Supporting Information

Exploration of *N*-hydroxy benzimidazole catalysts for hydrogen atom transfer reactions

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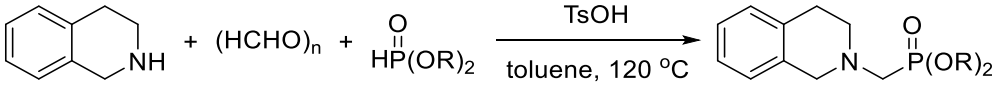
1 General Information

All solvents were received from commercial sources without further purification. Commercially available reagents were used without further purification. Thin-layer chromatography (TLC) was performed by UV absorbance (254 nm). 200-300 mesh silica gel was used for column chromatography separation. NMR spectra were recorded on Bruker AV 400 spectrometer at 400 MHz (^{1}H NMR), 100 MHz (^{13}C NMR) and 162 MHz (^{31}P NMR). Proton and carbon chemical shifts are reported relative to the solvent used as an internal reference ($CDCl_3$: δ_H = 7.26 ppm; δ_C = 77.16 ppm). All coupling constants (*J* values) were reported in Hertz (Hz). Multiplicities are reported as follows: singlet (s), doublet (d), doublet of doublets (dd), triplet (t), triplet of doublets (td), quartet (q), and multiplet (m). High resolution mass spectra (HRMS) were recorded on an Agilent 6520 Q-TOF LC/MS with Electron Spray Ionization (ESI) resource.

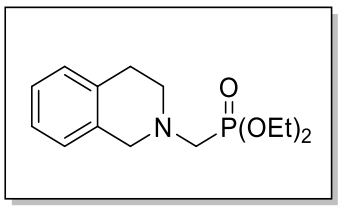
2 Preparation of Substrates

Procedure:



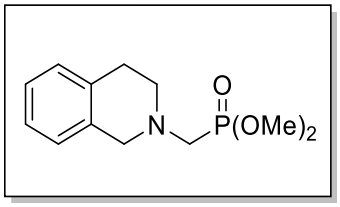
A **B**

To a 100-mL round bottom flask equipped with a stir bar was added toluene (15 mL), 1,2,3,4- tetrahydroisoquinoline (**A**) (10 mmol, 1.0 equiv) and phosphite (12.5 mmol), paraformaldehyde (12.5 mmol, 0.40 g) and TsOH (0.025 mmol, 45 mg) in sequence. The mixture was stirred at 120 °C until the reaction was completed (monitored by TLC). After completion of the reaction, the mixture was cooled to room temperature, concentrated in vacuo. The crude product was purified by flash column chromatography on silica gel, eluting with Hexane/EtOAc.



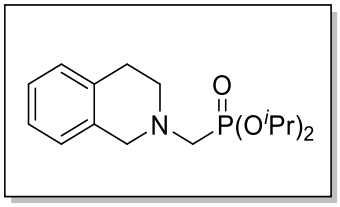
diethyl ((3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate

Yellow oil (1.96 g, 69% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.15 - 7.05 (m, 3H), 7.02 - 6.98 (m, 1H), 4.23 - 4.10 (m, 4H), 3.85 (s, 2H), 3.02 - 2.87 (m, 6H), 1.33 (t, *J* = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 134.1, 133.5, 128.2, 126.1, 125.8, 125.3, 61.7 (d, $^2J_{C\text{-}P}$ = 6.7 Hz), 56.9 (d, $^3J_{C\text{-}P}$ = 11.0 Hz), 53.3 (d, $^1J_{C\text{-}P}$ = 162.8 Hz), 52.1 (d, $^3J_{C\text{-}P}$ = 9.8 Hz), 28.6, 16.2 (d, $^3J_{C\text{-}P}$ = 5.7 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 24.24



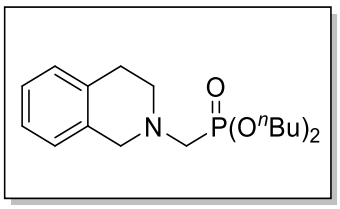
dimethyl ((3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate

Yellow oil (1.01 g, 36% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.13 - 7.06 (m, 3H), 7.01 - 6.99 (m, 1H), 3.83 (s, 2H), 3.79 (d, J = 10.8, 6H), 2.98 (d, J = 11.6 Hz, 2H), 2.94 (d, J = 5.2 Hz, 2H), 2.90 (d, J = 5.2 Hz, 2H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 134.2, 133.6, 128.5, 126.4, 126.1, 125.6, 57.2 (d, $^{3}J_{C\text{-}P}$ = 11.1 Hz), 52.8 (d, $^{1}J_{C\text{-}P}$ = 162.8 Hz), 52.7 (d, $^{2}J_{C\text{-}P}$ = 6.8 Hz), 52.3 (d, $^{3}J_{C\text{-}P}$ = 9.8 Hz), 28.7. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 26.59.



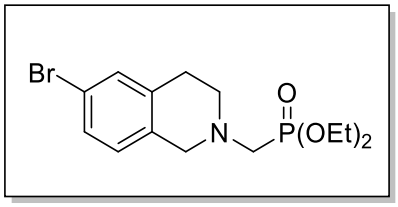
diisopropyl ((3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate

Yellow oil (2.10 g, 67% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.12 – 7.06 (m, 3H), 7.02 – 6.97 (m, 1H), 4.82 – 4.71 (m, 2H), 3.85 (s, 2H), 2.97 – 2.80 (m, 6H), 1.34 (dd, J = 6.4 Hz, 3.6 Hz, 12H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 134.6, 133.9, 128.5, 126.4, 126.0, 125.5, 70.5 (d, $^{2}J_{C\text{-}P}$ = 6.8 Hz), 57.3 (d, $^{3}J_{C\text{-}P}$ = 10.7 Hz), 54.5 (d, $^{1}J_{C\text{-}P}$ = 164.5 Hz) 52.4 (d, $^{3}J_{C\text{-}P}$ = 10.2 Hz), 28.9, 24.1 (d, $^{3}J_{C\text{-}P}$ = 3.7 Hz), 24.0 (d, $^{3}J_{C\text{-}P}$ = 4.9 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 22.46.

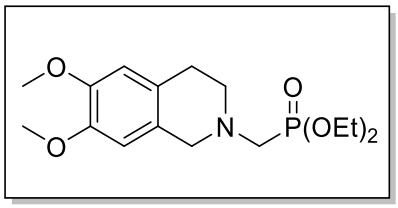


dibutyl ((3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate

Yellow oil (2.10 g, 67% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.11 (m, 3H), 7.04 – 6.97 (m, 1H), 4.09 (m, 4H), 3.84 (s, 2H), 3.02 – 2.83 (m, 6H), 1.66 (m, 4H), 1.40 (m, 4H), 0.92 (t, J = 7.4 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 134.4, 133.8, 128.5, 126.4, 126.0, 125.5, 65.8 (d, $^{2}J_{C\text{-}P}$ = 6.9 Hz), 57.2 (d, $^{3}J_{C\text{-}P}$ = 10.7 Hz), 53.5 (d, $^{1}J_{C\text{-}P}$ = 162.6 Hz), 52.4 (d, $^{3}J_{C\text{-}P}$ = 9.9 Hz), 32.6 (d, $^{3}J_{C\text{-}P}$ = 5.8 Hz), 28.8, 18.7, 13.5. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 24.33.



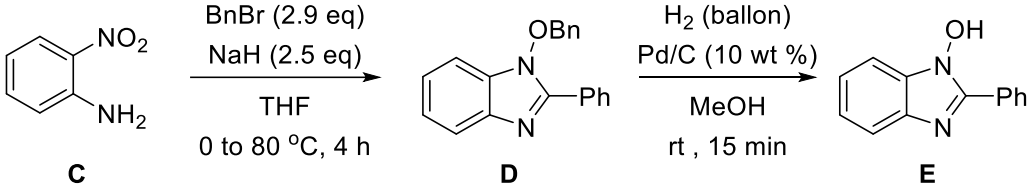
diethyl ((6-bromo-3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate
Yellow oil (1.26 g, 89% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.23 – 7.21 (m, 2H), 6.88 (d, J = 7.9 Hz, 1H), 4.17 (m, 4H), 3.79 (s, 2H), 3.02 – 2.85 (m, 6H), 1.33 (t, J = 7.1 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 136.1, 133.3, 131.2, 128.6, 128.0, 119.5, 62.0 (d, $^{2}J_{C\text{-}P}$ = 6.8 Hz), 56.6 (d, $^{3}J_{C\text{-}P}$ = 10.6 Hz), 53.4 (d, $^{1}J_{C\text{-}P}$ = 162.5 Hz), 51.8 (d, $^{3}J_{C\text{-}P}$ = 10.0 Hz), 28.6, 16.4 (d, J = 5.6 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 24.02. **HRMS** (ESI): *m/z* $[M+H]^+$ calcd. for $C_{14}H_{22}NO_3P$: 362.0516; Found: 362.0515.



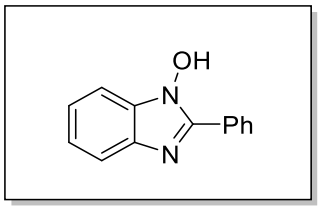
diethyl ((6,7-dimethoxy-3,4-dihydroisoquinolin-2(1*H*)-yl)methyl)phosphonate
Yellow oil (2.10 g, 67% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.58 (s, 1H), 6.52 (s, 1H), 4.24 – 4.08 (m, 4H), 3.84 (s, 3H), 3.83 (s, 3H), 3.78 (s, 2H), 3.01 – 2.88 (m, 4H), 2.82 (s, 2H), 1.34 (t, J = 7.0 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 147.4, 147.1, 126.2, 125.6, 111.2, 109.3, 62.1 (d, $^{2}J_{C\text{-}P}$ = 6.6 Hz), 56.8 (d, $^{3}J_{C\text{-}P}$ = 10.6 Hz), 55.8, 53.5 (d, $^{1}J_{C\text{-}P}$ = 162.9 Hz), 52.5 (d, $^{3}J_{C\text{-}P}$ = 10.3), 28.2, 16.5 (d, J = 5.7 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 24.31.

3 Synthesis of *N*-hydroxy catalysts

N-Hydroxy catalysts were synthesized according to previous literature.[1]
Procedure:



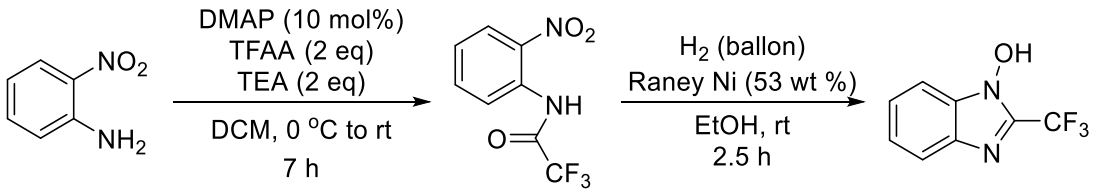
To a 50-mL round bottom flask equipped with a stir bar was added NaH (60% in oil, 2.3 g, 58 mmol, 2.9 equiv) in THF (30 mL), then 2-nitroaniline (2.68 g, 20 mmol, 1.0 equiv) was added portionwise to the suspension at 0 ℃. The mixture was stirred at the same temperature for further 15 min. Benzyl bromide (4.9 mL, 50 mmol, 2.5 equiv) was added slowly to the solution, and the mixture was stirred at 80 ℃ for 4 h. After the reaction, the reaction mixture was cooled to room temperature, quenched with H_2O and extracted with ethyl acetate for three times. The combined organic layer was dried over Na_2SO_4 and concentrated. The residue was purified by trituration with hexane and filtration to afford the following compound **D**.
To a 50-mL round bottom flask equipped with a stir bar was added **D** (1.4 g, 4.8 mmol) in MeOH (20 mL) and Pd/C (140 mg, 10 wt%), and the mixture was stirred under a H_2 atmosphere at room temperature for 15 min. The reaction mixture was filtered through high-flow celite, and the filtrate was concentrated to afford the following compound **E** without further purification.



2-phenyl-1*H*-benzo[d]imidazol-1-ol

White solid (580 mg, 57% yield). m.p. 226-227 ℃. **^{1}H NMR** (400 MHz, DMSO-d_6) δ 12.10 (s, 1H), 8.26 (d, J = 7.2 Hz, 2H), 7.67 (d, J = 7.6 Hz, 1H), 7.60 – 7.50 (m, 4H), 7.34 -7.21 (m, *2*H). **^{13}C NMR** (100 MHz, DMSO-d_6) δ 146.9, 137.8, 133.5, 129.9, 128.8, 128.7, 128.2, 122.8, 122.2, 119.3, 109.2.

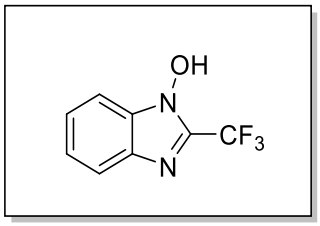
Procedure:



C **F** **G**

To a 250-mL round bottom flask equipped with a stir bar was added **C** (2.76 g, 20 mmol) in DCM (80 mL) at 0 ℃ and stirred for 30 min. To the solution was added 4-dimethylaminopyridine (244 mg, 2.0 mmol, 10 mol%), triethylamine (5.64 mL, 40 mmol, 2.0 equiv) and trifluoroacetic anhydride (5.64 mL, 40 mmol, 2.0 equiv), and the mixture was stirred at room temperature for 7 h. The reaction mixture was quenched with H_2O and extracted with ethyl acetate for three times. The combined organic layer was dried over Na_2SO_4 and concentrated. The crude product was purified by flash column chromatography on silica gel, eluting with Hexane/EtOAc (6:1) .

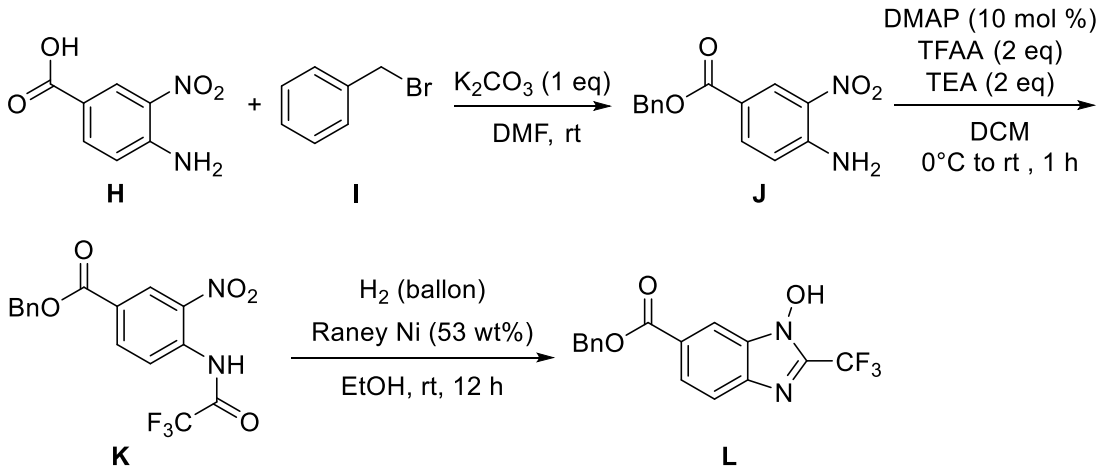
To a 50-mL round bottom flask equipped with a stir bar was added **F** (1.17 g, 5.0 mmol) in EtOH (20 mL), and Raney-Ni (625 mg, 53 wt%). The mixture was stirred under a H_2 atmosphere at room temperature for 2.5 h. The reaction mixture was filtered through high-flow celite, and the filtrate was concentrated. The crude product was purified by flash column chromatography on silica gel, eluting with Hexane/EtOAc (3:1).



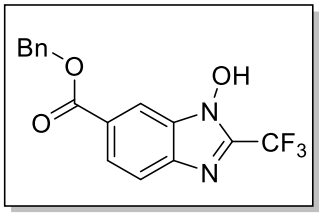
2-(trifluoromethyl)-1*H*-benzo[*d*]imidazol-1-ol

White solid (558 mg, 55% yield). m.p. 198-199 ℃. **^{1}H NMR** (400 MHz, MeOD-d_4) δ 7.73 (d, J = 7.6 Hz, 1H), 7.61 (d, J = 8.0 Hz, 1H), 7.47 (t, J = 7.6 Hz, 1H), 7.39 (t, J = 7.6 Hz, 1H). **^{13}C NMR** (100 MHz, MeOD-d_4) δ 138.2 (q, J_{C-F} = 39.5 Hz), 137.8, 134.0, 126.9, 125.1, 121.6, 119.9 (q, J_{C-F} = 268.5 Hz), 110.9. **^{19}F NMR** (376 MHz, MeOD-d_4) δ -65.3.

Procedure:



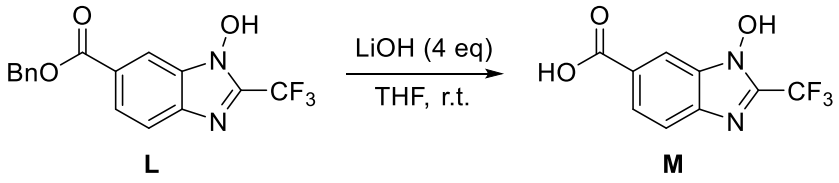
To a 50-mL round bottom flask equipped with a stir bar was added **H** (0.728 g, 4 mmol) and **I** (0.48 ml, 4 mmol) in DMF (20 mL). To the solution was added K_2CO_3 (0.608g, 4 mmol), and the mixture was stirred at room temperature for 18 h. The reaction mixture was quenched with H_2O (125 mL) and extracted with ethyl acetate for three times. The combined organic layer was dried over Na_2SO_4 and concentrated to afford the crude product **J**. The crude product was purified by flash column chromatography on silica gel, eluting with Hexane/EtOAc (6:1).



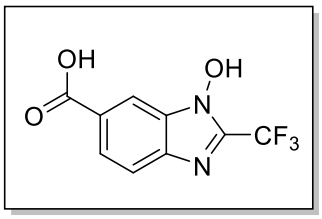
benzyl 1-hydroxy-2-(trifluoromethyl)-1*H*-benzo[d]imidazole-6-carboxylate

Yellow solid (532 mg, 75% yield). **^{1}H NMR** (400 MHz, MeOD-d_4) δ 8.32 (s, 1H), 8.09 (d, J = 8.8 Hz, 1H), 7.84 (d, J = 8.8 Hz, 1H), 7.51 - 7.34 (m, 5H), 5.42 (s, 2H). **^{13}C NMR** (100 MHz, MeOD-d_4) δ 167.1, 141.0, 140.7 (q, $J_{C\text{-}F}$ = 35.7 Hz), 137.4, 133.7, 129.6, 129.6, 129.3, 129.3, 129.2, 128.8, 125.8, 121.9, 119.6 (q, $J_{C\text{-}F}$ = 269.2 Hz), 113.3, 68.1. **^{19}F NMR** (376 MHz, MeOD-d_4) δ -65.6. **HRMS** (ESI): *m/z* $[M+H]^+$ calcd. for $C_{16}H_{12}F_3N_2O_3$: 337.0795; Found: 337.0799.

Procedure:



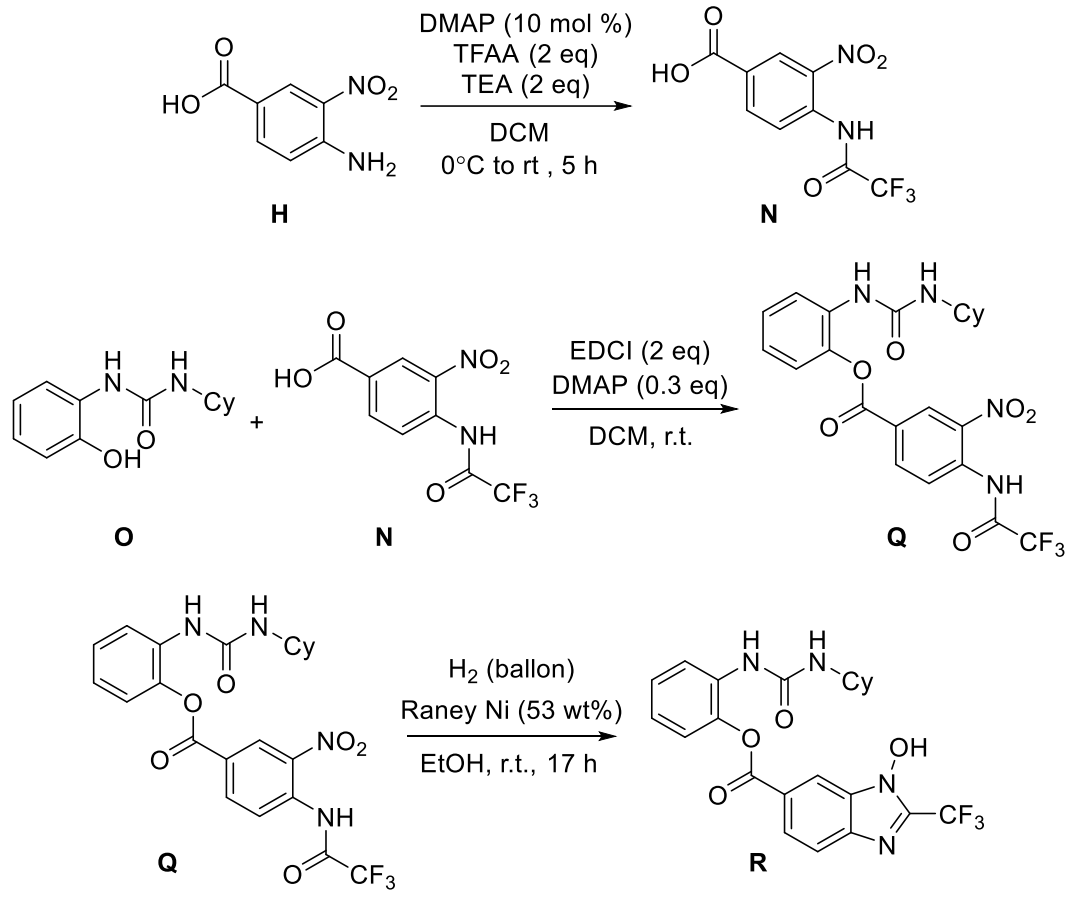
Dissolve **L** (322 mg, 1 mmol) in THF and LiOH (92 mg, 4 mmol) in water. Add the aqueous solution of LiOH to the solution of **L**, and the mixture was stirred at 30 ℃ for 4h. Then the reaction mixture was quenched with H_2O (1 mL) and extracted with ethyl acetate. The pH of water layer was adjusted to 3~4 with diluted hydrochloric acid, and extracted with ethyl acetate. The combined organic layer was dried over Na_2SO_4 and concentrated to afford the product without further purification.



2-(3-cyclohexylureido)phenyl 1-hydroxy-2-(trifluoromethyl)-1*H*-benzo[d]imidazole-6-carboxylate

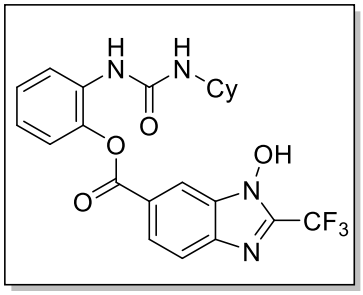
Yellow solid (558 mg, 70% yield). **^{1}H NMR** (400 MHz, MeOD-d_4) δ 8.30 (s, 1H), 8.06 (d, J = 8.4 Hz, 1H), 7.81 (d, J = 8.4 Hz, 1H). **^{13}C NMR** (100 MHz, MeOD-d_4) δ 169.2, 140.8, 140.5 (q, $J_{C\text{-}F}$ = 39.6 Hz), 133.7, 129.5, 126.1, 121.6, 119.6 (q, $J_{C\text{-}F}$ = 269.1 Hz), 113.4. **^{19}F NMR** (376 MHz, MeOD-d_4) δ -65.6. **HRMS** (ESI): *m/z* $[M\text{-}H]^-$ calcd. for $C_9H_4F_3N_2O_3$: 245.0180; Found: 245.0176.

Procedure:



The procedure for the reaction from **H** to **N** and from **Q** to **R** was similar to that of the previous routes. The procedure for the synthesis of **Q**: To a 50-mL round bottom flask equipped with a stir bar was added **N** (0.83g, 3.0 mmol), EDCI (1.14g, 5.9 mmol) and DMAP (0.11g, 0.89 mmol) in DMF (15 mL), which was stirred for 3 minutes. To the solution was added **O** (0.70g, 3.0 mmol), and the mixture was stirred at room temperature for 5 h. The reaction mixture was quenched with H_2O and extracted with ethyl acetate for three times. The combined organic layer was dried over Na_2SO_4 and

concentrated. The residue was purified by flash column chromatography on silica gel (PE:EA = 3:1) to afford the following compound.



2-(3-cyclohexylureido)phenyl 1-hydroxy-2-(trifluoromethyl)-1*H*-benzo[d]imidazole-6-carboxylate

Yellow solid (170 mg, 24% yield). **^{1}H NMR** (400 MHz, MeOD-d_4) δ 8.20 (s, 1H), 8.10 (d, J = 8.0 Hz, 1H), 7.90 (d, J = 8.4 Hz, 1H), 7.56 (d, J = 8.8 Hz, 1H), 7.22 (t, J = 8.0 Hz, 1H), 7.14 (d, J = 7.6 Hz, 1H), 7.06 (t, J = 7.6 Hz, 1H), 3.56 – 3.48 (m, 1H), 1.82 (d, J = 12.0 Hz, 2H), 1.65 – 1.56 (m, 2H), 1.55 – 1.46 (m, 1H), 1.34 – 1.24 (m, 2H), 1.15 - 1.03 (m, 3H). **^{13}C NMR** (100 MHz, MeOD-d_4) δ 166.3, 157.2, 141.9, 141.3, 140.7 (q, $J_{C\text{-}F}$ = 38.1 Hz), 134.5, 133.5, 127.3, 125.4, 125.2, 123.6, 122.5, 120.6, 120.5 (q, $J_{C\text{-}F}$ = 268.6 Hz), 114.7, 49.6, 34.3, 26.6, 25.7. **^{19}F NMR** (376 MHz, MeOD-d_4) δ -65.5. **HRMS** (ESI): m/z $[M\text{-}H]^-$ calcd. for $C_{22}H_{20}F_3N_4O_4$: 461.1142; Found: 461.1440.

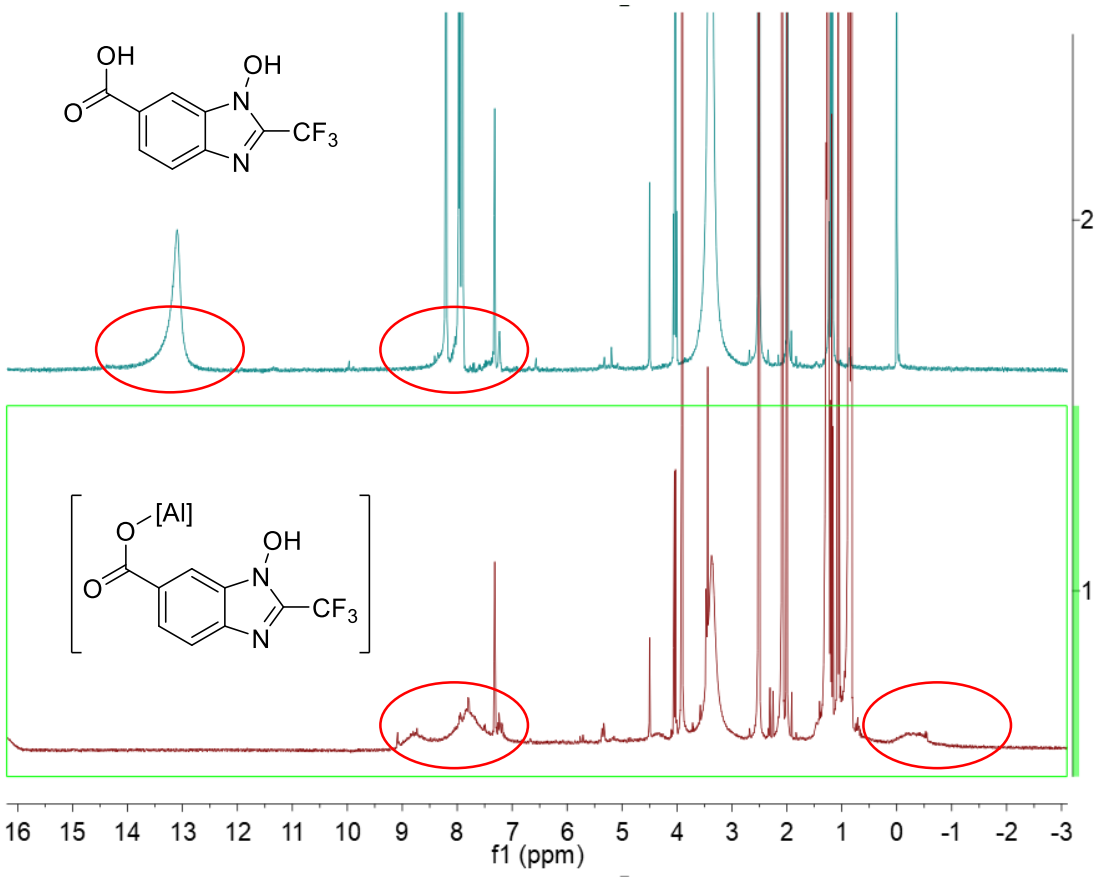
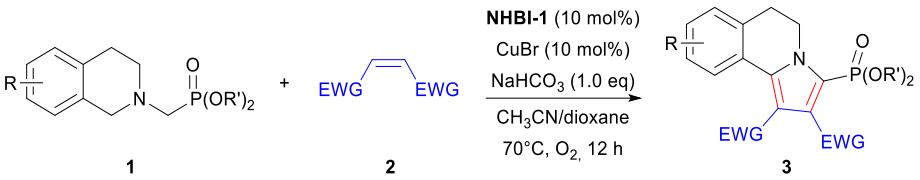
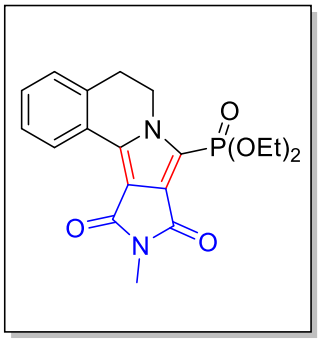


Figure S1. ^{1}H NMR (DMSO-d_6) comparison of **NHBI-5** (top) and **NHBI-6** (premixed **NHBI-5**/$AlEt_3$ (1/1)) (bottom).

4 Typical Procedure for Cu/*N*-Hydroxy Catalyzed Annulation

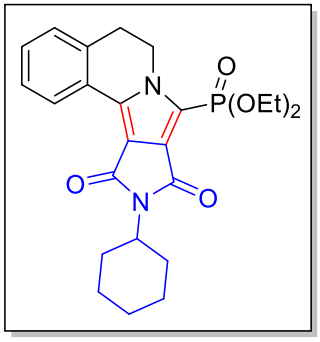


According to the general procedure, **1** (1 mmol), **2** (0.50 mmol), $NaHCO_3$ (0.5 mmol), CuBr (10 mol%), **NHBI-1** (10 mol%) and solvent (4 mL, CH_3CN:1,4-dioxane = 3:1) were added into sealed tube under oxygen atmosphere, and the mixture was stirred at 70 °C for 12 h. After the reaction, the mixture was filtered and purified by column chromatography (eluting with Hexane/EtOAc) to give **3** as the product.



diethyl (10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*pyrrolo[3',4':3,4]pyrrolo [2,1-a]isoquinolin-8-yl)phosphonate

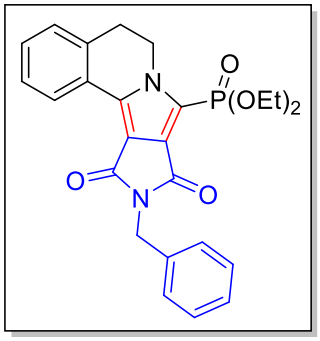
Yellow solid (162 mg, 80% yield). m.p. 136-137 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.49 (d, J = 8.5 Hz, 1H), 7.42 (t, J = 7.4 Hz, 1H), 7.36 (t, J = 7.4 Hz, 1H), 7.27 (d, J = 6.8 Hz, 1H), 4.60 (t, J = 6.8 Hz, 2H), 4.31 – 4.21 (m, 4H), 3.16 (t, J = 6.8 Hz, 2H), 3.12 (s, 3H), 1.41 (t, J = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.1, 163.1, 133.5 (d, $^3J_{C\text{-}P}$ = 9.2 Hz), 132.2, 130.0, 128.2 (d, $^2J_{C\text{-}P}$ = 15.4 Hz), 128.0, 127.7, 127.6, 125.7, 117.6 (d, $^1J_{C\text{-}P}$ = 222.2 Hz), 116.9 (d, $^3J_{C\text{-}P}$ = 10.4 Hz), 63.6 (d, $^2J_{C\text{-}P}$ = 7.0 Hz), 44.1, 28.5, 24.2, 16.3 (d, $^3J_{C\text{-}P}$ = 6.5 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.51.



Diethyl (10-cyclohexyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

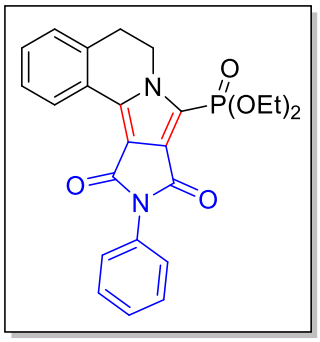
Yellow solid (146 mg, 65% yield). m.p. 198-199 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.51 (d, J = 7.6 Hz, 1H), 7.40 (t, J = 6.4 Hz, 1H), 7.35 (t, J = 7.2 Hz, 1H), 7.25 (d, J = 5.2 Hz, 1H), 4.58 (t, J = 6.8 Hz, 2H), 4.34 – 4.20 (m, 4H), 4.08 – 4.00 (m, 1H), 3.15 (t,

J = 6.8 Hz, 2H), 2.23 (q, *J* = 12.4, 11.0 Hz, 2H), 1.85 (d, *J* = 13.1 Hz, 2H), 1.78 – 1.64 (m, 3H), 1.40 (t, *J* = 7.1 Hz, 6H), 1.34– 1.23 (m, 3H).**^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.4, 163.0, 133.4 (d, $^3J_{C\text{-}P}$ = 9.2 Hz), 132.3, 130.0, 128.2 (d, $^2J_{C\text{-}P}$ = 15.5 Hz), 128.0, 127.7, 125.9, 117.4 (d, $^1J_{C\text{-}P}$ = 222.8 Hz), 117.1 (d, $^3J_{C\text{-}P}$ = 10.3 Hz), 63.6 (d, $^2J_{C\text{-}P}$ = 6.0 Hz), 51.1, 44.2, 30.0, 28.6, 26.3, 25.3, 16.4 (d, $^3J_{C\text{-}P}$ = 6.5 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.79.



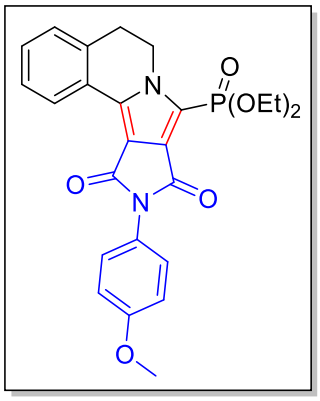
diethyl (10-benzyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (186 mg, 79% yield). m.p. 149-150 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.49 (d, *J* = 7.2 Hz, 1H), 7.50 – 7.22 (m, 8H), 4.79 (s, 2H), 4.58 (t, *J* = 6.4 Hz, 2H), 4.35 – 4.19 (m, 4H), 3.15 (t, *J* = 6.4 Hz, 2H), 1.42 (t, *J* = 6.8 Hz, 6H).**^{13}C NMR** (100 MHz, $CDCl_3$) δ 163.8, 162.7, 137.2, 133.7 (d, $^3J_{C\text{-}P}$ = 9.2 Hz), 132.3, 130.1, 128.6, 128.2, 128.0, 127.7, 127.7, 127.6, 125.7, 117.9 (d, $^1J_{C\text{-}P}$ = 233.7 Hz), 116.8, 63.7 (d, $^2J_{C\text{-}P}$ = 5.9 Hz), 44.2, 41.8, 28.5, 16.4 (d, $^3J_{C\text{-}P}$ = 6.4 Hz).**^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.57.



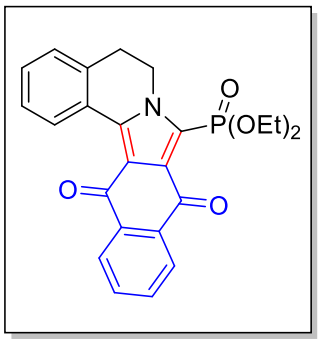
diethyl (9,11-dioxo-10-phenyl-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (162 mg, 72% yield). m.p. 189-190 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.56 (d, *J* = 8.8 Hz, 1H), 7.52 – 7.45 (m, 2H), 7.44 – 7.34 (m, 5H), 7.29 (d, *J* = 7.2 Hz, 1H), 4.66 (t, *J* = 6.8 Hz, 2H), 4.34 – 4.25 (m, 4H), 3.20 (t, *J* = 6.8 Hz, 2H), 1.41 (t, *J* = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 163.1, 162.0, 134.2 (d, $^3J_{C\text{-}P}$ = 9.3 Hz), 132.6, 132.4, 130.3, 129.0, 128.1, 127.8, 127.8, 127.6 (d, $^2J_{C\text{-}P}$ = 15.2 Hz), 127.1, 125.7, 118.5 (d, $^1J_{C\text{-}P}$ = 222.4 Hz), 116.5 (d, $^2J_{C\text{-}P}$ = 10.2 Hz), 63.8 (d, $^2J_{C\text{-}P}$ = 6.1 Hz), 44.4, 28.6, 16.4 (d, $^3J_{C\text{-}P}$ = 6.4 Hz).**^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.28.



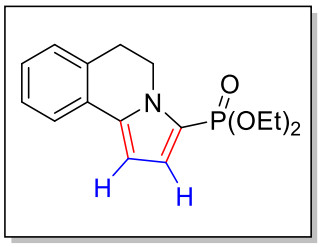
diethyl (10-(4-methoxyphenyl)-9,11-dioxo-5,9,10,11-tetrahydro-6H-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (161 mg, 67% yield). m.p. 173-174 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.58 (d, J = 7.2 Hz, 1H), 7.46 – 7.36 (m, 2H), 7.35 – 7.27 (m, 3H), 7.03 (d, J = 9.2 Hz, 2H), 4.68 (t, J = 6.8 Hz, 2H), 4.39 – 4.19 (m, 4H), 3.87 (s, 3H), 3.22 (t, J = 6.4 Hz, 2H), 1.47 – 1.39 (m, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 163.4, 162.3, 159.1, 134.1 (d, $^{3}J_{C\text{-}P}$ = 9.2 Hz), 132.4, 130.2, 128.4, 128.1, 127.8, 127.8, 127.6 (d, $^{2}J_{C\text{-}P}$ = 15.4 Hz), 125.7, 125.3, 118.4 (d, $^{1}J_{C\text{-}P}$ = 222.5 Hz), 116.6 (d, $^{3}J_{C\text{-}P}$ = 10.3 Hz), 114.3, 63.8 (d, $^{2}J_{C\text{-}P}$ = 6.1 Hz), 55.6, 44.4, 28.6, 16.4 (d, $^{3}J_{C\text{-}P}$ = 6.5 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.37. **HRMS** (ESI): *m/z* $[M+H]^+$ calcd. for $C_{25}H_{26}N_2O_6P$: 481.1523; Found: 481.1523.



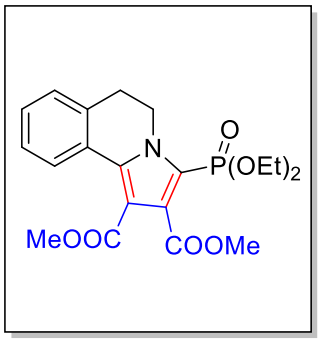
diethyl (9,14-dioxo-5,6,9,14-tetrahydrobenzo[5,6]isoindolo[1,2-a]isoquinolin-8-yl)phosphonate

Yellow solid (127 mg, 58% yield). m.p. 162-163 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.91 (d, J = 7.8 Hz, 1H), 8.34 – 8.25 (m, 2H), 7.78 – 7.72 (m, 2H), 7.50 – 7.40 (m, 2H), 7.32 (d, J = 7.2 Hz, 1H), 4.88 (t, J = 6.4 Hz, 2H), 4.42 – 4.22 (m, 4H), 3.10 (t, J = 6.4 Hz, 2H), 1.39 (t, J = 6.8 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 179.9, 179.4, 138.7 (d, $^{3}J_{C\text{-}P}$ = 10.6 Hz), 135.4, 134.8, 134.7, 133.4, 133.1, 130.3, 129.5 (d, $^{2}J_{C\text{-}P}$ = 13.5 Hz), 129.1, 127.3, 127.2, 127.1, 126.8, 126.5, 122.2 (d, $^{1}J_{C\text{-}P}$ = 217.7 Hz), 119.0 (d, $^{3}J_{C\text{-}P}$ = 9.7 Hz), 63.6 (d, $^{2}J_{C\text{-}P}$ = 5.8 Hz), 44.2, 29.6, 16.4 (d, $^{3}J_{C\text{-}P}$ = 6.6 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 5.22.



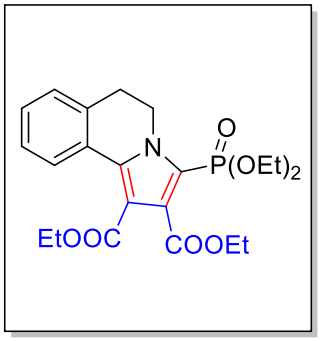
diethyl (5,6-dihydropyrrolo[2,1-a]isoquinolin-3-yl)phosphonate

Yellow oil (97mg, 63% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 (d, J = 7.6 Hz, 1H), 7.28 – 7.25 (m, 1H), 7.24 – 7.16 (m, 2H), 6.86 (t, J = 3.6 Hz, 1H), 6.55 (t, J = 4.0 Hz, 1H), 4.34 (t, J = 6.8 Hz, 2H), 4.21 – 4.05 (m, 4H), 3.09 (t, J = 6.8 Hz, 2H), 1.33 (t, J = 7.2 Hz, 6H).**^{13}C NMR** (100 MHz, $CDCl_3$) δ 136.3 (d, $^{3}J_{C\text{-}P}$ = 11.6 Hz), 131.2, 128.5, 128.0, 127.2 (d, $^{2}J_{C\text{-}P}$ = 4.5 Hz), 123.5, 121.7, 121.5, 118.3 (d, $^{1}J_{C\text{-}P}$ = 226.5 Hz), 104.3 (d, $^{3}J_{C\text{-}P}$ = 13.7 Hz), 62.3 (d, $^{2}J_{C\text{-}P}$ = 5.1 Hz), 43.1, 29.1, 16.4 (d, $^{3}J_{C\text{-}P}$ = 6.6 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 10.17. **HRMS** (ESI): *m/z* $[M+Na]^+$ calcd. for $C_{19}H_{20}NO_3PNa$: 328.1073; Found: 328.1072.



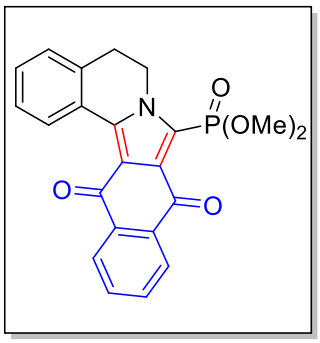
dimethyl 3-(diethoxyphosphoryl)-5,6-dihydropyrrolo[2,1-a]isoquinoline-1,2-dicarboxylate

Yellow solid (121 mg, 54% yield). m.p. 120-121 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.17 (d, J = 8.8 Hz, 1H), 7.36 – 7.28 (m, 2H), 7.25 – 7.23 (m, 1H), 4.37 (t, J = 6.4 Hz, 2H), 4.26 – 4.06 (m, 4H), 3.91 (s, 3H), 3.83 (s, 3H), 3.03 (t, J = 6.4 Hz, 2H), 1.33 (t, J = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 166.2, 164.2, 136.8 (d, $^{3}J_{C\text{-}P}$ = 10.0 Hz), 133.8, 129.6 (d, $^{2}J_{C\text{-}P}$ = 15.9 Hz), 129.2, 128.0, 127.5, 127.2, 126.6, 117.6 (d, $^{1}J_{C\text{-}P}$ = 221.3 Hz), 111.1 (d, $^{3}Jc\text{-}_P$ = 6.5 Hz), 63.0 (d, $^{2}J_{C\text{-}P}$ = 5.3 Hz), 52.6, 51.9, 43.7, 29.5, 16.2 (d, $^{3}J_{C\text{-}P}$ = 6.6 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 5.85.



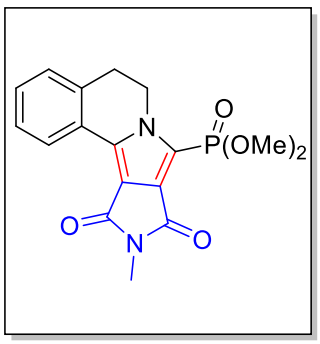
diethyl 3-(diethoxyphosphoryl)-5,6-dihydropyrrolo[2,1-a]isoquinoline-1,2-dicarboxylate

Yellow solid (124 mg, 55% yield). m.p. 62-63 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.22 (d, J = 7.6 Hz, 1H), 7.37 – 7.29 (m, 2H), 7.28 – 7.24 (m, 1H), 4.41 – 4.30 (m, 6H), 4.27 – 4.07 (m, 4H), 3.04 (t, J = 6.4 Hz, 2H), 1.44 – 1.31 (m, 12H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 165.7, 163.8, 136.7 (d, $^{3}J_{C\text{-}P}$ = 10.1 Hz), 133.8, 129.8 (d, J = 16.0 Hz), 129.1, 128.1, 127.5, 127.1, 126.7, 117.4 (d, $^{1}J_{C\text{-}P}$ = 221.2 Hz), 111.4 (d, $^{3}J_{C\text{-}P}$ = 11.7 Hz), 62.9 (d, $^{2}J_{C\text{-}P}$ = 5.2 Hz), 61.5, 60.8, 43.6, 29.5, 16.3 (d, $^{3}J_{C\text{-}P}$ = 6.6 Hz), 14.1, 14.1. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 6.10.



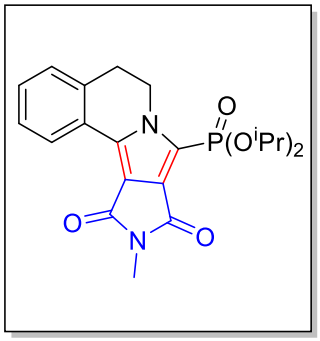
dimethyl (9,14-dioxo-5,6,9,14-tetrahydrobenzo[5,6]isoindolo[1,2-a]isoquinolin-8-yl)phosphonate

Yellow solid (168 mg, 82% yield). m.p. 178-179 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.88 (d, J = 7.6 Hz, 1H), 8.31– 8.24 (m, 2H), 7.77– 7.69 (m, 2H), 7.48 – 7.39 (m, 2H), 7.30 (d, J = 7.2 Hz, 1H), 4.86 (t, J = 6.4 Hz, 2H), 3.95 (d, J = 12.0 Hz, 6H), 3.09 (t, J = 6.4 Hz, 2H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 179.7, 179.5, 139.0 (d, $^{3}J_{C\text{-}P}$ = 10.8 Hz), 135.4, 134.7, 134.5, 133.5, 133.1, 130.3, 129.7 (d, $^{2}J_{C\text{-}P}$ = 13.8 Hz), 129.0, 127.2, 127.2, 127.1, 126.8, 126.3, 120.6 (d, $^{1}J_{C\text{-}P}$ = 220.3 Hz), 119.0 (d, $^{3}J_{C\text{-}P}$ = 9.8 Hz), 53.8 (d, $^{2}J_{C\text{-}P}$ = 5.8 Hz), 44.2, 29.5. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 8.43.



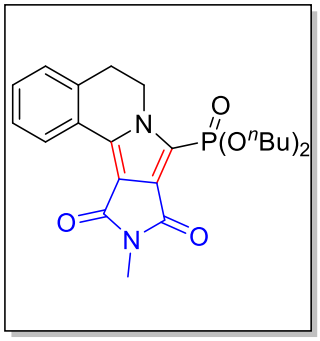
dimethyl (10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (102 mg, 56% yield). m.p. 165-166 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.51 (d, J = 7.6 Hz, 1H), 7.44 – 7.35 (m, 2H), 7.31 - 7.26 (m, 1H), 4.60 (t, J = 6.8 Hz, 2H), 3.93 (d, J = 11.6 Hz, 6H), 3.19 (t, J = 6.8 Hz, 2H), 3.15 (s, 3H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.0, 163.1, 133.9 (d, $^{3}J_{C\text{-}P}$ = 9.2 Hz), 132.3, 130.2, 128.6 (d, $^{2}J_{C\text{-}P}$ = 15.4 Hz), 128.0, 127.8, 127.7, 125.6, 116.9 (d, $^{3}J_{C\text{-}P}$ = 10.5 Hz), 116.2 (d, $^{1}J_{C\text{-}P}$ = 223.8 Hz), 53.9 (d, $^{2}J_{C\text{-}P}$ = 6.1 Hz), 44.2, 28.5, 24.3. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 6.47.



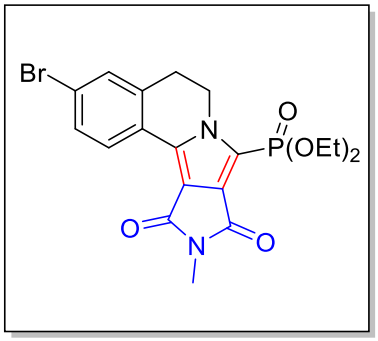
diisopropyl (10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (159 mg, 76% yield). m.p. 148-149 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.52 (d, J = 7.6 Hz, 1H), 7.44 (t, J = 7.6 Hz, 1H), 7.37 (t, J = 7.2 Hz, 1H), 7.31 - 7.26 (m, 1H), 4.87– 4.79 (m, 2H), 4.64 (t, J = 6.4 Hz, 2H), 3.17 (t, J = 6.8 Hz, 2H), 3.14 (s, 3H), 1.41 (d, J = 6.0 Hz, 6H), 1.37 (d, J = 6.0 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.3, 163.0, 133.1 (d, $^3J_{C\text{-}P}$ = 9.3 Hz), 132.3, 130.0, 128.2 (d, $^2J_{C\text{-}P}$ = 15.2 Hz), 128.0, 127.7, 127.7, 125.9, 119.3 (d, $^1J_{C\text{-}P}$ = 223.6 Hz), 117.1 (d, $^3J_{C\text{-}P}$ = 10.2 Hz), 72.7 (d, $^2J_{C\text{-}P}$ = 6.1 Hz), 44.1, 28.6, 24.3, 24.0 (d, $^3J_{C\text{-}P}$ = 4.7 Hz), 23.9 (d, $^3J_{C\text{-}P}$ = 4.4 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 0.87.



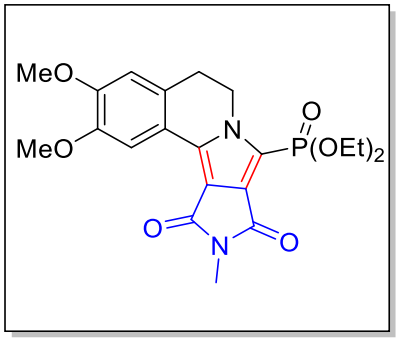
dibutyl (10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (155 mg, 69% yield). m.p. 104-105 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.50 (d, J = 7.6 Hz, 1H), 7.42 (t, J = 7.2 Hz, 1H), 7.36 (t, J = 7.2 Hz, 1H), 7.29 – 7.25 (m, 1H), 4.59 (t, J = 6.8 Hz, 2H), 4.26 – 4.09 (m, 4H), 3.16 (t, J = 6.8 Hz, 2H), 3.12 (s, 3H), 1.77 – 1.70 (m, 4H), 1.47 – 1.37 (m, 4H), 0.94 (t, J = 7.6 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.2, 163.2, 133.6 (d, $^3J_{C\text{-}P}$ = 9.2 Hz), 132.3, 130.1, 128.3 (d, $^2J_{C\text{-}P}$ = 15.4 Hz), 128.0, 127.8, 127.7, 125.8, 117.7 (d, $^1J_{C\text{-}P}$ = 222.4 Hz), 117.0 (d, $^3J_{C\text{-}P}$ = 10.4 Hz), 67.3 (d, $^2J_{C\text{-}P}$ = 6.3 Hz), 44.2, 32.4 (d, $^3J_{C\text{-}P}$ = 6.4 Hz), 28.6, 24.3, 18.8, 13.7. **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.72.



diethyl (3-bromo-10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

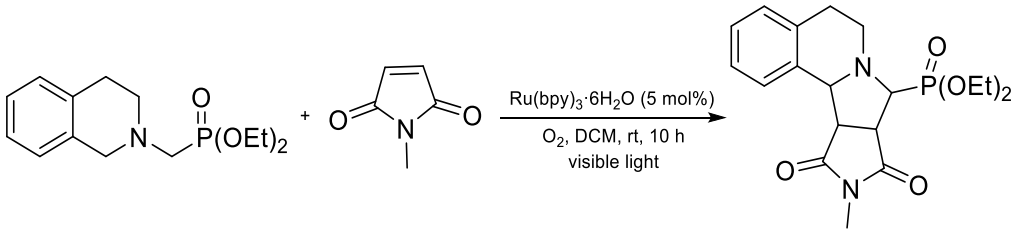
Yellow solid (171 mg, 72% yield). m.p. 177-178 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.39 (d, J = 8.4 Hz, 1H), 7.56 (d, J = 8.4 Hz, 1H), 7.46 (s, 1H), 4.60 (t, J = 6.8 Hz, 2H), 4.32 – 4.19 (m, 4H), 3.17 (t, J = 6.8 Hz, 2H), 3.13 (s, 3H), 1.42 (t, J = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.1, 163.1, 134.1, 132.5 (d, $^{3}J_{C\text{-}P}$ = 9.4 Hz), 131.3, 130.9, 129.1, 128.3 (d, J = 15.0 Hz), 124.7, 124.0, 118.1 (d, $^{1}J_{C\text{-}P}$ = 221.9 Hz), 117.3 (d, $^{2}J_{C\text{-}P}$ = 10.4 Hz), 63.8 (d, $^{2}J_{C\text{-}P}$ = 6.1 Hz), 43.9, 28.4, 24.4, 16.4 (d, $^{3}J_{C\text{-}P}$ = 6.6 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.22. **HRMS** (ESI): *m/z* $[M+Na]^+$ calcd. for $C_{19}H_{20}N_2O_5PNa$: 489.0186; Found: 489.0188.



diethyl (2,3-dimethoxy-10-methyl-9,11-dioxo-5,9,10,11-tetrahydro-6*H*-pyrrolo[3',4':3,4]pyrrolo[2,1-a]isoquinolin-8-yl)phosphonate

Yellow solid (115 mg, 52% yield). m.p. 195-196 ℃. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.17 (s, 1H), 6.74 (s, 1H), 4.55 (t, J = 6.8 Hz, 2H), 4.32 – 4.19 (m, 4H), 4.02 (s, 3H), 3.93 (s, 3H), 3.13 – 3.07 (m, 5H), 1.40 (t, J = 7.2 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 164.7, 163.3, 150.6, 148.7, 134.3 (d, $^{3}J_{C\text{-}P}$ = 9.5 Hz), 128.1 (d, $^{2}J_{C\text{-}P}$ = 15.0 Hz), 125.5, 118.5, 116.2, 115.6 (d, J = 10.2 Hz), 110.4, 110.4, 63.7 (d, $^{2}J_{C\text{-}P}$ = 5.9 Hz), 56.2, 56.1, 44.4, 28.2, 24.2, 16.4 (d, $^{3}J_{C\text{-}P}$ = 6.5 Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 3.65.

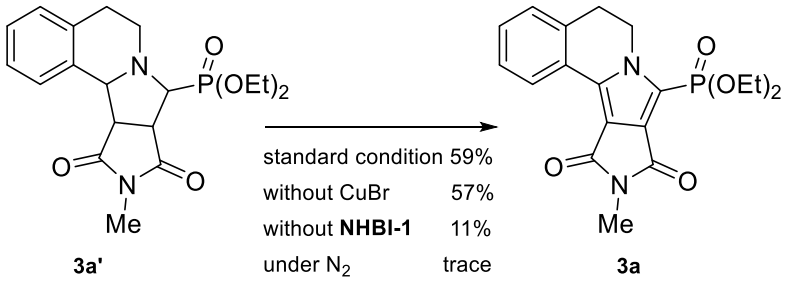
5 Mechanistic Experiments



1a **2a** **3a'**

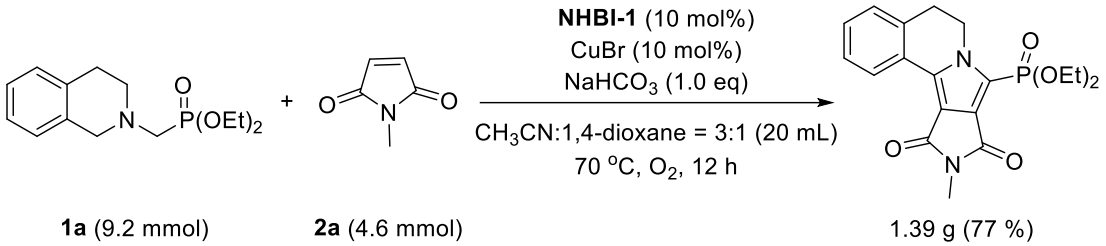
Synthesis of **3a'**: To a tube equipped with a stir bar was added **1a** (0.48 mmol, 1.2 equiv) and *N*-methylmaleimide (0.4 mmol, 1.0 equiv) in DCM (2 mL), then $Ru(bpy)_3$ $6H_2O$ (5 mol %) (12.5 mmol, 0.40 g) was introduced. The mixture was reacted for 10 hours at room temperature under oxygen condition and visible light. After the solvent was removed under reduced pressure. The crude product was purified by flash column chromatography on silica gel, eluting with Hexane/EtOAc (1:1). The pure product was obtained as yellow oil (27 mg, 17% yield). Yellow oil (27 mg, 17% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.41 (d, J = 7.6 Hz, 1H), 7.26 (t, J = 7.0 Hz, 1H), 7.20 (t, J = 7.4 Hz, 1H), 7.10 (d, J = 7.5 Hz, 1H), 5.06 (d, J = 8.1 Hz, 1H), 4.17 – 4.31(m, 4H), 3.86 (d, J = 12.0 Hz, 1H), 3.77 (t, J = 8.1 Hz, 1H), 3.63 (dd, J = 16.1, 8.8 Hz, 1H), 2.96 – 3.07 (m, 1H), 2.87– 2.95 (m, 1H), 2.86 (s, 1H), 2.83 (s, 3H), 2.69 – 2.80 (m, 1H), 1.39 (dt, J = 15.2, 7.1 Hz, 6H). **^{13}C NMR** (100 MHz, $CDCl_3$) δ 178.4 (d, $^3J_{C\text{-}P}$ = 15.7 Hz), 178.3, 175.9, 133.8, 131.6, 128.7, 128.5, 126.8, 125.4, 64.3 (d, $^1J_{C\text{-}P}$ = 172.0 Hz), 63.5 (d, $^2J_{C\text{-}P}$ = 4.0 Hz), 63.4, 62.3 (d, $^3J_{C\text{-}P}$ = 7.6 Hz), 48.7, 48.1 (d, $^3J_{C\text{-}P}$ = 11.7 Hz), 46.9 (d, $^2J_{C\text{-}P}$ = 4.2 Hz) 30.2, 25.3, 16.6, 16.6 (d, $^3J_{C\text{-}P}$ = 10.5 Hz Hz). **^{31}P NMR** (162 MHz, $CDCl_3$) δ 22.45. **HRMS** (ESI): *m/z* $[M+H]^+$ calcd. for $C_{19}H_{26}N_2O_5P$: 393.1574; Found: 393.1573.

The proposed intermediate **3a′** was subjected into standard conditions, or in the absence of NHBI, Cu salt, O_2, according to the typical procedure for Cu/*N*-hydroxy catalyzed annulation. After the reaction, the mixture was filtered and purified by column chromatography to give **3a** as the product.



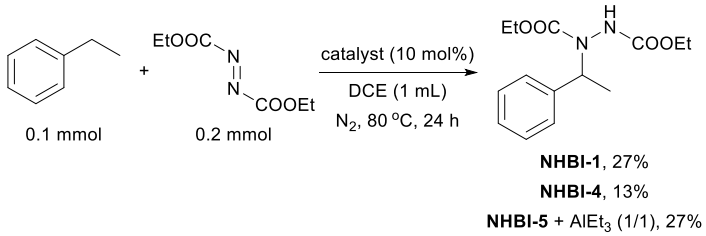
3a' **3a**

6 Gram-Scale Reaction



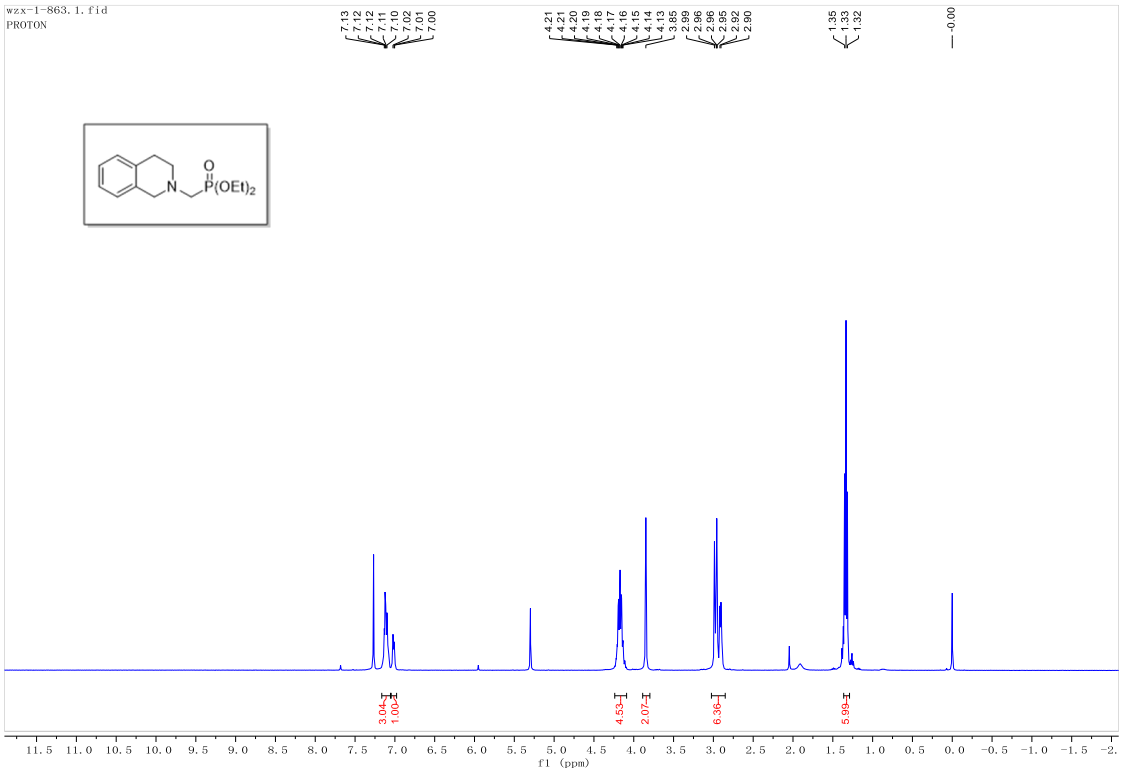
According to the general procedure, **1a** (2.61g, 9.2 mmol), **2a** (0.51g, 4.6 mmol), $NaHCO_3$ (4.6 mmol), CuBr (10 mol%), **NHBI-1** (10 mol%) and solvent (20 mL, CH_3CN:1,4-dioxane = 3:1) were added into sealed tube under oxygen atmosphere, and the mixture was stirred at 70 °C for 12 h. After the reaction, the mixture was filtered and purified by column chromatography (eluting with Hexane/EtOAc) to give **3a** (1.39g, 77%) as the product.

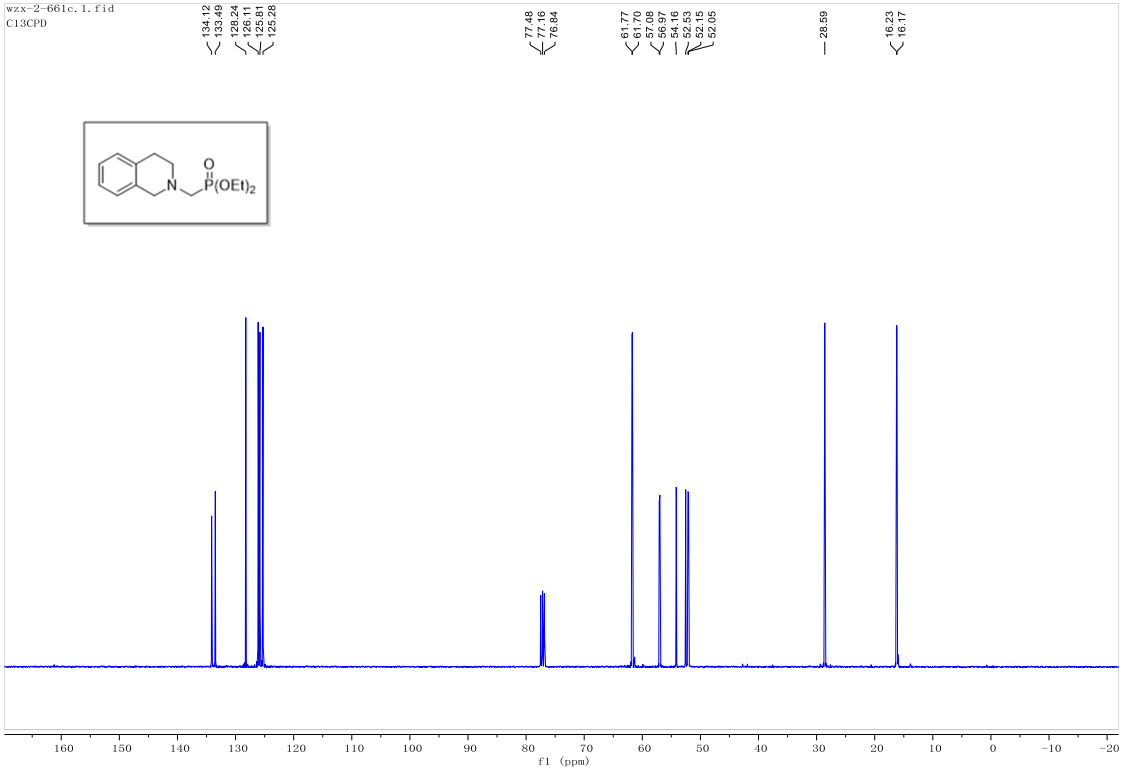
7 NHBI Catalyzed Other C–H Functionalization Reaction

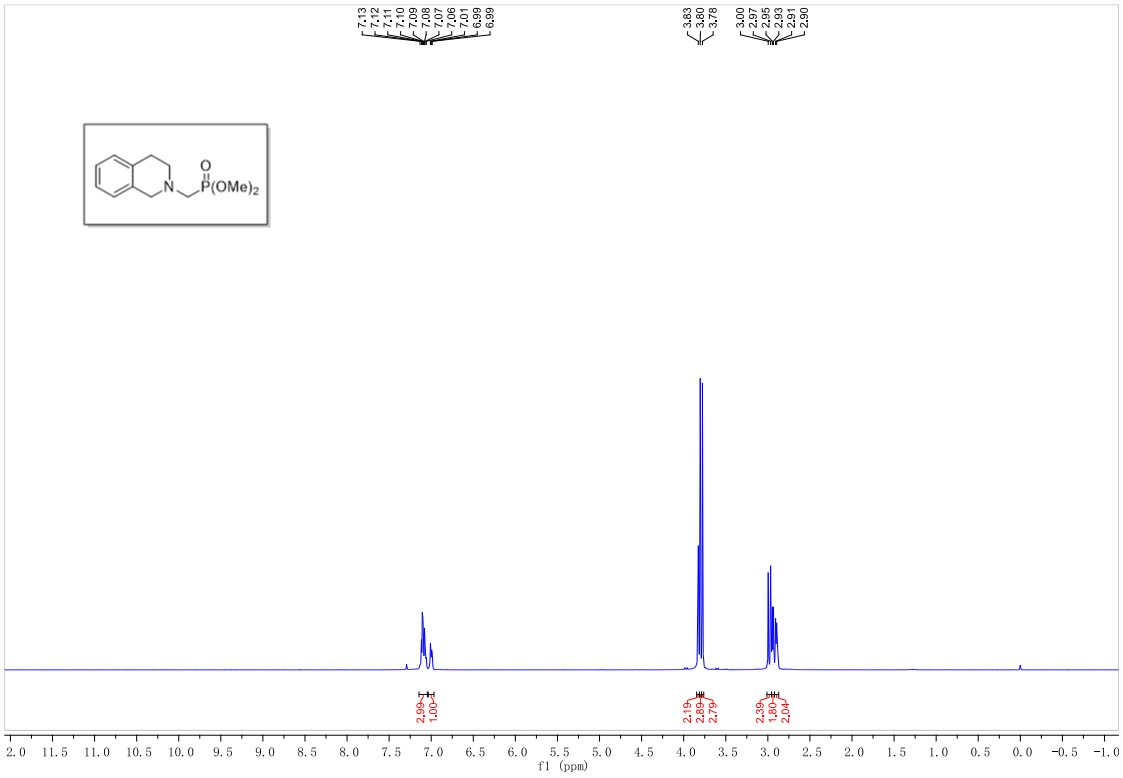


The premixed **NHBI-5** and $AlEt_3$ provided a comparable yield with **NHBI-1** in the reaction of benzylic C–H amination with diethyl azodicarboxylate under otherwise identical conditions. This result suggests the potential cooperative catalysis in this system. Obviously, further reaction condition optimization, modification of NHBI catalyst, mechanistic studies, etc., was required before practical application.

8 NMR Spectra



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7.10
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7.08
7.07
7.06
7.01
6.99
6.99
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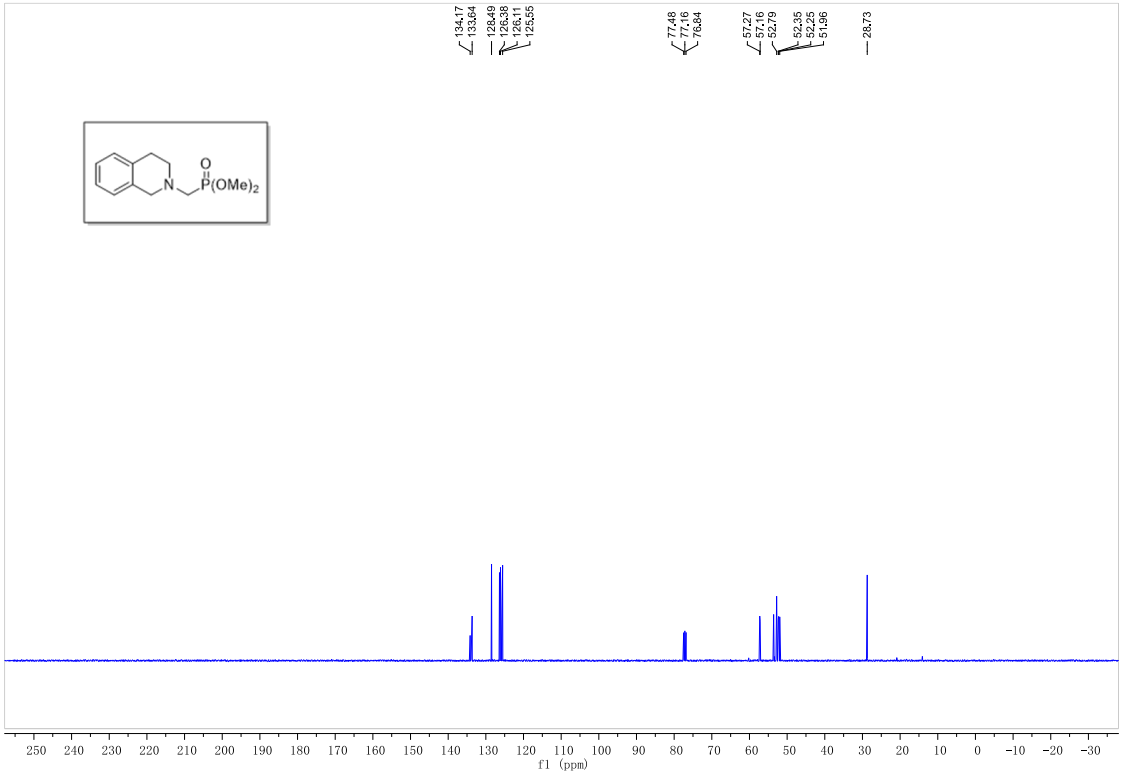
3.80
3.78
3.00
2.97
2.95
2.93
2.91
2.90
O
P(OMe)2
N
2.99
1.00
2.19
2.89
2.79
2.39
1.80
2.04
f1 (ppm)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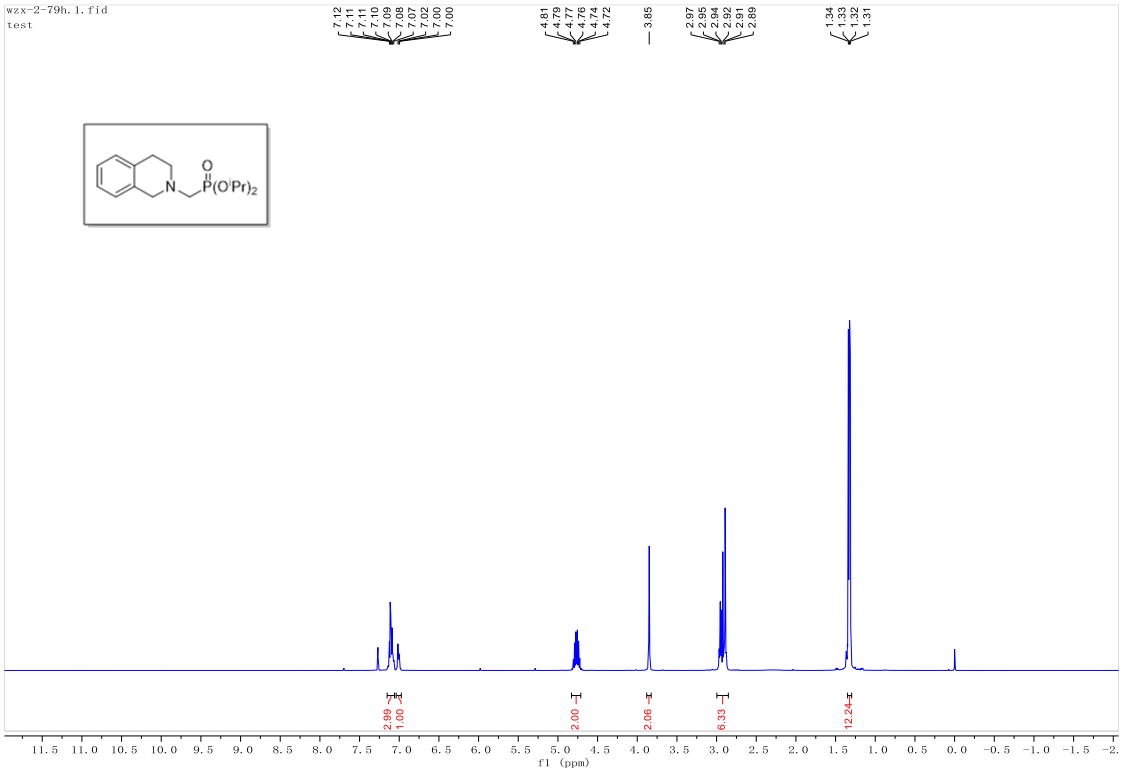
28.73
O
P(OMe)2
N
f1 (ppm)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7.08
7.07
7.02
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4.77
4.76
4.74
4.72
3.85
2.97
2.95
2.94
2.92
2.91
2.89
1.34
1.33
1.32
1.31
O
N
P(O^{i}Pr)$_2$
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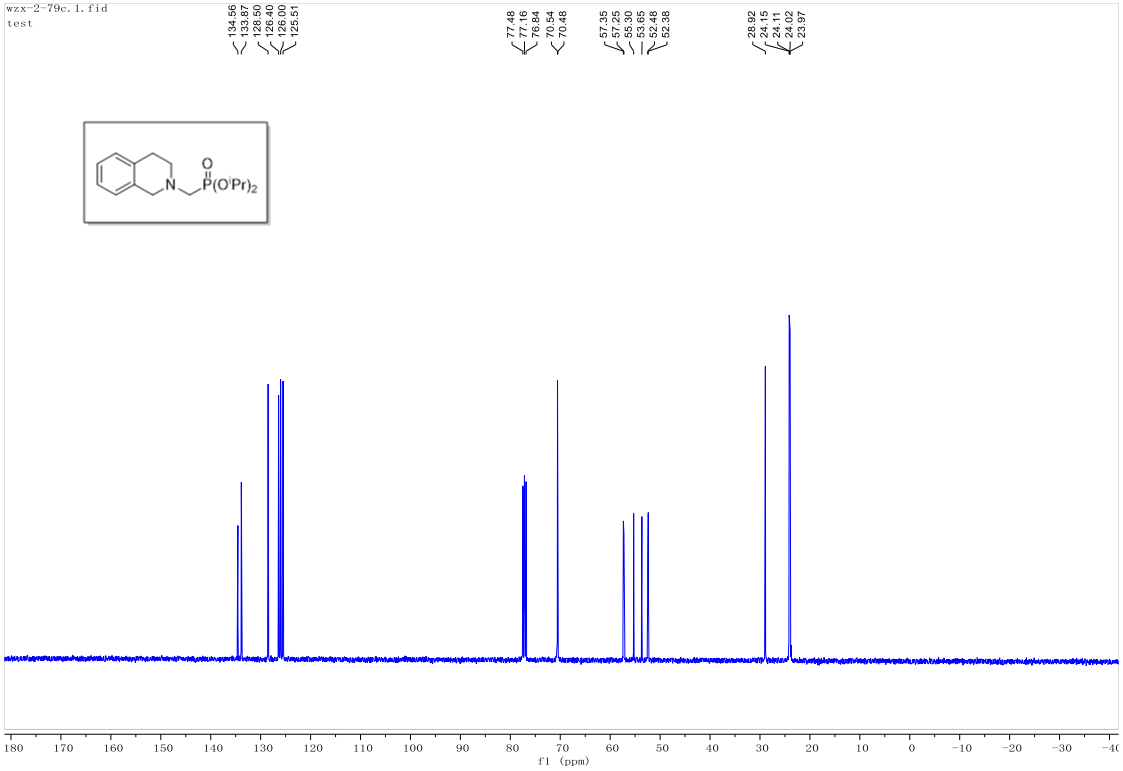
1.00
2.00
2.06
6.33
12.24
f1 (ppm)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77.16
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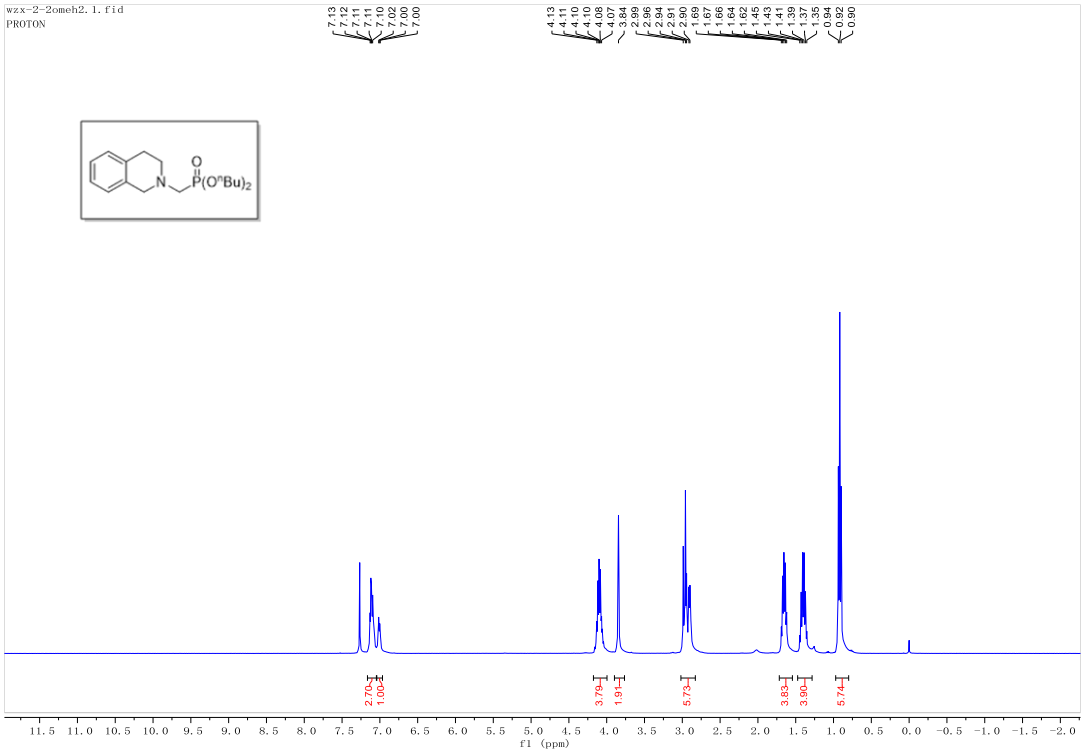
70.48
57.35
57.25
55.30
53.65
52.48
52.38
28.92
24.15
24.11
24.02
23.97
O
N
P(O^{i}Pr)$_2$
f1 (ppm)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7.11
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7.02
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7.00
4.13
4.11
4.10
4.10
4.08
4.07
3.84
2.99
2.96
2.94
2.91
2.90
1.69
1.67
1.66
1.64
1.62
1.45
1.43
1.41
1.39
1.37
1.35
0.94
0.92
0.90
O
N
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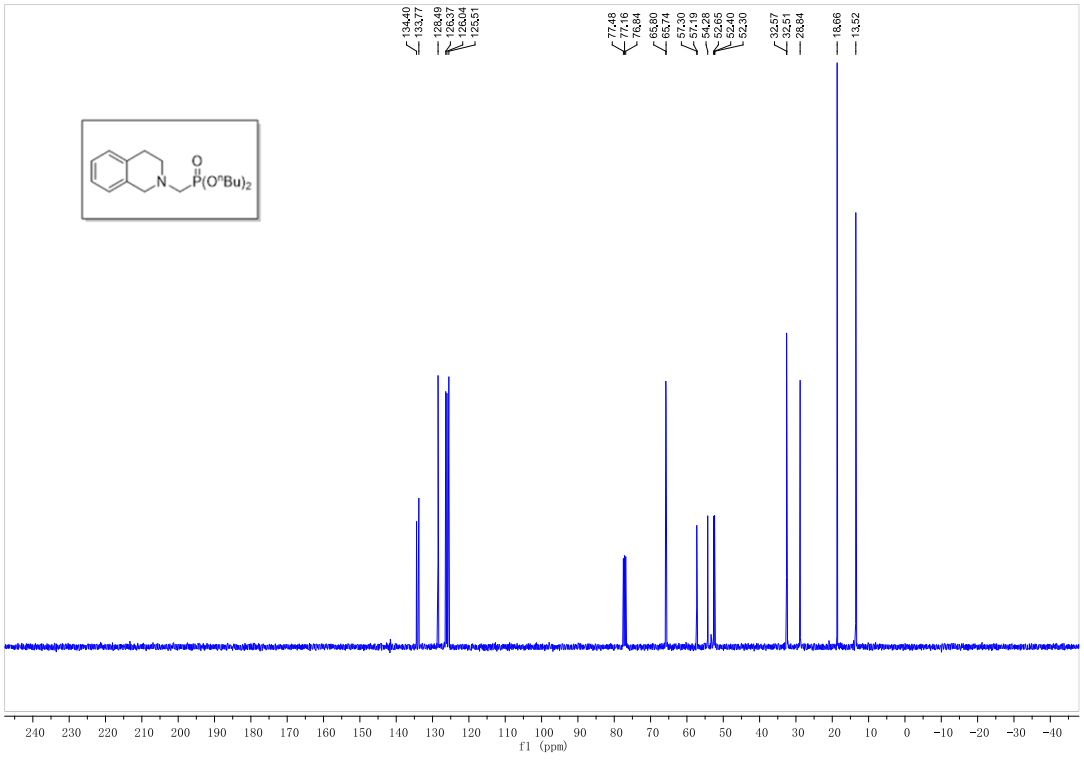
3.83
3.90
5.74
f1 (ppm)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57.19
54.28
52.65
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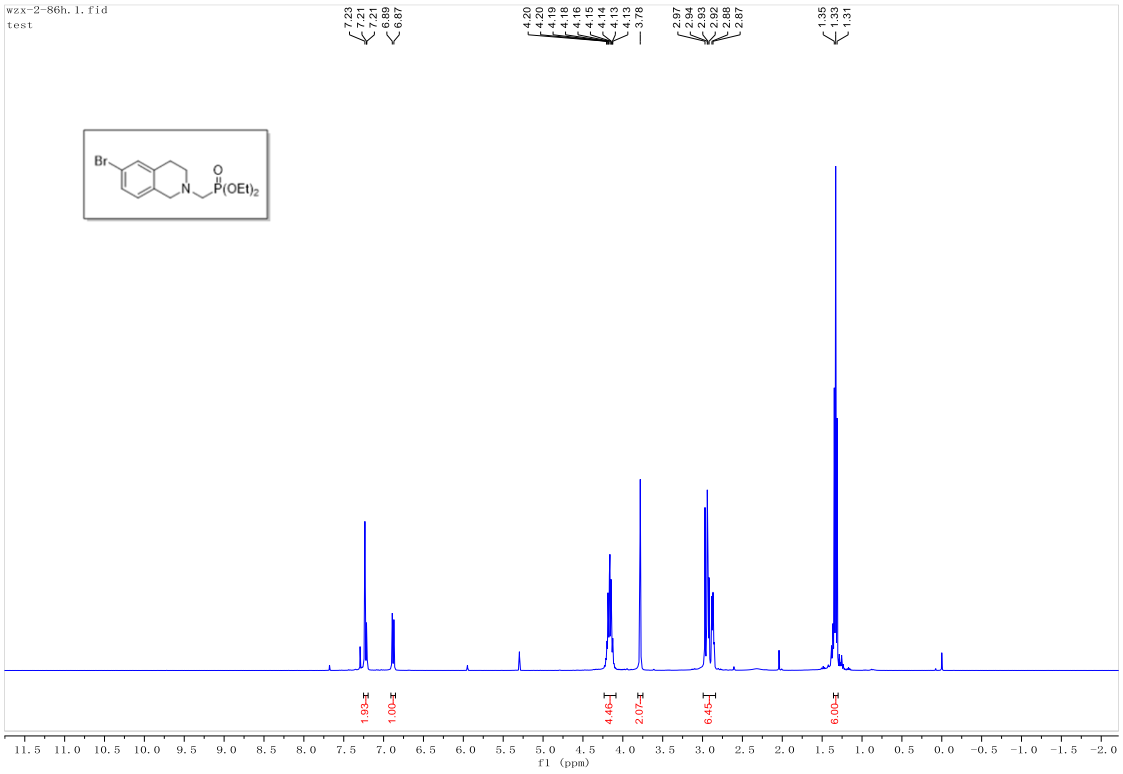
32.51
26.84
18.66
13.52
O
N
P(O^{n}Bu)$_2$
f1 (ppm)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4.18
4.16
4.15
4.14
4.13
4.13
3.78
2.97
2.94
2.93
2.92
2.88
2.87
1.35
1.33
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N
P(OEt)2
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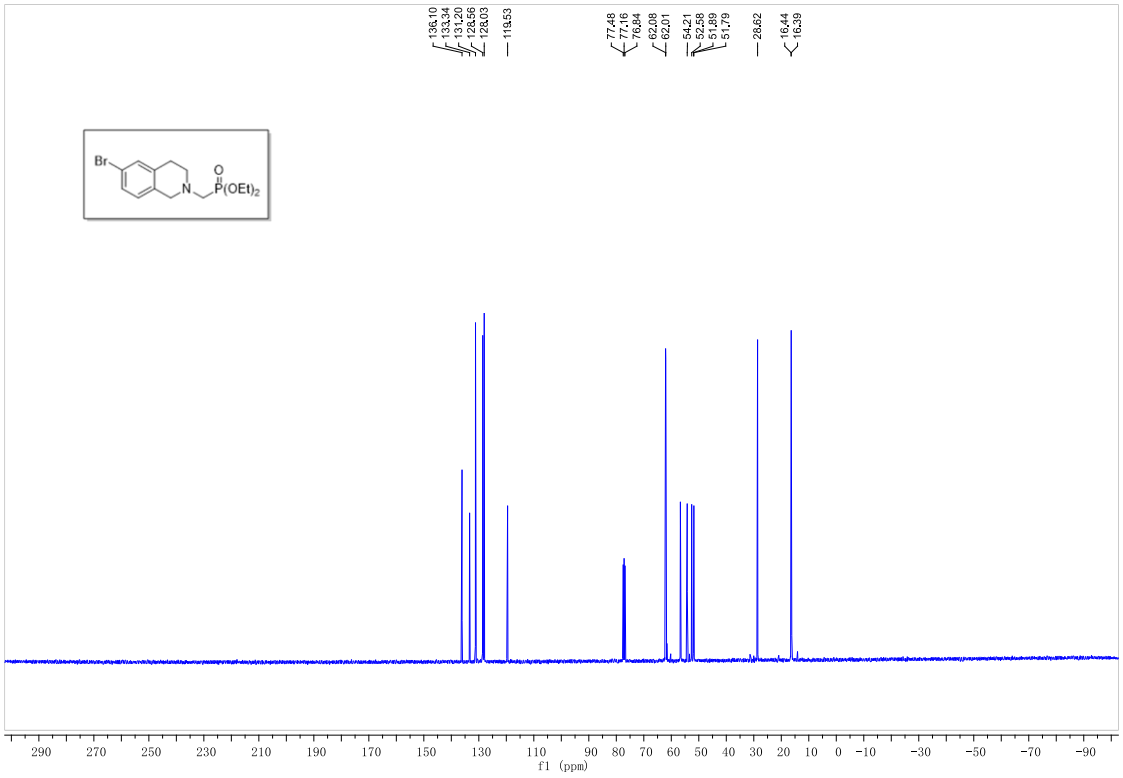
2.07
6.45
6.00
f1 (ppm)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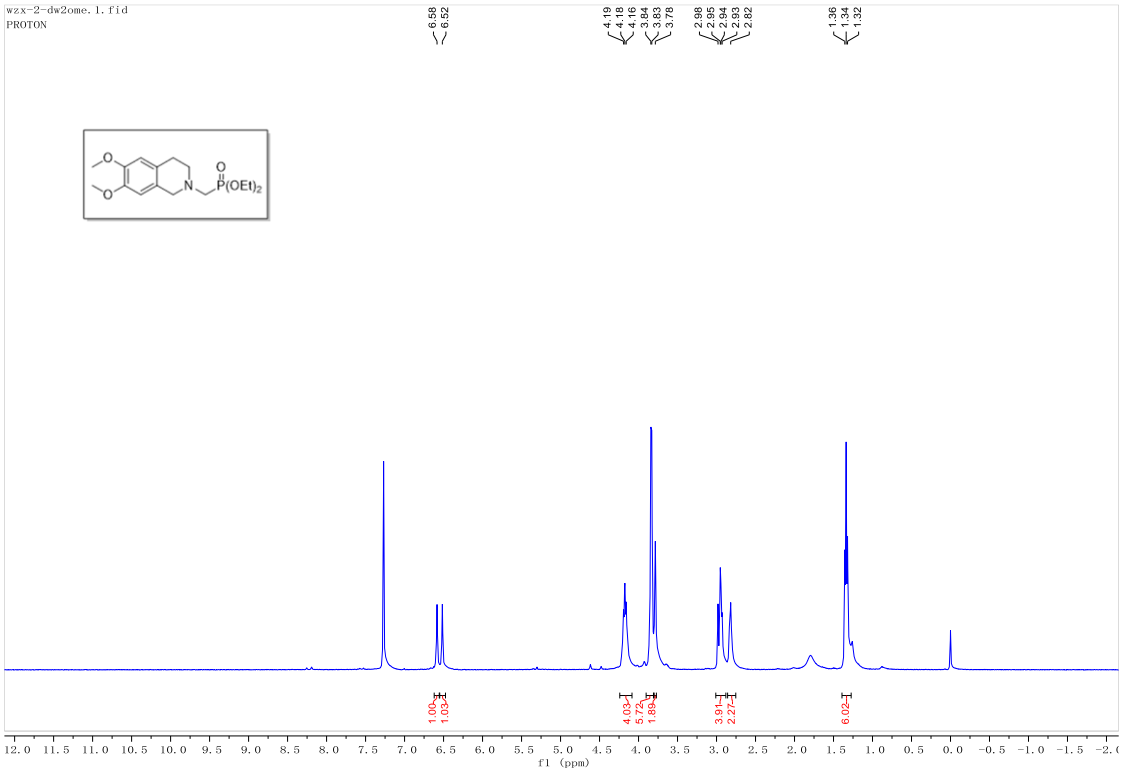
Br
O
N
P(OEt)2
f1 (ppm)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3.91
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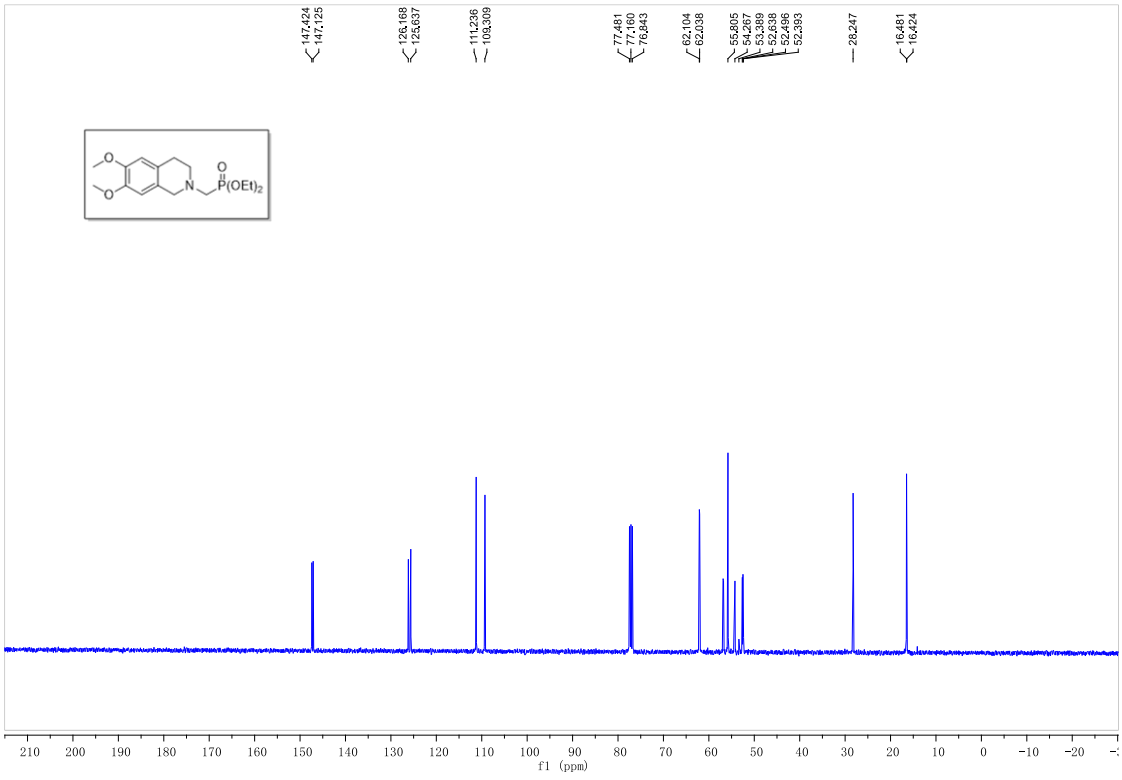
6.02
f1 (ppm)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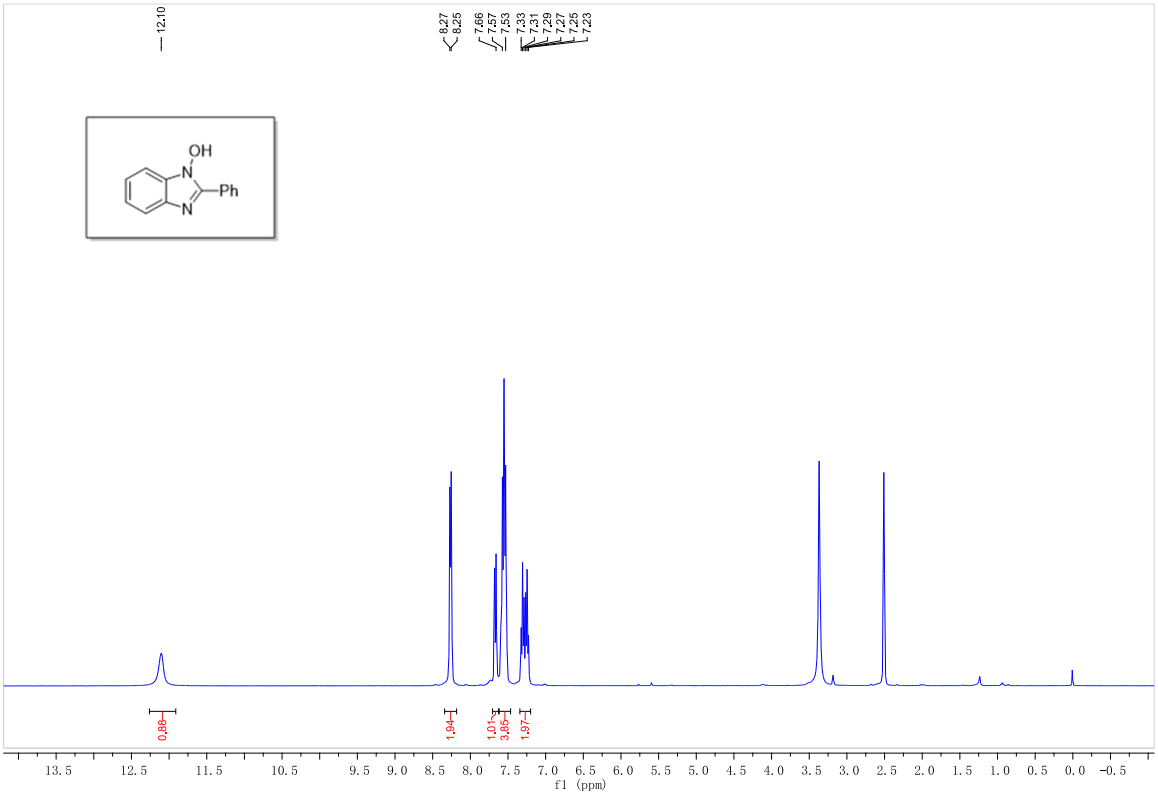
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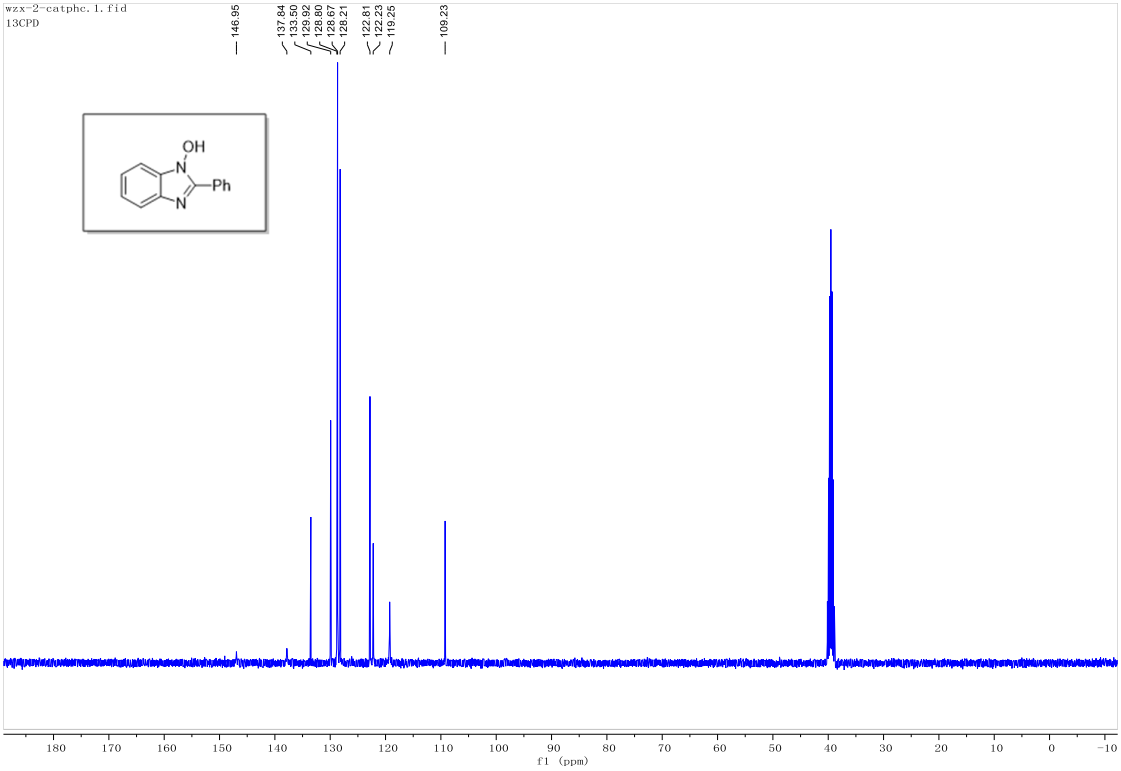
7.25
7.23
OH
N
Ph
N
0.88
1.94
1.01
3.85
1.97
13.5 12.5 11.5 10.5 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)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109.23
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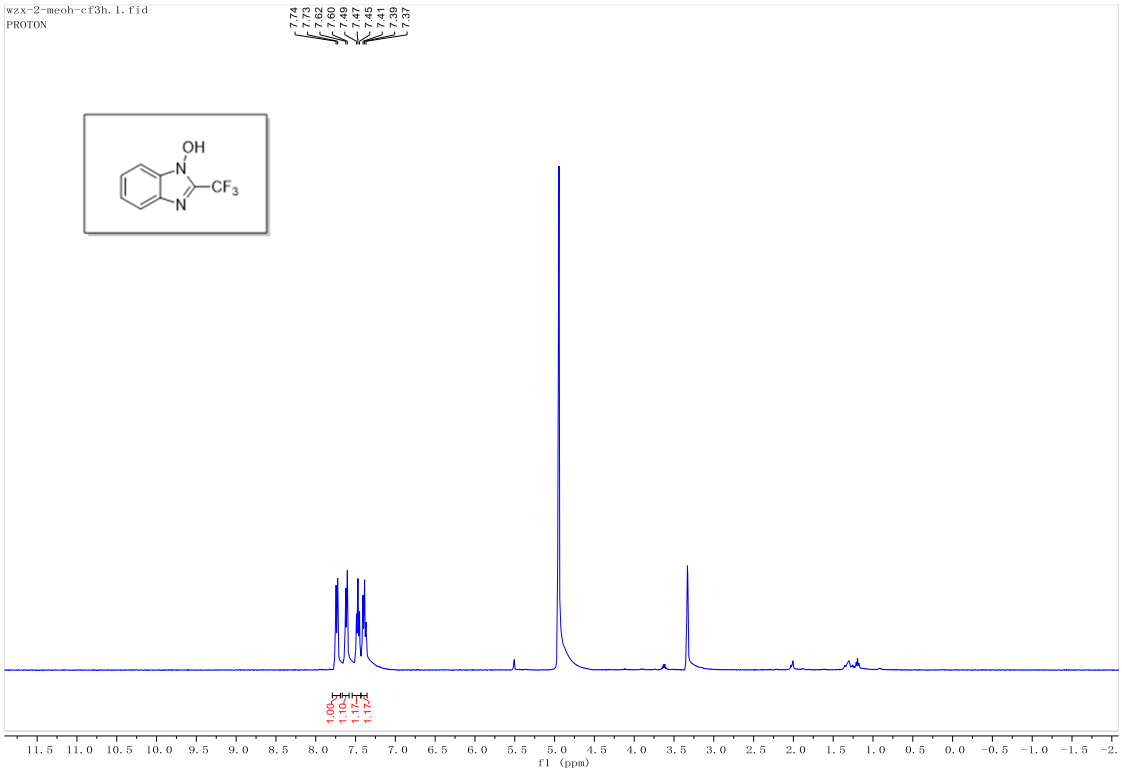
N
Ph
N
180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)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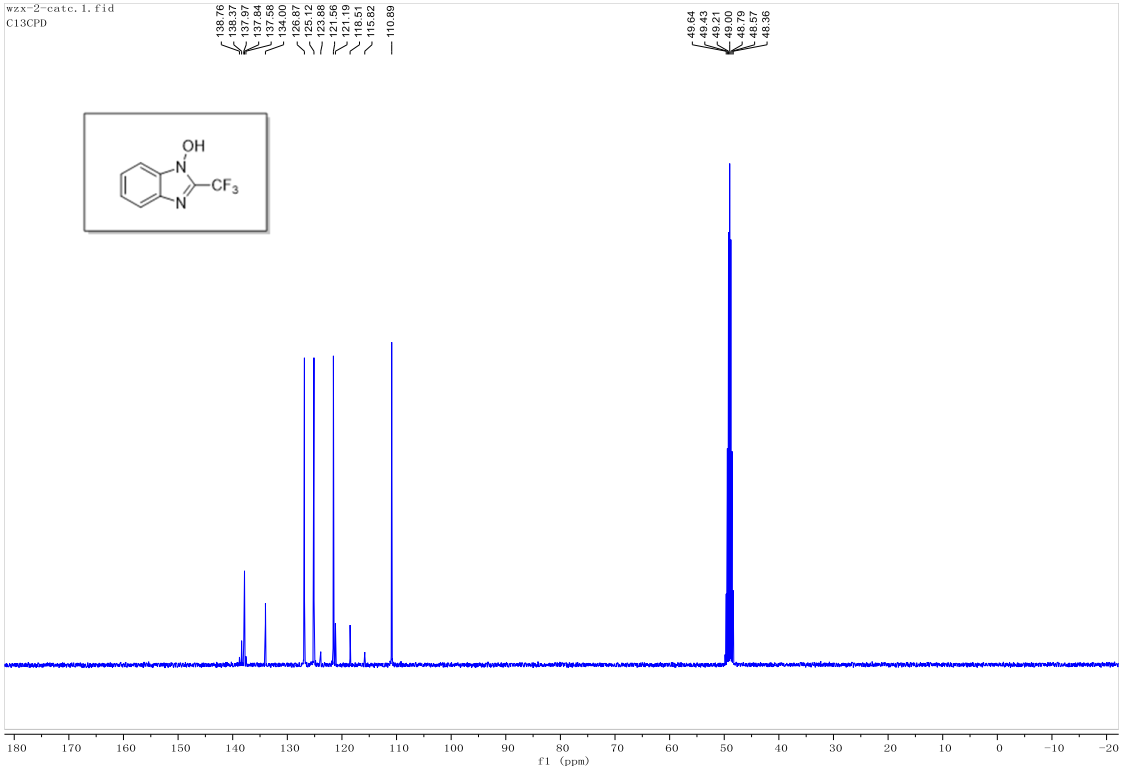
f1 (ppm)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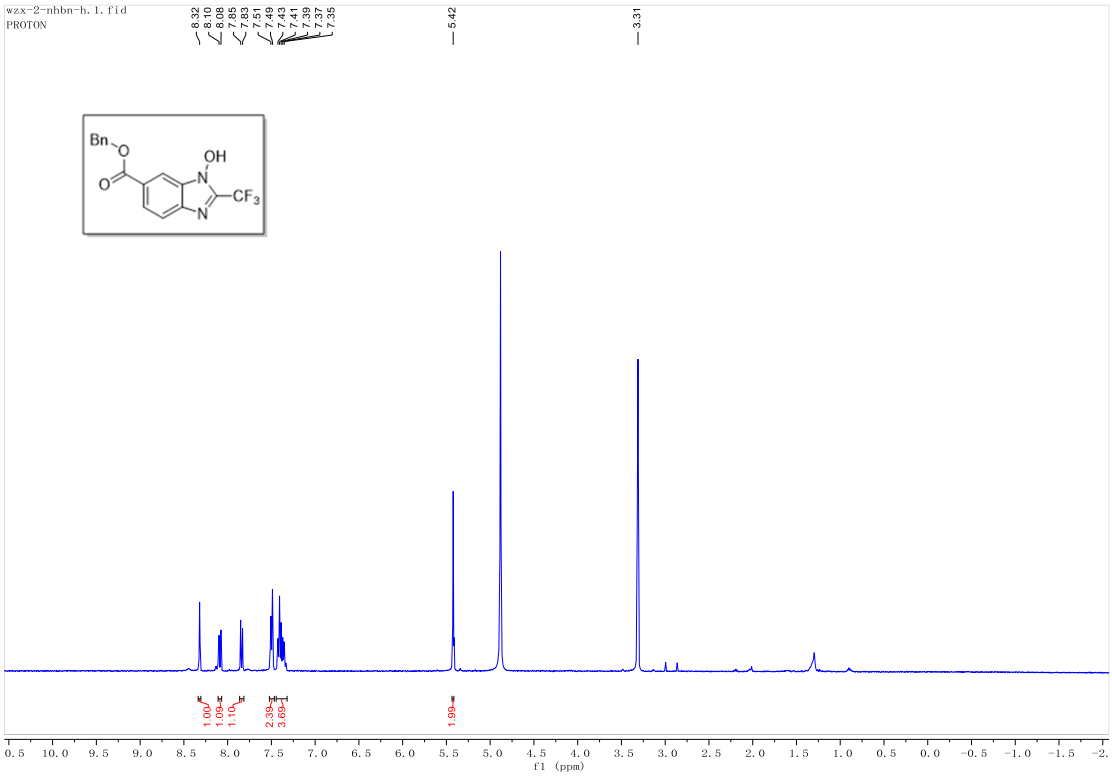
OH
N
CF3
N
f1 (ppm)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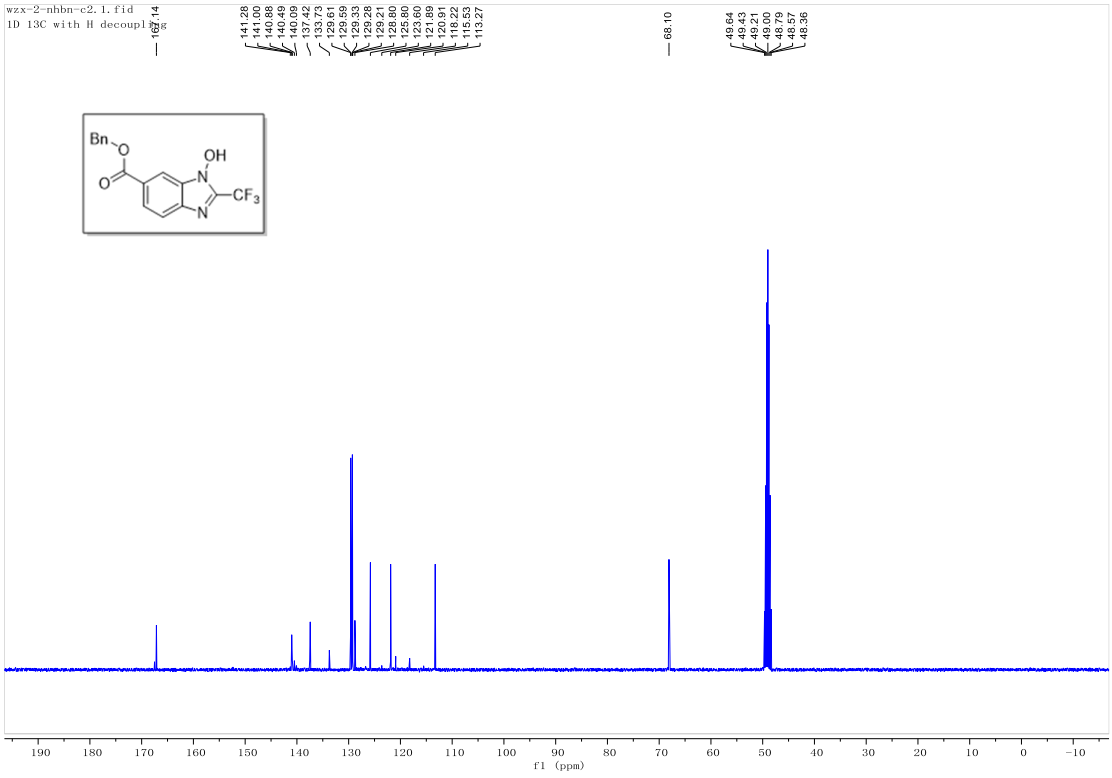
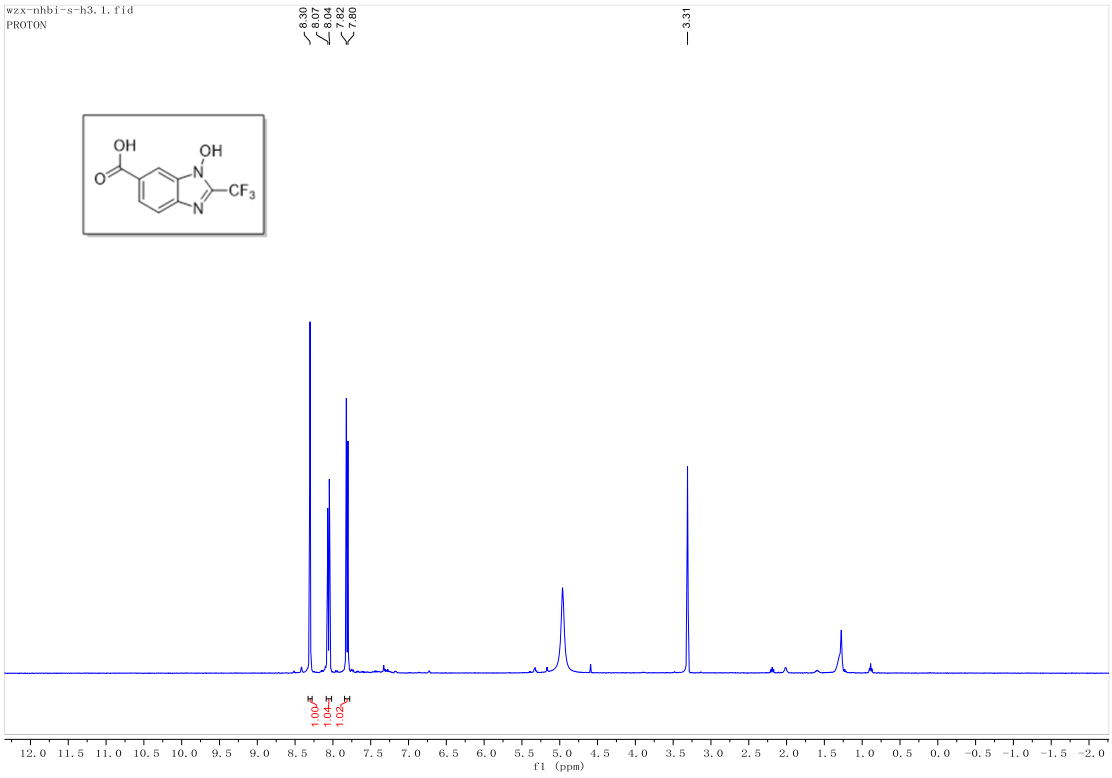
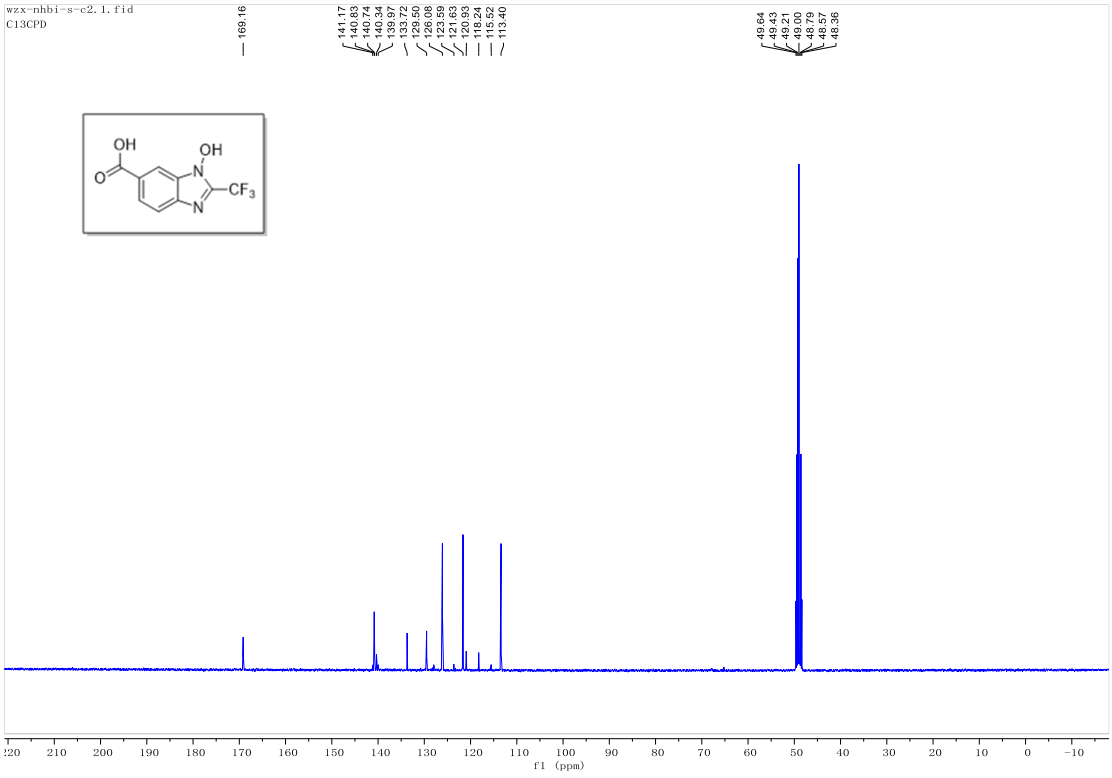
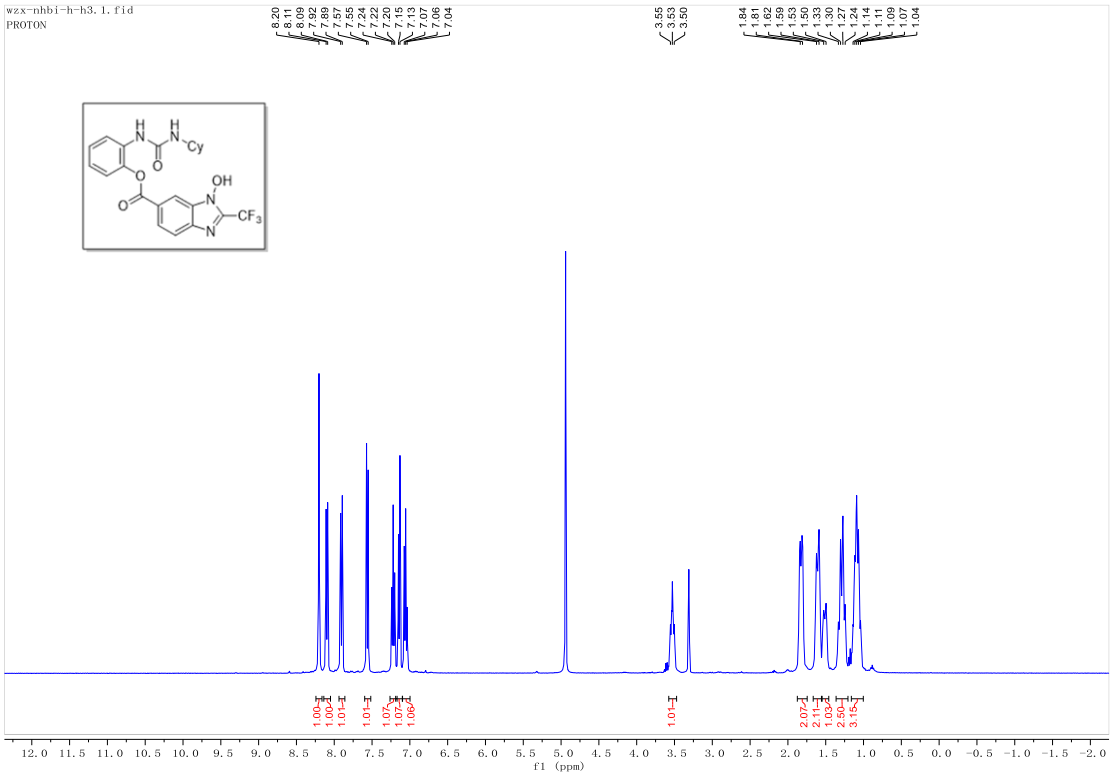
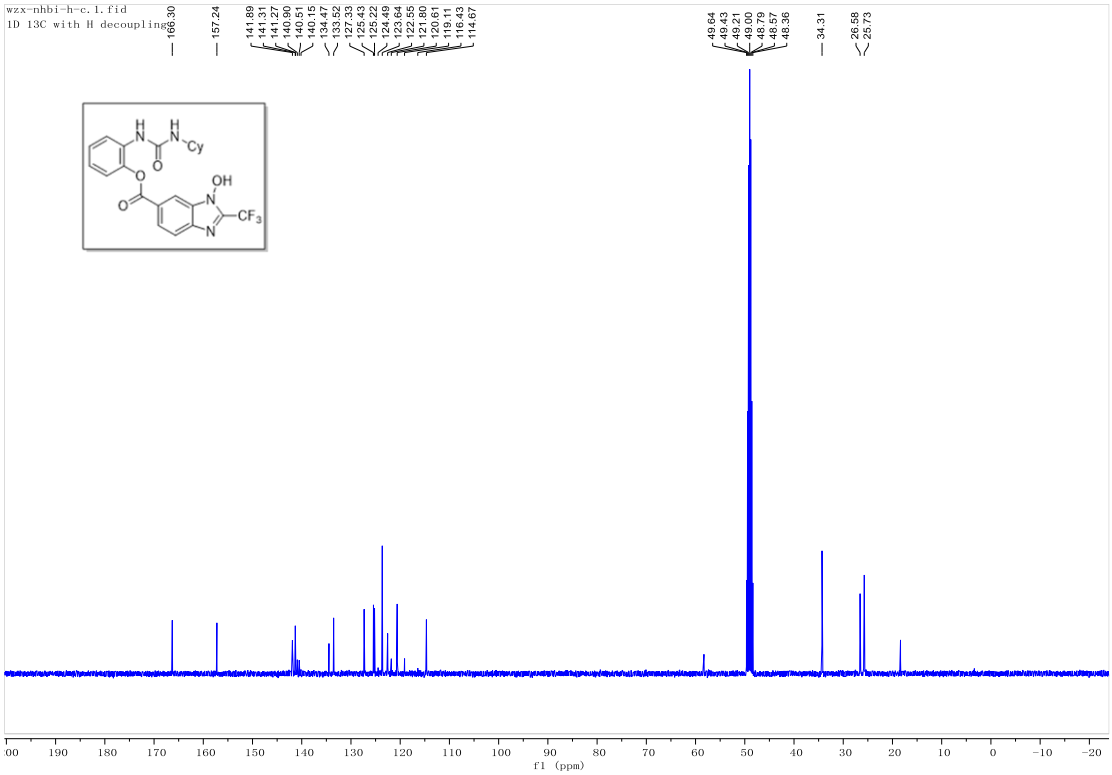
7.39
7.37
7.35
5.42
3.31
Bn
O
OH
N
CF3
1.00
1.09
1.10
2.39
3.68
1.99
f1 (ppm)

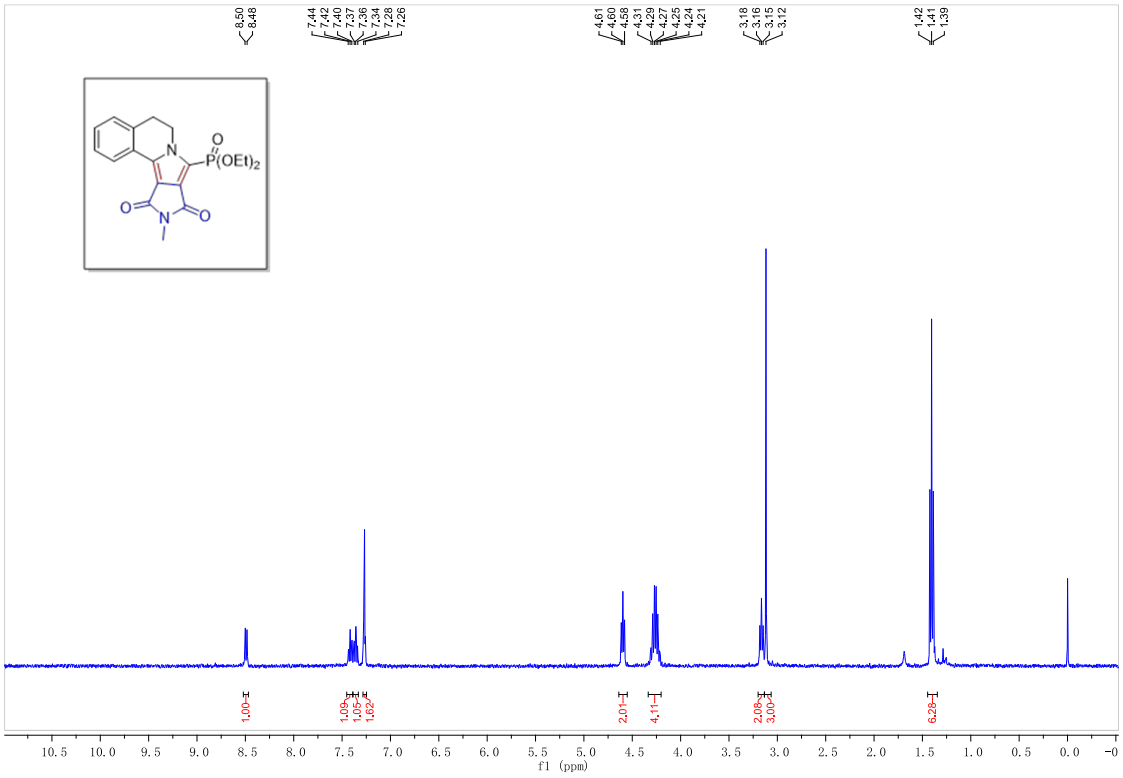

wzx-2-nhbn-c2.1.fid
1D 13C with H decoupl
167.14
141.28
141.00
140.88
140.46
140.09
137.42
133.73
129.61
129.59
129.33
129.28
129.21
128.80
125.80
123.60
121.89
120.91
118.22
115.53
113.27
68.10
49.64
49.43
49.21
49.00
48.79
48.57
48.36
Bn
O
OH
N
CF3
f1 (ppm)

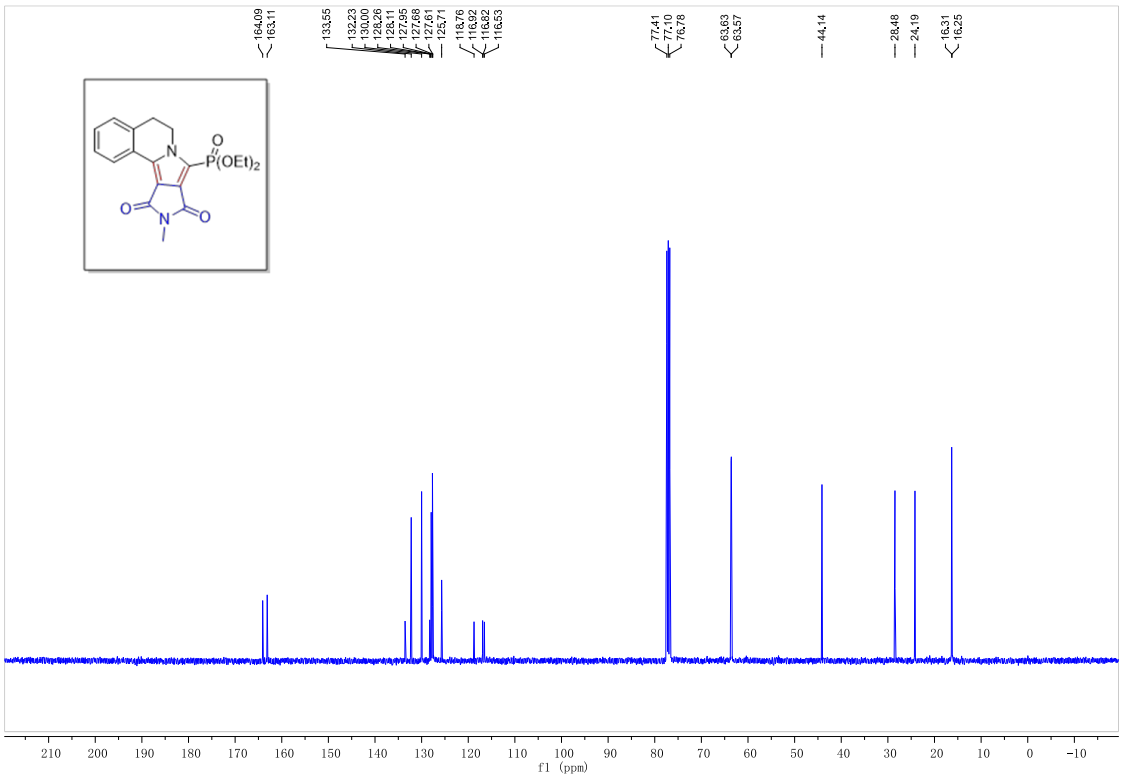

wzx-nhbi-s-h3.1.fid
PROTON
8.30
8.07
8.04
7.82
7.80
3.31
OH
OH
N
N
CF3
O
1.00
1.04
1.05
f1 (ppm)

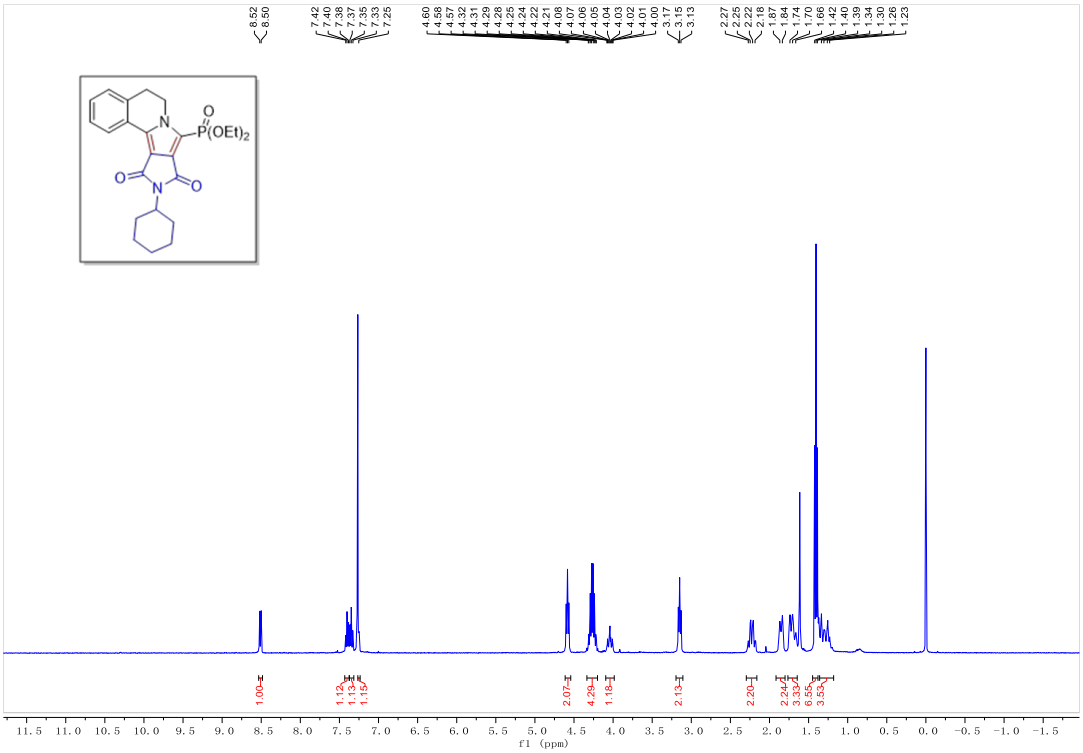

wzx-nhbi-s-c2.1.fid
C13CPD
169.16
141.17
140.83
140.74
140.34
139.97
133.72
129.50
126.08
123.59
121.63
120.93
118.24
115.52
113.40
49.64
49.43
49.21
49.00
48.79
48.57
48.36
OH
OH
N
N
CF3
O
f1 (ppm)

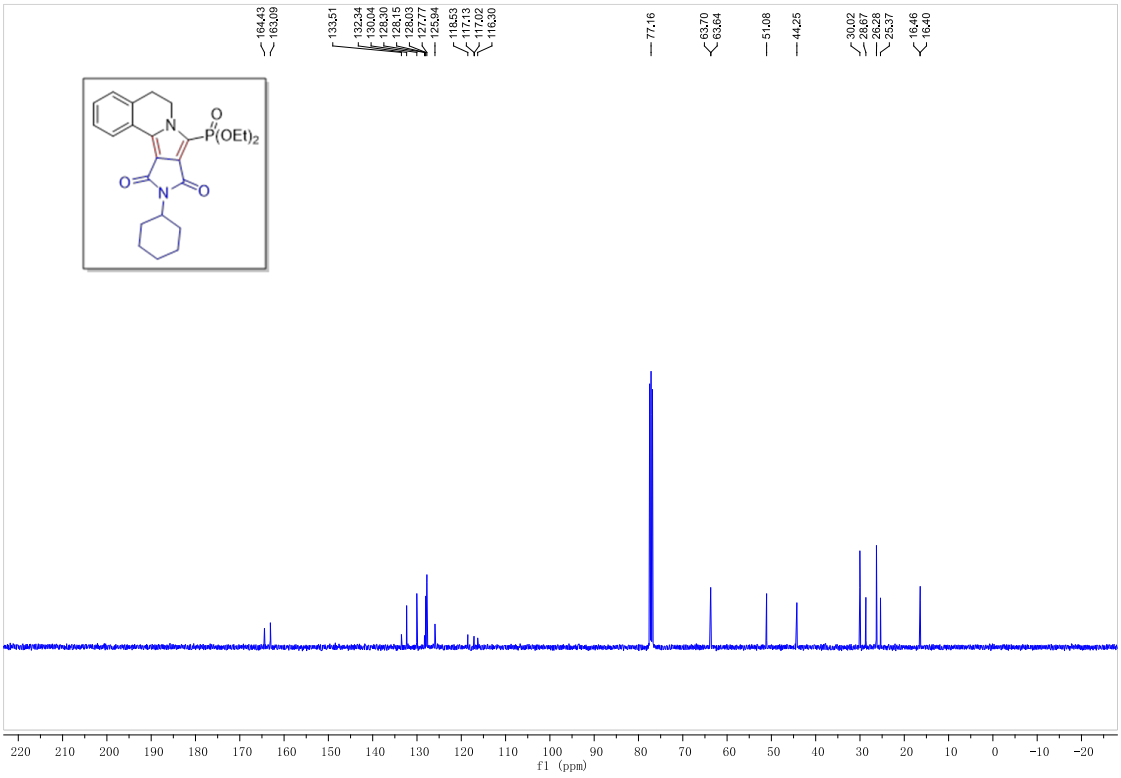

wzx-nhbi-h-h3.1.fid
PROTON
8.20
8.11
8.09
7.92
7.89
7.57
7.55
7.24
7.22
7.20
7.15
7.13
7.07
7.06
7.04
3.55
3.53
3.50
1.84
1.81
1.62
1.59
1.53
1.50
1.33
1.30
1.27
1.24
1.14
1.11
1.09
1.07
1.04
Cy
OH
CF3
1.00
1.00
1.01
1.01
1.07
1.07
1.06
1.01
2.07
2.11
1.03
2.04
3.16
f1 (ppm)

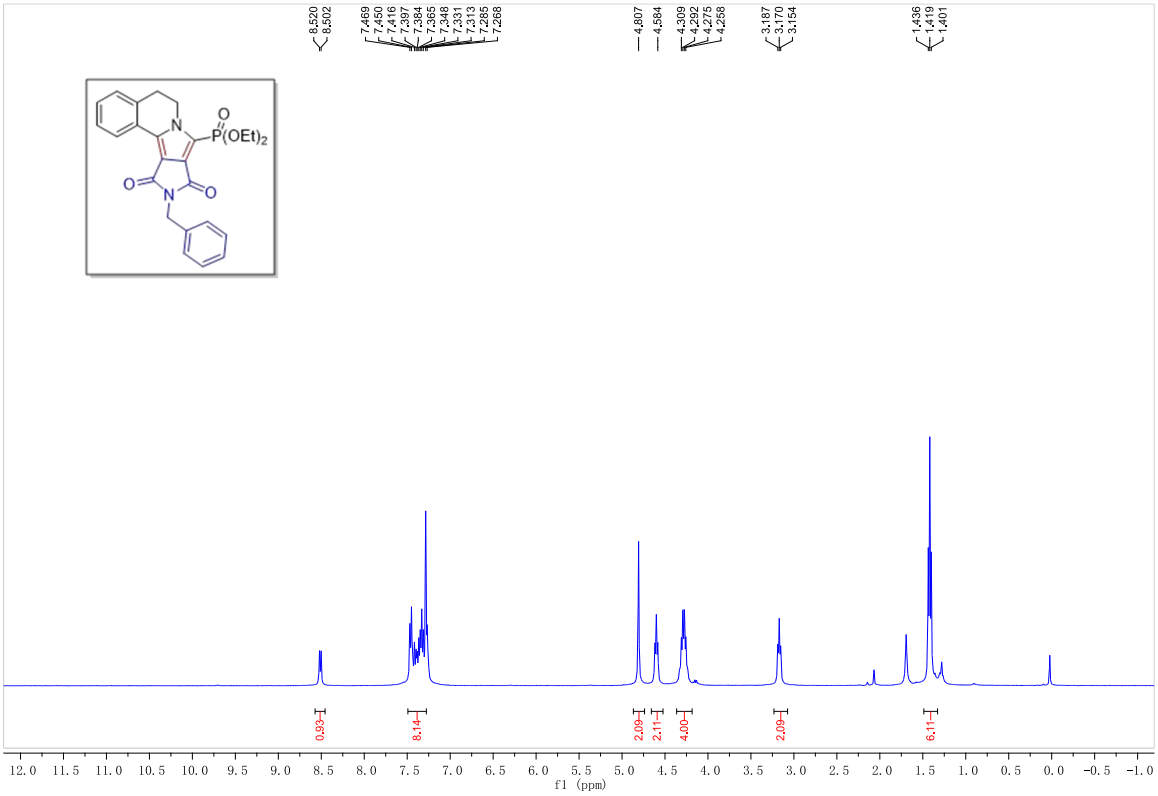

wzx-nhbi-h-c.1.fid
1D 13C with H decoupling
166.30
157.24
141.89
141.31
141.27
140.90
140.51
140.15
134.47
133.52
127.33
125.43
125.22
124.49
123.64
122.55
121.80
120.61
119.11
116.43
114.67
49.64
49.43
49.21
49.00
48.79
48.57
48.36
34.31
26.58
25.73
Cy
OH
CF3
f1 (ppm)


8.50
8.48
7.44
7.42
7.40
7.37
7.36
7.34
7.28
7.26
4.61
4.60
4.58
4.31
4.29
4.27
4.25
4.24
4.21
3.18
3.16
3.15
3.12
1.42
1.41
1.39
O
P(OEt)2
O
N
O
1.00
1.09
1.05
1.62
2.01
4.11
2.08
3.00
6.28
f1 (ppm)


164.09
163.11
133.55
132.23
130.00
128.26
128.11
127.95
127.68
127.61
125.71
118.76
116.92
116.82
116.53
77.41
77.10
76.78
63.63
63.57
44.14
28.48
24.19
16.31
16.25
O
P(OEt)2
O
N
O
f1 (ppm)


8.52
8.50
7.42
7.40
7.38
7.37
7.35
7.33
7.25
4.60
4.58
4.57
4.32
4.31
4.29
4.28
4.25
4.24
4.22
4.21
4.08
4.07
4.06
4.05
4.04
4.03
4.02
4.01
4.00
3.17
3.15
3.13
2.27
2.25
2.22
2.18
1.87
1.84
1.74
1.70
1.66
1.42
1.40
1.39
1.34
1.30
1.26
1.23
P(OEt)2
1.00
1.12
1.13
1.15
2.07
4.29
1.18
2.13
2.20
2.24
3.33
6.55
3.53
f1 (ppm)


164.43
163.09
133.51
132.34
130.04
128.30
128.15
128.03
127.77
125.94
118.53
117.13
117.02
116.30
77.16
63.70
63.64
51.08
44.25
30.02
28.67
26.28
25.37
16.46
16.40
P(OEt)2
f1 (ppm)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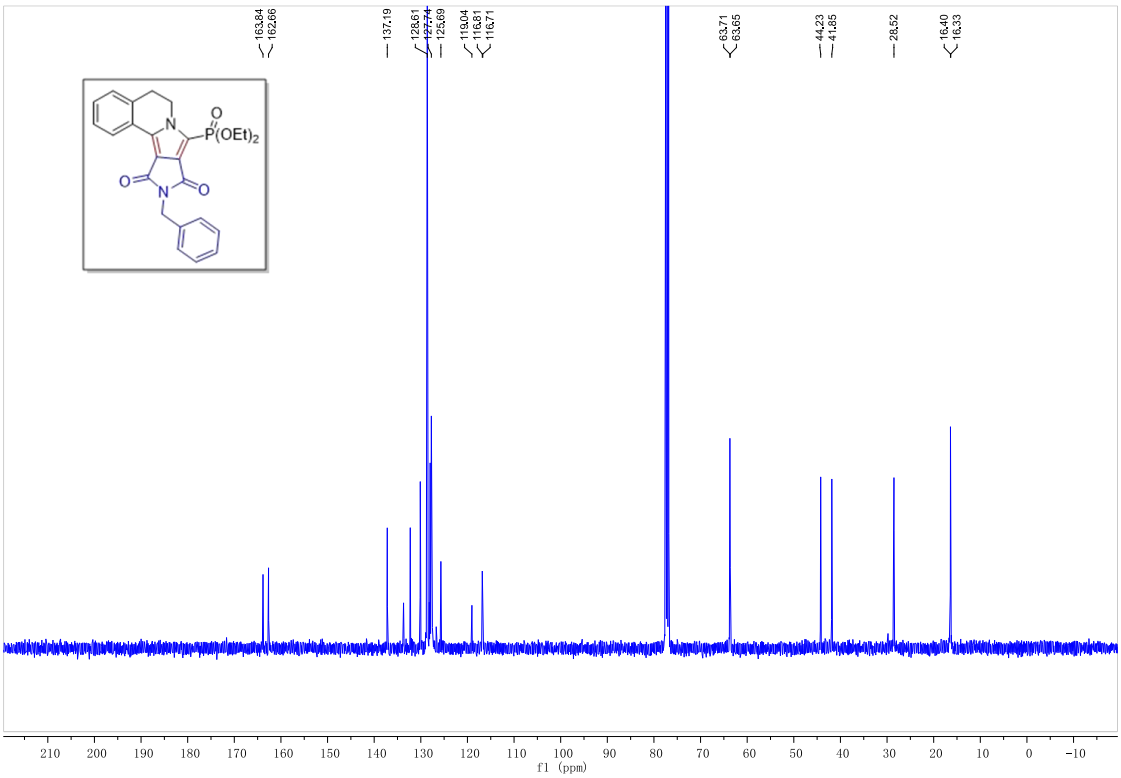
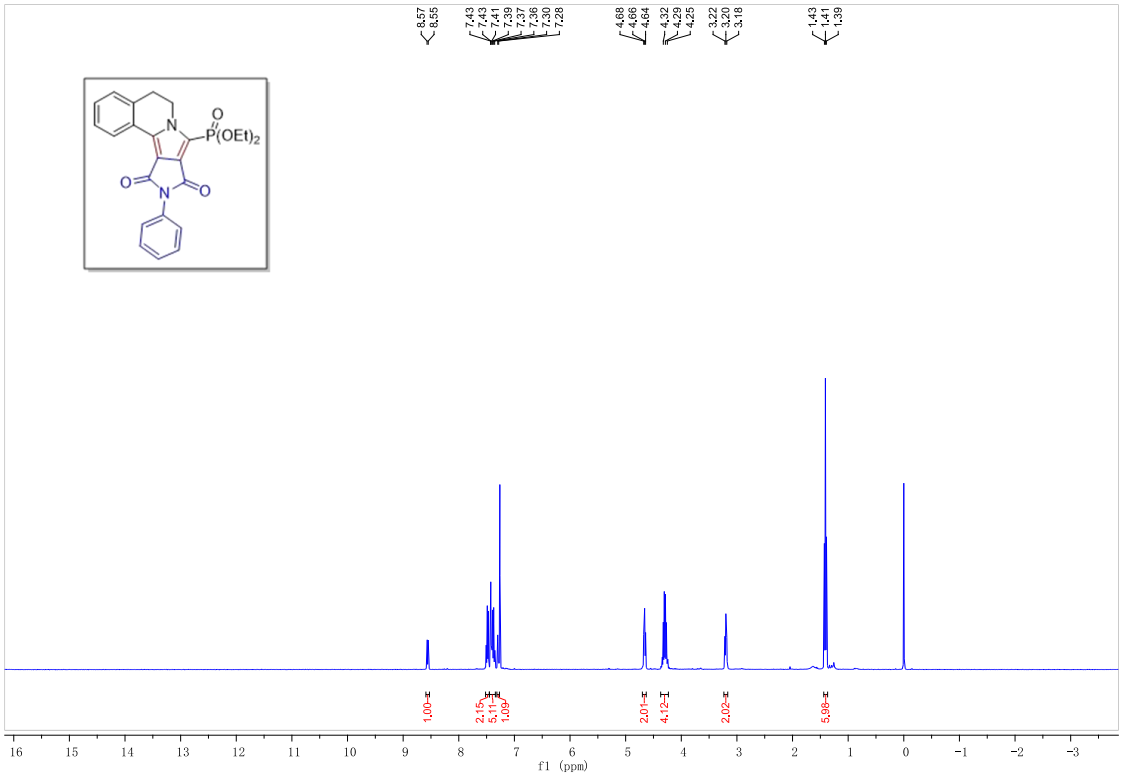
8.502
7.469
7.460
7.416
7.397
7.384
7.365
7.348
7.331
7.313
7.285
7.268
4.807
4.584
4.309
4.292
4.275
4.258
3.187
3.170
3.154
1.436
1.419
1.401
P(OEt)2
0.93
8.14
2.09
2.11
4.00
2.09
6.11
f1 (ppm)


163.84
162.66
137.19
128.61
127.74
125.69
119.04
116.61
116.71
63.71
63.65
44.23
41.85
28.52
16.40
16.33
P(OEt)2
f1 (ppm)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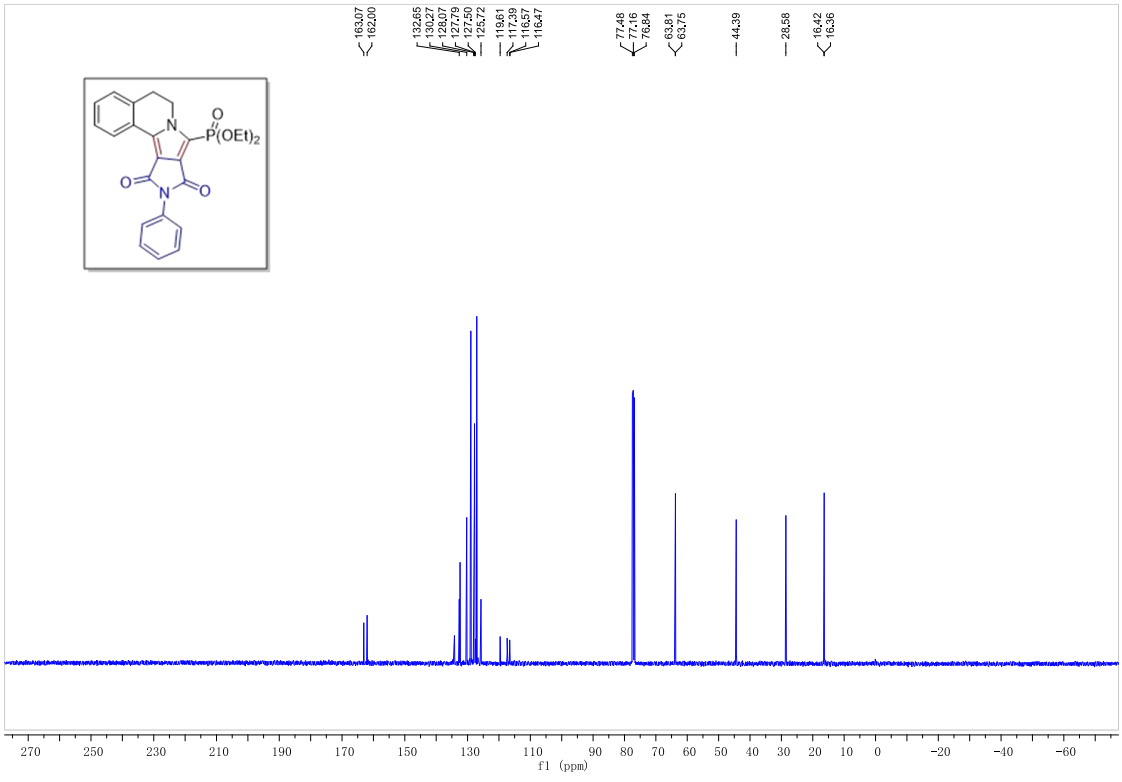
8.55
7.43
7.43
7.41
7.39
7.37
7.36
7.30
7.28
4.68
4.66
4.64
4.32
4.29
4.25
3.22
3.20
3.18
1.43
1.41
1.39
1.00
2.15
5.11
1.09
2.01
4.12
2.02
5.98
f1 (ppm)


163.07
162.00
132.65
130.27
128.07
127.79
127.50
125.72
119.61
117.39
116.57
116.47
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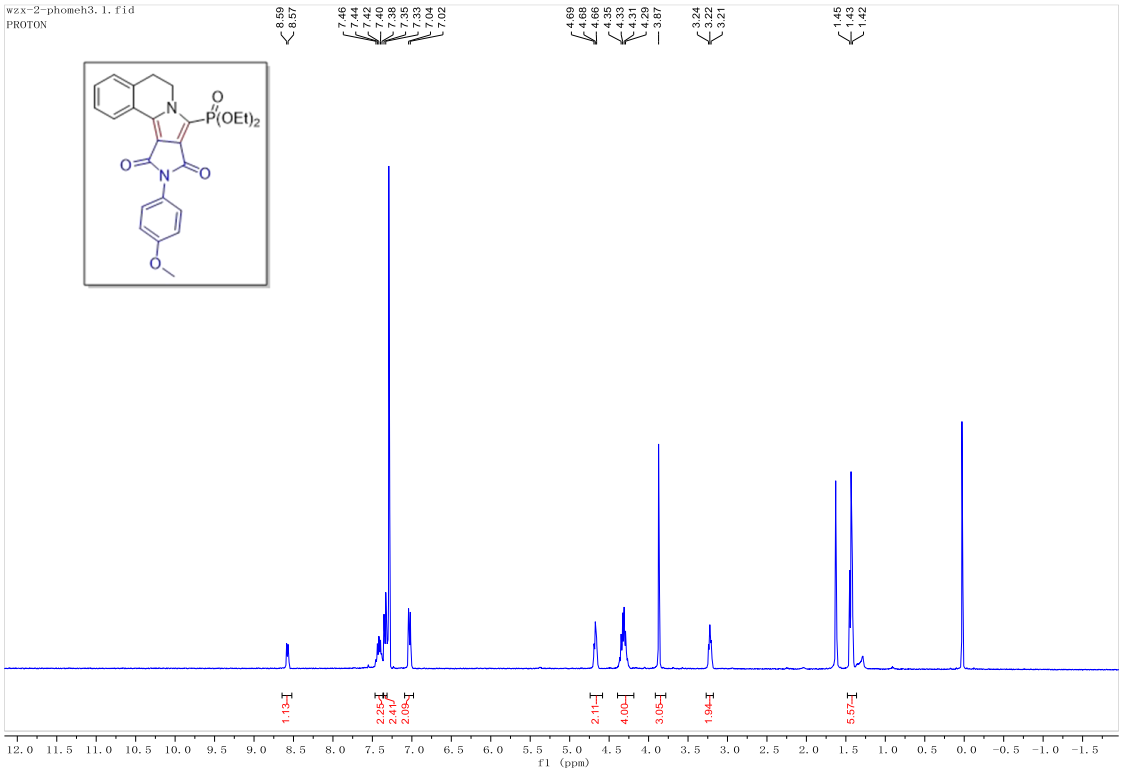
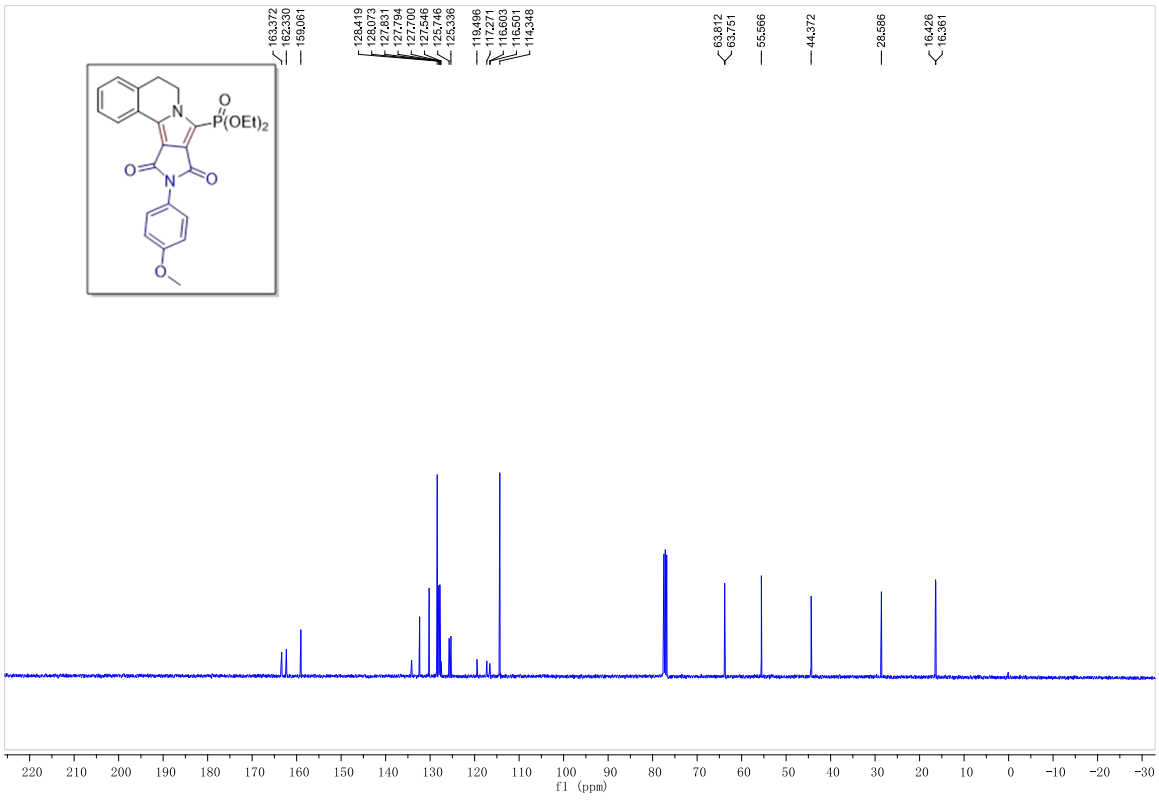
44.39
28.58
16.42
16.36
f1 (ppm)


wzx-2-phomeh3.1.fid
PROTON
8.59
8.57
7.46
7.44
7.42
7.40
7.38
7.35
7.33
7.04
7.02
4.69
4.68
4.66
4.35
4.33
4.31
4.29
3.87
3.24
3.22
3.21
1.45
1.43
1.42
1.13
2.25
2.41
2.09
2.11
4.00
3.05
1.94
5.57
f1 (ppm)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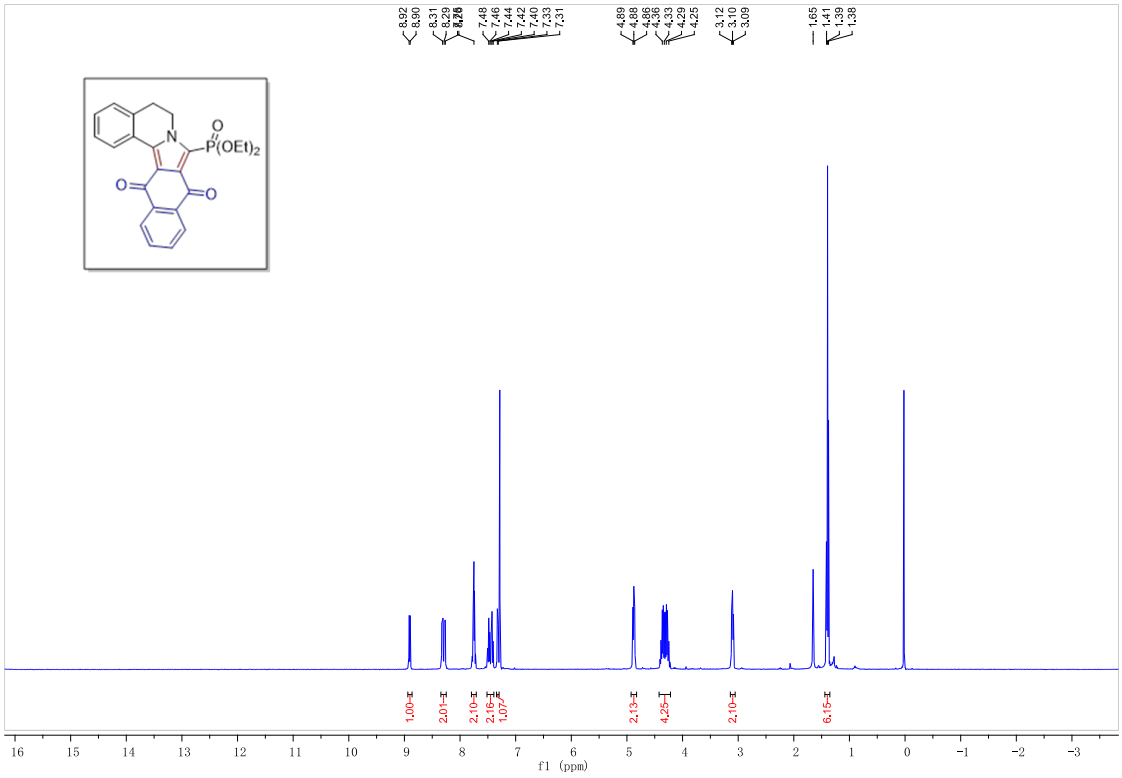
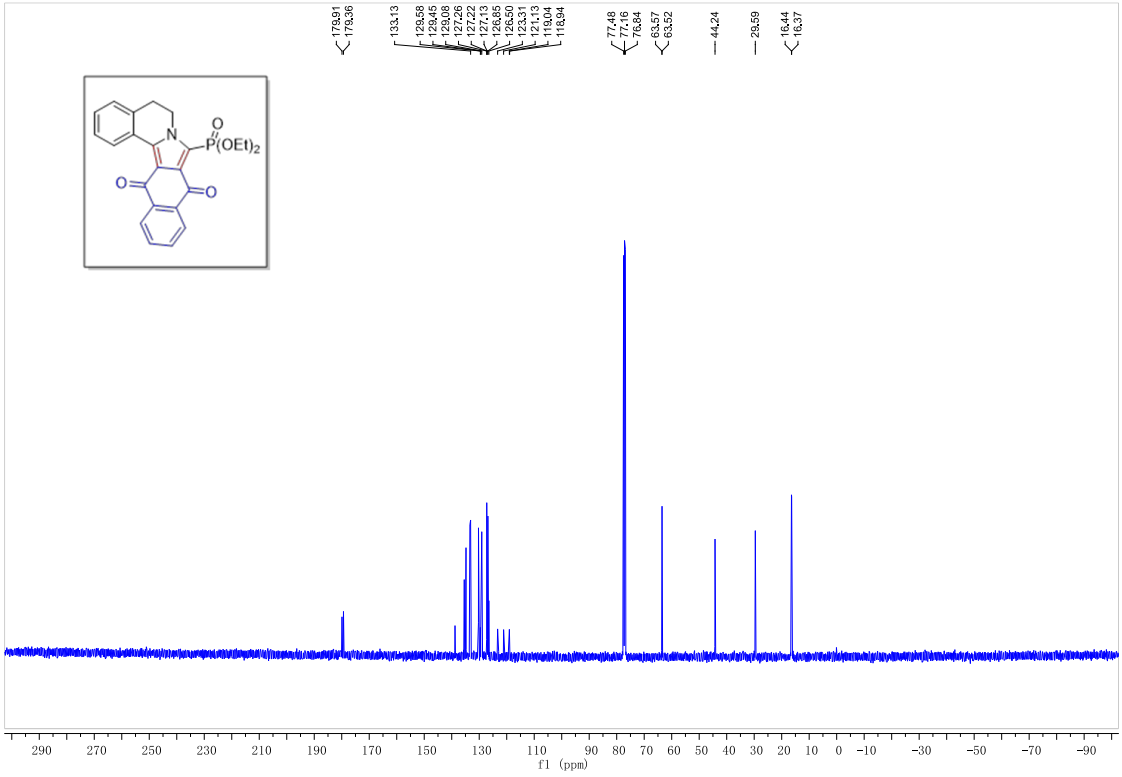
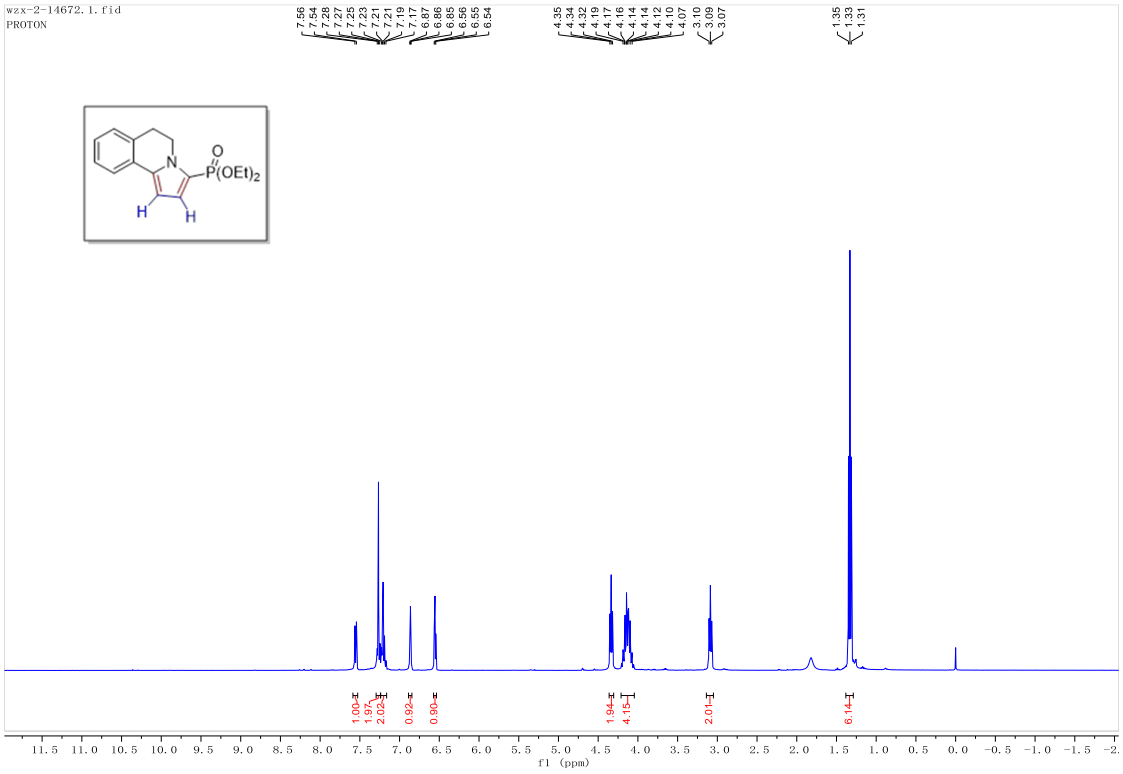
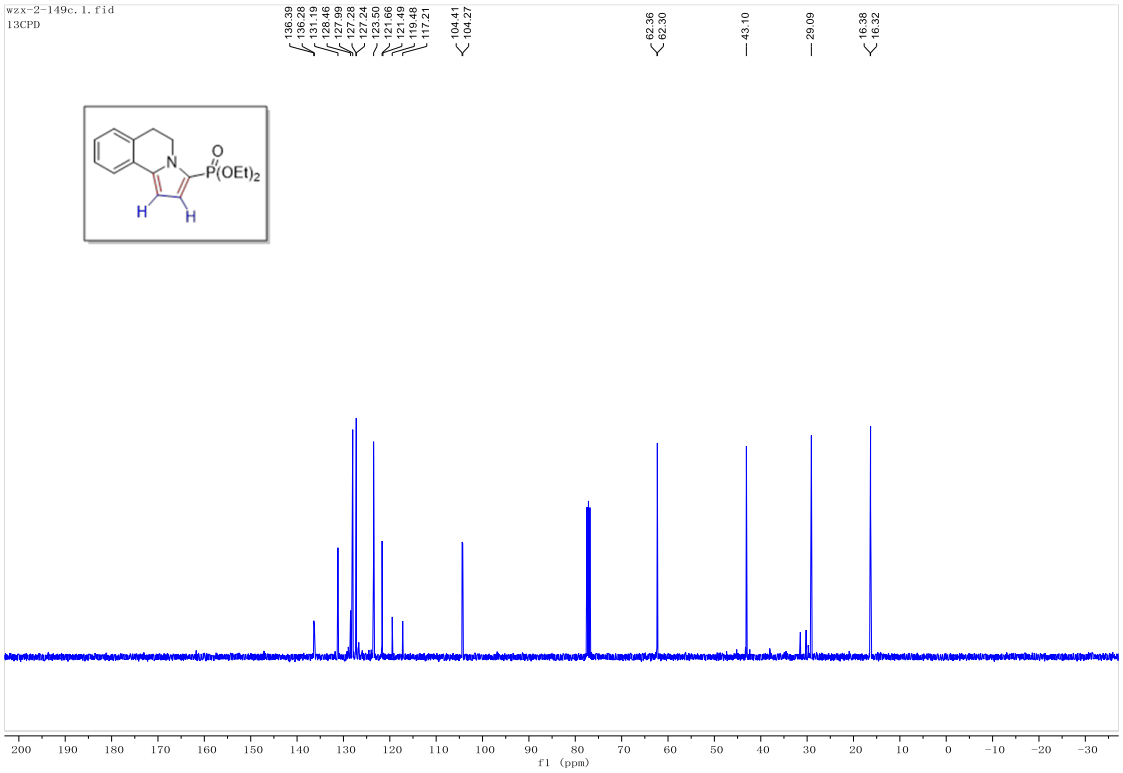
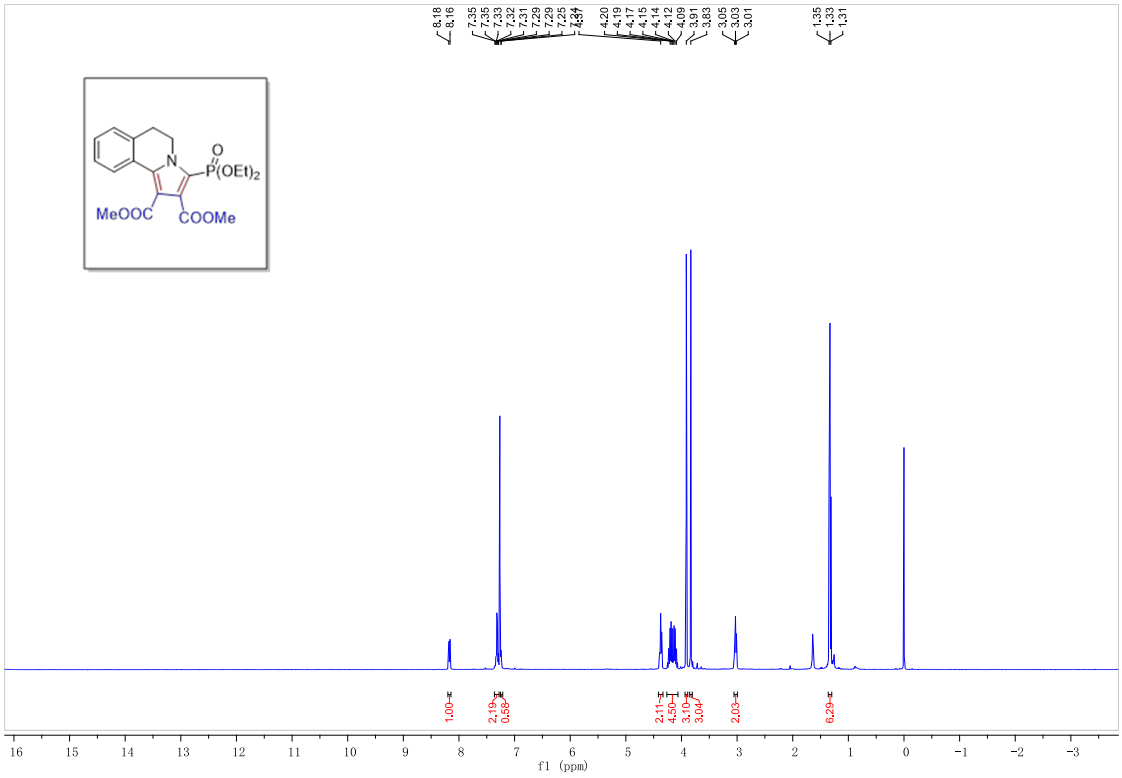
162.330
159.061
128.419
128.073
127.831
127.794
127.700
127.546
125.746
125.336
119.496
117.271
116.603
116.501
114.348
63.812
63.751
55.566
44.372
28.586
16.426
16.361
f1 (ppm)

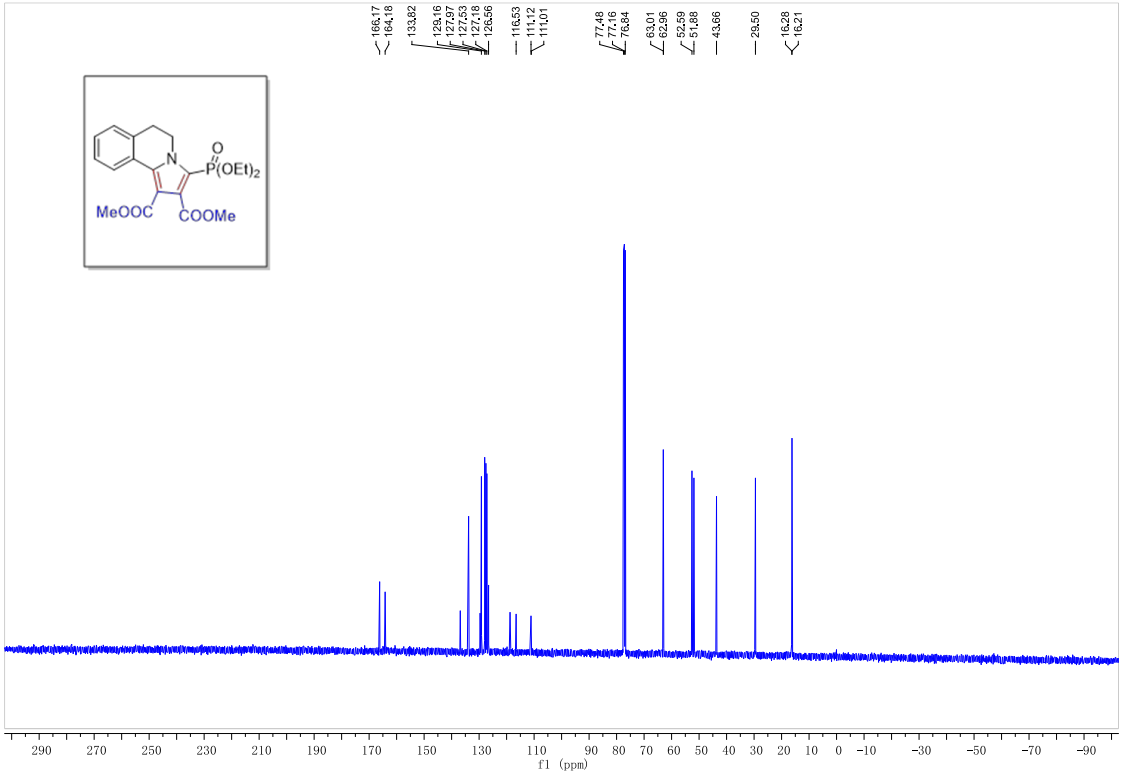

8.92
8.90
8.31
8.29
7.48
7.46
7.44
7.42
7.40
7.33
7.31
4.89
4.88
4.86
4.33
4.29
4.25
3.12
3.10
3.09
1.65
1.41
1.39
1.38
1.00
2.01
2.10
2.16
1.07
2.13
4.25
2.10
6.15
f1 (ppm)

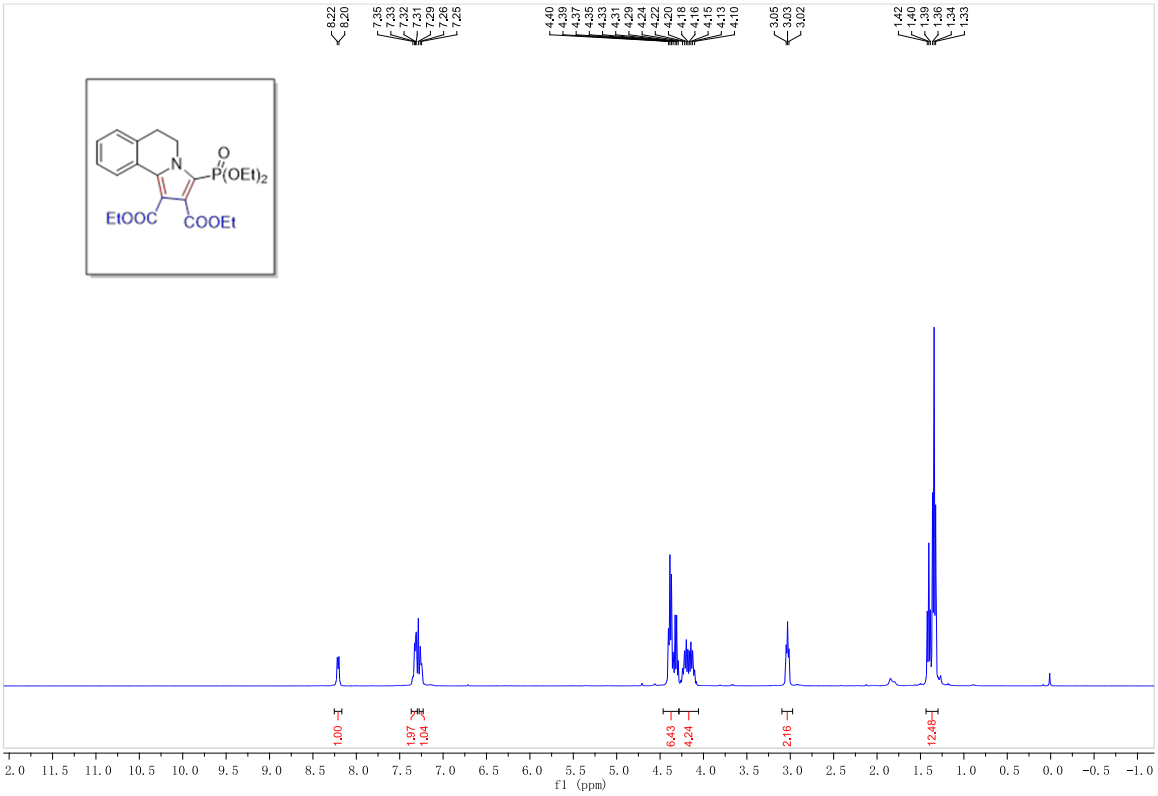

179.91
178.36
133.13
129.58
129.45
129.08
127.26
127.22
127.13
126.85
126.50
123.31
121.13
110.04
118.94
77.48
77.16
76.84
63.57
63.52
44.24
29.59
16.44
16.37
f1 (ppm)

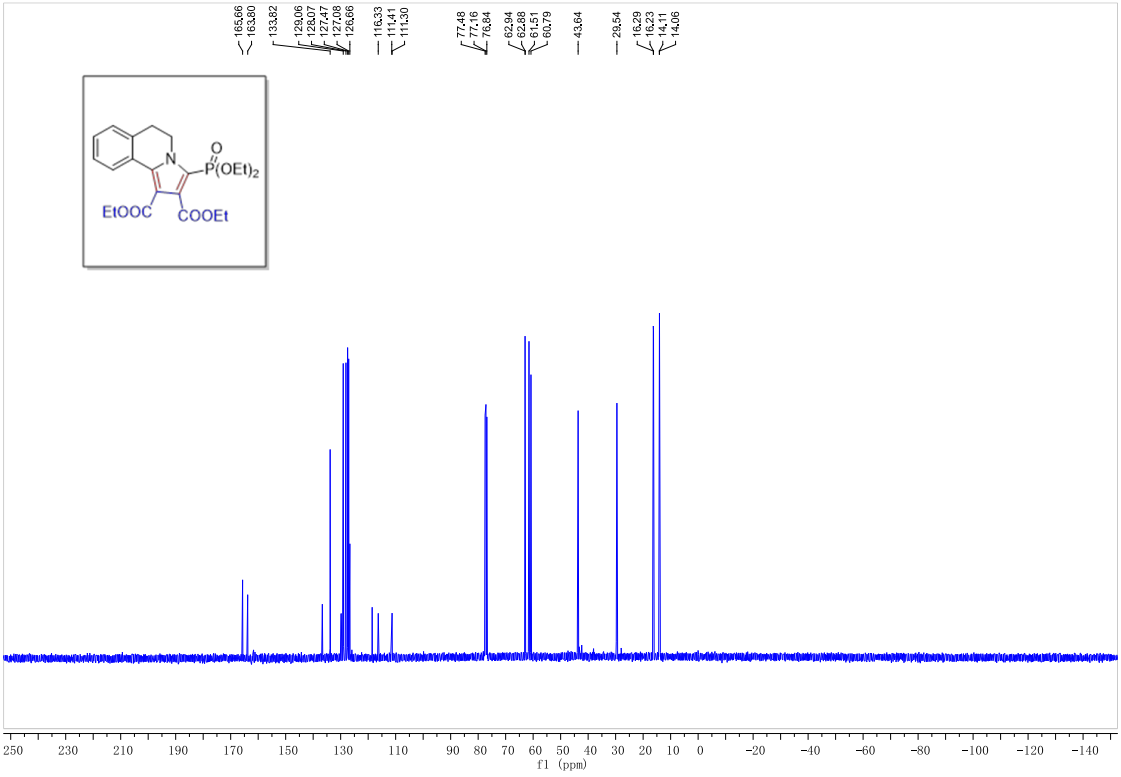

wzx-2-14672.1.fid
PROTON
7.56
7.54
7.28
7.27
7.25
7.23
7.21
7.21
7.19
7.17
6.87
6.86
6.85
6.85
6.55
6.54
4.35
4.34
4.32
4.19
4.17
4.16
4.14
4.14
4.12
4.10
4.07
3.10
3.09
3.07
1.35
1.33
1.31
O
P(OEt)2
N
H
H
1.00
1.97
2.02
0.92
0.90
1.94
4.15
2.01
6.14
f1 (ppm)

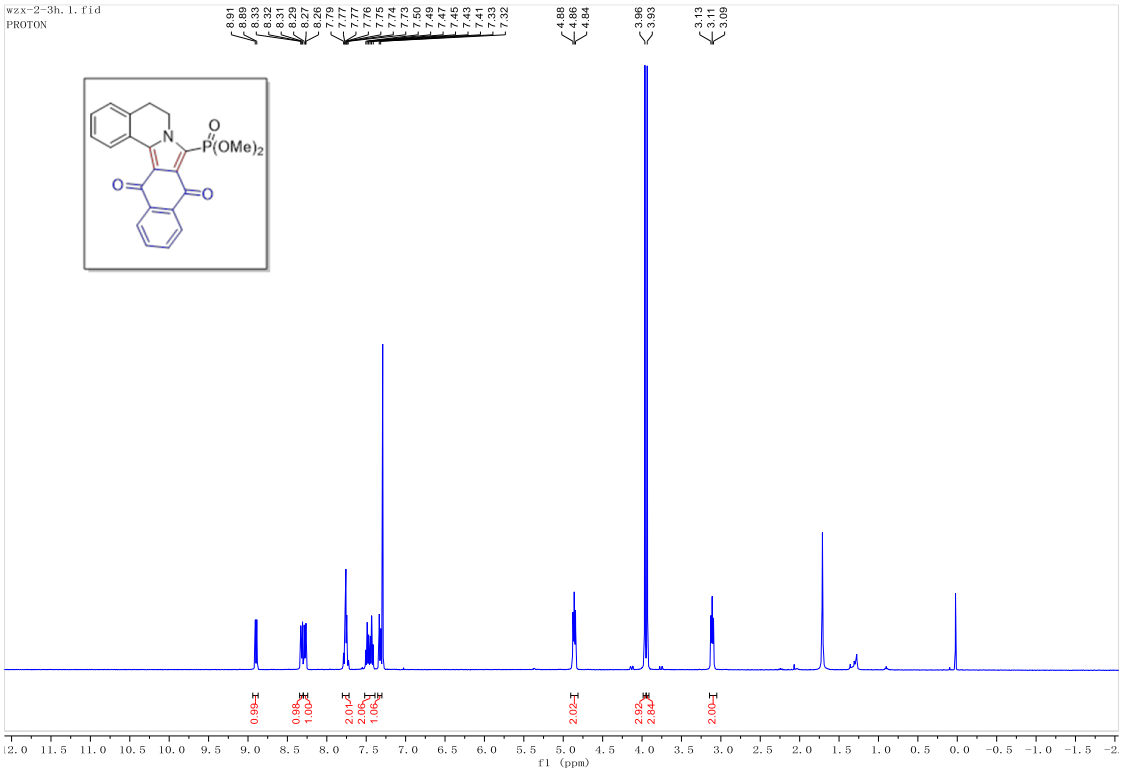

wzx-2-149c.1.fid
13CPD
136.39
136.28
131.19
128.46
127.99
127.28
127.24
123.50
121.66
121.49
119.48
117.21
104.41
104.27
62.36
62.30
43.10
29.09
16.38
16.32
O
P(OEt)2
N
H
H
f1 (ppm)

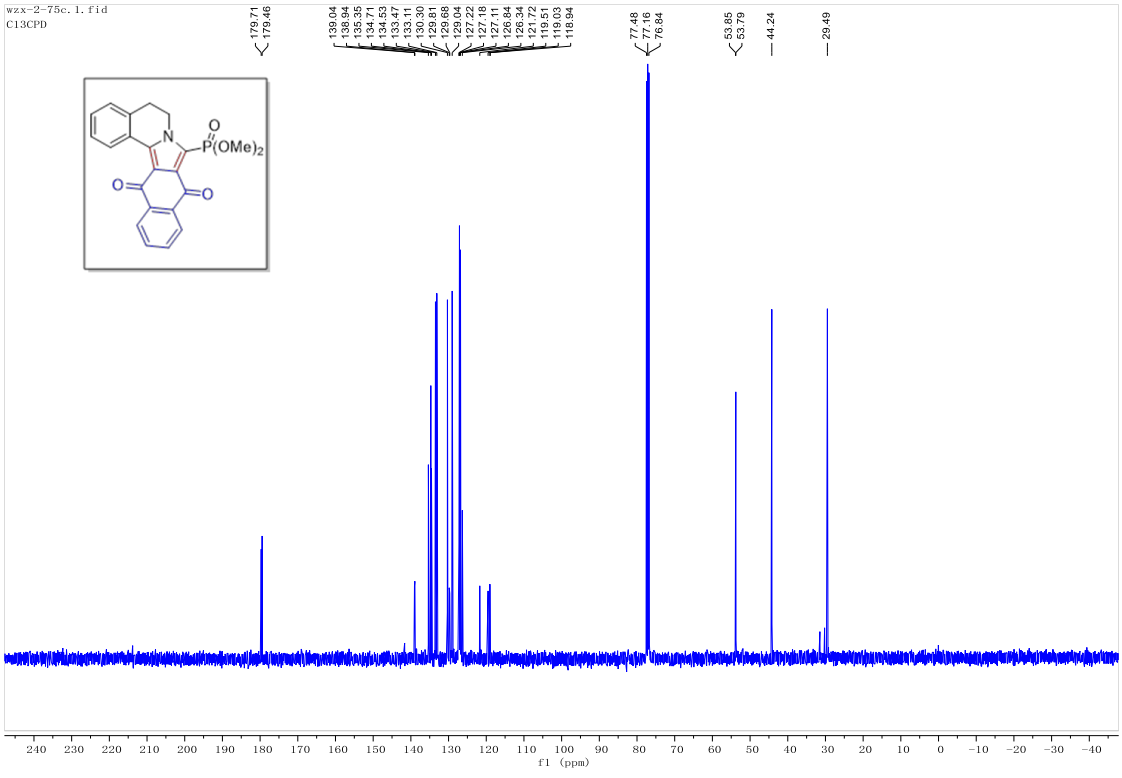

8.18
8.16
7.35
7.35
7.33
7.32
7.31
7.29
7.29
7.25
4.20
4.19
4.17
4.15
4.14
4.12
4.09
3.91
3.83
3.05
3.03
3.01
1.35
1.33
1.31
O
P(OEt)2
N
MeOOC
COOMe
1.00
2.19
0.98
2.11
4.50
3.10
3.04
2.03
6.29
f1 (ppm)

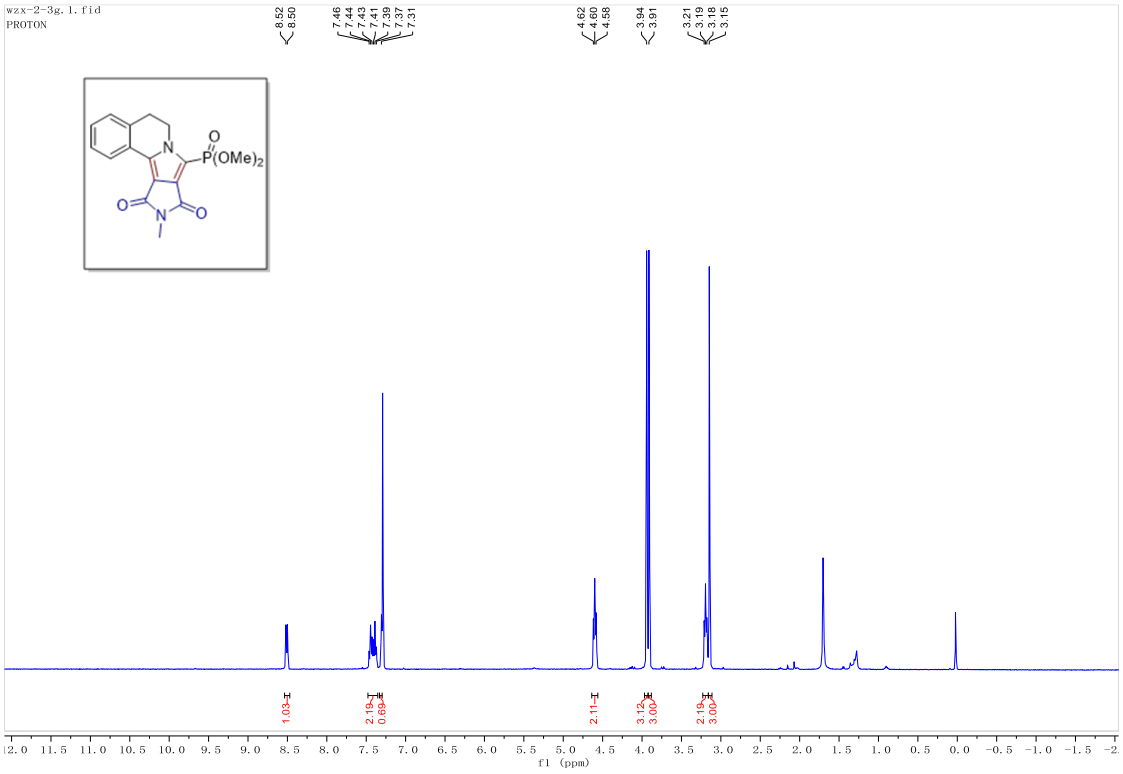

166.17
164.18
133.82
129.16
127.97
127.53
127.18
126.56
116.53
111.12
111.01
77.48
77.16
76.84
63.01
62.96
52.59
51.88
43.66
29.50
16.28
16.21
O
P(OEt)2
N
MeOOC
COOMe
f1 (ppm)


8.22
8.20
7.35
7.33
7.32
7.31
7.29
7.26
7.25
4.40
4.39
4.37
4.35
4.33
4.31
4.29
4.24
4.22
4.20
4.18
4.16
4.15
4.13
4.10
3.05
3.03
3.02
1.42
1.40
1.39
1.36
1.34
1.33
O
P(OEt)2
N
EtOOC
COOEt
1.00
1.97
1.04
6.43
4.24
2.16
12.48
f1 (ppm)


165.66
163.80
133.82
129.06
128.07
127.47
127.08
126.66
116.33
111.41
111.30
77.48
77.16
76.84
62.94
62.68
61.51
60.79
43.64
29.54
16.29
16.23
14.11
14.06
O
P(OEt)2
N
EtOOC
COOEt
f1 (ppm)


wzx-2-3h.1.fid
PROTON
8.91
8.89
8.33
8.32
8.31
8.29
8.27
8.26
7.79
7.77
7.77
7.76
7.75
7.74
7.73
7.50
7.49
7.47
7.45
7.43
7.41
7.33
7.32
4.88
4.86
4.84
3.96
3.93
3.13
3.11
3.09
0.99
0.98
1.00
2.01
2.06
1.06
2.02
2.92
2.84
2.00
f1 (ppm)


wzx-2-75c.1.fid
C13CPD
179.71
179.46
139.04
138.94
135.35
134.71
134.53
133.47
133.11
130.30
129.81
129.68
129.04
127.22
127.18
127.11
126.84
126.34
121.72
119.51
119.03
118.94
77.48
77.16
76.84
53.85
53.79
44.24
29.49
f1 (ppm)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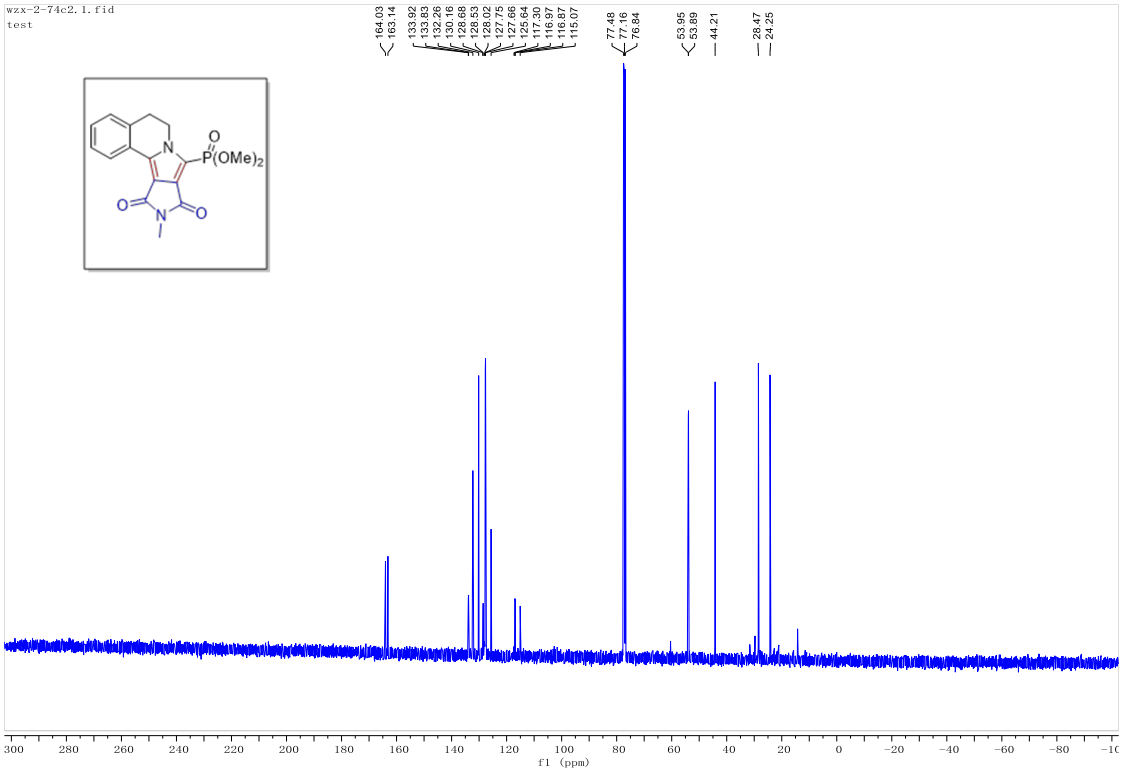
PROTON
8.52
8.50
7.46
7.44
7.43
7.41
7.39
7.37
7.31
4.62
4.60
4.58
3.94
3.91
3.21
3.19
3.18
3.15
1.03
2.19
0.69
2.11
3.12
3.00
2.19
3.00
f1 (ppm)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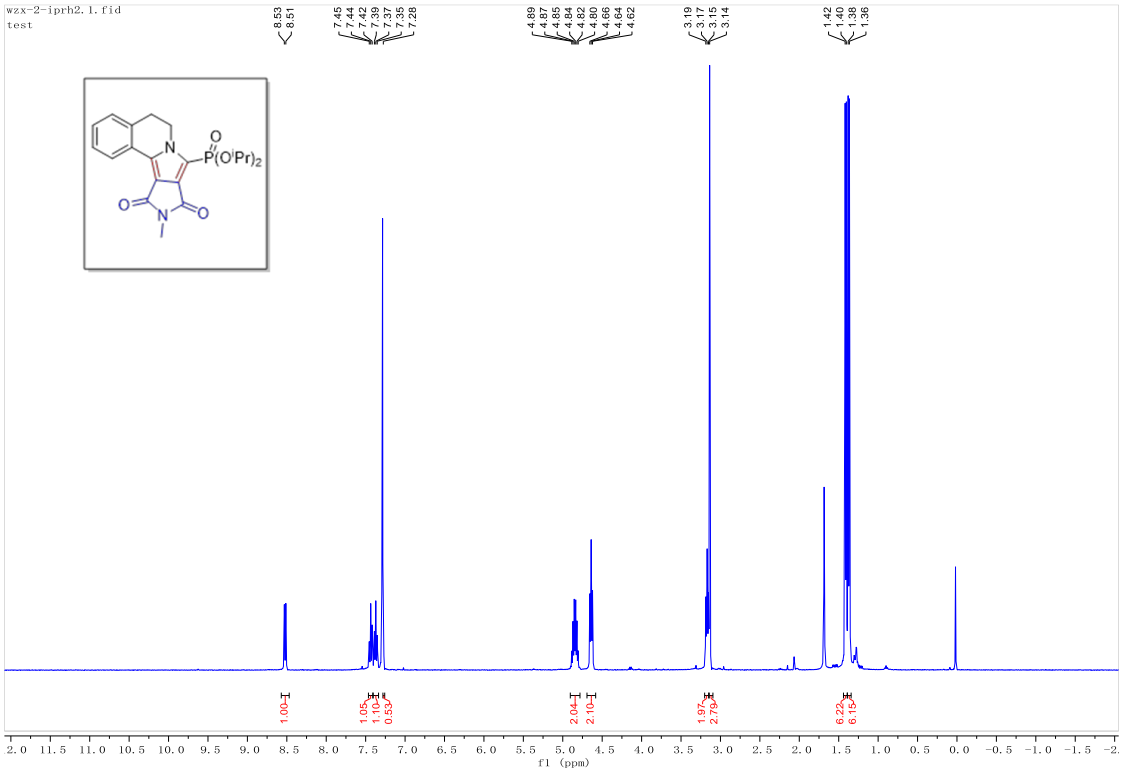
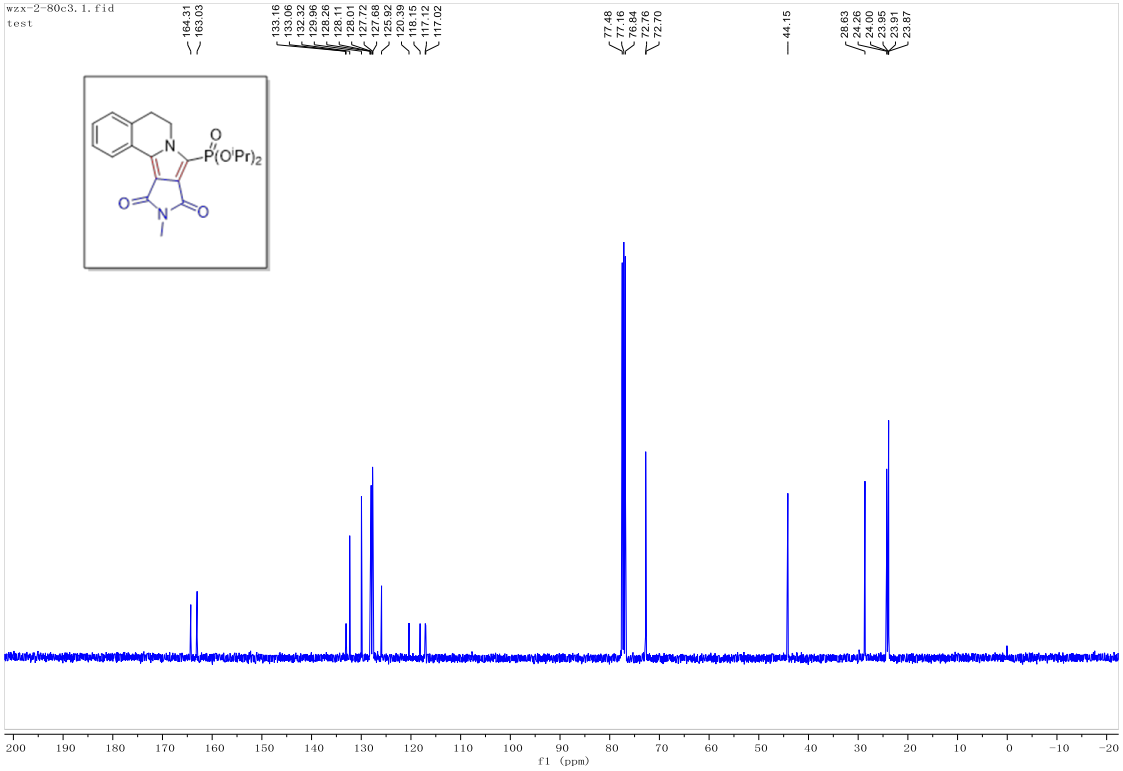
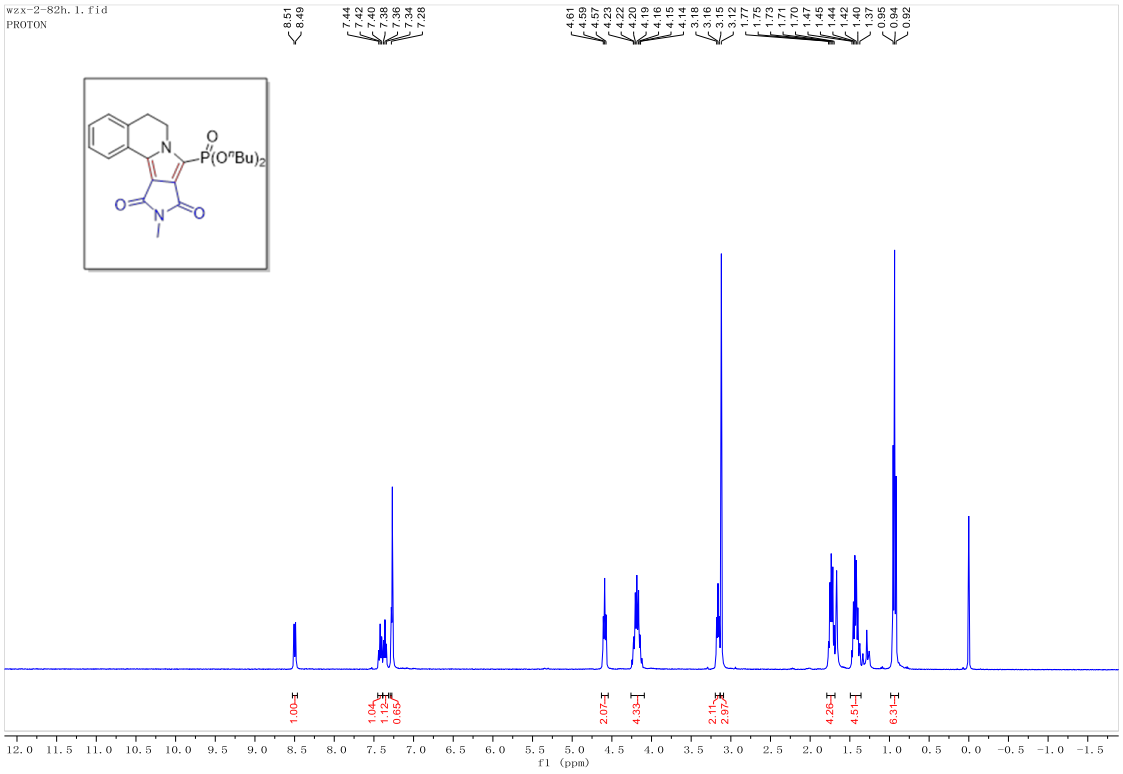
test
164.03
163.14
133.92
133.83
132.26
130.45
128.88
128.53
128.02
127.75
127.66
125.64
117.30
116.97
116.87
115.07
77.48
77.16
76.84
53.95
53.89
44.21
28.47
24.25
f1 (ppm)


wzx-2-iprh2.1.fid
test
8.53
8.51
7.45
7.44
7.42
7.39
7.37
7.35
7.28
4.89
4.87
4.85
4.84
4.82
4.80
4.66
4.64
4.62
3.19
3.17
3.15
3.14
1.42
1.40
1.38
1.36
1.00
1.05
1.10
0.53
2.04
2.10
1.97
2.79
6.22
6.15
f1 (ppm)


wzx-2-80c3.1.fid
test
164.31
163.03
133.16
133.06
132.32
129.96
128.26
128.11
128.01
127.72
127.68
125.92
120.39
118.15
117.12
117.02
77.48
77.16
76.84
72.76
72.70
44.15
28.63
24.26
24.00
23.95
23.91
23.87
f1 (ppm)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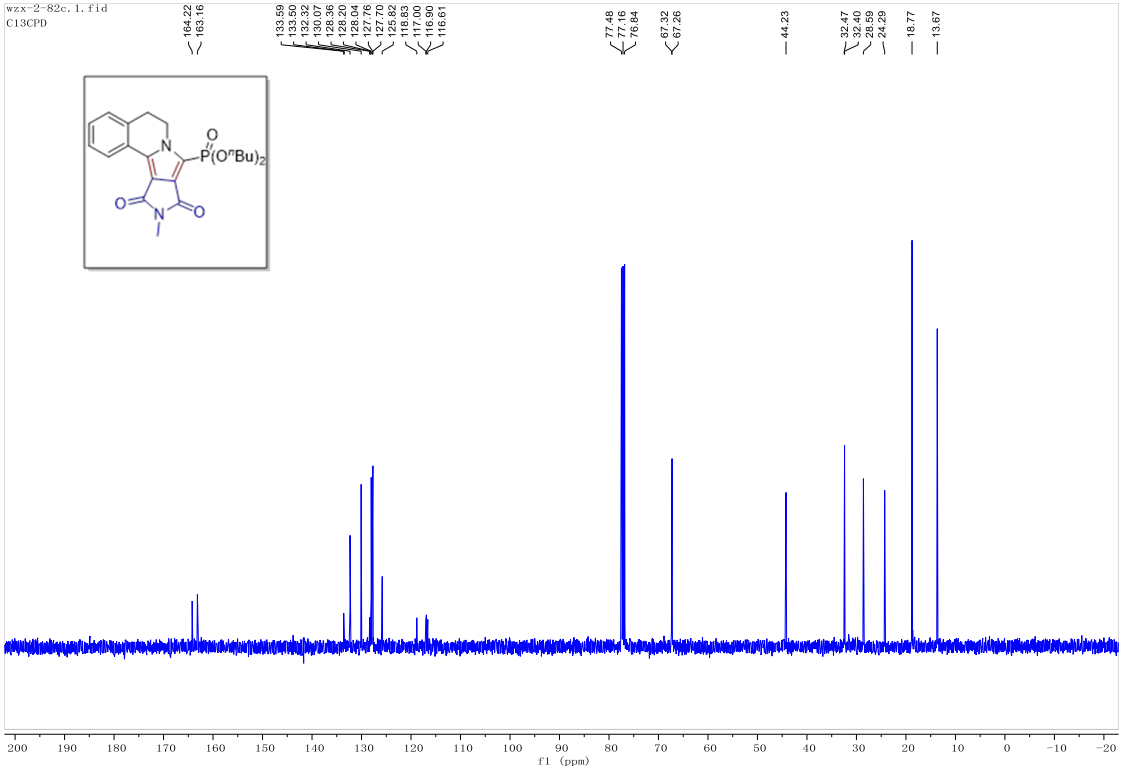
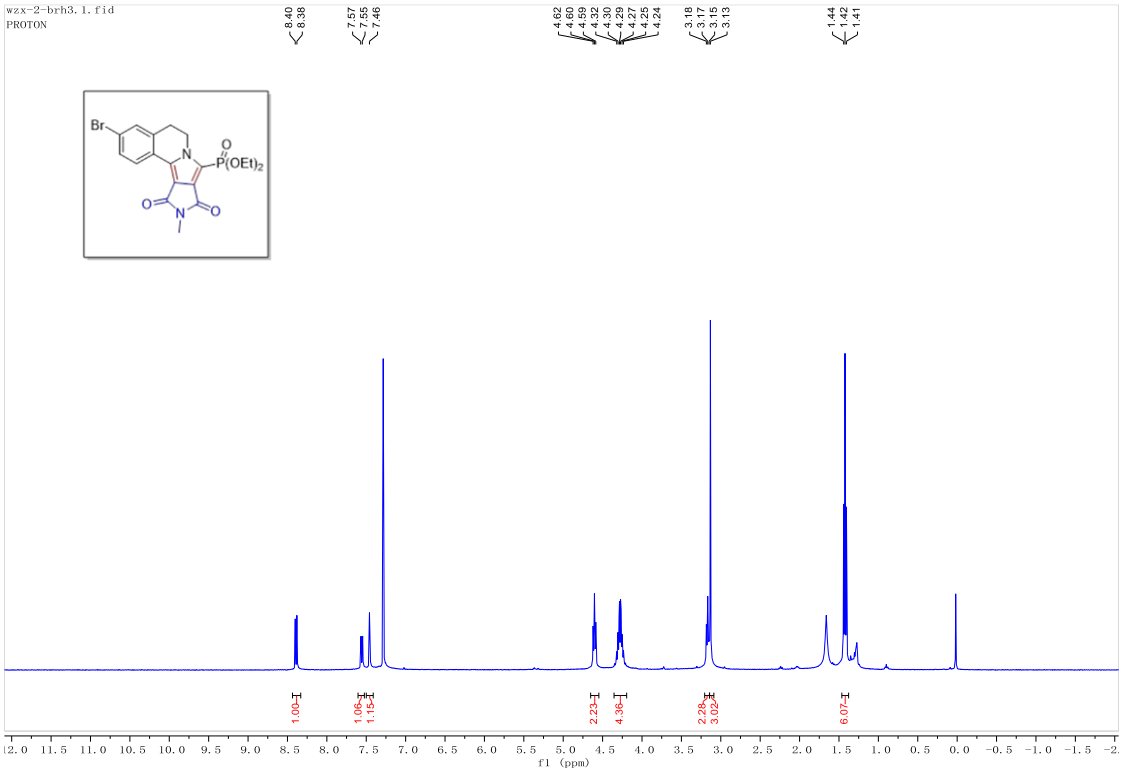
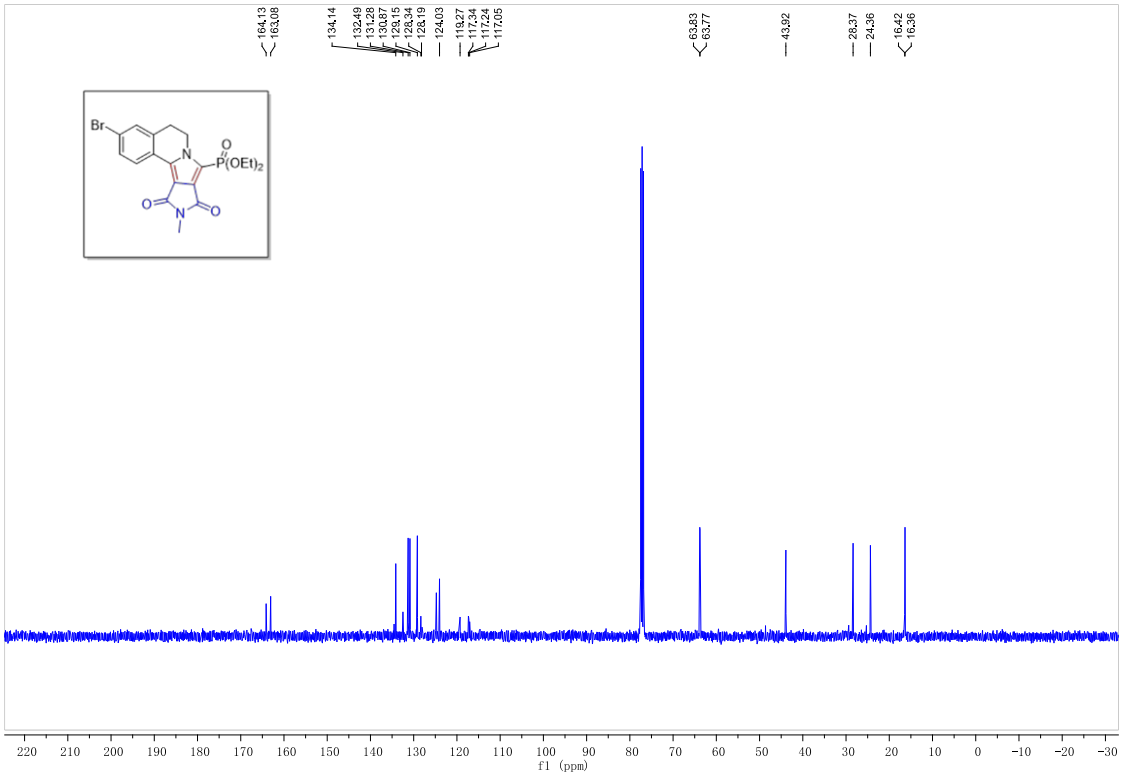
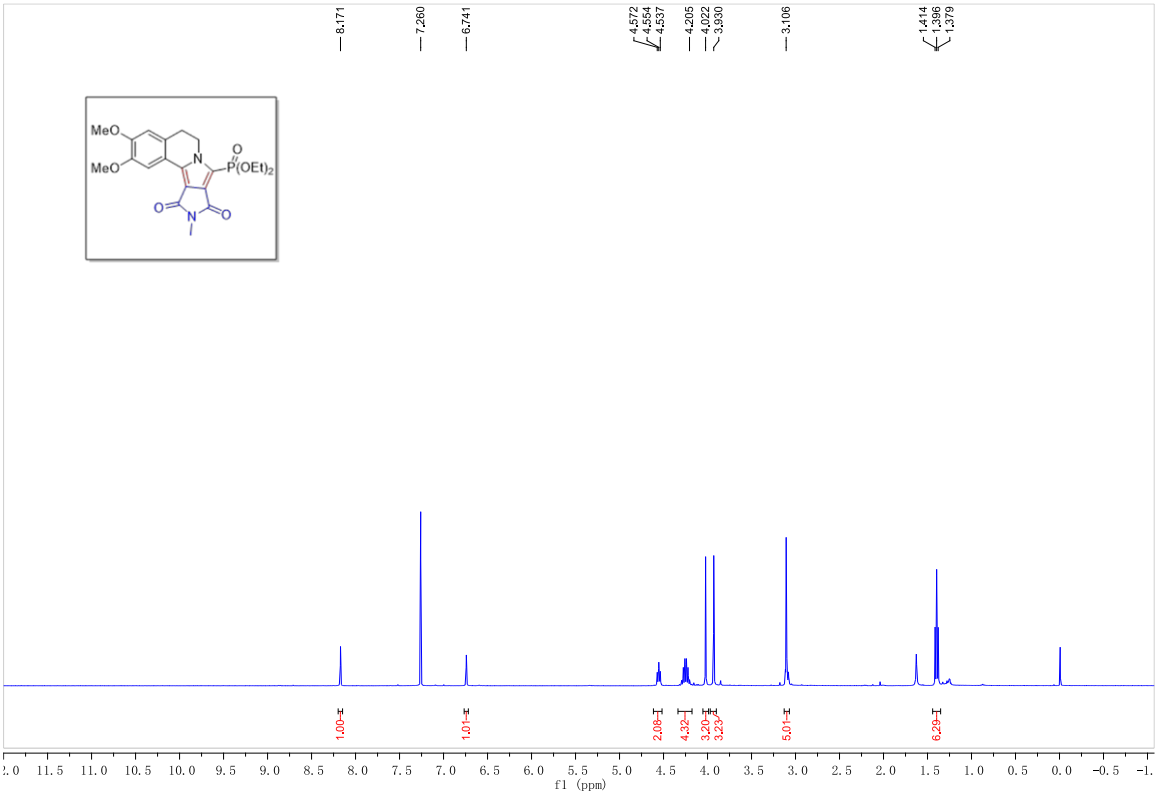
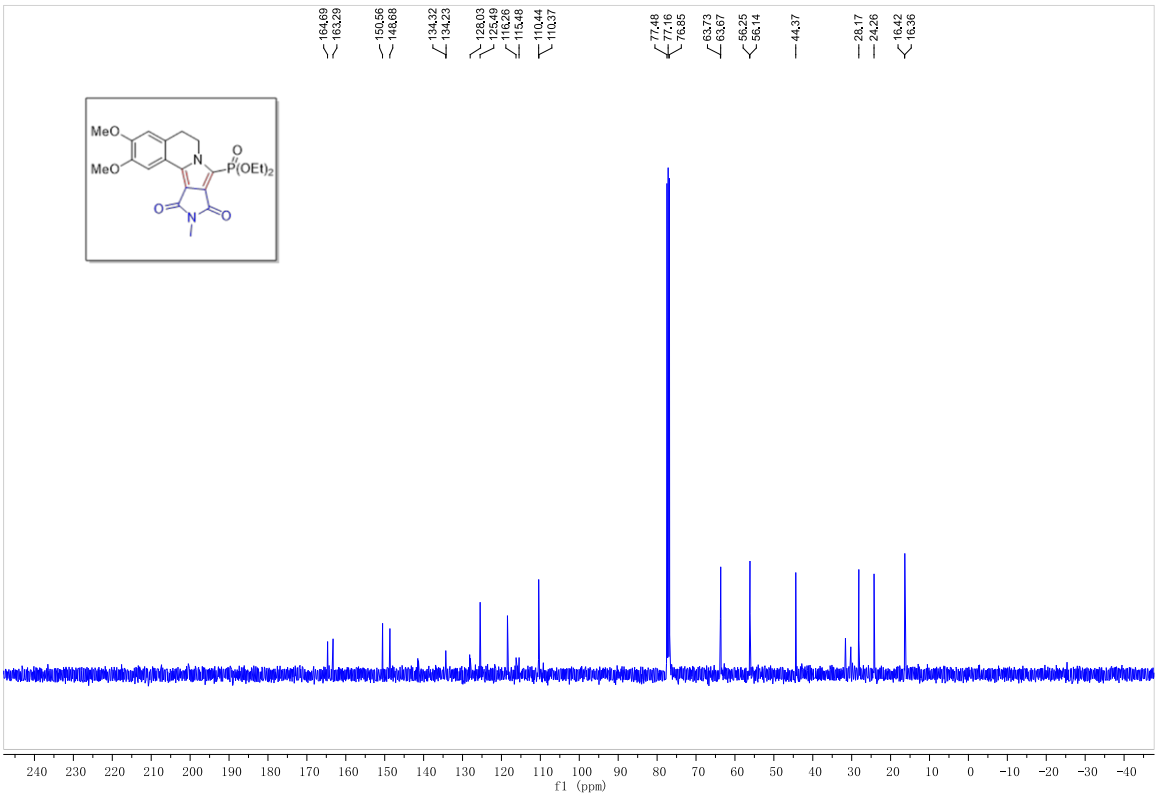
PROTON
8.51
8.49
7.44
7.42
7.40
7.38
7.36
7.34
7.28
4.61
4.59
4.57
4.23
4.22
4.20
4.19
4.16
4.15
4.14
3.18
3.16
3.15
3.12
1.77
1.75
1.73
1.71
1.70
1.47
1.45
1.44
1.42
1.40
1.37
0.95
0.94
0.92
O
P(OnBu)2
O
N
O
N
1.00
1.04
1.12
0.65
2.07
4.33
2.11
2.97
4.26
4.51
6.31
12.0 11.5 11.0 10.5 10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5 -1.0 -1.5
f1 (ppm)


wzx-2-82c.1.fid
C13CPD
164.22
163.16
133.59
133.50
132.32
130.07
128.36
128.20
128.04
127.76
127.70
125.82
118.83
117.00
116.90
116.61
77.48
77.16
76.84
67.32
67.26
44.23
32.47
32.40
25.53
24.29
18.77
13.67
O
P(OnBu)2
O
N
O
N
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)


wzx-2-brh3.1.fid
PROTON
8.40
8.38
7.57
7.55
7.46
4.62
4.60
4.59
4.32
4.30
4.29
4.27
4.25
4.24
3.18
3.17
3.15
3.13
1.44
1.42
1.41
Br
O
P(OEt)2
N
O
O
N
1.00
1.06
1.15
2.23
4.36
2.28
3.02
6.07
f1 (ppm)


164.13
163.08
134.14
132.49
131.28
130.87
128.15
128.34
128.19
124.03
119.27
117.34
117.24
117.05
63.83
63.77
43.92
26.37
24.36
16.42
16.36
Br
O
P(OEt)2
N
O
O
N
f1 (ppm)


8.171
7.260
6.741
4.572
4.554
4.537
4.205
4.022
3.930
3.106
1.414
1.396
1.379
MeO
MeO
O
P(OEt)2
N
O
O
N
1.00
1.01
2.08
4.32
3.20
3.23
5.01
6.29
f1 (ppm)


164.69
163.29
150.56
146.68
134.32
134.23
128.03
125.49
116.26
115.48
110.44
110.37
77.48
77.16
76.85
63.73
63.67
56.25
56.14
44.37
28.17
24.26
16.42
16.36
MeO
MeO
O
P(OEt)2
N
O
O
N
f1 (ppm)

9 References

1 T. Yoshii, S. Tsuzuki, S. Sakurai, R. Sakamoto, J. Jiang, M. Hatanaka, A. Matsumoto and K. Maruoka, N-Hydroxybenzimidazole as a Structurally Modifiable Platform for N-Oxyl Radicals for Direct C–H Functionalization Reactions, *Chem. Sci.*, 2020, **11**, 5772.