Synthesis of polydisubstituted 3-aminoindenes via rhodium-catalysed [3 + 2] cascade annulations of benzimidates with alkenes

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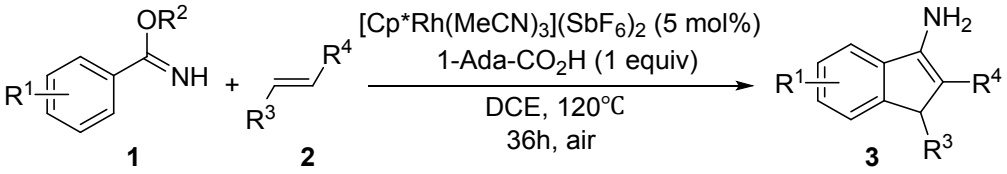
1. General Information

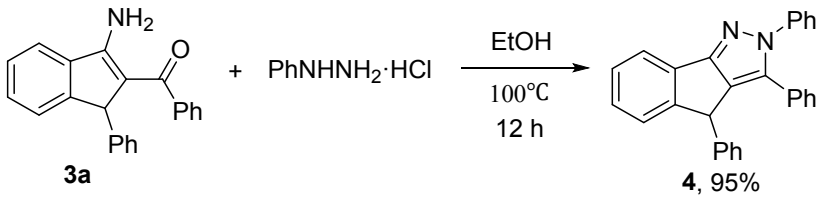
Unless otherwise stated, all commercial materials and solvents were used directly without further purification. Commercially available chemicals were obtained from Energy Chemical, TCI, Alfa Aesar, J&K. Melting points were determined in open glass capillaries and were uncorrected. ^{1}H NMR spectra were recorded on 400 MHz spectrometers, and ^{13}C NMR spectra were recorded on a 100 MHz spectrometer. High-resolution mass spectra (HRMS) were equipped with an ESI source and a TOF detector. Column chromatography was performed on silica gel (70-230 mesh ASTM) using the reported eluents. Thin-layer chromatography (TLC) was carried out on 4×15 cm plates with a layer thickness of 0.2 mm (silica gel 60 F254). Benzimidates[1] and α,β-unsaturated ketones[2] were synthesized according to the previously reported procedure.

2. Typical procedure for synthesis of 3a



To a test tube equipped with magnetic stir bar, alkene (**2**, 0.40 mmol), $[Cp^*Rh(MeCN)_3](SbF_6)_2$ (0.01 mmol, 8.3 mg), 1-Ada-CO_2H (0.2 mmol, 36.0 mg), DCE (2ml) and benzimidate (**1**, 0.20 mmol) were added sequentially under air atmosphere. The reaction mixture was stirred at 120°C for 36 h. After cooled to room temperature, Na_2CO_3 (0.2 mmol, 21.2mg) was added. The resulting mixture was stirred at room temperature for another 1 h. After removal of the solvent under reduced pressure, purification was performed by flash column chromatography on silica gel with petroleum ether/ethyl acetate (gradient mixture ratio from 5:1 to 2:1) as eluent to afford the desired product **3**.

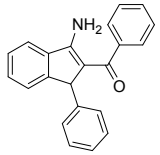
3. Conversion of 3a



To a test tube equipped with magnetic stir bar, **3a** (0.1 mmol), phenylhydrazine hydrochloride (0.3 mmol) and dry ethanol (1 ml) were added sequentially under air atmosphere. The reaction mixture was stirred at 100°C for 12 h and cooled to room temperature. After evaporation of solvent, the residue was dissolved in ethyl acetate, and the organic layer was washed subsequently with H_2O and then dried with anhydrous $MgSO_4$. After concentration under reduced pressure, the residue was purified by column chromatography on silica gel to afford the product **4** in 95% yield.[3]

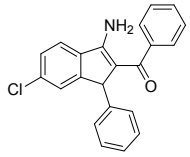
4. Characterization data of the products

3-Amino-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3a)



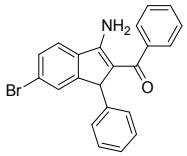
yellow solid, 88% yield, mp: 209-210°C. ^{1}H NMR (400 MHz, DMSO) δ 8.71 (s, 2H), 8.07-8.01 (m, 1H), 7.44-7.34 (m, 4H), 7.28-7.17 (m, 3H), 7.17-7.07 (m, 1H), 6.99-6.89 (m, 3H), 6.81-6.73 (m, 2H), 5.28(s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.3, 161.9, 150.6, 142.8, 142.3, 136.6, 130.8, 129.4, 128.3, 128.0, 127.6, 127.4, 127.2, 126.2, 125.1, 122.0, 110.8, 52.7. HRMS (ESI) Calcd for $C_{22}H_{17}NO$ $[M+H]^+$ 312.1383; found 312.1386.

3-Amino-6-chloro-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3b)



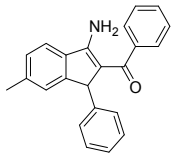
yellow solid, 77% yield, mp: 207-208°C. ^{1}H NMR (400 MHz, DMSO) δ 8.71 (s, 2H), 8.07 (d, J = 8.2 Hz, 1H), 7.52-7.46 (m, 1H), 7.42-7.35 (m, 2H), 7.29-7.17 (m, 3H), 7.11 (d, J = 1.9 Hz, 1H), 7.02-6.92 (m, 3H), 6.84-6.76 (m, 2H), 5.31 (s,1H). ^{13}C NMR (100 MHz, DMSO) δ 191.4, 160.6, 152.4, 142.6, 141.5, 135.6, 135.4, 129.6, 128.5, 128.0, 127.8, 127.6, 127.2, 126.5, 125.0, 123.7, 110.8, 52.5. HRMS (ESI) Calcd for $C_{22}H_{16}ClNO$ $[M+H]^+$ 346.0993; found 346.0994.

3-Amino-6-bromo-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3c)



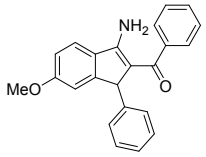
yellow solid, 87% yield, mp: 189-190°C. ^{1}H NMR (400 MHz, DMSO) δ 8.70 (s, 2H), 8.00 (d, J = 8.2 Hz, 1H), 7.66-7.59 (m, 1H), 7.41-7.36 (m, 2H), 7.28-7.18 (m, 4H), 7.02-6.92 (m, 3H), 6.85-6.78 (m, 2H), 5.31 (s,1H). ^{13}C NMR (100 MHz, DMSO) δ 191.4, 160.7, 152.6, 142.6, 141.4, 135.9, 130.6, 129.6, 128.5, 128.0, 127.9, 127.6, 127.2, 126.6, 124.1, 124.0, 110.7, 52.5. HRMS (ESI) Calcd for $C_{22}H_{16}BrNO$ $[M+H]^+$ 390.0488; found 390.0488.

3-Amino-6-methyl-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3d)



yellow solid, 88% yield, mp: 211-212°C. ^{1}H NMR (400 MHz, DMSO) δ 8.69 (s, 2H), 7.91 (d, J = 7.8 Hz, 1H), 7.39-7.33 (m, 2H), 7.26-7.17 (m, 4H), 6.99-6.89 (m, 4H), 6.80-6.73 (m, 2H), 5.21 (s,1H), 2.28 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 191.0, 162.2, 151.0, 142.9, 142.5, 140.9, 134.0, 129.3, 128.4, 128.3, 127.9, 127.6, 127.2, 126.2, 125.5, 121.8, 110.5, 52.5, 21.8. HRMS (ESI) Calcd for $C_{23}H_{19}NO$ $[M+H]^+$ 326.1539; found 326.1540.

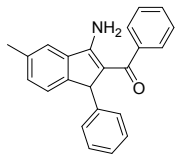
3-Amino-6-methoxy-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3e)



yellow solid, 68% yield, mp: 177-178°C. ^{1}H NMR (400 MHz, DMSO) δ 8.68 (s, 2H), 7.96 (d, J = 8.6 Hz, 1H), 7.40-7.27 (m, 2H), 7.26-7.15 (m, 3H), 7.02-6.89 (m, 4H), 6.79-6.73 (m, 2H), 6.62 (d, J = 2.3 Hz, 1H), 5.20 (s,1H), 3.70 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 190.4, 162.3, 162.1, 153.1, 143.0, 142.6, 129.2, 129.1, 128.3, 127.9,

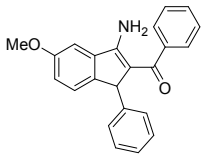
127.6, 127.2, 126.2, 123.4, 113.8, 110.3, 110.2, 55.9, 52.5. HRMS (ESI) Calcd for $C_{23}H_{19}NO_2$ $[M+H]^+$ 342.1489; found 342.1490.

3-Amino-5-methyl-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3f)



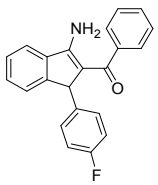
yellow solid, 76% yield, mp: 198-199°C. ^{1}H NMR (400 MHz, DMSO) δ 8.68 (s, 2H), 7.86 (s, 1H), 7.40-7.35 (m, 2H), 7.27-7.17 (m, 4H), 7.01-6.88 (m, 4H), 6.79-6.71 (m, 2H), 5.21 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.2, 162.1, 148.0, 142.8, 142.5, 136.8, 136.7, 131.7, 129.4, 128.3, 127.9, 127.5, 127.2, 126.2, 124.8, 122.2, 111.2, 52.3, 21.5. HRMS (ESI) Calcd for $C_{23}H_{19}NO$ $[M+H]^+$ 326.1539; found 326.1539.

3-Amino-5-methoxy-1-phenyl-1H-inden-2-yl)(phenyl)methanone (3g)



yellow solid, 57% yield, mp: 213-214°C. ^{1}H NMR (400 MHz, DMSO) δ 8.66 (s, 2H), 7.70 (d, J = 2.0 Hz, 1H), 7.39-7.35 (m, 2H), 7.27-7.17 (m, 3H), 7.00-6.88 (m, 5H), 6.77-6.71 (m, 2H), 5.19 (s, 1H), 3.81 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 191.2, 161.9, 159.3, 143.0, 142.8, 142.5, 137.8, 129.4, 128.3, 127.9, 127.5, 127.3, 126.1, 125.8, 117.9, 111.8, 106.3, 55.9, 52.0. HRMS (ESI) Calcd for $C_{23}H_{19}NO_2$ $[M+H]^+$ 342.1489; found 342.1489.

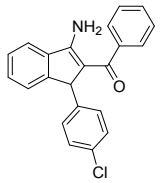
3-Amino-1-(4-fluorophenyl)-1H-inden-2-yl)(phenyl)methanone (3h)



yellow solid, 85% yield, mp: 205-206°C. ^{1}H NMR (400 MHz, DMSO) δ 8.73 (s, 2H), 8.09-8.01 (m, 1H), 7.45-7.36 (m, 4H), 7.29-7.19 (m, 3H), 7.15-7.06 (m, 1H), 6.77 (d,

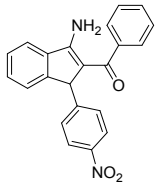
J = 7.14 Hz, 4H), 5.29 (s,1H). ^{13}C NMR (100 MHz, DMSO) δ 191.4, 161.9, 160.8 (d, J_{CF}= 241.6 Hz),150.5, 142.8, 138.3 (d, J_{CF}= 3.0 Hz), 136.5, 130.9, 129.5, 129.3 (d, J_{CF}= 8.0 Hz), 128.0, 127.6, 127.2, 125.1, 122.1, 115.0 (d, J_{CF}= 21.3 Hz), 110.8, 51.8. ^{19}F NMR (376 MHz, DMSO) δ -117.25. HRMS (ESI) Calcd for $C_{22}H_{16}FNO$ $[M+H]^+$ 330.1289; found 330.1290.

3-Amino-1-(4-chlorophenyl)-1H-inden-2-yl)(phenyl)methanone (3i)



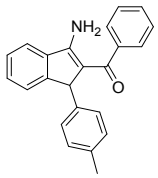
yellow solid, 75% yield, mp: 235-236°C. ^{1}H NMR (400 MHz, DMSO) δ 8.72 (s, 2H), 8.09-8.00 (m, 1H), 7.46-7.36 (m, 4H), 7.32-7.18 (m, 3H), 7.15-7.07 (m, 1H), 7.06-6.97 (m, 2H), 6.81-6.74 (m, 2H), 5.31 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.2, 162.0, 150.2, 142.7, 141.4, 136.5, 131.0, 130.6, 129.5, 129.4, 128.3, 128.1, 127.6, 127.2, 125.1, 122.1, 110.5, 51.9. HRMS (ESI) Calcd for $C_{22}H_{16}ClNO$ $[M+H]^+$ 346.0993; found 346.0994.

3-Amino-1-(4-nitrophenyl)-1H-inden-2-yl)(phenyl)methanone (3j)



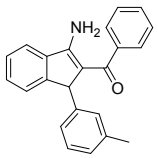
yellow solid, 76% yield, mp: 93-94°C. ^{1}H NMR (400 MHz, DMSO) δ 8.79 (s, 2H), 8.13-8.06 (m, 1H), 7.88-7.80 (m, 2H), 7.48-7.35 (m, 4H), 7.28-7.18 (m, 3H), 7.12 (d, J = 7.4 Hz, 1H), 7.08-6.98 (m, 2H), 5.48 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.1, 162.1, 151.1, 149.4, 146.0, 142.6, 136.7, 131.2, 129.6, 128.9, 128.2, 128.0, 127.1, 125.2, 123.6, 122.4, 110.3, 52.1. HRMS (ESI) Calcd for $C_{22}H_{16}N_2O_3$ $[M+H]^+$ 357.1234; found 357.1236.

3-Amino-1-(*p*-tolyl)-1H-inden-2-yl)(phenyl)methanone (3k)



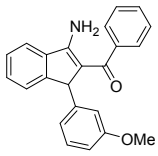
yellow solid, 74% yield, mp: 219-220°C. ^{1}H NMR (400 MHz, DMSO) δ 8.68 (s, 2H), 8.06-7.96 (m, 1H), 7.46-7.33 (m, 4H), 7.31-7.17 (m, 3H), 7.14-7.06 (m, 1H), 6.78 (d, J = 8.32 Hz, 2H), 6.71-6.61 (m, 2H), 5.26 (s, 1H), 2.09 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 191.2, 161.9, 150.8, 142.7, 139.2, 136.5, 135.1, 130.8, 129.5, 129.0, 128.0, 127.5, 127.4, 127.3, 125.1, 121.9, 110.7, 52.3, 21.0. HRMS (ESI) Calcd for $C_{23}H_{19}NO$ $[M+H]^+$ 326.1539; found 326.1541.

3-Amino-1-(*m*-tolyl)-1H-inden-2-yl)(phenyl)methanone (3l)



yellow solid, 81% yield, mp: 218-219°C. ^{1}H NMR (400 MHz, DMSO) δ 8.69 (s, 2H), 8.07-8.02 (m, 1H), 7.43-7.35 (m, 4H), 7.29-7.19 (m, 3H), 7.15-7.08 (m, 1H), 6.85 (t, J = 7.5 Hz, 1H), 6.73 (d, J = 7.5 Hz, 1H), 6.58-6.51 (m, 2H), 5.21 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.4, 161.8, 150.6, 142.9, 142.1, 137.1, 136.7, 130.8, 129.3, 128.3, 128.2, 127.9, 127.4, 127.2, 126.9, 125.1, 124.8, 122.0, 110.9, 52.6, 21.3. HRMS (ESI) Calcd for $C_{23}H_{19}NO$ $[M+H]^+$ 326.1539; found 326.1542.

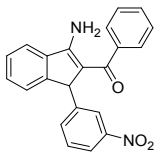
3-Amino-1-(3-methoxyphenyl)-1H-inden-2-yl)(phenyl)methanone (3m)



yellow solid, 53% yield, mp: 132-133°C. ^{1}H NMR (400 MHz, DMSO) δ 8.69 (s, 2H), 8.07-7.98 (m, 1H), 7.48-7.35 (m, 4H), 7.32-7.19 (m, 3H), 7.19-7.11 (m, 1H), 6.88 (t, J = 7.9 Hz, 1H), 6.54-6.47 (m, 1H), 6.41-6.28 (m, 2H), 5.25 (s, 1H), 3.55 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 191.3, 161.9, 159.2, 150.4, 143.9, 142.8, 136.5, 130.8,

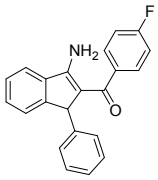
129.5, 129.4, 128.0, 127.5, 127.3, 125.0, 121.9, 119.6, 113.6, 111.7, 110.6, 55.2, 52.6. HRMS (ESI) Calcd for $C_{23}H_{19}NO_2$ $[M+H]^+$ 342.1489; found 342.1492.

3-Amino-1-(3-nitrophenyl)-1H-inden-2-yl)(phenyl)methanone (3n)



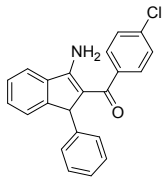
yellow solid, 74% yield, mp: 226-227°C. ^{1}H NMR (400 MHz, DMSO) δ 8.77 (s, 2H), 8.12-8.06 (m, 1H), 7.83-7.78 (m, 1H), 7.57-7.53 (m, 1H), 7.49-7.40 (m, 2H), 7.36-7.31 (m, 2H), 7.28-7.11 (m, 6H), 5.47 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 191.3, 162.0, 149.6, 147.6, 144.9, 142.7, 136.8, 134.4, 131.2, 129.9, 129.4, 128.1, 128.0, 127.0, 125.2, 122.6, 122.3, 121.4, 110.5, 51.77. HRMS (ESI) Calcd for $C_{22}H_{16}N_2O_3$ $[M+H]^+$ 357.1234; found 357.1236.

3-Amino-1-phenyl-1H-inden-2-yl)(4-fluorophenyl)methanone (3o)



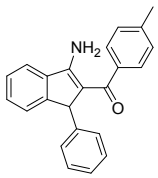
yellow solid, 75% yield, mp: 218-219°C. ^{1}H NMR (400 MHz, DMSO) δ 8.75 (s, 2H), 8.08-8.02 (m, 1H), 7.51-7.37 (m, 4H), 7.13-7.09 (m, 1H), 7.05-6.91 (m, 5H), 6.85-6.76 (m, 2H), 5.29 (s,1H). ^{13}C NMR (100 MHz, DMSO) δ 189.9, 162.8 (d, J_{CF}= 245.7 Hz), 162.2, 150.6, 142.2, 139.3 (d, J_{CF}= 3.1 Hz), 136.5, 130.9, 129.8 (d, J_{CF}= 8.6 Hz), 128.4, 127.6, 127.5, 126.4, 125.1, 122.0, 114.8 (d, J_{CF}= 21.3 Hz), 110.6, 52.6. ^{19}F NMR (376 MHz, DMSO) δ -111.98. HRMS (ESI) Calcd for $C_{22}H_{16}FNO$ $[M+H]^+$ 330.1289; found 330.1288.

3-Amino-1-phenyl-1H-inden-2-yl)(4-chlorophenyl)methanone (3p)



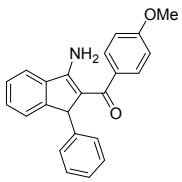
yellow solid, 82% yield, mp: 204-205°C. ^{1}H NMR (400 MHz, DMSO) δ 8.77 (s, 2H), 8.17-7.97 (m, 1H), 7.54-7.32 (m, 4H), 7.31-7.19 (m, 2H), 7.17-7.06 (m, 1H), 7.06-6.89(m, 3H), 6.89-6.72 (m, 2H), 5.28 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 189.7, 162.4, 150.6, 142.1, 141.4, 136.4, 134.1, 131.0, 129.2, 128.4, 128.0, 127.6, 127.5, 126.4, 125.1, 122.1, 110.5, 52.47. HRMS (ESI) Calcd for $C_{22}H_{16}ClNO$ $[M+H]^+$ 346.0993; found 346.0993.

3-Amino-1-phenyl-1H-inden-2-yl)(*p*-tolyl)methanone (3q)



yellow solid, 67% yield, mp: 160-161°C. ^{1}H NMR (400 MHz, DMSO) δ 8.67 (s, 2H), 8.04-7.99 (m, 1H), 7.43-7.34 (m, 4H), 7.15-7.10 (m, 1H), 7.05-6.92 (m, 5H), 6.87-6.80 (m, 2H), 5.33 (s, 1H), 2.24 (s,3H). ^{13}C NMR (100 MHz, DMSO) δ 190.9, 161.8, 150.5, 142.4, 139.9, 139.1, 136.6, 130.7, 128.5, 128.4, 127.6, 127.5, 127.4, 126.3, 125.0, 121.9, 110.6, 52.7, 21.4. HRMS (ESI) Calcd for $C_{23}H_{19}NO$ $[M+H]^+$ 326.1539; found 326.1542.

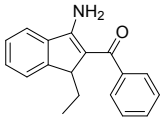
3-Amino-1-phenyl-1H-inden-2-yl)(4-methoxyphenyl)methanone (3r)



yellow solid, 64% yield, mp: 180-181°C. ^{1}H NMR (400 MHz, DMSO) δ 8.63 (s, 2H), 8.03-7.97 (m, 1H), 7.54-7.47 (m, 2H), 7.43-7.34 (m, 2H), 7.16-7.10 (m, 1H), 7.04-6.91 (m, 3H), 6.91-6.85 (m, 2H), 6.79-6.73 (m, 2H), 5.38 (s, 1H), 3.72 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 190.0, 161.7, 160.5, 150.4, 142.5, 136.6, 135.1, 130.6,

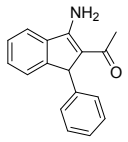
129.6, 128.4, 127.5, 127.4, 126.4, 125.0, 121.8, 113.2, 110.5, 55.6, 52.8. HRMS (ESI) Calcd for $C_{23}H_{19}NO_2$ $[M+H]^+$ 342.1489; found 342.1491.

(3-Amino-1-ethyl-1H-inden-2-yl)(phenyl)methanone (3s)



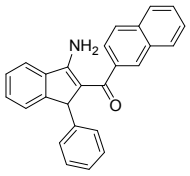
yellow solid, 62% yield, mp: 157-158°C. ^{1}H NMR (400 MHz, DMSO) δ 8.61 (s, 2H), 7.98 (d, J = 7.52 Hz, 1H), 7.67-7.59 (m, 2H), 7.56-7.39 (m, 6H), 4.30-4.18 (m, 1H), 1.74-1.62 (m, 1H), 1.17-1.05 (m, 1H), 0.19 (t, J = 7.44 Hz, 3H). ^{13}C NMR (100 MHz, DMSO) δ 190.7, 161.6, 149.4, 143.3, 137.6, 130.4, 129.9, 128.6, 127.2, 127.1, 124.2, 121.8, 108.3, 46.4, 24.0, 8.1. HRMS (ESI) Calcd for $C_{18}H_{17}NO$ $[M+H]^+$ 264.1383; found 264.1386.

1-(3-Amino-1-phenyl-1H-inden-2-yl)ethan-1-one (3t)



yellow solid, 56% yield, mp: 194-195°C. ^{1}H NMR (400 MHz, DMSO) δ 8.45 (s, 2H), 7.97-7.92 (m, 1H), 7.40-7.33 (m, 2H), 7.30-7.23 (m, 2H), 7.22-7.10 (m, 4H), 4.96 (s, 1H), 1.76 (s, 3H). ^{13}C NMR (100 MHz, DMSO) δ 193.7, 159.1, 149.8, 142.8, 136.9, 130.4, 129.1, 127.8, 127.4, 127.0, 125.1, 121.9, 111.3, 52.2, 28.7. HRMS (ESI) Calcd for $C_{17}H_{15}NO$ $[M+H]^+$ 250.1226; found 250.1228.

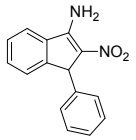
3-Amino-1-phenyl-1H-inden-2-yl)(naphthalen-2-yl)methanone (3u)



yellow solid, 66% yield, mp: 187-188°C. ^{1}H NMR (400 MHz, DMSO) δ 8.84 (s, 2H), 8.12-8.06 (m, 2H), 7.95-7.91 (m, 1H), 7.85-7.81 (m, 1H), 7.73 (d, J = 8.5 Hz, 1H), 7.55-7.49 (m, 3H), 7.47-7.37 (m, 2H), 7.17-7.10 (m, 1H), 6.90-6.81 (m, 5H), 5.51

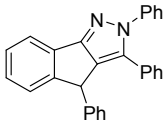
(s,1H). ^{13}C NMR (100 MHz, DMSO) δ 190.7, 162.3, 150.7, 142.5, 139.7, 136.5, 133.5, 132.4, 130.9, 129.1, 128.4, 127.8, 127.6, 127.5, 127.4, 127.3, 127.2, 126.6, 126.3, 125.2, 125.1, 122.0, 110.9, 52.7. HRMS (ESI) Calcd for $C_{26}H_{19}NO$ $[M+H]^+$ 362.1539; found 362.1538.

2-Nitro-1-phenyl-1H-inden-3-amine (3v)



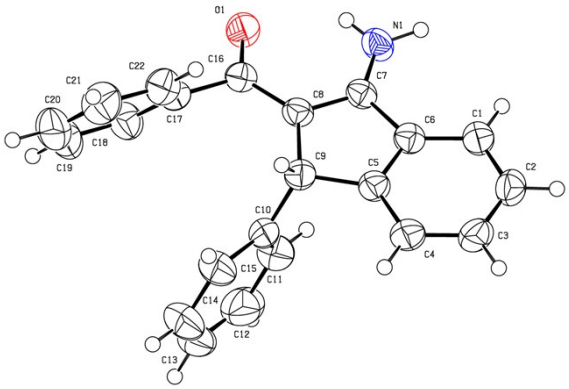
yellow solid, 71% yield, mp: 249-250°C. ^{1}H NMR (400 MHz, DMSO) δ 9.38 (s, 1H), 8.99 (s, 1H), 8.21-8.14 (m, 1H), 7.53-7.45 (m, 2H), 7.30-7.24 (m, 2H), 7.23-7.17 (m, 2H), 7.16-7.09 (m, 2H), 5.14 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ 156.1, 147.1, 140.4, 134.2, 132.6, 129.0, 128.2, 127.7, 127.2, 125.5, 123.4, 122.4, 50.6. HRMS (ESI) Calcd for $C_{15}H_{12}N_2O_2$ $[M+H]^+$ 253.0972; found 253.0976.

2,3,4-Triphenyl-2,4-dihydroindeno[1,2-c]pyrazole (4)



white solid, 95% yield, mp: 188-189°C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98-7.90 (m, 1H), 7.43-7.12 (m, 16H), 6.98-6.90 (m, 2H), 5.05 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.7, 153.4, 141.7, 140.8, 137.9, 133.6, 130.0, 129.9, 129.1, 128.9, 128.6, 128.2, 128.1, 128.0, 127.7, 127.6, 127.2, 126.9, 126.0, 125.4, 120.4, 47.8. HRMS (ESI) Calcd for $C_{28}H_{20}N_2$ $[M+H]^+$ 385.1699; found 385.1699.

5. **X-ray Crystallographic data of 3a**



X-ray molecular structure of **3a**

Table 1 Crystal data and structure refinement for 3a.

Identification code	3a
Empirical formula	$C_{22}H_{17}NO$
Formula weight	311.36
Temperature/K	293(2)
Crystal system	orthorhombic
Space group	$P2_12_12_1$
a/Å	9.8259(6)
b/Å	12.3491(8)
c/Å	13.8190(9)
α/°	90
β/°	90
γ/°	90
Volume/Å^3	1676.82(18)
Z	4
ρ_{calc}g/cm^3	1.233
μ/mm^{-1}	0.588
F(000)	656.0
Crystal size/mm^3	0.18 × 0.16 × 0.15

Radiation	CuKα (λ = 1.54184)
2Θ range for data collection/°	9.606 to 142.272
Index ranges	$-11 \leq h \leq 11$, $-13 \leq k \leq 15$, $-16 \leq l \leq 16$
Reflections collected	6963
Independent reflections	3192 [R_{int} = 0.0307, R_{sigma} = 0.0408]
Data/restraints/parameters	3192/0/226
Goodness-of-fit on F^2	1.043
Final R indexes [I>=2σ (I)]	R_1 = 0.0404, wR_2 = 0.0944
Final R indexes [all data]	R_1 = 0.0477, wR_2 = 0.1006
Largest diff. peak/hole / e $Å^{-3}$	0.13/-0.12
Flack parameter	-0.1(3)

Table 2 Fractional Atomic Coordinates (×10^4) and Equivalent Isotropic Displacement Parameters ($Å^2$×10^3) for 3a. U_{eq} is defined as 1/3 of of the trace of the orthogonalised U_{IJ}tensor.

Atom	*x*	*y*	*z*	U(eq)
C1	-918(3)	3718(2)	3194(2)	45.6(6)
C2	-1712(3)	4333(3)	2584(2)	51.7(7)
C3	-1253(3)	5319(3)	2238(2)	55.5(7)
C4	11(3)	5709(2)	2493(2)	52.7(6)
C5	821(3)	5105(2)	3103.5(18)	42.2(6)
C6	362(3)	4109(2)	3445.4(18)	40.3(5)
C7	1430(2)	3650.4(19)	4061.0(17)	37.8(5)
C8	2501(3)	4380(2)	4130.8(18)	39.3(5)
C9	2235(3)	5359(2)	3491.4(19)	43.3(6)

C10	3277(3)	5524(2)	2700(2)	49.3(7)
C11	3636(4)	4687(3)	2091(2)	64.8(8)
C12	4596(4)	4828(4)	1363(3)	85.0(12)
C13	5207(4)	5822(5)	1249(3)	92.5(15)
C14	4881(5)	6649(4)	1847(3)	93.7(15)
C15	3911(4)	6515(3)	2572(3)	71.2(10)
C16	3654(2)	4202.2(19)	4713.7(17)	39.2(5)
C17	4673(3)	5095(2)	4836.8(18)	41.3(5)
C18	5986(3)	4970(3)	4490(2)	55.6(7)
C19	6929(4)	5787(3)	4603(3)	69.3(9)
C20	6579(4)	6716(3)	5083(3)	72.4(10)
C21	5288(4)	6845(3)	5444(3)	67.4(9)
C22	4330(3)	6036(2)	5321(2)	52.7(7)
N1	1367(3)	2678.8(18)	4468.5(18)	46.8(5)
O1	3857(2)	3324.2(15)	5144.2(15)	51.6(5)

Table 3 Anisotropic Displacement Parameters ($Å^2 \times 10^3$) for 3a. The Anisotropic displacement factor exponent takes the form: $-2\pi^2[h^2a^{*2}U_{11}+2hka^*b^*U_{12}+\cdots]$.

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C1	42.8(14)	47.5(14)	46.4(14)	-2.8(11)	1.3(11)	-2.5(11)
C2	36.7(13)	67.7(17)	50.8(15)	-4.9(14)	-1.5(11)	-0.4(13)
C3	45.8(15)	70.1(18)	50.5(15)	11.0(13)	-7.2(12)	8.4(13)
C4	51.7(14)	54.3(15)	52.2(14)	14.8(13)	-4.9(13)	2.1(13)
C5	41.3(14)	42.0(13)	43.2(13)	4.6(10)	-0.4(10)	1.8(10)
C6	39.2(12)	41.0(12)	40.6(12)	-0.3(10)	2.8(10)	2.3(10)
C7	35.9(12)	38.2(11)	39.4(12)	1.0(9)	5.6(10)	2.4(10)
C8	40.2(13)	36.8(11)	40.8(12)	6.7(10)	1.8(10)	0.5(10)
C9	44.4(14)	39.7(13)	45.9(13)	7.6(10)	-5.5(11)	-1.3(10)

C10	42.1(13)	56.8(16)	49.1(15)	17.5(12)	-10.1(11)	-6.0(12)
C11	59.1(19)	78(2)	57.2(17)	7.3(16)	0.7(15)	-4.3(16)
C12	68(2)	129(4)	58(2)	8(2)	3.5(18)	9(2)
C13	52(2)	159(5)	66(2)	50(3)	0.4(17)	-15(3)
C14	80(3)	107(3)	94(3)	47(3)	-2(2)	-33(3)
C15	71(2)	68(2)	74(2)	27.0(18)	-3.9(18)	-20.1(17)
C16	38.9(12)	39.0(12)	39.9(12)	2.8(10)	2.8(10)	5.6(10)
C17	41.5(13)	44.3(13)	38.0(12)	5.3(10)	-4.7(10)	0.2(11)
C18	49.9(16)	58.3(17)	58.6(17)	-4.8(13)	7.0(13)	-4.2(13)
C19	54.2(18)	78(2)	76(2)	-3.7(19)	10.8(16)	-16.4(17)
C20	73(2)	66(2)	78(2)	-2.5(17)	-3.6(19)	-27.2(18)
C21	81(2)	50.0(16)	71(2)	-10.5(14)	-7.6(19)	-4.0(16)
C22	51.4(15)	50.9(15)	55.9(16)	-2.1(12)	-2.6(13)	3.1(12)
N1	42.1(13)	39.9(11)	58.4(14)	12.7(10)	-0.1(11)	-2.4(10)
O1	45.4(10)	45.5(10)	63.8(12)	15.1(8)	-8.1(9)	4.0(8)

Table 4 Bond Lengths for 3a.

Atom	**Atom**	**Length/Å**	**Atom**	**Atom**	**Length/Å**
C1	C2	1.377(4)	C10	C15	1.385(4)
C1	C6	1.392(4)	C11	C12	1.390(5)
C2	C3	1.384(4)	C12	C13	1.376(7)
C3	C4	1.378(4)	C13	C14	1.352(7)
C4	C5	1.380(4)	C14	C15	1.393(5)
C5	C6	1.393(4)	C16	C17	1.499(4)
C5	C9	1.522(3)	C16	O1	1.253(3)
C6	C7	1.465(3)	C17	C18	1.384(4)
C7	C8	1.389(3)	C17	C22	1.383(4)

C7	N1	1.327(3)	C18	C19	1.379(4)
C8	C9	1.521(3)	C19	C20	1.369(5)
C8	C16	1.407(3)	C20	C21	1.371(5)
C9	C10	1.512(4)	C21	C22	1.384(4)
C10	C11	1.379(5)			

Table 5 Bond Angles for 3a.

Atom	Atom	Atom	Angle/°	Atom	Atom	Atom	Angle/°
C2	C1	C6	118.2(3)	C11	C10	C9	120.9(3)
C1	C2	C3	120.8(3)	C11	C10	C15	118.1(3)
C4	C3	C2	120.9(3)	C15	C10	C9	121.0(3)
C3	C4	C5	119.2(3)	C10	C11	C12	121.4(4)
C4	C5	C6	119.9(3)	C13	C12	C11	119.4(4)
C4	C5	C9	129.1(3)	C14	C13	C12	120.0(4)
C6	C5	C9	111.0(2)	C13	C14	C15	120.8(4)
C1	C6	C5	121.0(2)	C10	C15	C14	120.3(4)
C1	C6	C7	131.2(2)	C8	C16	C17	119.2(2)
C5	C6	C7	107.8(2)	O1	C16	C8	122.4(2)
C8	C7	C6	109.4(2)	O1	C16	C17	118.4(2)
N1	C7	C6	124.3(2)	C18	C17	C16	120.1(2)
N1	C7	C8	126.3(2)	C22	C17	C16	120.6(2)
C7	C8	C9	110.2(2)	C22	C17	C18	119.2(3)
C7	C8	C16	123.3(2)	C19	C18	C17	120.4(3)
C16	C8	C9	126.5(2)	C20	C19	C18	119.9(3)
C8	C9	C5	101.4(2)	C19	C20	C21	120.4(3)
C10	C9	C5	113.0(2)	C20	C21	C22	120.1(3)

C10	C9	C8	114.2(2)	C17	C22	C21	120.0(3)

Table 6 Hydrogen Bonds for 3a.

D	H	A	d(D-H)/Å	d(H-A)/Å	d(D-A)/Å	D-H-A/°
N1	H1A	O1	0.84(3)	2.11(3)	2.737(3)	131(3)
N1	H1B	O1[1]	0.93(3)	1.91(3)	2.811(3)	164(3)

[1]-1/2+X,1/2-Y,1-Z

Table 7 Torsion Angles for 3a.

A	B	C	D	Angle/°	A	B	C	D	Angle/°
C1	C2	C3	C4	0.2(4)	C8	C16	C17	C22	66.5(3)
C1	C6	C7	C8	-176.8(3)	C9	C5	C6	C1	179.1(2)
C1	C6	C7	N1	4.2(4)	C9	C5	C6	C7	-0.5(3)
C2	C1	C6	C5	1.1(4)	C9	C8	C16	C17	8.0(4)
C2	C1	C6	C7	-179.5(3)	C9	C8	C16	O1	-172.7(2)
C2	C3	C4	C5	-0.2(5)	C9	C10	C11	C12	-179.8(3)
C3	C4	C5	C6	0.7(4)	C9	C10	C15	C14	179.2(3)
C3	C4	C5	C9	-179.6(3)	C10	C11	C12	C13	0.3(5)
C4	C5	C6	C1	-1.1(4)	C11	C10	C15	C14	-0.1(5)
C4	C5	C6	C7	179.3(2)	C11	C12	C13	C14	0.5(6)
C4	C5	C9	C8	178.6(3)	C12	C13	C14	C15	-1.1(7)
C4	C5	C9	C10	-58.7(4)	C13	C14	C15	C10	0.9(6)
C5	C6	C7	C8	2.7(3)	C15	C10	C11	C12	-0.5(5)
C5	C6	C7	N1	-176.3(2)	C16	C8	C9	C5	-177.0(2)
C5	C9	C10	C11	-64.7(3)	C16	C8	C9	C10	61.1(3)

C5	C9	C10	C15	116.1(3)	C16	C17	C18	C19	-179.9(3)
C6	C1	C2	C3	-0.6(4)	C16	C17	C22	C21	178.9(3)
C6	C5	C9	C8	-1.7(3)	C17	C18	C19	C20	1.8(6)
C6	C5	C9	C10	121.0(2)	C18	C17	C22	C21	0.8(4)
C6	C7	C8	C9	-3.9(3)	C18	C19	C20	C21	-0.8(6)
C6	C7	C8	C16	176.5(2)	C19	C20	C21	C22	-0.2(6)
C7	C8	C9	C5	3.4(3)	C20	C21	C22	C17	0.2(5)
C7	C8	C9	C10	-118.5(2)	C22	C17	C18	C19	-1.8(5)
C7	C8	C16	C17	-172.5(2)	N1	C7	C8	C9	175.1(2)
C7	C8	C16	O1	6.9(4)	N1	C7	C8	C16	-4.5(4)
C8	C9	C10	C11	50.5(3)	O1	C16	C17	C18	65.2(3)
C8	C9	C10	C15	-128.7(3)	O1	C16	C17	C22	-112.9(3)
C8	C16	C17	C18	-115.4(3)					

Table 8 Hydrogen Atom Coordinates (Å×10^4) and Isotropic Displacement Parameters (Å^2×10^3) for 3a.

Atom	***x***	***y***	***z***	**U(eq)**
H1	-1230	3058	3431	55
H2	-2568	4083	2402	62
H3	-1805	5724	1828	67
H4	314	6372	2256	63
H9	2192	6011	3895	52
H11	3227	4013	2169	78
H12	4822	4255	957	102
H13	5846	5925	761	111
H14	5309	7315	1773	112

H15	3687	7094	2973	85
H18	6233	4332	4180	67
H19	7802	5708	4353	83
H20	7219	7263	5165	87
H21	5058	7477	5771	81
H22	3454	6125	5564	63
H1A	2000(30)	2530(20)	4850(20)	44(8)
H1B	570(30)	2280(30)	4490(20)	53(8)

6. References

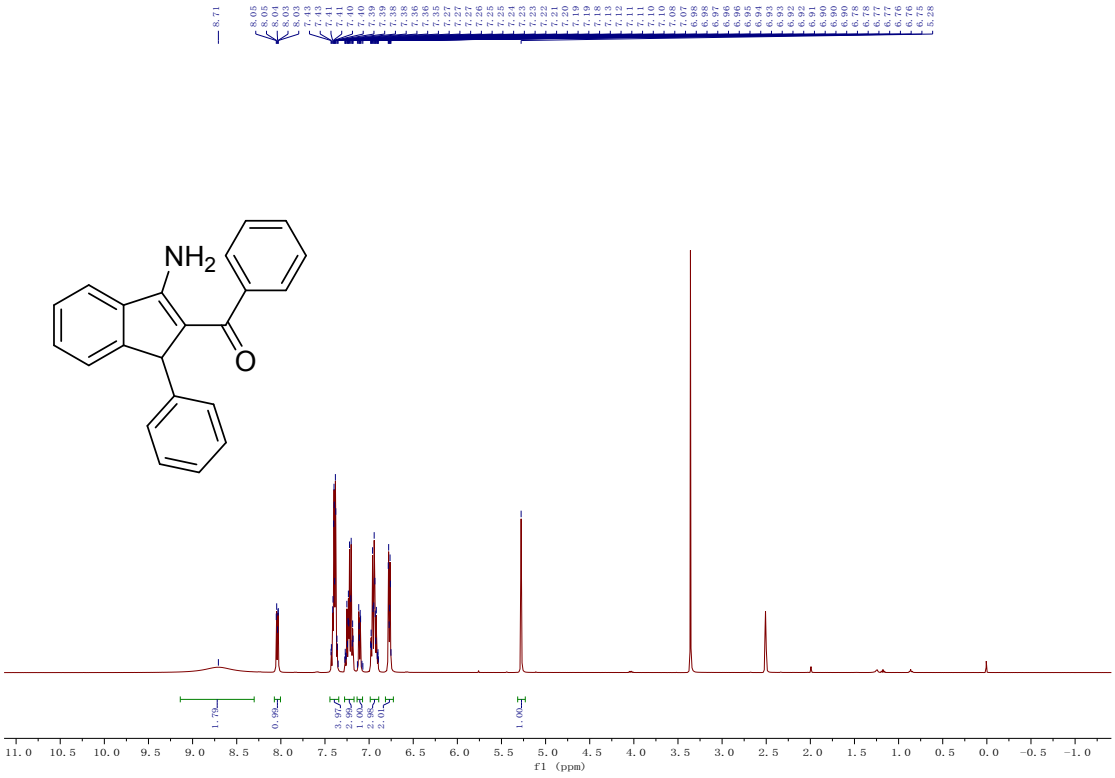
[1] V. Yadav and K. Babu, *Eur. J. Org. Chem.* 2005, 452-456.

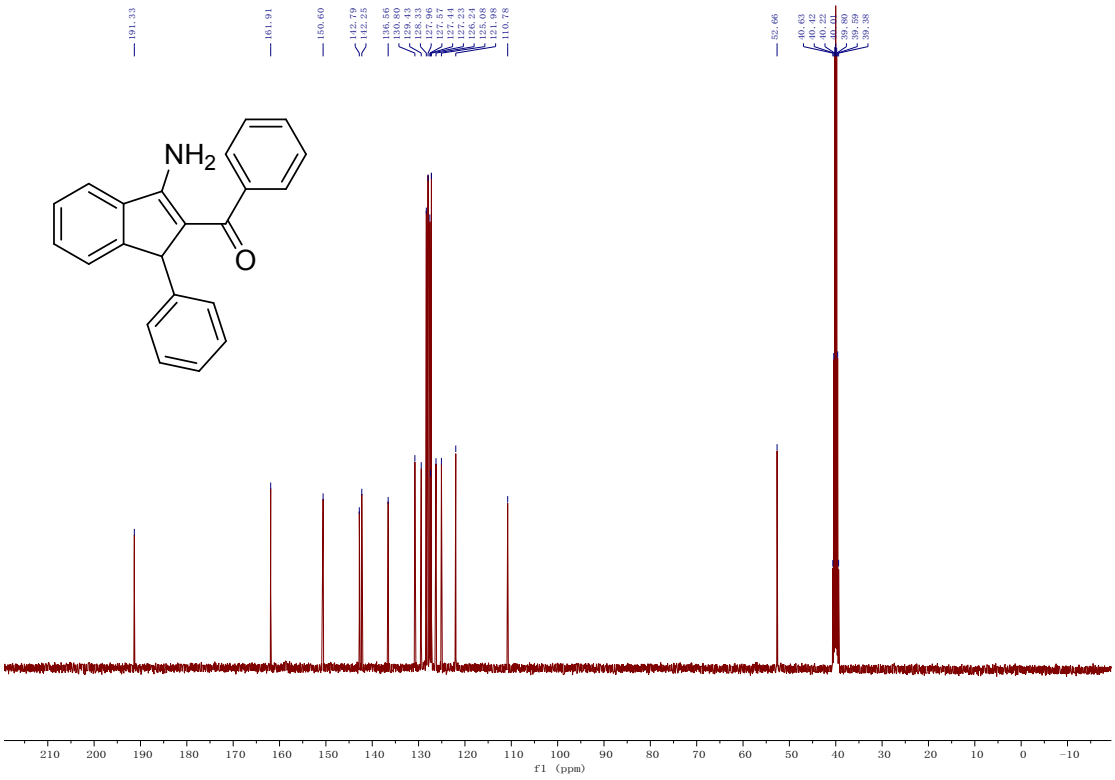
[2] T. Lei, C. Zhou, M. Huang, L. Zhao, B. Yang, C. Ye, H. Xiao, Q. Meng, V. Ramamurthy, C. Tung and L. Wu, *Angew. Chem. Int. Ed.* 2017, **56**, 15407-15410.

[3] L. Calvo, A. Gonzalez-Nogal, A. Gonzalez-Ortega and M. Sanudo, *Tetrahedron Lett.* 2001, **42**, 8981.

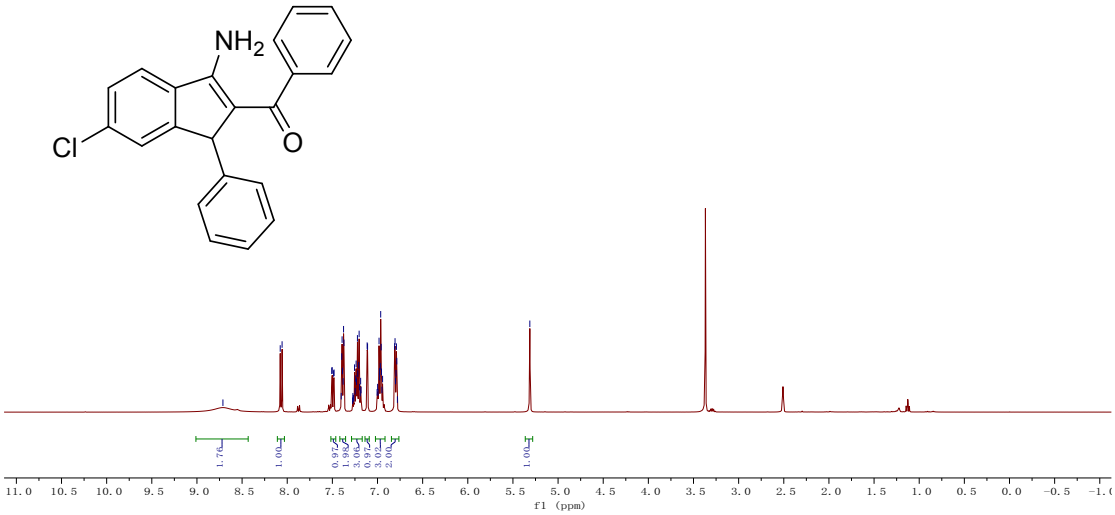
7. NMR Spectra of the Products

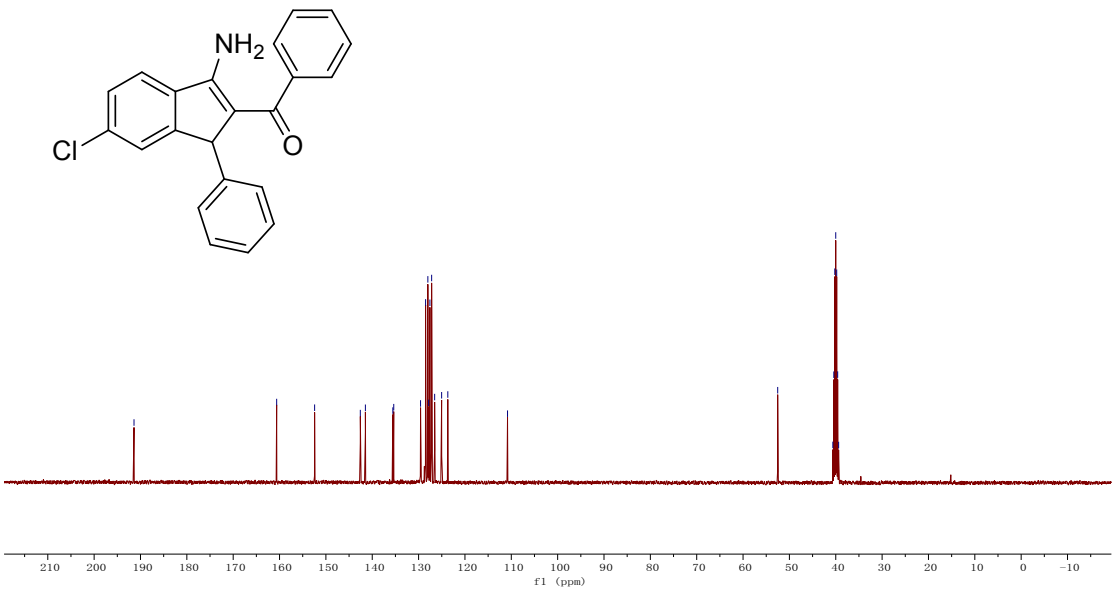
^{1}H, ^{13}C spectra of **3a**



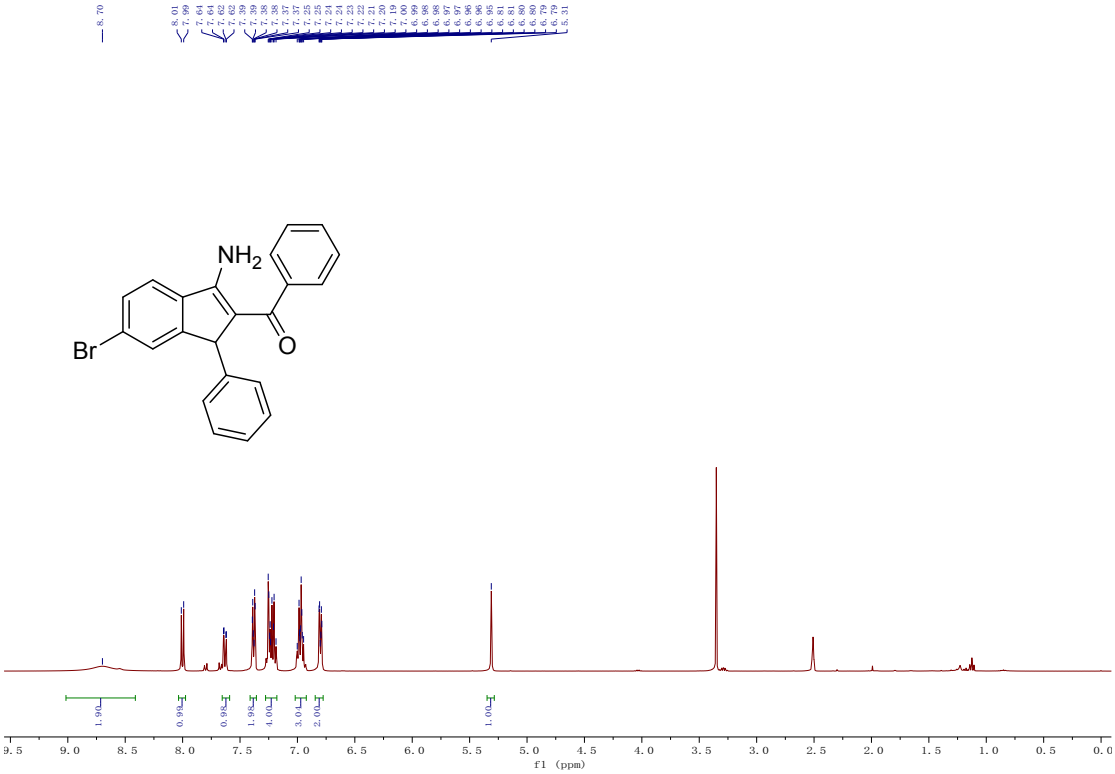


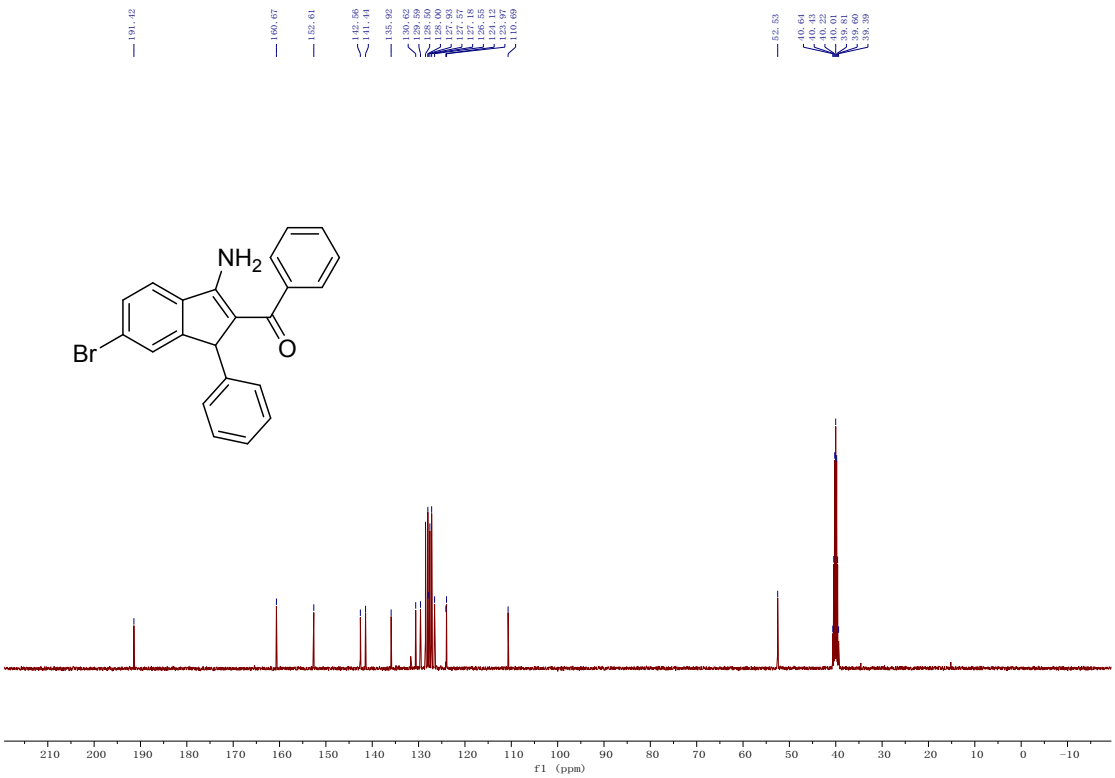
^{1}H, ^{13}C spectra of **3b**



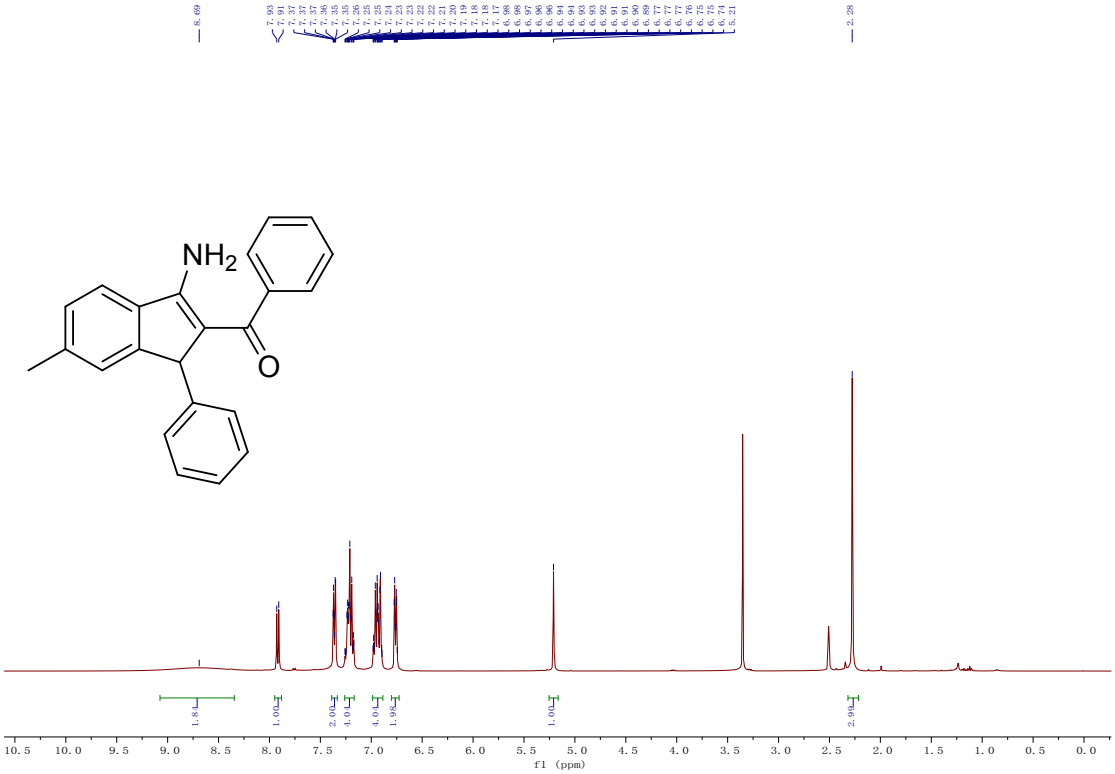


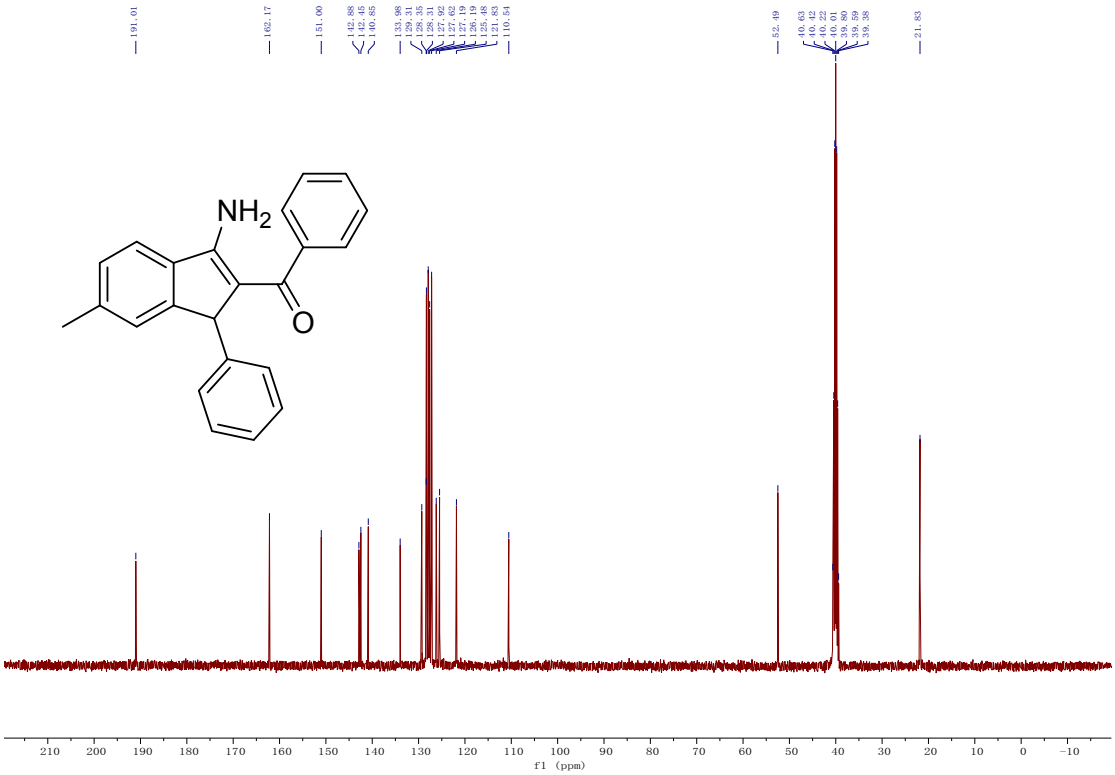
^{1}H, ^{13}C spectra of **3c**



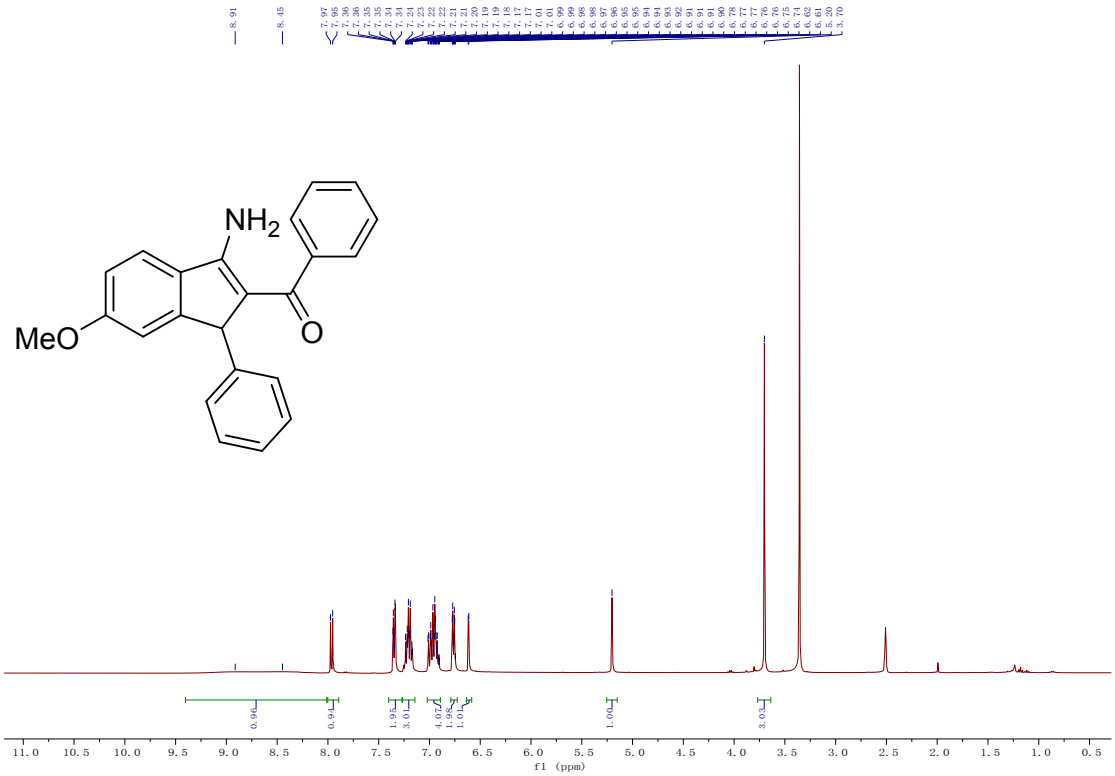


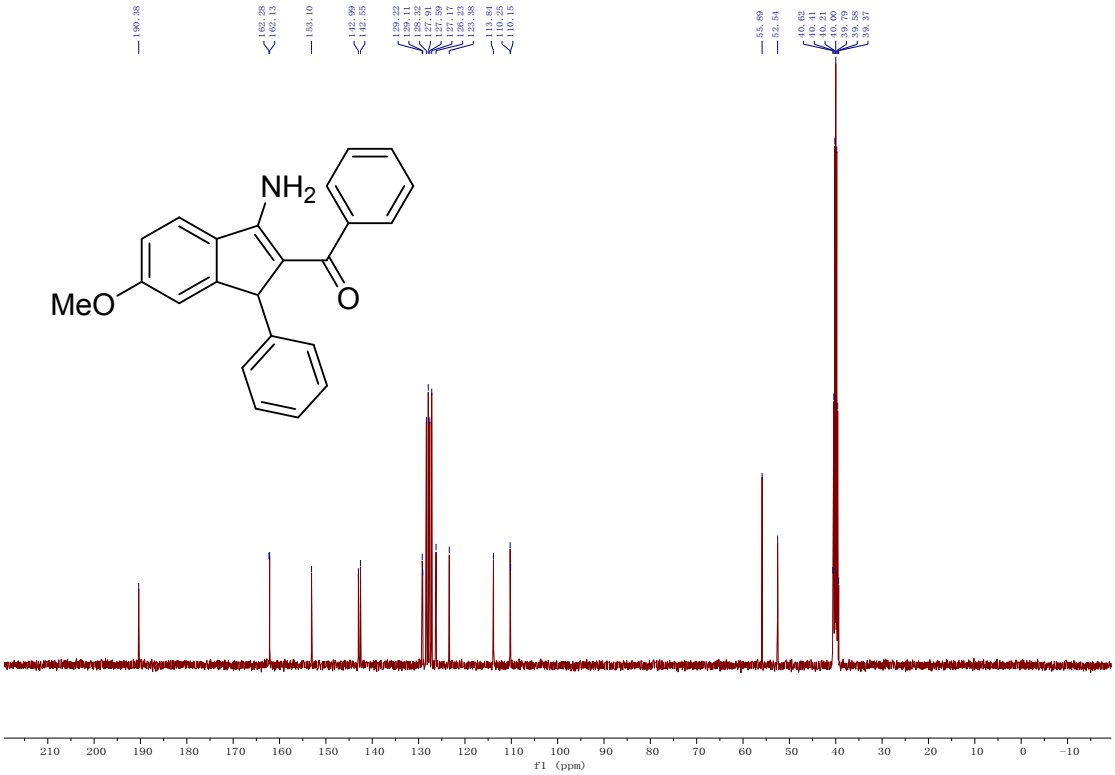
^{1}H, ^{13}C spectra of **3d**



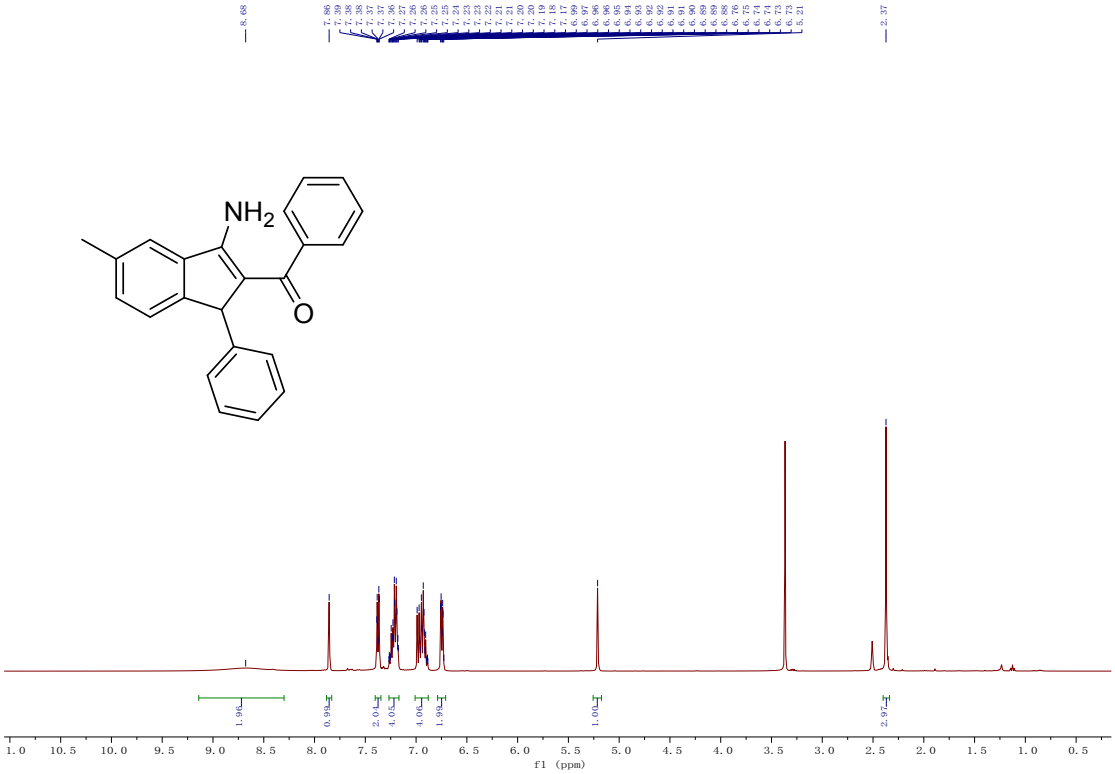


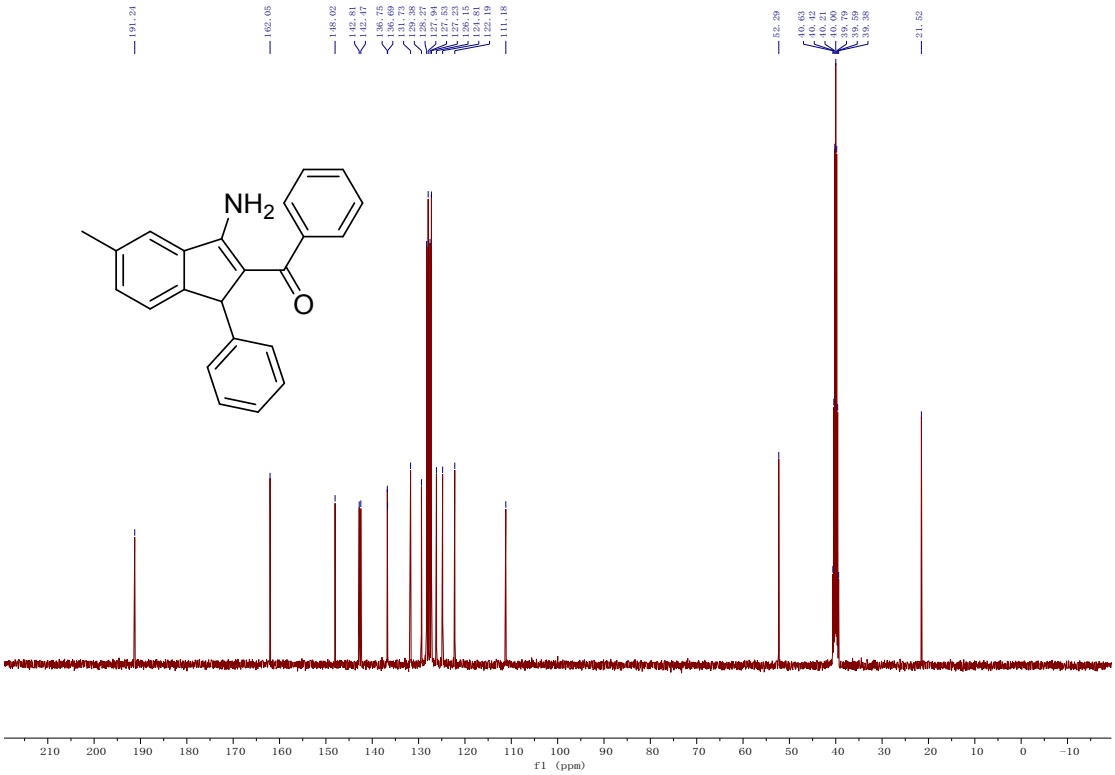
^{1}H, ^{13}C spectra of **3e**



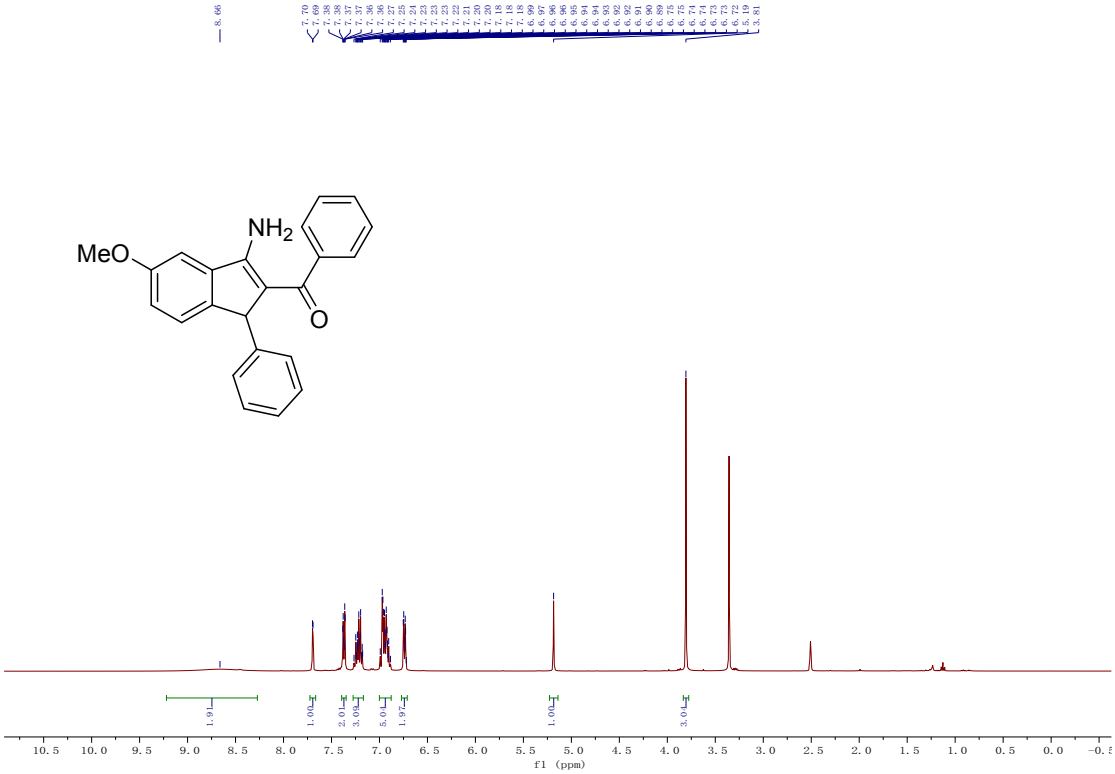


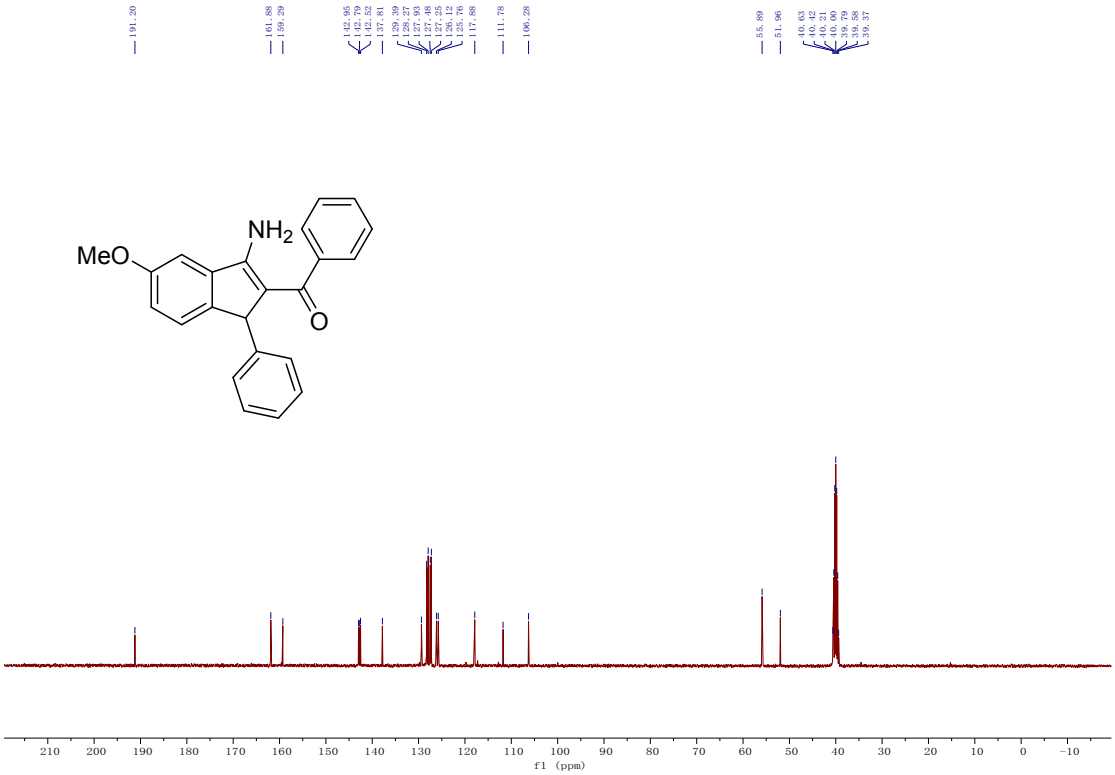
^{1}H, ^{13}C spectra of **3f**



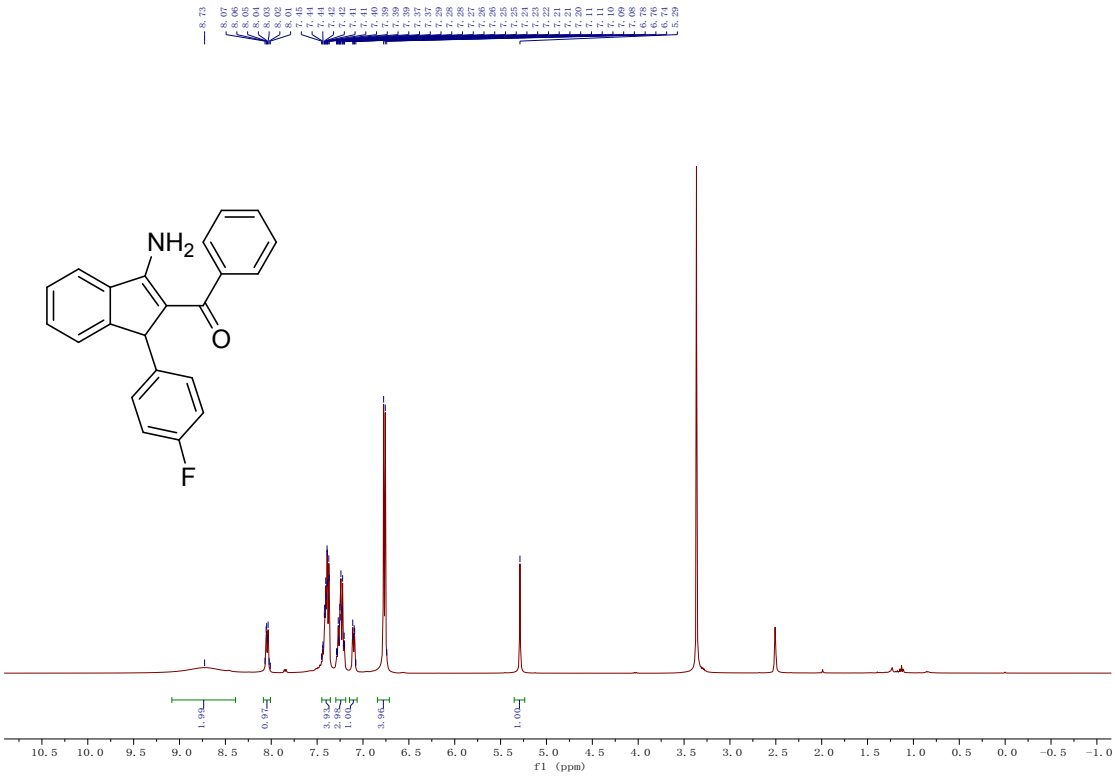


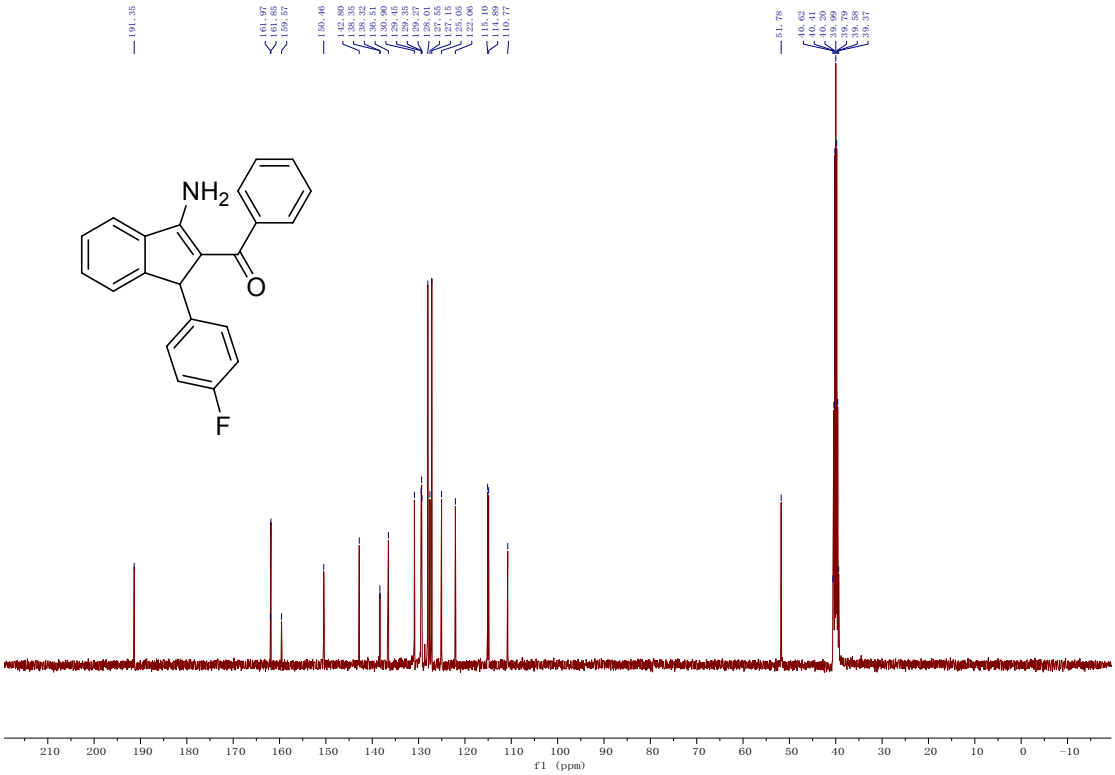
^{1}H, ^{13}C spectra of **3g**

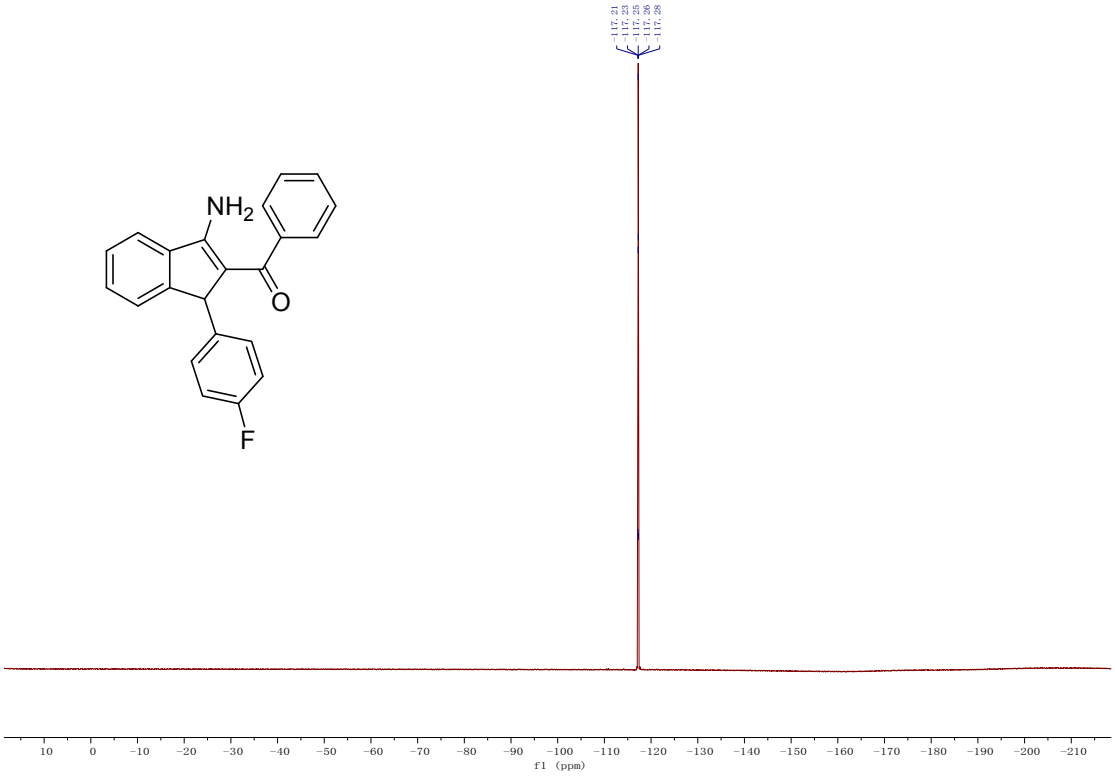




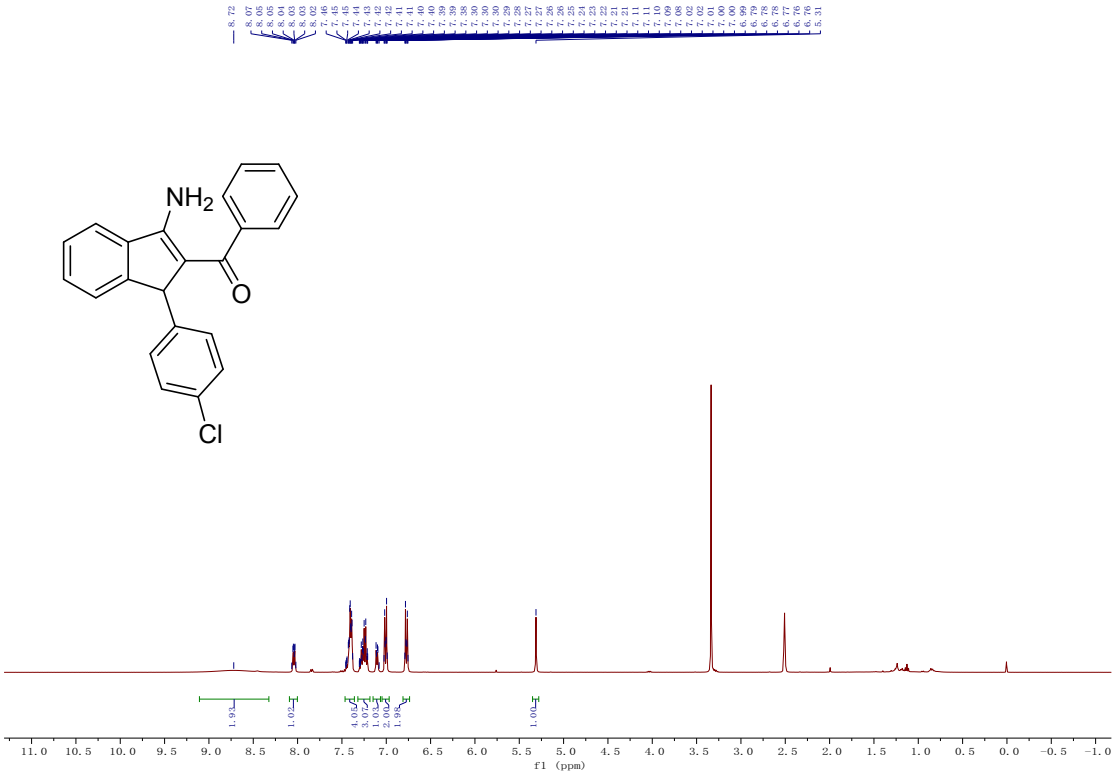
^{1}H, ^{13}C, ^{19}F spectraspectra of **3h**

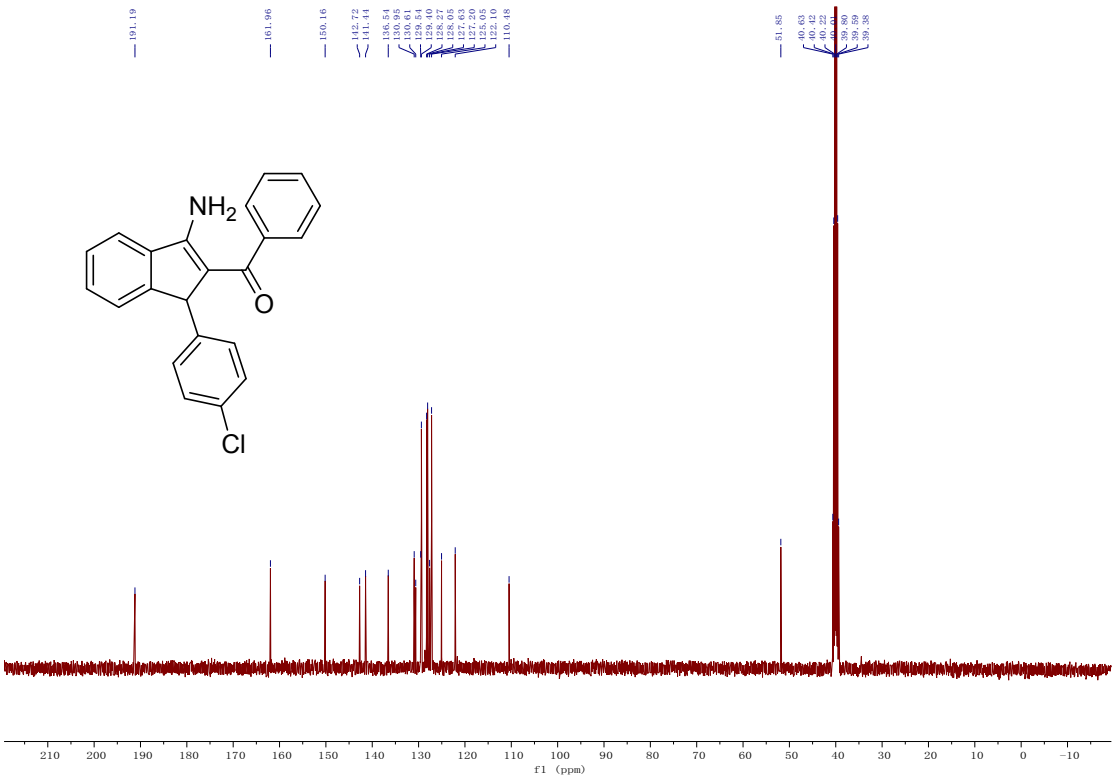




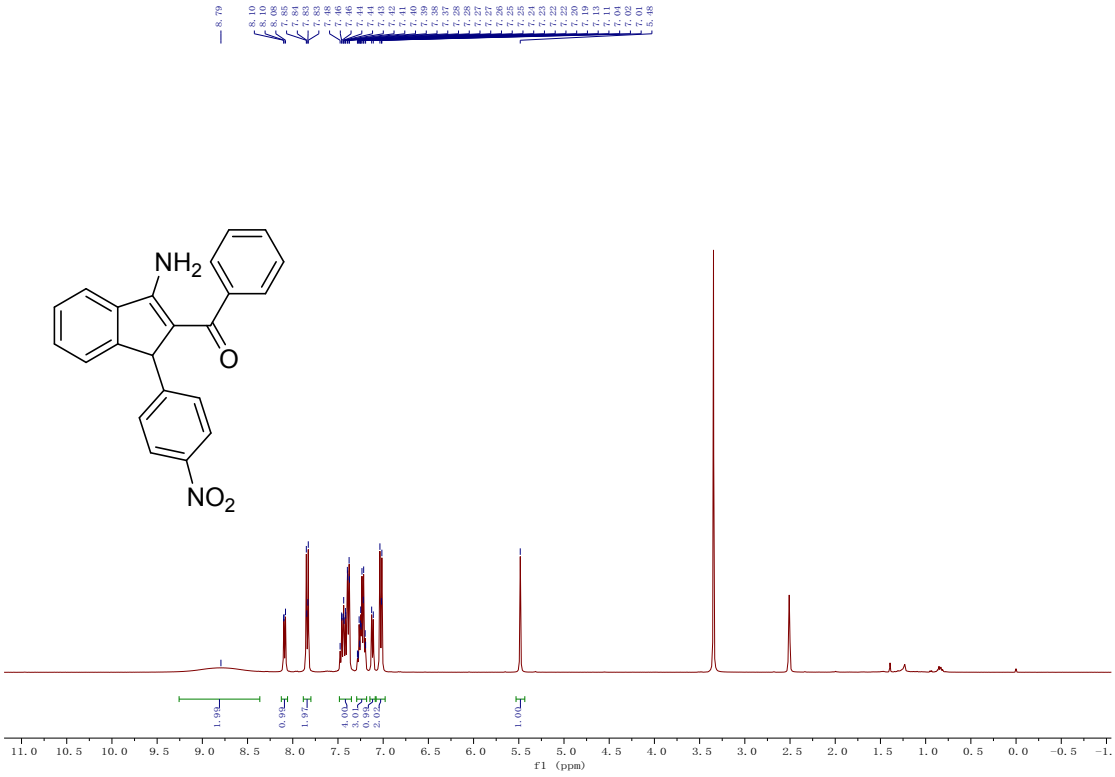


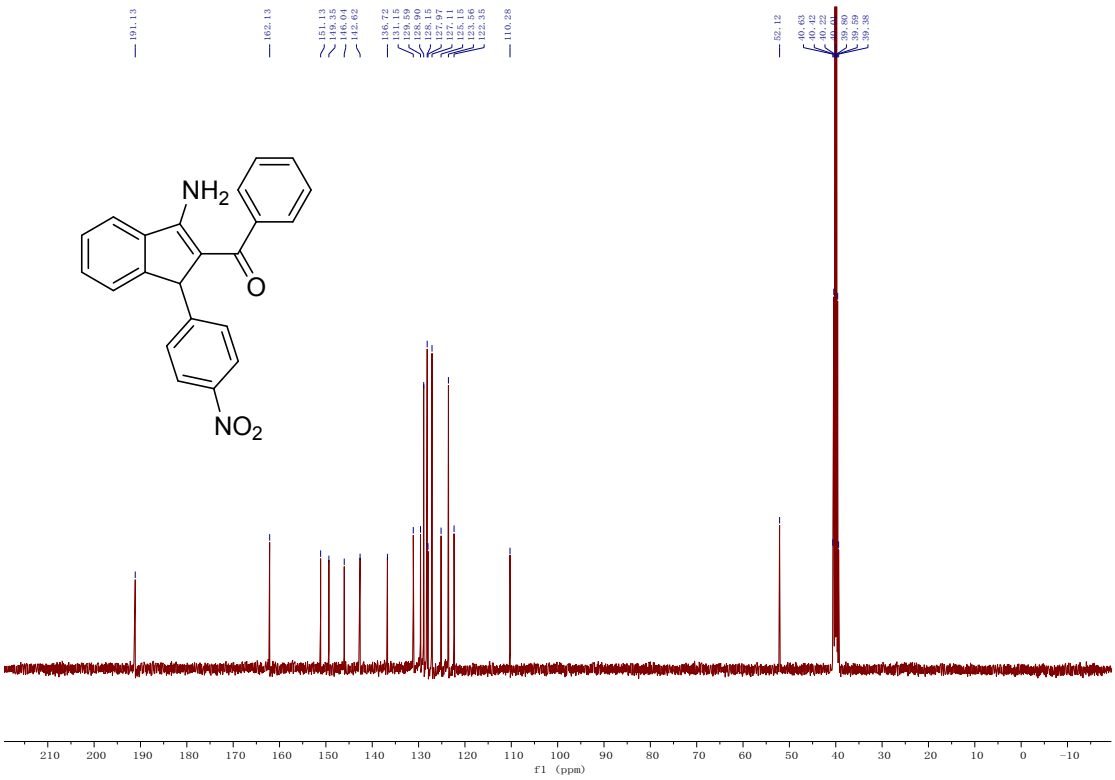
^{1}H, ^{13}C spectra of **3i**



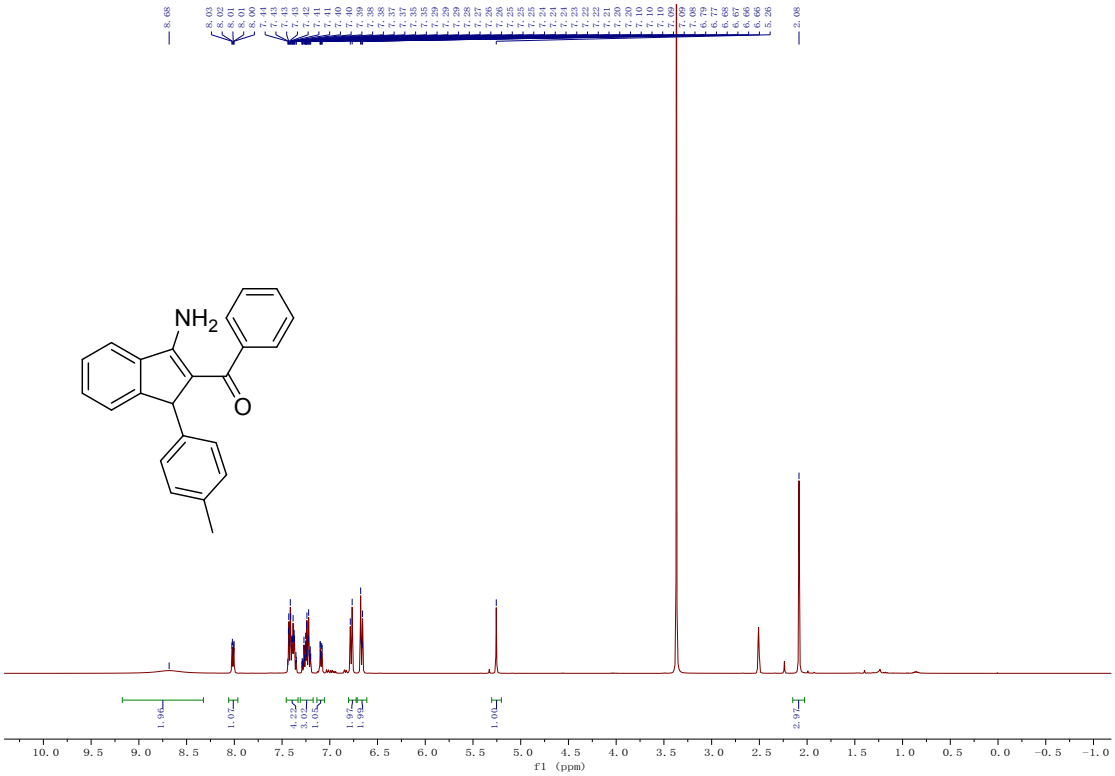


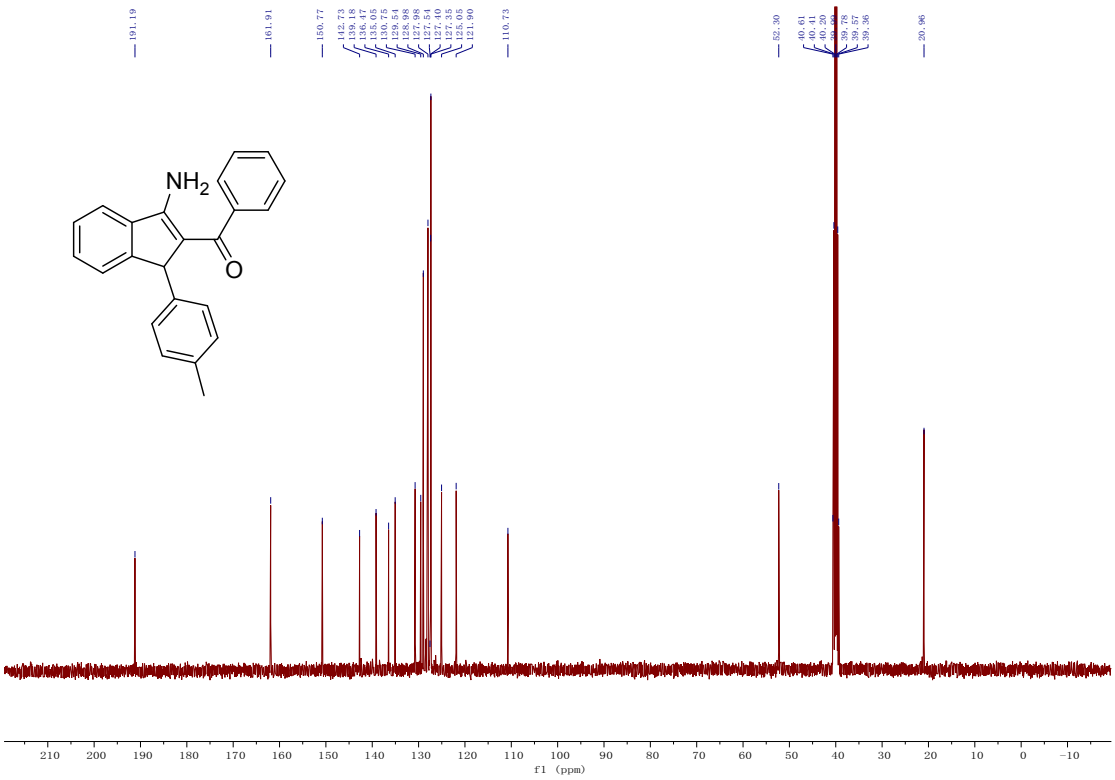
^{1}H, ^{13}C spectra of **3j**



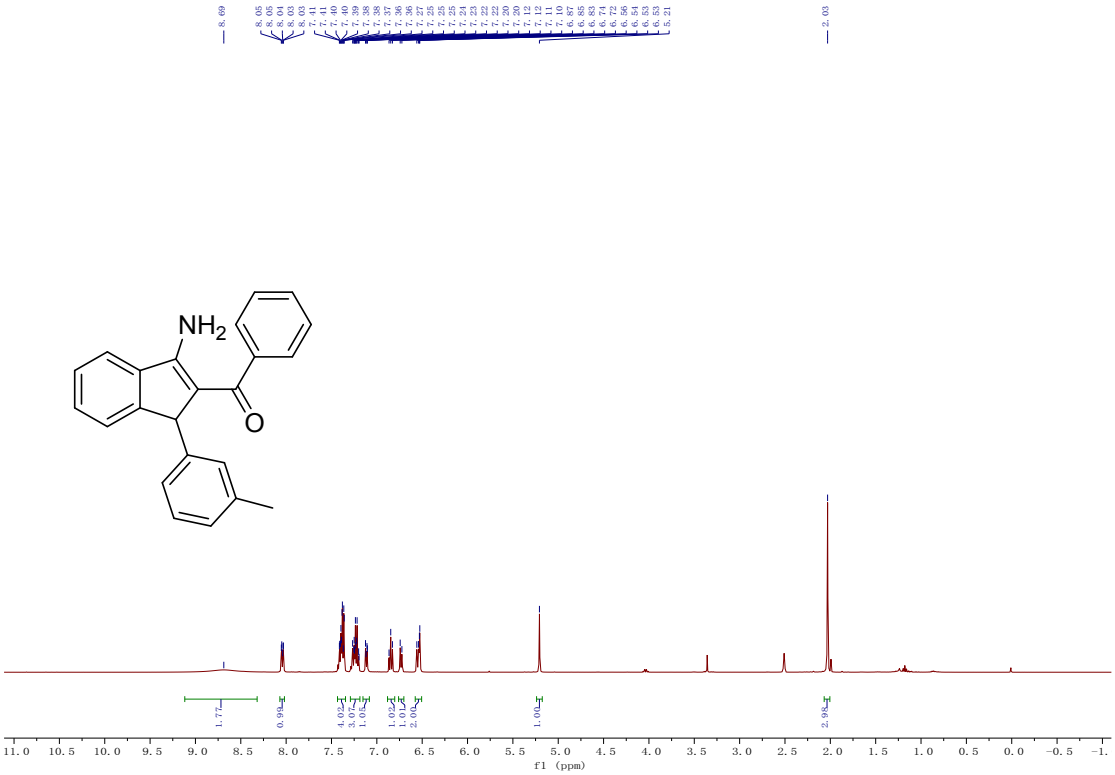


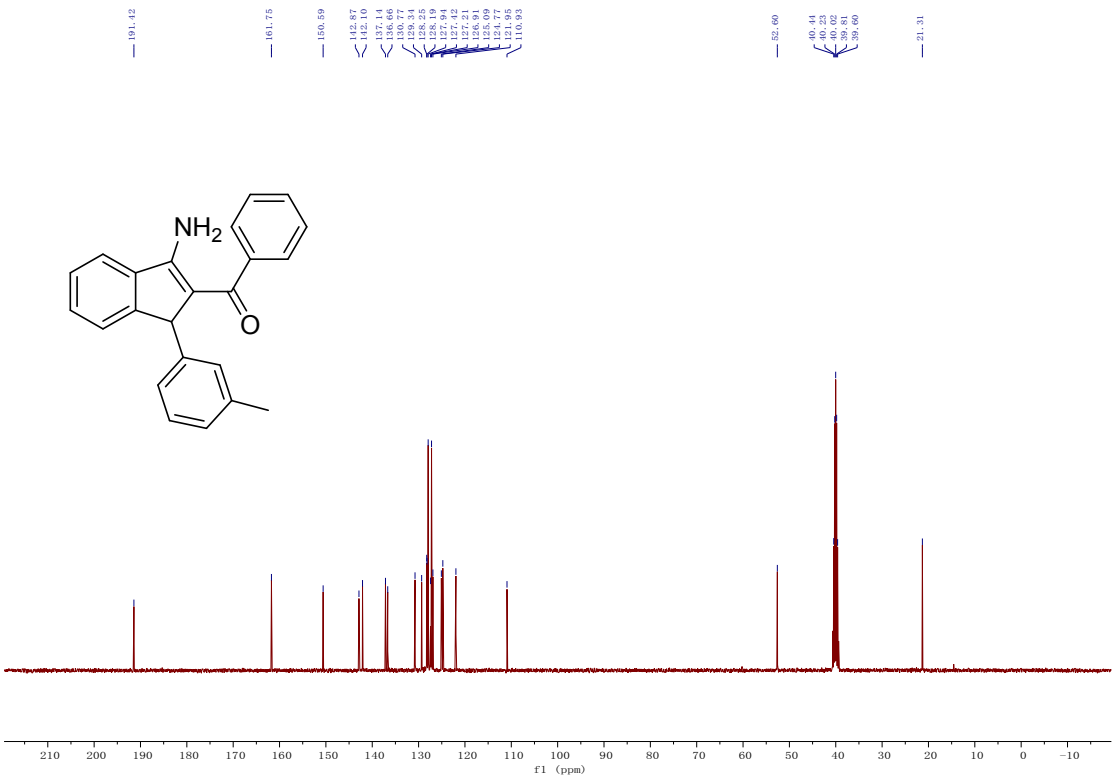
^{1}H, ^{13}C spectra of **3k**



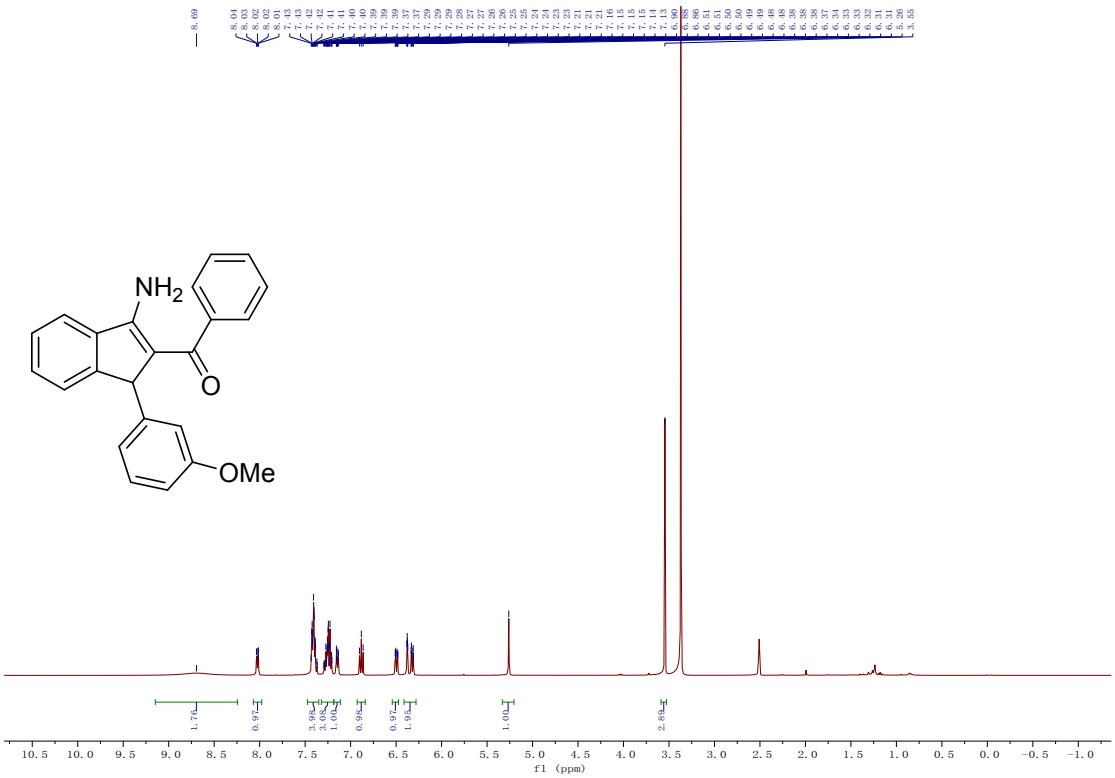


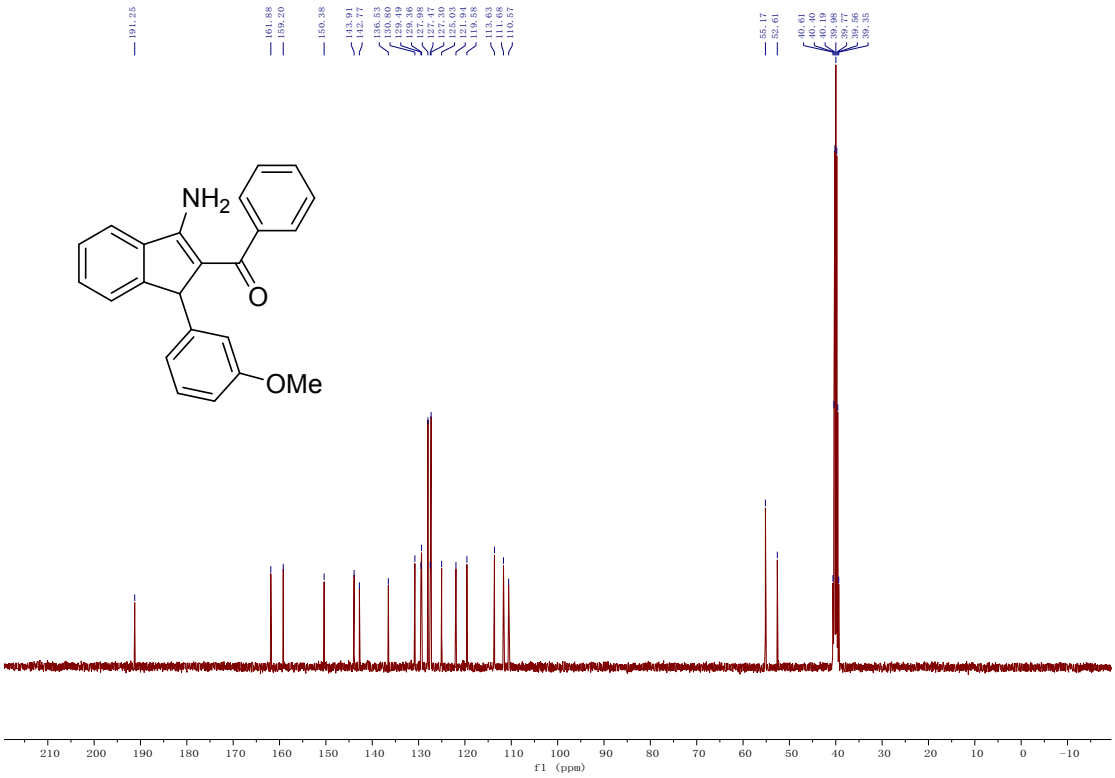
^{1}H, ^{13}C spectra of **3l**



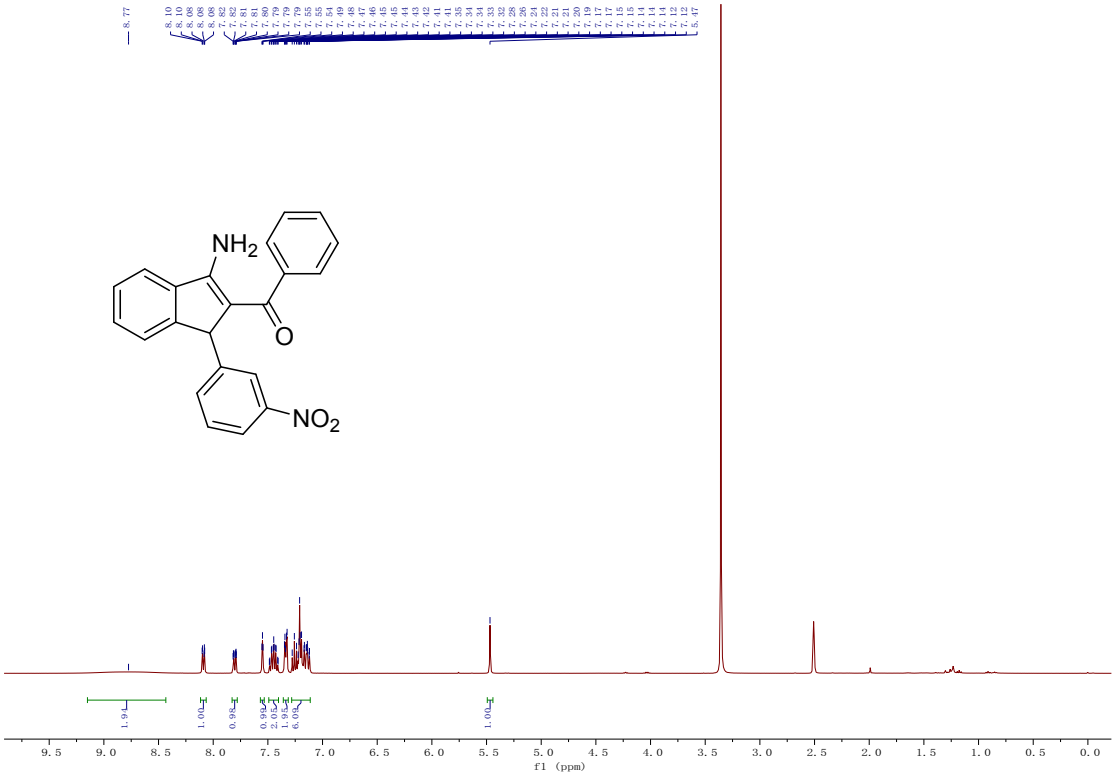


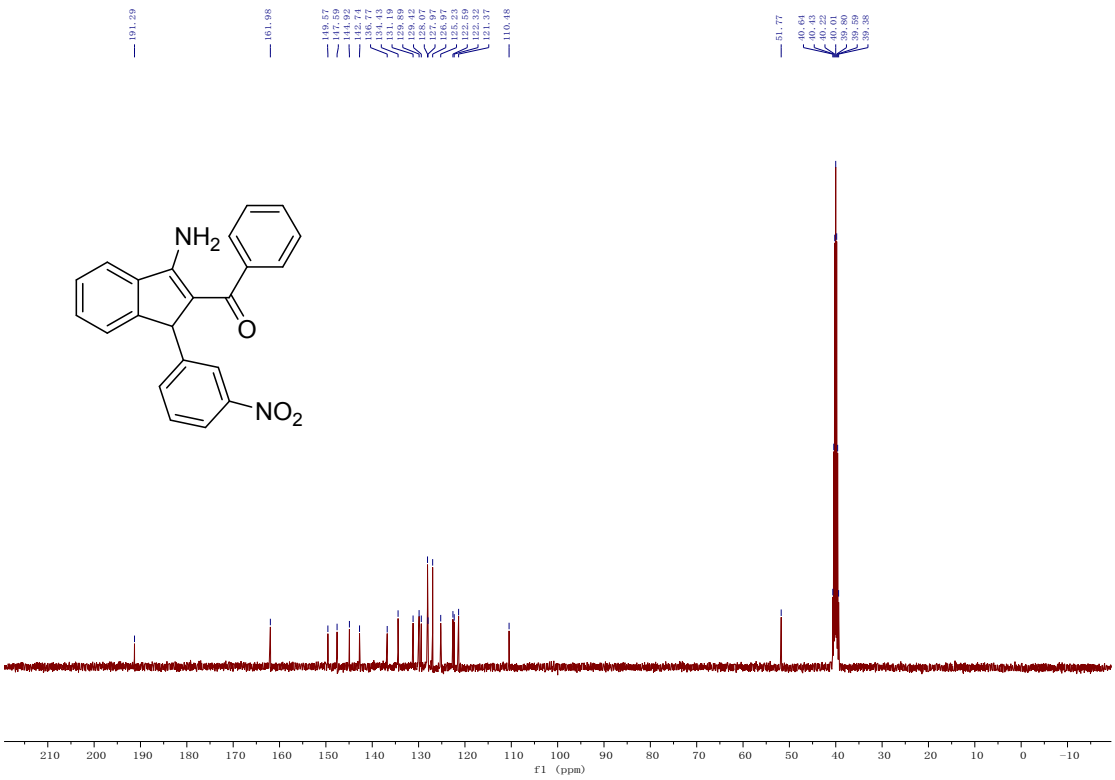
^{1}H, ^{13}C spectra of **3m**



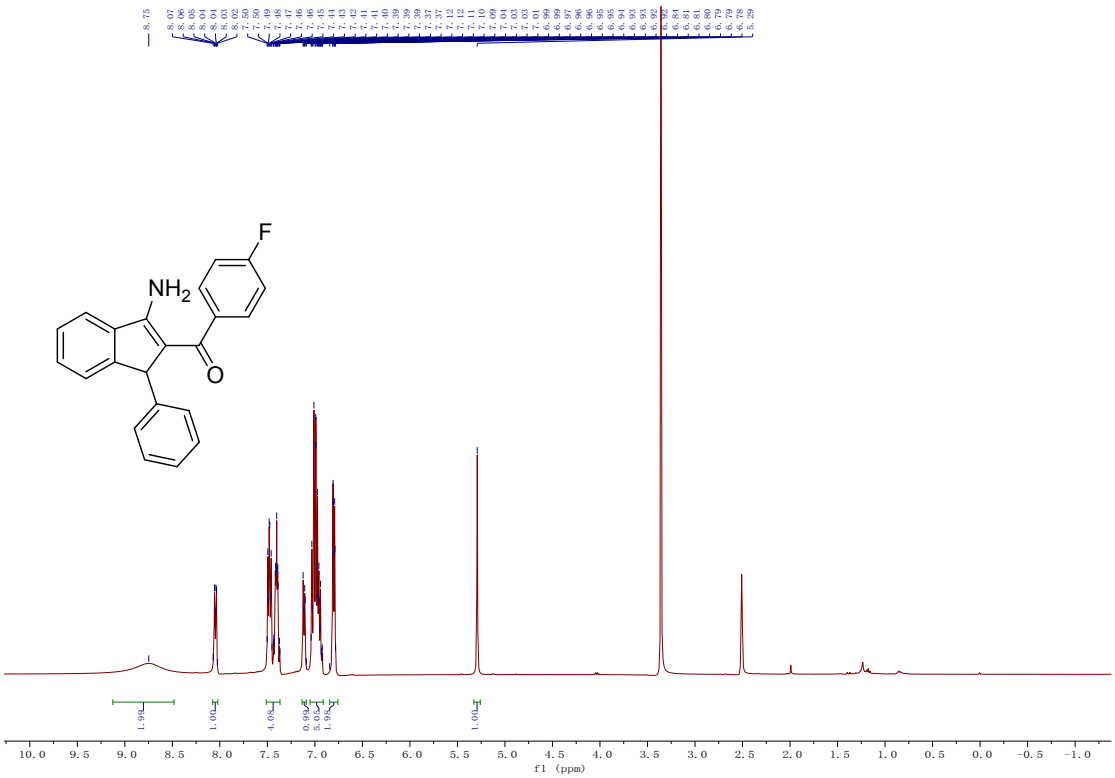


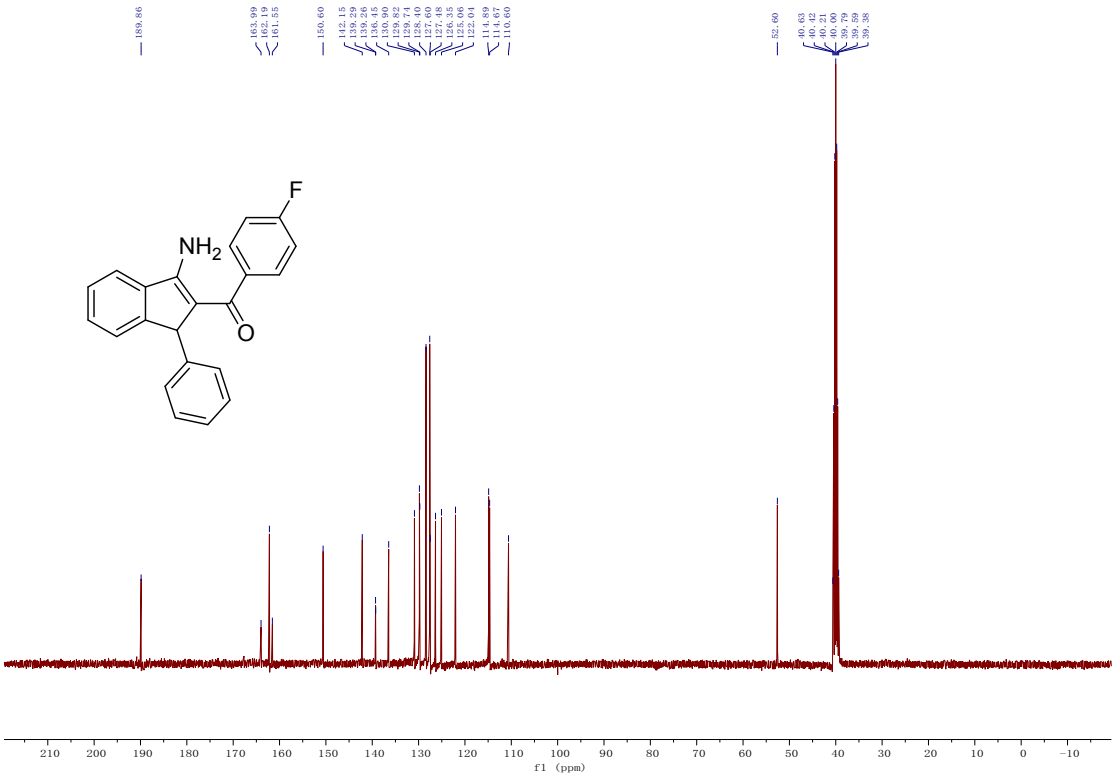
^{1}H, ^{13}C spectra of **3n**

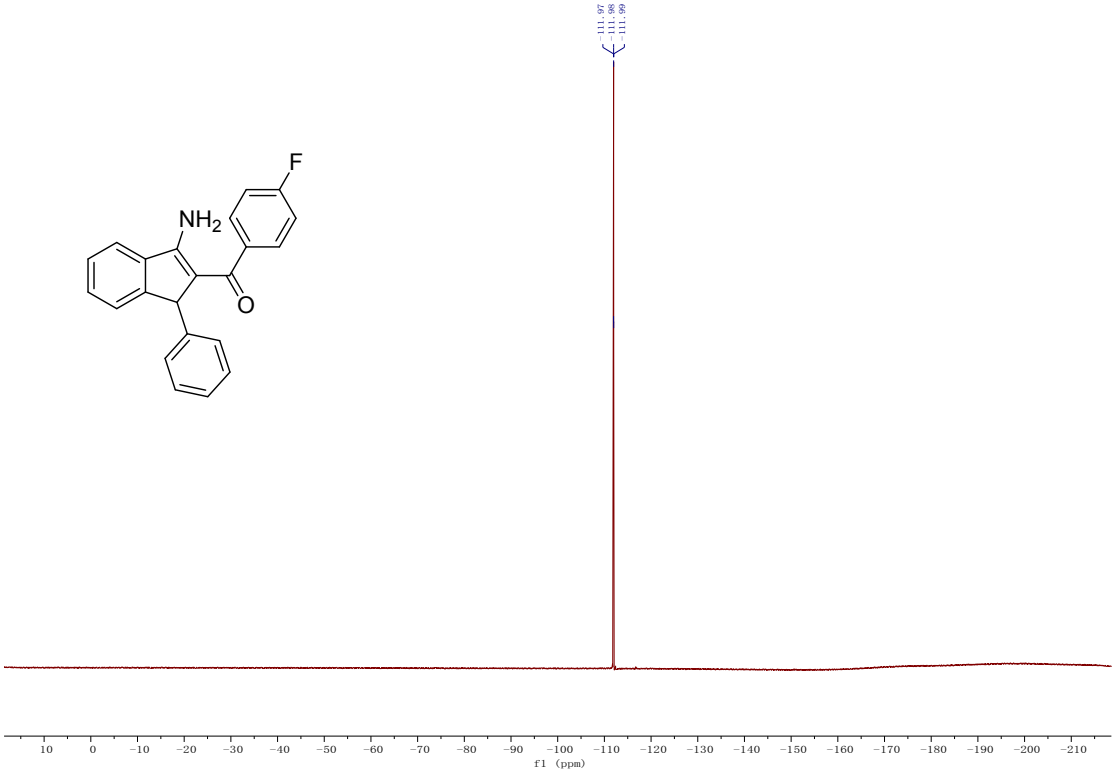




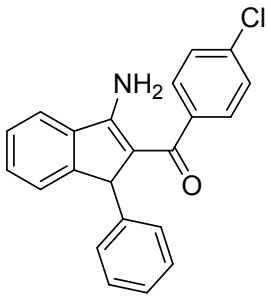
^{1}H, ^{13}C, ^{19}F spectraspectra of **3o**

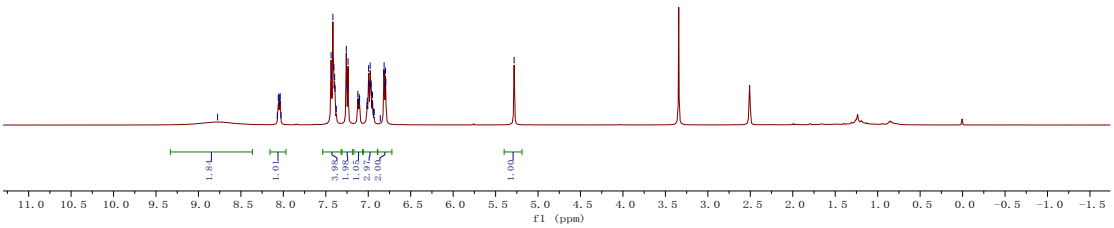


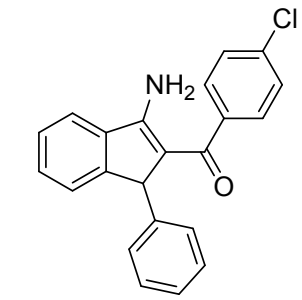

189.86
163.99
162.19
161.55
150.60
142.15
139.29
139.26
136.45
130.90
129.82
128.74
128.40
127.60
127.48
126.85
125.06
122.04
114.89
114.67
114.60
52.60
40.63
40.42
40.21
40.00
39.79
39.58
39.38
F
NH2
O
f1 (ppm)


-111.97
-111.98
-111.99
F
NH2
O
f1 (ppm)

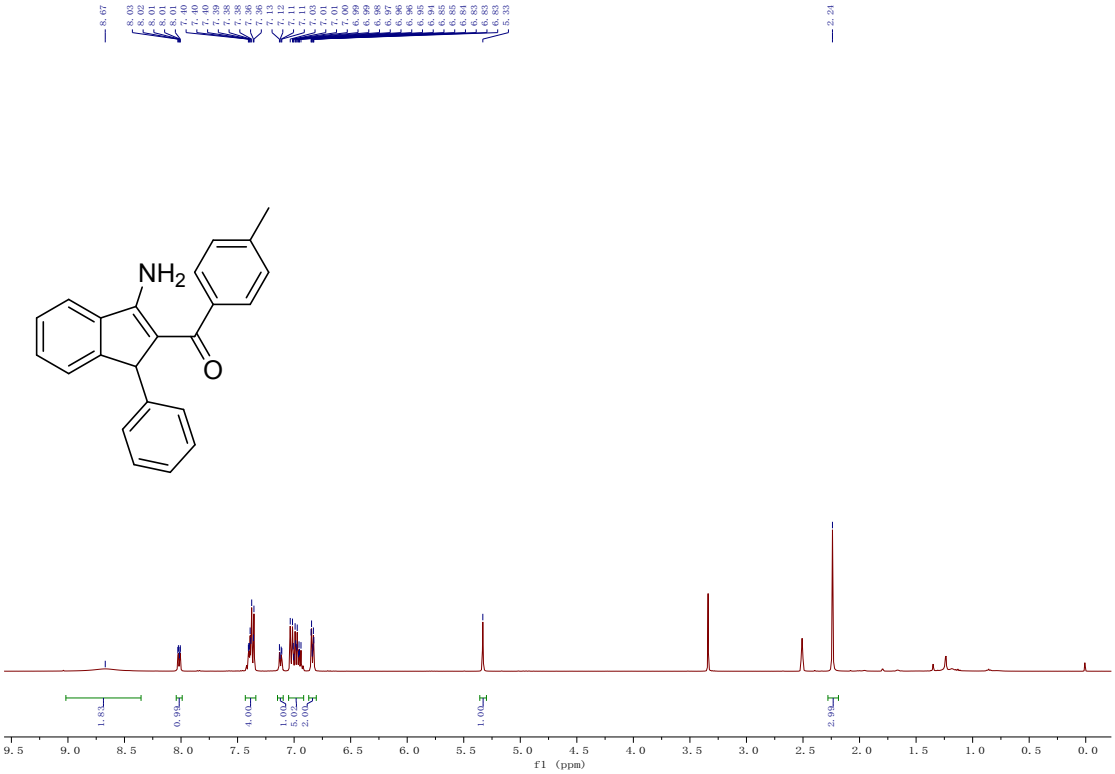
^{1}H, ^{13}C spectra of **3p**

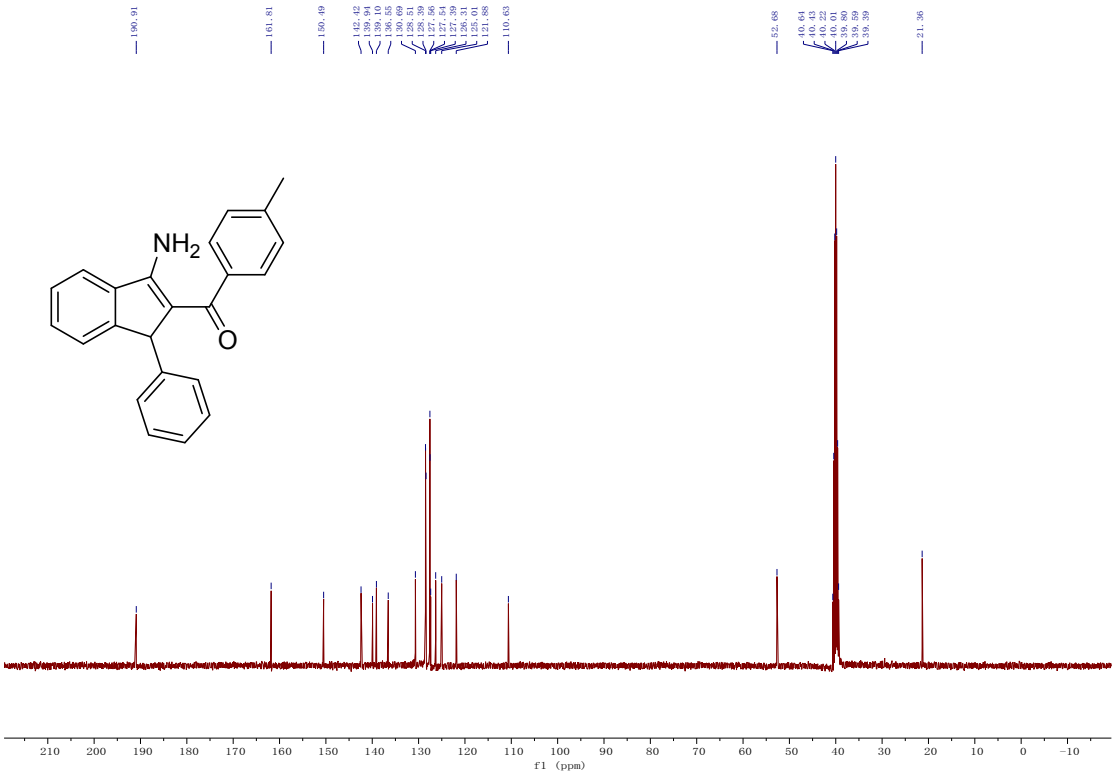




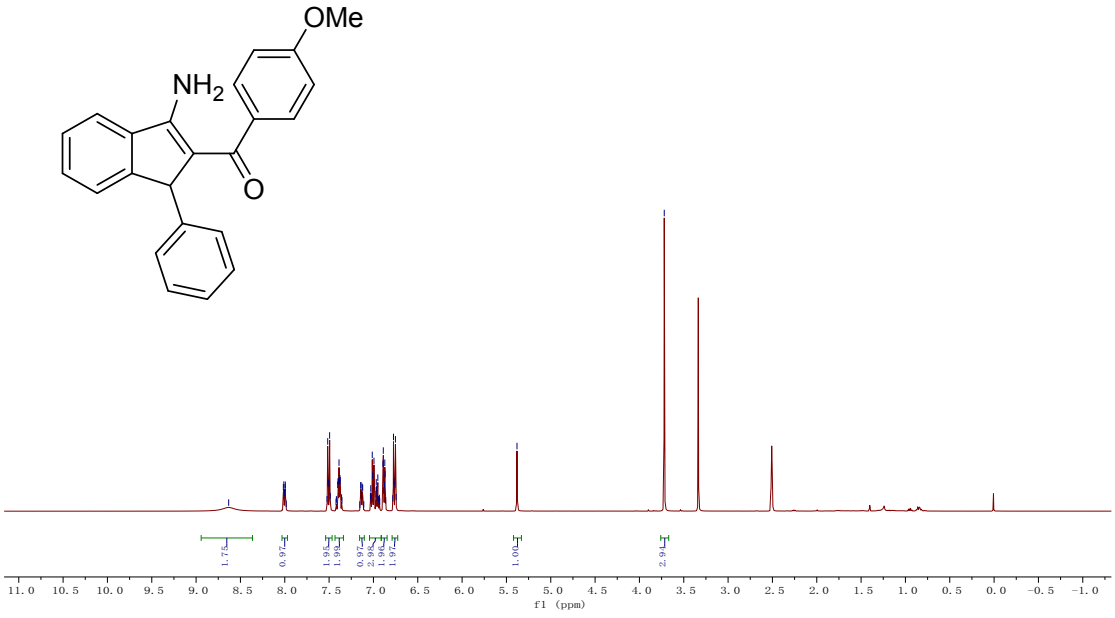


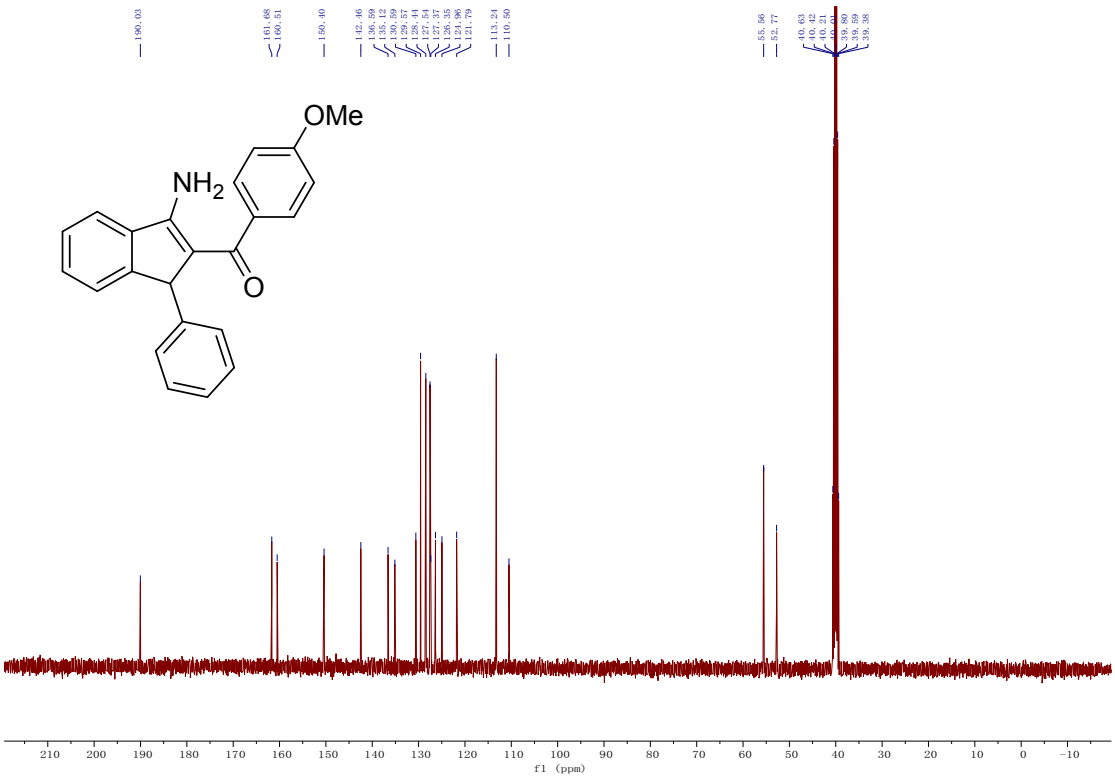
^{1}H, ^{13}C spectra of **3q**



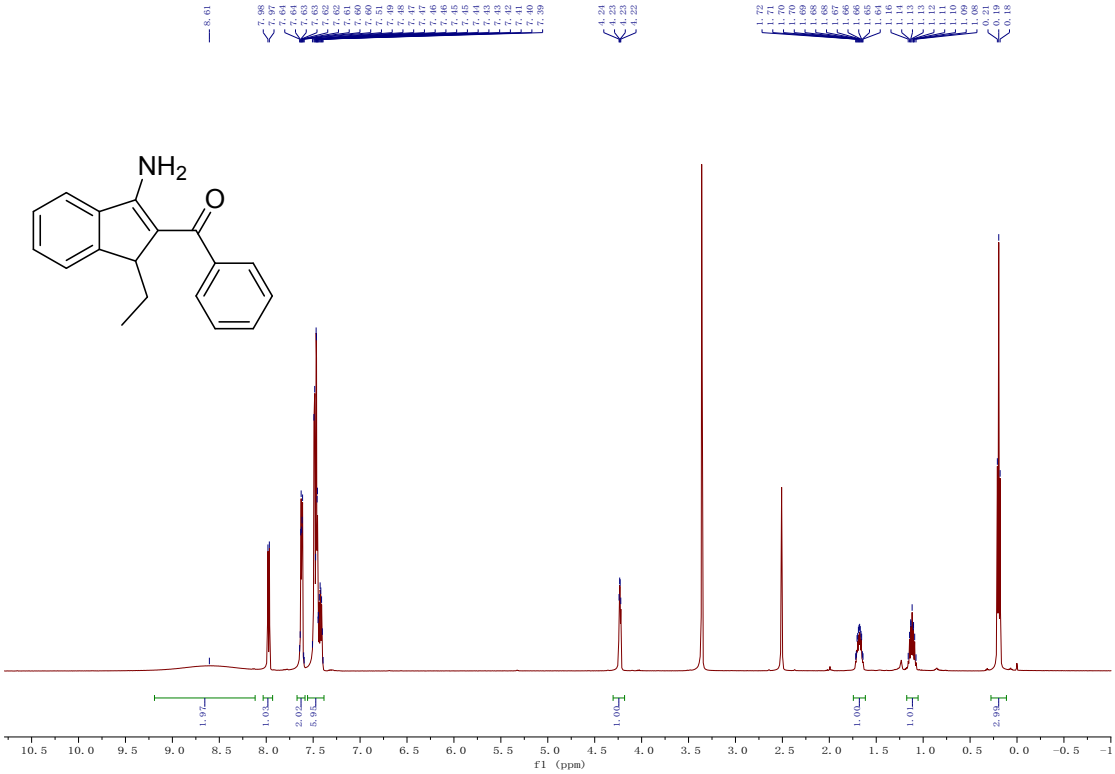


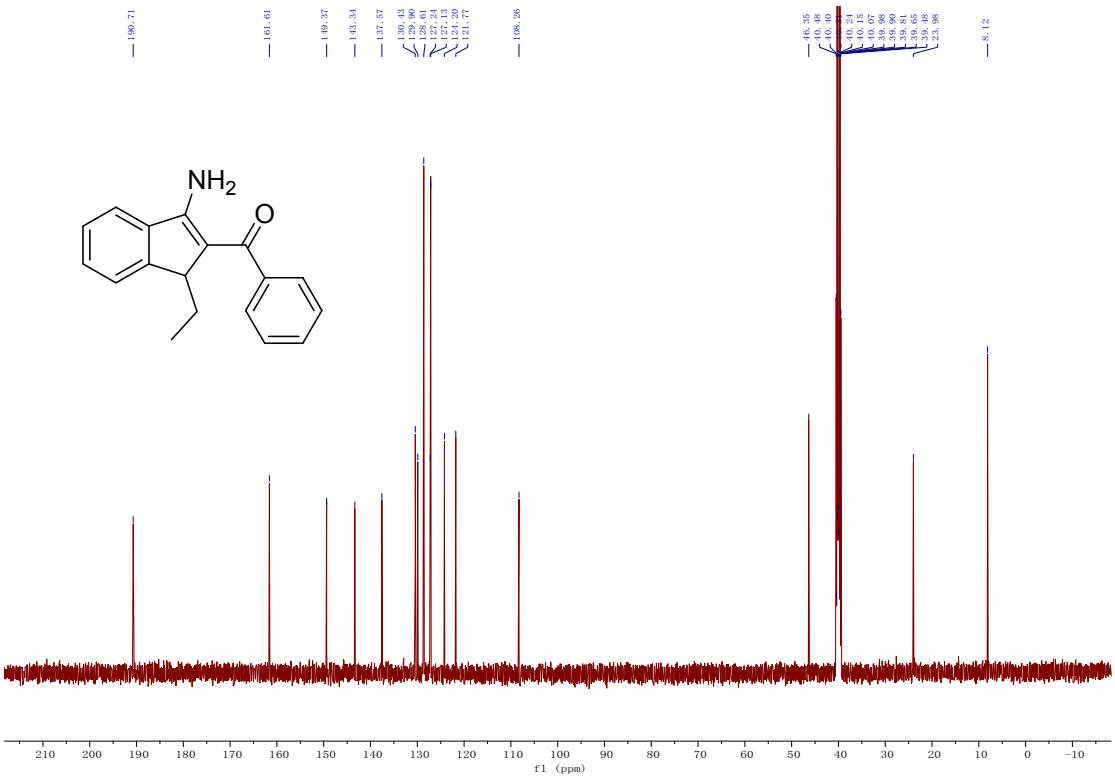
^{1}H, ^{13}C spectra of **3r**



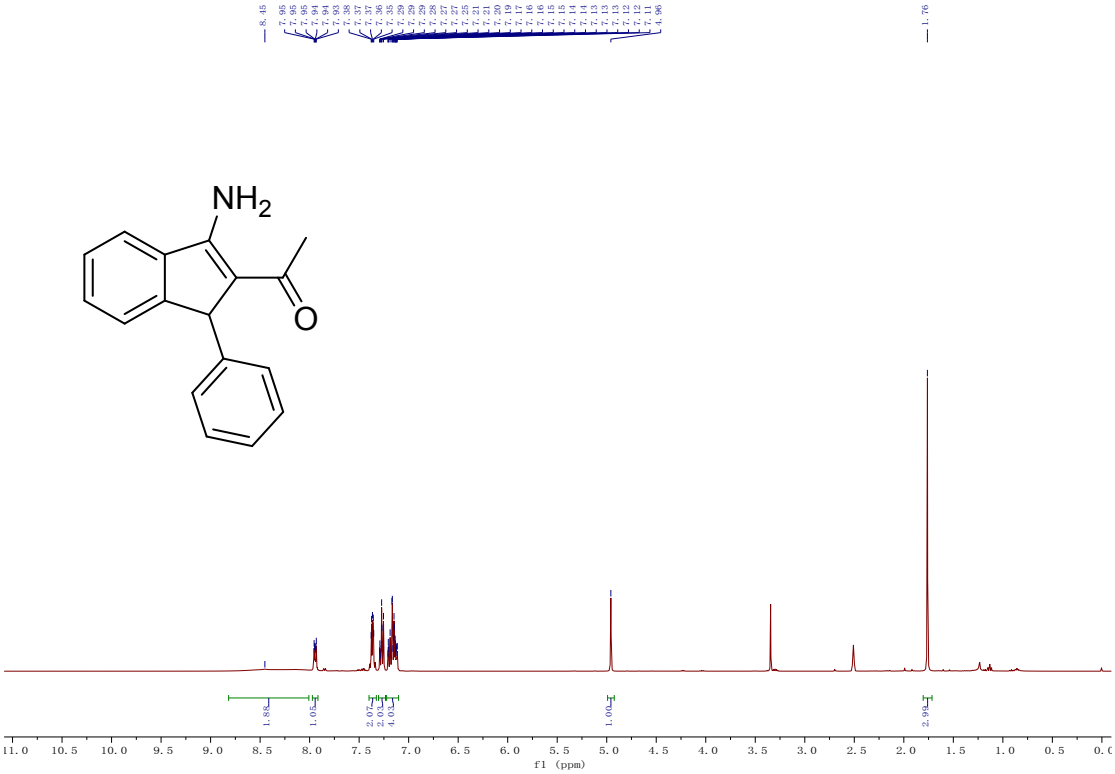


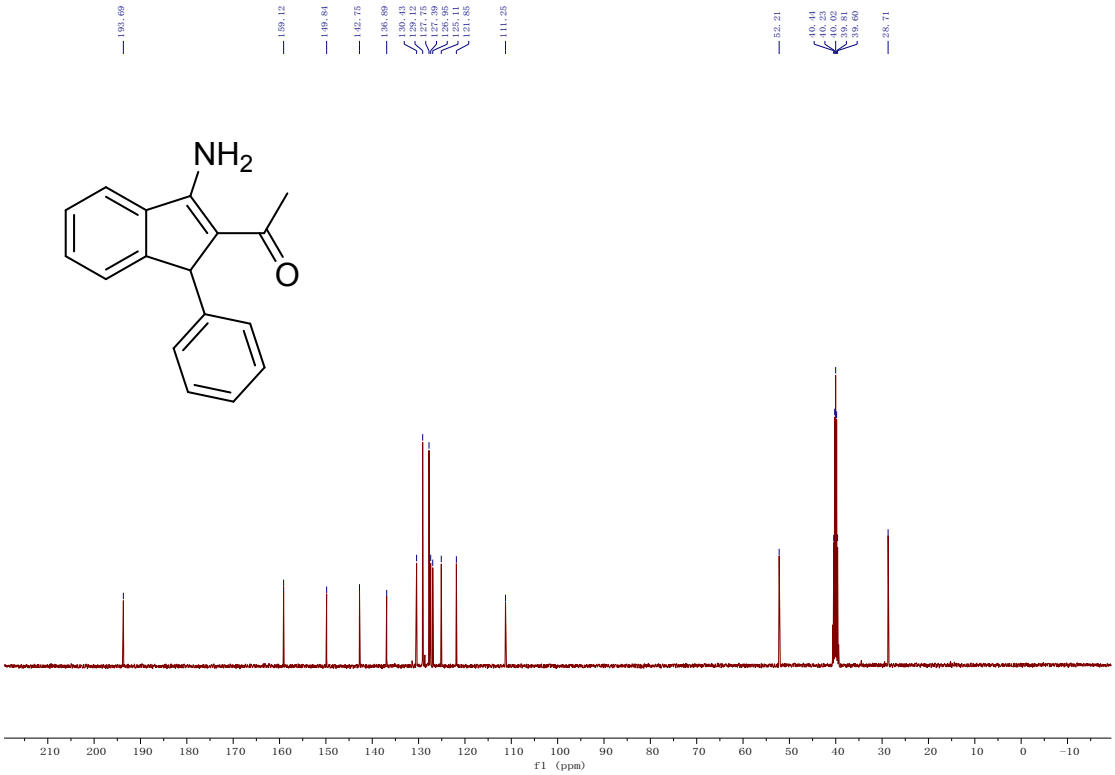
^{1}H, ^{13}C spectra of **3s**



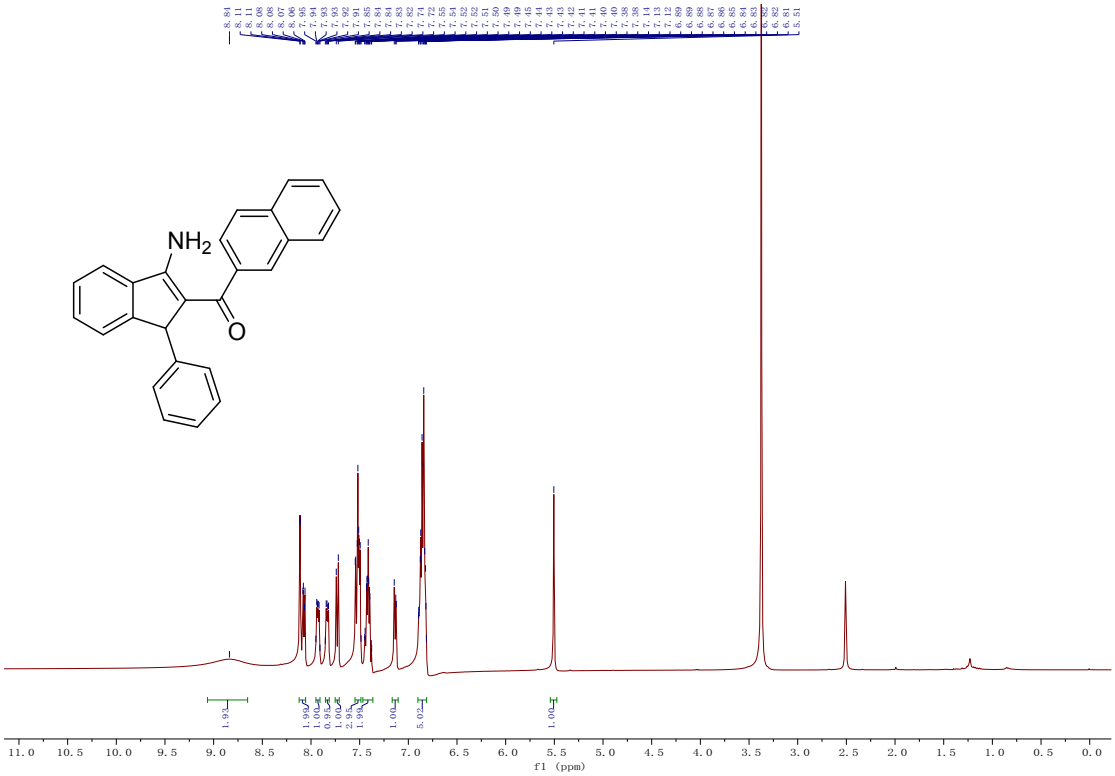


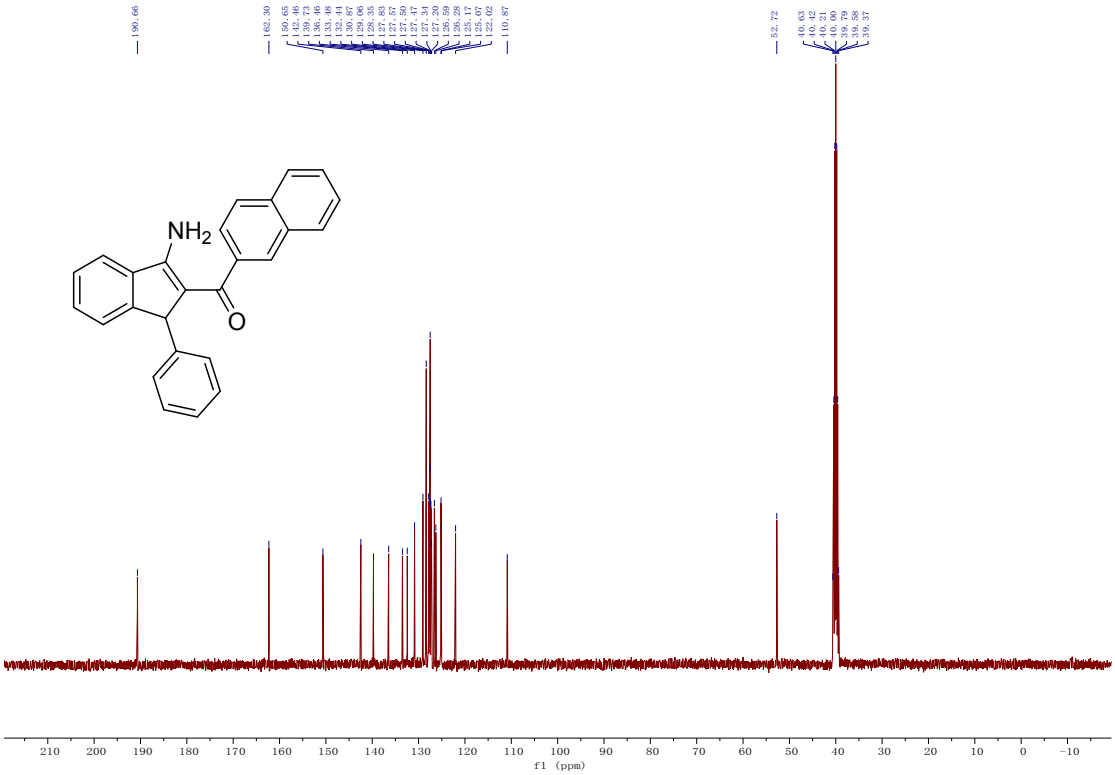
^{1}H, ^{13}C spectra of **3t**



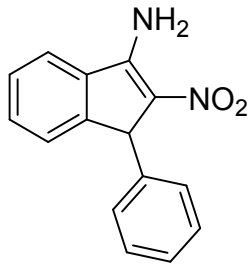


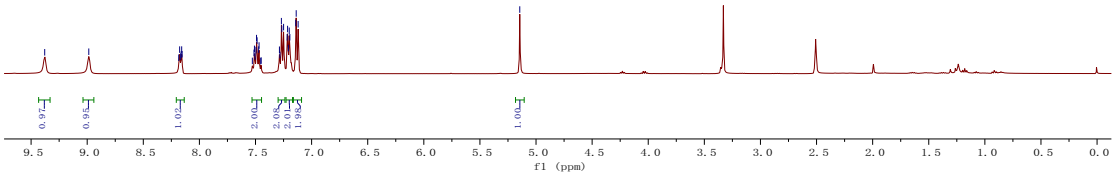
^{1}H, ^{13}C spectra of **3u**

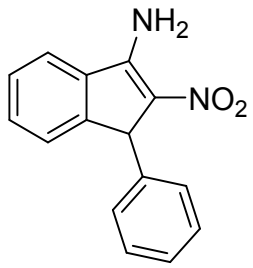




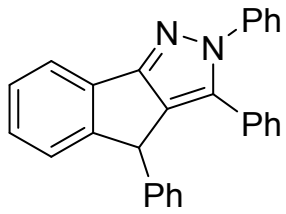
^{1}H, ^{13}C spectra of **3v**

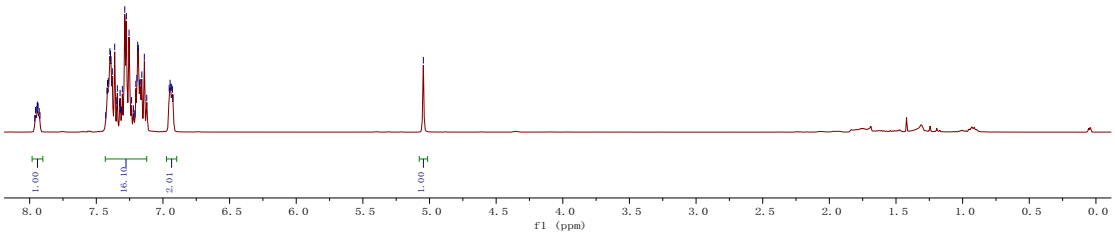


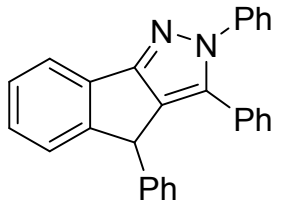




^{1}H, ^{13}C spectra of **4**







8. HRMS spectra of the intermediate E