Supporting Information

Electrochemical synthesis of γ-carbolinones via sulfonylation-triggered cyclization of indole-3-carboxamides

Dan Luo, Qian Wang, Jiang Liu, Haibo Mei,* and Jianlin Han*

Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, College of Chemical Engineering, Nanjing Forestry University, Nanjing 210037, China.

E-mail: meihb@njfu.edu.cn; hanjl@njfu.edu.cn

Table of Contents

1. General information

The instrument for electrolysis is DC power supply UTP1303 made in China. The size of electrodes is 1.0 × 1.0 cm^2. All the commercial reagents including solvents were used directly without further purification. All *N*-alkyl-acryloyl-1*H*-indole-3-carboxamides **1** were prepared following a literature procedure.[1] All the experiments were monitored by thin layer chromatography (TLC) with UV light. The TLC employed 0.25 mm silica gel coated on glass plates. Purification of products was carried out by silica gel 60 F-254 TLC plates of 20 cm × 20 cm and column chromatography with silica gel 60 (300-400 mesh). Melting points were recorded without correction on RY-1G of Tianjin Xintianguang instrument company. NMR spectra were recorded on Bruker 400 MHz and 600 MHz spectrometers. High resolution mass spectra (HRMS) were measured on Agilent 6210 ESI/TOF MS instrument. The X-ray data were collected at 100 K on a Rigaku Oxford Diffraction Supernova Dual Source, Cu at Zero equipped with an AtlasS2 CCD using Cu Kα radiation.

2. Graphical guide for the set-up

As experimental set-up, the anode electrode and cathode electrode were platinum flakes (10 mm × 10 mm × 0.2 mm), plastic plugs, an undivided three-necked bottle were used.

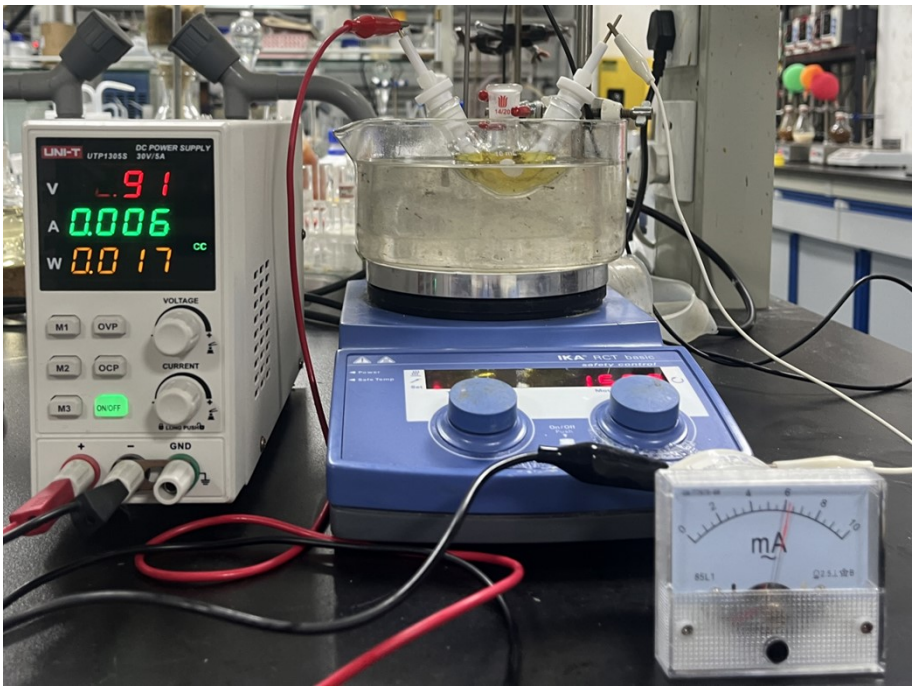
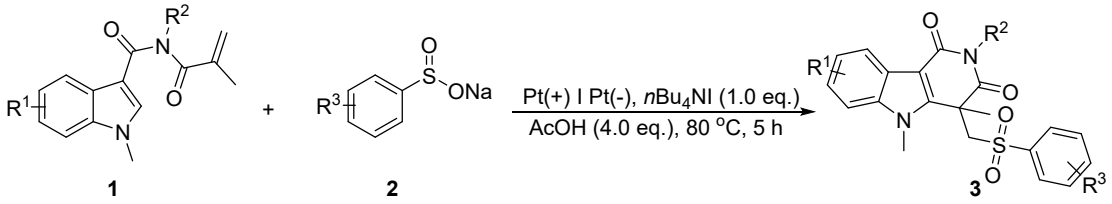


Figure S1. Graphical guide for the set-up.

3. General procedure for the electrochemical reaction



Into an undivided cell equipped with a platinum anode (1.0 cm × 1.0 cm × 0.2 mm) and a platinum cathode (1.0 cm × 1.0 cm × 0.2 mm) were taken indole derivative **1** (0.2 mmol), sodium sulfinates **2** (0.6 mmol), *n*Bu_4NI (0.2 mmol), acetic acid (0.8 mmol), MeCN (8 mL), H_2O (4 mL). The reaction mixture was stirred at a constant current of 6 mA at 80 ℃ for 5 h. Then, the reaction was diluted with H_2O (25 mL) and extracted with DCM (10 mL × 3). The combined organic layers were dried with anhydrous Na_2SO_4, filtered and concentrated in vacuo. The product **3** was purified by TLC plate of 20 cm × 20 cm using petroleum ether/ethyl acetate (1:1, v/v) as eluent.

4. Cyclic voltammetry experiments

The cyclic voltammetry experiments were measured at room temperature. Cyclic voltammetry (CV) was performed on an electrochemical workstation (Chenhua CHI730E). The experiment was performed in a three-electrode cell with MeCN (4 mL) and H_2O (2 mL) as the solvent, $LiClO_4$ (0.1 mmol) as the supporting electrolyte, and the concentration of the **1a** was 16.7 mM; the concentration of the **2a** was 50.0 mM; the concentration of the TBAI was 16.7 mM. The scan speed was 150 mV/s. The potential ranges investigated were 0 V to 3.0 V vs Ag/AgCl (saturated aqueous KCl (3 M)). CV plotting convention is IUPAC.

Working electrode: The working electrode is a 2 mm diameter platinum platter.

Reference electrode: The reference electrode is Ag/AgCl (saturated aqueous KCl (3 M)).

Counter electrode: The counter electrode is a platinum wire.

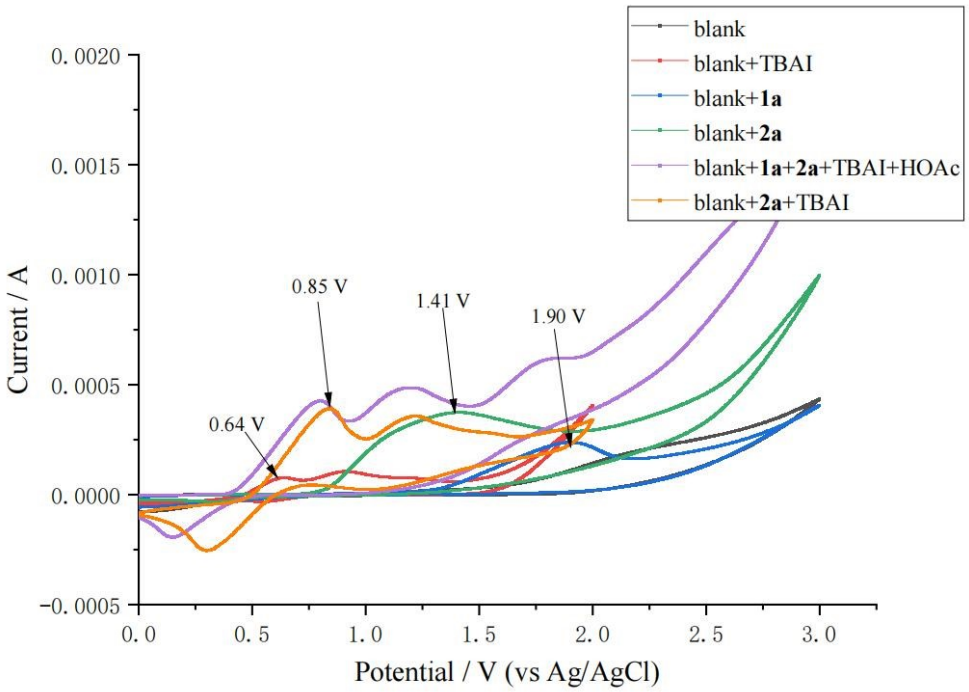


Figure S2. CV experiments.

5. Control experiments

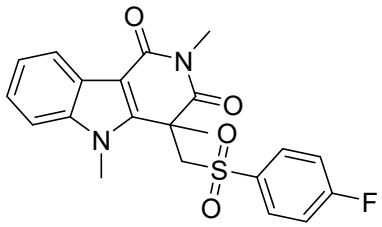
a) radical-trapping experiment with TEMPO

Into an undivided cell equipped with a platinum anode (1.0 cm × 1.0 cm × 0.2 mm) and a platinum cathode (1.0 cm × 1.0 cm × 0.2 mm) were taken indole derivative **1** (0.2 mmol), sodium sulfinates **2** (0.6 mmol), *n*Bu_4NI (0.2 mmol), acetic acid (0.8 mmol), MeCN (8 mL), H_2O (4 mL), and TEMPO (0.6 mmol, 3.0 equiv). The reaction mixture was stirred at a constant current of 6 mA at 80 ℃ for 5 h. The conversion was completely suppressed, and almost no desired product **3aa** was obtained.

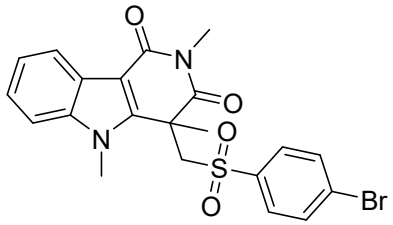
6. Scale-up synthesis

Into an undivided cell equipped with a platinum anode (1.0 cm × 1.0 cm × 0.2 mm) and a platinum cathode (1.0 cm × 1.0 cm × 0.2 mm) were taken indole derivative **1** (2.0 mmol), sodium sulfinates **2** (6.0 mmol), *n*Bu_4NI (2.0 mmol), acetic acid (8 mmol), MeCN (16 mL), H_2O (8 mL). The reaction mixture was stirred at a constant current of 6 mA at 80 ℃ for 10 h. Then, the reaction was diluted with H_2O (25 mL) and extracted with DCM (10 mL × 3). The combined organic layers were dried with anhydrous Na_2SO_4, filtered and concentrated in vacuo. The product was purified by column chromatography using petroleum ether/ethyl acetate (2:1, v/v) as eluent to afford the corresponding product **3aa** (582.1 mg, 70%).

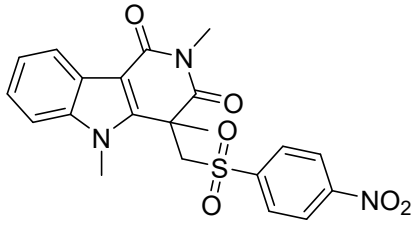
7. Characterization data of 3



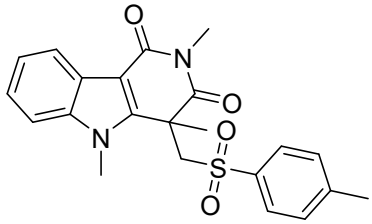
Compound **3aa**: 52.1 mg, 61% yield, white solid, mp 145-146 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 8.37-8.35 (m, 1H), 7.49-7.46 (m, 2H), 7.41-7.39 (m, 2H), 7.27-7.24 (m, 1H), 6.94-6.89 (m, 2H), 4.60 (d, *J* = 15.1 Hz, 1H), 4.00 (d, *J* = 15.0 Hz, 1H), 3.69 (s, 3H), 3.25 (s, 3H), 1.73 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 173.6, 167.1 (d, *J* = 256.2 Hz), 161.4, 141.9, 138.5, 134.2, 131.1 (d, *J* = 9.8 Hz), 124.4, 124.2, 123.2, 121.7, 116.3 (d, *J* = 22.8 Hz), 109.4, 104.7, 62.5, 43.8, 32.0, 27.4, 26.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -102.3 (s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{19}FN_2KO_4S^+$ 453.0681, found 453.0683.



Compound **3ab**: 51.0 mg, 53% yield, white solid, mp 234-235 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.34-8.31 (m, 1H), 7.38-7.36 (m, 2H), 7.31-7.28 (m, 2H), 7.26-7.23 (m, 2H), 7.21-7.19 (m, 1H), 4.54 (d, *J* = 15.1 Hz, 1H), 3.95 (d, *J* = 15.1 Hz, 1H), 3.62 (s, 3H), 3.23 (s, 3H), 1.69 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.6, 161.4, 141.7, 138.5, 137.0, 132.1, 129.5, 129.4, 124.5, 124.1, 123.2, 121.6, 109.4, 104.8, 62.5, 43.8, 32.0, 27.2, 26.9. HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{19}BrN_2KO_4S^+$ 449.0932, found 449.0925.

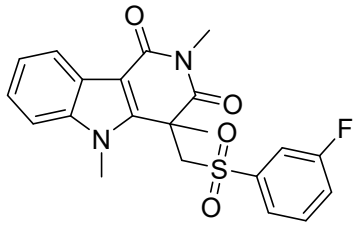


Compound **3ac**: 44.0 mg, 50% yield, white solid, mp 230-232 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.38-8.35 (m, 1H), 7.42-7.40 (m, 2H), 7.36-7.30 (m, 4H), 7.26-7.24 (m, 1H), 4.59 (d, *J* = 15.1 Hz, 1H), 3.99 (d, *J* = 15.1 Hz, 1H), 3.68 (s, 3H), 3.26 (s, 3H), 1.74 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, CD_3COCD_3): δ = 174.0, 161.3, 142.3, 138.7, 138.0, 132.0, 129.2, 128.3, 124.2, 123.9, 122.5, 120.9, 110.0, 104.4, 62.2, 43.6, 31.5, 26.0, 25.6. HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{19}N_3KO_6S^+$ 480.0626, found 480.0600.

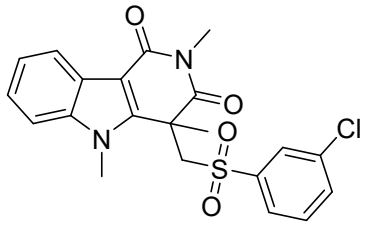


Compound **3ad**: 34.3 mg, 40% yield, white solid, mp 203-205 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.32-8.30 (m, 1H), 7.35-7.32 (m, 2H), 7.28-7.25 (m, 2H), 7.18-7.15 (m, 1H), 6.97-6.95 (m, 2H), 4.52 (d, *J* = 15.0 Hz, 1H), 3.94 (d, *J* = 15.0 Hz, 1H), 3.61 (s, 3H), 3.18 (s, 3H), 2.27 (s, 3H), 1.67 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.7, 161.6, 145.2, 142.1, 138.7, 135.1, 129.5, 128.1, 124.3, 124.2, 123.0, 121.7, 109.4, 104.8, 62.5, 43.9, 32.1, 27.4, 26.8, 21.6. HRMS (ESI) m/z:

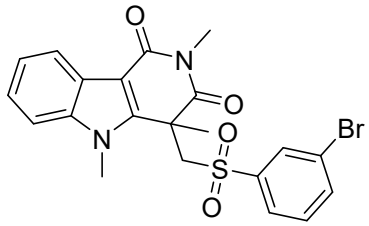
[M+K]$^+$ calcd for $C_{22}H_{22}N_2KO_4S^+$ 449.0932, found 449.0936.



Compound **3ae**: 34.1 mg, 42% yield, white solid, mp 206-207 ^{o}C . ^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.37-8.36 (m, 1H), 7.40-7.38 (m, 2H), 7.27-7.17 (m, 5H), 4.60 (d, *J* = 15.1 Hz, 1H), 4.01 (d, *J* = 15.1 Hz, 1H), 3.71 (s, 3H), 3.30 (s, 3H), 1.74 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.7, 163.0 (d, *J* = 253.9 Hz), 161.4, 141.8, 140.4 (d, *J* = 6.4 Hz), 138.5, 130.8 (d, *J* = 7.7 Hz), 124.3, 124.2, 123.9 (d, *J* = 3.3 Hz), 123.1, 121.8, 121.2 (d, *J* = 21.3 Hz), 115.3 (d, *J* = 24.3 Hz), 109.4, 104.7, 62.5, 43.8, 32.0, 27.3, 26.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -108.4 (s). HRMS (ESI) m/z: [M+K]$^+$ calcd for $C_{21}H_{19}FN_2KO_4S^+$ 453.0681, found 453.0686.

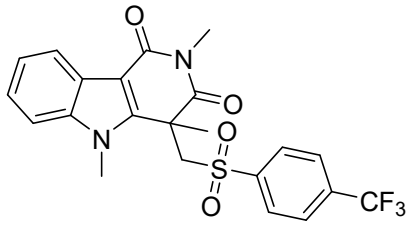


Compound **3af**: 34.7 mg, 40% yield, white solid, mp 220-221 ^{o}C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.32 (d, *J* = 7.3 Hz, 1H), 7.65 (d, *J* = 7.8 Hz, 1H), 7.36-7.30 (m, 3H), 7.14-7.06 (m, 2H), 6.78-6.75 (m, 1H), 4.65 (d, *J* = 15.3 Hz, 1H), 4.49 (d, *J* = 15.1 Hz, 1H), 3.69 (s, 3H), 3.32 (s, 3H), 1.80 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.6, 161.4, 141.7, 139.9, 138.5, 135.4, 133.9, 130.1, 127.9, 126.2, 124.4, 124.2, 123.2, 121.8, 109.4, 104.8, 62.5, 43.8, 32.0, 27.3, 26.9. HRMS (ESI) m/z: [M+K]$^+$ calcd for $C_{21}H_{19}ClN_2NaO_4S^+$ 469.0386, found 469.0389.

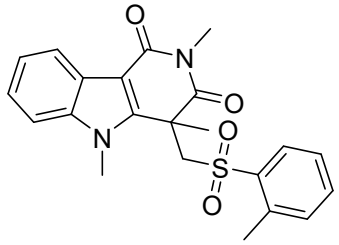


Compound **3ag**: 49.4 mg, 53% yield, white solid, mp 220-221 ^{o}C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.36(s, 1H), 7.69(s, 1H), 7.58-7.56 (m, 1H), 7.38-7.33 (m, 3H), 7.25(s, 1H), 7.07-7.03 (m, 1H), 4.60 (d, *J* = 15.1 Hz, 1H), 4.02 (d, *J*=15.0 Hz, 1H), 3.70 (s, 3H), 3.30 (s, 3H), 1.74 (s,3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.6, 161.4, 141.6, 140.0, 138.5, 136.8, 130.8, 130.3, 126.7, 124.4,

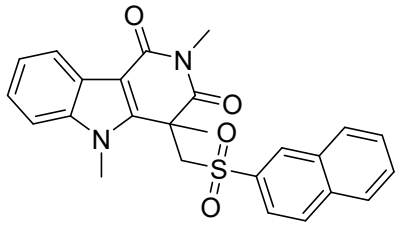
124.2, 123.2, 123.0, 121.9, 109.4, 104.8, 62.5, 43.8, 32.0, 27.3, 26.9. HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{19}BrN_2KO_4S^+$ 512.9881, found 512.9876.



Compound **3ah**: 33.5 mg, 36% yield, white solid, decomposition. ^1H NMR (400 MHz, $CDCl_3$): δ = 8.38-8.35 (m, 1H), 7.58-7.56 (m, 2H), 7.46-7.38 (m, 4H), 7.18-7.14 (m, 1H), 4.62 (d, *J* = 15.1 Hz, 1H), 4.04 (d, *J* = 15.1 Hz, 1H), 3.61 (s, 3H), 3.27 (s, 3H), 1.75 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 173.5, 170.7, 161.4, 141.5, 138.3 135.6 (d, *J* = 33.3 Hz), 128.6, 126.0 (d, *J* = 283.5 Hz), 125.9 (d, *J* = 3.7 Hz), 124.5, 124.1, 123.3, 121.7, 109.4, 104.8, 62.7, 43.8, 31.9, 27.1, 26.8. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -63.2 (s). HRMS (ESI) m/z: $[M+NH_4]^+$ calcd for $C_{22}H_{23}F_3N_3O_4S^+$ 495.1349, found 495.1349.

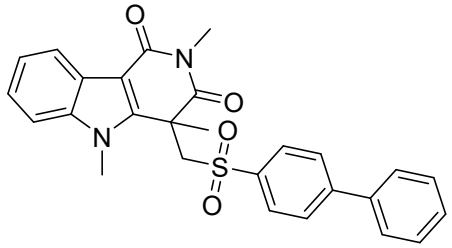


Compound **3ai**: 21.2 mg, 26% yield, white solid, mp 215-216 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 8.35-8.33 (m, 1H), 7.40-7.36 (m, 3H), 7.31-7.24 (m, 3H), 6.99-6.95 (m, 1H), 4.62 (d, *J* = 15.0 Hz, 1H), 3.97 (d, *J* = 15.0 Hz, 1H), 3.81 (s, 3H), 3.06 (s, 3H), 2.70 (s, 3H), 1.72 (s, 3H). $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ = 173.5, 161.3, 142.3, 138.8, 138.7, 135.8, 134.2, 132.4, 130.3, 126.3, 124.3, 124.1, 122.9, 121.6, 109.6, 104.6, 60.8, 43.8, 32.2, 27.7, 26.7, 20.3. HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{22}H_{22}N_2NaO_4S^+$ 433.1193, found 433.1193.

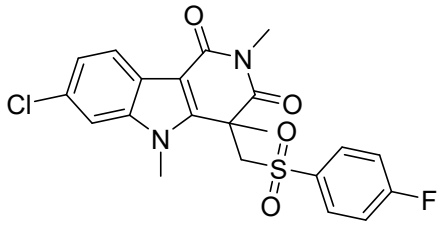


Compound **3aj**: 51.5 mg, 58% yield, white solid, decomposition. ^1H NMR (600 MHz, CDCl3): δ =

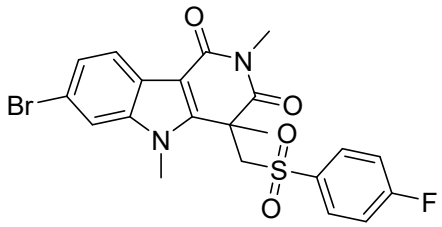
8.37-8.35 (m, 1H), 7.82-7.80 (m, 2H), 7.77-7.76 (m, 1H), 7.64-7.61 (m, 1H), 7.57-7.55 (m, 1H), 7.51-7.45 (m, 2H), 7.35-7.33 (m, 1H), 7.21-7.19 (m, 1H), 6.91-6.90 (m, 1H), 4.66 (d, *J* = 15.3 Hz, 1H), 4.07 (d, *J* = 15.3 Hz, 1H), 3.52 (s, 3H), 3.06 (s, 3H), 1.71 (s, 3H). $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ = 173.7, 161.5, 141.9, 138.4, 135.0, 134.6, 131.6, 130.3, 129.6, 129.5, 129.2, 127.7, 127.6, 124.3, 124.2, 123.0, 122.3, 121.5, 109.2, 104.8, 62.4, 43.9, 31.9, 27.3, 26.6. HRMS (ESI) m/z: $[M+NH_4]^+$ calcd for $C_{25}H_{26}N_3O_4S^+$ 495.1349, found 495.1349.



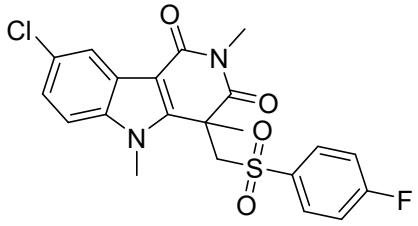
Compound **3ak**: 31.5 mg, 33% yield, white solid, mp 183-185 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.40-8.39 (m, 1H), 7.51-7.46 (m, 7H), 7.44-7.42 (m, 2H), 7.41-7.39 (m, 1H), 7.37-7.34 (m, 1H), 7.22-7.20 (m, 1H), 4.64 (d, *J* = 15.2 Hz, 1H), 4.04 (d, *J* = 15.2 Hz, 1H), 3.69 (s, 3H), 3.20 (s, 3H), 1.74 (s, 3H). $^{13}C\{^{1}H\}$ NMR (150 MHz, CDCl3): δ = 173.7, 161.5, 146.9, 142.0, 138.7, 138.6, 136.3, 129.1, 128.9, 128.7, 127.4, 124.3, 123.0, 121.7, 109.5, 104.8, 62.5, 43.8, 32.0, 27.4, 26.8. HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{27}H_{24}N_2NaO_4S^+$ 495.1349, found 495.1349.



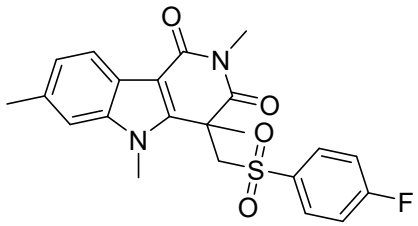
Compound **3ba**: 43.5 mg, 49% yield, yellow solid, decomposition. ^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.28-8.26 (m, 1H), 7.57-7.33 (m, 2H), 7.38-7.32 (m, 2H), 7.05-7.00 (m, 2H), 4.59 (d, *J* = 15.0 Hz, 1H), 3.96 (d, *J* = 15.0 Hz, 1H), 3.76 (s, 3H), 3.23 (s, 3H), 1.74 (s, 3H). $^{13}C\{1H\}$ NMR (150 MHz, $CDCl_3$): δ = 173.5, 166.8 (d, *J* = 258.8 Hz), 162.2, 161.1, 142.7, 139.1, 134.2, 131.2 (d, *J* = 9.9 Hz), 130.4, 123.8, 122.7 (d, *J* = 11.4 Hz), 116.4 (d, *J* = 22.6 Hz), 109.8, 104.8, 62.3, 43.9, 32.3, 27.4, 26.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -101.9 (s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{18}ClFN_2KO_4S^+$ 487.0291, found 487.0309.



Compound **3ca**: 51.7 mg, 53% yield, white solid, decomposition. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.23-8.21 (m, 1H), 7.56-7.49 (m, 4H), 7.05-7.00 (m, 2H), 4.59 (d, *J* = 15.0 Hz, 1H), 3.96 (d, *J* = 14.9 Hz, 1H), 3.76 (s, 3H), 3.23 (s, 3H), 1.73 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.5, 166.8 (d, *J* = 258.3 Hz), 161.1, 142.6, 139.4, 134.2 (d, *J* = 3.3 Hz), 131.1 (d, *J* = 9.4 Hz), 126.4, 123.0, 122.9, 118.0, 116.3 (d, *J* = 22.7 Hz), 112.8, 104.8, 62.3, 43.8, 32.2, 27.3, 26.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -101.9 (s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{21}H_{18}BrFN_2KO_4S^+$ 530.9786, found 530.9808.

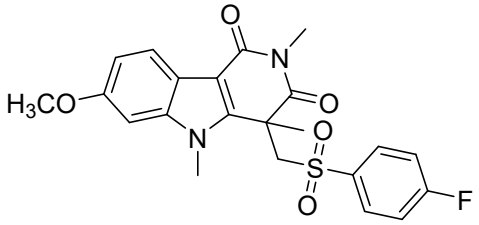


Compound **3da**: 30.0 mg, 33% yield, white solid, decomposition. ^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.36-8.35 (m, 1H), 7.54-7.51 (m, 2H), 7.36-7.35 (m, 1H), 7.22-7.21 (m, 1H), 7.02-7.00 (m, 2H), 4.58 (d, *J* = 15.1 Hz, 1H), 3.96 (d, *J* = 15.1 Hz, 1H), 3.74 (s, 3H), 3.22 (s, 3H), 1.73 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.4, 167.2 (d, *J* = 257.5 Hz), 161.0, 137.0, 134.2 (d, *J* = 3.3 Hz), 131.2 (d, *J* = 9.7 Hz), 129.1, 125.2, 124.7, 121.2, 116.5 (d, *J* = 22.7 Hz), 110.6, 104.3, 99.8, 62.3, 43.9, 32.3, 27.4, 26.9. ^{19}F NMR (575 MHz, $CDCl_3$): δ = -101.9 (s). HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{21}H_{18}ClFN_2NaO_4S^+$ 471.0552, found 471.0553.

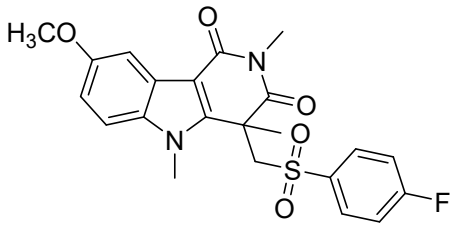


Compound **3ea**: 56.4 mg, 66% yield, white solid, mp 212-213 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.21 (d, *J* = 8.04 Hz, 1H), 7.46-7.43 (m, 2H), 7.22 (d, *J* = 8.04 Hz, 1H), 7.01 (s, 1H), 6.89-6.85 (m, 2H), 4. 54-4.50（m, 1H），3.99-3.95 (m, 1H), 3.61-3.60 (m, 3H), 3.25 (s, 3H), 2.53 (s, 3H), 1.70 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.8, 167.0 (d, *J* = 255.8 Hz), 161.5, 141.3,

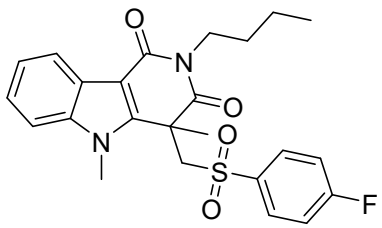
138.9, 134.5, 134.2 (d, J = 3.0 Hz), 131.0 (d, J = 9.78 Hz), 124.8, 121.9, 121.2, 116.2 (d, J = 22.6 Hz), 109.4, 104.6, 62.6, 43.8, 31.9, 27.2, 26.8, 21.9. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -102.6 (s). HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{22}H_{21}FN_2NaO_4S^+$ 451.1098, found 451.1103.



Compound **3fa**: 56.8 mg, 64% yield, white solid, mp 210-211 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.20 (d, J = 8.7 Hz, 1H), 7.47-7.44 (m, 2H), 7.03-7.01 (m, 1H), 6.92-6.88 (m, 2H), 6.66-6.65 (m, 1H), 4.54 (d, J = 15.1 Hz, 1H), 3.98 (d, J = 15.0 Hz, 1H), 3.90 (s, 3H), 3.59 (s, 3H), 3.24 (s, 3H), 1.70 (s, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.8, 171.2, 167.1 (d, J = 255.7 Hz), 161.5, 158.0, 140.8, 139.5, 131.0 (d, J = 9.6 Hz), 122.3, 118.1, 116.3 (d, J = 22.5 Hz), 112.5, 104.7, 93.4, 62.7, 55.8, 43.8, 32.0, 27.3, 26.8. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -102.5 (s). HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{22}H_{21}FN_2NaO_5S^+$ 483.0787, found 483.0789.

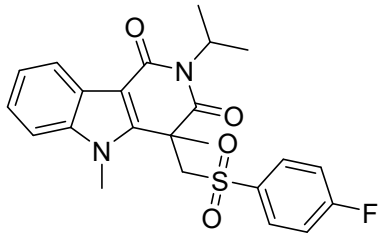


Compound **3ga**: 57.3 mg, 65% yield, white solid, mp 197-199 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.83-7.82 (m, 1H), 7.49-7.47 (m, 2H), 7.14-7.13 (m, 1H), 7.03-7.01 (m, 1H), 6.96-6.93 (m, 2H), 4. 58-4.55（m, 1H), 3.97-3.95 (m, 4H), 3.64 (s, 3H), 3.25 (s, 3H), 1.72 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.7, 166.7 (d, J = 259.5 Hz), 161.6, 156.7, 141.7, 134.3 (d, J = 2.9 Hz), 133.4, 131.1 (d, J = 9.7 Hz), 124.9, 116.3 (d, J = 22.5 Hz), 114.8, 110.3, 104.3, 102.7, 62.6, 55.9, 43.9, 32.1, 27.3, 26.8. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -102.3 (s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{22}H_{21}FN_2KO_5S^+$ 483.0786, found 483.0783.

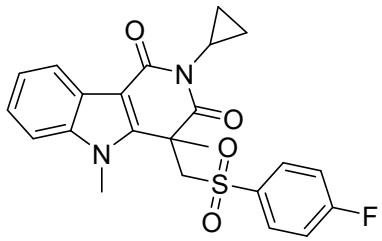


Compound **3ha**: 35.4 mg, 39% yield, white solid, mp 161-162 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ

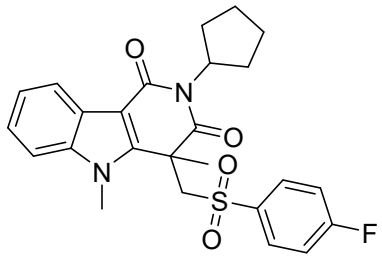
= 8.36-8.35 (m, 1H), 7.47-7.44 (m, 2H), 7.39-7.37 (m, 2H), 7.21-7.20 (m, 1H), 6.88-6.85 (m, 2H), 4.56 (d, *J* = 15.1 Hz, 1H), 3.98 (d, *J* = 15.1 Hz, 1H), 3.94-3.85 (m, 2H), 3.60 (s, 3H), 1.70 (s, 3H), 1.67-1.62 (m, 2H), 1.45-1.39 (m, 2H), 0.99-0.97 (m, 3H). $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ = 173.4, 166.6 (d, *J* = 258.1 Hz), 161.4, 141.8, 138.5, 134.5 (d, *J* = 2.9 Hz), 130.9 (d, *J* = 9.8 Hz), 124.3, 124.2, 123.1, 121.7, 116.3 (d, *J* = 22.6 Hz), 109.4, 104.8, 62.6, 43.8, 40.1, 31.9, 29.8, 27.3, 20.3, 13.9. ^{19}F NMR (565 MHz, $CDCl_3$): δ = -102.4 (s). HRMS (ESI) m/z: $[M+Na]^+$ calcd for $C_{24}H_{25}FN_2NaO_4S^+$ 479.1411, found 479.1422.



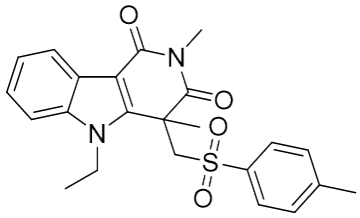
Compound **3ia**: 62.4 mg, 70% yield, white solid, mp 220-221 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.38-8.35 (m, 1H), 7.47-7.43 (m, 2H), 7.38-7.36 (m, 2H), 7.16-7.14 (m, 1H), 6.84-6.80 (m, 2H), ,5.30-5.23 (m, 1H), 4.57 (d, *J* = 15.3 Hz, 1H), 3.95 (d, *J* = 15.0 Hz, 1H), 3.52 (s, 3H), 1.70-1.67 (m, 3H), 1.56-1.52 (m, 6H). $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$): δ = 173.7, 166.5 (d, *J* = 257.7 Hz), 162.0, 141.5, 138.4, 134.9 (d, *J* = 3.1 Hz), 130.7 (d, *J* = 9.8 Hz), 124.4, 124.2, 123.0, 121.7, 116.2 (d, *J* = 22.6 Hz), 109.2, 105.2, 62.7, 45.0, 44.1, 31.7, 27.0, 19.5, 19.4. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -120.7(s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{23}H_{23}FN_2KO_4S^+$ 481.0994, found 481.0997.



Compound **3ja**: 31.3 mg, 36% yield, white solid, decomposition. ^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.37-8.35 (m, 1H), 7.49-7.47 (m, 2H), 7.39-7.37 (m, 2H), 7.21-7.20 (m, 1H), 6.90-6.87 (m, 2H), 4.55 (d, *J* = 15.1 Hz, 1H), 3.96 (d, *J* = 15.0 Hz, 1H), 3.62 (s, 3H), 2.64-2.61 (m, 1H), 1.69 (s, 3H), 1.21-1.14 (m, 2H), 0.98-0.94 (m, 1H), 0.72-0.70 (m,1H). $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ = 174.8, 167.1 (d, *J* = 257.7 Hz), 162.3, 141.6, 138.5, 134.6 (d, *J* = 4.2 Hz), 131.0 (d, *J* = 9.9 Hz), 124.4, 124.3, 123.2, 121.8, 116.4 (d, *J* = 22.7 Hz), 109.4, 105.2, 62.6, 44.2, 31.9, 27.0, 24.2, 8.5, 8.4. ^{19}F NMR (565 MHz, $CDCl_3$): δ = -102.4 (s). HRMS (ESI) m/z: $[M+K]^+$ calcd for $C_{23}H_{21}FN_2KO_4S^+$ 479.0838, found 479.0840.



Compound **3ka**: 58.9 mg, 61% yield, white solid, mp 188-189 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.34-8.32 (m, 1H), 7.41-7.31 (m, 4H), 7.14-7.11 (m, 1H), 6.80-6.76 (m, 2H), 5.40-5.31 (m, 1H), 4.54 (d, *J* = 15.0 Hz, 1H), 3.92 (d, *J* = 15.0 Hz, 1H), 3.50 (s, 3H), 2.17-2.10 (m, 2H), 2.04-2.00 (m, 2H), 1.89-1.84 (m, 2H), 1.67 (s, 3H), 1.62-1.61 (m, 2H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 173.5, 167.0 (d, *J* = 257.7 Hz), 162.1, 141.5, 138.5, 134.7 (d, *J* = 3.8 Hz), 130.8 (d, *J* = 9.8 Hz), 124.5, 124.3, 123.1, 121.8, 116.4 (d, *J* = 22.8 Hz), 109.3, 105.2, 62.8, 52.5, 44.2, 31.8, 28.7, 28.4, 27.1, 26.2, 26.1. ^{19}F NMR (376 MHz, $CDCl_3$): δ = -102.5 (s). HRMS (ESI) m/z: $[M+NH_4]^+$ calcd for $C_{25}H_{29}FN_3O_4S^+$ 486.1857, found 486.1853.



Compound **3ld**: 28.7 mg, 34% yield, white solid, mp 231-232 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.37 (d, *J* = 7.6 Hz, 1H), 7.38-7.30 (m, 2H), 7.24 (d, *J* = 8.1 Hz, 2H), 7.11 (d, *J* = 7.8 Hz, 1H), 6.89 (d, *J* = 8.0 Hz, 2H), 4.49 (d, *J* = 15.1 Hz, 1H), 4.00-3.93 (m, 2H), 3.88-3.79 (m, 1H), 3.29 (s, 3H), 2.25 (s, 3H), 1.75 (s, 3H), 1.44 (t, *J* = 7.2 Hz, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ = 173.8, 164.2, 144.8, 140.9, 137.1, 135.1, 129.3, 127.6, 124.7, 124.0, 122.8, 121.9, 109.9, 104.8, 62.9, 43.9, 40.5, 27.6, 26.8, 21.5, 14.7. HRMS (ESI) m/z: $[M+H]^+$ calcd for $C_{23}H_{25}N_2O_4S^+$ 425.1530, found 425.1534.

Reference:

1. D. Y. Yang, L. Liu, J. Y. Gu, Y. H. He, Z. Guan, *J. Org. Chem.*, 2021, **86**, 18042–18055.

8. X-ray crystallography of 3ga

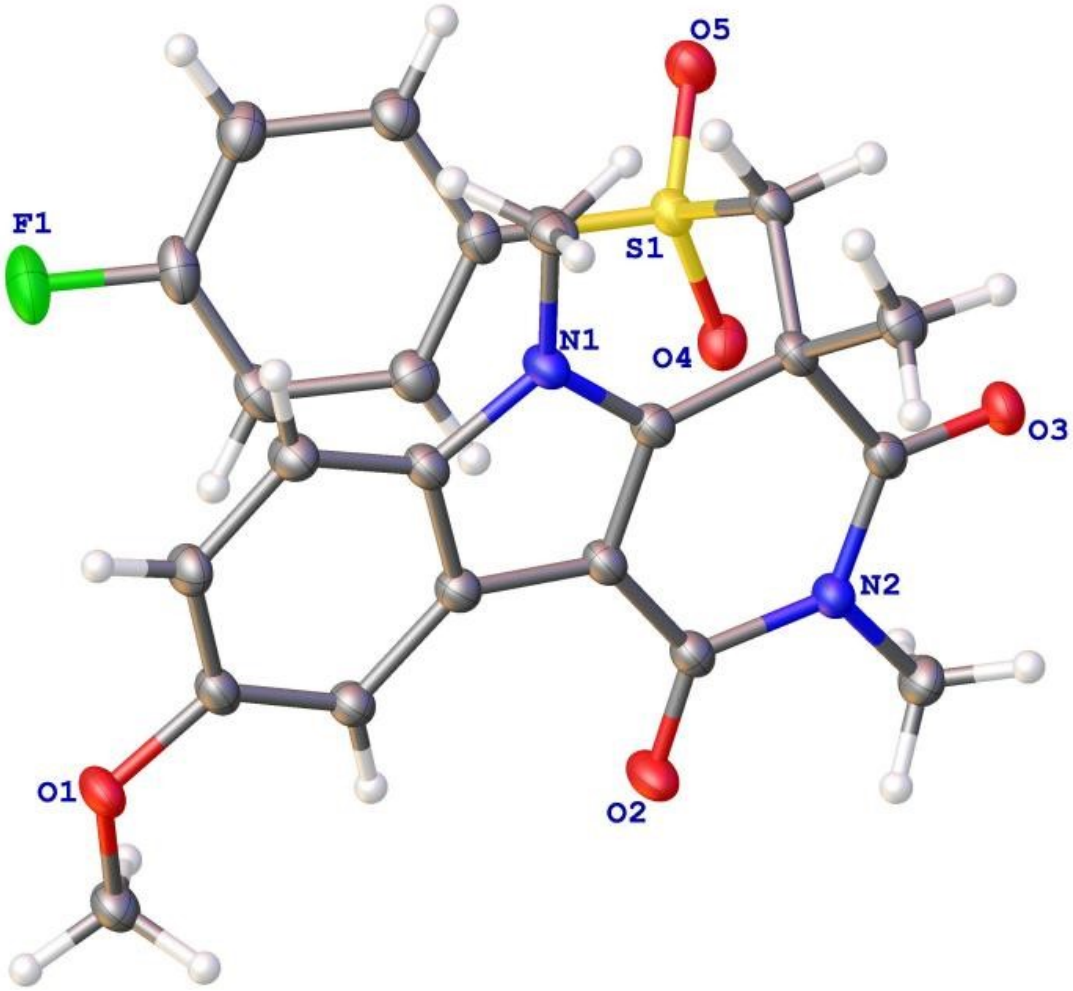
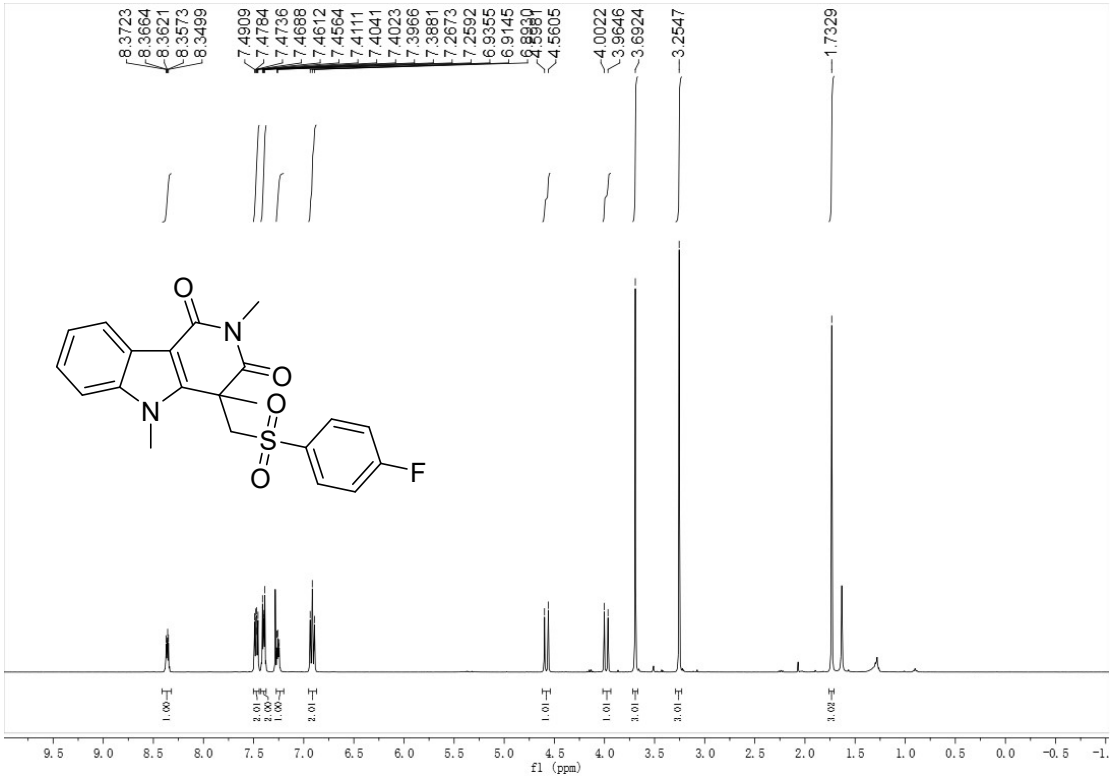


Figure S3. Single crystal x-ray analysis of **3ga** (ellipsoid contour 30% probability, 2389286).

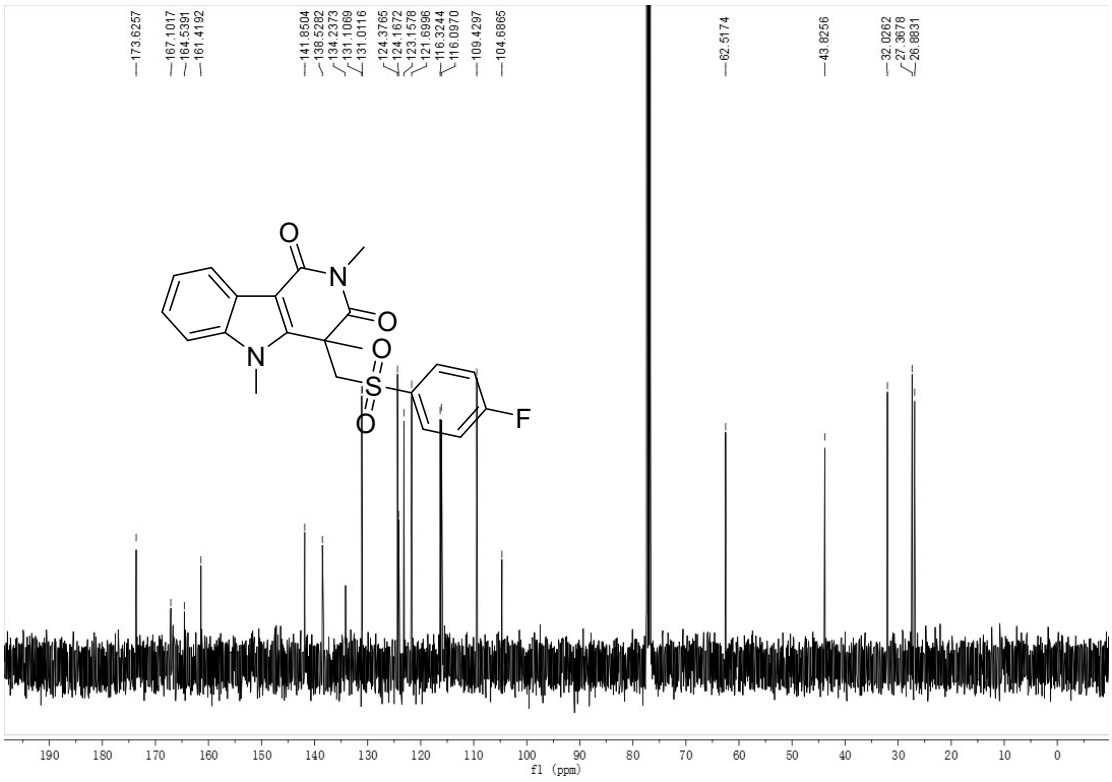
Suitable crystals of compound **3ga** were obtained by slowly evaporating a mixture of petroleum ether and dichloromethane solution at ambient temperature.

9. ^{1}H, ^{13}C, and ^{19}F NMR spectra for 3

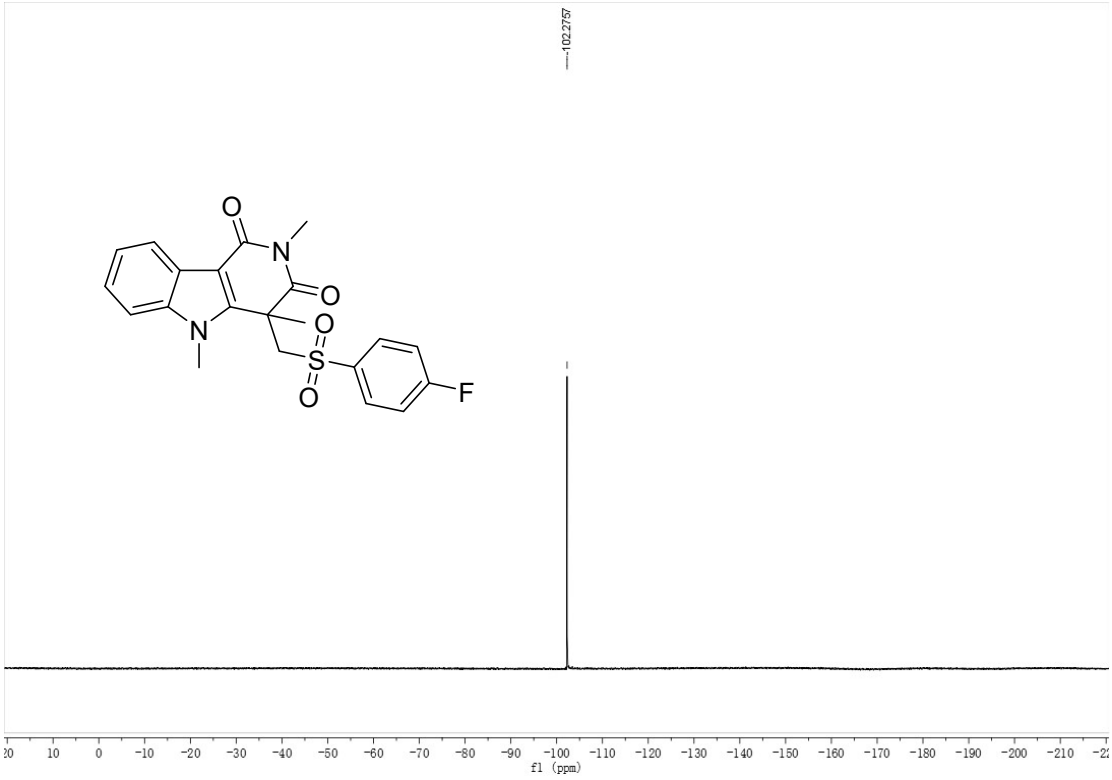
^{1}H NMR (400 MHz, $CDCl_3$) of **3aa**:



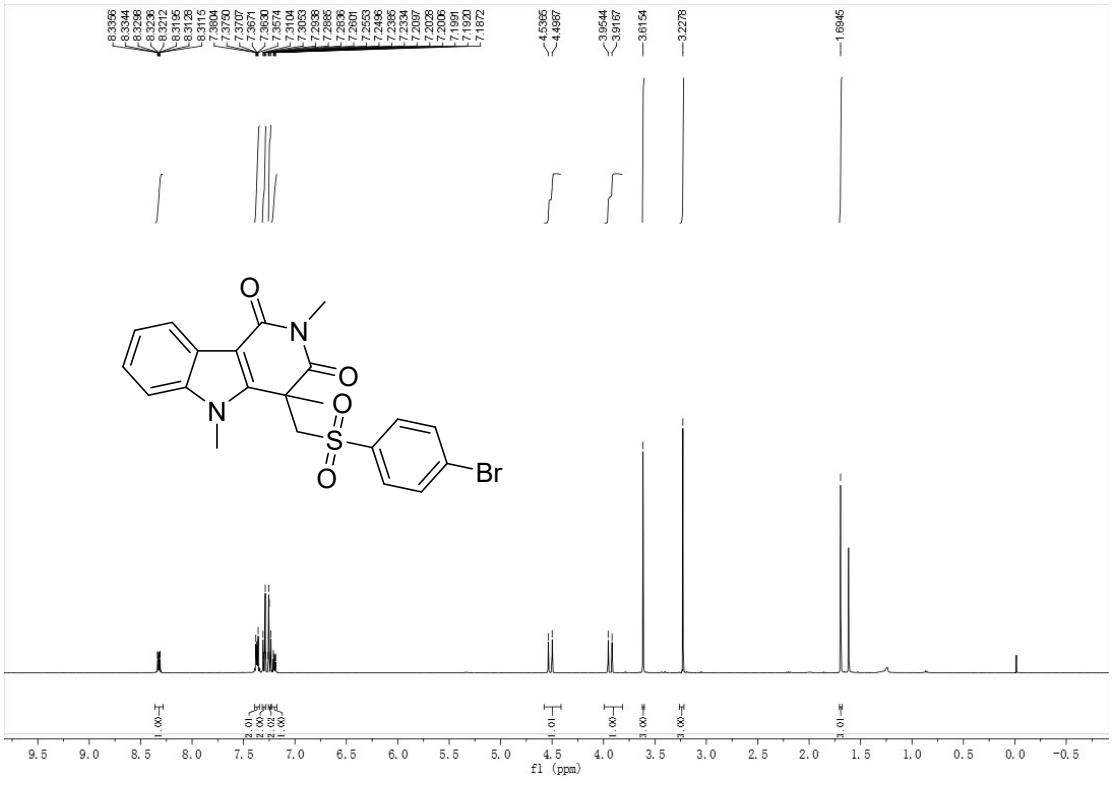
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3aa**:



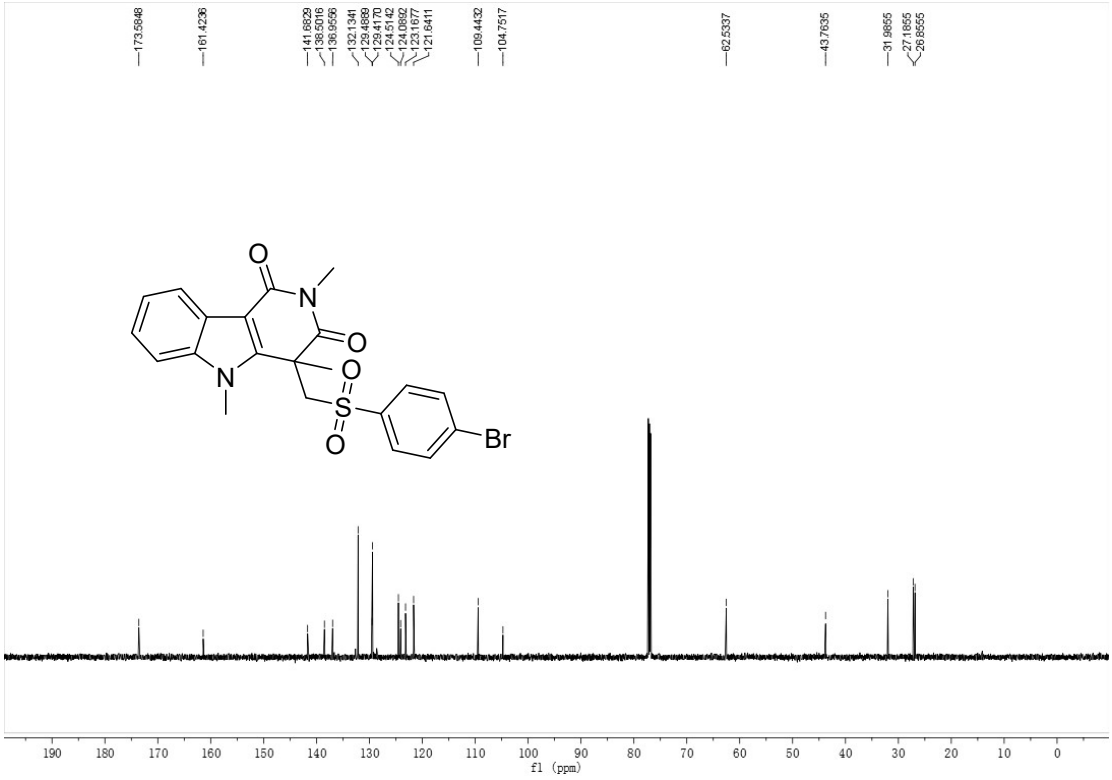
^{19}F NMR (376 MHz, $CDCl_3$) of **3aa**:



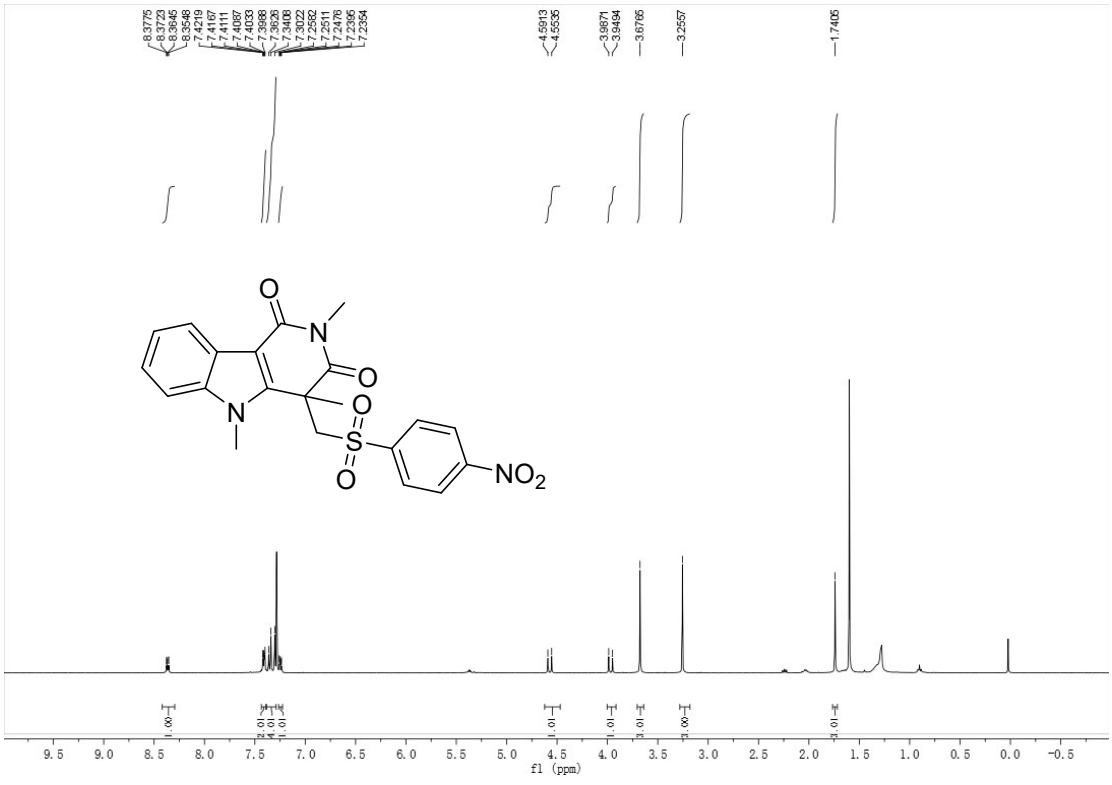
^{1}H NMR (400 MHz, $CDCl_3$) of **3ab**:



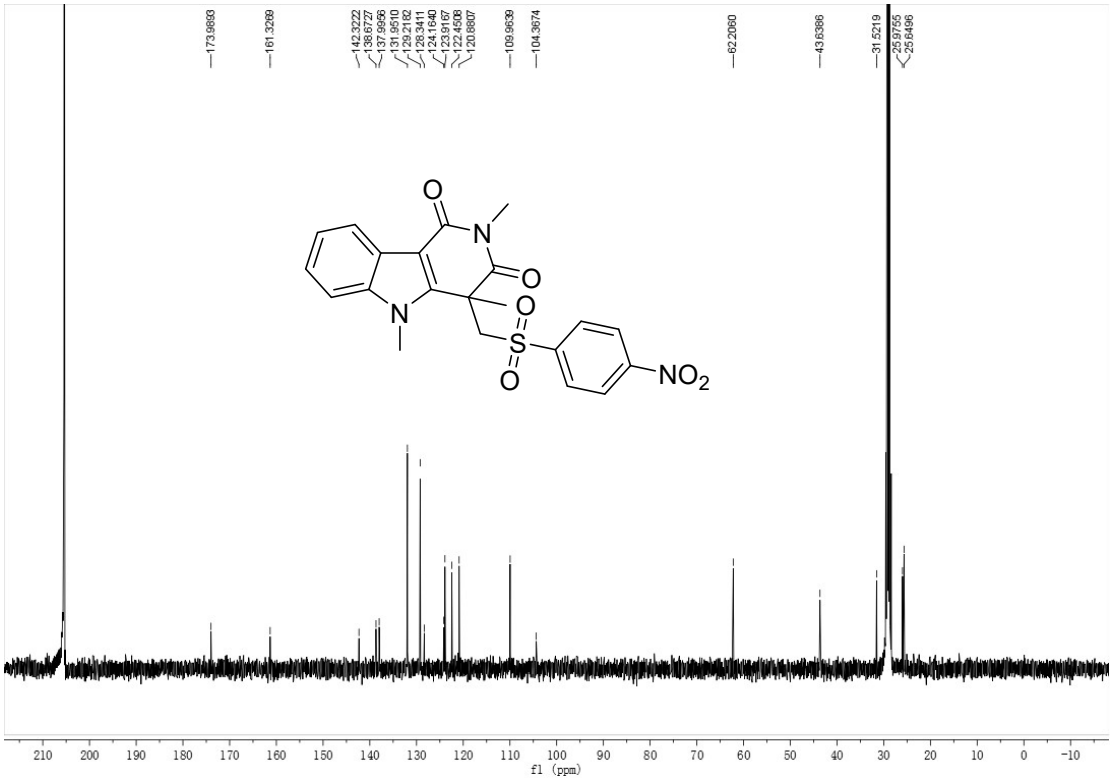
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ab**:



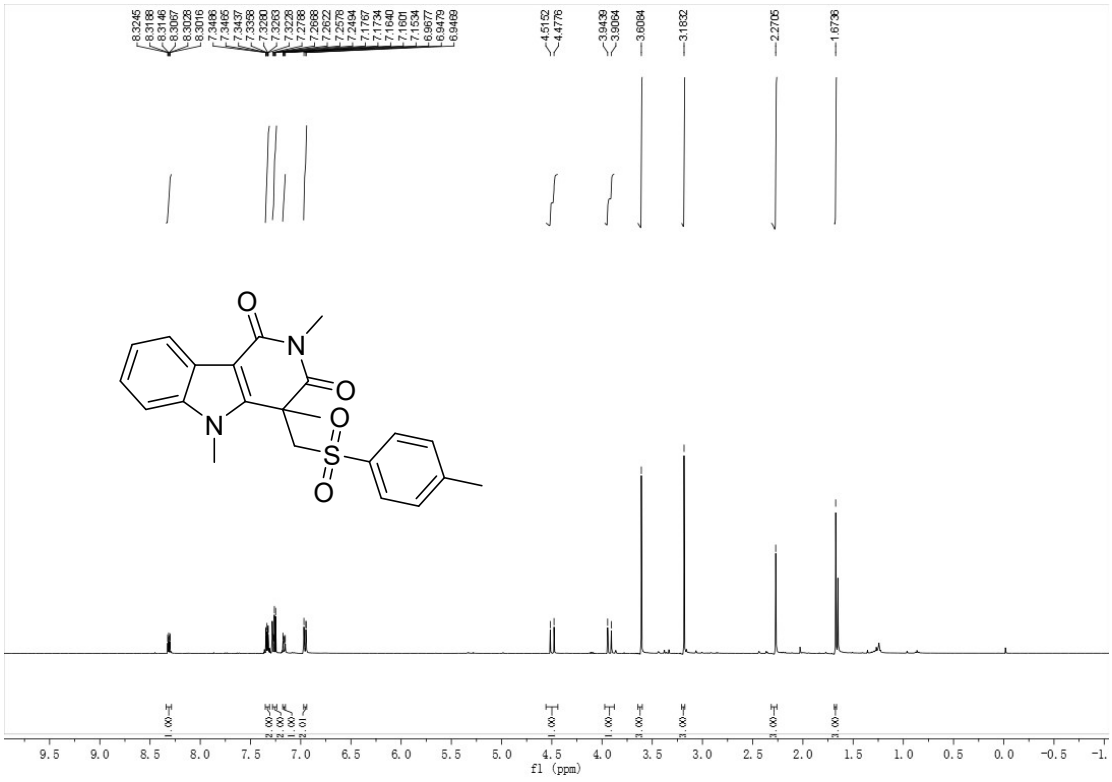
^{1}H NMR (400 MHz, $CDCl_3$) of **3ac**



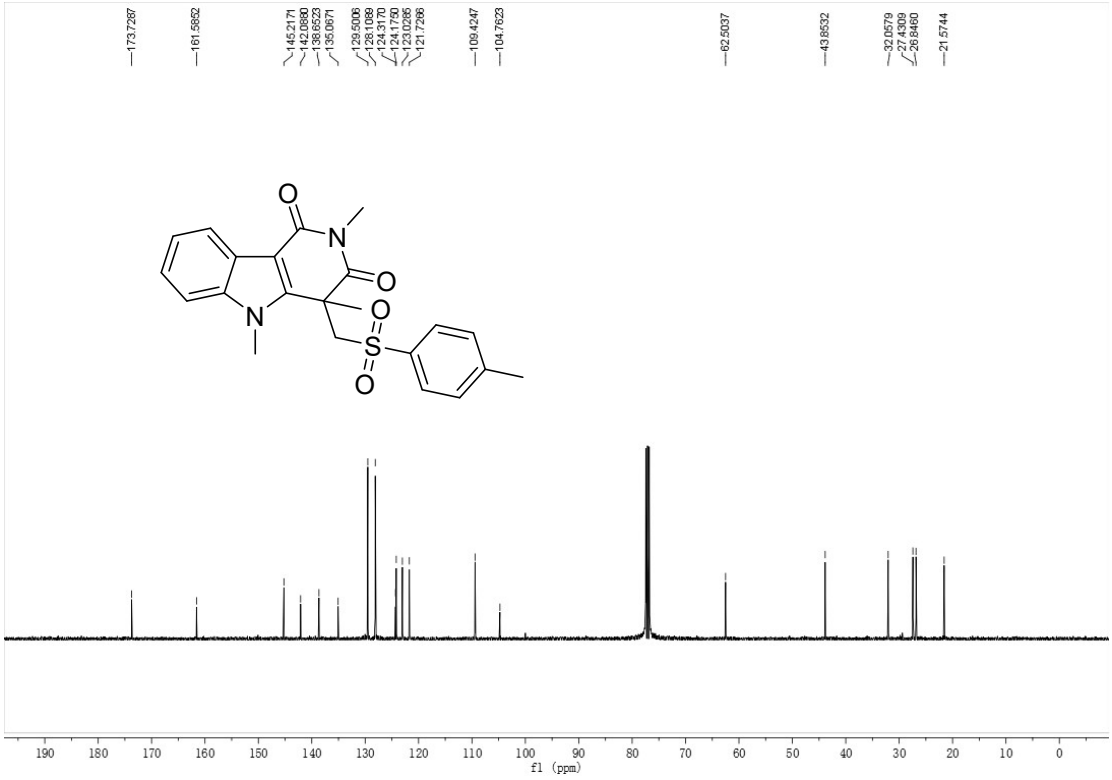
$^{13}C\{^{1}H\}$ NMR (100 MHz, CD_3COCD_3) of **3ac**



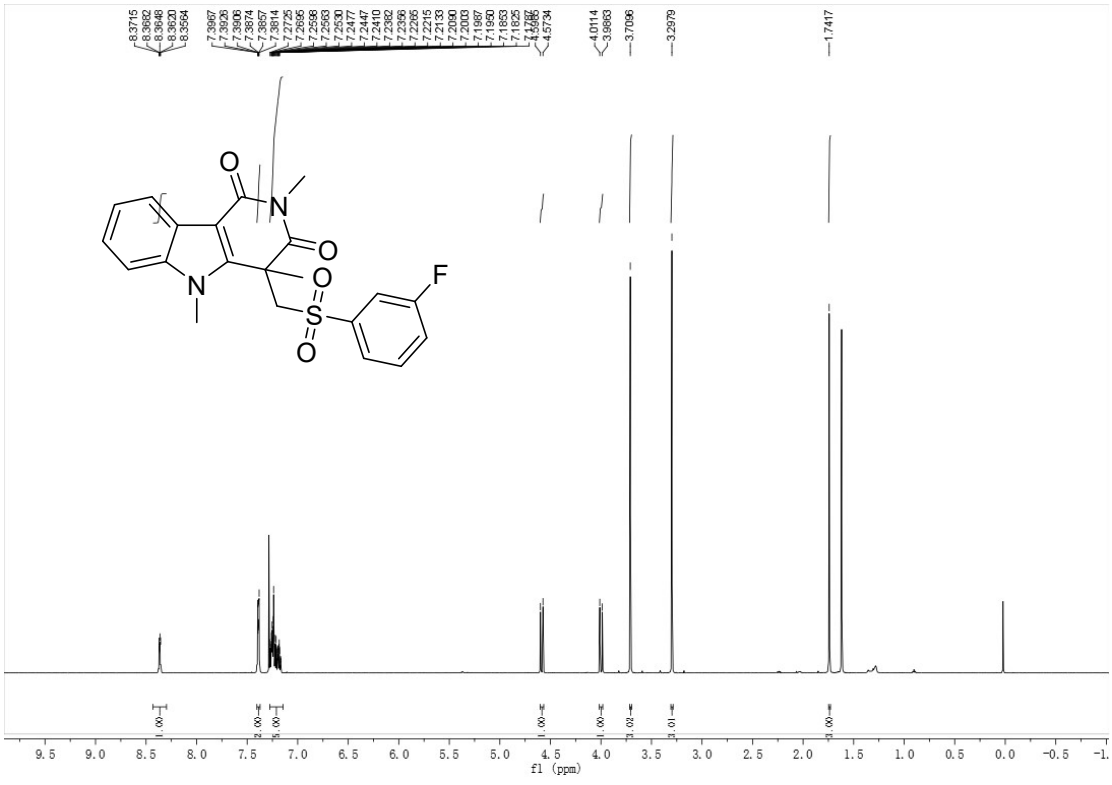
^{1}H NMR (400 MHz, $CDCl_3$) of **3ad**:



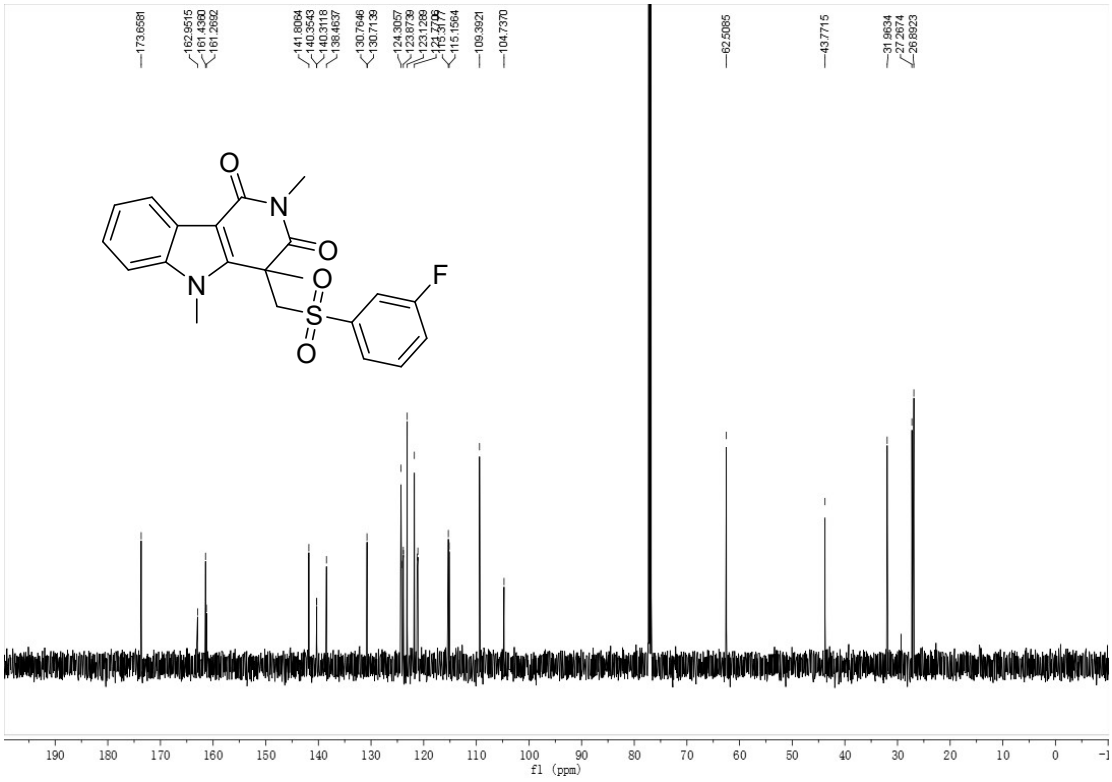
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3ad**:



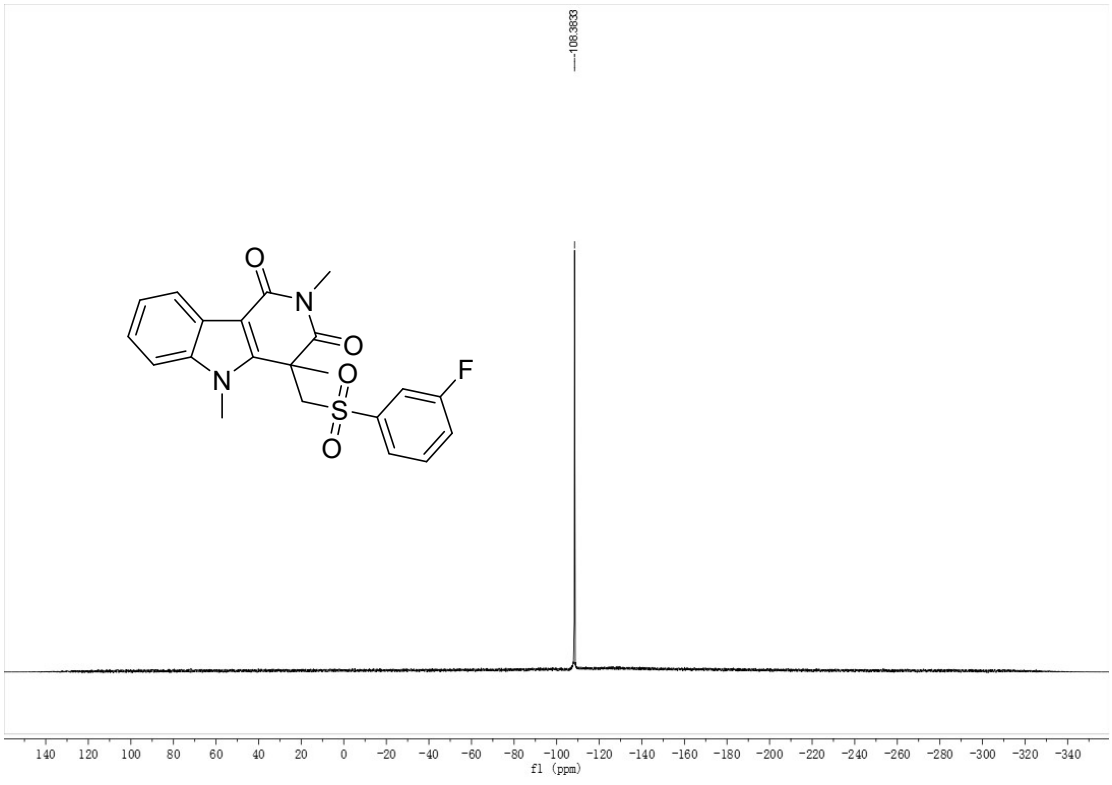
^{1}H NMR (600 MHz, $CDCl_3$) of **3ae**:



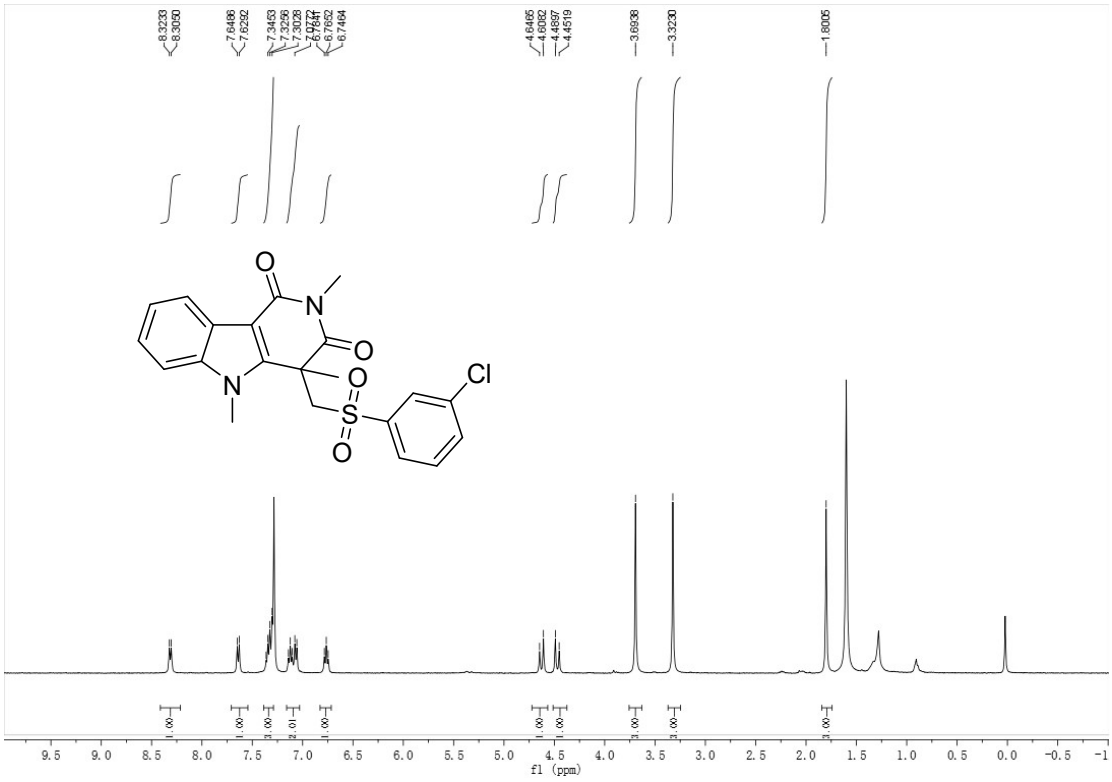
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ae**:



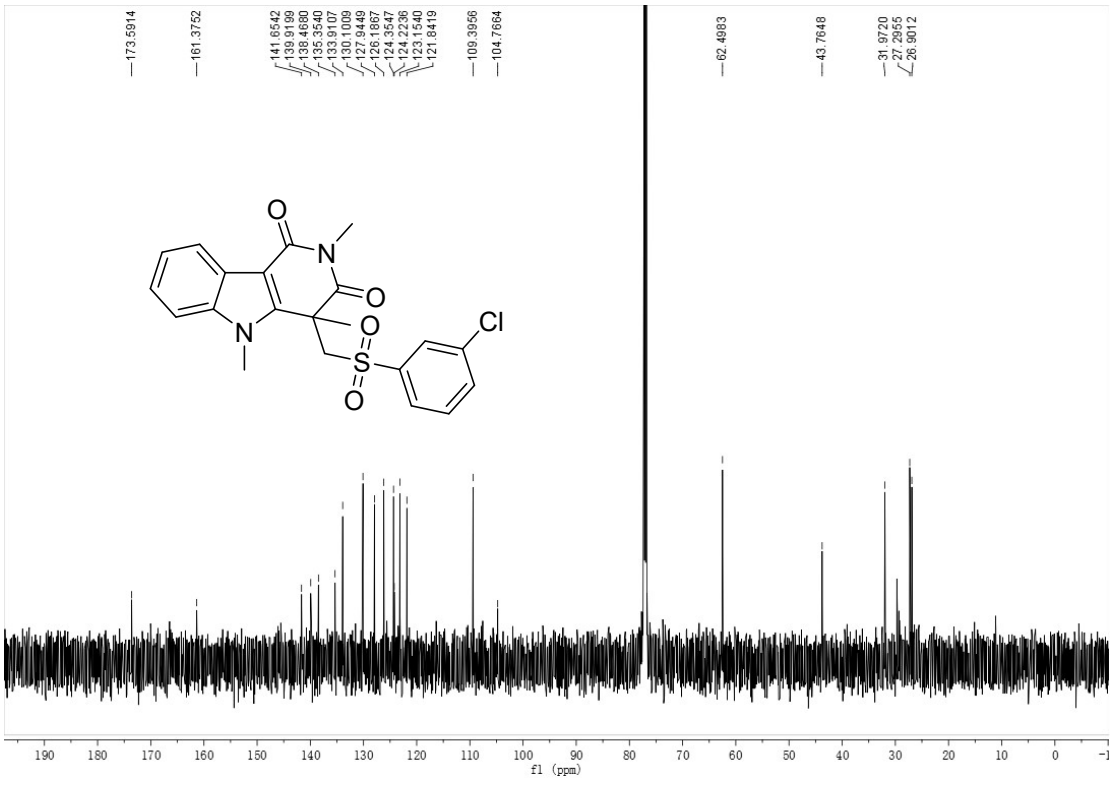
^{19}F NMR (376 MHz, $CDCl_3$) of **3ae**:



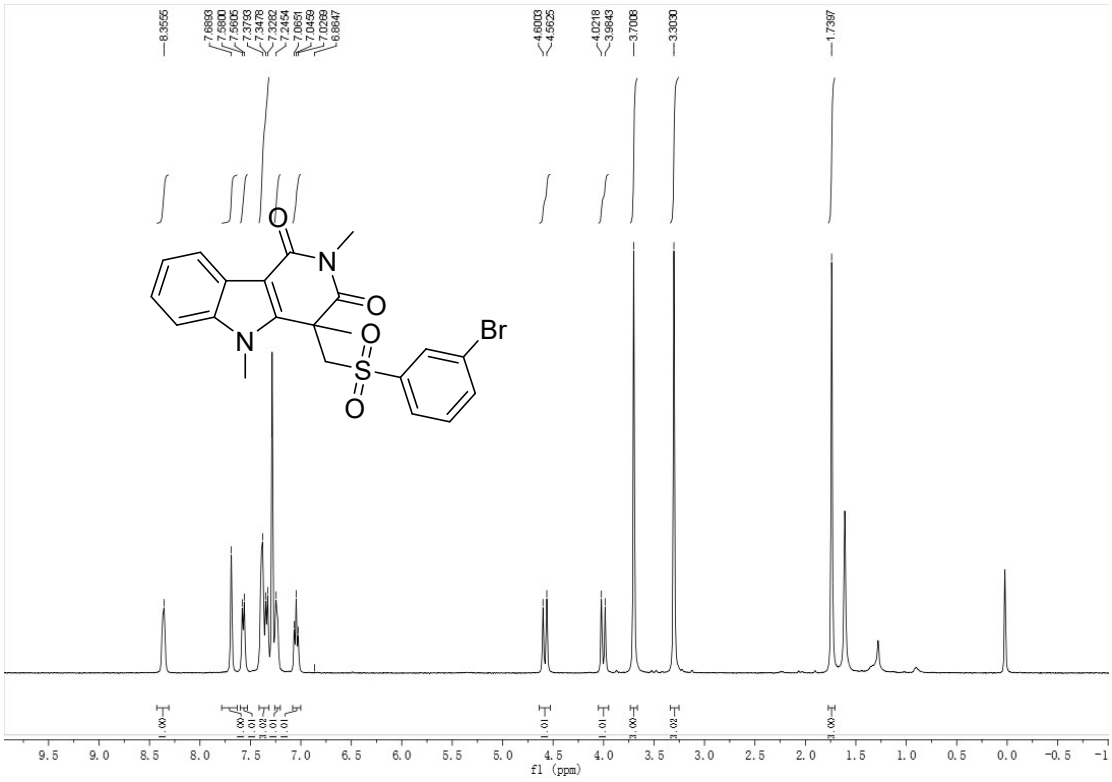
^{1}H NMR (400 MHz, $CDCl_3$) of **3af**:



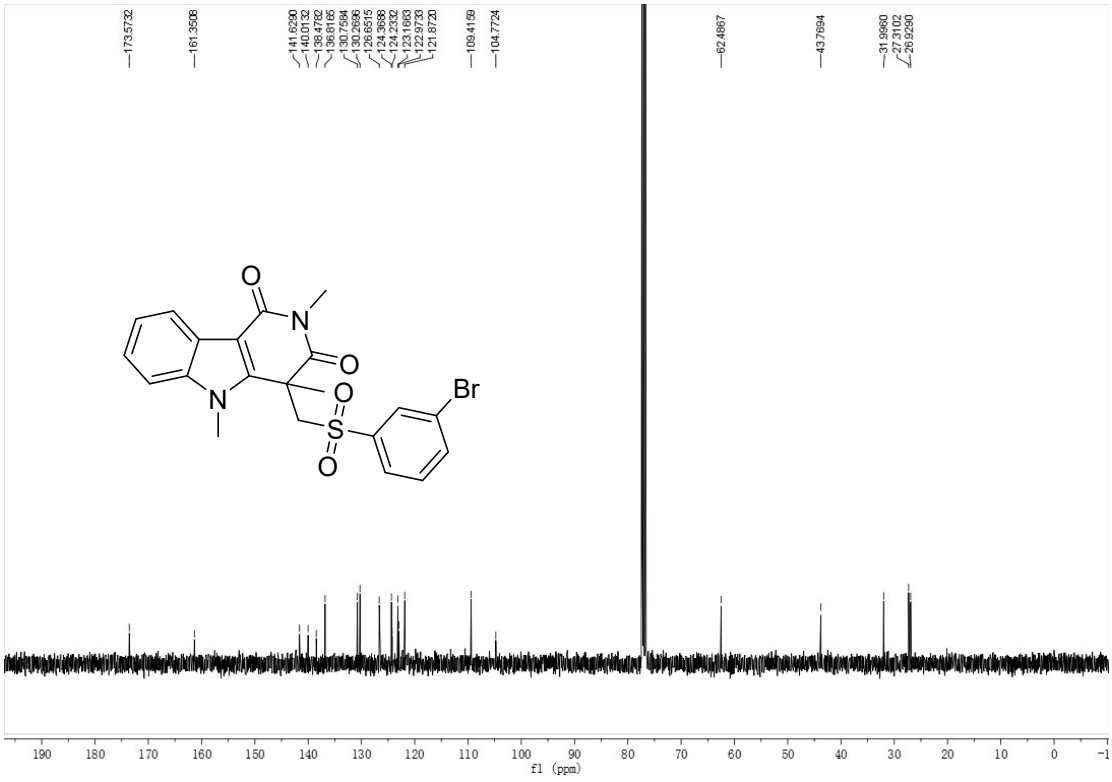
^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) of **3af**:



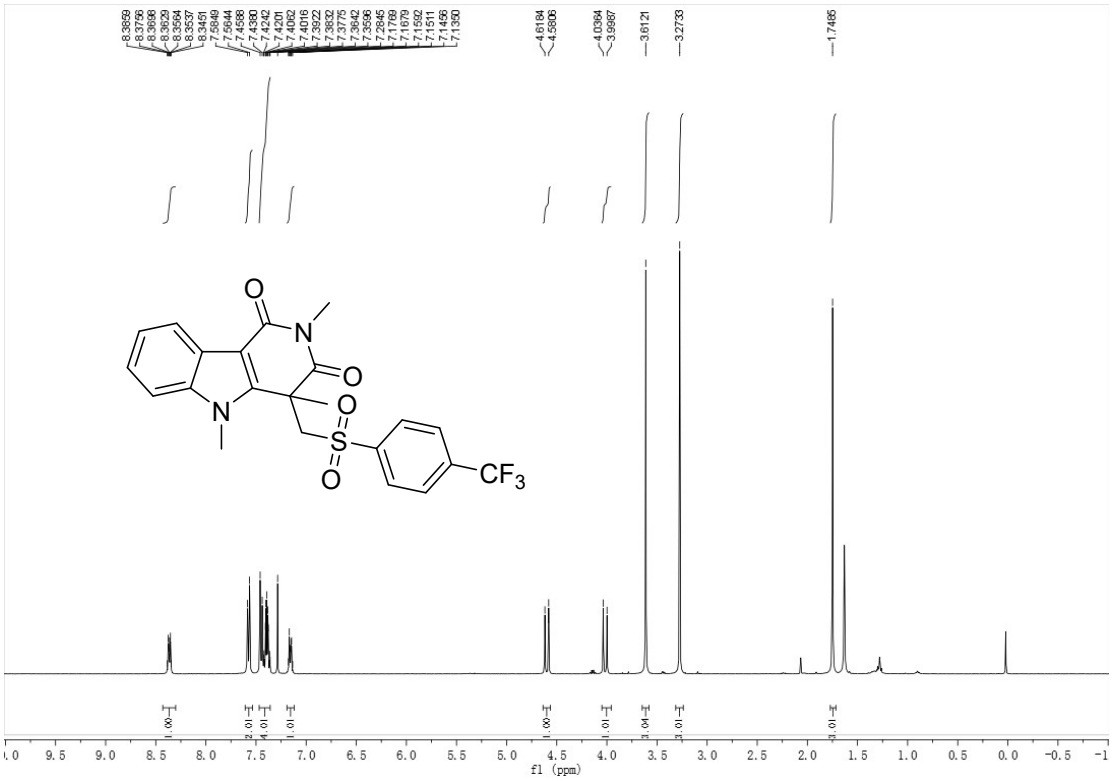
^{1}H NMR (400 MHz, $CDCl_3$) of **3ag**:



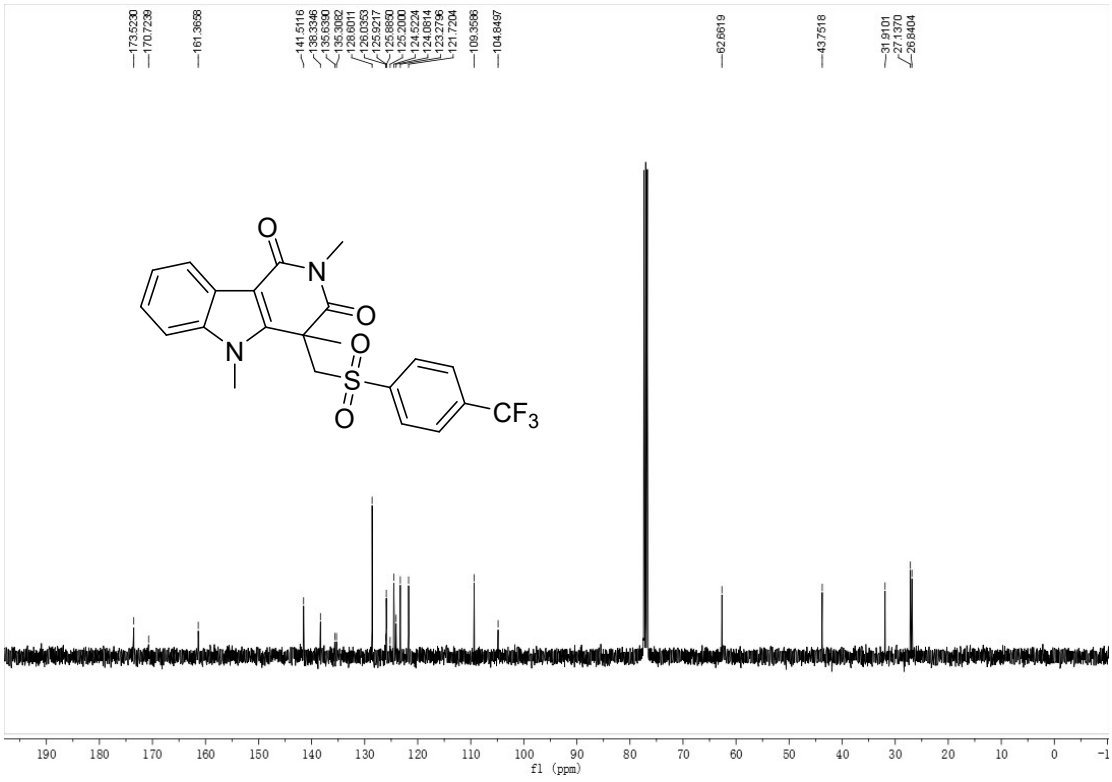
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3ag**:



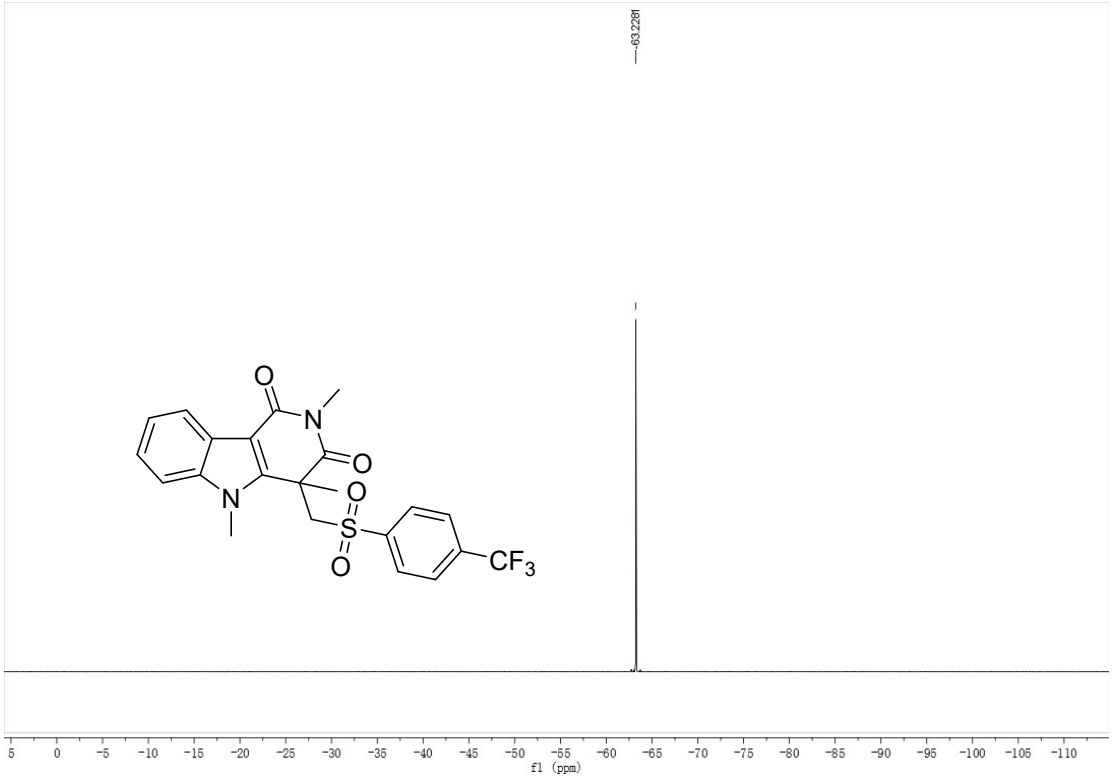
^{1}H NMR (400 MHz, $CDCl_3$) of **3ah**:



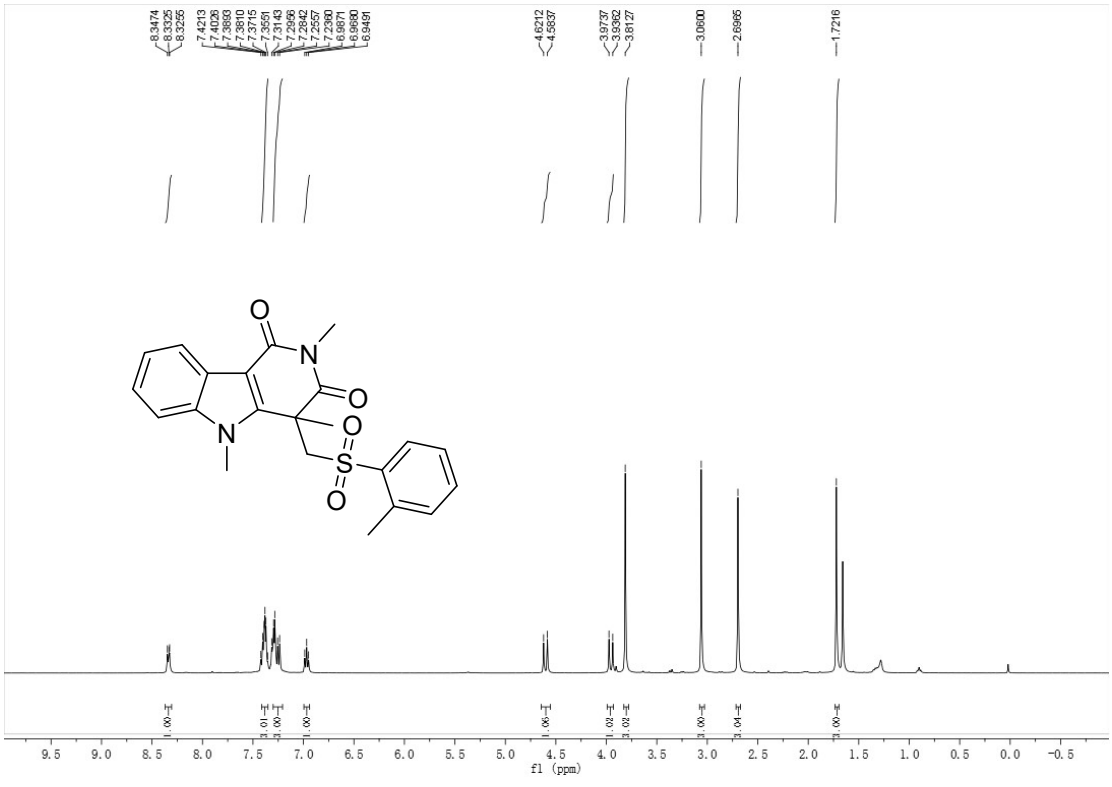
^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) of **3ah**:



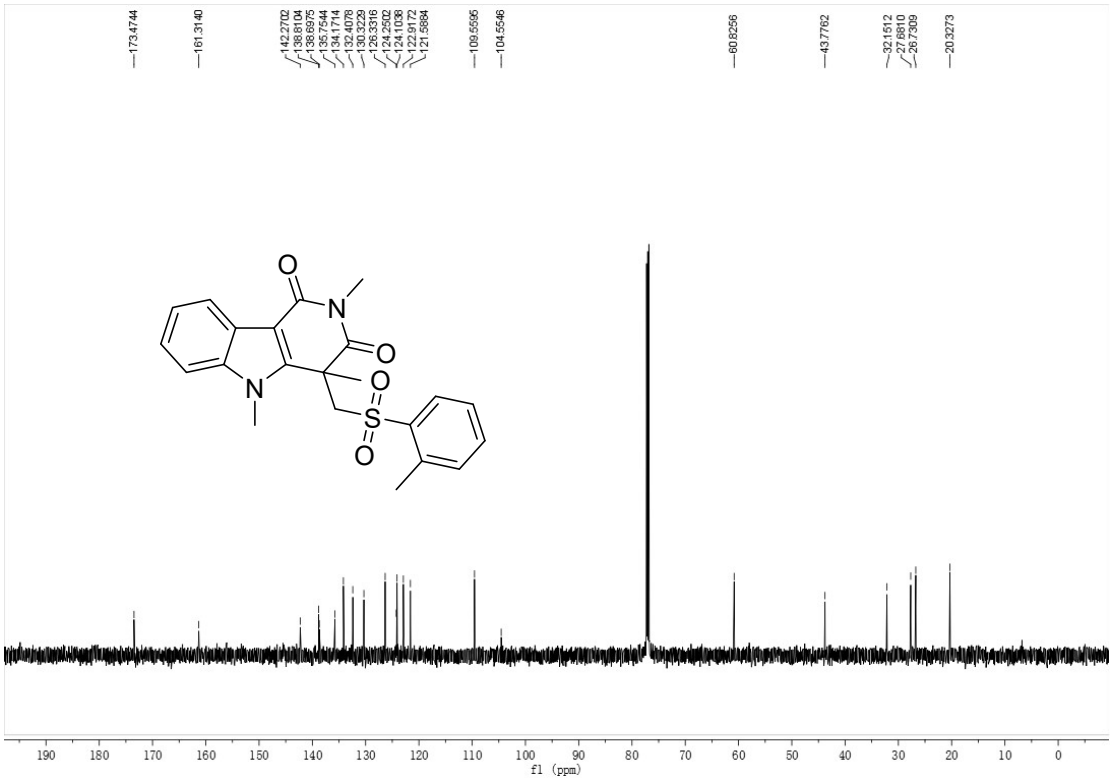
^{19}F NMR (376 MHz, $CDCl_3$) of **3ah**:



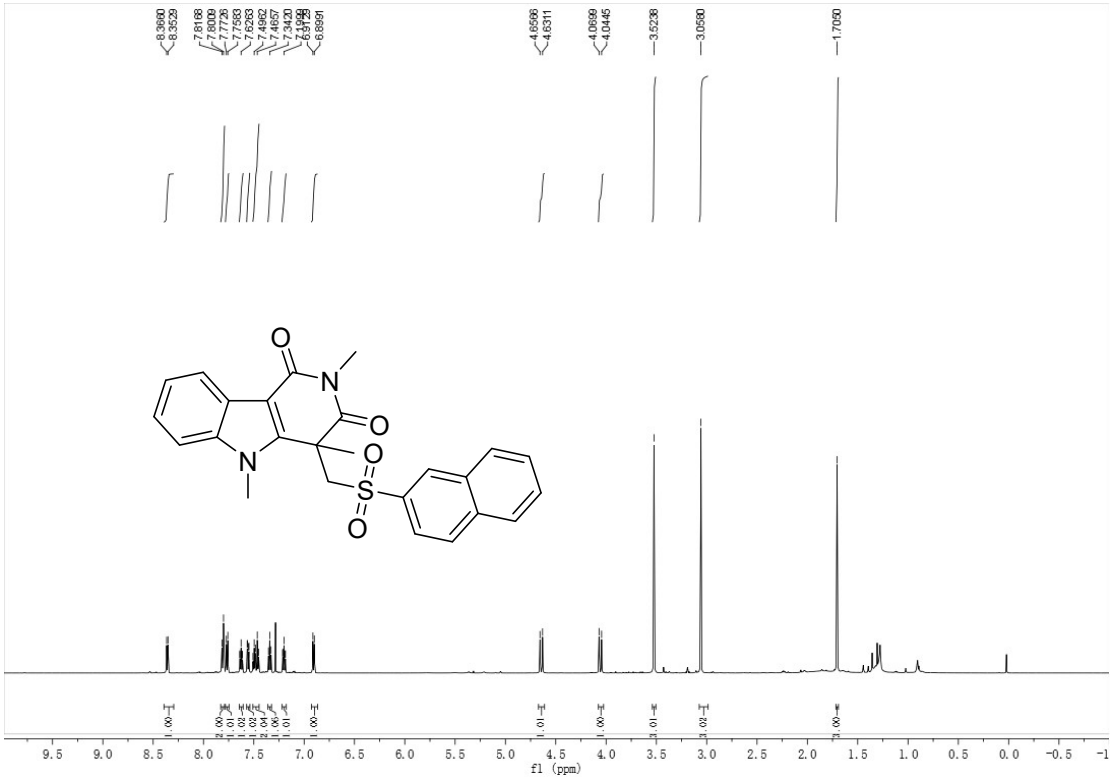
^{1}H NMR (400 MHz, $CDCl_3$) of **3ai**:



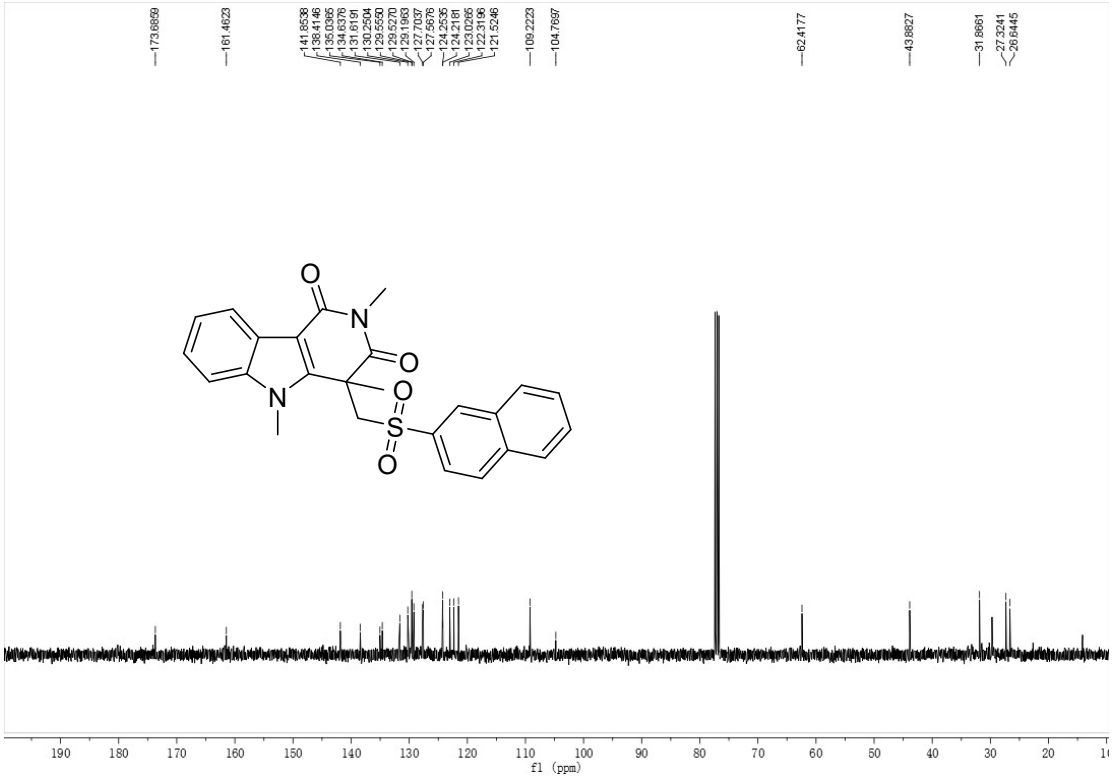
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ai**:



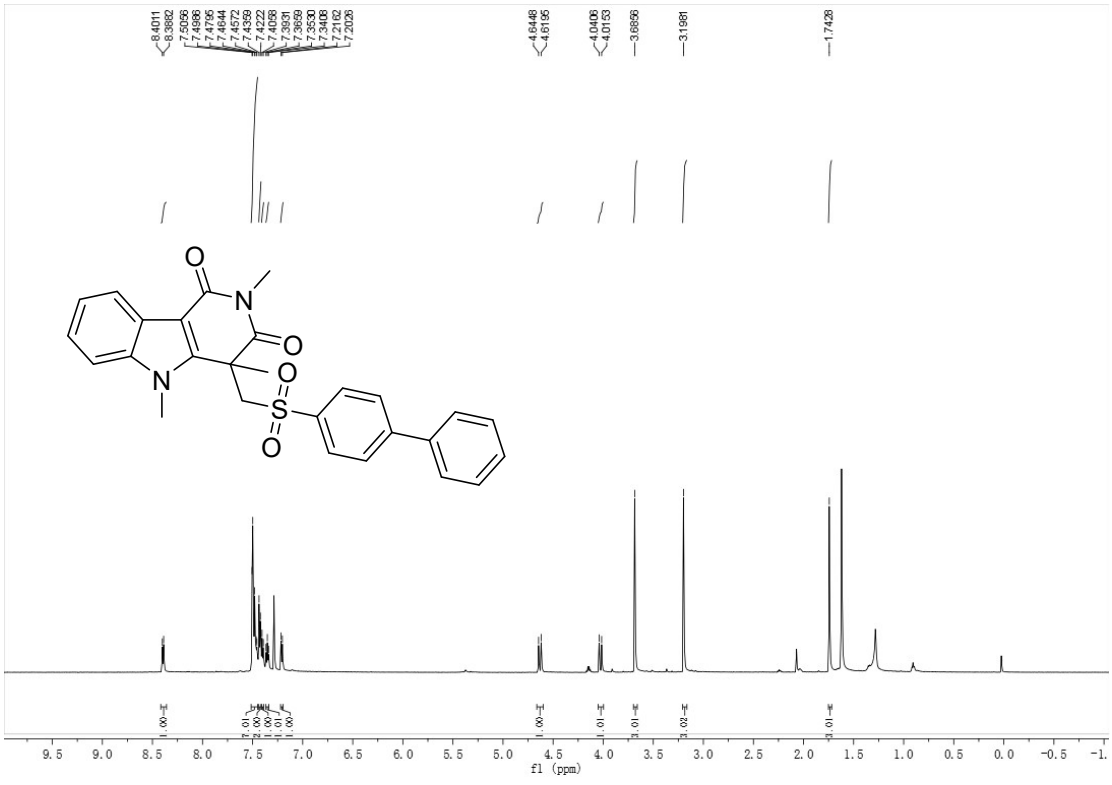
^{1}H NMR (600 MHz, $CDCl_3$) of **3aj**:



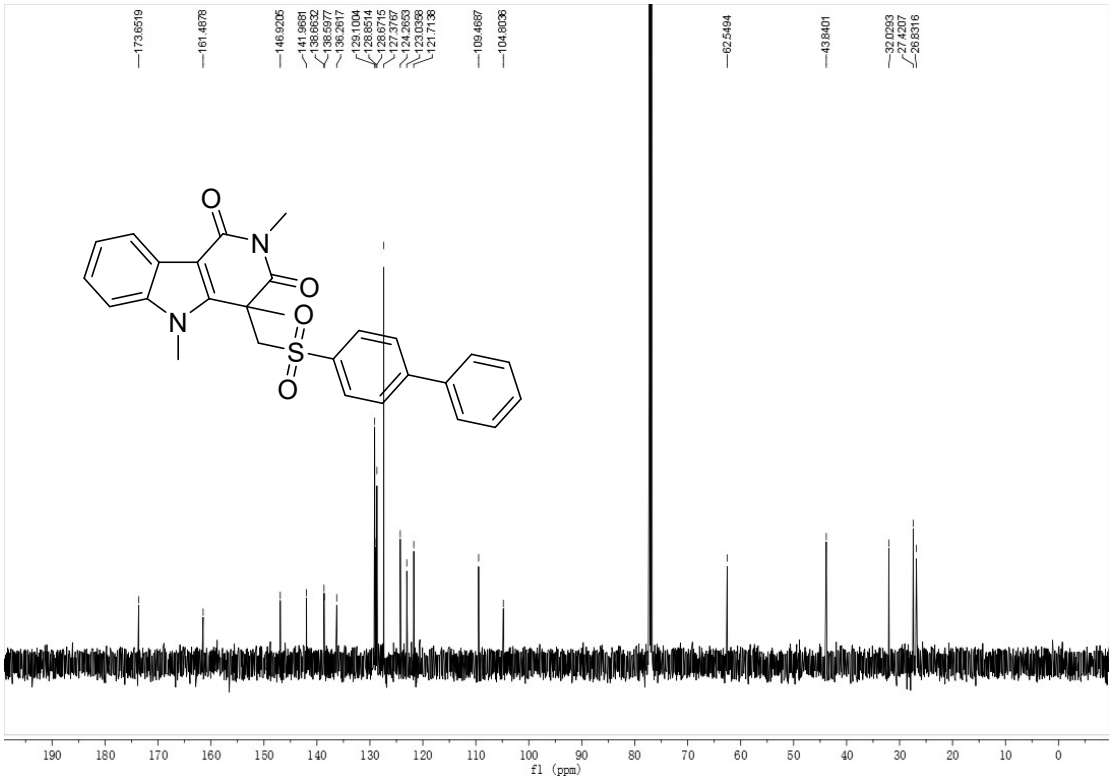
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3aj**:



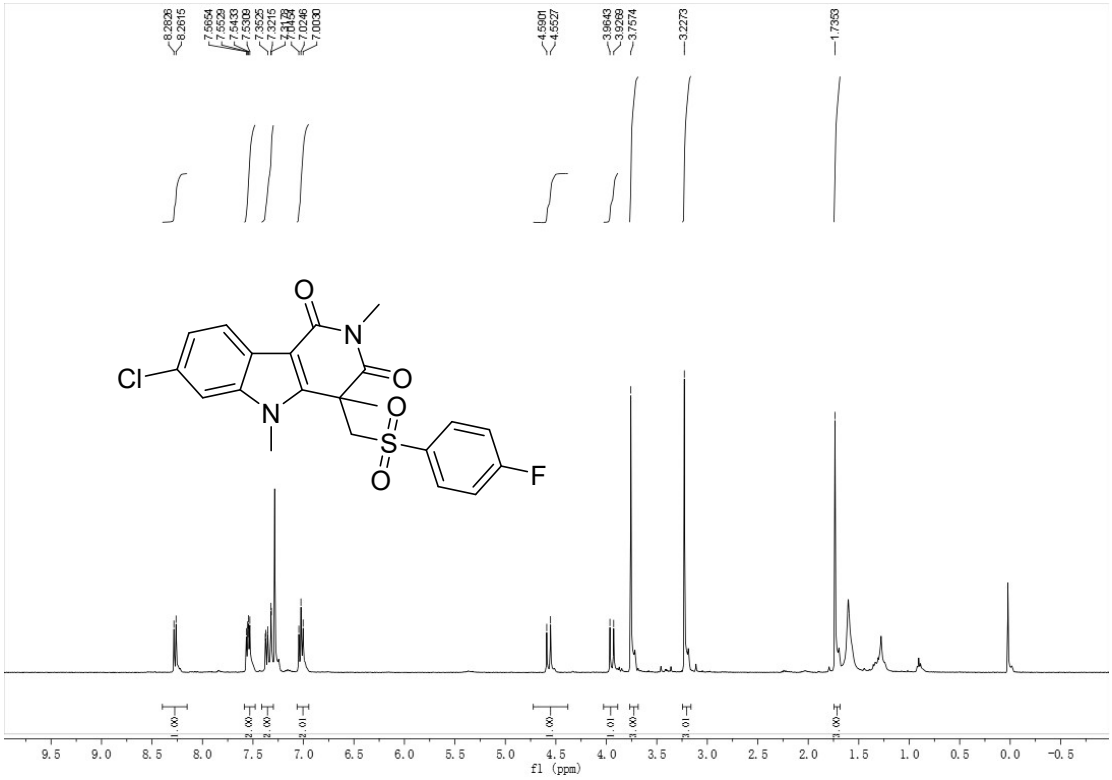
^{1}H NMR (600 MHz, $CDCl_3$) of **3ak**:



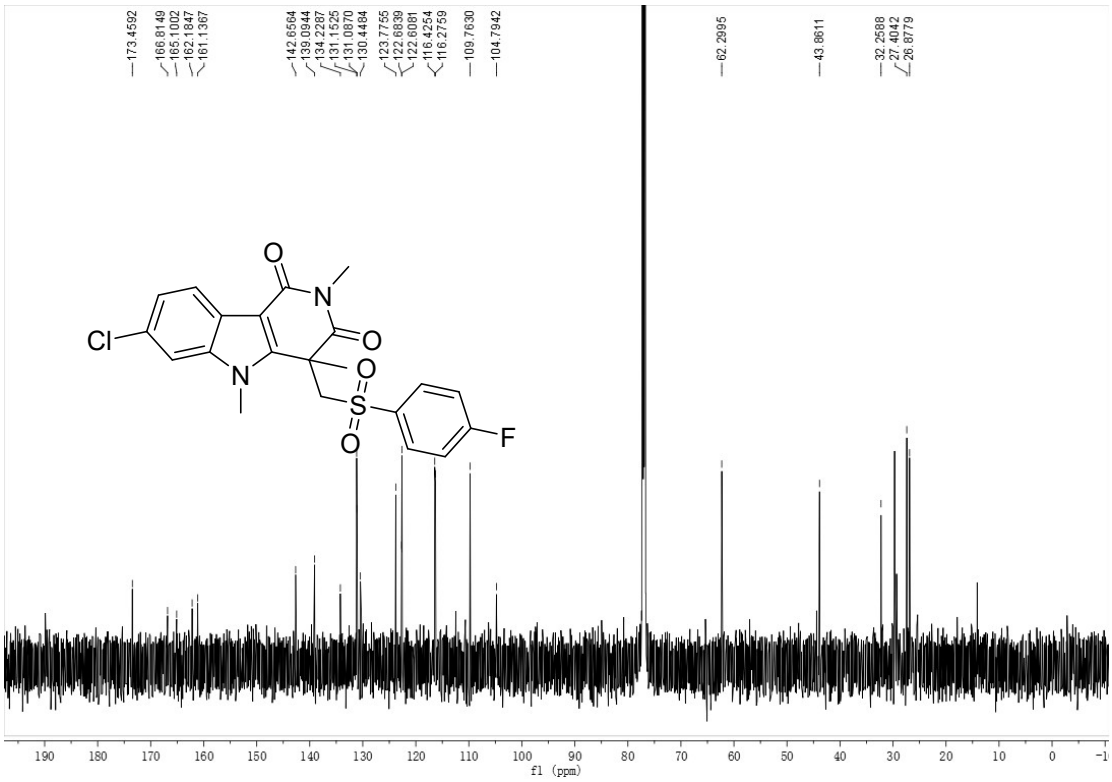
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ak**:



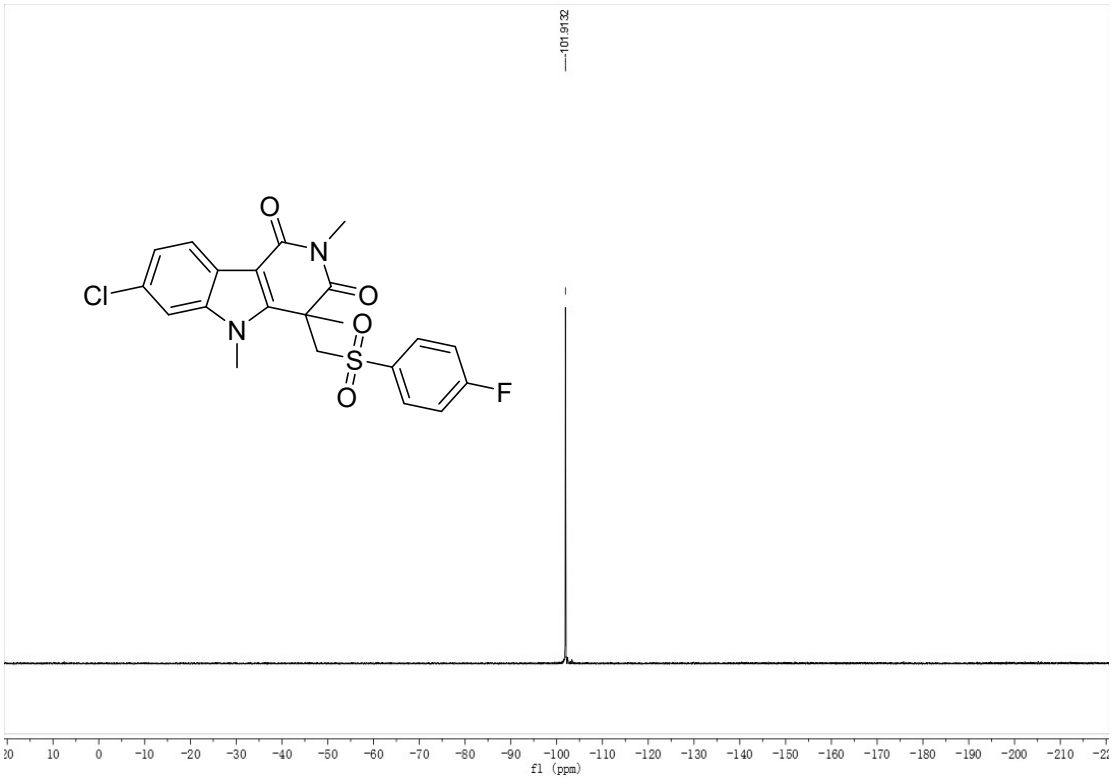
^{1}H NMR (400 MHz, $CDCl_3$) of **3ba**:



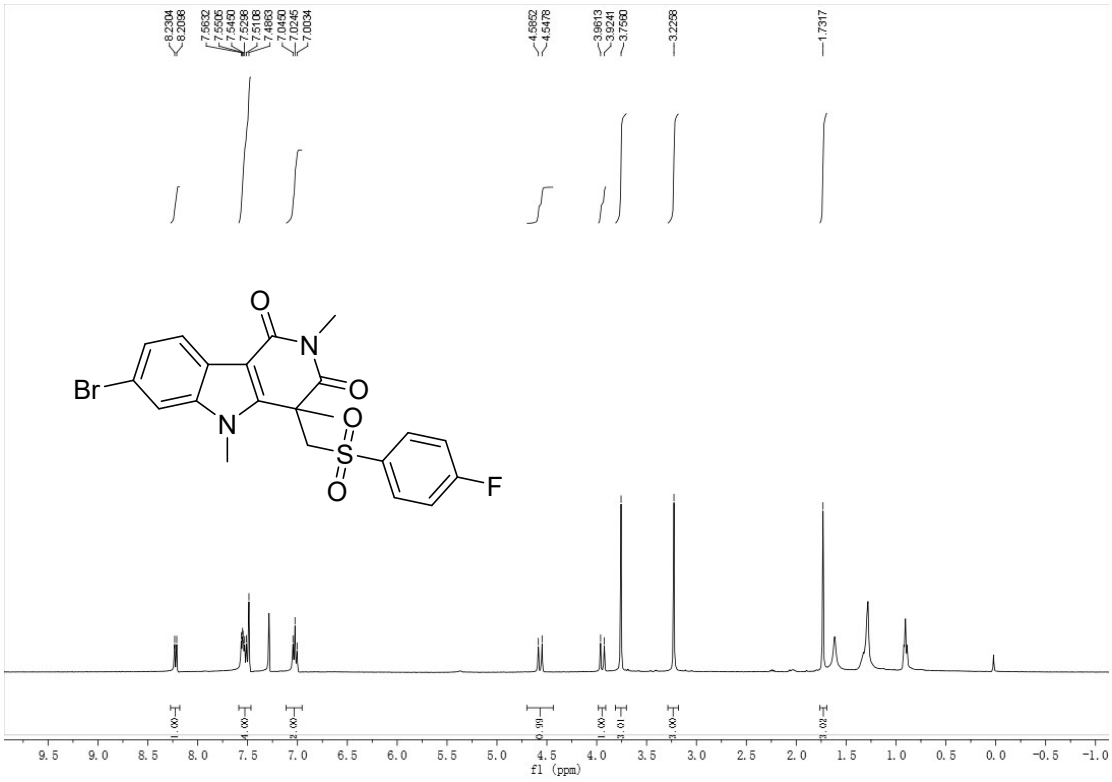
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ba**:



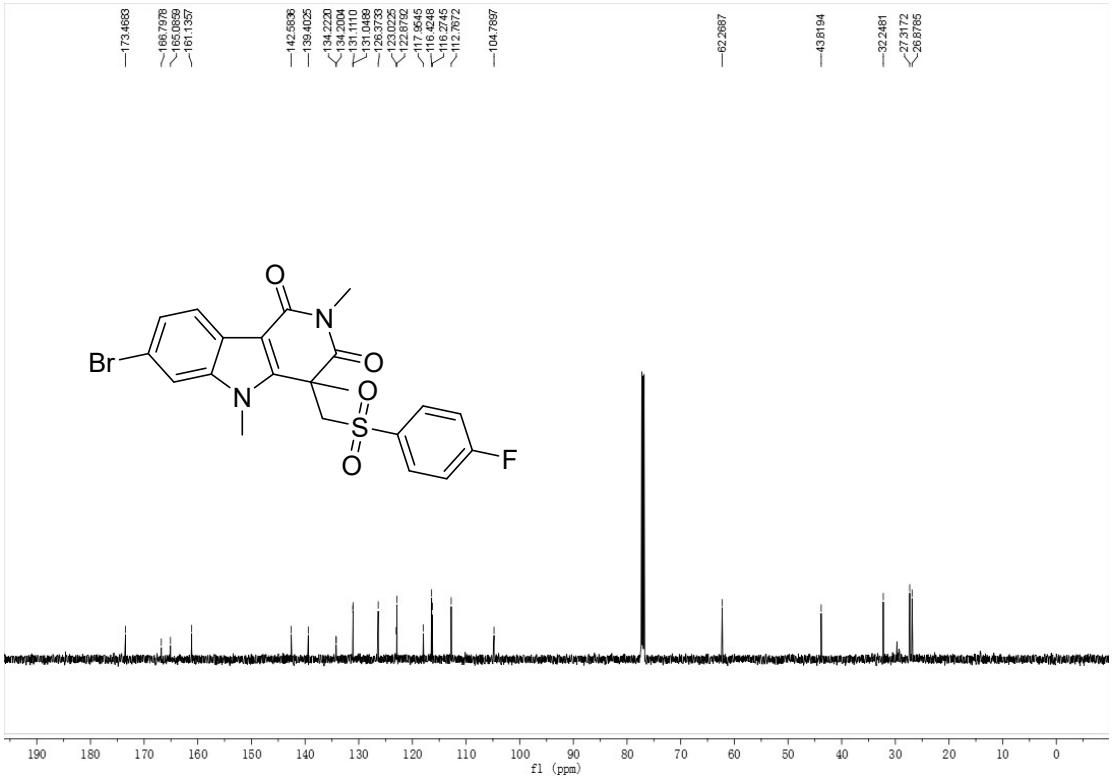
^{19}F NMR (376 MHz, $CDCl_3$) of **3ba**:



^{1}H NMR (400 MHz, $CDCl_3$) of **3ca**:

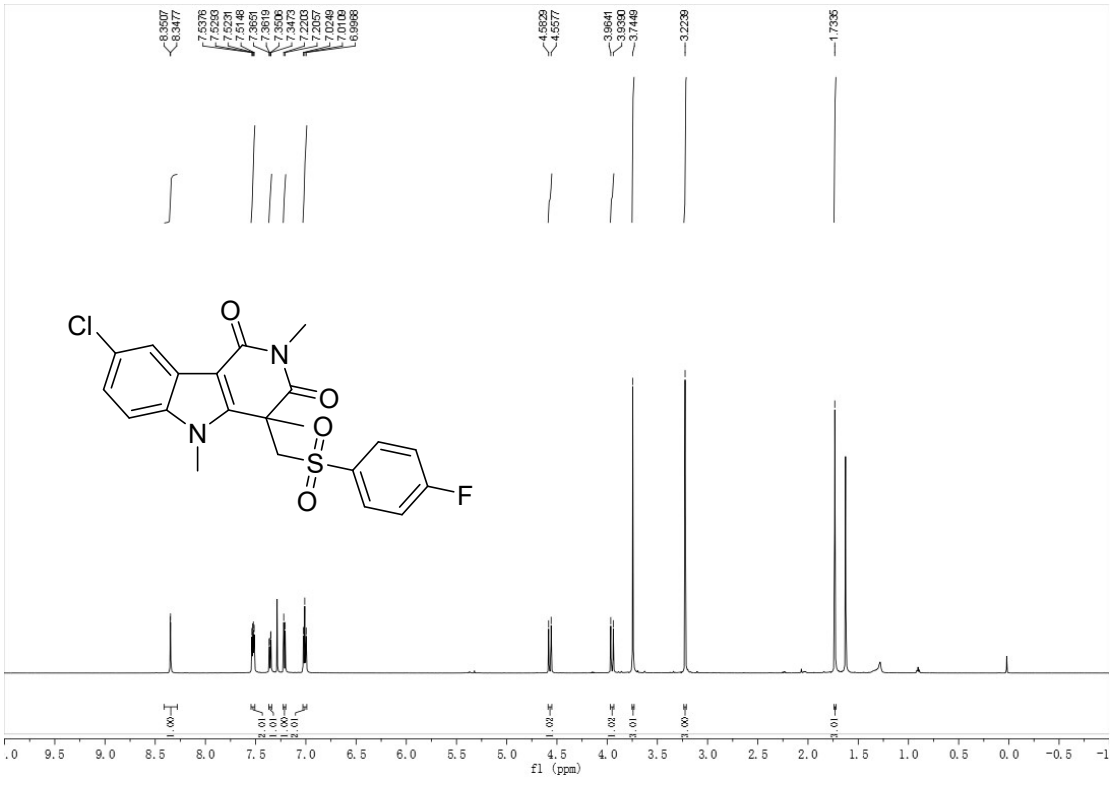


^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) of **3ca**:

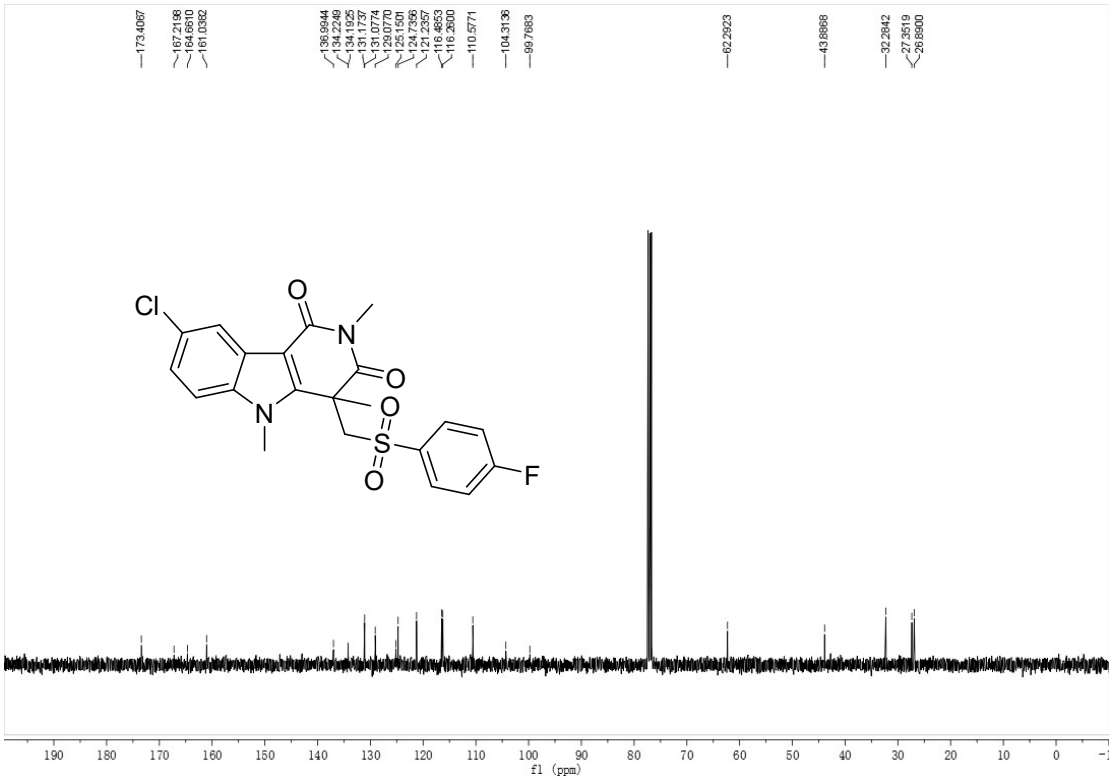


^{19}F NMR (376 MHz, $CDCl_3$) of **3ca**:

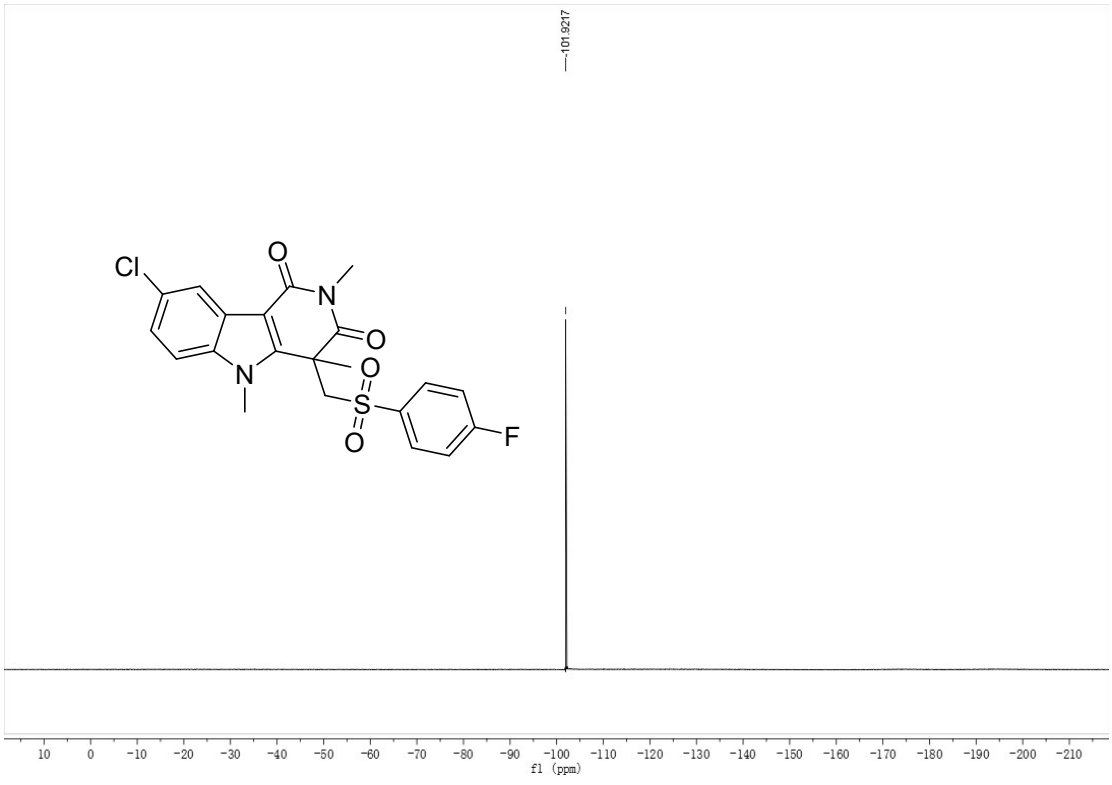
^{1}H NMR (600 MHz, $CDCl_3$) of **3da**:



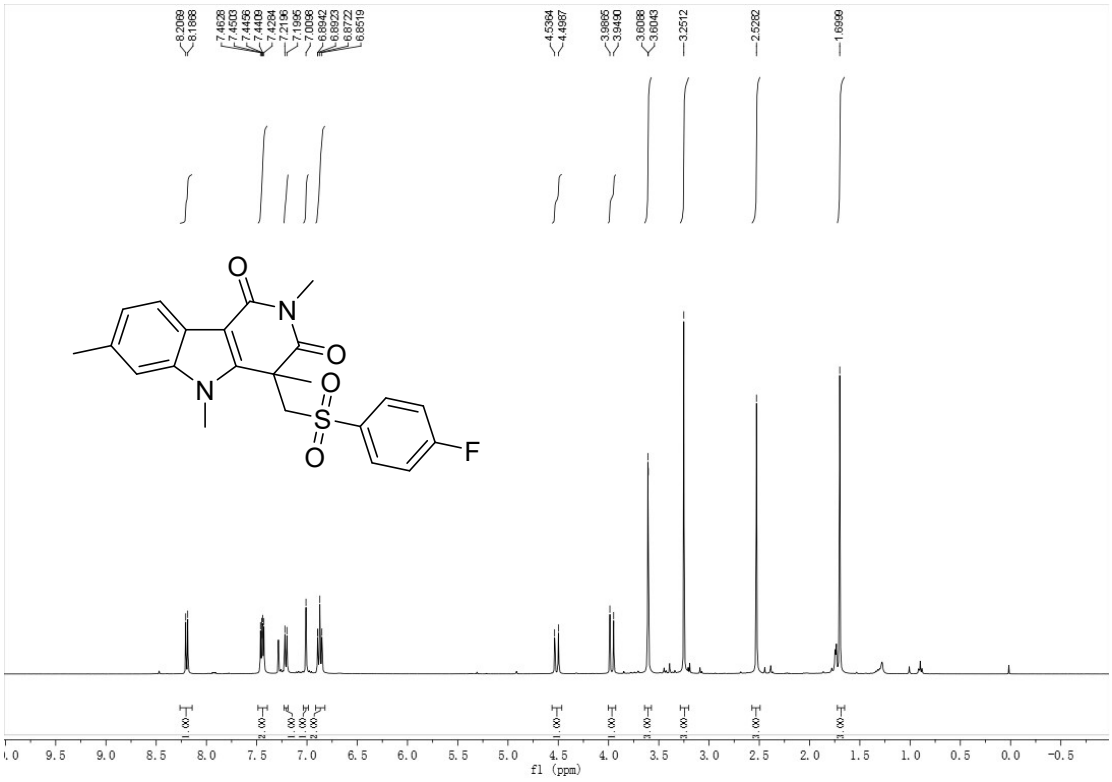
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3da**:



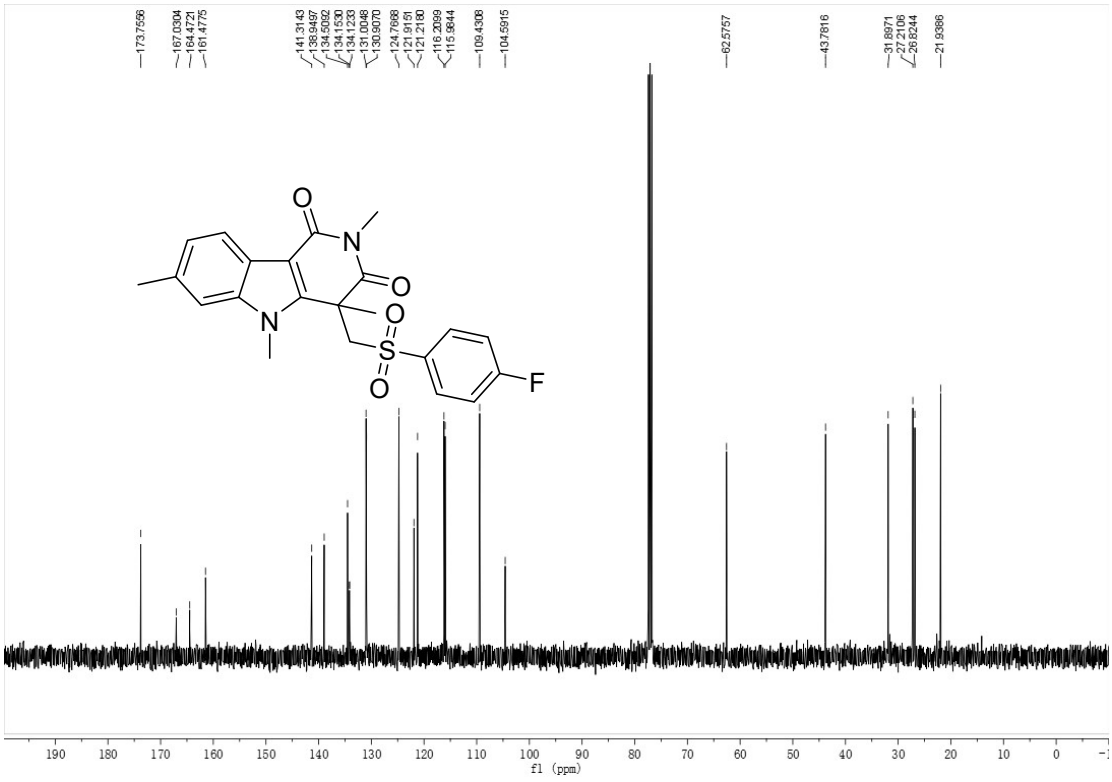
^{19}F NMR (575 MHz, $CDCl_3$) of **3da**:



^{1}H NMR (400 MHz, $CDCl_3$) of **3ea**:

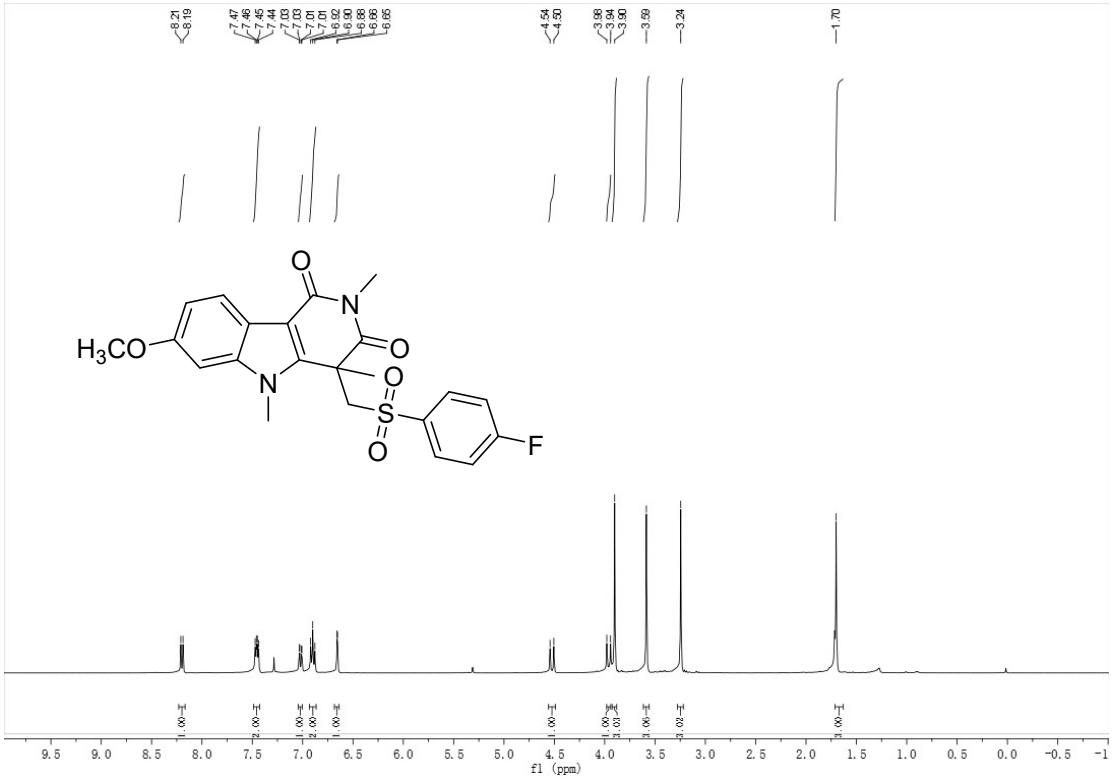


^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) of **3ea**:

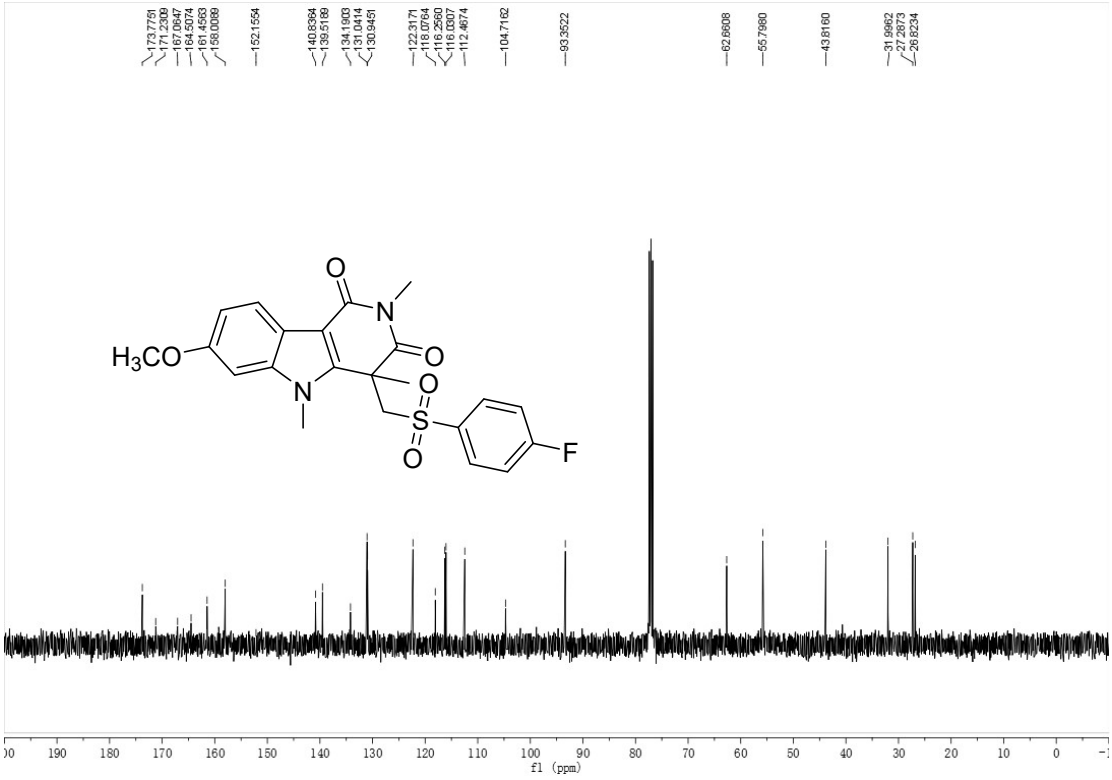


^{19}F NMR (376 MHz, $CDCl_3$) of **3ea**:

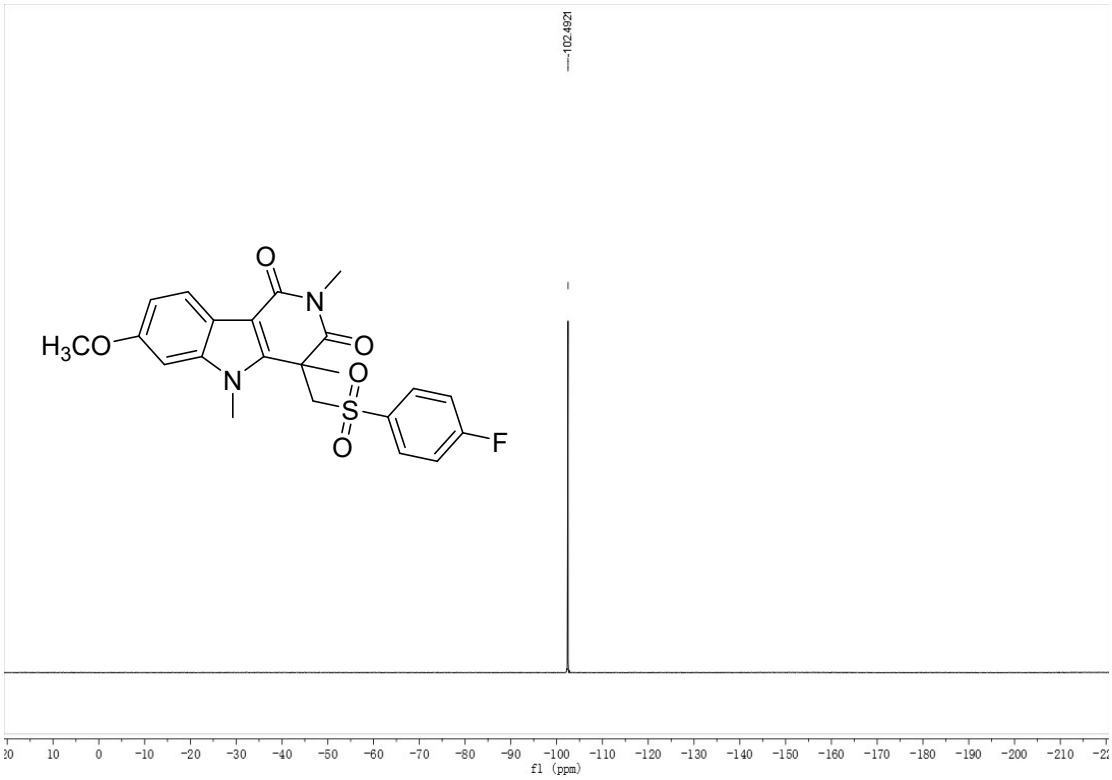
^{1}H NMR (400 MHz, $CDCl_3$) of **3fa**:



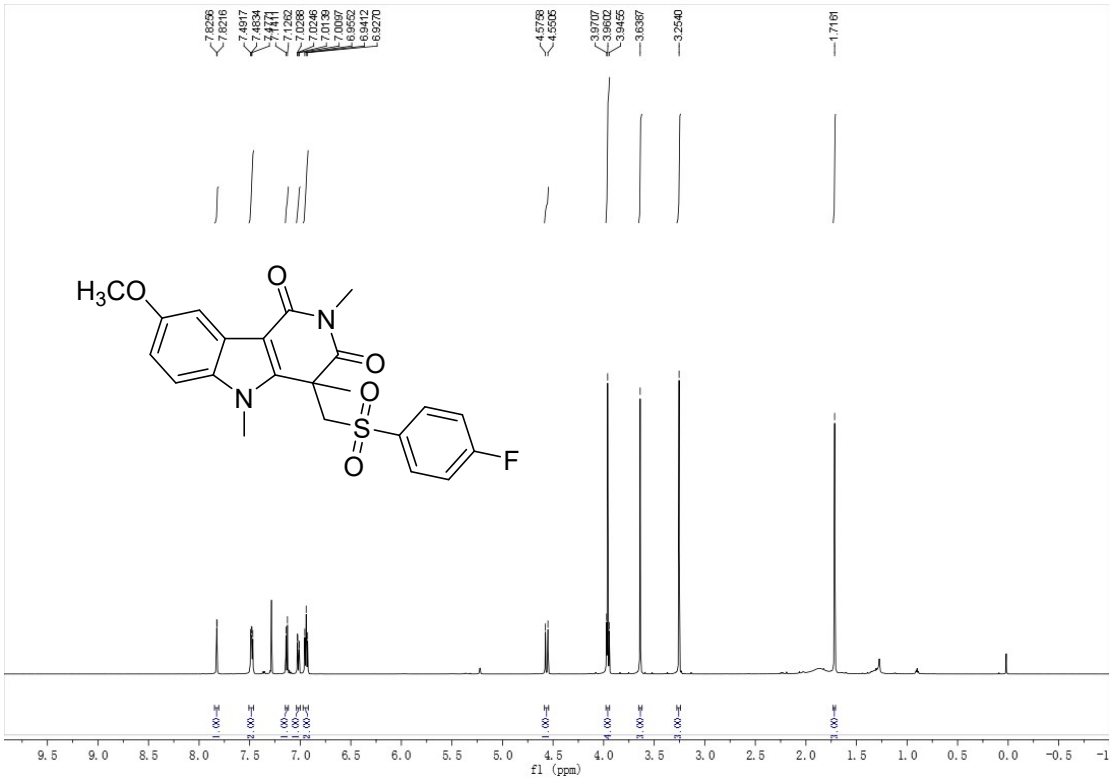
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **fa**:



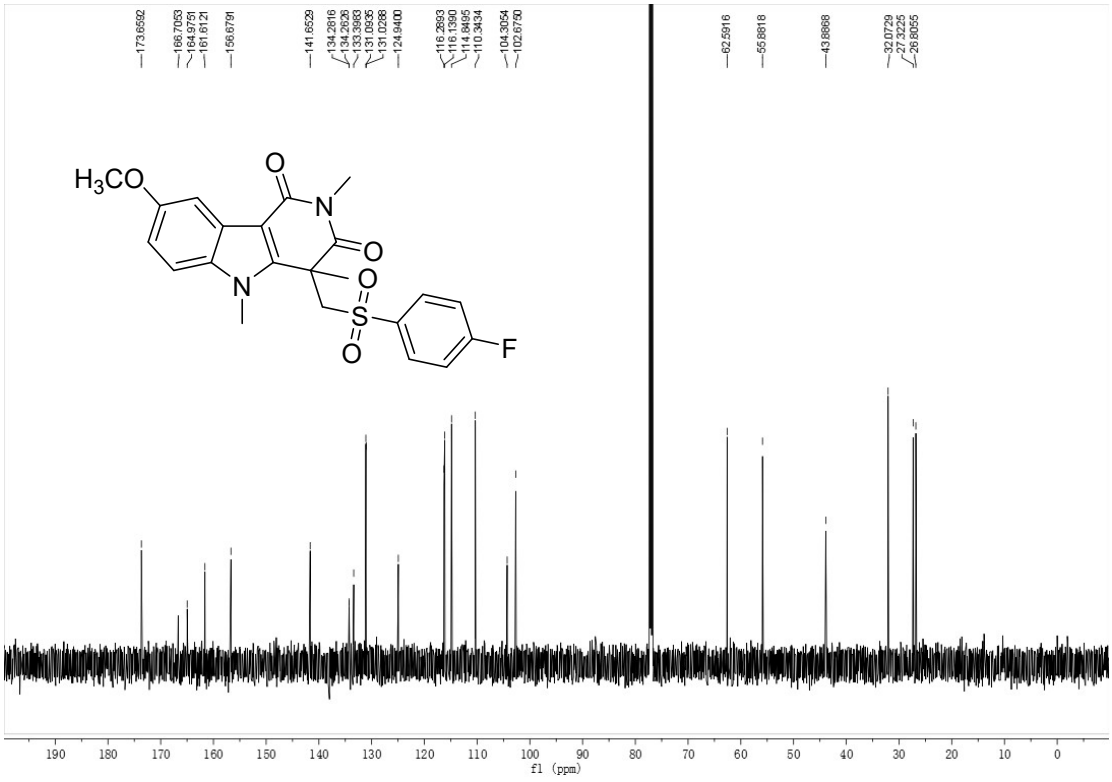
^{19}F NMR (376 MHz, $CDCl_3$) of **3fa**:



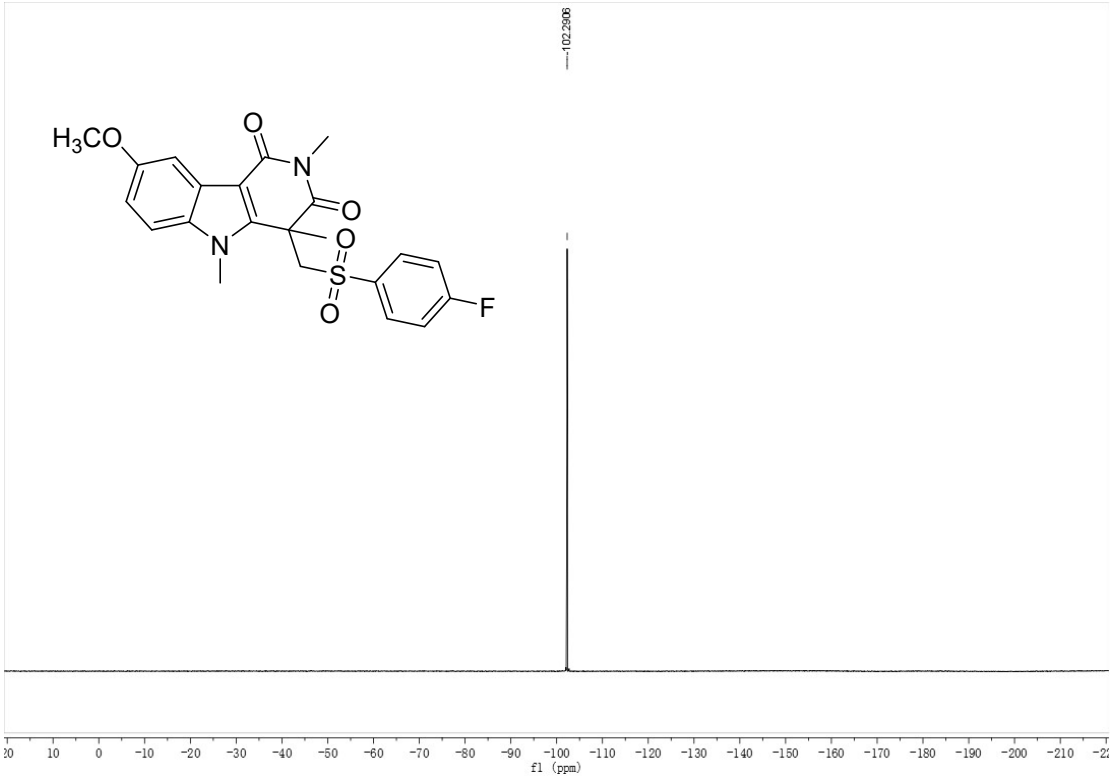
^{1}H NMR (600 MHz, $CDCl_3$) of **3ga**:



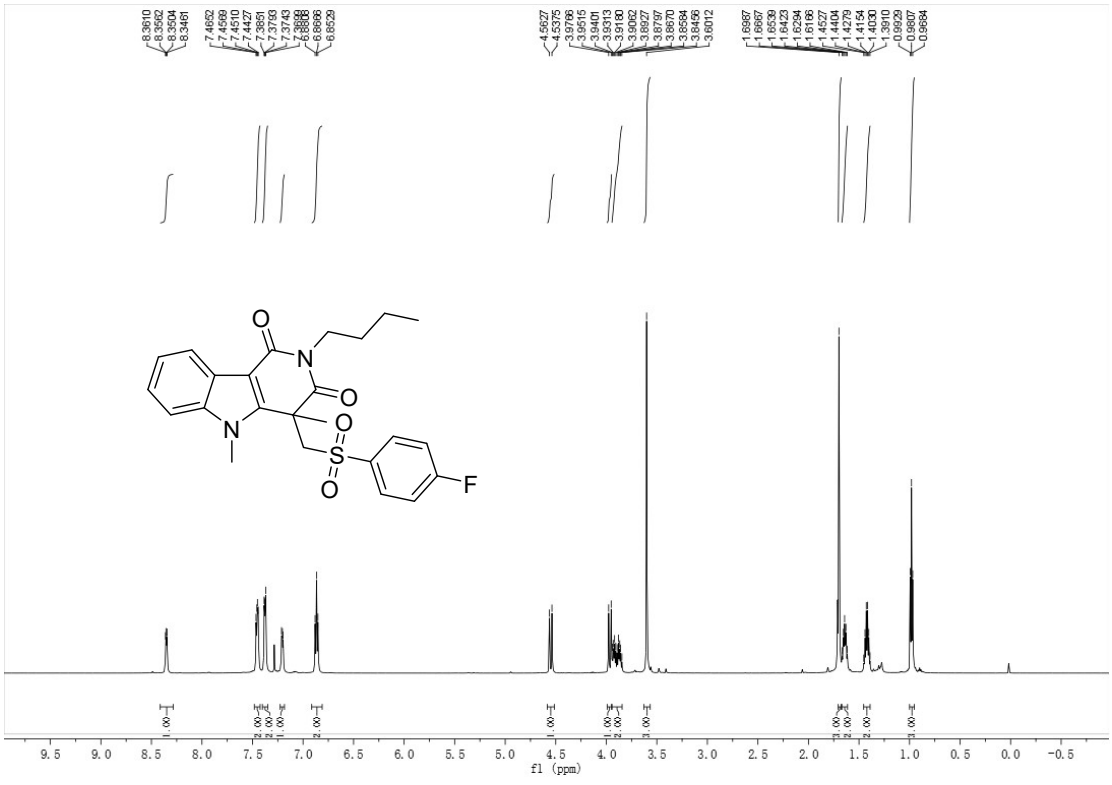
^{13}C{1H} NMR (150 MHz, $CDCl_3$) of **3ga**:



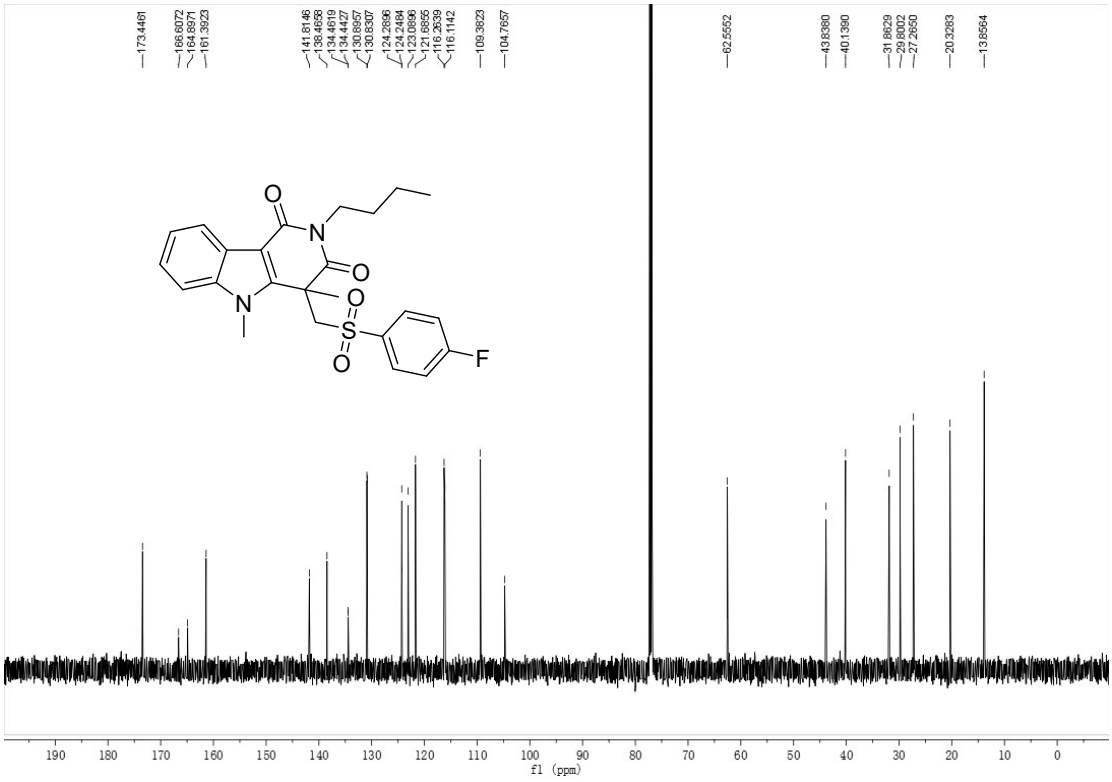
^{19}F NMR (376 MHz, $CDCl_3$) of **3ga**:



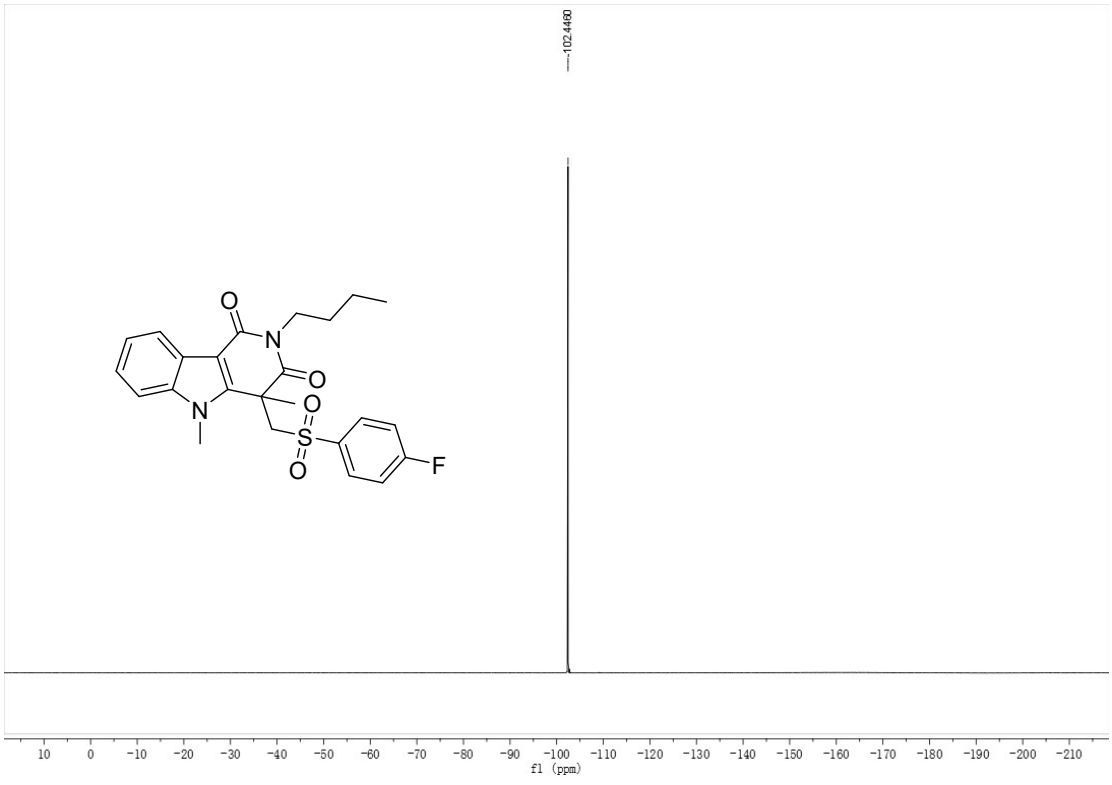
^{1}H NMR (600 MHz, $CDCl_3$) of **3ha**:



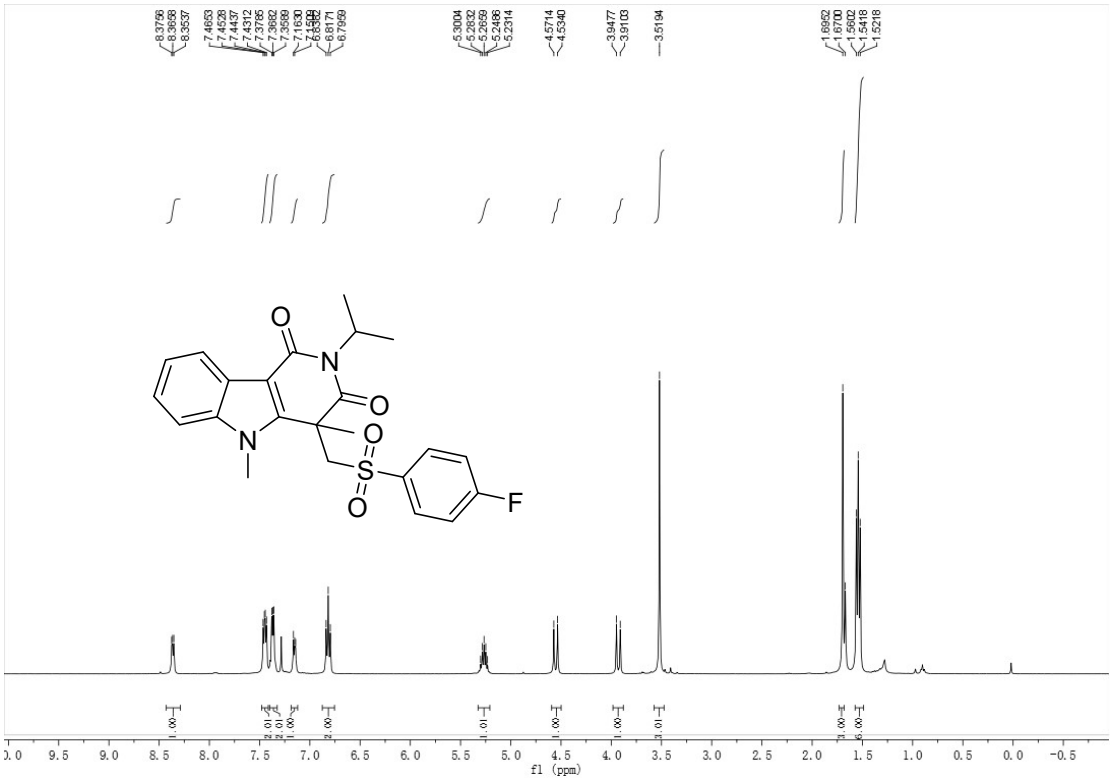
$^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$) of **3ha**:



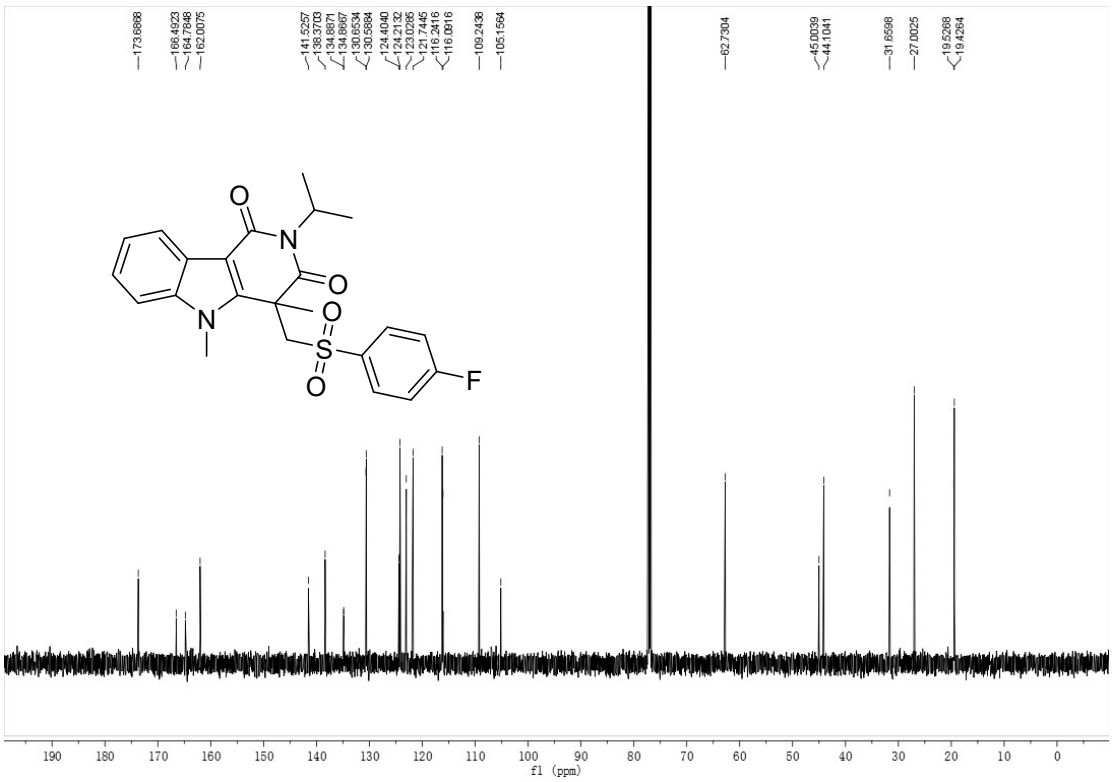
^{19}F NMR (565 MHz, $CDCl_3$) of **3ha**:



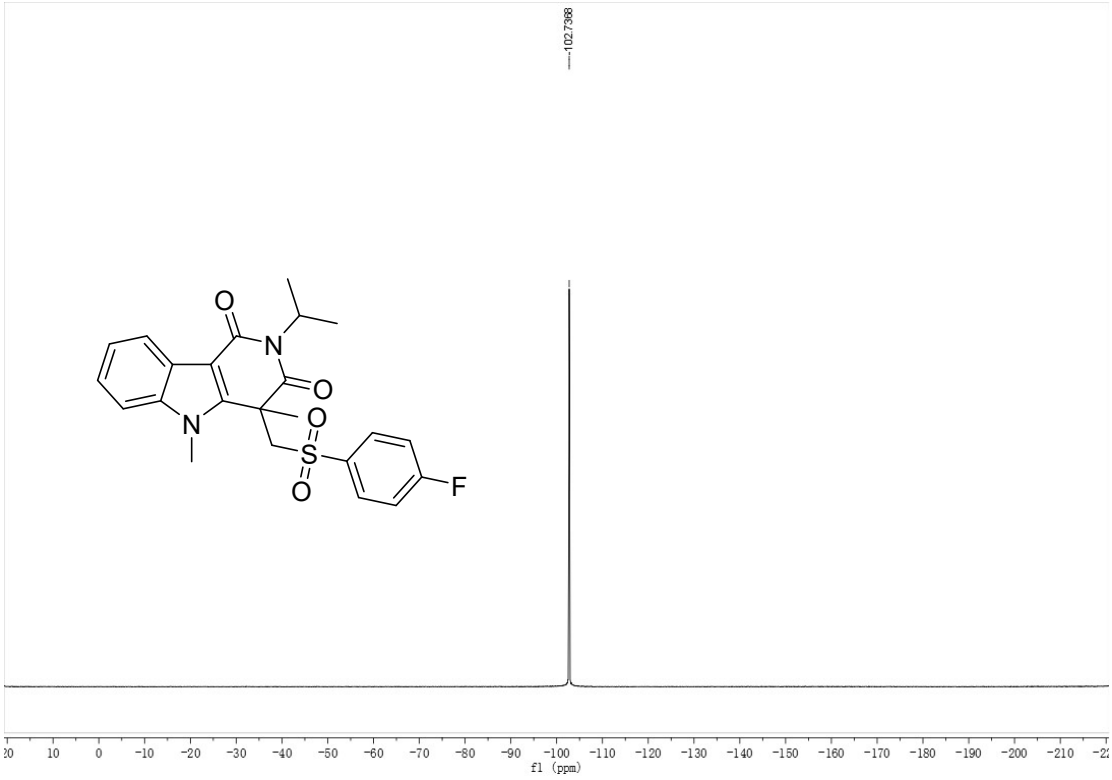
^{1}H NMR (400 MHz, $CDCl_3$) of **3ia**:



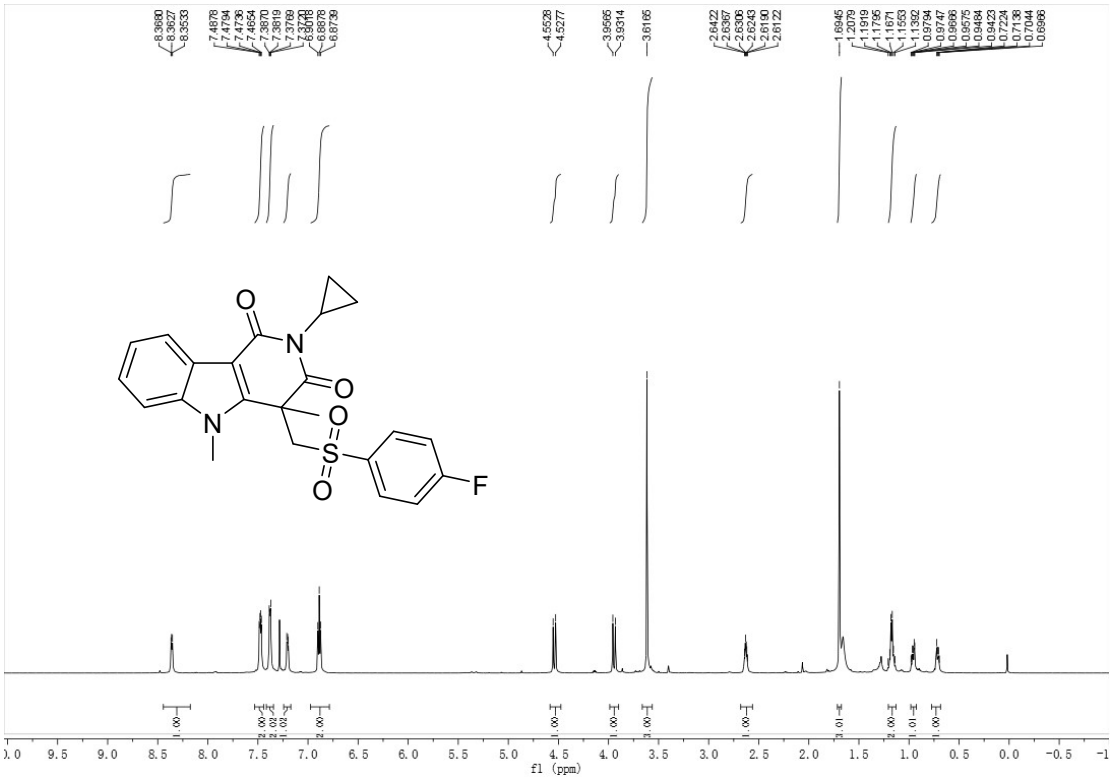
^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) of **3ia**:



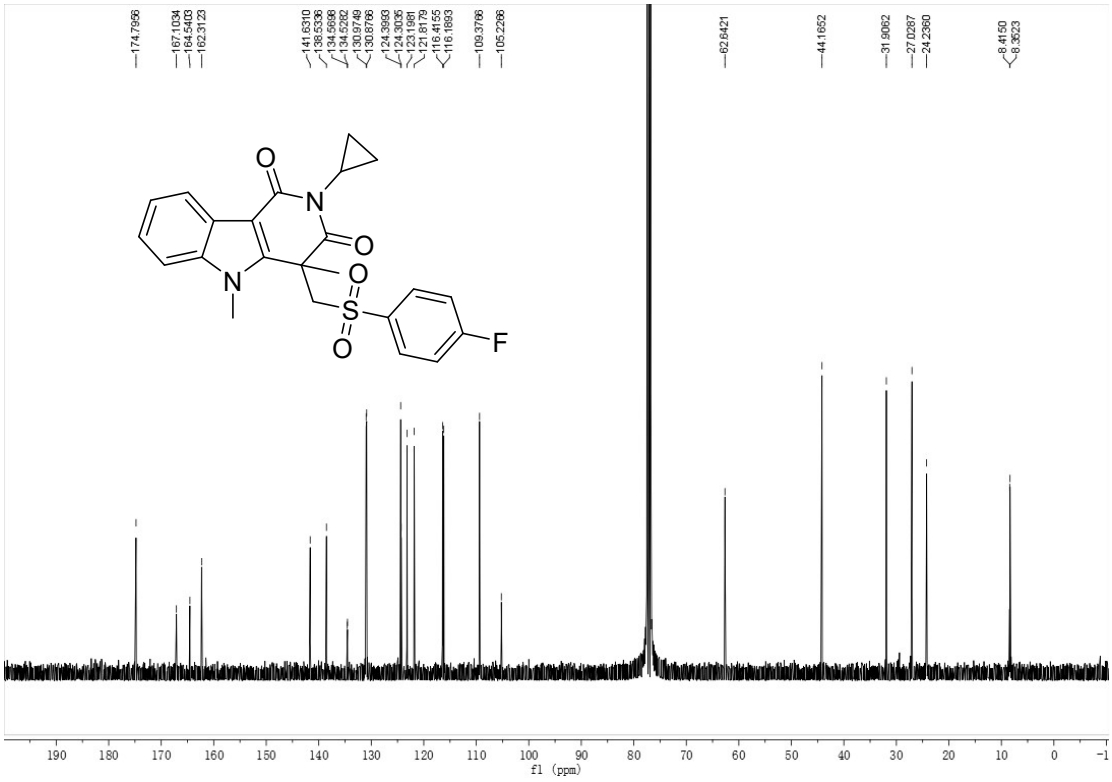
^{19}F NMR (376 MHz, $CDCl_3$) of **3ia**:



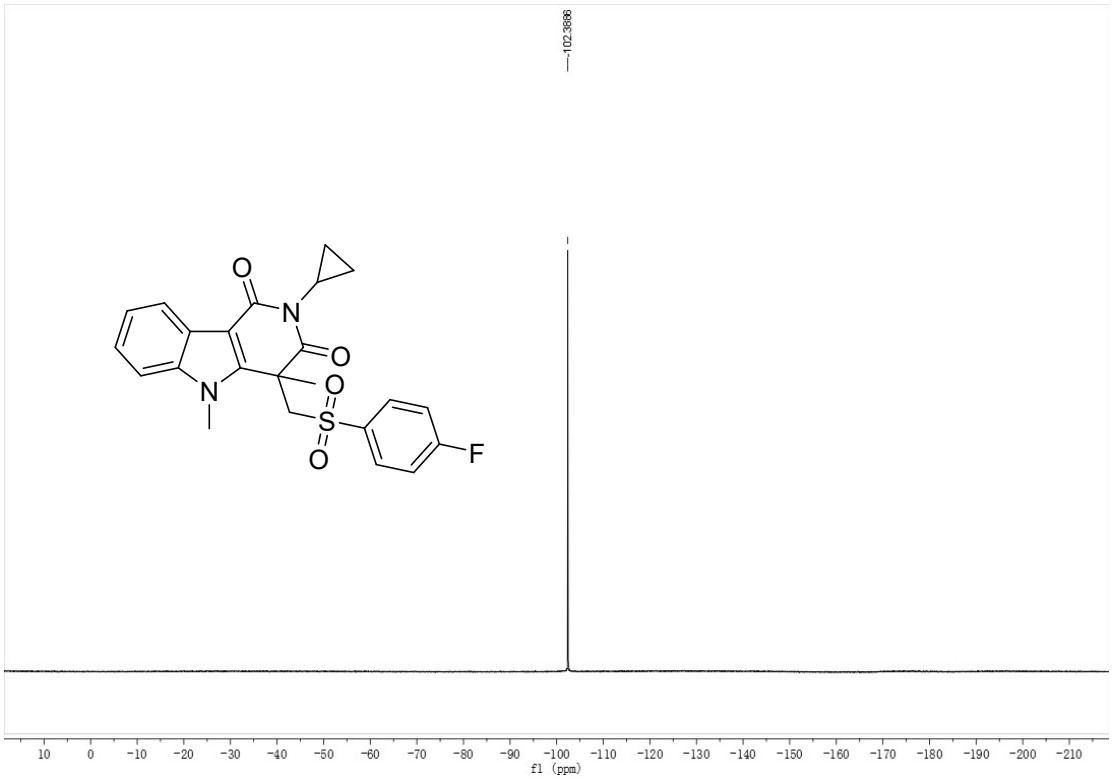
^{1}H NMR (600 MHz, $CDCl_3$) of **3ja**:



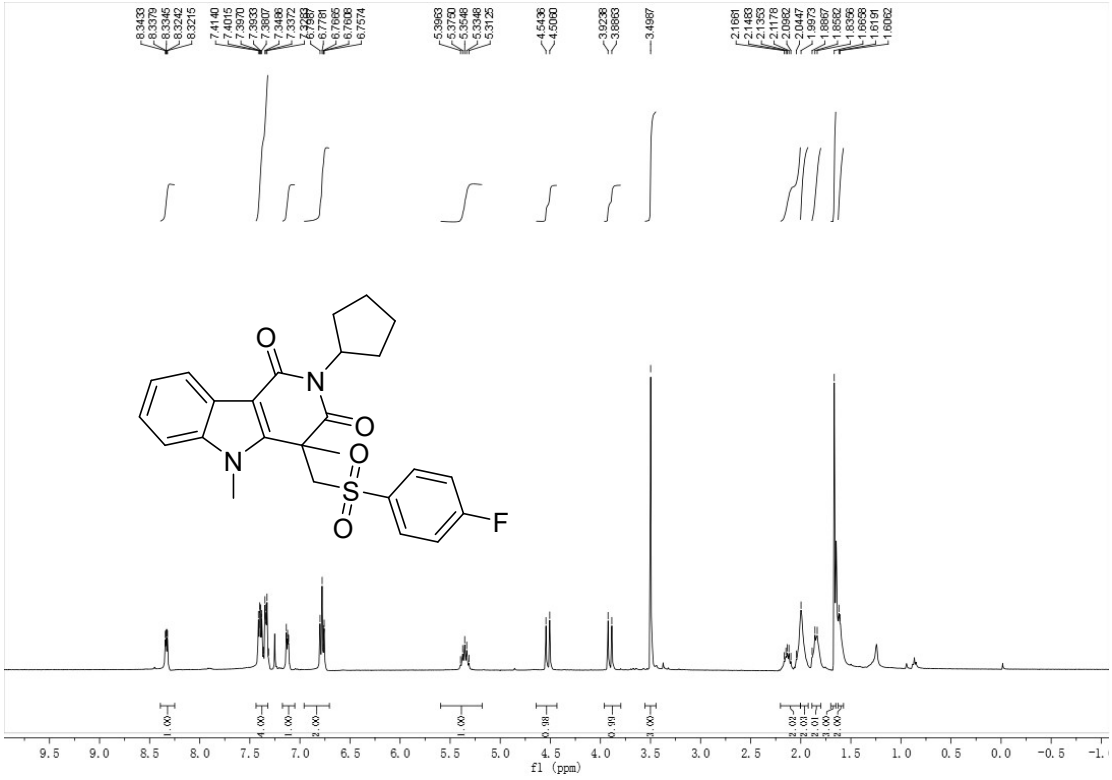
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3ja**:



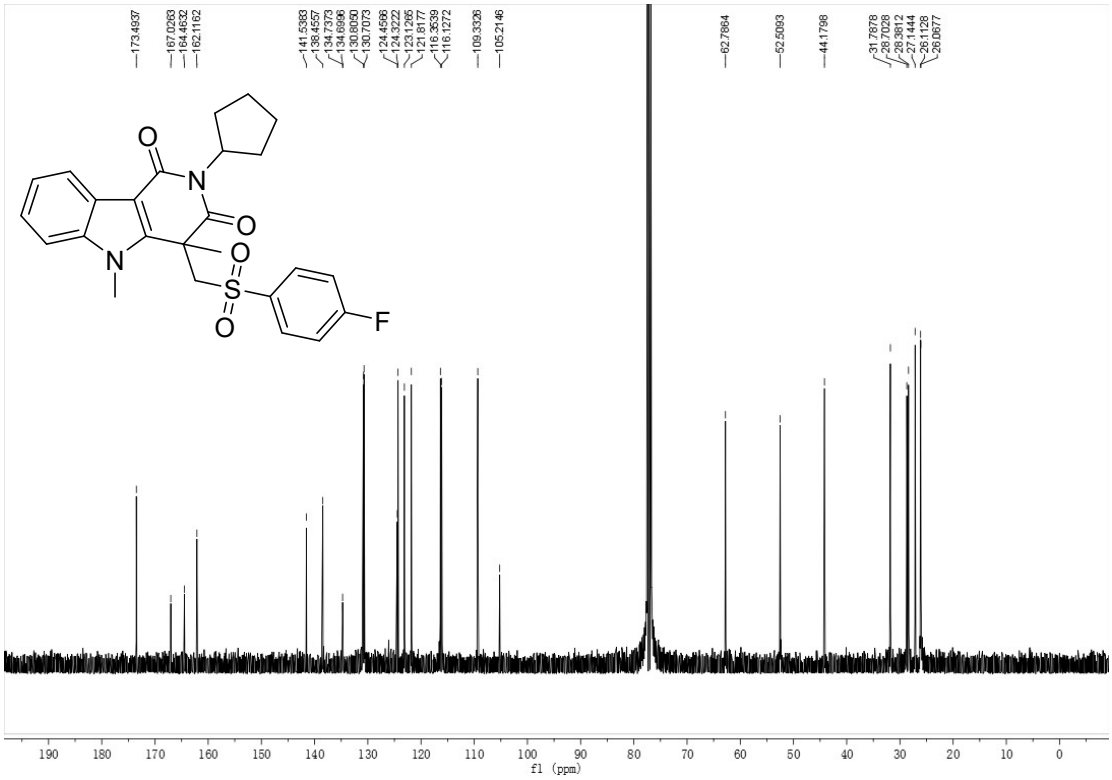
^{19}F NMR (565 MHz, $CDCl_3$) of **3ja**:



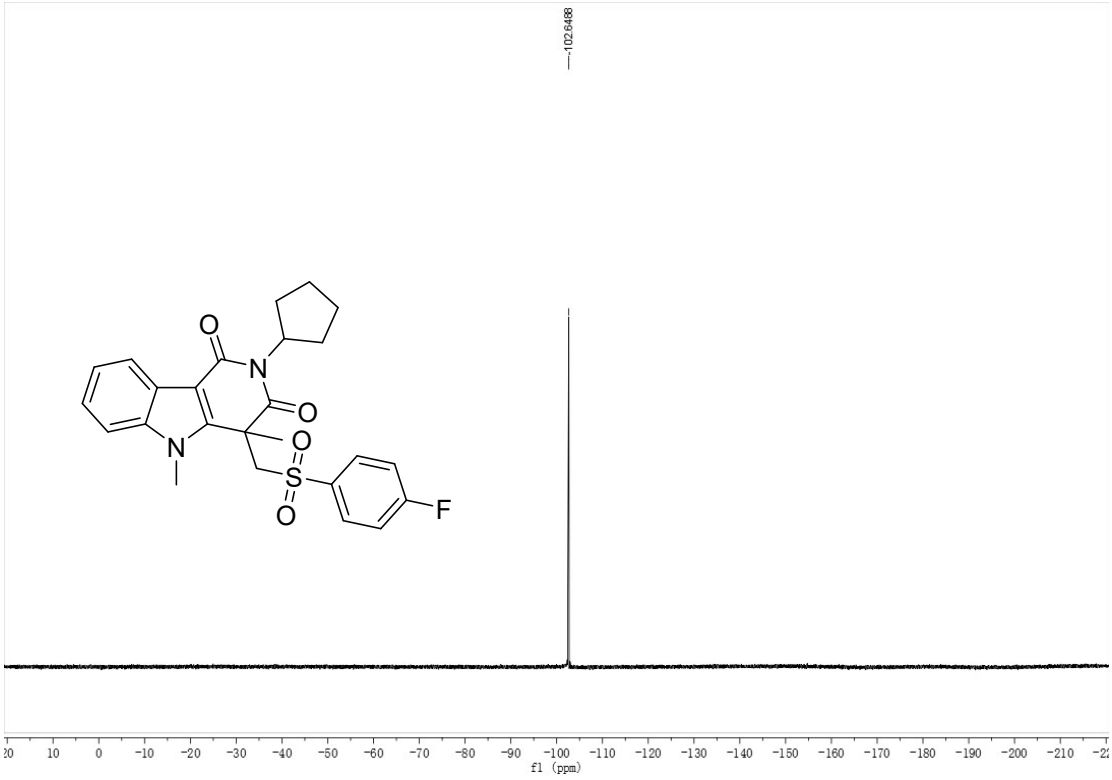
^{1}H NMR (400 MHz, $CDCl_3$) of **3ka**:



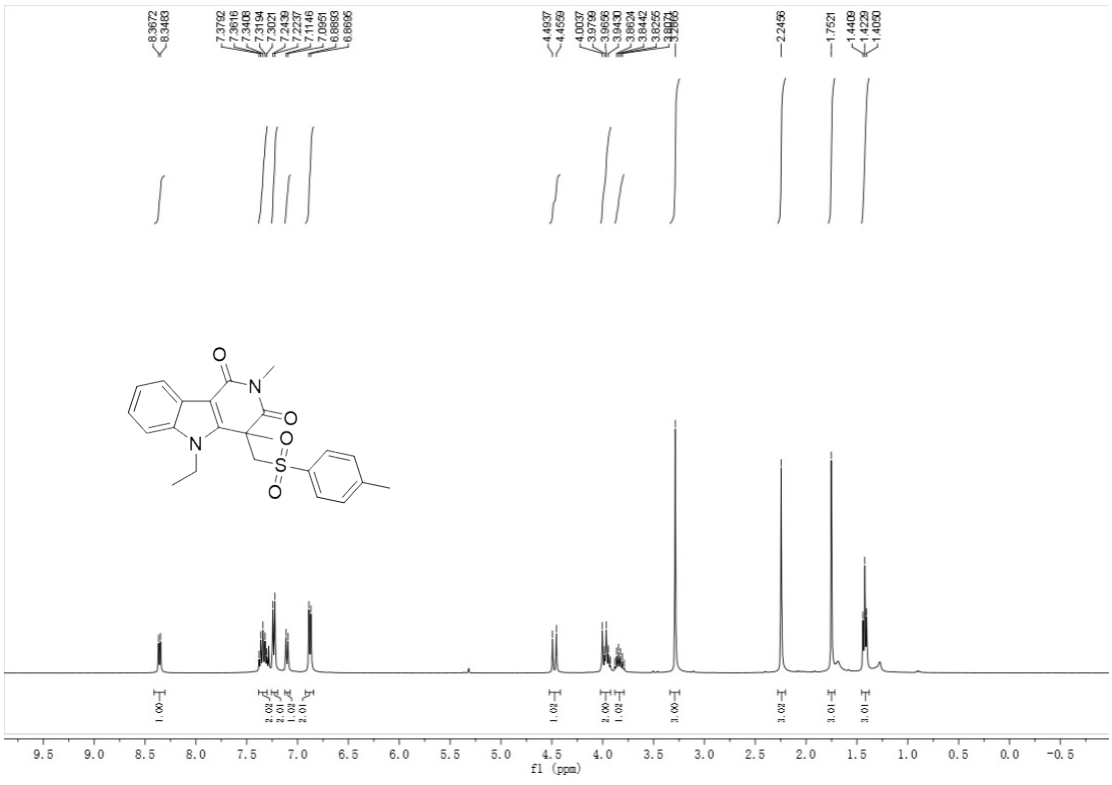
$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3ka**:



^{19}F NMR (376 MHz, $CDCl_3$) of **3ka**:



^{1}H NMR (400 MHz, $CDCl_3$) of **3ld**:



$^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$) of **3ld**: