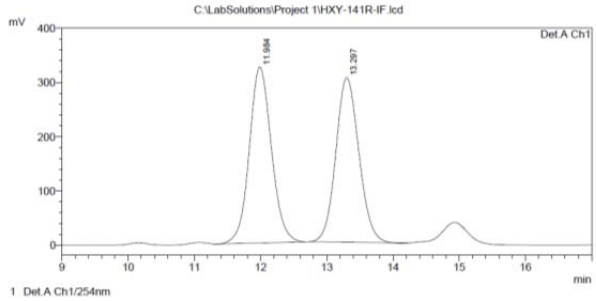
Enantiomerically enriched **3d**

(*R*,*E*)-9-Methyl-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3e**)



3e

83% yield, a white solid; $[\alpha]^{25}_{D}$ = -50.12 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, $CDCl_3$) δ 7.96 – 7.89 (m, 2H), 7.68 – 7.62 (m, 1H), 7.61 – 7.49 (m, 5H), 7.49 – 7.43 (m, 2H), 7.09 (d, *J* = 7.9 Hz, 1H), 6.98 (d, *J* = 8.2 Hz, 1H), 6.82 (s, 1H), 3.91 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.50 (dd, *J* = 14.2Hz, 5.7 Hz, 1H), 2.44 (ddd, *J* = 14.2Hz, 12.1Hz, 2.2 Hz, 1H), 2.30 (s, 3H), 2.17 (d, *J* = 2.0 Hz, 3H);^{13}C NMR (126 MHz, $CDCl_3$) δ 197.73, 162.83, 162.53, 150.48, 148.64, 137.63, 134.24, 133.64, 133.36, 130.66, 129.31, 129.12, 128.96, 128.93, 128.24, 125.61, 122.63, 118.30, 116.77, 100.51, 31.44, 27.28, 20.82, 14.05; HRMS (APCI) m/z calcd for $C_{28}H_{23}O_4$ $[M+H]^+$ = 423.1591, found = 423.1596; the ee value was 90%, t_R (minor) = 13.5 min, t_R (major) = 12.0min (Chiralcel IF-H, λ = 254 nm, 30% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

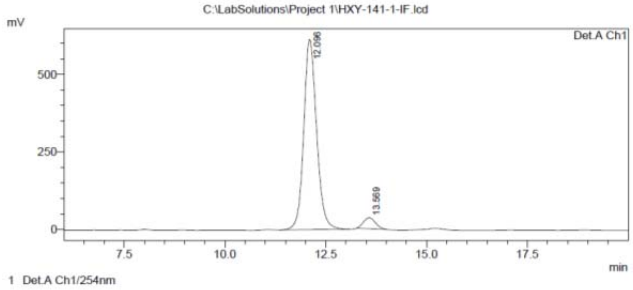


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	11.984	7539177	324101	50.615	51.647
2	13.297	7355893	303432	49.385	48.353
Total		14895070	627533	100.000	100.000

Racemic**3e**



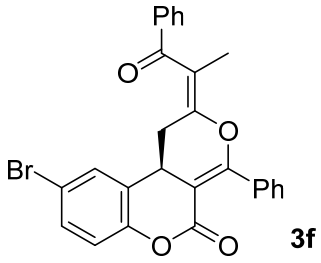
PeakTable

Detector A Ch1 254nm

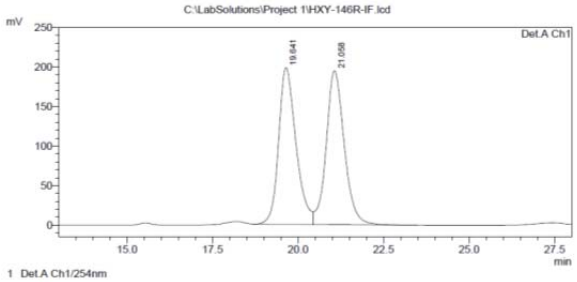
Peak#	Ret. Time	Area	Height	Area %	Height %
1	12.096	13582379	612981	94.957	94.603
2	13.569	721371	34971	5.043	5.397
Total		14303749	647952	100.000	100.000

Enantiomerically enriched **3e**

(*R*,*E*)-9-Bromo-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3f**)



88% yield, a white solid; $[\alpha]^{25}_{D}$ = -141.83 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, Acetone-d_6) δ 8.02 – 7.94 (m, 2H), 7.72 – 7.67 (m, 1H), 7.67 – 7.57 (m, 4H), 7.53 – 7.42 (m, 4H), 7.28 – 7.23 (m, 1H), 7.00 (d, *J* = 8.6 Hz, 1H), 4.11 (dd, *J* = 11.8Hz, 5.7 Hz, 1H), 3.49 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.51 (ddd, *J* = 14.1Hz, 11.9Hz, 2.1 Hz, 1H), 2.14 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, acetone-d_6) δ^{13}C NMR (126 MHz, $CDCl_3$) δ 196.66, 162.99, 150.22, 150.06, 138.07, 134.29, 133.10, 131.52, 130.23, 129.10, 128.99, 128.90, 128.51, 128.15, 127.98, 126.14, 118.55, 118.20, 116.33, 99.78, 31.24, 27.01, 13.15;HRMS (APCI) m/z calcd for $C_{27}H_{20}BrO_4$ $[M+H]^+$ = 487.0539, found = 487.0545;the ee value was 91%, t_R (major) = 19.7 min, t_R (minor) = 21.2 min (Chiralcel IF-H, λ = 254 nm, 10% *i*PrOH/hexanes, flow rate = 1.2 mL/min).

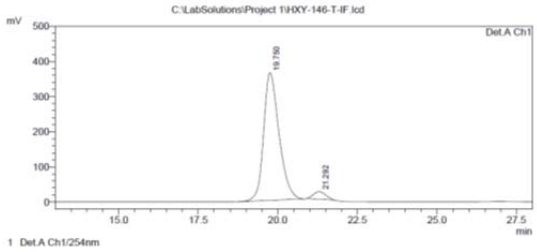


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	19.641	6997774	198128	49.446	50.441
2	21.058	7154548	194663	50.554	49.559
Total		14152321	392791	100.000	100.000

Racemic**3f**



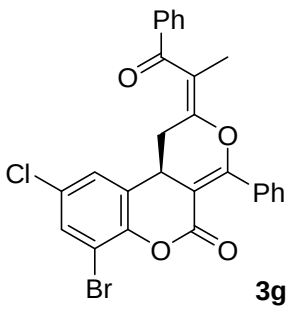
PeakTable

Detector A Ch1 254nm

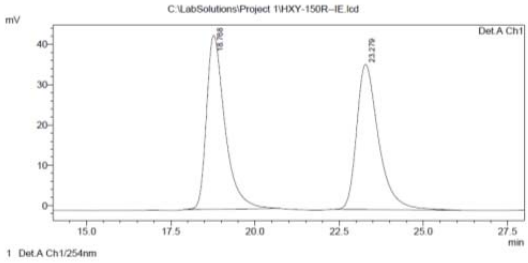
Peak#	Ret. Time	Area	Height	Area %	Height %
1	19.750	12192345	362812	95.434	94.418
2	21.292	583358	21449	4.566	5.582
Total		12775703	384261	100.000	100.000

Enantiomerically enriched **3f**

(*R*,*E*)-7-Bromo-9-chloro-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-c]chromen-5-one (**3g**)



89% yield, a white solid; $[\alpha]^{25}_{D}$ = -81.74 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94 – 7.87 (m, 2H), 7.66 (ddd, *J* = 6.9Hz, 2.3Hz, 1.1 Hz, 1H), 7.62 – 7.51 (m, 6H), 7.49 – 7.44 (m, 2H), 6.97 (dd, *J* = 2.3Hz, 1.3 Hz, 1H), 3.95 (dd, *J* = 11.7Hz, 5.7 Hz, 1H), 3.44 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.46 (ddd, *J* = 14.0Hz, 11.8Hz, 2.1 Hz, 1H), 2.17 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.35, 164.21, 160.57, 149.22, 146.81, 137.29, 133.58, 133.06, 132.20, 131.01, 129.88, 129.13, 129.01, 129.00, 128.31, 126.03, 124.46, 119.27, 111.56, 98.48, 31.99, 26.92, 14.12; HRMS (APCI) m/z calcd for $C_{27}H_{19}BrClO_4$ $[M+H]^+$ = 521.0150, found = 521.0145;the ee value was 94%, t_R (major) = 18.6 min, t_R (minor) = 23.5 min (Chiralcel IE-H, λ = 254 nm, 8% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

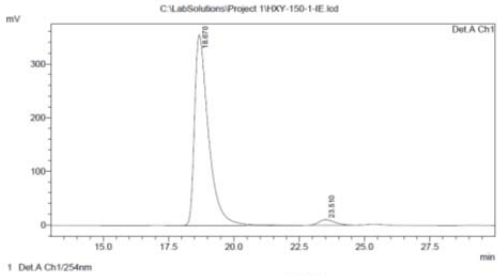


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	18.768	1639710	43128	50.110	54.515
2	23.279	1632532	35985	49.890	45.485
Total		3272242	79113	100.000	100.000

Racemic**3g**



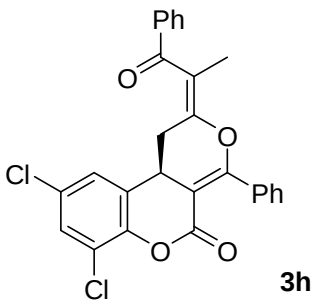
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	18.670	13219413	355289	96.817	97.153
2	23.510	434649	10410	3.183	2.847
Total		13654062	365698	100.000	100.000

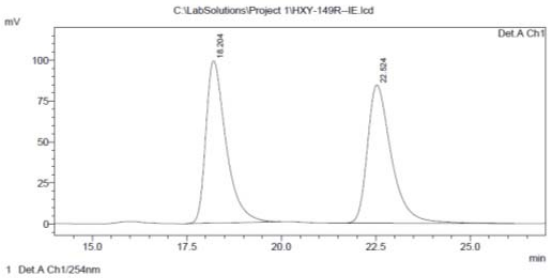
Enantiomerically enriched **3g**

(*R*,*E*)-7,9-Dichloro-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3h**)



3h

94% yield, a white solid; $[\alpha]^{25}_{D}$ = -174.28 (c 1.00, $CHCl_3$);^{1}H NMR (500 MHz, $CDCl_3$) δ 7.95 – 7.89 (m, 2H), 7.66 (t, *J* = 7.4 Hz, 1H), 7.62 – 7.50 (m, 5H), 7.47 (t, *J* = 7.5 Hz, 2H), 7.38 (d, *J* = 2.3 Hz, 1H), 6.95 – 6.88 (m, 1H), 3.94 (dd, *J* = 11.8Hz, 5.7 Hz, 1H), 3.44 (dd, *J* = 14.1Hz, 5.8 Hz, 1H), 2.46 (ddd, *J* = 14.0Hz, 11.9Hz, 2.1 Hz, 1H), 2.17 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.35, 164.25, 160.51, 149.21, 145.73, 137.28, 133.58, 133.06, 131.03, 129.53, 129.34, 129.13, 129.00(2 carbon overlap), 128.32, 126.12, 123.75, 122.99, 119.28, 98.39, 31.93, 26.93, 14.11;HRMS (APCI) m/z calcd for $C_{27}H_{19}Cl_2O_4$ $[M+H]^+$ = 477.0655, found = 477.0658; the ee value was 92%, t_R (major) = 17.9 min, t_R (minor) = 22.5 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

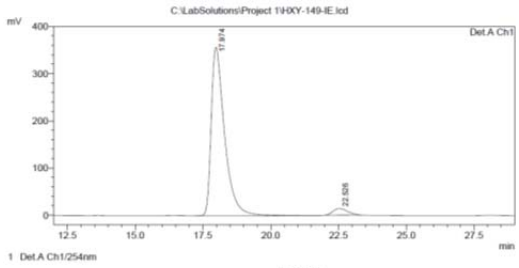


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	18.204	3680373	99166	49.614	53.984
2	22.524	3737660	84528	50.386	46.016
Total		7418033	183694	100.000	100.000

Racemic**3h**



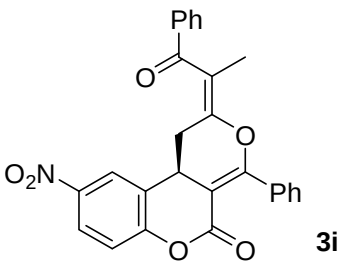
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	17.974	12247565	357191	95.960	96.213
2	22.526	515619	14058	4.040	3.787
Total		12763185	371249	100.000	100.000

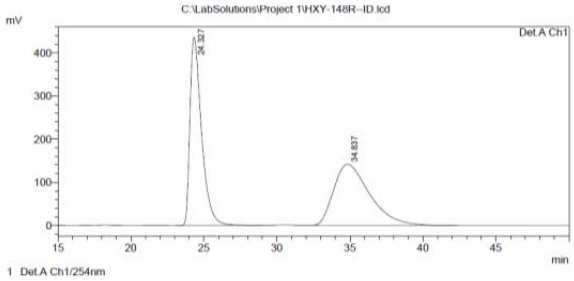
Enantiomerically enriched **3h**

(*R*,*E*)-9-Nitro-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3i**)



3i

90% yield, a yellow solid; $[\alpha]^{25}_{D}$ = -174.28(c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.21 (ddd, *J* = 8.9Hz, 2.6Hz, 0.7 Hz, 1H), 7.96 – 7.91 (m, 2H), 7.71 – 7.65 (m, 1H), 7.63 – 7.52 (m, 4H), 7.49 (t, *J* = 7.4 Hz, 2H), 7.28 (t, *J* = 7.5 Hz, 1H), 7.21 (d, *J* = 8.9 Hz, 2H), 4.01 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.55 (dd, *J* = 14.0Hz, 5.7 Hz, 1H), 2.50 (ddd, *J* = 14.0Hz, 11.9Hz, 2.2 Hz, 1H), 2.19 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.25, 164.87, 155.32, 148.95, 144.30, 137.27, 133.71, 133.06, 131.13, 129.14, 129.06, 128.93, 128.38, 128.23, 124.86, 124.39, 121.56, 119.67, 117.97, 97.89, 31.56, 26.95, 14.11; HRMS (APCI) m/z calcd for $C_{27}H_{20}NO_6$ $[M+H]^+$ = 454.1285, found = 454.1294; the ee value was 83%, t_R (major) = 35.8 min, t_R (minor) = 25.0 min (Chiralcel ID-H, λ = 254 nm, 30% *i*PrOH/hexanes, flow rate = 1.2 mL/min).

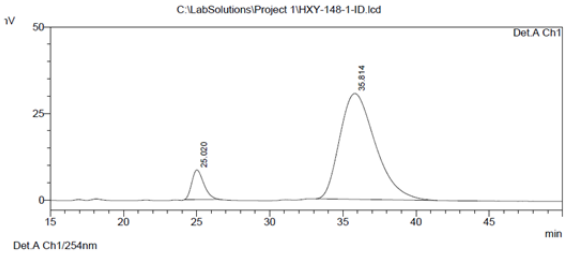


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	24.327	24122993	436643	49.877	75.505
2	34.837	24242247	141656	50.123	24.495
Total		48365240	578299	100.000	100.000

Racemic**3i**



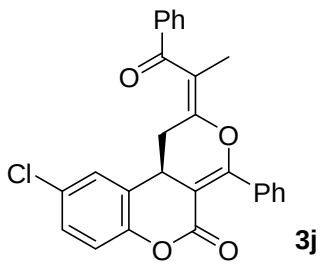
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	25.020	489557	8538	8.639	21.827
2	35.814	5177507	30579	91.361	78.173
Total		5667064	39117	100.000	100.000

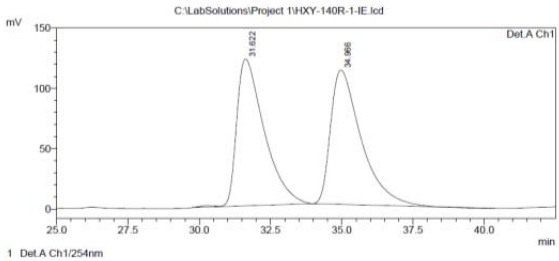
Enantiomerically enriched **3i**

(*R*,*E*)-9-Chloro-2-(1-oxo-1-phenylpropan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3j**)



3j

87% yield, a white solid; $[\alpha]^{25}_{D}$ = -169.36(c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.95 – 7.90 (m, 2H), 7.69 – 7.64 (m, 1H), 7.61 – 7.56 (m, 2H), 7.56 – 7.51 (m, 2H), 7.50 – 7.44 (m, 2H), 7.31 – 7.24 (m, 1H), 7.20 (dd, *J* = 6.6Hz, 6.0 Hz, 1H), 7.05 – 6.98 (m, 2H), 3.93 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.46 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.45 (ddd, *J* = 14.1Hz, 12.0Hz, 2.2 Hz, 1H), 2.18 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.48, 163.68, 149.62, 149.34, 137.41, 133.54, 130.87, 129.78, 129.14, 129.05, 129.00, 128.95, 128.90, 128.30, 128.24, 125.38, 124.75, 118.90, 118.41, 99.24, 31.51, 27.05, 14.09; HRMS (APCI) m/z calcd for $C_{27}H_{20}ClO_4$ $[M+H]^+$ = 443.1045, found = 443.1047; the ee value was 90%, t_R (minor) = 9.0 min,t_R (major) = 11.1 min (Chiralcel IF-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

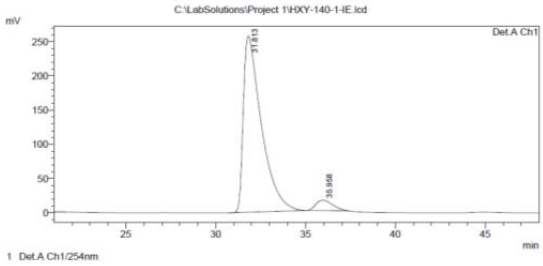


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	31.622	8186034	121697	49.584	52.219
2	34.966	8323523	111355	50.416	47.781
Total		16509558	233051	100.000	100.000

Racemic**3j**



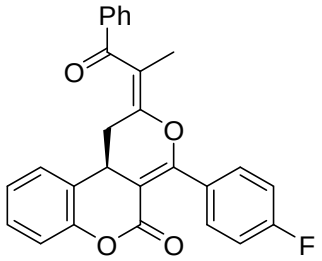
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	31.813	17991289	257277	94.763	94.358
2	35.958	994297	15383	5.237	5.642
Total		18985586	272660	100.000	100.000

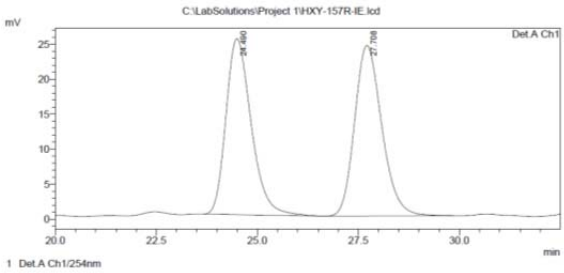
Enantiomerically enriched **3j**

(*R*,*E*)-4-(4-Fluorophenyl)-2-(1-oxo-1-phenylpropan-2-ylidene)-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3k**)



3k

88% yield, a white solid; $[\alpha]^{25}_{D}$ = -96.93 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.99 – 7.88 (m, 2H), 7.65 (t, *J* = 7.4 Hz, 1H), 7.59 – 7.44 (m, 4H), 7.28 (t, *J* = 11.9 Hz, 2H), 7.20 – 7.14 (m, 1H), 7.09 (t, *J* = 7.5 Hz, 2H), 7.00 (d, *J* = 7.7 Hz, 1H), 3.97 (dd, *J* = 12.0Hz, 5.6 Hz, 1H), 3.48 (dd, *J* = 14.2Hz, 5.6 Hz, 1H), 2.45 (ddd, *J* = 14.2Hz, 12.1Hz, 2.2 Hz, 1H), 2.14 (d, *J* = 2.1 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.61, 161.37, 150.60, 150.02, 137.61, 133.45, 132.13, 130.23, 129.11, 128.97, 128.91, 125.35, 124.59, 124.14, 122.44, 118.67, 117.17, 116.08, 115.19, 103.07, 31.25, 27.47, 13.93.; HRMS (APCI) m/z calcd for $C_{27}H_{20}FO_4$ $[M+H]^+$ = 427.1340, found = 427.1345; the ee value was 93%, t_R (major) = 23.3 min, t_R (minor) = 28.1 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

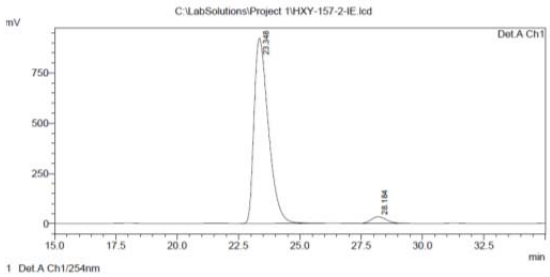


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	24.490	10950722	25167	48.954	50.789
2	27.708	11418862	24384	51.046	49.211
Total		22369935	49551	100.000	100.000

Racemic**3k**



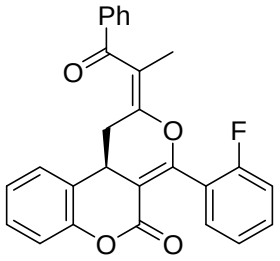
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	23.348	37680952	922180	96.364	96.548
2	28.184	1421661	32971	3.636	3.452
Total		39102613	955151	100.000	100.000

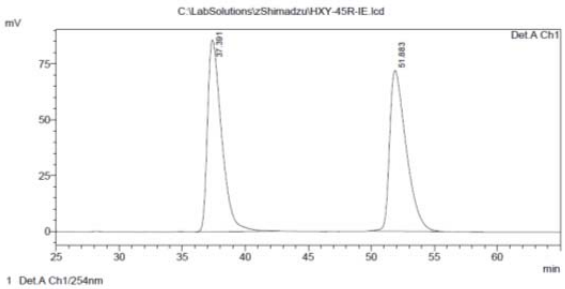
Enantiomerically enriched **3k**

(*R*,*E*)-4-(2-Fluorophenyl)-2-(1-oxo-1-phenylpropan-2-ylidene)-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3l**)



3l

92% yield, a white solid; $[\alpha]^{25}_{D}$ = -90.97(c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.92 (dd, *J* = 8.2Hz, 1.1 Hz, 2H), 7.65 (t, *J* = 7.4 Hz, 1H), 7.62 – 7.51 (m, 4H), 7.31 (t, *J* = 8.0 Hz, 1H), 7.19 – 7.06 (m, 4H), 7.01 (d, *J* = 7.7 Hz, 1H), 3.93 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.47 (dd, *J* = 14.2Hz, 5.7 Hz, 1H), 2.43 (ddd, *J* = 14.1Hz, 12.0Hz, 2.2 Hz, 1H), 2.17 (d, *J* = 2.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.53, 162.35, 161.92, 150.69, 149.99, 137.54, 133.49, 131.20, 131.13, 129.11, 128.97, 128.92, 125.17, 124.67, 122.94, 118.53, 117.08, 115.55, 115.37, 100.30, 31.44, 27.25, 14.05; HRMS (APCI) m/z calcd for $C_{27}H_{20}FO_4$ $[M+H]^+$ = 427.1344, found = 427.1340; the ee value was 91%, t_R(major) = 24.2 min, t_R (minor) = 27.7 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0mL/min).

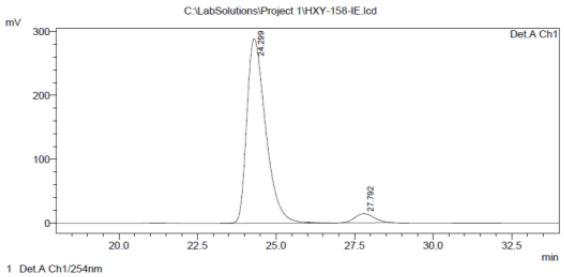


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	37.391	6683086	85769	50.398	54.374
2	51.883	6577607	71971	49.602	45.626
Total		13260693	157740	100.000	100.000

Racemic**3l**



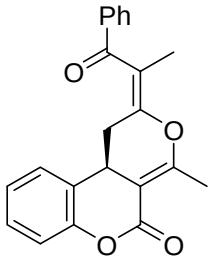
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	24.299	12067177	288655	95.256	95.386
2	27.792	600993	13963	4.744	4.614
Total		12668170	302618	100.000	100.000

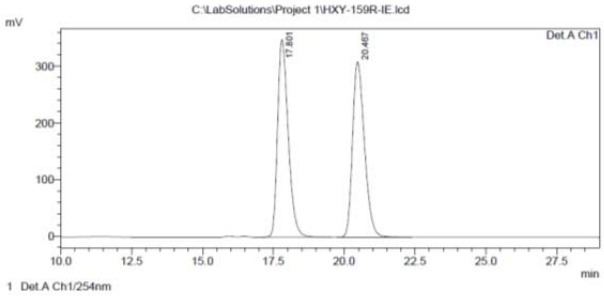
Enantiomerically enriched **3l**

(*R*,*E*)-4-Methyl-2-(1-oxo-1-phenylpropan-2-ylidene)-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3m**)



3m

94% yield, acolorless oil; $[\alpha]^{25}_{D}$ = -118.26 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.89 (dd, *J* = 8.2Hz, 1.1 Hz, 2H), 7.69 – 7.59 (m, 1H), 7.53 (t, *J* = 7.7 Hz, 2H), 7.24 (t, *J* = 7.7 Hz, 1H), 7.04 (dd, *J* = 12.6Hz, 4.8 Hz, 2H), 6.89 (d, *J* = 7.7 Hz, 1H), 3.84 – 3.74 (m, 1H), 3.38 (dd, *J* = 14.3Hz, 5.2 Hz, 1H), 2.55 (d, *J* = 2.2 Hz, 3H), 2.28 (ddd, *J* = 14.4Hz, 12.2Hz, 2.2 Hz, 1H), 2.09 (d, *J* = 2.2 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.78, 165.24, 162.43, 150.56, 150.28, 137.78, 133.31, 129.02, 128.91, 128.58, 125.33, 124.40, 122.36, 117.62, 116.92, 99.29, 30.39, 27.97, 20.10, 13.77; HRMS (APCI) m/z calcd for $C_{22}H_{19}O_4$ $[M+H]^+$ = 347.1278, found = 347.1282; the ee value was 76%, t_R (major) = 17.5 min, t_R (minor) = 20.2 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

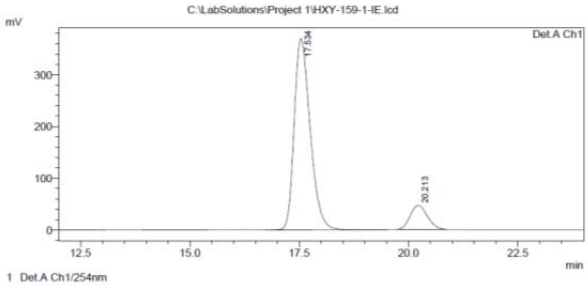


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	17.801	9091920	349019	50.151	53.003
2	20.467	9037293	309476	49.849	46.997
Total		18129214	658496	100.000	100.000

Racemic**3m**



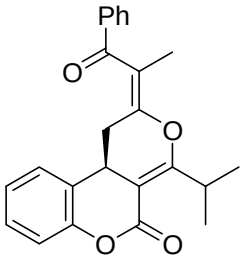
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	17.534	9399089	369721	88.098	88.826
2	20.213	1269817	46512	11.902	11.174
Total		10668907	416233	100.000	100.000

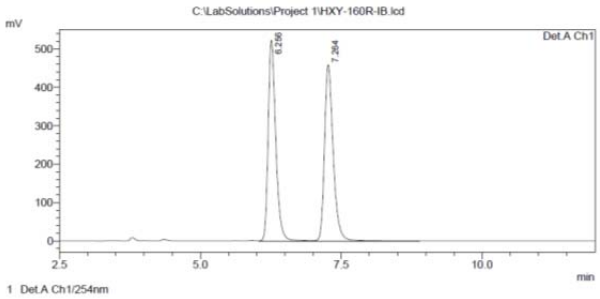
Enantiomerically enriched **3m**

(*R*,*E*)-4-Isopropyl-2-(1-oxo-1-phenylpropan-2-ylidene)-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3n**)



3n

91% yield, a white solid; $[\alpha]^{25}_{D}$ = -28.49 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.89 (dd, *J* = 8.2Hz, 1.2 Hz, 2H), 7.63 (t, *J* = 7.4 Hz, 1H), 7.54 (dd, *J* = 10.8Hz, 4.4 Hz, 2H), 7.27 – 7.21 (m, 1H), 7.09 – 7.02 (m, 2H), 6.91 (d, *J* = 7.7 Hz, 1H), 4.04 (dt, *J* = 13.6Hz, 6.8 Hz, 1H), 3.78 (dd, *J* = 12.1Hz, 5.3 Hz, 1H), 3.39 (dd, *J* = 14.3Hz, 5.3 Hz, 1H), 2.26 (ddd, *J* = 14.3Hz, 12.2Hz, 2.2 Hz, 1H), 2.11 (d, *J* = 2.1 Hz, 3H), 1.38 (d, *J* = 6.8 Hz, 3H), 1.19 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.77, 172.24, 162.11, 150.72, 150.60, 137.86, 133.26, 129.03, 128.89, 128.70, 125.26, 124.40, 122.66, 117.52, 116.85, 97.73, 30.63, 30.57, 27.83, 20.26, 19.62, 13.61; HRMS (APCI) m/z calcd for $C_{24}H_{23}O_4$ $[M+H]^+$ = 375.1591, found = 375.1594; the ee value was 94%, t_R (major) = 7.2 min, t_R (minor) = 6.2 min (Chiralcel IB-H, λ = 254 nm, 10% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

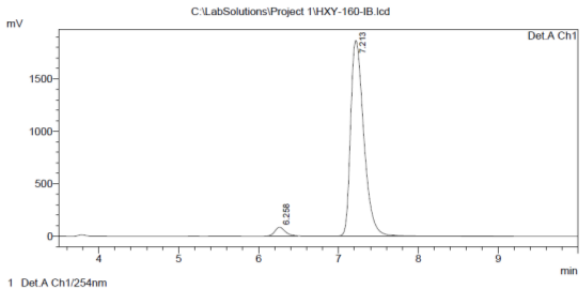


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	6.256	4876100	523524	49.910	53.300
2	7.264	4893734	458704	50.090	46.700
Total		9769834	982228	100.000	100.000

Racemic**3n**



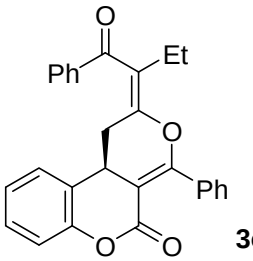
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	6.258	709992	81342	3.216	4.177
2	7.213	21365813	1865812	96.784	95.823
Total		22075806	1947153	100.000	100.000

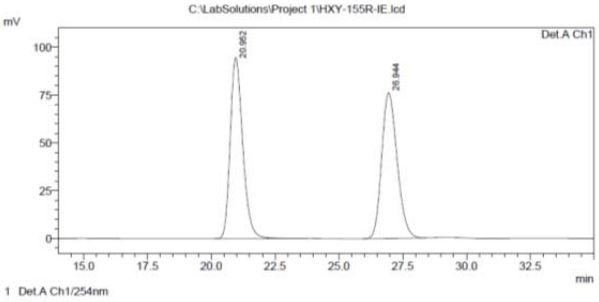
Enantiomerically enriched **3n**

(*R*,*E*)-2-(1-Oxo-1-phenylbutan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3o**)



3o

91% yield, a white solid; $[\alpha]^{25}_{D}$ = -81.74(c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97 (d, *J* = 7.1 Hz, 2H), 7.69 – 7.63 (m, 1H), 7.62 – 7.50 (m, 5H), 7.47 (dd, *J* = 8.0Hz, 6.5 Hz, 2H), 7.34 – 7.25 (m, 1H), 7.14 – 7.06 (m, 2H), 6.93 (d, *J* = 8.0 Hz, 1H), 3.92 (dd, *J* = 11.9Hz, 5.7 Hz, 1H), 3.26 (dd, *J* = 14.1Hz, 5.7 Hz, 1H), 2.72 (q, *J* = 7.5 Hz, 2H), 2.41 (dd, *J* = 13.8Hz, 12.1 Hz, 1H), 1.14 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.62, 163.20, 162.39, 150.78, 148.36, 138.08, 133.63, 133.55, 130.69, 129.04, 129.02, 128.92, 128.83, 128.26, 125.08, 124.86, 124.54, 123.11, 117.07, 100.04, 31.51, 27.64, 21.55, 12.89; HRMS (APCI) m/z calcd for $C_{28}H_{23}O_4$ $[M+H]^+$ = 423.1591, found = 423.1598; the ee value was 93%, t_R (major) = 20.9 min, t_R (minor) = 27.0min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

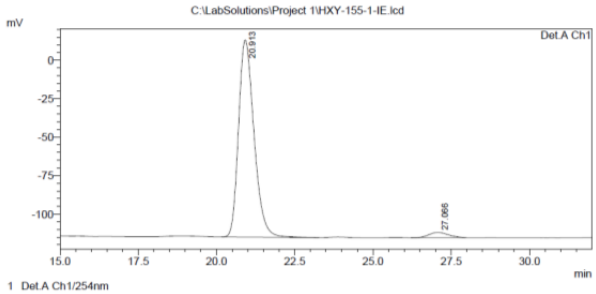


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	20.952	3228229	94694	50.114	55.409
2	26.944	3213546	76205	49.886	44.591
Total		6441775	170899	100.000	100.000

Racemic**3o**



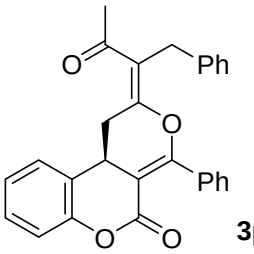
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	20.913	4402194	128063	96.815	97.428
2	27.066	144818	3381	3.185	2.572
Total		4547012	131444	100.000	100.000

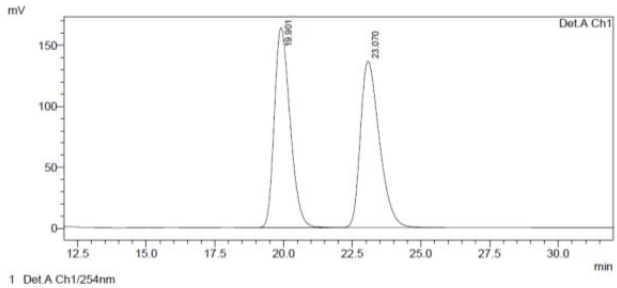
Enantiomerically enriched **3o**

(*R*,*E*)-2-(3-Oxo-1-phenylbutan-2-ylidene)-4-phenyl-1,10b-dihydro-2*H*,5*H*-pyrano[3,4-*c*]chromen-5-one (**3p**)



3p

81% yield, a colorless oil; $[\alpha]^{25}_{D}$ = -48.67(c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 – 7.31 (m, 9H), 7.27 – 7.21 (m, 4H), 7.13 (dd, *J* = 8.1Hz, 1.1 Hz, 1H), 4.59 (dd, *J* = 14.7Hz, 5.7 Hz, 1H), 4.12 – 4.00 (m, 3H), 2.69 – 2.57 (m, 1H), 2.28 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 201.09, 162.42, 161.77, 155.47, 150.77, 138.46, 133.17, 130.62, 128.96, 128.88, 128.81, 128.17, 127.91, 126.61, 125.67, 124.76, 122.93, 121.29, 117.11, 101.42, 32.52, 31.07, 30.14, 26.73; HRMS (APCI) m/z calcd for $C_{28}H_{23}O_4$ $[M+H]^+$ = 423.1591, found = 423.1593; the ee value was 87%, t_R (minor) = 23.3 min,t_R (major) = 20.0 min (Chiralcel IE-H, λ = 254 nm, 20% *i*PrOH/hexanes, flow rate = 1.0 mL/min).

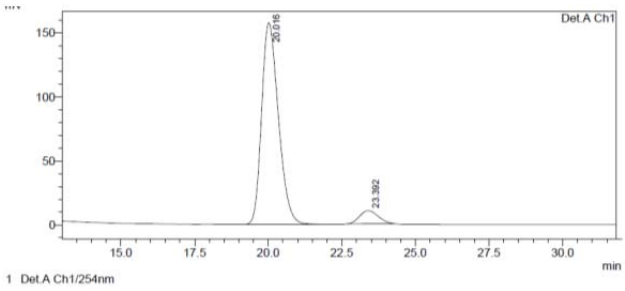


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	19.901	6579194	164121	49.930	54.586
2	23.070	6597621	136541	50.070	45.414
Total		13176815	300662	100.000	100.000

Racemic**3p**



PeakTable

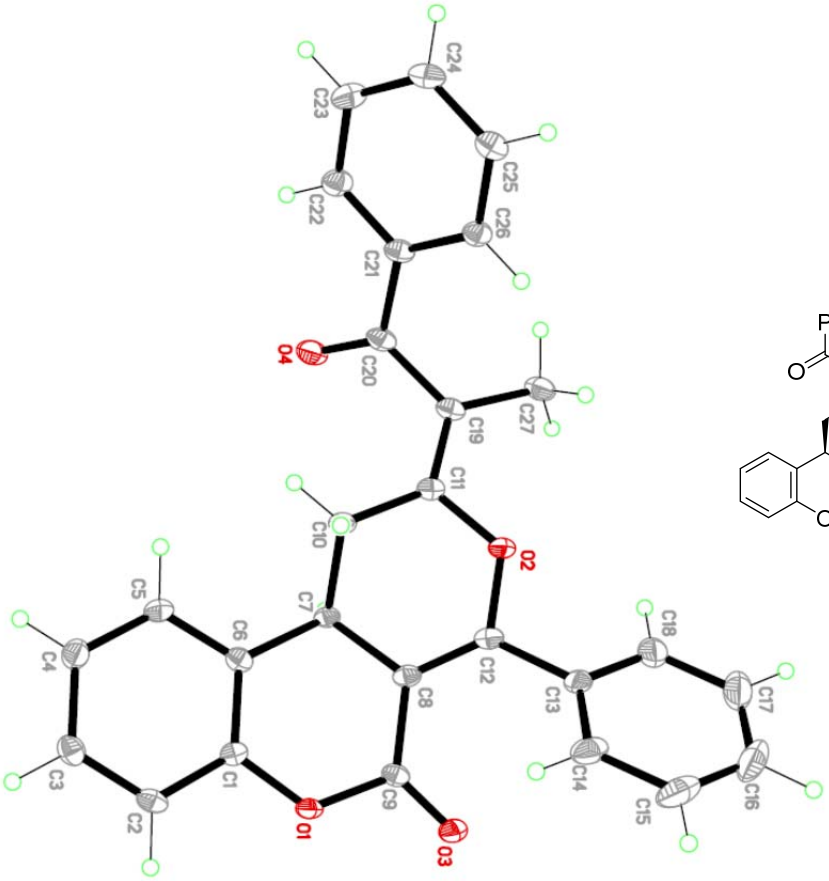
Detector A Ch1 254nm

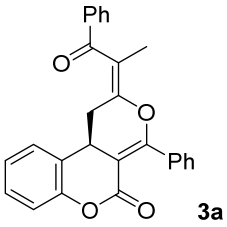
Peak#	Ret. Time	Area	Height	Area %	Height %
1	20.016	6249080	157548	93.256	93.847
2	23.392	451889	10330	6.744	6.153
Total		6700968	167878	100.000	100.000

Enantiomerically enriched **3p**

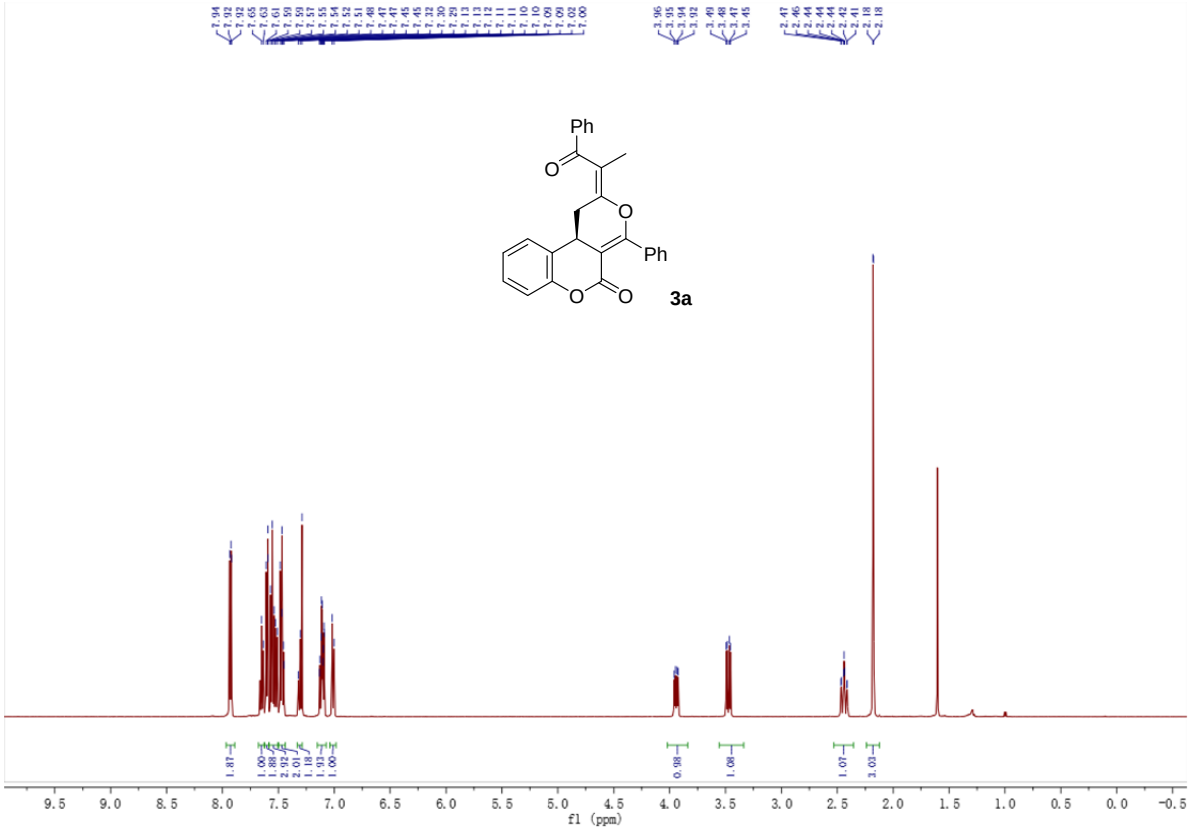
D. Determination of Absolute Configurations of [4+2] Cyclization Adducts

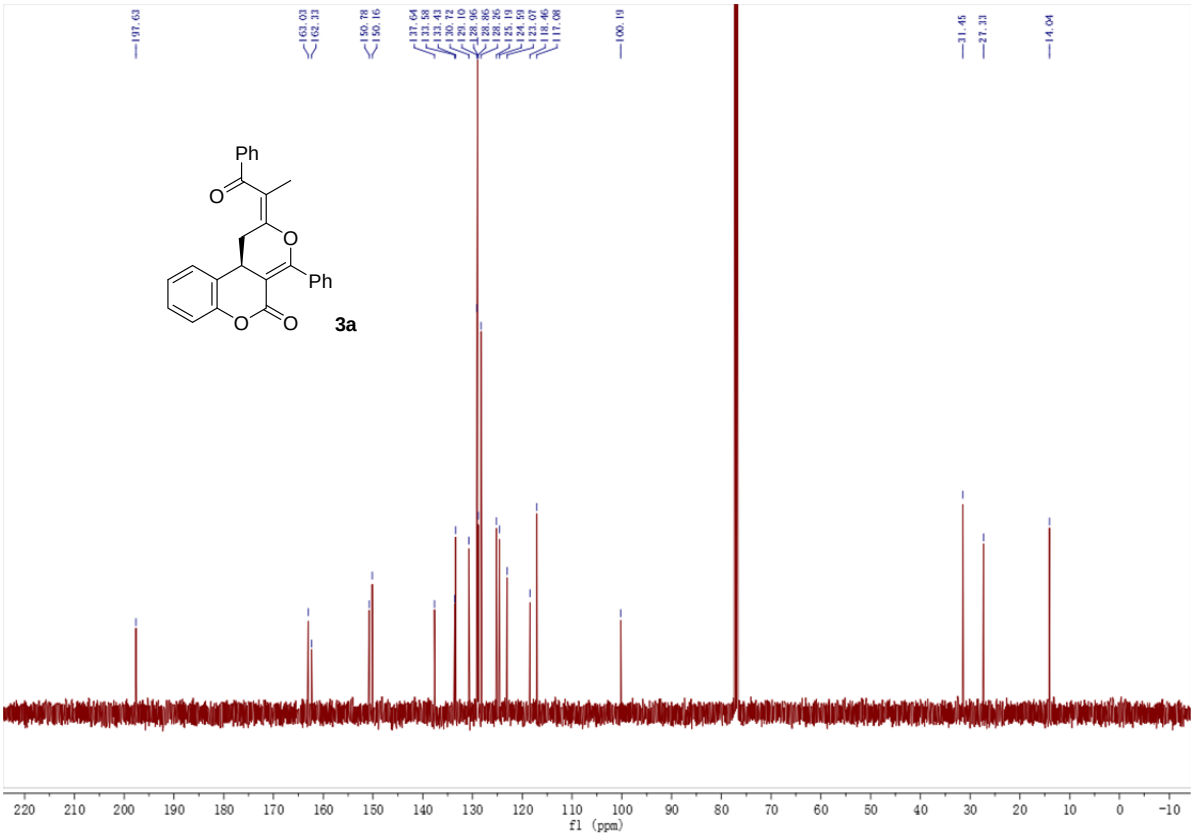
X-Ray crystal structure of 3a

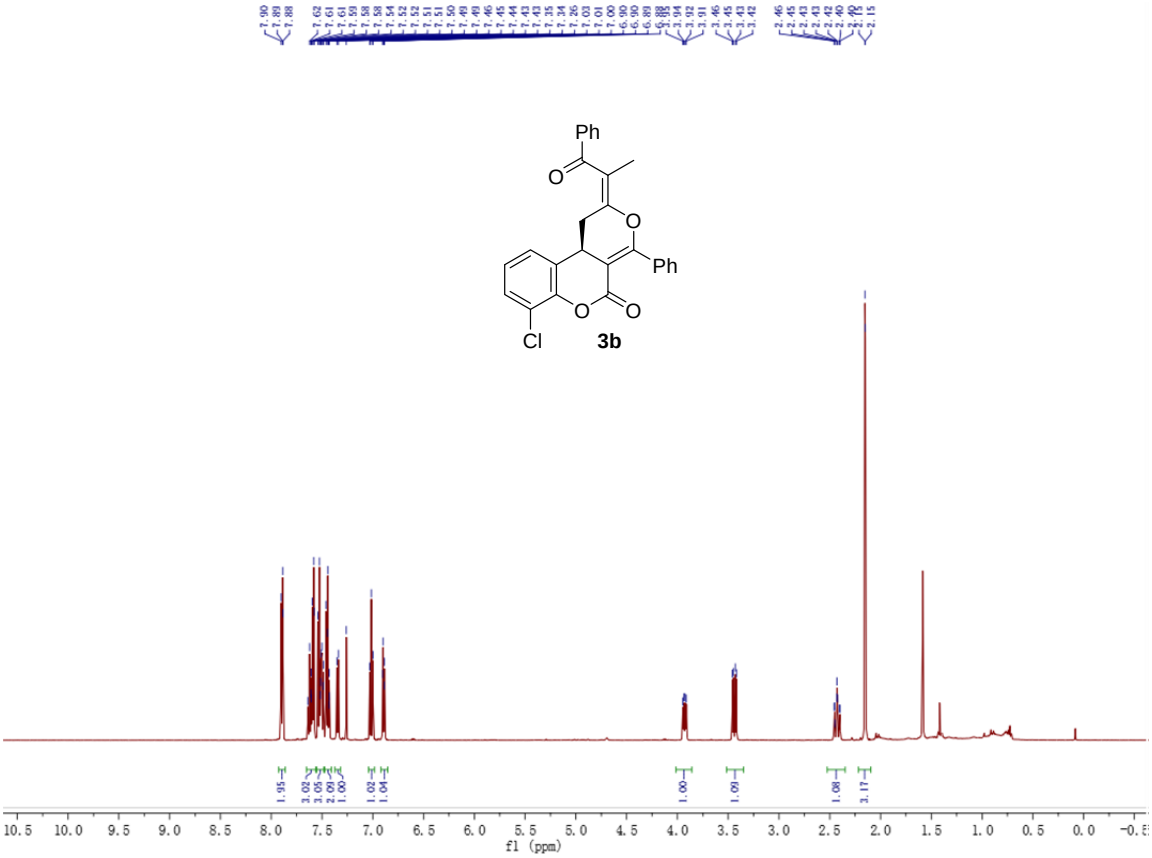


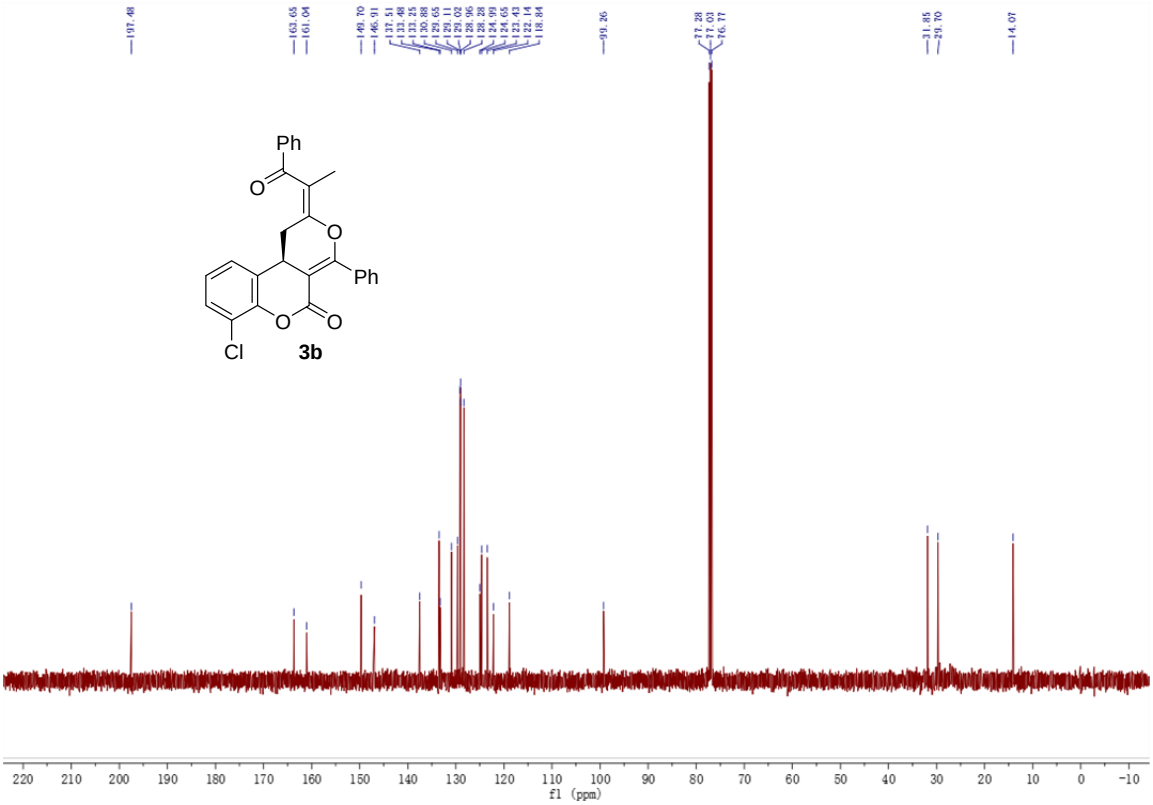


E. NMR Spectra of the [4+2] Cyclization Adducts






Ph
O
O
Ph
O
O
Cl
3b
f1 (ppm)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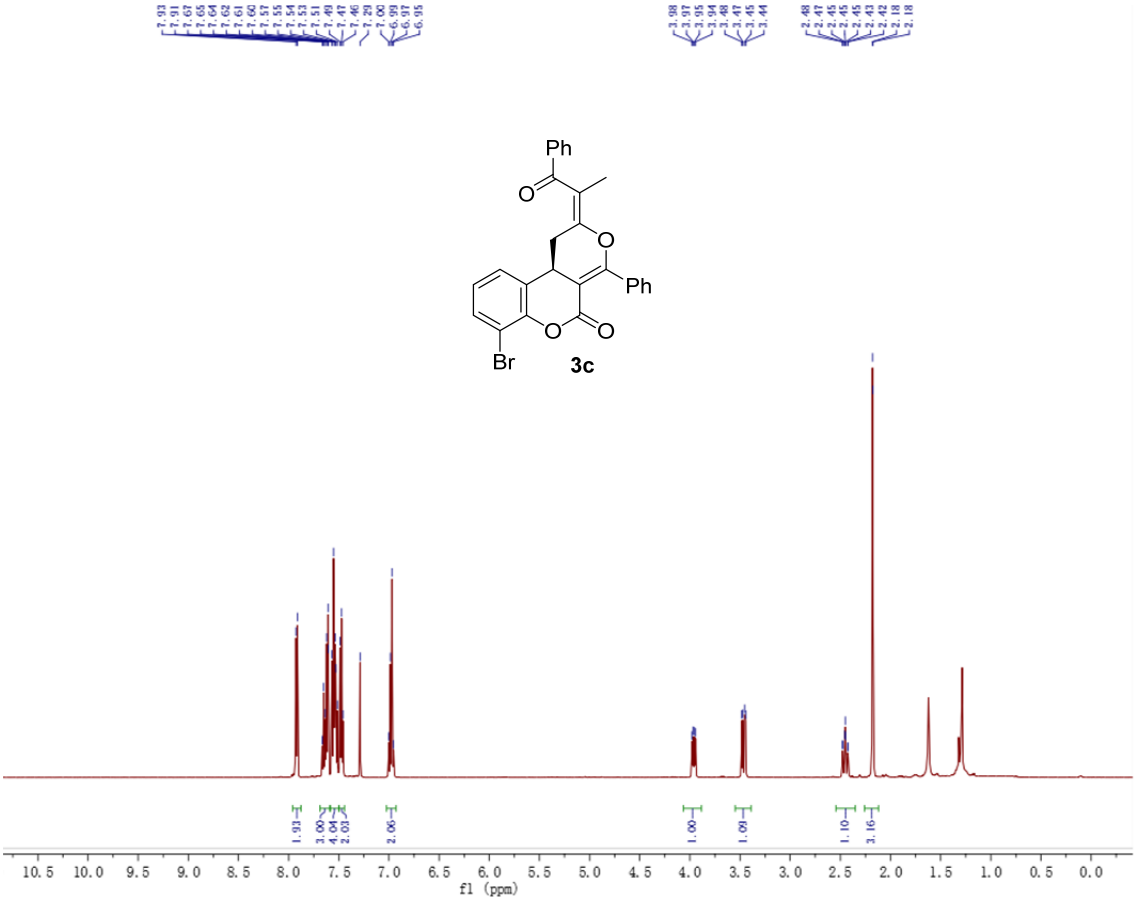
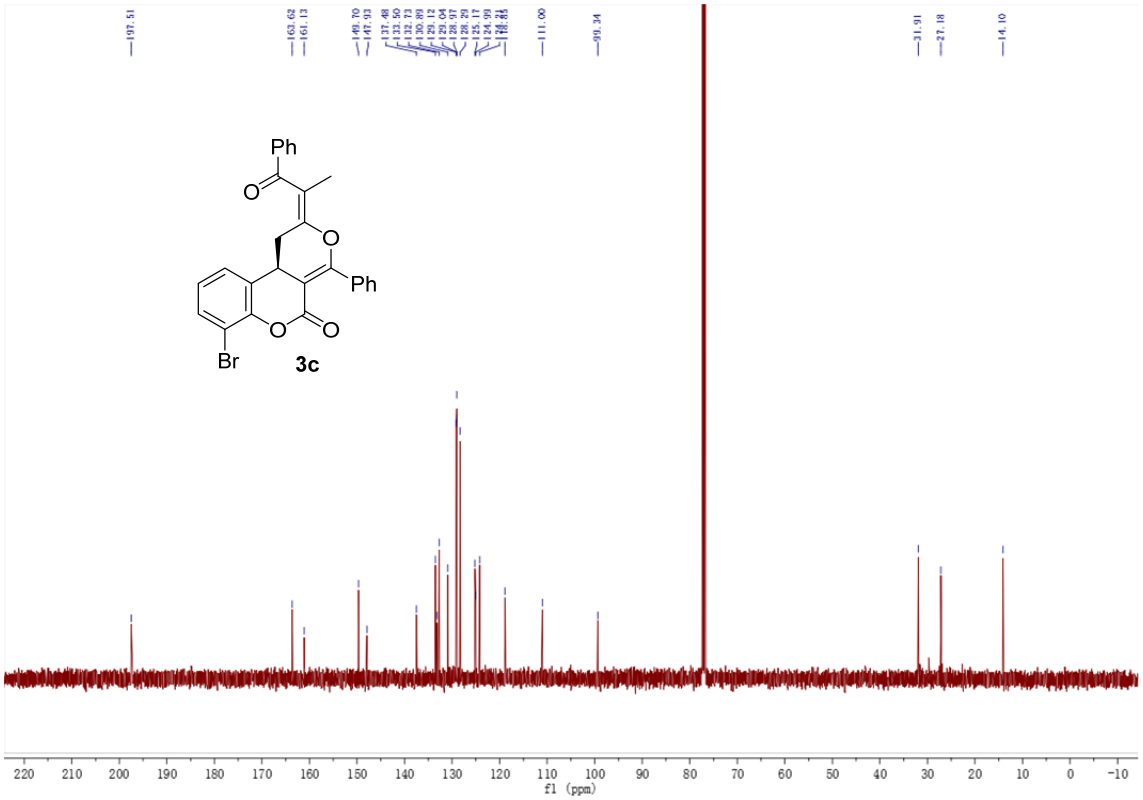
O
Ph
O
O
Cl
3b
f1 (ppm)


Ph
O
O
Ph
O
O
Br
3c
f1 (ppm)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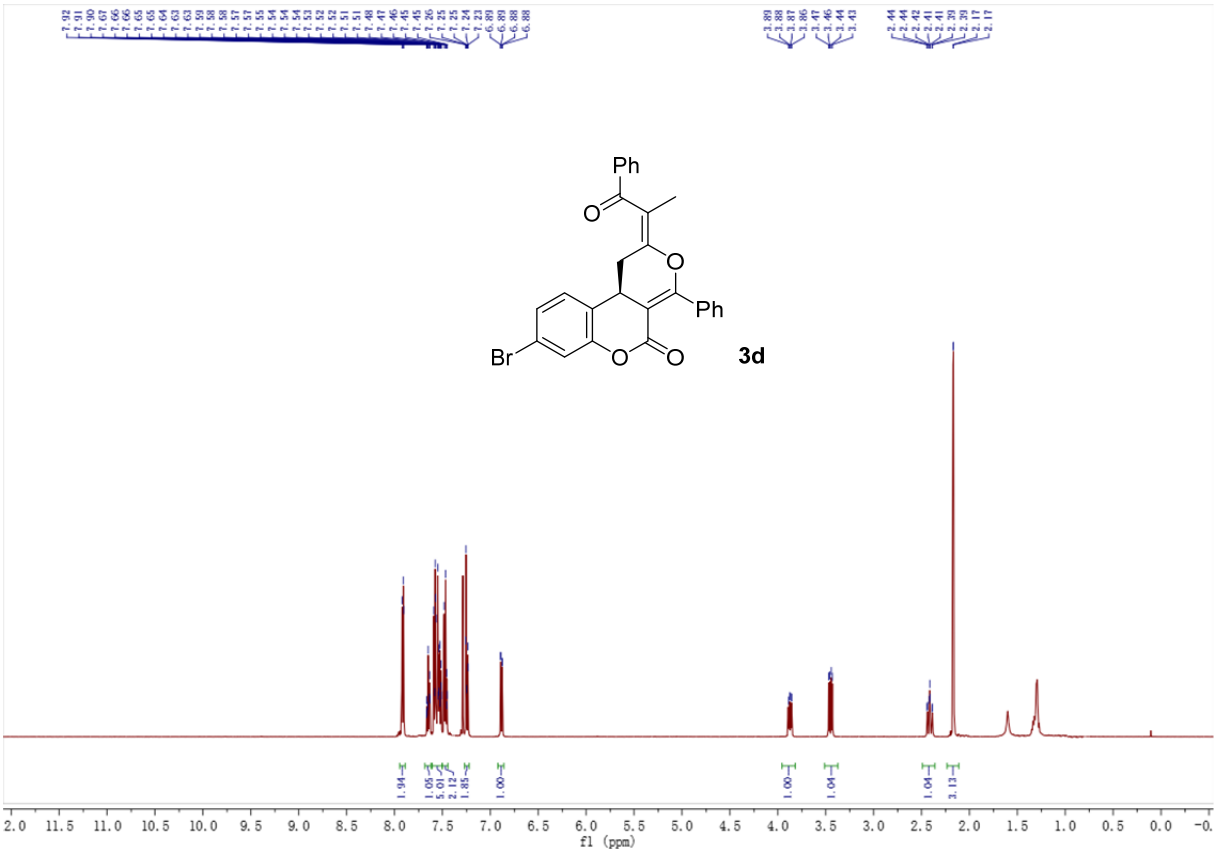
O
Ph
O
O
Br
3c
f1 (ppm)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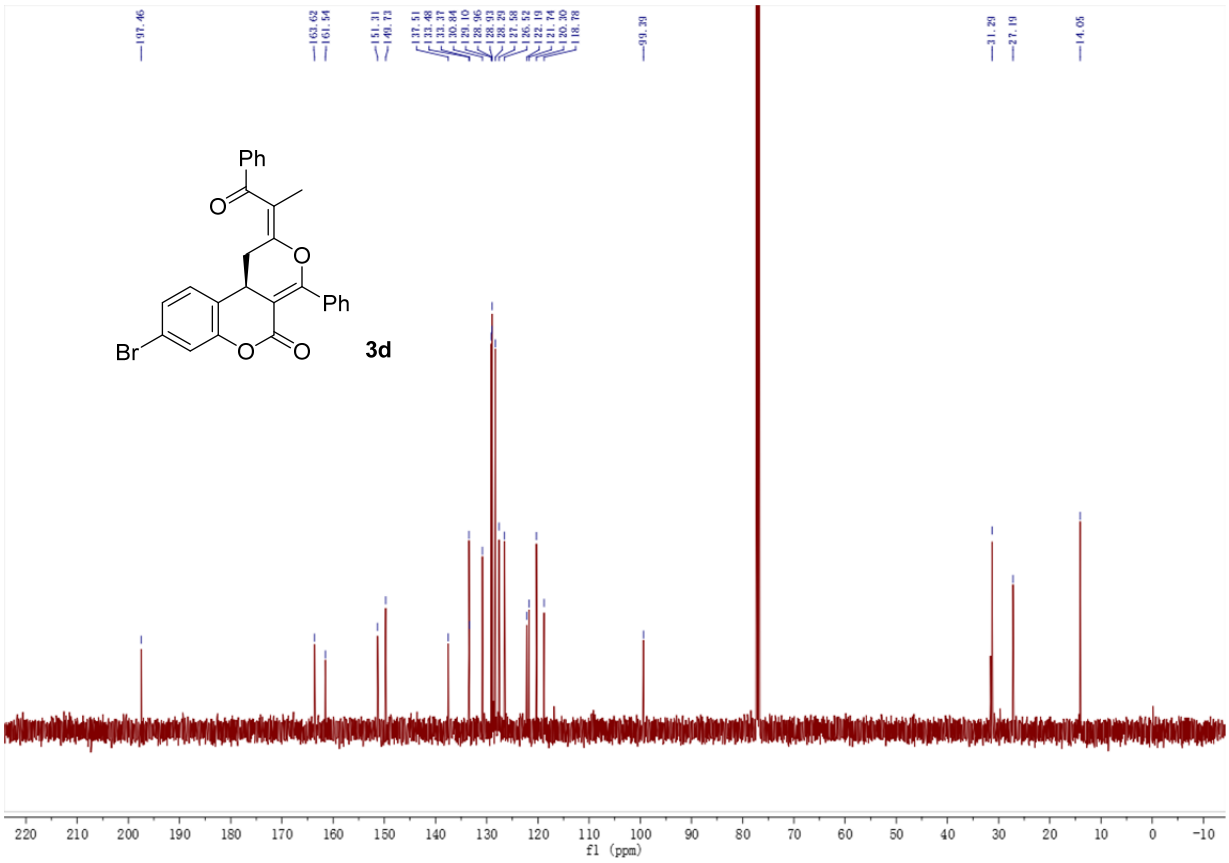
O
Ph
Br
O
O
3d
f1 (ppm)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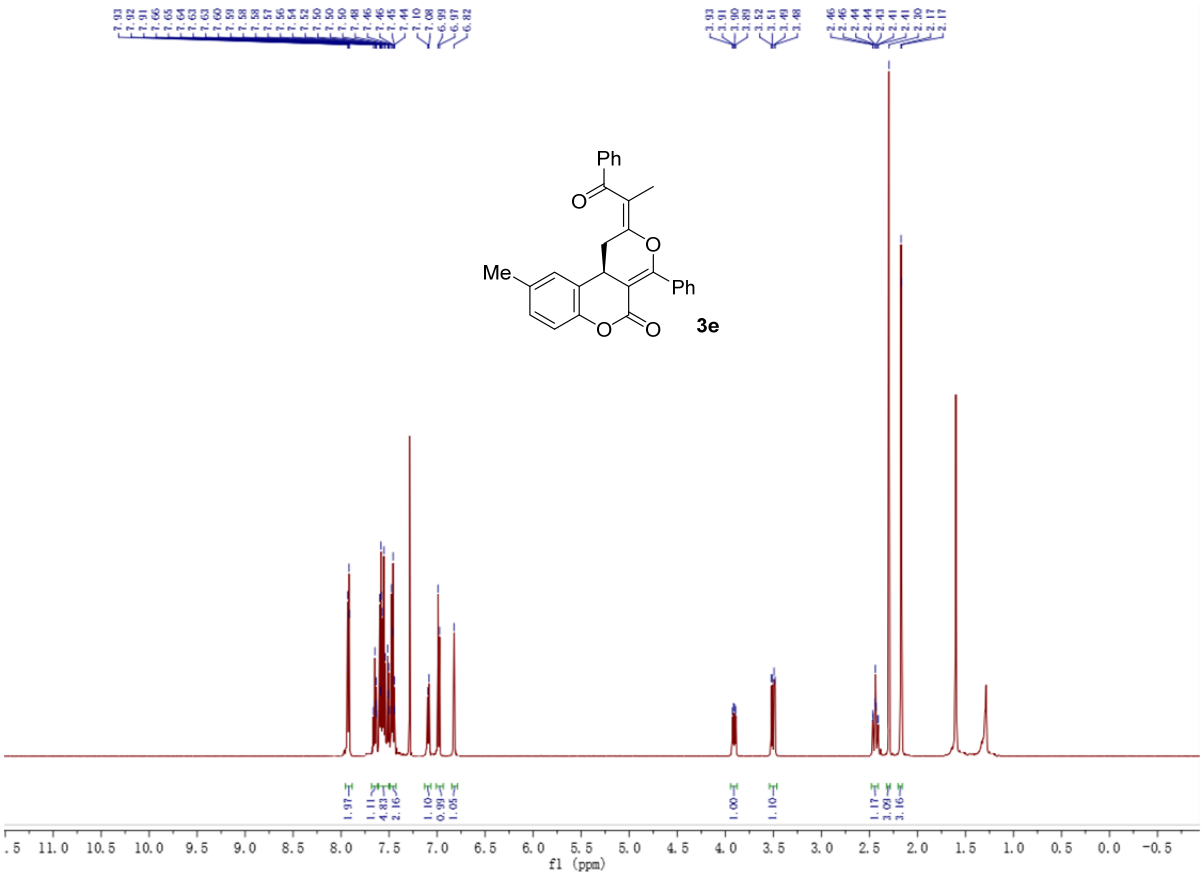
O
Ph
Br
O
O
3d
f1 (ppm)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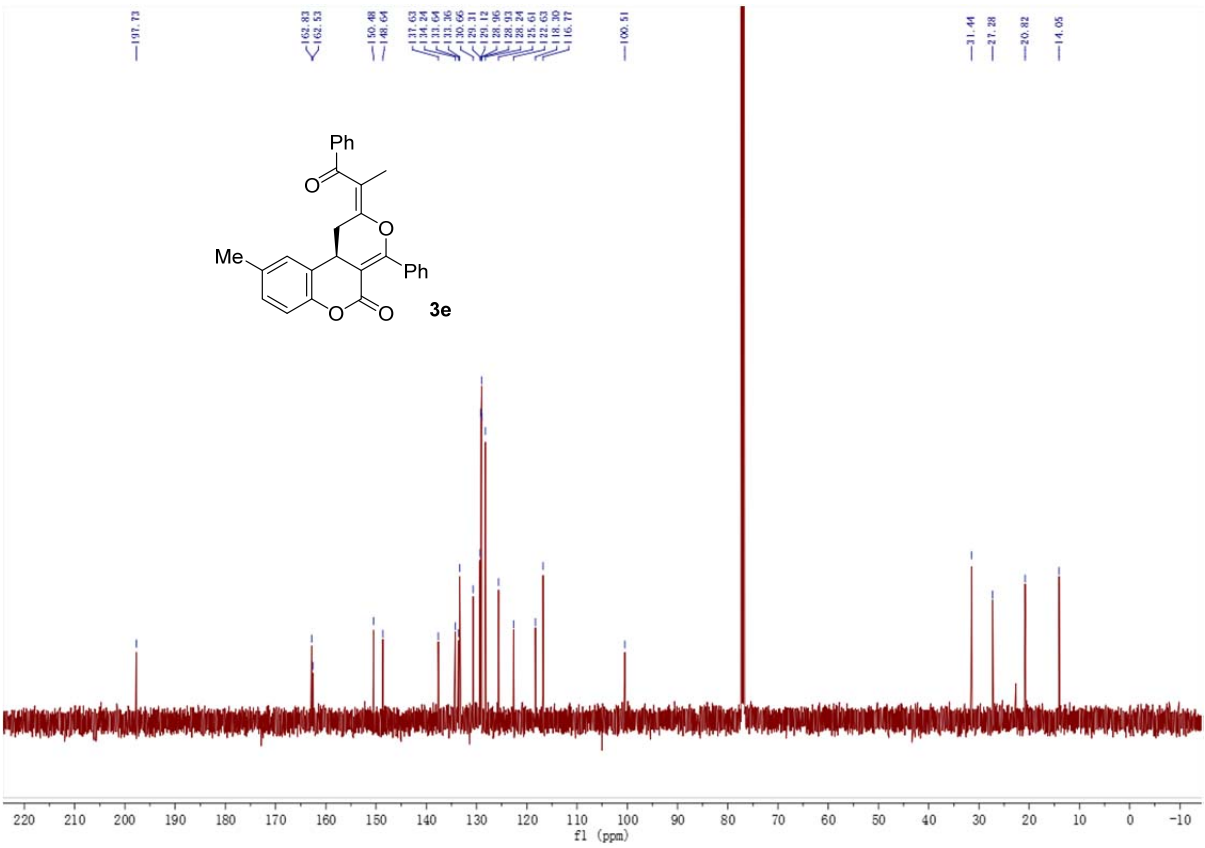
O
Me
Ph
O
O
3e
f1 (ppm)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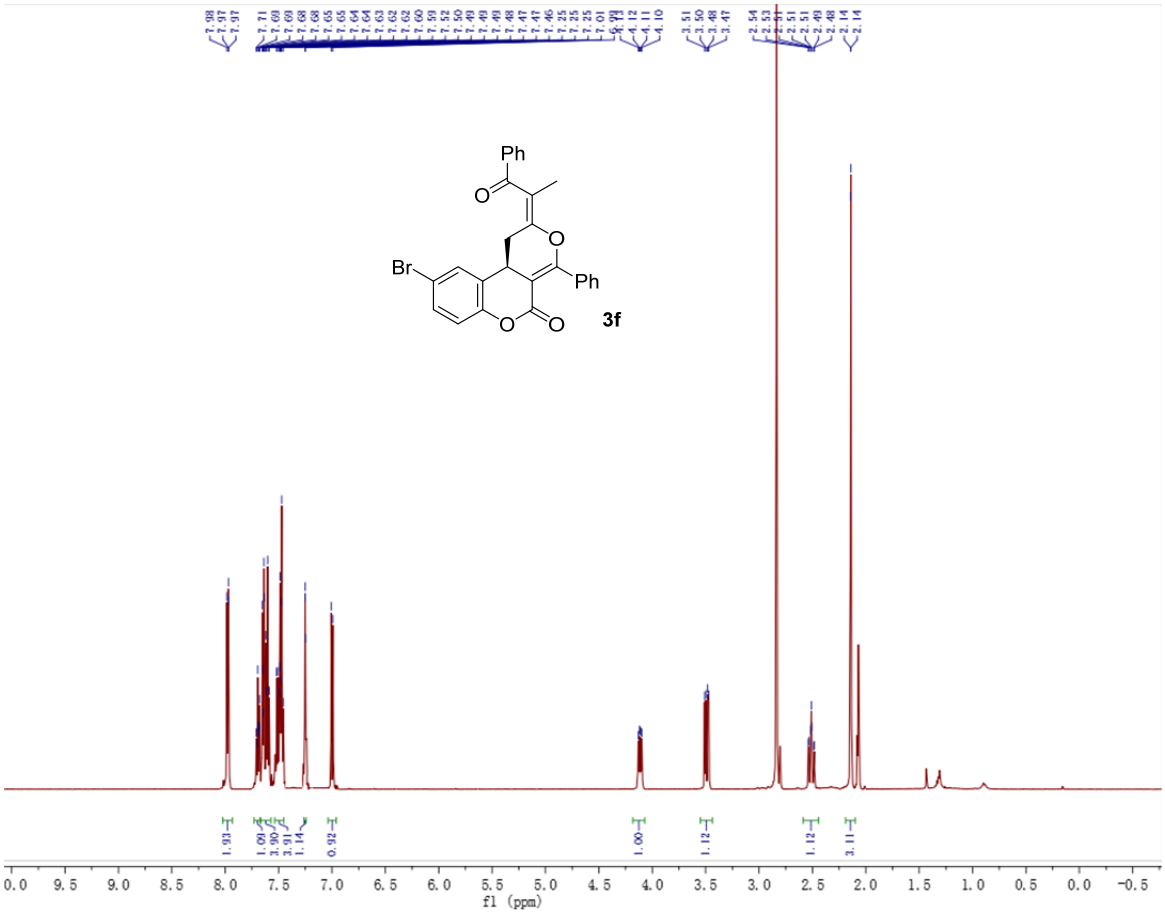
O
Me
Ph
O
O
3e
f1 (ppm)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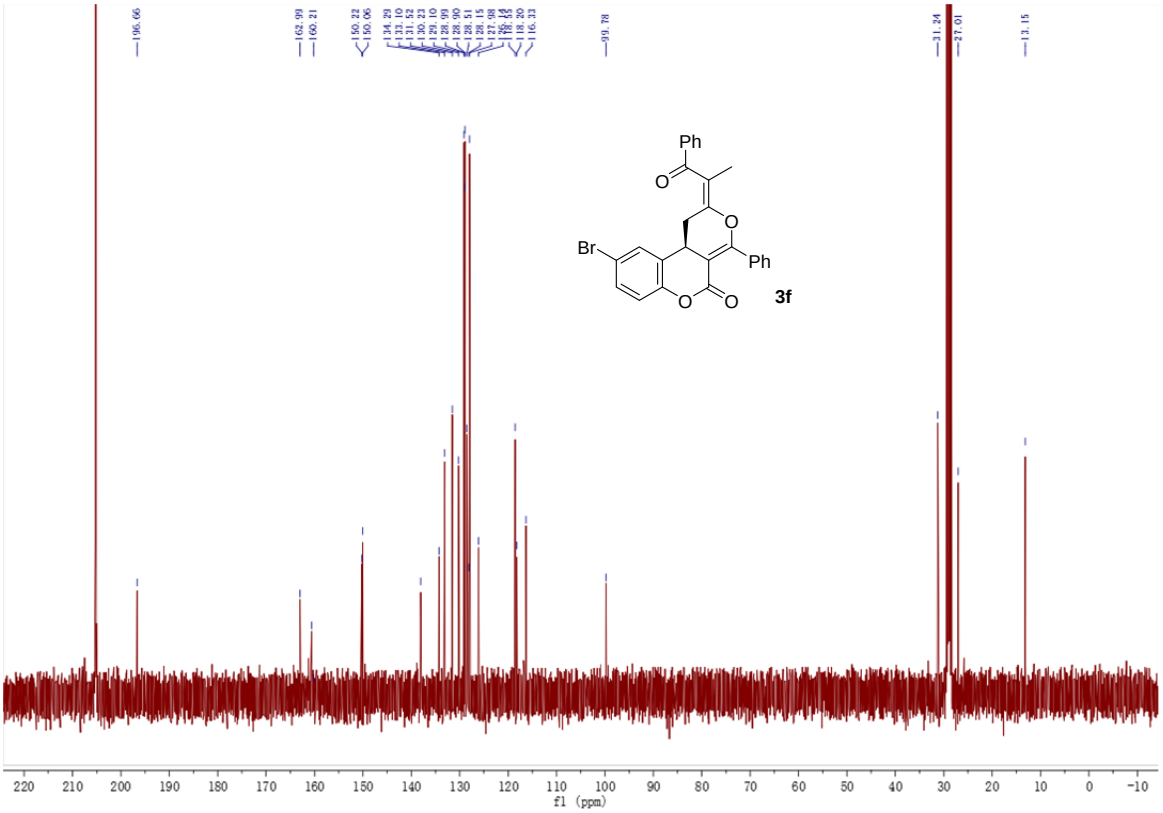
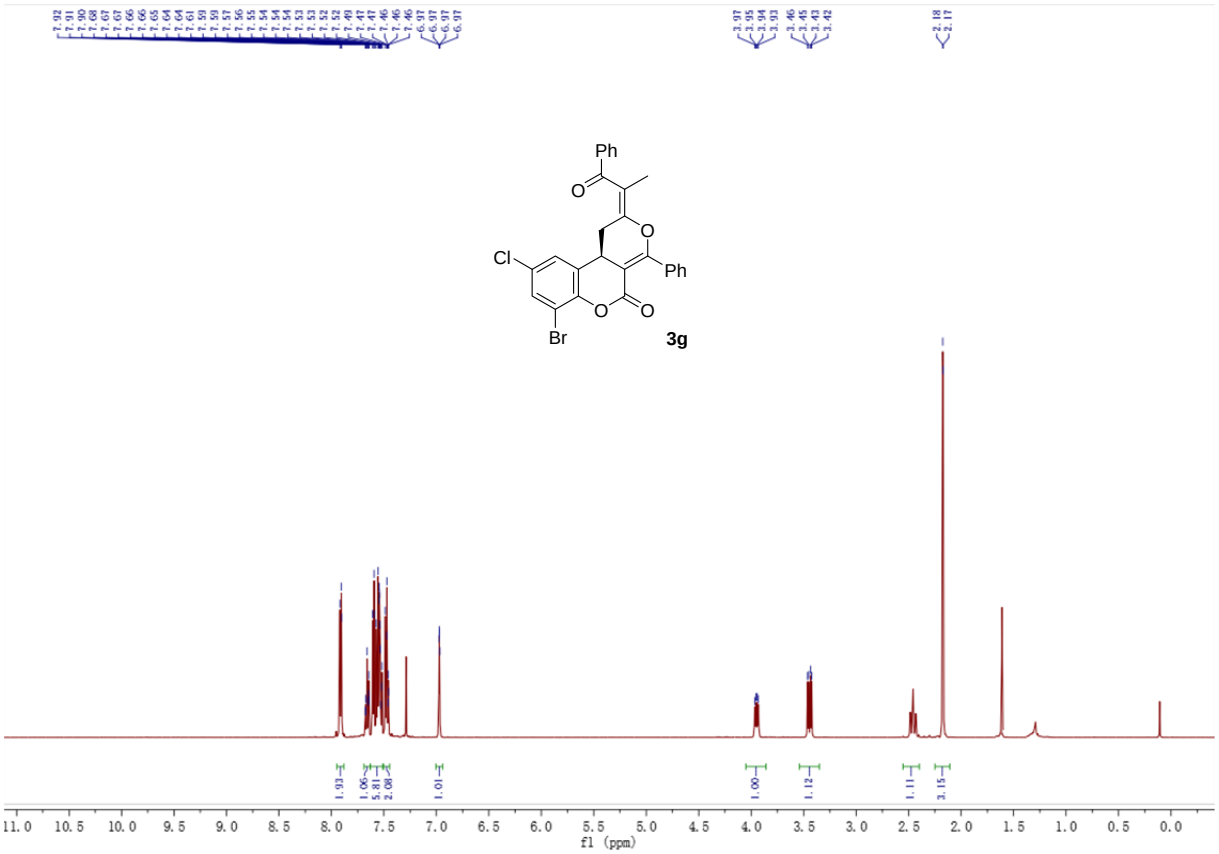
O
Br
Ph
O
O
3f
f1 (ppm)


Ph
O
O
Br
Ph
O
O
3f
f1 (ppm)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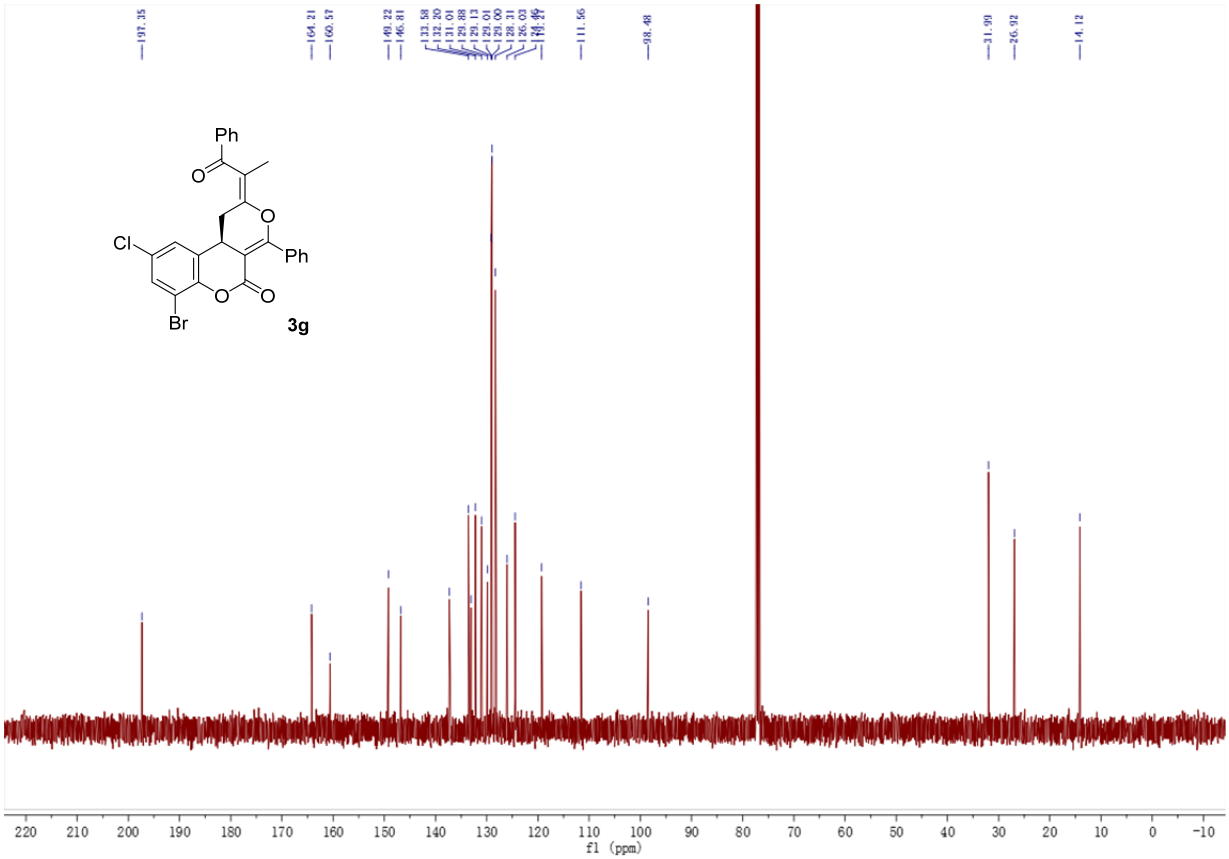
O
O
Cl
Ph
O
O
Br
3g
f1 (ppm)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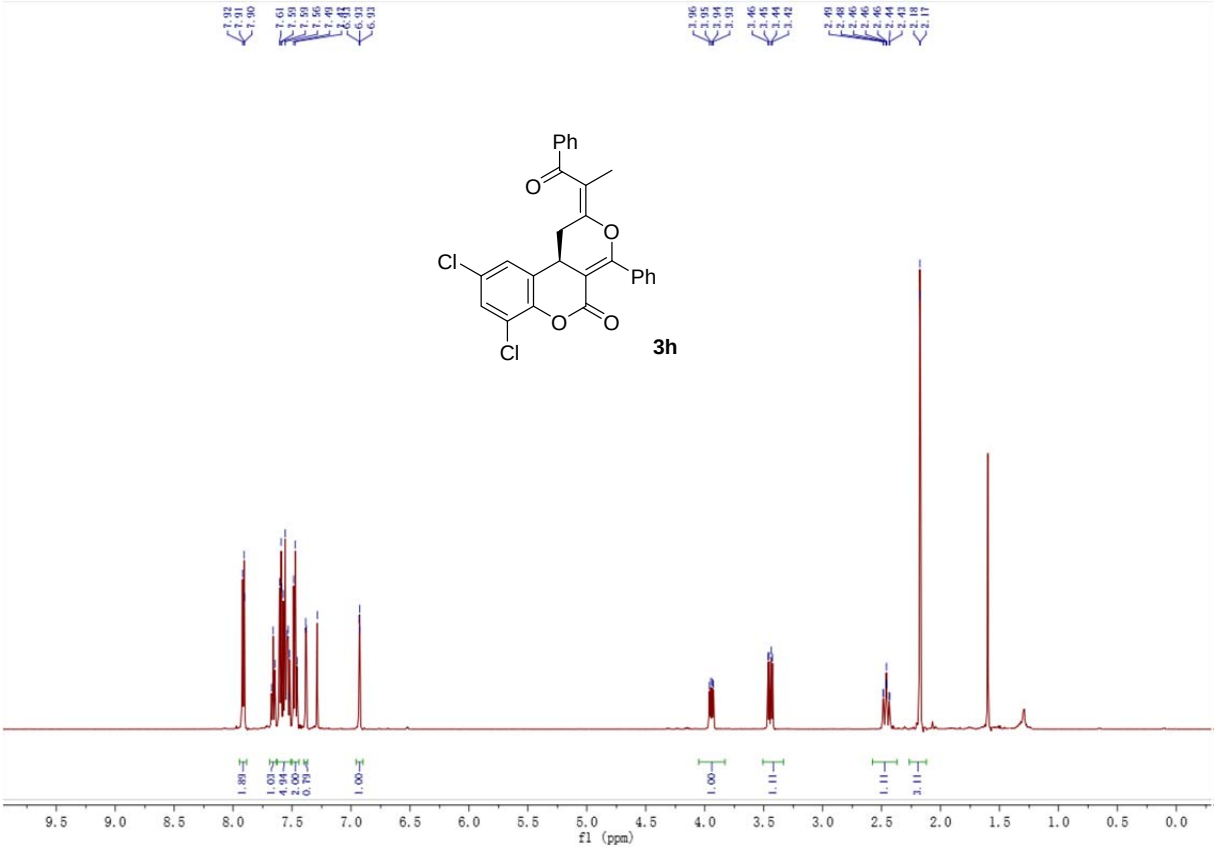
O
O
Cl
Ph
O
O
Br
3g
f1 (ppm)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Cl
Ph
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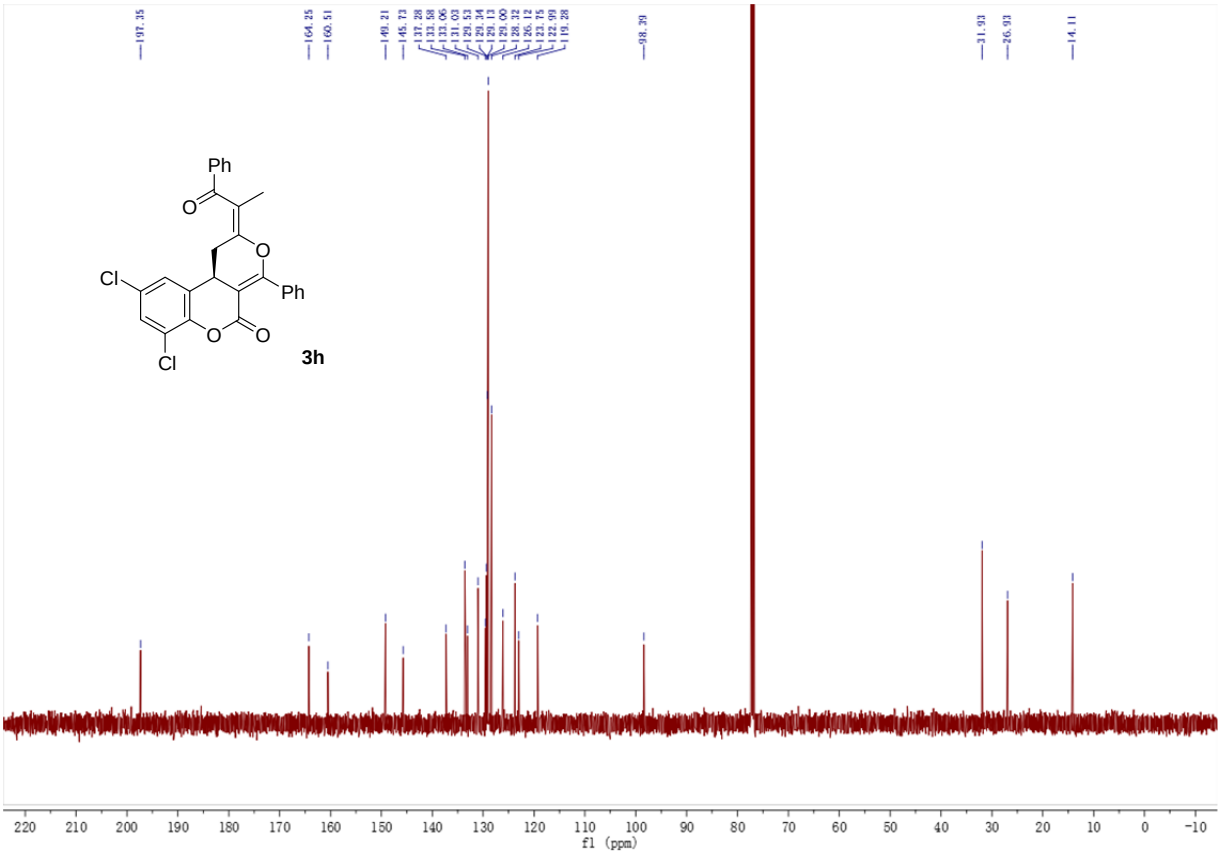
O
Cl
3h
f1 (ppm)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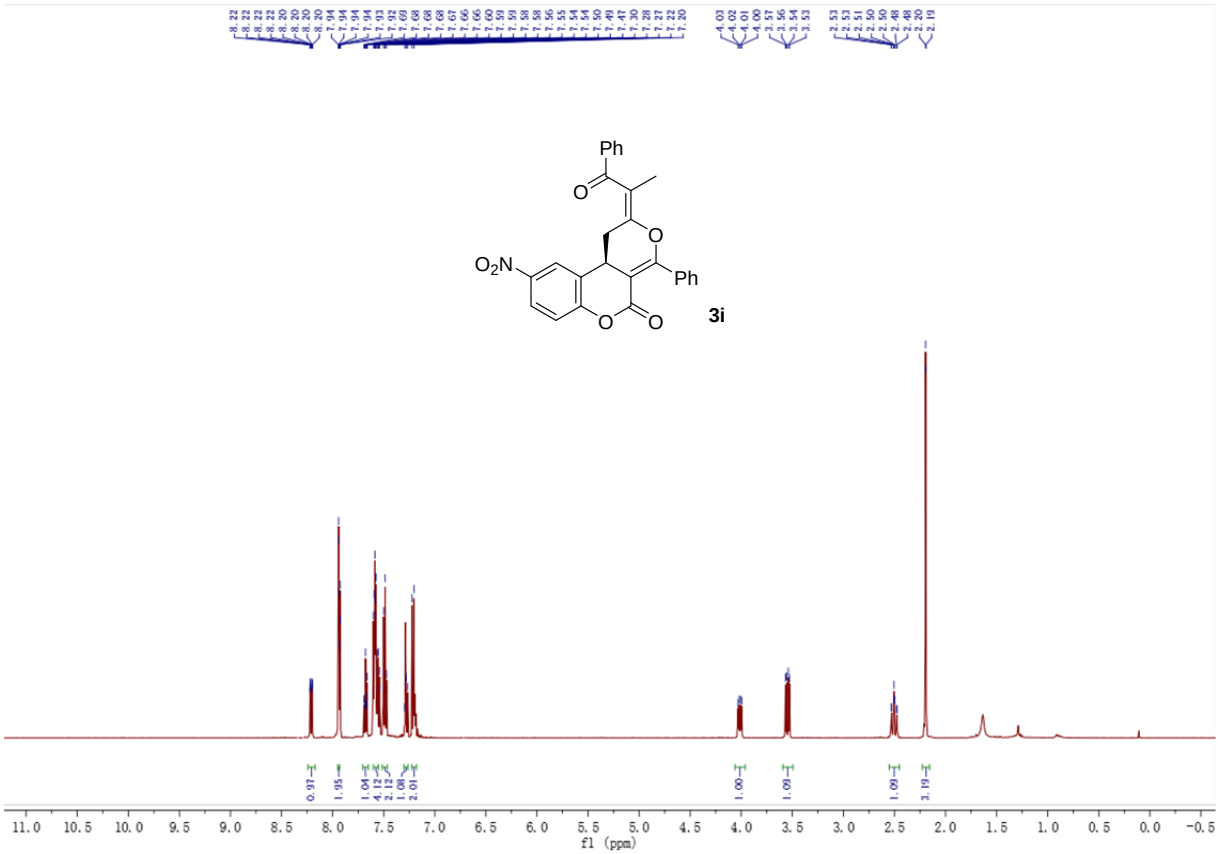
O
Cl
Ph
O
O
Cl
3h
f1 (ppm)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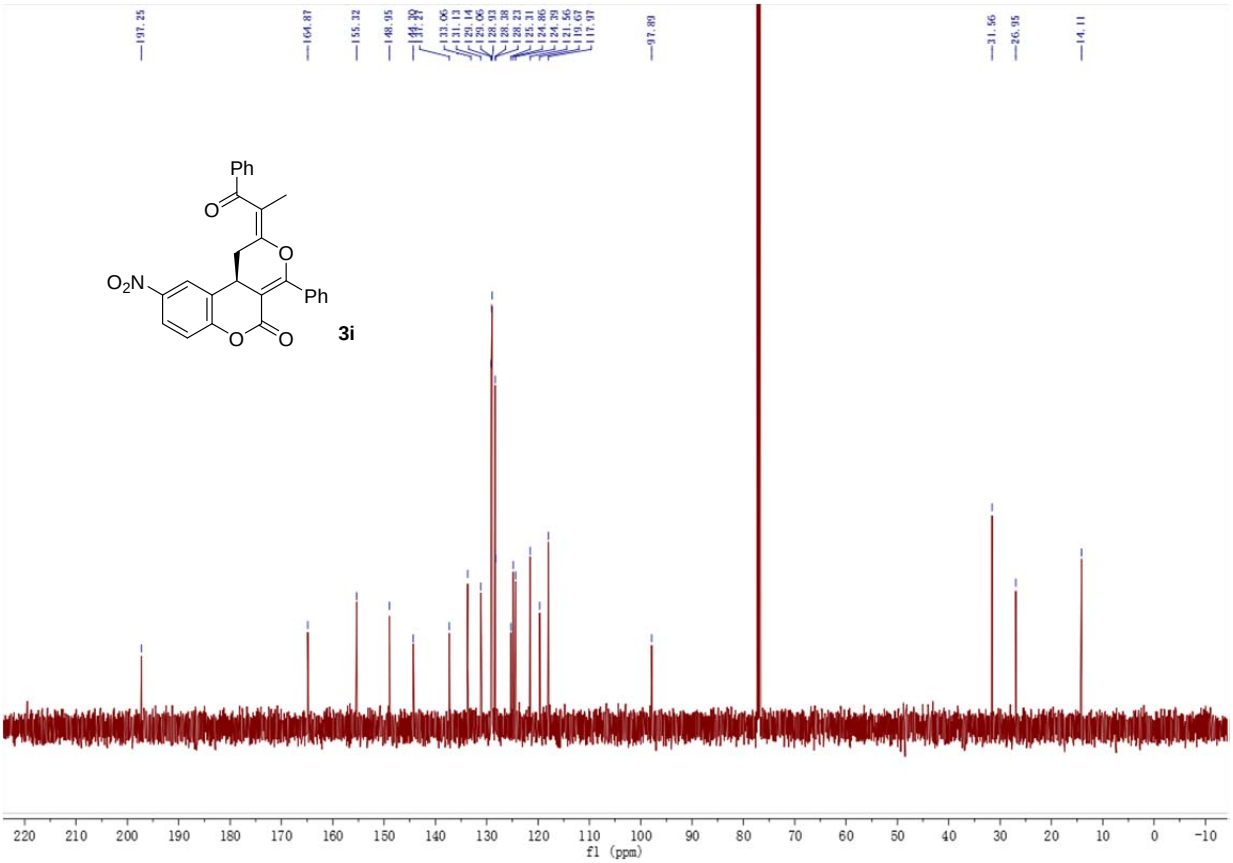
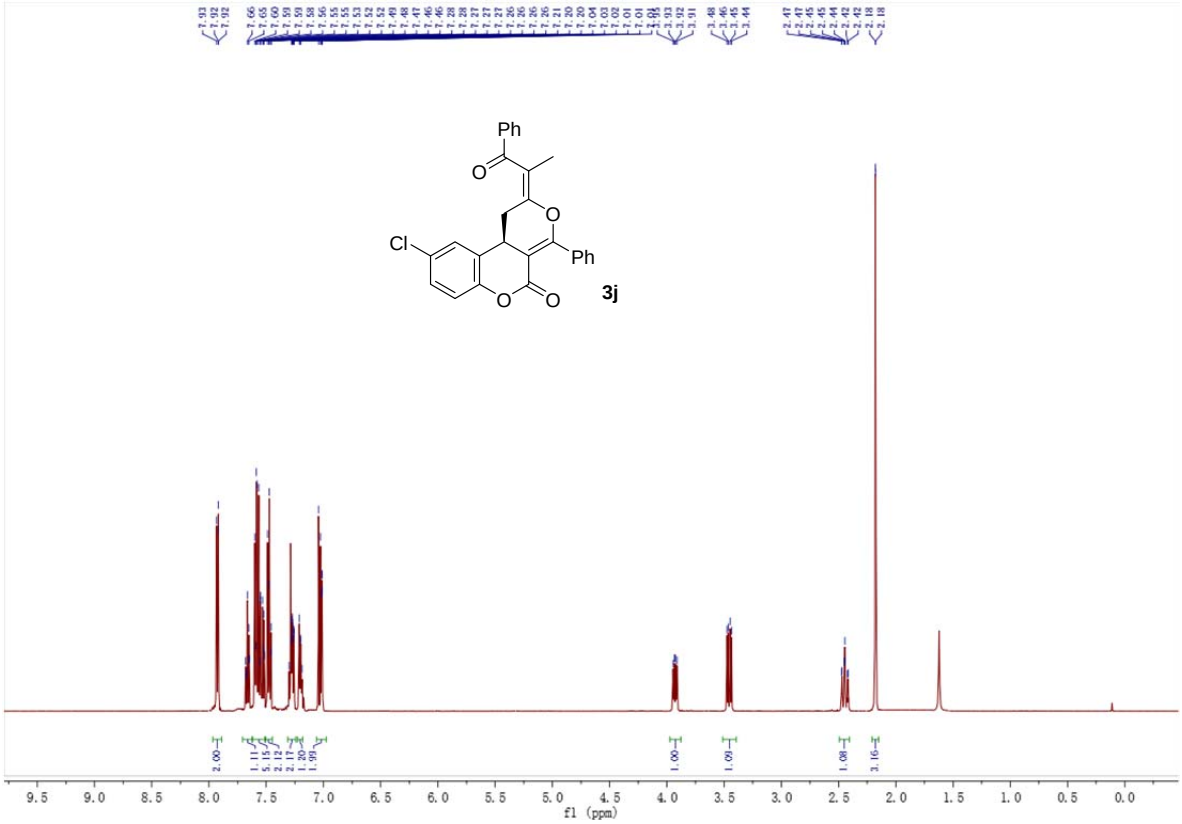
O
O2N
Ph
O
O
3i
f1 (ppm)


Ph
O
O
O2N
Ph
O
O
3i
f1 (ppm)


Ph
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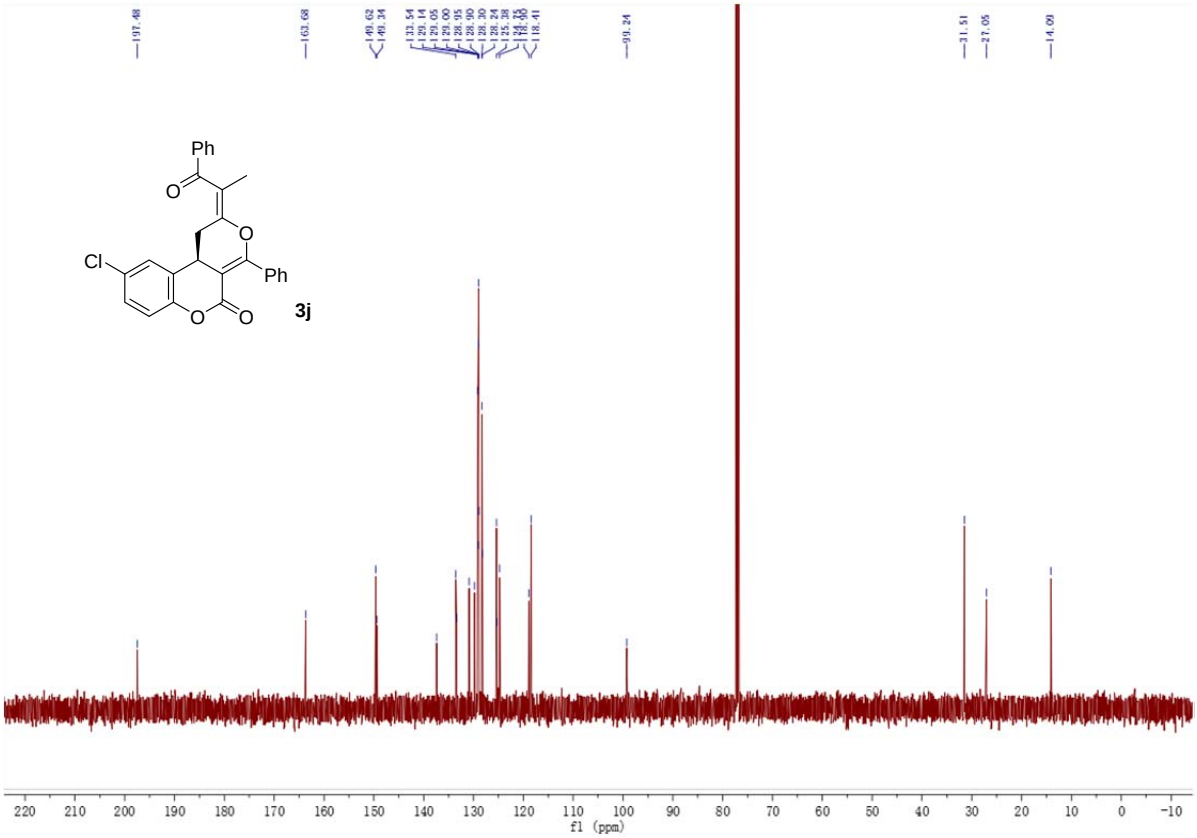
O
Cl
Ph
O
O
3j
f1 (ppm)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Cl
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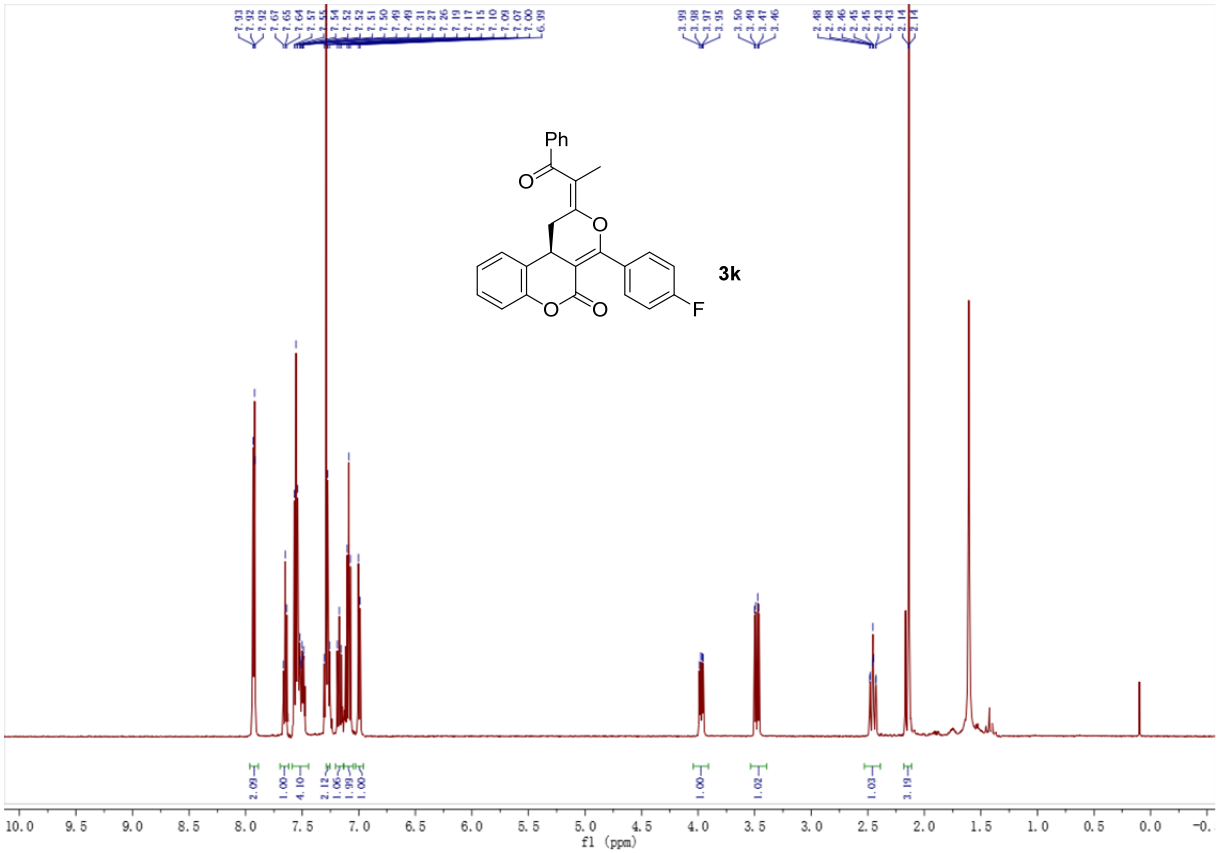
3j
f1 (ppm)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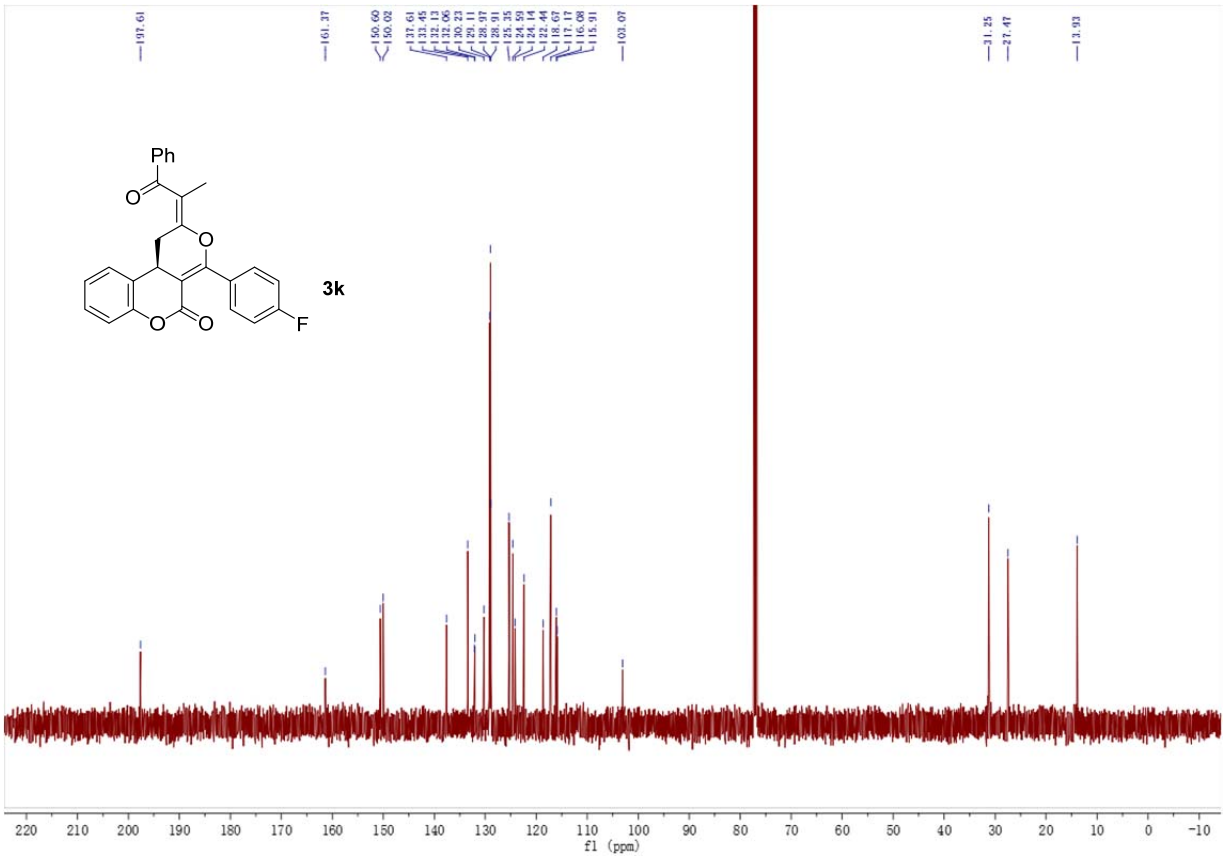
3k
f1 (ppm)


Ph
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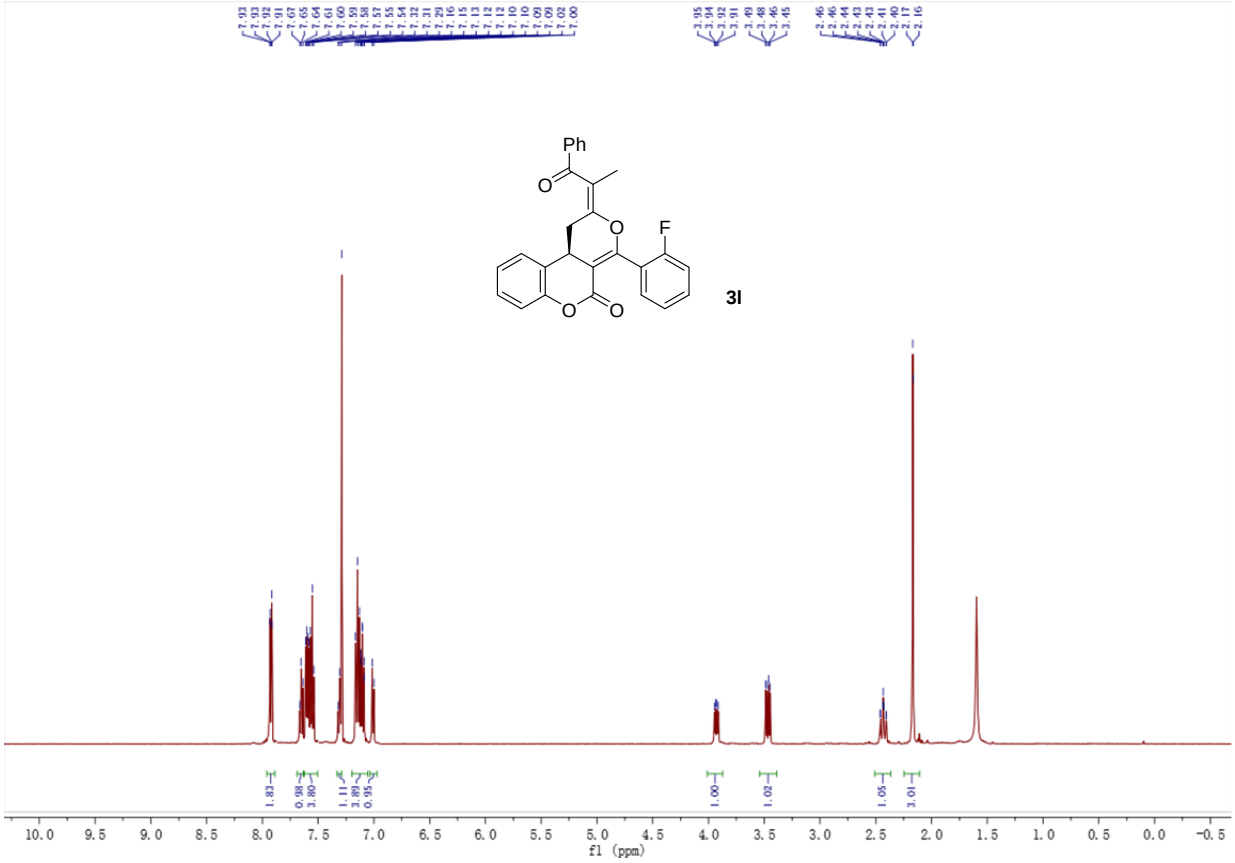
3k
f1 (ppm)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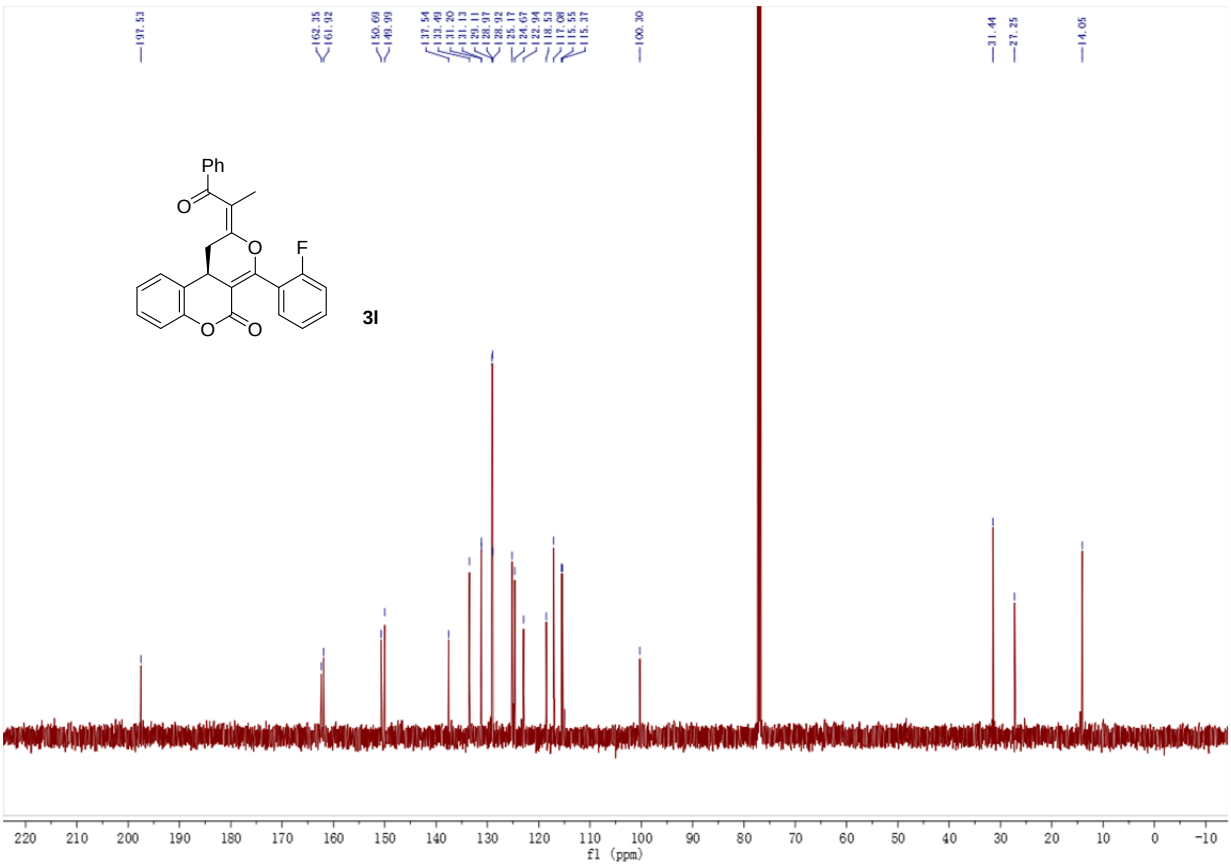
f1 (ppm)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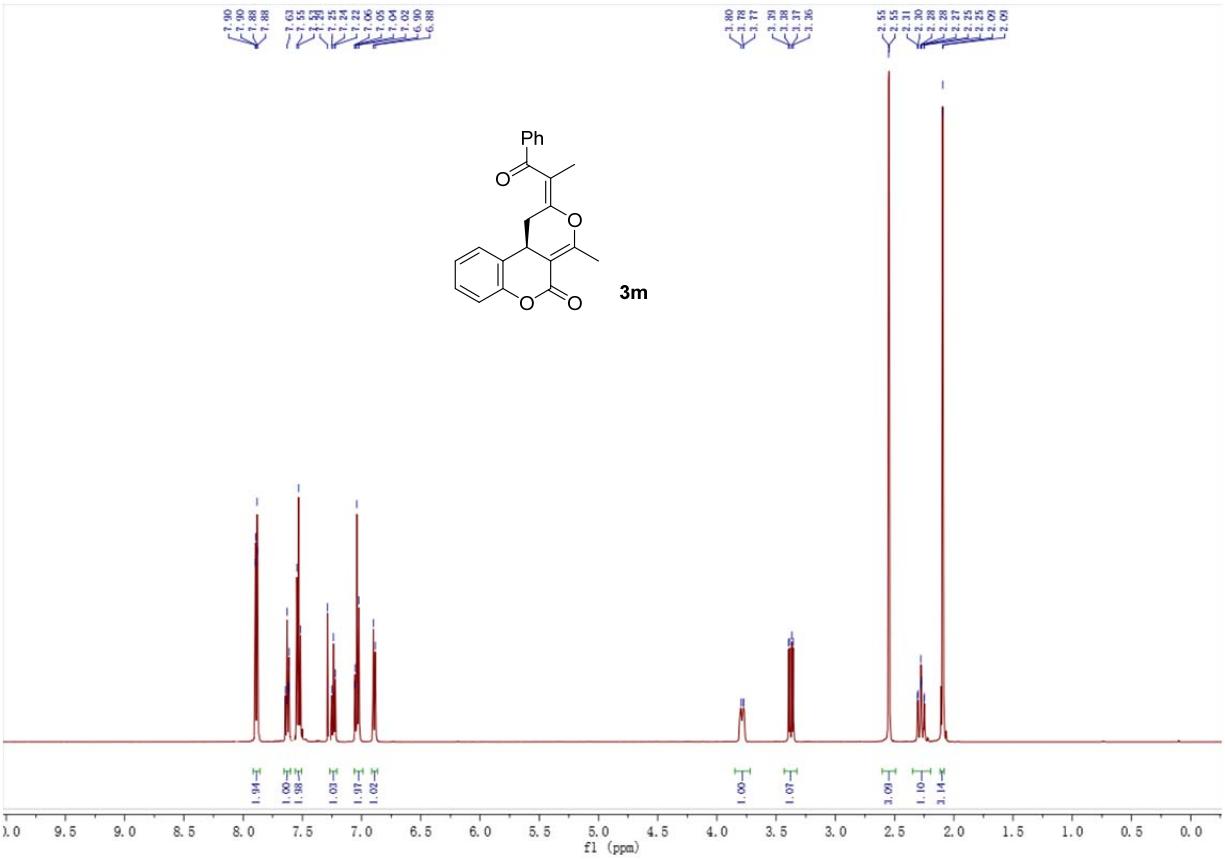
f1 (ppm)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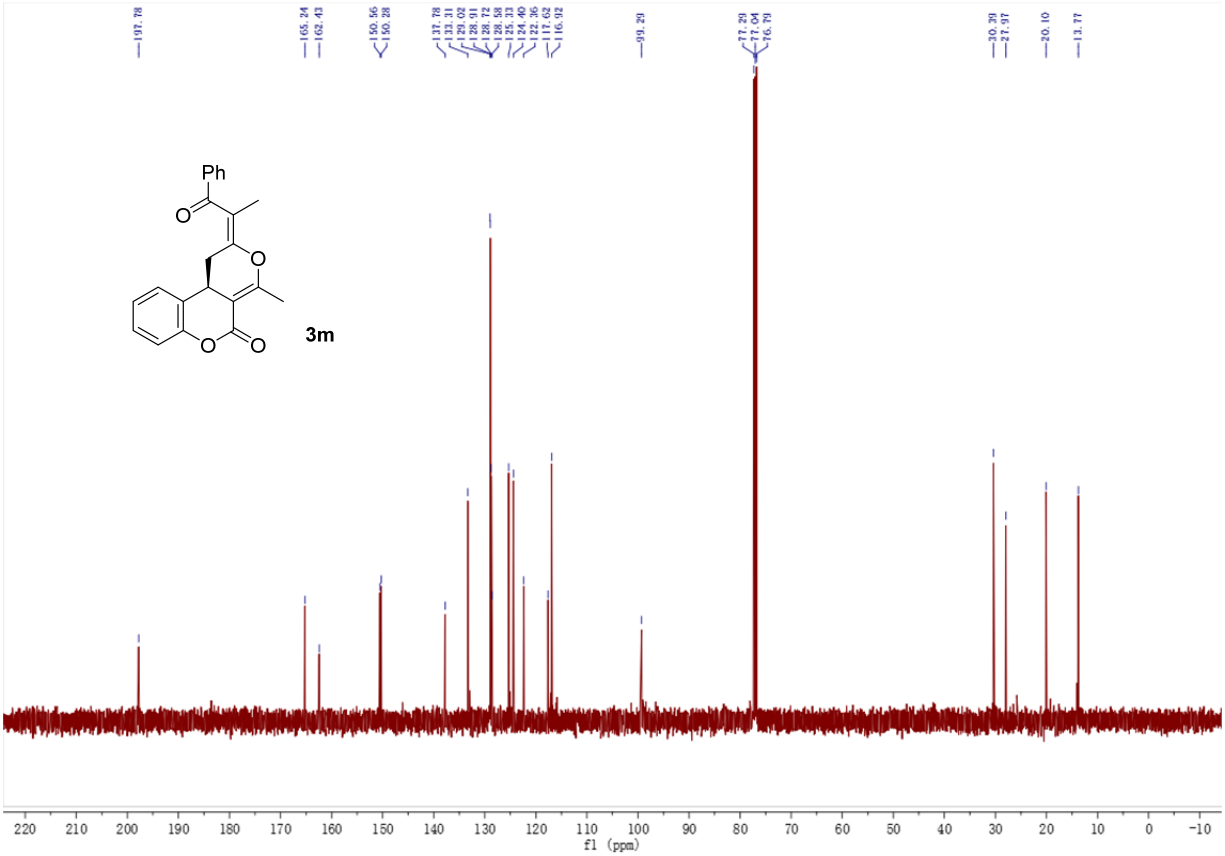
f1 (ppm)


Ph
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O
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O
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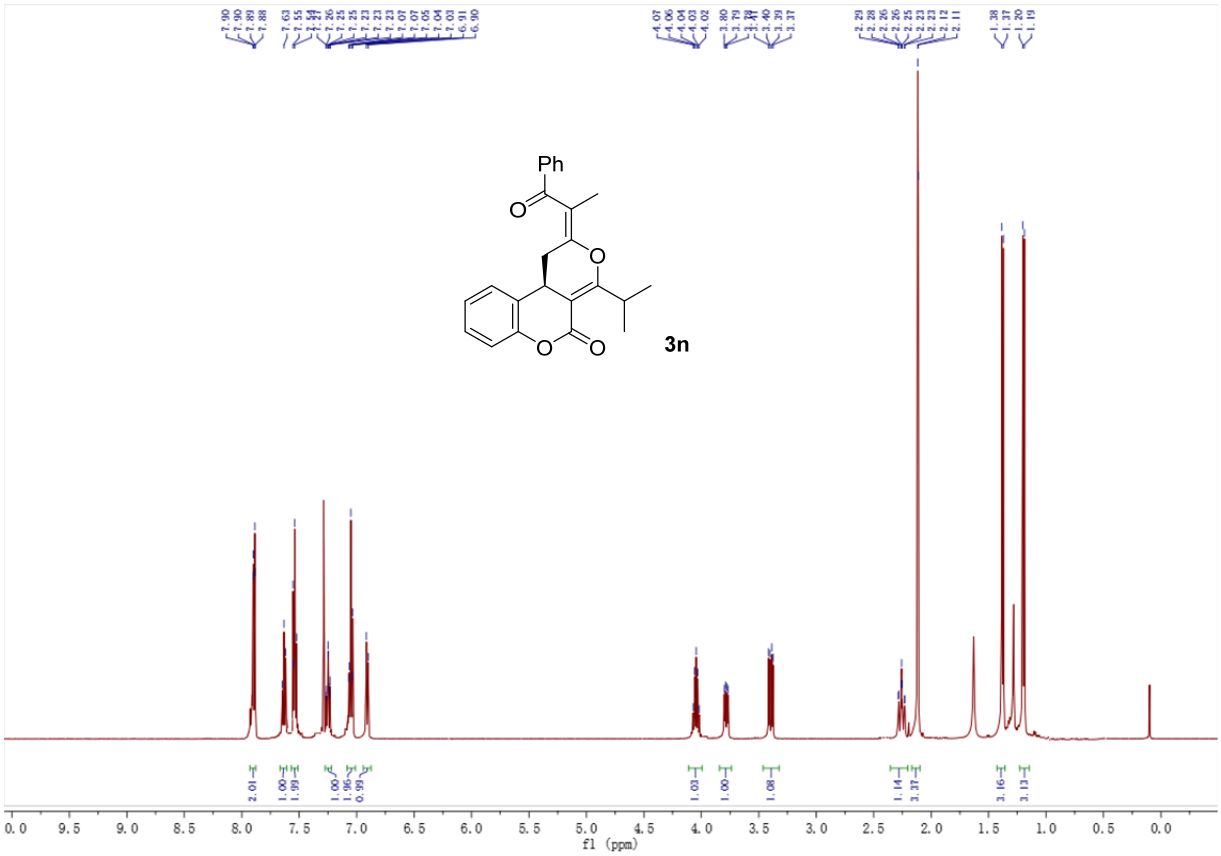
f1 (ppm)


Ph
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O
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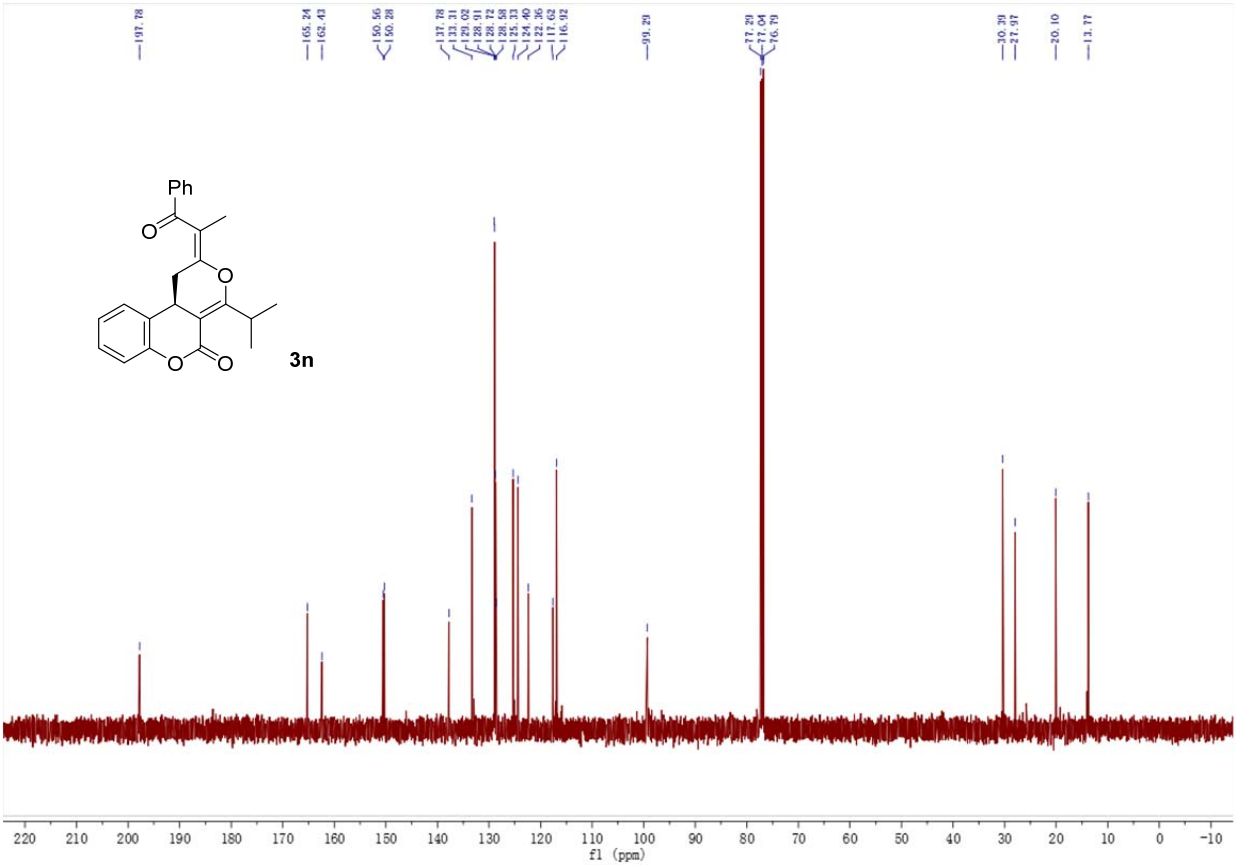
f1 (ppm)


Ph
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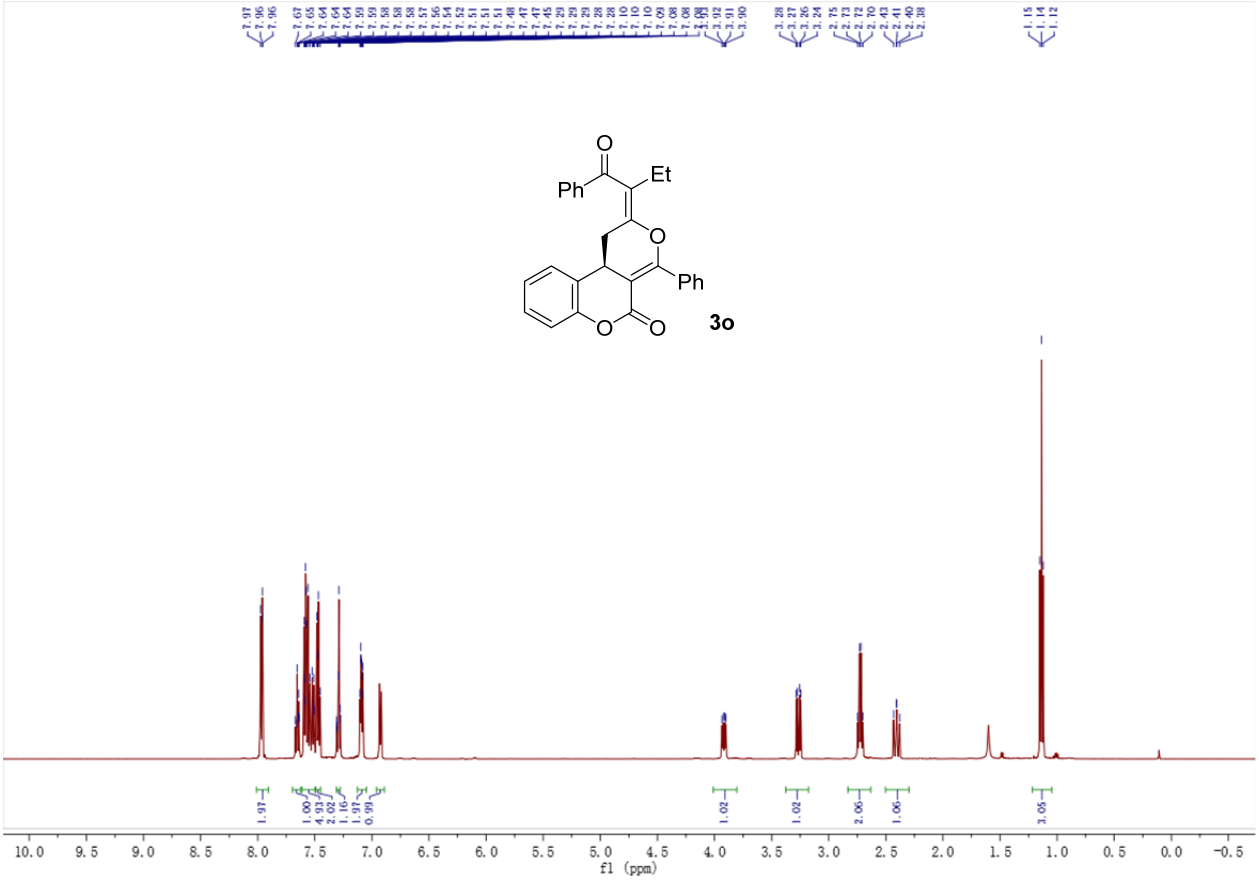
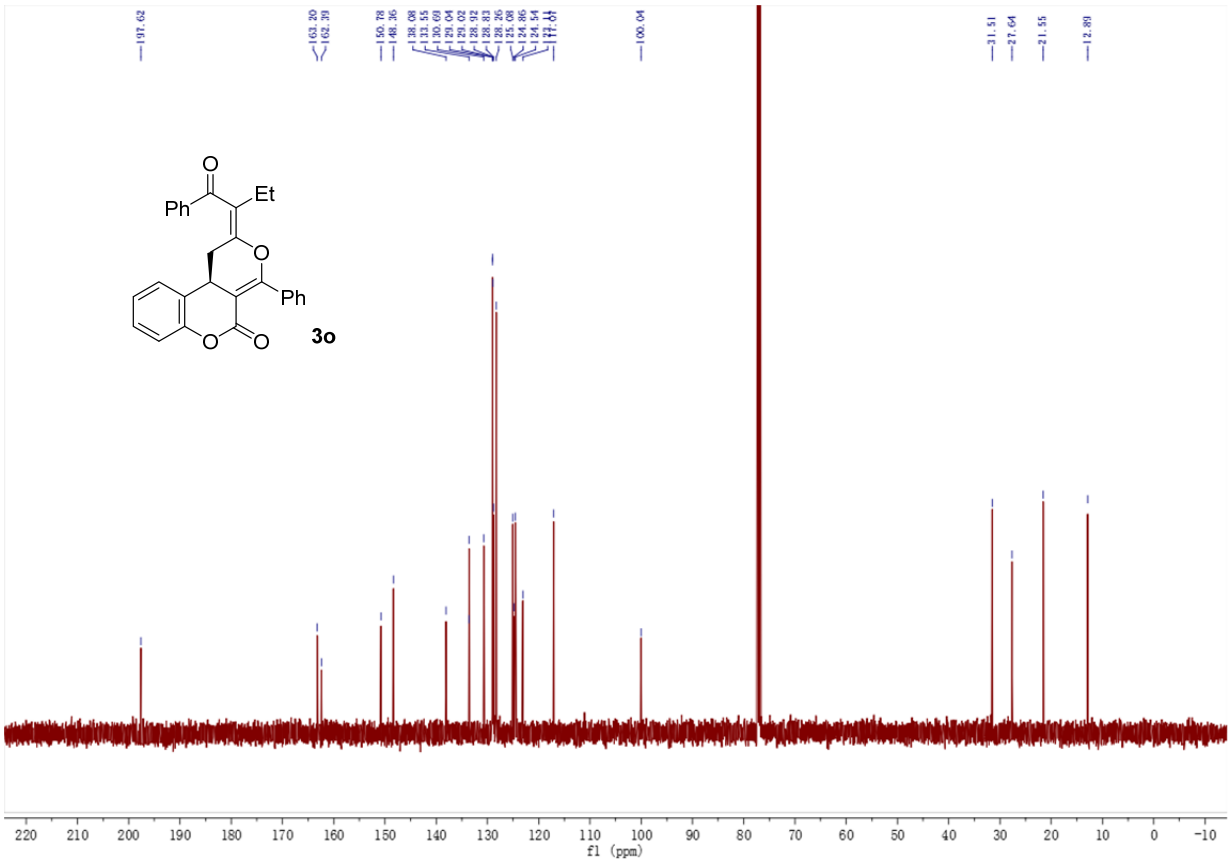
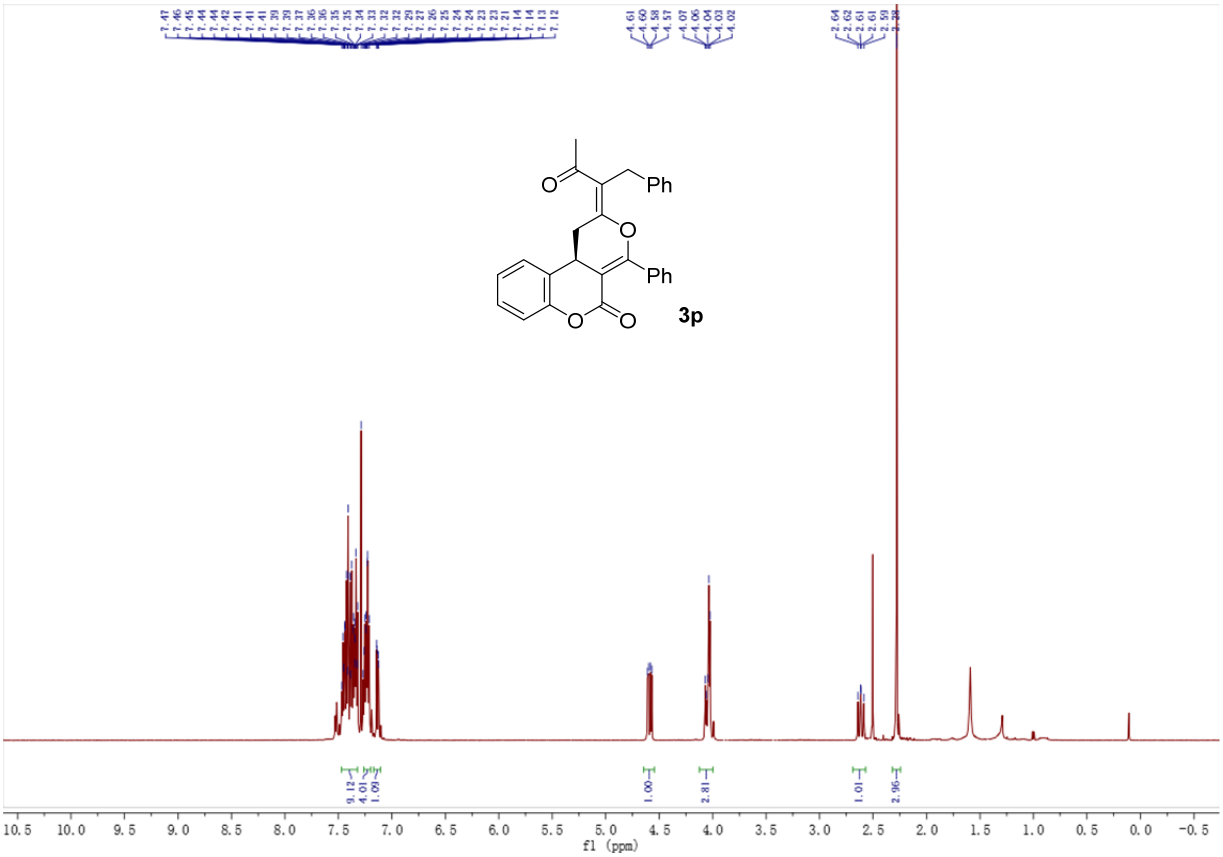
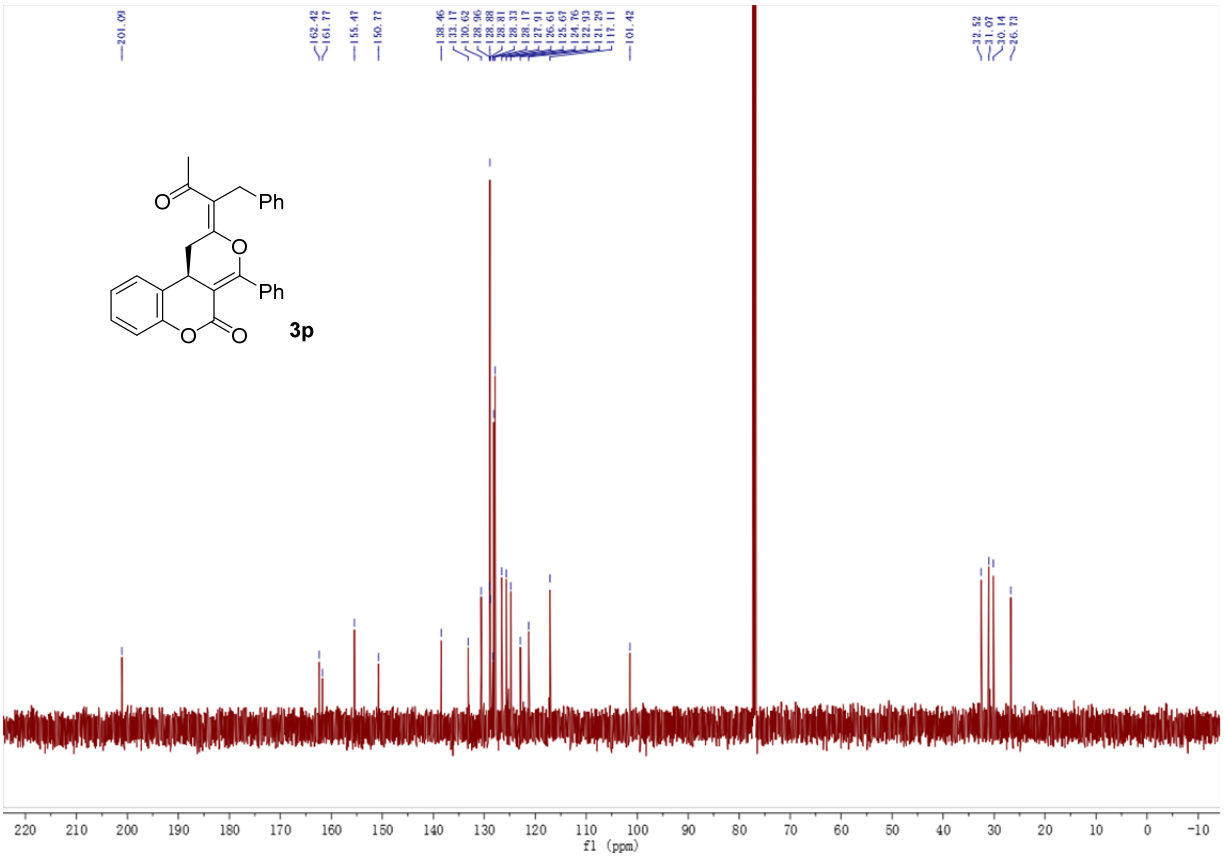
O
O
O
3n
f1 (ppm)


Ph
Et
O
O
Ph
O
O
3o
f1 (ppm)


Ph
Et
O
O
Ph
O
O
3o
f1 (ppm)


Ph
Ph
3p
f1 (ppm)


Ph
Ph
3p
f1 (ppm)