Supporting Information for:

One-pot synthesis of α-aminophosphonates by yttrium-catalyzed Birum–Oleksyszyn reaction

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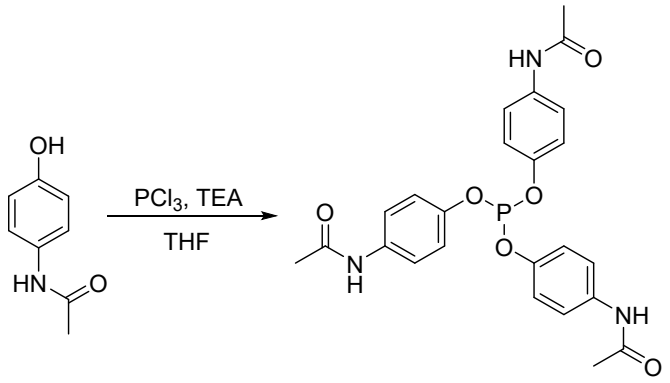
Experiment section

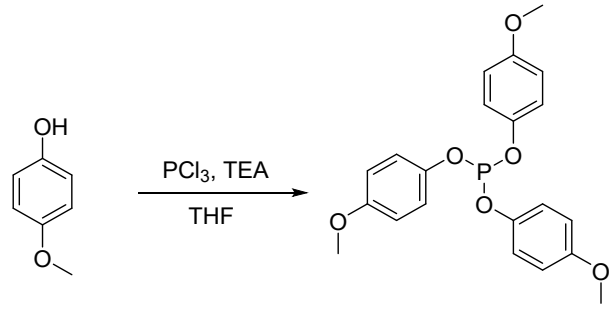
General information: Unless otherwise specified, all commercially available reagents were used as received. ^{1}H, ^{13}C NMR and ^{31}P NMR spectra were obtained on a 400 MHz Bruker Avance 400 spectrometer at ambient temperature at 400 and 101 MHz, respectively. Chemical shifts (δ) are reported in parts per million (ppm) relative to residual DMSO peak (s, δ 2.50 for ^{1}H and t, δ 39.53 for ^{13}C, respectively). Multiplicities are given as s (singlet), d (doublet), t (triplet), q (quartet), and m (multiplet). Complex splittings are described by a combination of these abbreviations, *i.e.* dd (doublet of doublets). Reaction conversion was estimated LC-MS on Waters Acquity UPLC H-class instrument, column Waters Acquity UPLC BEH-C18, 2.1 × 50 mm, 1.7 µm, eluent 5–95% MeCN in 0.1% aq. HCOOH; flow rate: 0.8 mL/min; detection Waters PDA Detector (200-300 nm). HRMS spectra were acquired on an electrospray ionization mass spectrometer with a TOF analyzer, using the following parameters: positive ionization mode, drying gas 10 mL/min and 325°C, fragment or ionization 100V.

Procedure of synthesis of Tris(4-acetamidophenyl) phosphite (1)



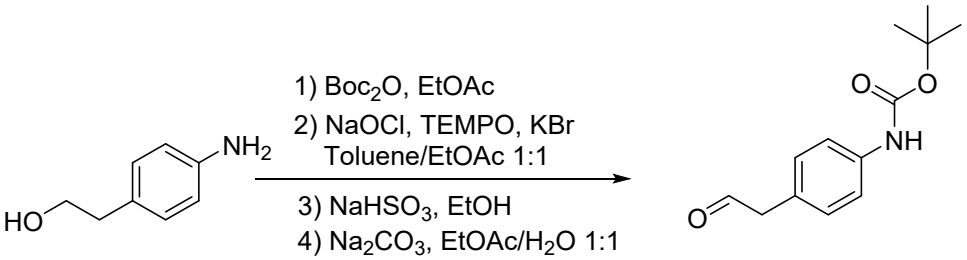
To a well dry 500 mL flask equipped with a magnetic stirrer, were added, under argon atmosphere, 4-acetamidophenol (3.0 equiv.), previously dried in vacuum for 24h, dry-THF (100 mL) and dry-triethylamine (3.0 equiv.), the flask was placed in an ice bath and after 10 minutes was added dropwise phosphorous trichloride (1.0 equiv.). The mixture was stirred for 1h at 0°C, then was filtered off in a filter of 150 mL to remove the solid and the filtrate cake was washed with dry-THF (50 mL), the liquid was poured into a 500 mL flask and the solvent removed with rotavapor. Once solid was formed in the flask was kept in a vacuum for 6 h to give a white foamy solid. Yield 98%

Procedure of synthesis of Tris(4-methoxyphenyl) phosphite (38)



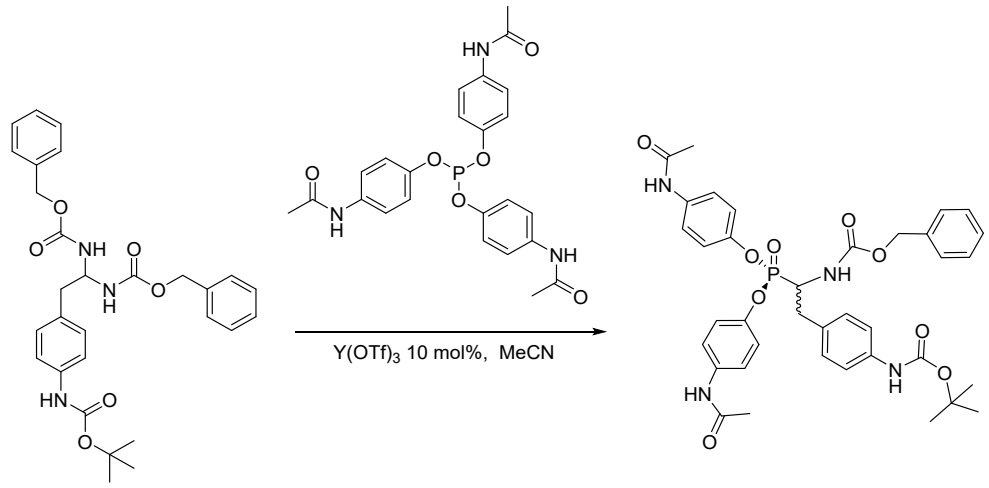
To a well dry 250 mL flask equipped with a magnetic stirrer, were added, under argon atmosphere, 4-methoxyphenol (3.0 equiv.), previously dried in vacuum for 24h, dry-THF (50 mL) and dry-triethylamine (3.0 equiv.), the flask was placed in an ice bath and after 10 minutes was added dropwise phosphorous trichloride (1.0 equiv.). The mixture was stirred for 1 h at 0°C, then was filtered off in a filter of 150 mL to remove the solid and the filtrate cake was washed with dry-THF (25 mL), the liquid was poured into a 250 mL flask and the solvent removed with rotavapor. Once solid was formed in the flask was kept in a vacuum for 6 h to give a white-off solid. Yield 69%

Procedure of synthesis of Tert-butyl (4-(2-oxoethyl)phenyl)carbamate (2)



To a 500 mL flask equipped with a magnetic stirrer, were added 4-Aminophenetyl alcohol (1.0 equiv.), ethyl acetate (200 mL) and di-tert-butyldicarbonate (1.1 equiv.). The flask was covered with aluminum foil and the mixture was stirred for 16 h at r.t., then heptane (100 mL) was added to the reaction mixture. A plug with 180 g of Silica was prepared in a 350 mL vacuum filter, the solution was poured in the filter and washed with 500 mL of ethyl acetate/heptane 2:1, the solvent was removed to give the product as a white solid. The product was used without further treatment for the next step of oxidation. To a 500 mL flask equipped with a magnetic stirrer were added in this sequence: Boc-protected intermediate (1.0 equiv.), dissolved in ethyl acetate (90.0 mL) and TEMPO (0.01 equiv.) dissolved in toluene (90.0 mL), then potassium bromide (0.1 equiv.) dissolved in 67.0 mL $NaHCO_3$ sat. The mixture was vigorously stirred for 10 minutes in an ice bath, then 67.0 mL of sodium hypochlorite 13% were added dropwise in 5 minutes. The reaction was vigorously stirred for 10 minutes, then was quenched with sodium thiosulfate 10% (250.0 mL), the reaction mixture was washed with ethyl acetate (3 x 200 mL), the combined organic layers were then washed with brine (500 mL) and dried with Na_2SO_4, the solvent was removed by rotary evaporation. The crude aldehyde was dissolved in ethanol (340.0 mL) in a 500 mL flask equipped with a magnetic stirrer, a solution of sodium bisulfite (1.5 equiv.) in 20 mL of deionized water, was added dropwise in 5 minutes, the mixture was stirred for 18h at r.t. and 1h at 0°C, the solid was filtrated, washed with cold ethanol (300 mL). And dried in a vacuum for 18h to give a white solid. To a 500 mL flask, were added the white solid (1.0 equiv.) dissolved in deionized water (260 mL), sodium carbonate (2.2 equiv.) and ethyl acetate (300 mL), the mixture was stirred for 3 h, the solution was placed in a 1.0 L separation funnel and extracted with ethyl acetate 3 x 250 mL, the combined organic layers were washed with brine (400 mL) and dry on Na_2SO_4, the solvent was removed with rotary evaporation to get a pale yellow solid. Yield 77%

Procedure for the synthesis of compound 4 from compound aminal 7



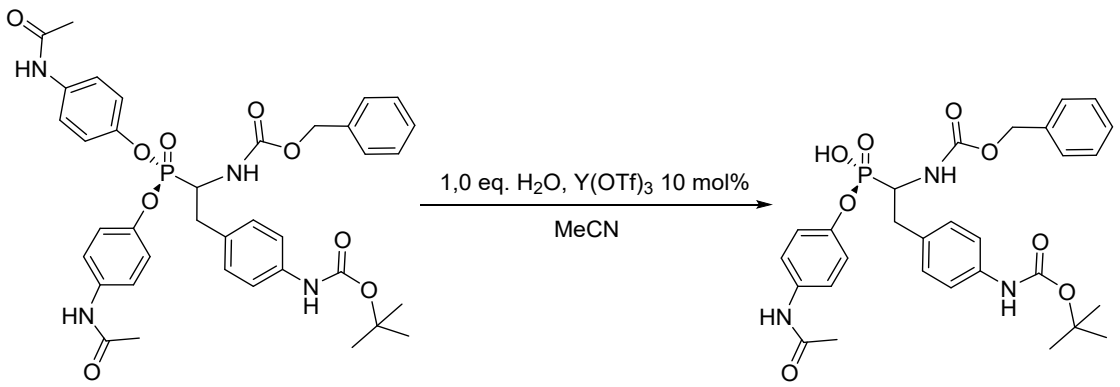
Scheme S1: Synthesis of compound 4 from aminal 7

In a 5 mL tube, under argon atmosphere, were added 1.0 equiv. of aminal (7), 1.0 equiv. phosphite (1) and 0.6 mL of anhydrous acetonitrile. The mixture was stirred for 24h. Product monitored with naphthalene as internal standard

Time	Birum-Oleksyszyn reaction with aminal (7)	Birum-Oleksyszyn reaction with aldehyde (2)
2 h	0.94	1.30
4 h	0.79	1.55
6 h	0.74	1.44

Table S1: Ratio of chromatographic concentration of product compare with the chromatographic concentration of the internal standard

Procedure for testing stability of compound 4 in the presence of water and yttrium triflate



Scheme S2: hydrolysis of compound 4 catalyzed by yttrium triflate

In a 5 mL tube were added the phosphonate 7, 1.0 equiv. of water, 0.1 eq. of $Y(OTf)_3$, and naphthalene as internal standard, the mixture was stirred for 24h.

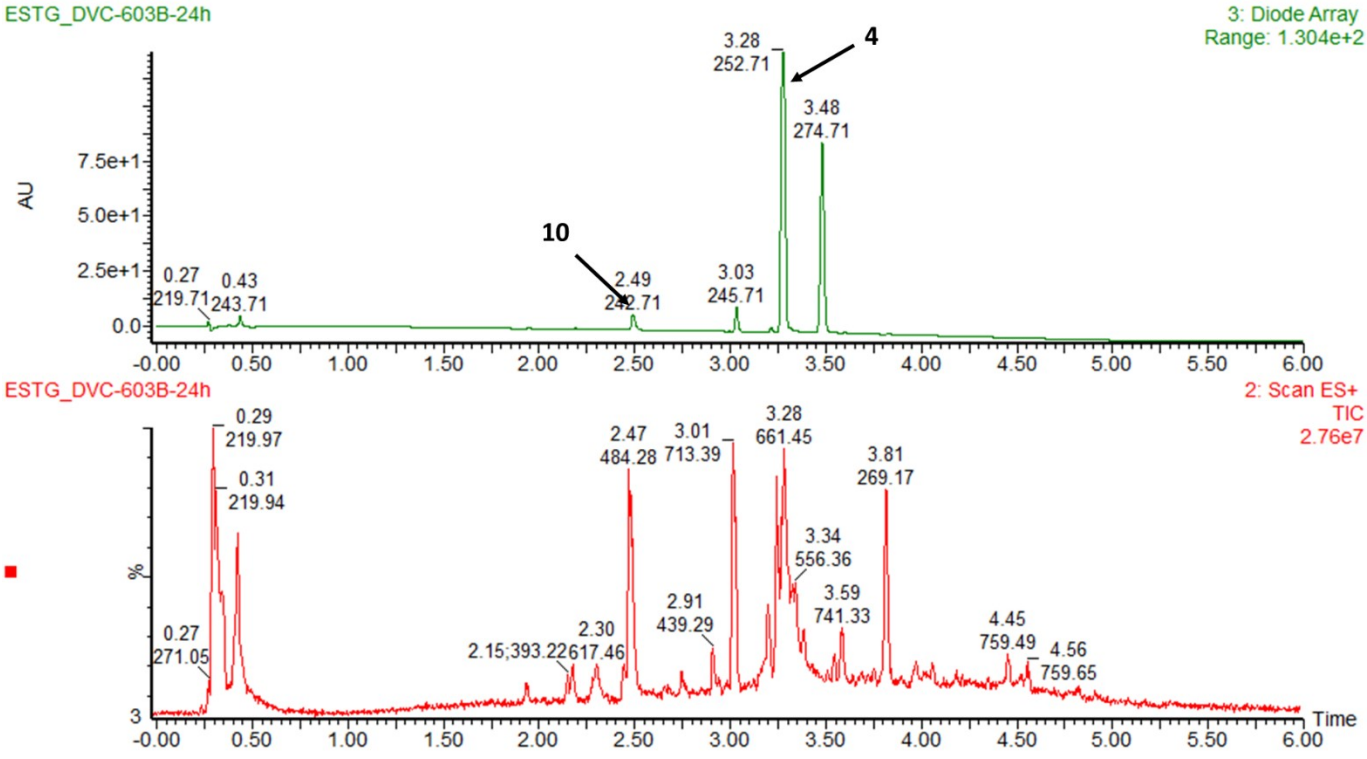


Figure S2: Chromatogram of the reaction mixture after 24h, at 2.49 minutes is possible to notice the hydrolized product (10)

Kinetic profile of the Birum-Oleksyszyn reaction for the synthesis of compound 4

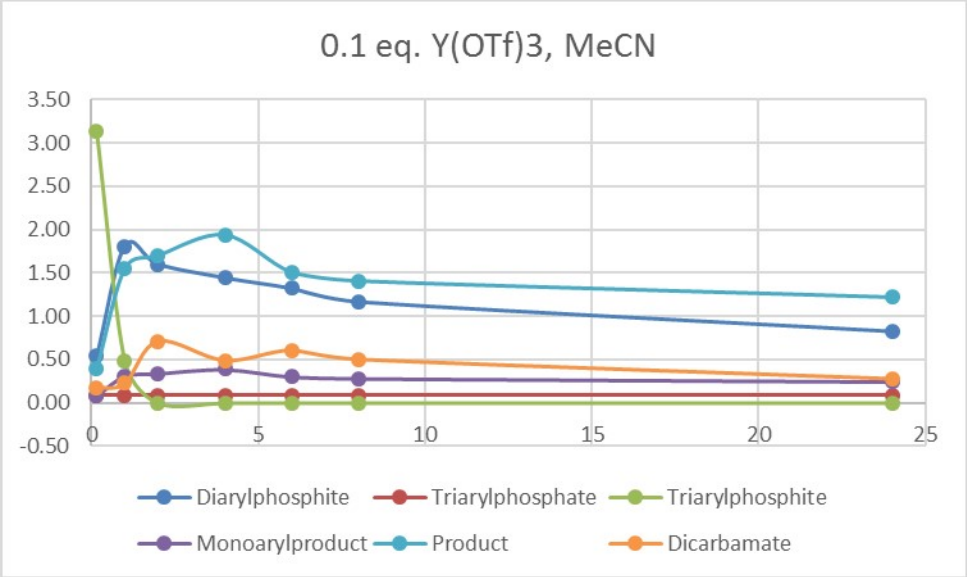


Figure S3: In 5 mL tube added 1.0 equiv. of phospite (**1**), 1.0 equiv. of aldehyde (**2**), 1.0 equiv. of carbamate (**3**), 0.1 eq. of Y(OTf)3, 50 uL of a stock solution of naphthalene in EtOAc (25 g/L). The mixture was stirred at r.t. for 24 h, sampling at 1 h, 2 h, 4 h, 6 h, 8 h, 24 h. On the vertical axis reported relative concentration of interesting compound with the naphthalene peak, on the horizontal axis reported the time in h. List of compound investigated: diarylphosphite (**9**), triarylphosphate (**37**), triarylphosphite (**1**), monoarylproduct (**10**), product (**4**), dicarbamate / aminal (**7**)

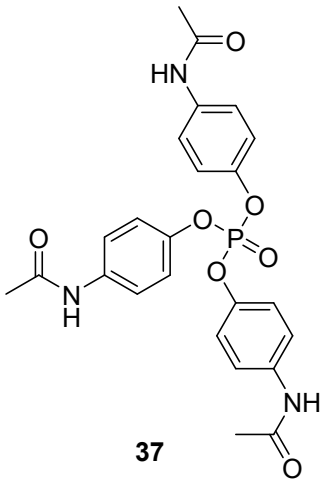


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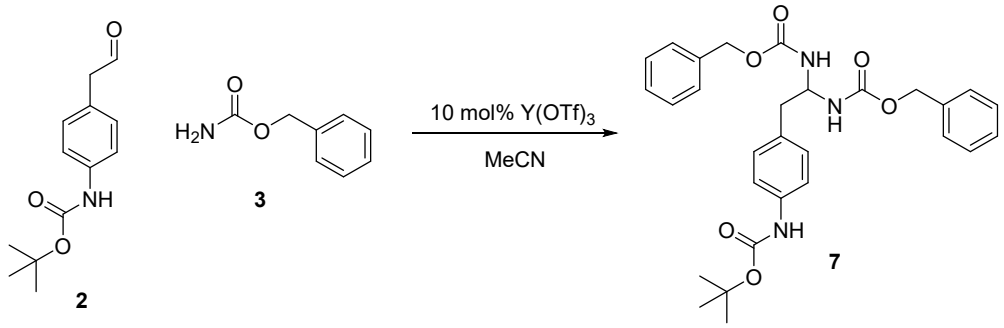
Figure S4: tris(4-acetamidophenyl) phosphate formed after oxidation of compound 1

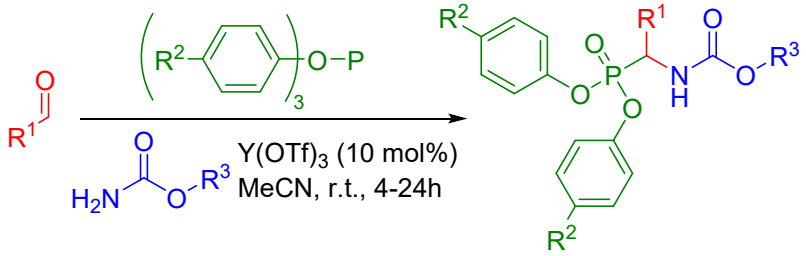
Procedure of synthesis of Dibenzyl (2-(4-((tert-butoxycarbonyl)amino)phenyl)ethane-1,1-diyl)dicarbamate (7)



Scheme S3: Preparation of aminal **7** from 1.0 eq. of aldehyde **2** and 2.0 eq. of carbamate **3**

In a 25 mL flask were added 0.85 mmol of aldehyde, 1.7 mmol of benzyl carbamate and 0.085 mmol of $Y(OTf)_3$ dissolved in 2.5 mL of anhydrous acetonitrile. The solution was stirred for 4h. The precipitate was filtered off and washed with 2 mL of acetonitrile, dried to get 102 mg with purity 100%. Yield 23%.

General procedure for the synthesis of α-aminophosphonate

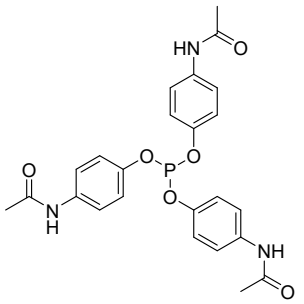


Scheme S4: One-pot three-component synthesis of α-aminophosphonate

In a 50 mL flask were added, under an argon atmosphere, previously dissolved in anhydrous acetonitrile, the aldehyde (1.0 eq.), the carbamate (1.0 eq.) the yttrium triflate (0.1 eq.), and the phosphite (1.0 eq.) The solution was kept stirring for 4-24 h at r.t. then the solvent was removed. The residue was purified with flash chromatography on silica gel (gradient Heptane/Ethylacetate) to obtain the desired product.

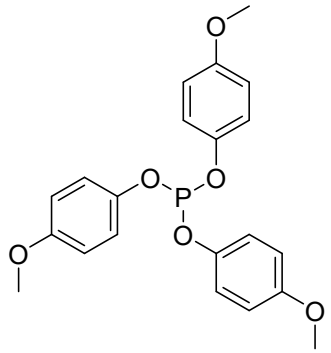
Product characterization

Tris(4-acetamidophenyl) phosphite (1)



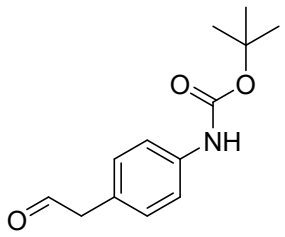
Yield: 98%
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.99 (3H, s), 7.58 (6H, d, J=8Hz), 7.09 (6H, d, J=8Hz), 2.03 (9H, s)
^{13}C NMR: (101 MHz, DMSO-d_6) δ: 168.14, 146.06, 136.00, 120.75, 120.47, 23.89
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 129.32
HRMS (ESI+): m/z calc'd for $C_{24}H_{25}N_3O_6P$ $[M+H]^+$:482.1481, found 482.1492

Tris(4-methoxyphenyl) phosphite (38)



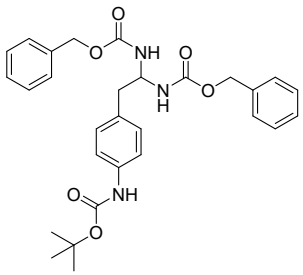
Yield: 69%
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 7.22 (6H, dd, J=12,4Hz), 6.98 (6H, d, J=12Hz), 3.73 (9H, s)
^{13}C NMR: (101 MHz, d6-DMSO-d6) δ: 156.89, 143.59, 120.92, 114.95, 55.38.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 129.49
HRMS (ESI+): m/z calc'd for $C_{21}H_{22}O_6P$ $[M+H]^+$:400.1076, found 400.1084

Tert-butyl (4-(2-oxoethyl)phenyl)carbamate (2)



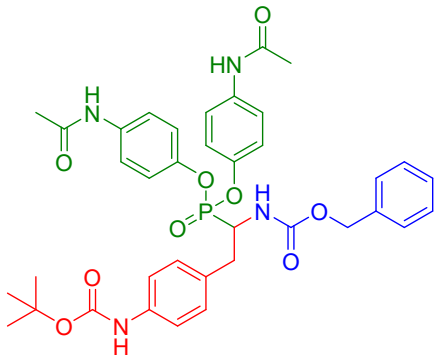
Yield: 77%
1H-NMR (400 MHz, DMSO-d_6) δ: 9.63 (1H, t, J=4Hz), 9.32 (1H, s), 7.43 (2H, d, J=8 Hz), 7.11 (2H, d, J=8Hz), 3.66 (2H, d, J=4Hz), 1.47 (9H, s)
13C-NMR (101 MHz, DMSO-d_6) δ: 200.52, 152.80, 138.44, 129.91, 126.04, 118.39, 78.99, 48.95, 28.13.
HRMS (ESI+) m/z calc'd for C13H17NO3Na [M+Na]+: 258.1106, found 258.1115

Dibenzyl (2-(4-((tert-butoxycarbonyl)amino)phenyl)ethane-1,1-diyl)dicarbamate (7)



Yield: 23%; white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.28 (1H, s), 7.71 (2H, s), 7.35 (6H, t, J=8Hz), 7.30 (6H, t, J=8Hz), 7.12 (2H, d, J=8Hz), 5.16 (1H, s), 5.00 (4H, m), 2.83 (2H, d, J=4Hz), 1.49 (9H, s),
^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.41, 153.27, 138.31, 137.56, 131.41, 129.94, 128.76, 128.15, 128.06, 118.32, 79.33, 65.55, 61.70, 28.62.
HRMS (ESI+): m/z calc'd for $C_{29}H_{33}N_3O_6Na$ $[M+Na]^+$: 542.2267, found 542.2267

Benzyl(1-(bis(4-acetamidophenoxy)phosphoryl)-2-(4-((tertbutoxycarbonyl)amino)phenyl) ethyl) carbamate (4)



Yield: 42%; white solid

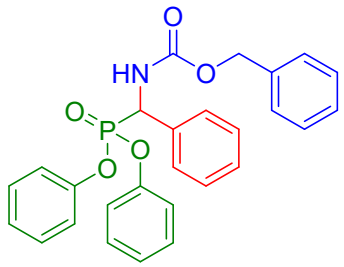
^{1}H NMR: NMR (400 MHz, DMSO-d_6) δ: 10.00 (s, 2H), 9.32 (s, 1H), 8.11 (d, J=8Hz, 1H), 7.57 (m, 4H), 7.39 (d, J=8Hz, 2H), 7.30 (m, 3H), 7.19 (d, J=8Hz, 2H), 7.12 (m, 6H), 4.97 (dd, J=32,12Hz, 2H), 4.42 (q, J=12Hz, 1H), 3.18 (d, J=12Hz, 1H), 2.90 (m, 1H), 2.04 (s, 6H), 1.49 (s, 9H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 168.70, 156.39, 153.27, 145.74, 145.46, 138.60, 137.45, 137.01, 130.92, 129.83, 128.71, 128.02, 127.59, 121.29, 121.03, 120.62, 118.36, 79.40, 65.87, 50.51, 34.04, 28.62, 24.37.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 18.35

HRMS (ESI+): *m/z* calc'd for $C_{37}H_{41}N_4O_9P$ $[M+Na]^+$: 739.2509, found 739.2519

Benzyl ((diphenoxyphosphoryl)(phenyl)methyl)carbamate (14)



Yield: 82%; white solid

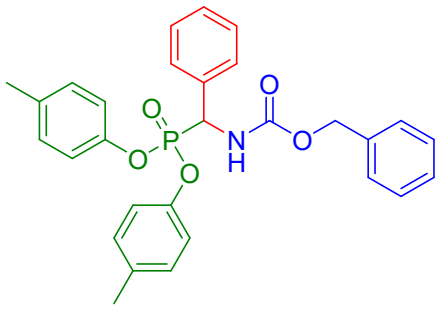
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.95 (d, J=12Hz, 1H), 7.66 (d, J=8Hz, 2H), 7.35 (m, 12H), 7.19 (m, 2H), 7.07 (d, J=8Hz, 2H), 6.97 (d, J=8Hz, 2H), 5.64 (dd, J=24,8 Hz, 1H), 5.12 (dd, J=36,12Hz, 2H).

^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.85, 149.91, 149.61, 136.46, 134.17, 129.63, 128.35, 128.24, 128.17, 128.06, 127.75, 125.07, 120.15, 120.09, 66.00, 53.50, 51.94, 39.33.

^{31}P NMR: NMR (162 MHz, DMSO-d_6) δ: 14.80

HRMS (ESI+): *m/z* calc'd for $C_{27}H_{25}NO_5P$ $[M+H]^+$:474.1470, found 474.1476

Benzyl ((bis(p-tolyloxy)phosphoryl)(phenyl)methyl)carbamate (15)



Yield: 75%, white solid

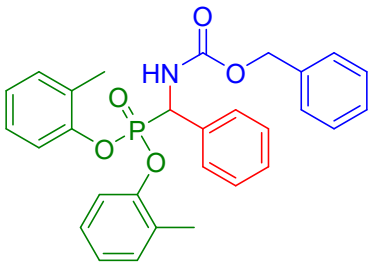
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.87 (d, J=8Hz, 1H), 7.61 (m, 2H), 7.36 (m, 8H), 7.12 (m, 4H), 6.92 (d, J=8Hz, 2H), 6.82 (d, J=8Hz, 2H), 5.54 (dd, J=24,12 Hz, 1H), 5.10 (dd, J=36,12 Hz, 2H), 2.25 (s, 6H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.47, 148.43, 148.10, 137.14, 134.97, 134.84, 130.55, 128.99, 128.89, 128.83, 128.66, 128.43, 128.41, 120.51, 120.45, 66.63, 53.26, 20.71.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.79

HRMS (ESI+): *m/z* calc'd for $C_{29}H_{29}NO_5P$ $[M+H]^+$: 502.1783, found 502.1801

Benzyl ((bis(o-tolyloxy)phosphoryl)(phenyl)methyl)carbamate (16)



Yield: 34%, white solid

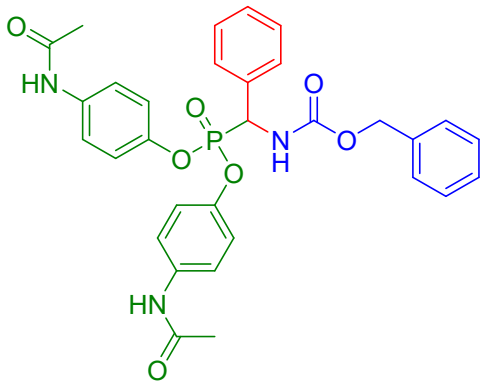
^{1}H NMR: (400 MHz, DMSO-d^6) δ: 8.92 (J=12 Hz, 1H), 7.63 (J=8 Hz, 2H), 7.36 (m, 8H), 7.18 (m, 2H), 7.05 (m, 6H), 5.64 (dd, J=24,12 Hz, 1H), 5.06 (dd, J=28,12 Hz, 1H), 1.98 (d, J=20 Hz, 6H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.51, 149.21, 149.11, 137.09, 135.05, 131.83, 129.44, 129.09, 128.87, 128.82, 128.73, 128.40, 128.34, 127.42, 125.54, 120.29, 66.64, 53.44, 16.09.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.80

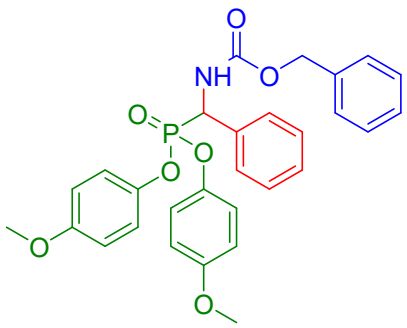
HRMS (ESI+): *m/z* calc'd for $C_{29}H_{29}NO_5P$ $[M+H]^+$: 502.1795, found 502.1783

Benzyl ((bis(4-acetamidophenoxy)phosphoryl)(phenyl)methyl)carbamate (17)



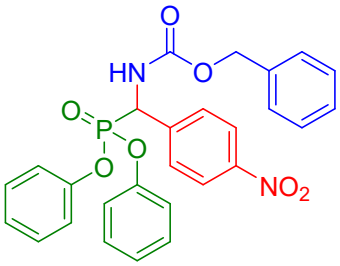
Yield: 72%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.98 (s, 2H), 8.89 (d, J=12 Hz, 1H), 7.62 (d, J=8 Hz, 2H), 7.51 (t, J=8 Hz, 4H), 7.37 (m, 8H), 6.97 (d, J=8 Hz, 2H), 6.88 (d, J= 8 Hz, 2H), 5.55 (dd, J= 24,8 Hz, 1H), 5.10 (dd, J=36,12 Hz, 2H), 2.03 (d, J=4 Hz, 6H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 168.21, 156.01, 145.24, 144.92, 136.66, 136.52, 134.47, 128.54, 128.45, 128.37, 128.22, 127.98, 127.95, 120.49, 120.43, 120.08, 66.21, 52.61, 23.90
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 15.05
HRMS (ESI+): *m/z* calc'd for $C_{31}H_{31}N_3O_7P$ [M+H]+:588.1900, found 588.1909

Benzyl ((bis(4-methoxyphenoxy)phosphoryl)(phenyl)methyl) (18)



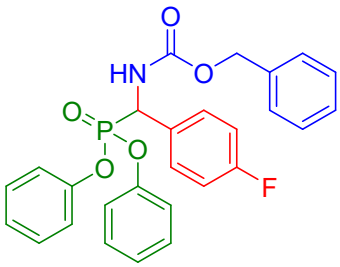
Yield: 92%, white solid
^{1}H NMR: NMR (400 MHz, DMSO-d_6) δ: 8.87 (s J=12 Hz, 1H), 7.61 (d, J=4 Hz, 2H), 7.37 (m, 8H), 6.95 (d, J=12 Hz, 2H), 6.86 (m, 6H), 5.53 (dd, J=24,8 Hz, 1H), 5.10 (dd, J=80,12 Hz, 2H), 3.69 (s, 6H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.86, 156.50, 144.04, 143.69, 137.15, 135.04, 128.98, 128.89, 128.84, 128.65, 128.44, 121.71, 121.64, 115.12, 66.65, 55.90, 53.14.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 15.27
HRMS (ESI+): *m/z* calc'd for $C_{29}H_{29}NO_7P$ $[M+H]^+$:534.1682, found 534.1689

Benzyl ((diphenoxyphosphoryl)(4-nitrophenyl)methyl)carbamate (19)



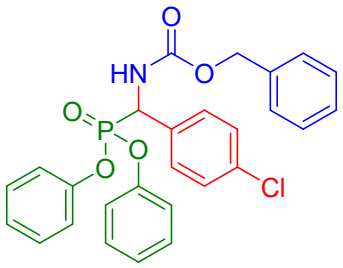
Yield: 64%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.11 (d, J=12Hz, 1H), 8.28 (d, J=12Hz, 2H), 7.96 (d, J=8Hz, 2H), 7.36 (m, 9H), 7.20 (t, J=8Hz, 2H), 7.05 (m, 4H), 5.88 (dd, J=24,12Hz, 1H), 5.12 (dd, J=32,12Hz, 2H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.00, 149.95, 149.65, 147.35, 142.12, 136.52, 129.93, 129.73, 128.40, 128.00, 125.46, 123.55, 120.33, 120.24, 66.38, 52.52
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 13.24
HRMS (ESI+): *m/z* calc'd for $C_{27}H_{24}N_2O_7P$ $[M+H]^+$: 519.1321, found 519.1325

Benzyl ((diphenoxyphosphoryl)(4-fluorophenyl)methyl)carbamate (20)



Yield: 36%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.93 (d, J=12Hz, 1H), 7.70 (m, 2H), 7.35 (m, 9H), 7.25 (t, J=8Hz, 2H), 7.20 (t, J=8Hz, 2H), 7.06 (d, J=8Hz, 2H), 6.98 (d, J=12Hz, 2H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 163.17, 160.75, 155.92, 150.03, 149.77, 136.59, 130.70, 130.60, 129.82, 128.35, 127.95, 125.29, 120.28, 120.23, 115.30, 66.21, 52.03. (100 MHz,)
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.50
HRMS (ESI+): *m/z* calc'd for $C_{27}H_{24}FNO_5P$ $[M+H]^+$: 492.1298, found 492.1377

Benzyl ((4-chlorophenyl)(diphenoxyphosphoryl)methyl)carbamate (21)



Yield: 55%, white solid

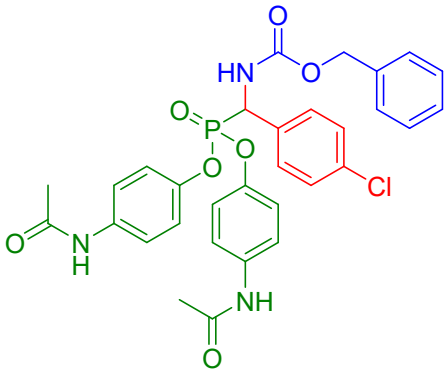
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.94 (d, J=12Hz, 1H), 7.67 (d, J=8Hz, 2H), 7.48 (d, J=8Hz, 2H), 7.34 (t, J=8Hz, 9H), 7.20 (t, J=8Hz, 2H), 7.05 (d, J=8Hz, 2H), 7.00 (d, J=8Hz, 2H), 5.65 (dd, J=24,8 Hz, 1H), 5.10 (dd, J=32,12 Hz, 2H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.42, 150.51, 150.21, 137.07, 133.97, 133.52, 130.83, 130.35, 128.92, 128.85, 128.44, 125.82, 120.79, 120.72, 66.73, 52.76

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.18

HRMS (ESI+): m/z calc'd for $C_{27}H_{24}ClNO_5P$ $[M+H]^+$: 508.1081, found 508.1096

Benzyl ((bis(p-tolyloxy)phosphoryl)(4-chlorophenyl)methyl)carbamate (22)



Yield: 43%, white solid

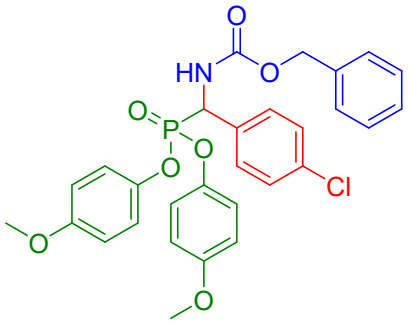
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.98 (2H, s), 8.89 (1H, d, J=8Hz), 7.63 (2H, dd, J=8,4 Hz), 7.48 (6H, m), 7.33 (5H, m), 6.96 (2H, d, J=8Hz), 6.90 (2H, d, J=8Hz), 5.58 (1H, dd, J=24,12Hz), 5.05 (2H, dd, J=32,12Hz), 2.01 (6H, s)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 168.22, 155.95, 145.15, 144.84, 136.61, 136.57, 133.63, 133.02, 130.33, 128.47, 128.38, 128.00, 127.96, 120.48, 120.39, 120.10, 66.28, 52.05, 23.90

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.19

HRMS (ESI+): m/z calc'd for $C_{31}H_{30}ClN_3O_7P$ [M+H]+: 622.1510, found 622.1526

Benzyl ((bis(4-methoxyphenoxy)phosphoryl)(4-chlorophenyl)methyl)carbamate (23)



Yield: 81%, white solid

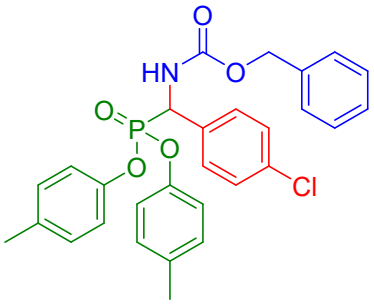
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.89 (d, J=8Hz, 1H), 7.64 (dd, J=8,4 Hz, 2H), 7.46 (d, J=8 Hz, 2H), 7.35 (m, 5H), 6.95 (dd, J=8,4 Hz, 2H), 6.87 (m, 6H), 5.58 (dd, J=24,12 Hz, 1H), 5.10 (dd, J=36,12 Hz, 2H), 3.70 (s, 6H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.90, 156.44, 143.96, 143.62, 137.09, 134.16, 133.45, 130.76, 128.90, 128.85, 128.47, 121.71, 121.69, 121.60, 115.19, 115.15, 66.72, 55.92, 52.51.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.64

HRMS (ESI+): m/z calc'd for $C_{29}H_{28}ClNO_7P$ $[M+H]^+$ 568.1292:, found 568.1302

Benzyl ((bis(4-acetamidophenoxy)phosphoryl)(4-chlorophenyl)methyl)carbamate (24)



Yield: 87%, white solid

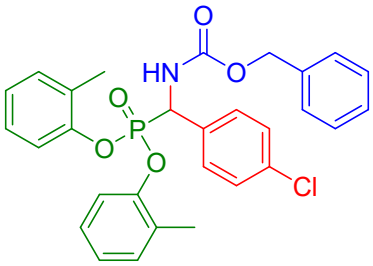
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.98 (s, 2H), 8.89 (d, J= 8Hz, 1H), 7.63 (dd, J=8,4 Hz, 2H), 7.48 (m, 6H), 7.33 (m, 5H), 6.96 (d, J=8Hz, 2H), 6.90 (d, J=8 Hz, 2H), 5.58 (dd, J=24,12 Hz, 1H), 5.05 (dd, J=32,12 Hz, 2H), 2.01 (s, 6H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 168.68, 156.41, 145.61, 145.31, 137.07, 137.04, 134.09, 133.48, 130.80, 128.93, 128.84, 128.46, 128.42, 120.95, 120.85, 120.56, 66.74, 52.52, 24.36.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.44

HRMS (ESI+): *m/z* calc'd for $C_{29}H_{28}ClNO_5P$ $[M+H]^+$: 536.1394, found 536.1395

Benzyl ((bis(o-tolyloxy)phosphoryl)(4-chlorophenyl)methyl)carbamate (25)



Yield: 26%, white solid

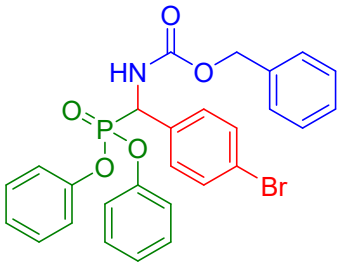
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.95 (d, J=12Hz, 1H), 7.68 (dd, J=8,2 Hz, 2H), 7.49 (d, J=8Hz, 2H), 7.34 (m, 5H), 7.22 (d, J=8Hz, 2H), 7.08 (m, 6H), 5.70 (dd, J=24,12 Hz, 1H), 5.08 (dd, J=32,12 Hz, 2H), 2.00 (d, J=24 Hz, 6H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.45, 149.11, 149.03, 137.03, 134.19, 133.53, 131.88, 130.90, 129.46, 129.38, 128.89, 128.82, 128.43, 128.35, 127.52, 127.40, 125.63, 120.41, 120.18, 66.70, 52.93, 16.10.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.22

HRMS (ESI+): *m/z* calc'd for $C_{29}H_{28}ClNO_5P$ $[M+H]^+$: 536.1394, found 536.1395

Benzyl ((4-bromophenyl)(diphenoxyphosphoryl)methyl)carbamate (26)



Yield: 54%, white solid

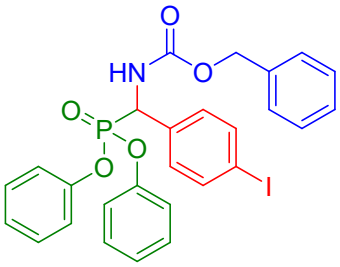
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.96 (d, J=12Hz, 1H), 7.62 (s, 4H), 7.35 (m, 9H), 7.20 (t, J=8Hz, 2H), 7.07 (d, J=8Hz, 2H), 7.03 (d, J=8Hz, 2H), 5.66 (dd, J=24,8 Hz, 1H,), 5.12 (dd, J=32,12 Hz, 2H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.97, 150.04, 149.74, 136.60, 133.94, 131.39, 130.66, 129.88, 128.38, 127.96, 125.35, 121.68, 120.33, 120.25, 66.27, 52.20.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.02

HRMS (ESI+): *m/z* calc'd for $C_{27}H_{24}BrNO_5P$ $[M+H]^+$: 552.0575, found 552.0582

Benzyl ((diphenoxyphosphoryl)(4-iodophenyl)methyl)carbamate (27)



Yield: 25%, white solid

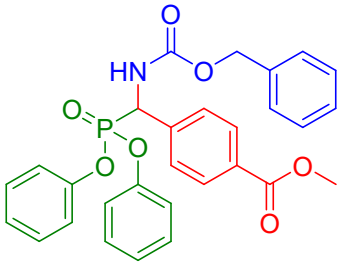
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.86 (d, J=8Hz, 1H), 7.70 (d, J=8Hz, 2H), 7.38 (d, J=8Hz, 2H), 7.26 (m, 9H), 7.12 (t, J=8Hz, 2H), 6.99 (d, J=8Hz, 2H), 6.94 (d, J=8Hz, 2H), 5.53 (dd, J=24,12 Hz, 1H), 5.03 (dd, J=32,12 Hz, 2H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.97, 150.03, 149.73, 137.25, 136.60, 134.30, 130.68, 129.86, 128.37, 127.97, 125.35, 120.33, 120.25, 94.78, 66.25, 52.32.

^{31}P NMR: (162 MHz, DMSO-d_6) δ: 14.03

HRMS (ESI+): *m/z* calc'd for $C_{27}H_{24}INO_5P$ [M+H]+: 600.0437, found 600.0446

Methyl 4-((((benzyloxy)carbonyl)amino)(diphenoxyphosphoryl)methyl)benzoate (28)



Yield: 69%, white solid

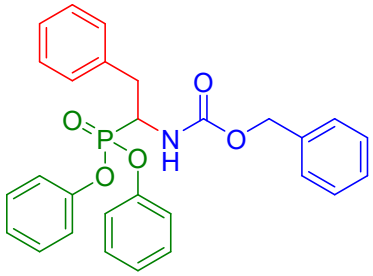
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.03 (d, J=12 Hz, 1H), 7.97 (d, J=8Hz, 2H), 7.79 (d, J=8Hz, 2H), 7.32 (9H, m), 7.17 (t, J=8Hz, 2H), 7.02 (dd, J=20,8 Hz, 4H), 5.73 (dd, J=24,8 Hz, 1H), 5.09 (dd, J=36,12 Hz, 2H), 3.84 (s, 3H)

^{13}C NMR: (101 MHz, DMSO-d_6) δ 165.89, 156.03, 150.01, 149.71, 139.78, 136.59, 129.89, 129.44, 129.23, 128.82, 128.38, 127.99, 125.39, 120.33, 120.26, 66.31, 52.69, 52.23.

^{31}P NMR: NMR (162 MHz, DMSO-d_6) δ: 13.87

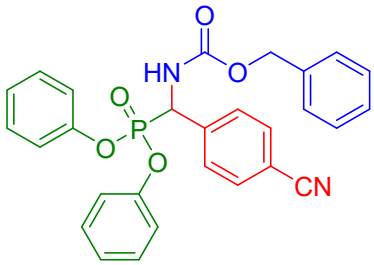
HRMS (ESI+): *m/z* calc'd for $C_{29}H_{27}NO_7P$ $[M+H]^+$: 532.1525, found 532.1506

Benzyl (1-(diphenoxyphosphoryl)-2-phenylethyl)carbamate (29)



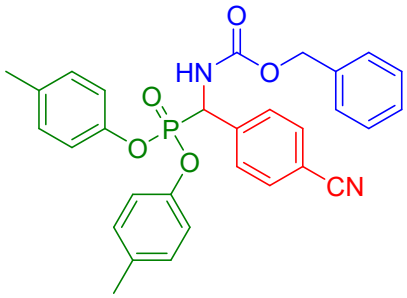
Yield: 48%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.20 (d, J=8Hz, 1H), 7.39 (m, 4H), 7.24 (m, 15H), 4.97 (dd, J=24,12 Hz, 2H), 4.55 (m, 1H), 3.29 (dt, J= 24,4 Hz, 1H), 3.02 (m, 1H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.91, 150.14, 149.87, 137.13, 136.95, 136.92, 129.90, 129.14, 128.27, 127.68, 127.25, 126.80, 126.63, 125.32, 120.66, 120.41, 65.47, 49.97, 34.18.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 18.00
HRMS (ESI+): *m/z* calc'd for $C_{28}H_{27}NO_5P$ $[M+H]^+$:488.1627, found 488.1639

Benzyl ((4-cyanophenyl)(diphenoxyphosphoryl)methyl)carbamate (30)



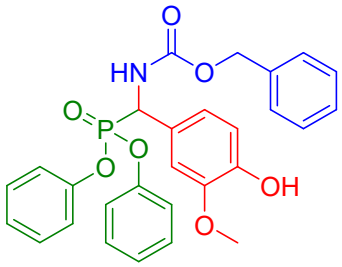
Yield: 67%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.07 (d, J=12 Hz, 1H), 7.90 (t, J=8Hz, 4H), 7.35 (m, 9H), 7.21 (t, J=8Hz, 2H), 7.05 (m, 4H), 5.83 (dd, J=24,12 Hz, 1H), 5.13 (dd, J=32,12 Hz, 2H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 157.35, 155.98, 149.68, 149.68, 140.08, 136.54, 132.40, 129.90, 129.40, 128.39, 128.02, 125.44, 120.31, 120.23, 118.80, 118.58, 115.24, 111.11, 66.37, 52.66,
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 13.45
HRMS (ESI+): *m/z* calc'd for $C_{28}H_{24}N_2O_5P$ $[M+H]^+$: 499.1428, found 499.1423

Benzyl ((bis(p-tolyloxy)phosphoryl)(4-cyanophenyl)methyl)carbamate (31)



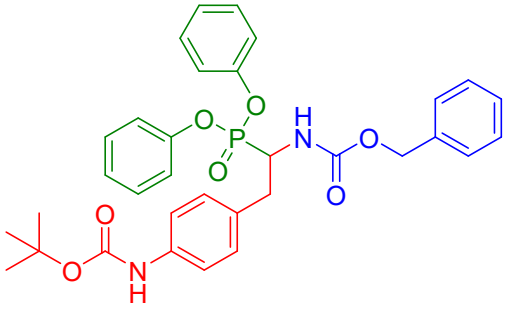
Yield: 63%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.00 (d, J=8Hz, 1H), 7.87 (m, 4H), 7.35 (m, 5H), 7.13 (m, 4H), 6.91 (m, 4H), 5.74 (dd, J=24,12 Hz, 1H), 5.10 (dd, J=36,12 Hz, 2H), 2.24 (s, 6H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.43, 148.29, 147.99, 140.69, 137.01, 135.02, 132.84, 130.61, 129.83, 128.85, 128.46, 120.46, 120.39, 119.05, 115.48, 111.49, 66.80, 53.12, 20.70.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 13.46
HRMS (ESI+): *m/z* calc'd for $C_{30}H_{28}N_2O_5P$ $[M+H]^+$: 527.1742, found 527.1736

Benzyl ((diphenoxyphosphoryl)(4-hydroxy-3-methoxyphenyl)methyl)carbamate (32)



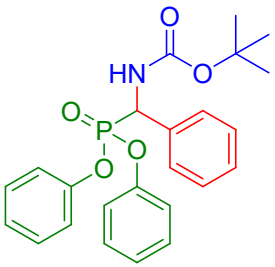
Yield: 75%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.11 (s, 1H), 8.76 (d, J=12Hz, 1H), 7.34 (m, 9H), 7.24 (m, 1H), 7.19 (m, 2H), 7.07 (d, J=8Hz, 2H), 6.76 (d, J=8Hz, 1H), 5.47 (dd, J=20,12 Hz, 1H), 5.10 (dd, J=36,12 Hz, 2H), 3.73 (s, 3H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.91, 150.24, 149.95, 147.46, 146.64, 136.71, 129.80, 128.38, 127.97, 125.18, 124.67, 121.43, 120.34, 120.26, 115.19, 112.87, 66.13, 55.70, 52.62.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 15.18
HRMS (ESI+): *m/z* calc'd for $C_{28}H_{27}NO_7P$ $[M+H]^+$: 520.1528, found 520.1525

Benzyl (2-(4-((tert-butoxycarbonyl)amino)phenyl)-1-(diphenoxyphosphoryl)ethyl)carbamate (33)



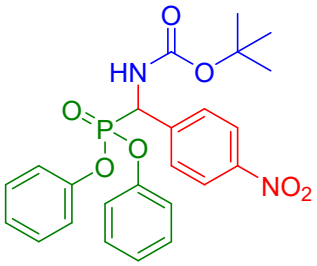
Yield: 38%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 9.32 (s, 1H), 8.15 (d, J=8Hz, 1H), 7.39 (m, 6H), 7.21 (m, 13H), 4.97 (dd, J=32,12 Hz, 2H), 4.46 (m, 1H), 3.20 (m, 1H), 2.92 (m, 1H), 1.49 (s, 9H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.96, 152.81, 150.16, 149.88, 138.17, 137.00, 130.42, 129.89, 129.37, 128.26, 127.56, 127.13, 125.31, 120.69, 120.43, 117.90, 78.94, 65.40, 50.14, 33.55, 28.16.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 18.11
HRMS (ESI+): *m/z* calc'd for $C_{33}H_{35}N_2O_7PNa$ $[M+Na]^+$: 625.2080, found 625.2101

Tert-butyl ((diphenoxyphosphoryl)(phenyl)methyl)carbamate (34)



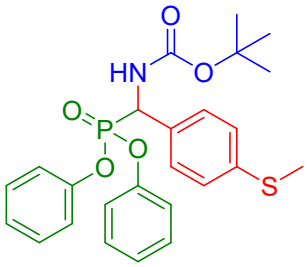
Yield: 43%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.48 (d, J=12Hz, 1H), 7.63 (d, J=8Hz, 2H), 7.36 (m, 7H), 7.19 (t, J=8Hz, 2H), 7.09 (d, J=8Hz, 2H), 7.00 (d, J=8Hz, 2H), 5.56 (dd, J=32,12 Hz, 1H), 1.40 (s, 9H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 170.32, 155.16, 150.20, 149.87, 134.62, 129.80, 128.61, 128.38, 128.13, 125.22, 120.33, 120.26, 79.12, 59.75, 52.27, 28.11, 20.76, 14.08.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 15.16
HRMS (ESI+): *m/z* calc'd for $C_{24}H_{26}NO_5PNa$ $[M+Na]^+$: 462.1446, found 462.1468

Tert-butyl ((diphenoxyphosphoryl)(4-nitrophenyl)methyl)carbamate (35)



Yield: 41%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.67 (d, J=12Hz, 1H), 8.26 (d, J=8Hz, 2H), 7.93 (m, 2H), 7.35 (t, J=8Hz, 4H), 7.19 (m, 2H), 7.08 (m, 4H), 5.78 (dd, J=32,12Hz, 1H), 1.39 (s, 9H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 156.24, 155.13, 150.04, 149.71, 147.28, 142.38, 129.89, 129.77, 125.41, 123.50, 120.31, 120.23, 79.47, 77.02, 52.04, 28.21, 28.06.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 13.60
HRMS (ESI+): *m/z* calc'd for $C_{27}H_{23}N_2O_7PNa$ $[M+Na]^+$: 507.1311, found 507.1297

Tert-butyl ((diphenoxyphosphoryl)(4-(methylthio)phenyl)methyl)carbamate (36)



Yield: 17%, white solid
^{1}H NMR: (400 MHz, DMSO-d_6) δ: 8.44 (d, J=12 Hz, 1H), 7.57 (dd, J=8,4 Hz, 2H), 7.37 (td, J=8,4 Hz, 4H), 7.28 (d, J=8Hz, 2H), 7.20 (t, J=8Hz, 2H), 7.10 (d, J=8Hz, 2H), 7.04 (d, J=8Hz, 2H), 5.50 (dd, J=24,12 Hz, 1H), 2.48 (s, 3H), 1.40 (s, 9H)
^{13}C NMR: (101 MHz, DMSO-d_6) δ 155.13, 150.21, 149.86, 138.34, 131.07, 129.83, 129.11, 125.72, 125.23, 120.36, 120.26, 79.14, 51.83, 28.12, 14.58.
^{31}P NMR: (162 MHz, DMSO-d_6) δ: 15.49
HRMS (ESI+): *m/z* calc'd for $C_{27}H_{23}N_2O_7PNa$ $[M+Na]^+$: 508.1333, found 508.1323

Section 3: NMR studies

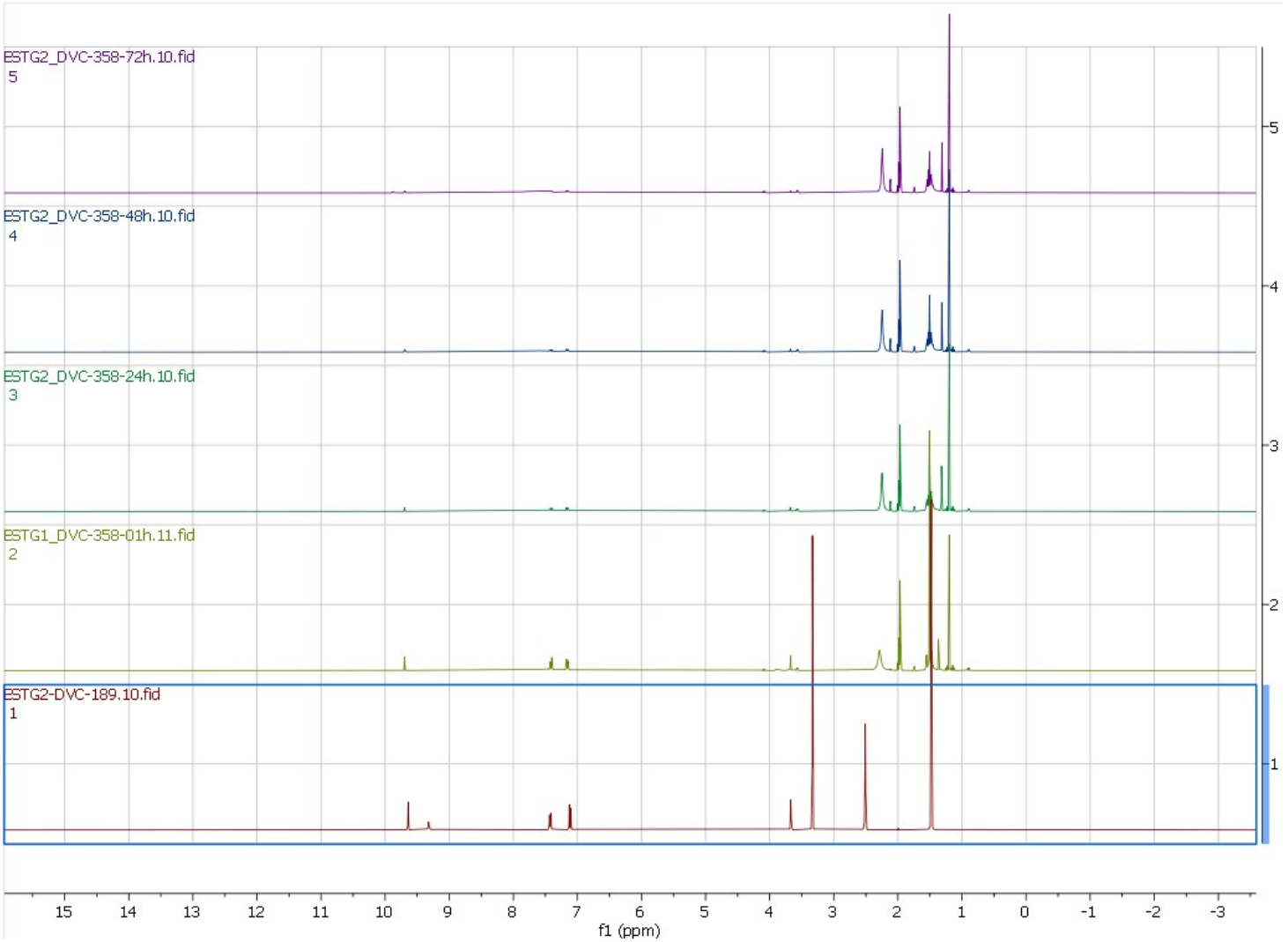
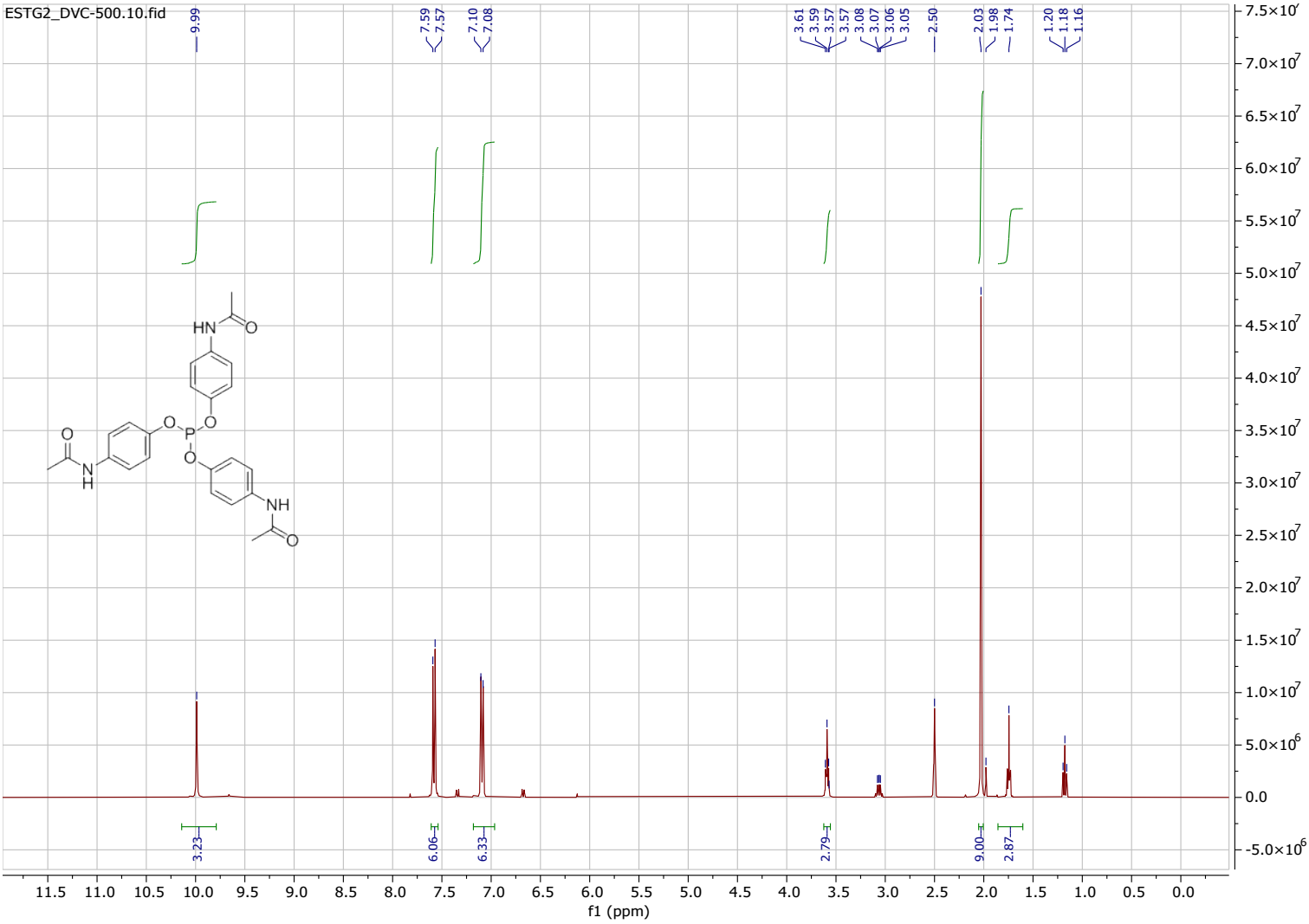


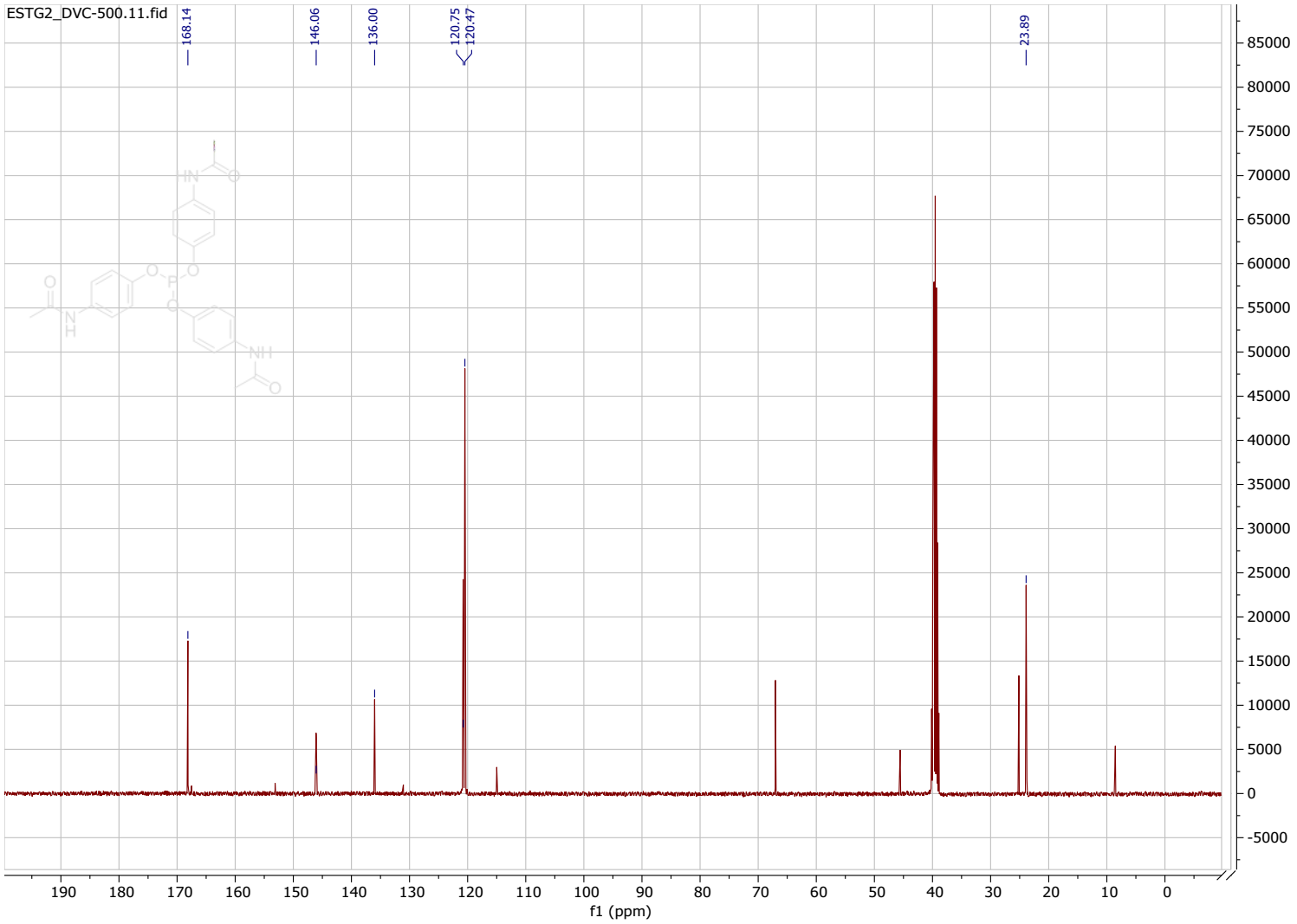
Figure S5: NMR study of Boc-removal from aldehyde (**2**) catalyzed by Lewis acid ($Bi(OTf)_3$)

^{1}H NMR ^{13}C NMR and ^{31}P NMR of synthesized compounds

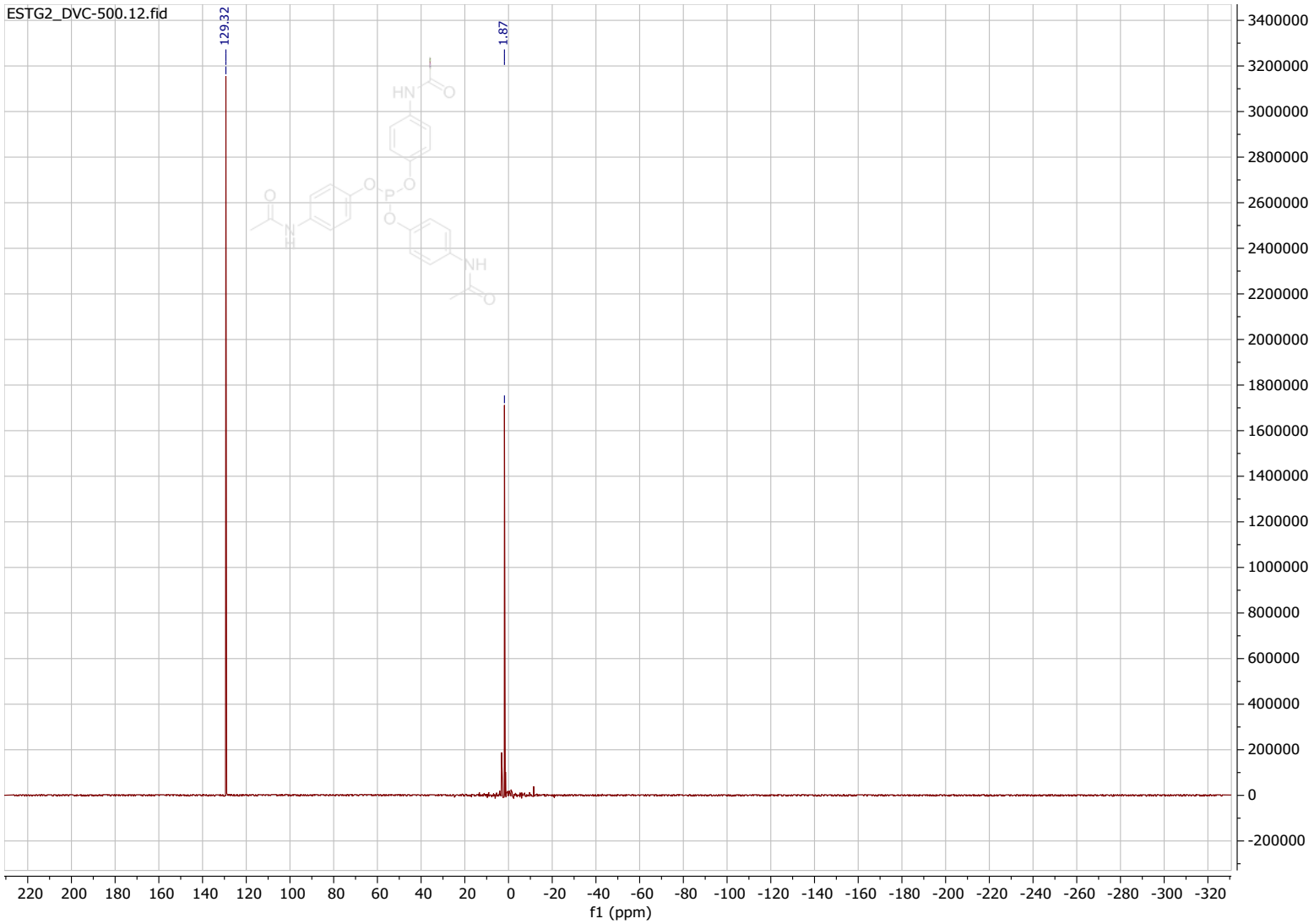
^{1}H NMR spectrum of compound **1**



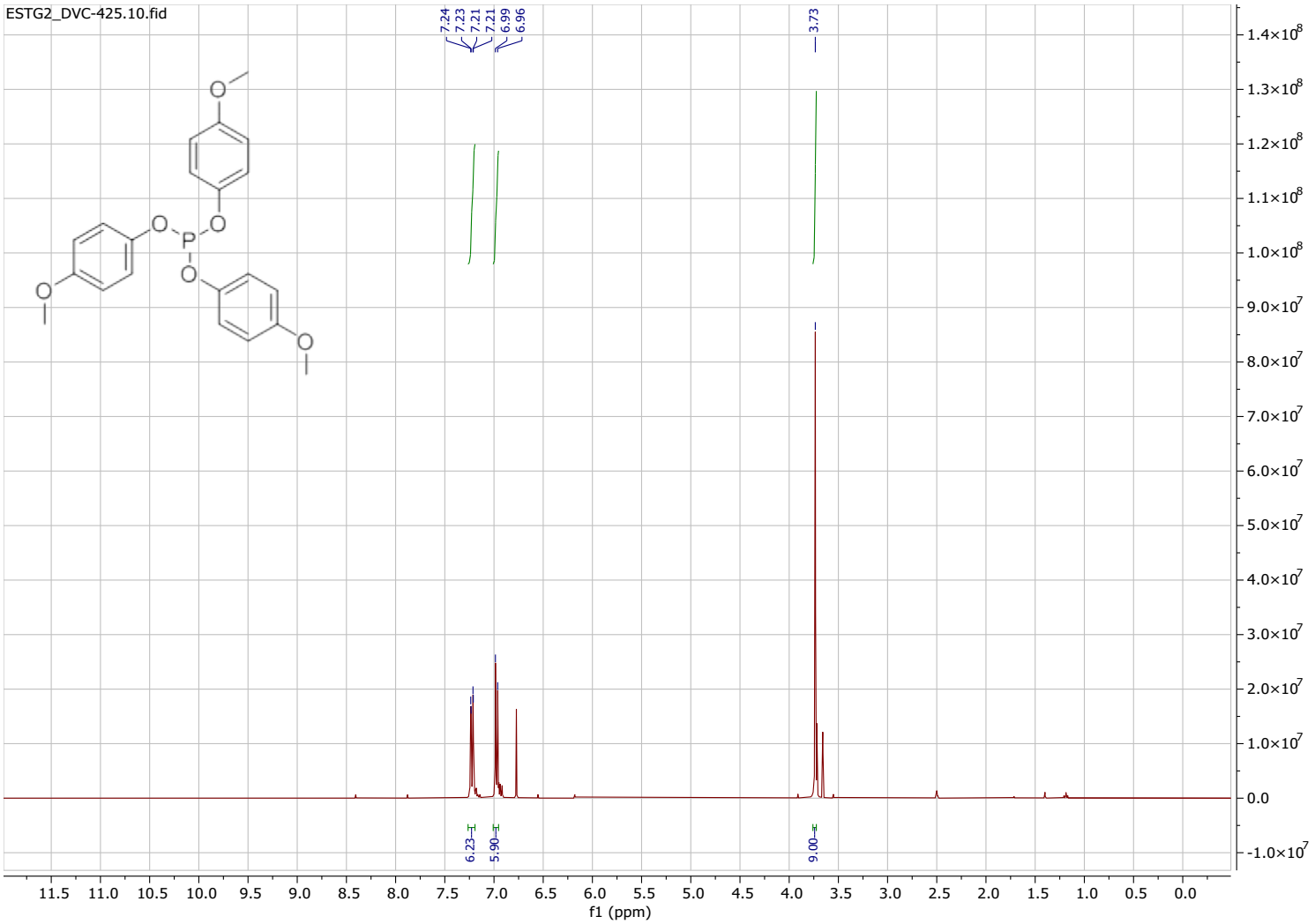
^{13}C NMR spectrum of compound **1**



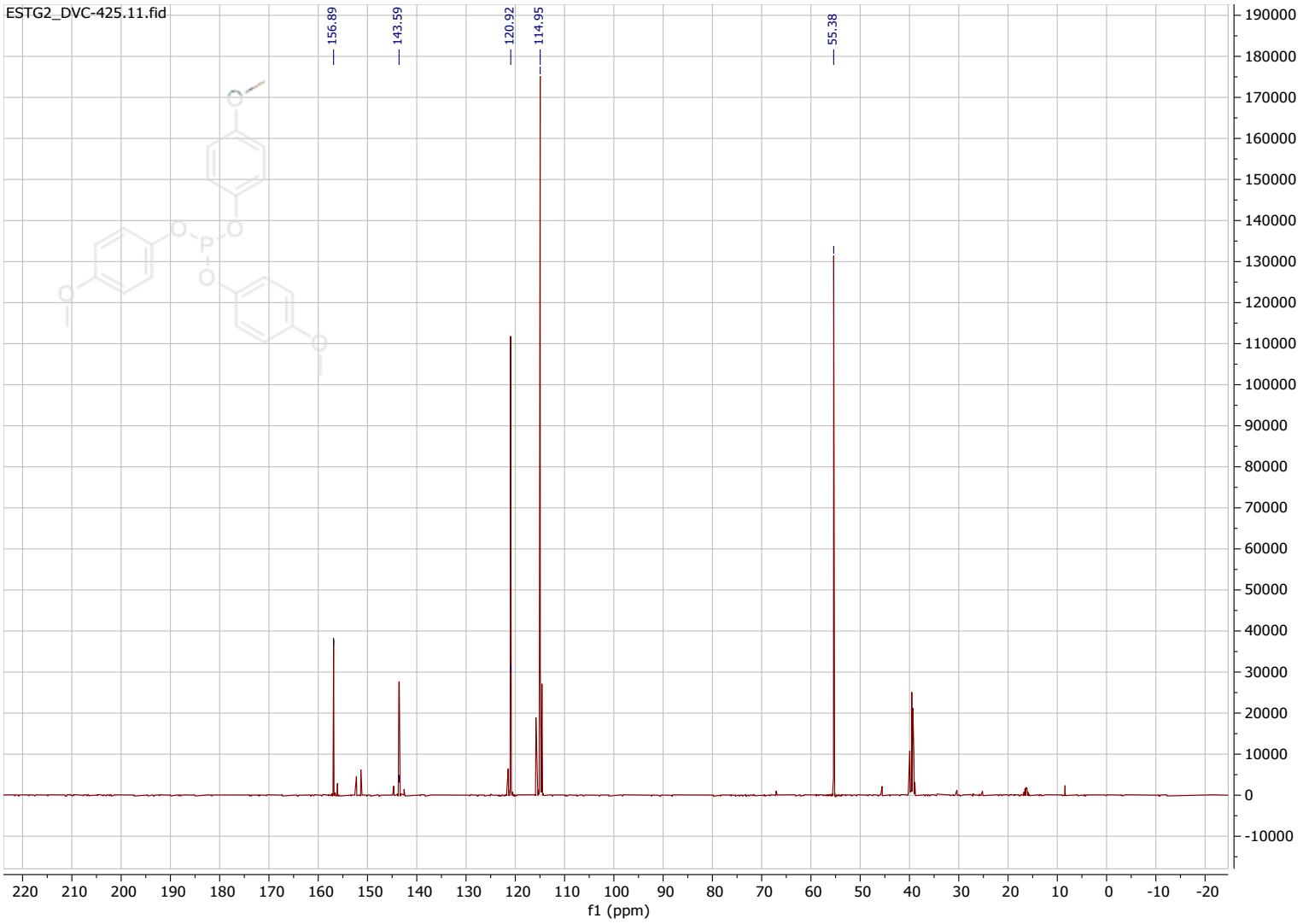
^{31}P NMR spectrum of compound **1**



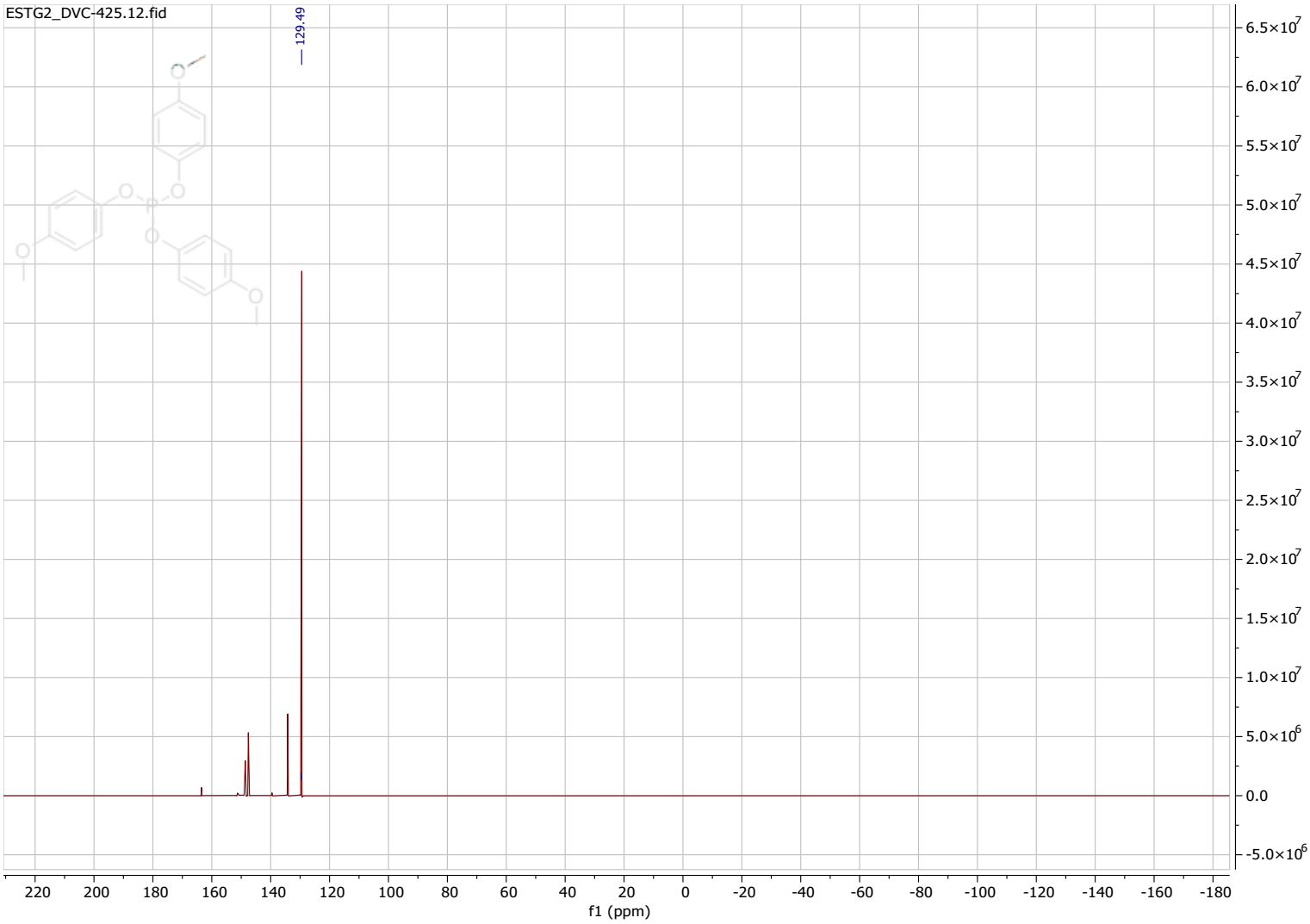
^{1}H NMR spectrum of compound **38**



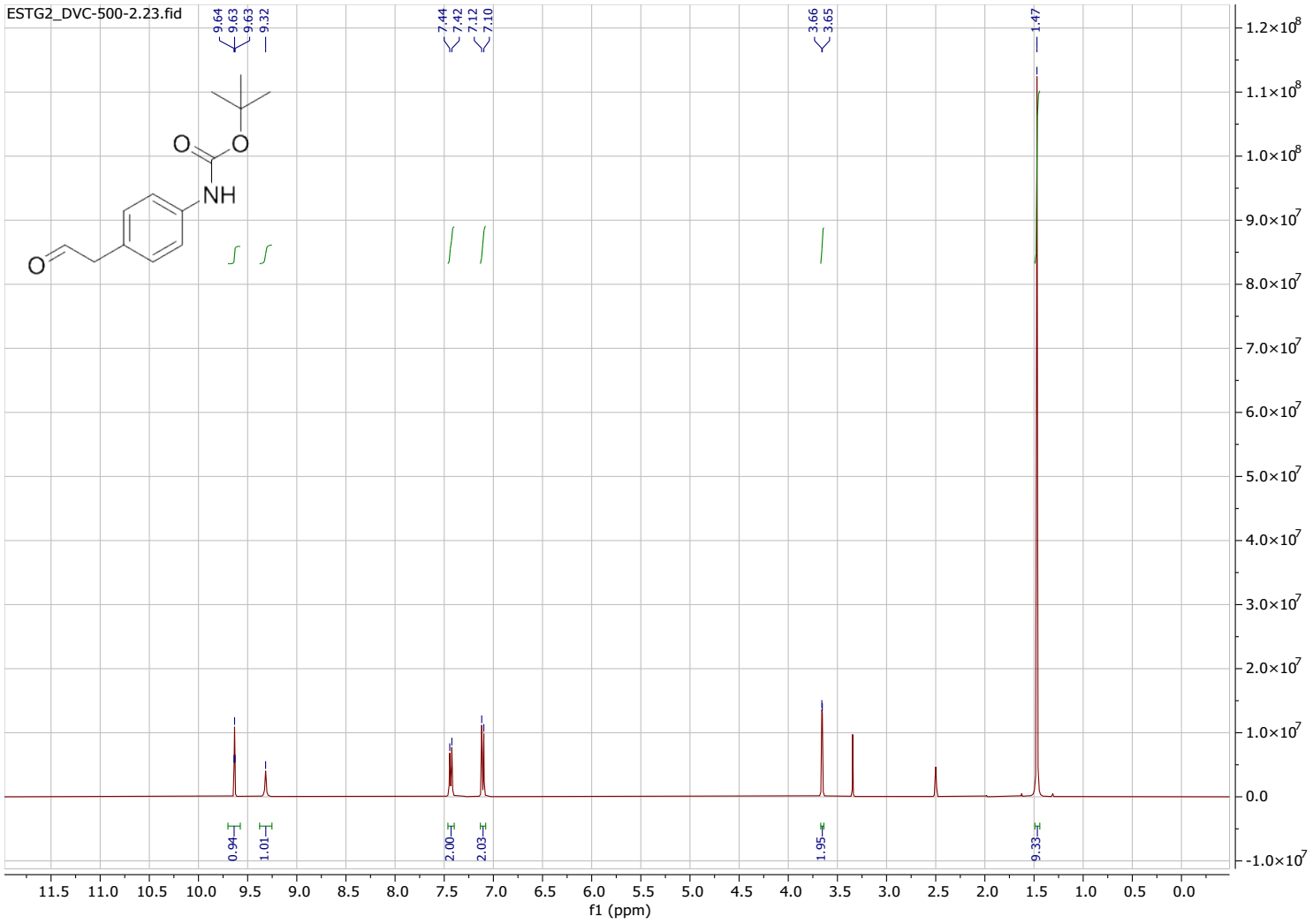
^{13}C NMR spectrum of compound **38**



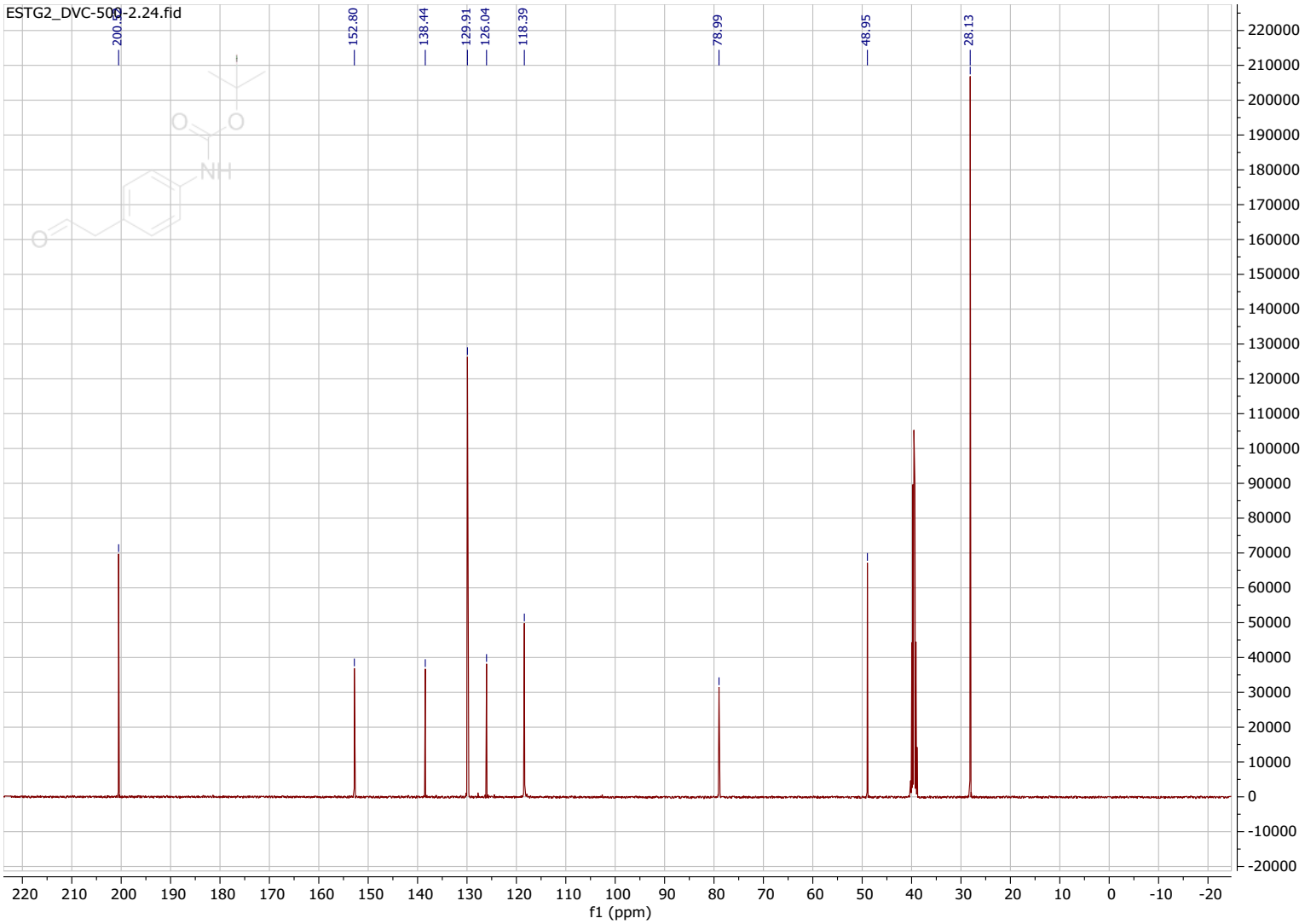
^{31}P NMR spectrum of compound **38**



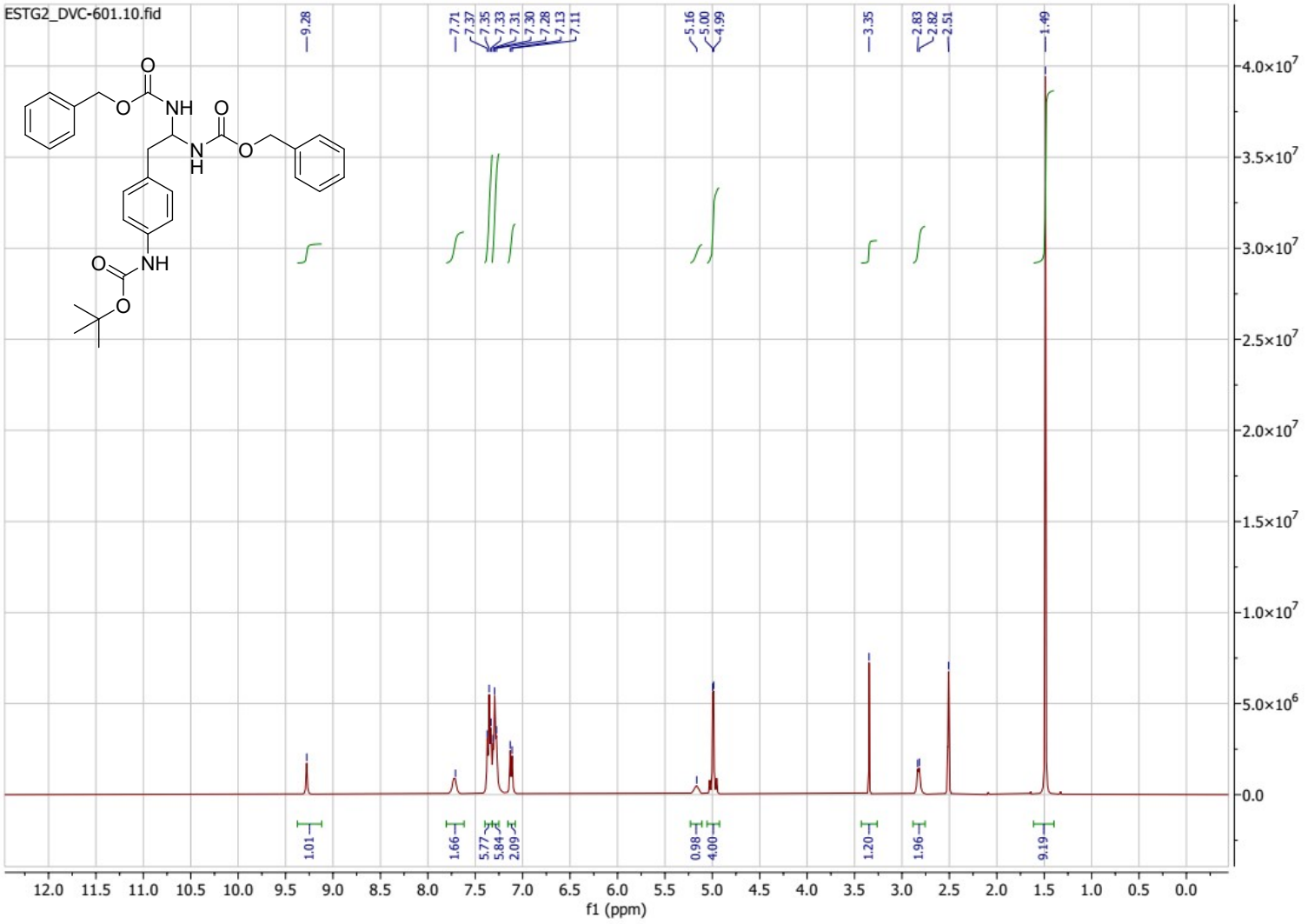
[1]H NMR spectrum of compound **2**



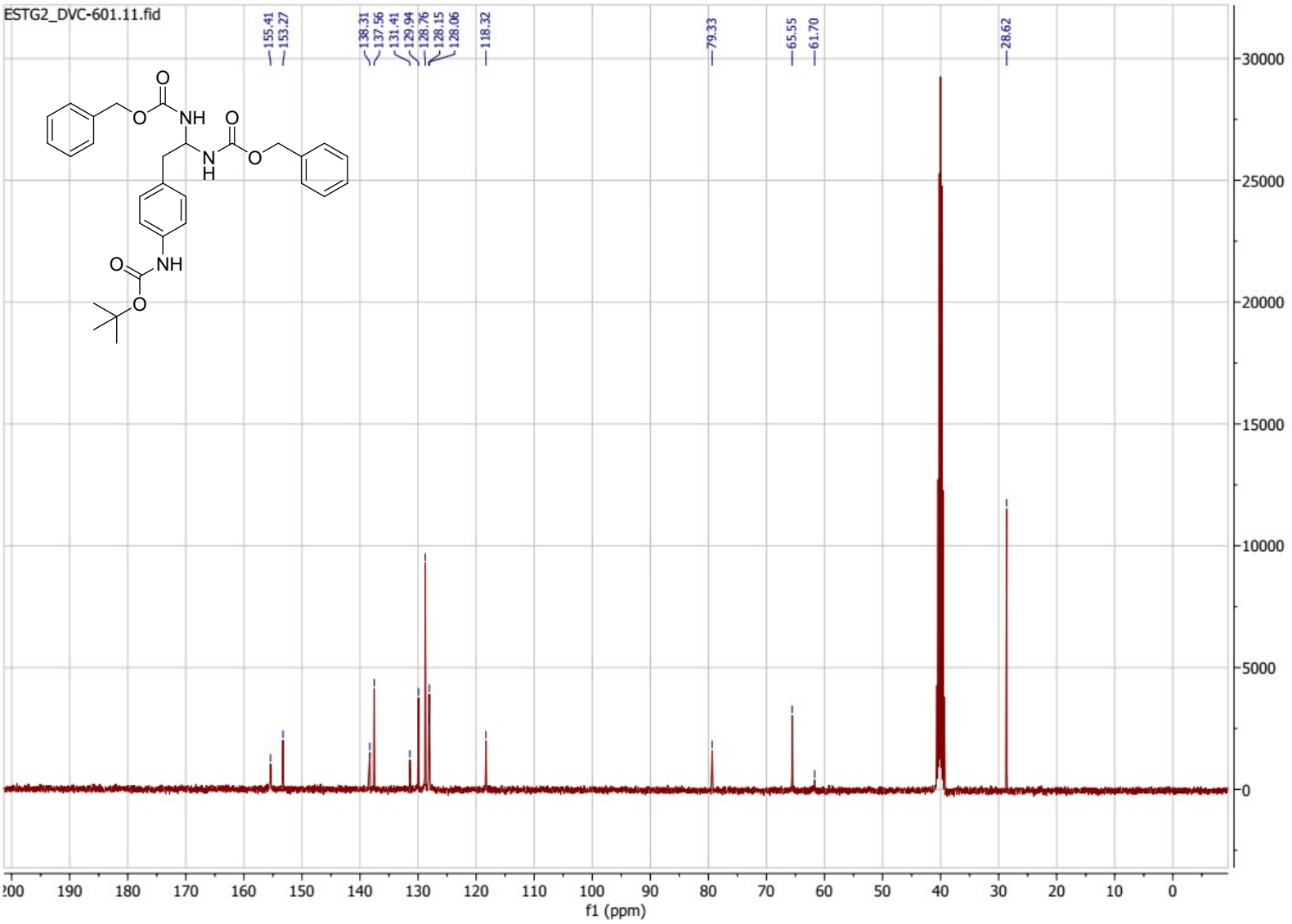
^{13}C NMR spectrum of compound **2**



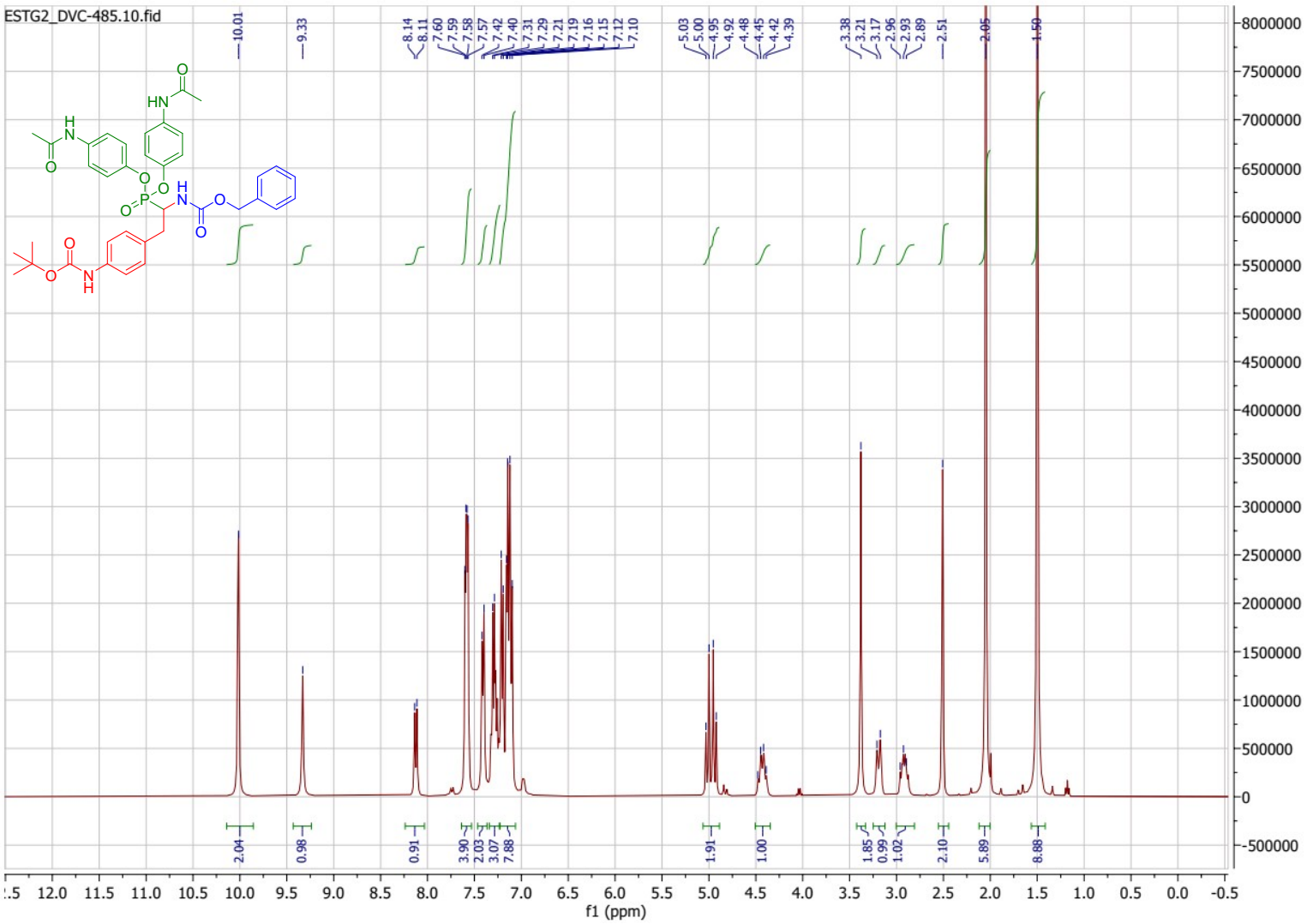
^{1}H NMR spectrum of compound **7**



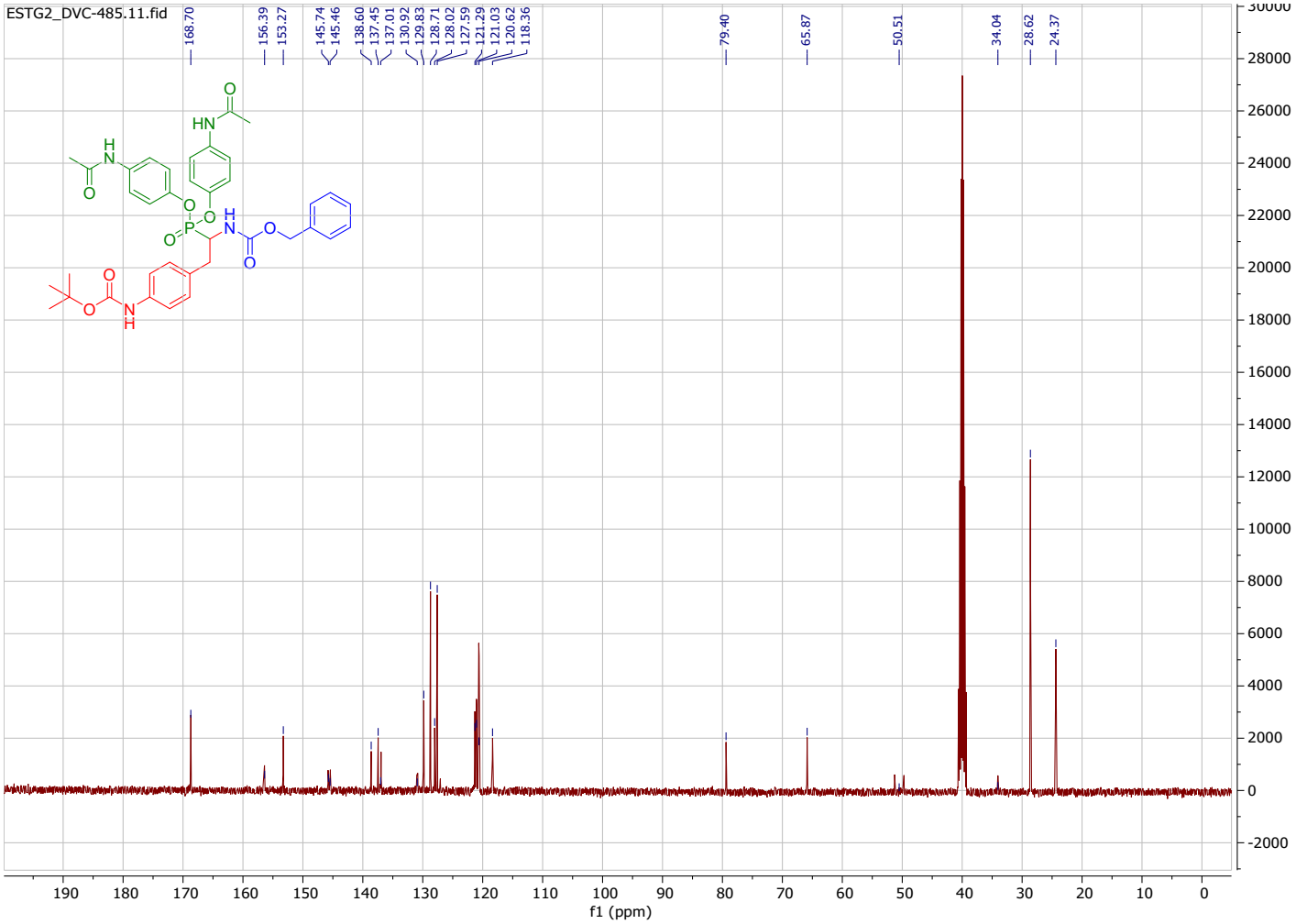
^{13}C NMR spectrum of compound **7**



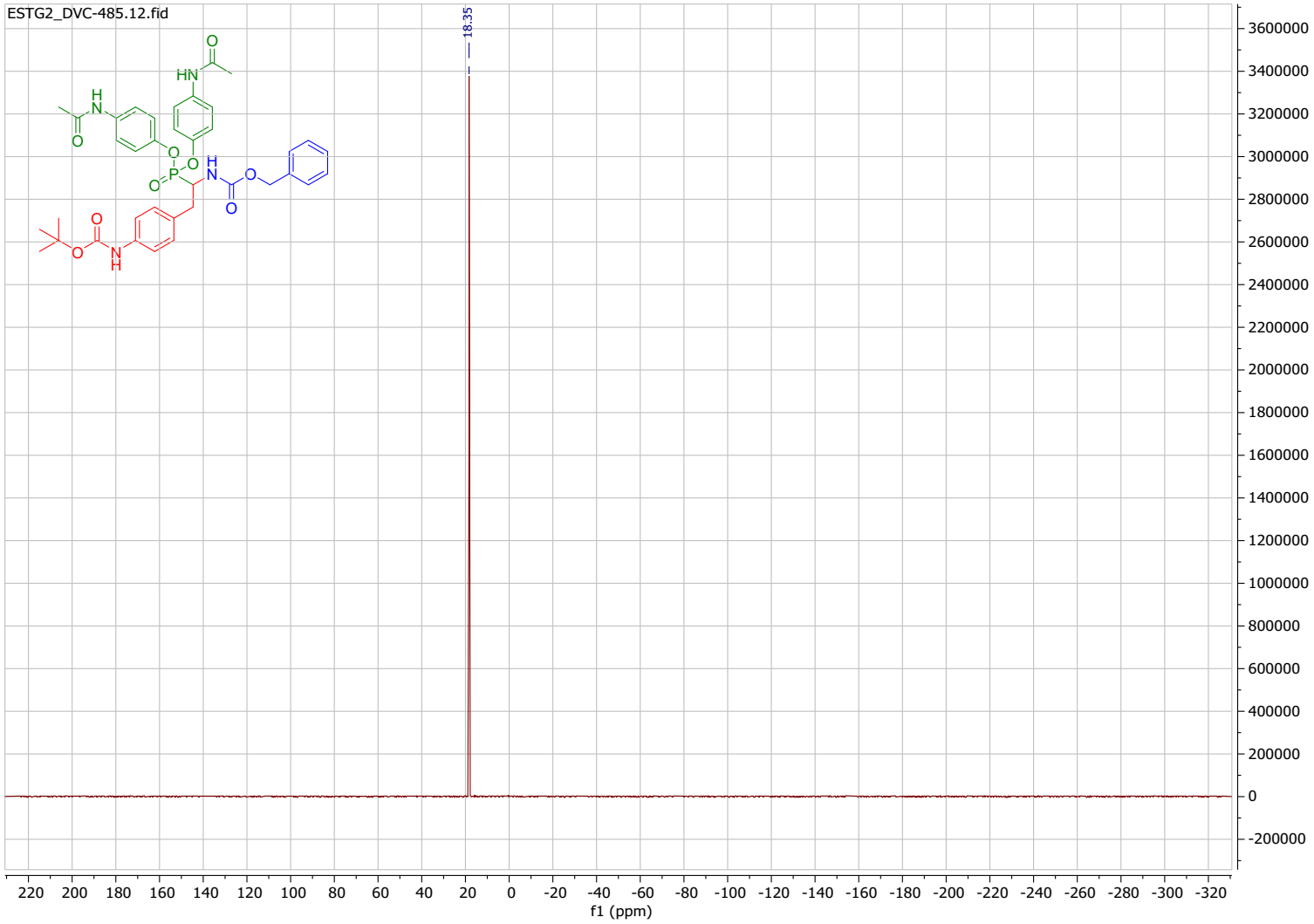
^{1}H NMR spectrum of compound **4**



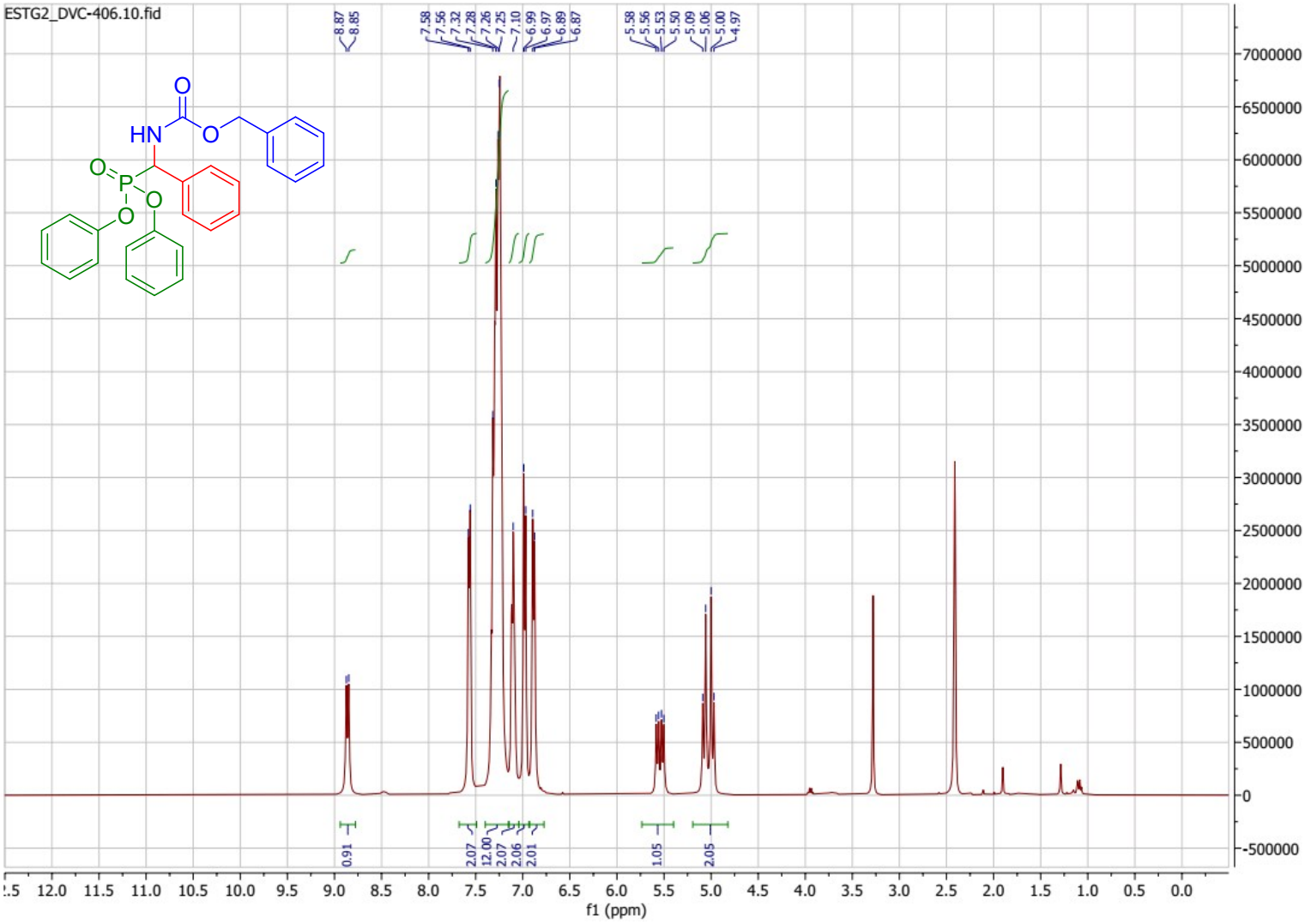
^{13}C NMR spectrum of compound **4** (without ^{31}P decoupling)



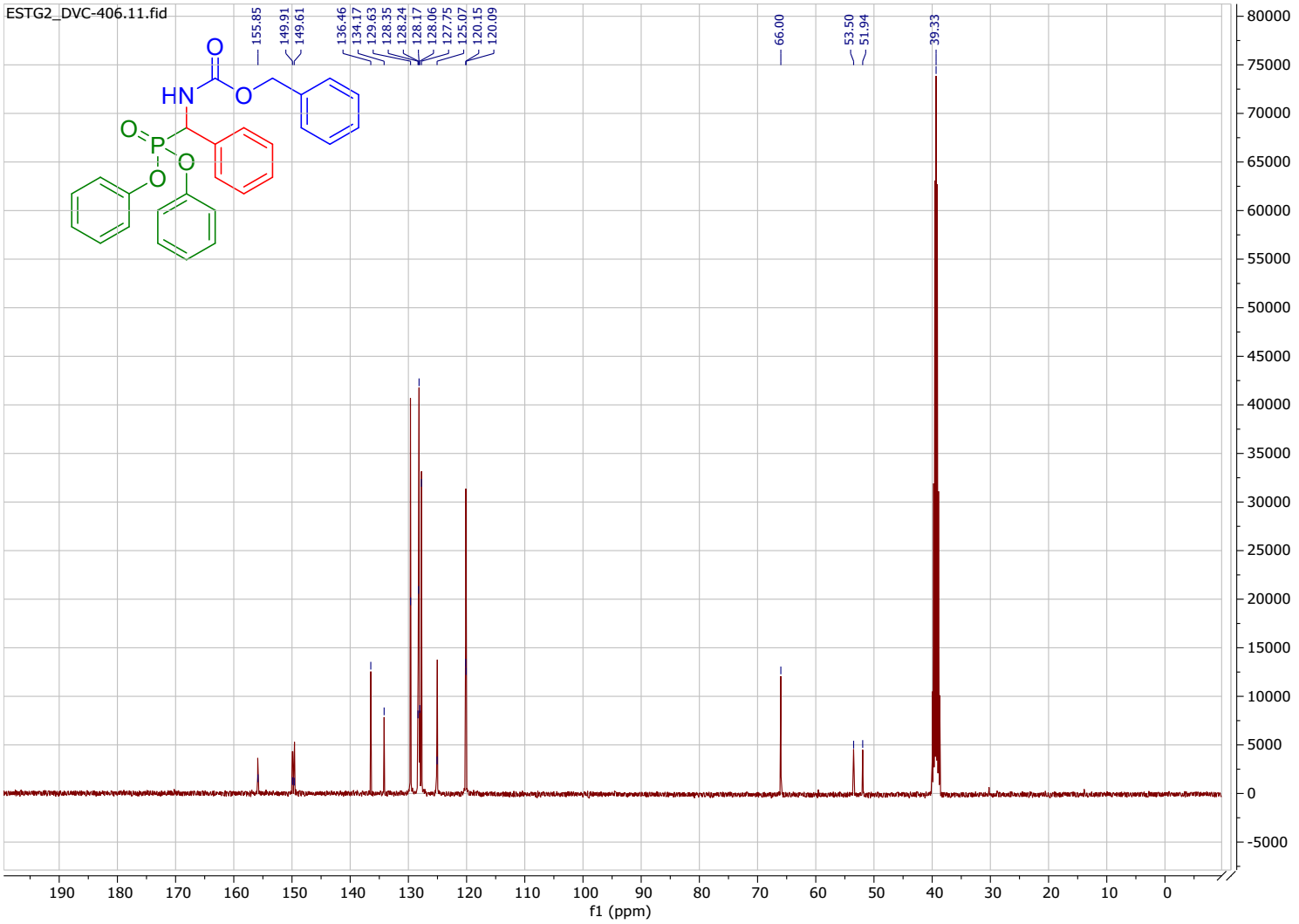
^{31}P NMR spectrum of compound **4**



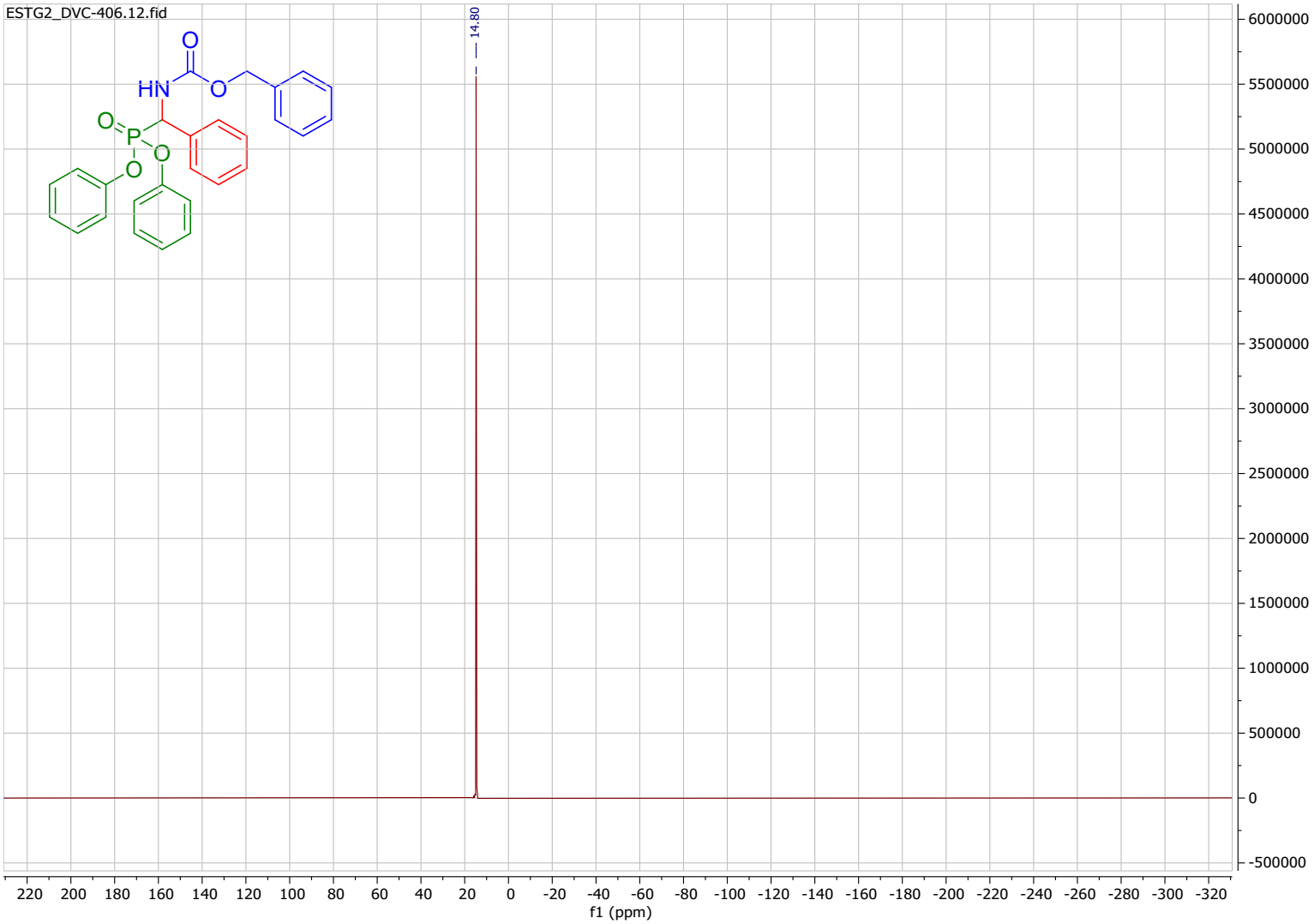
^{1}H NMR spectrum of compound **14**



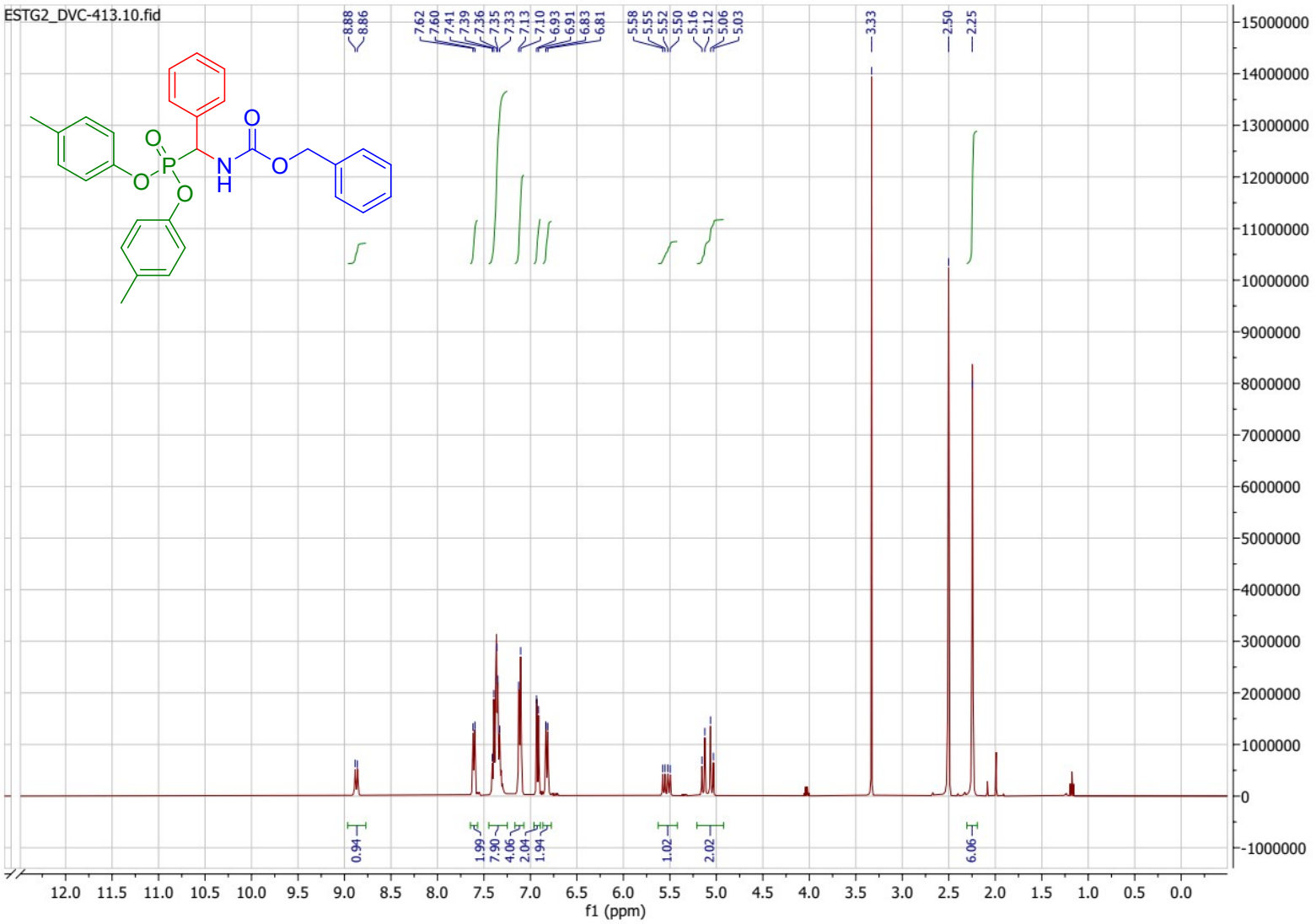
^{13}C NMR spectrum compound **14** (without ^{31}P decoupling)



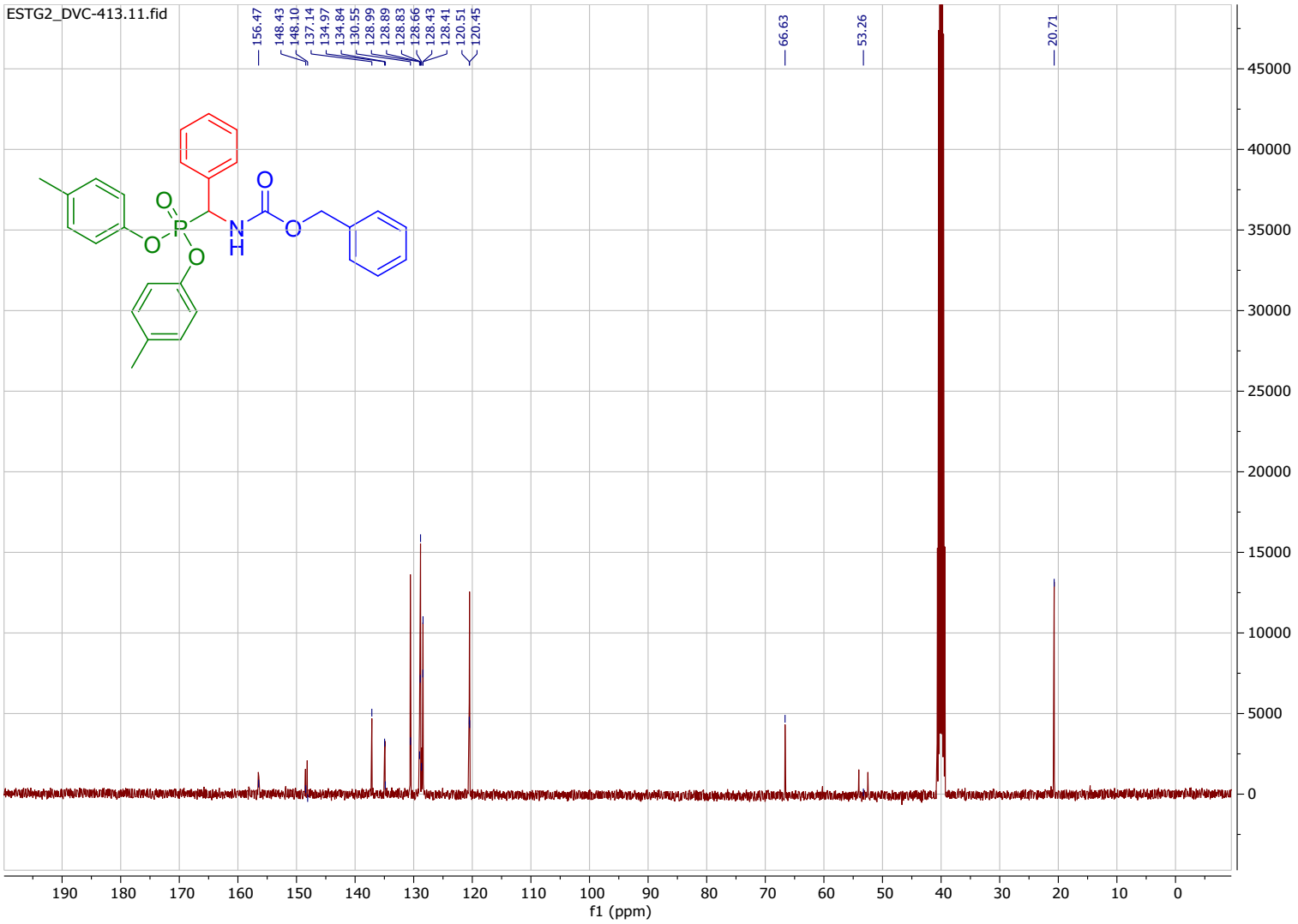
^{31}P NMR spectrum of compound **14**



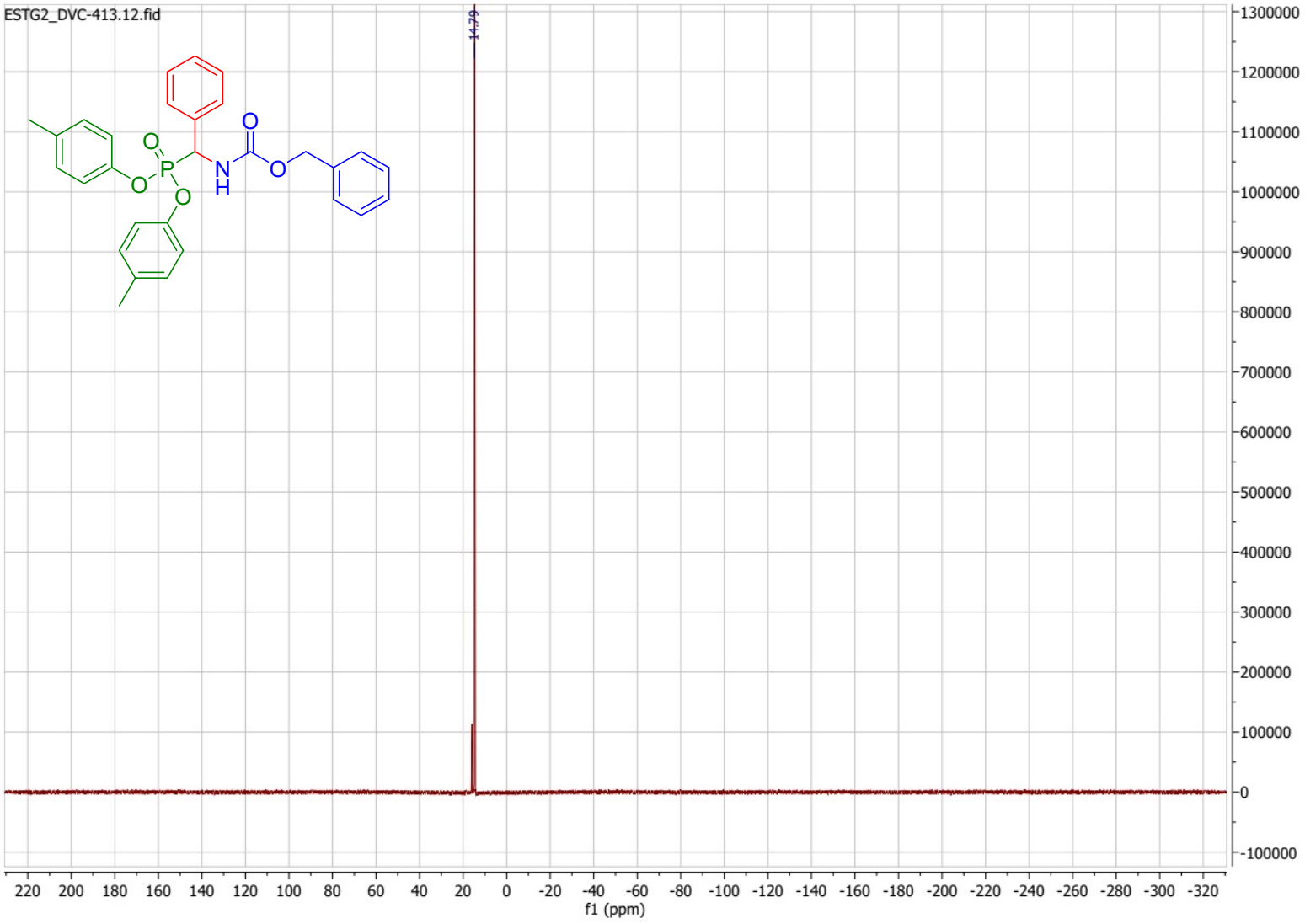
^{1}H NMR spectrum of compound **15**



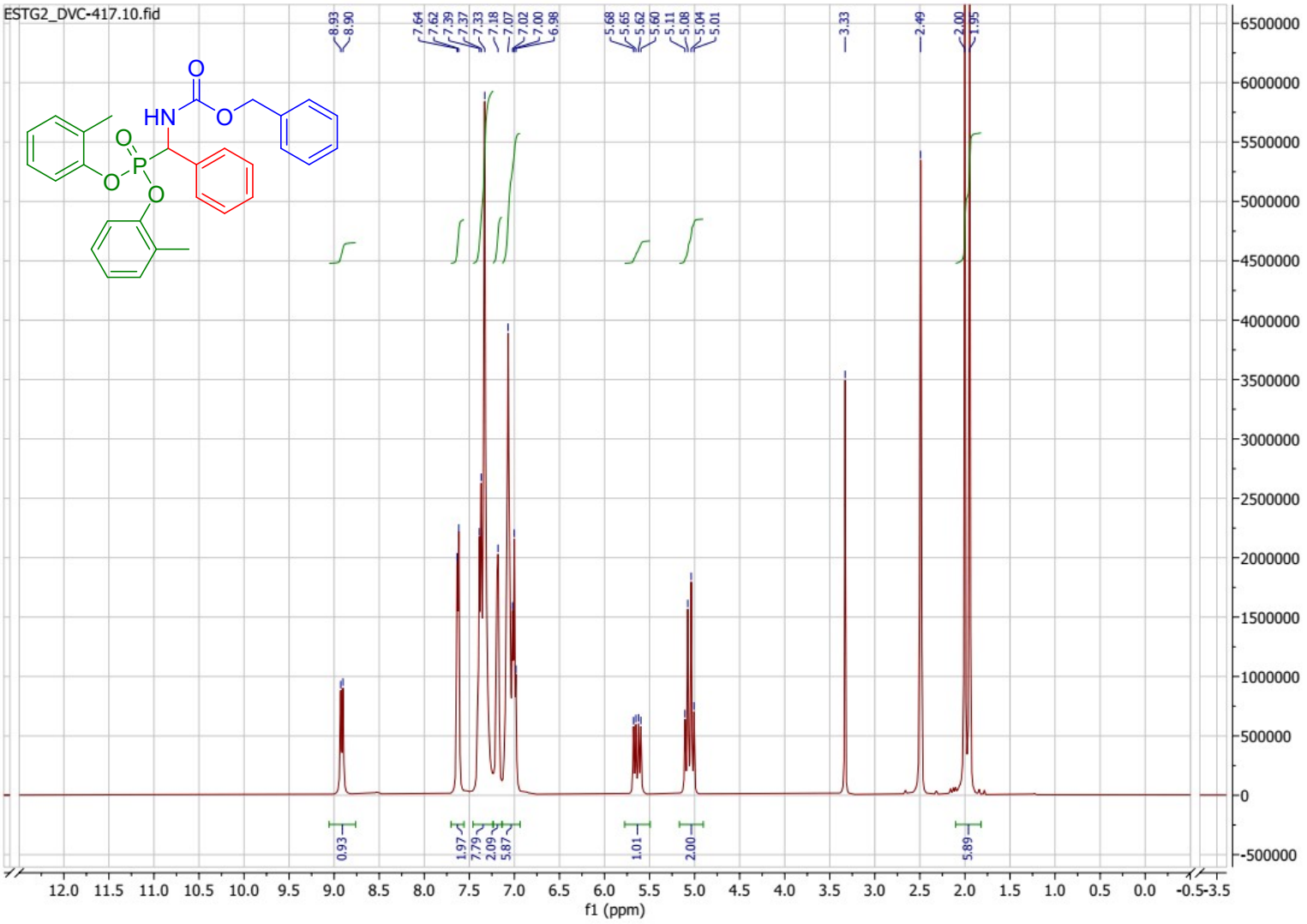
^{13}C NMR spectrum of compound **15** (without ^{31}P decoupling)



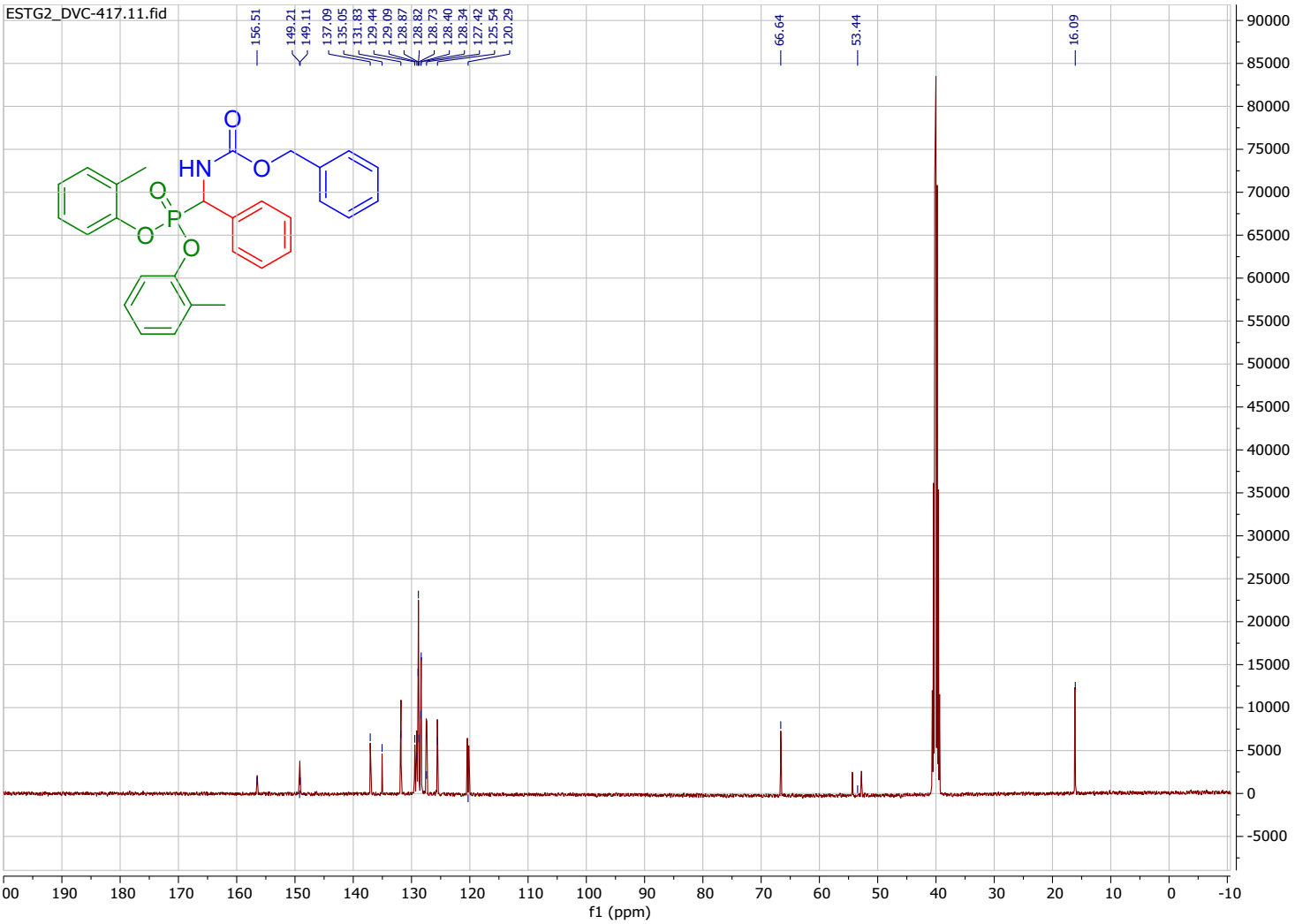
^{31}P NMR spectrum of compound **15**



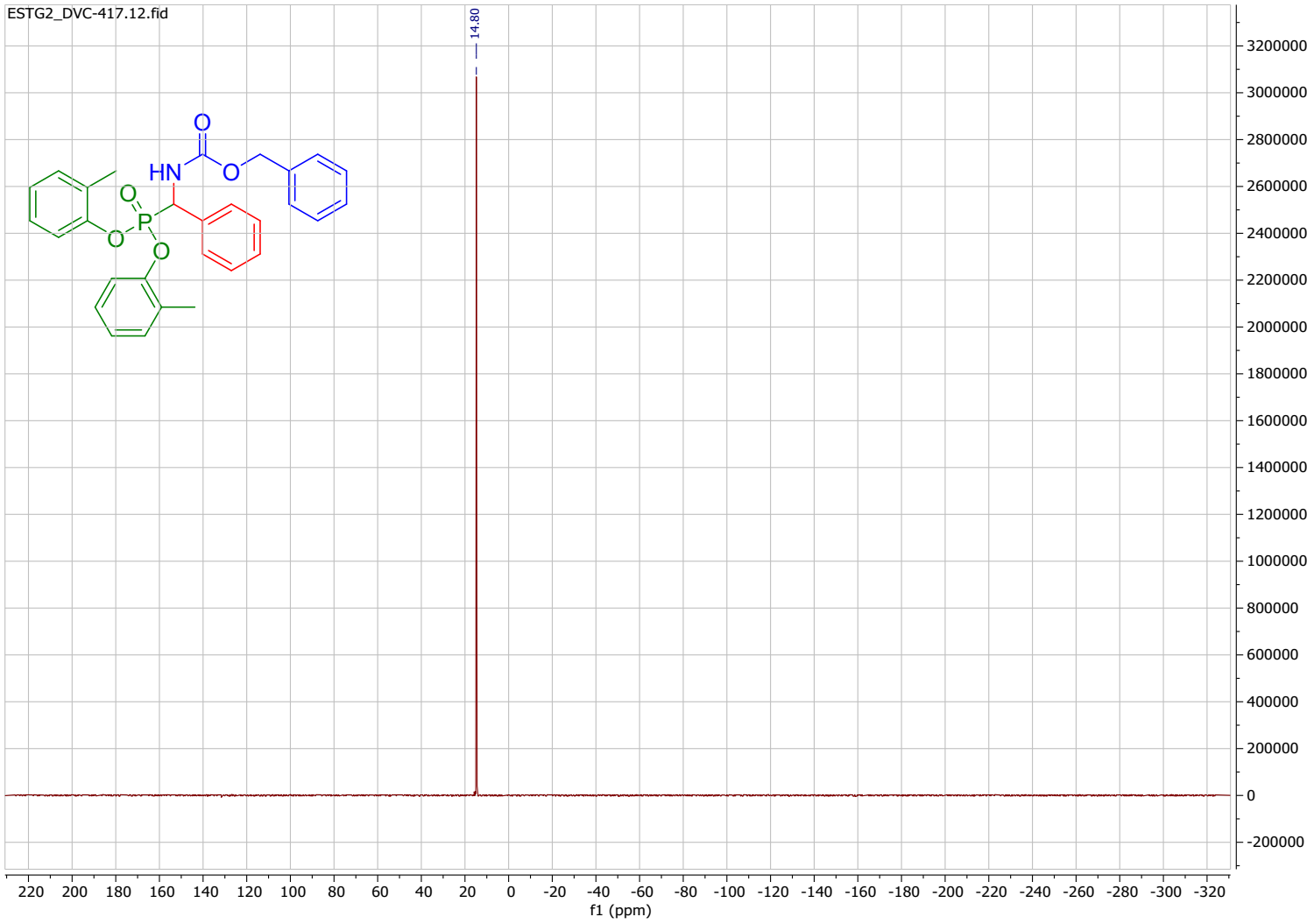
[1]H NMR spectrum of compound **16**



^{13}C NMR spectrum of compound **16** (without ^{31}P decoupling)

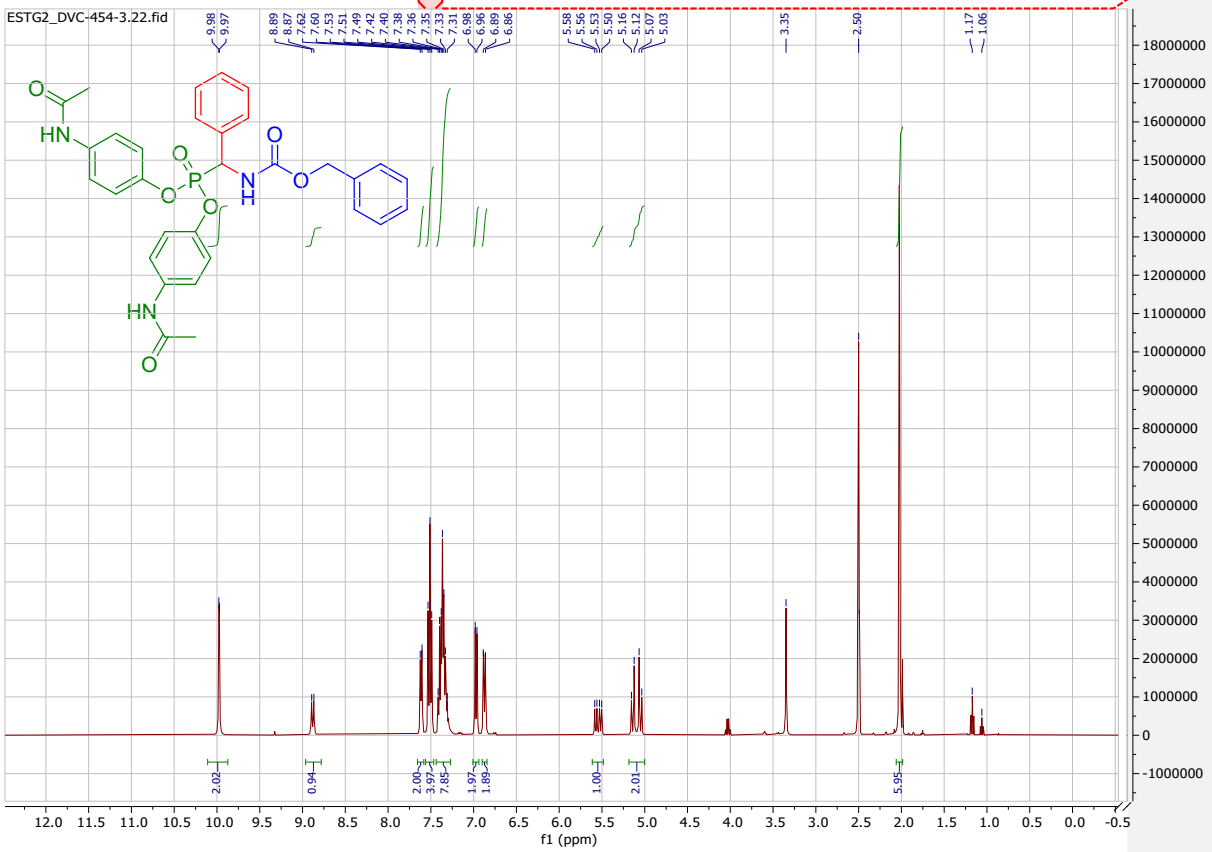


^{31}P NMR spectrum of compound **16**

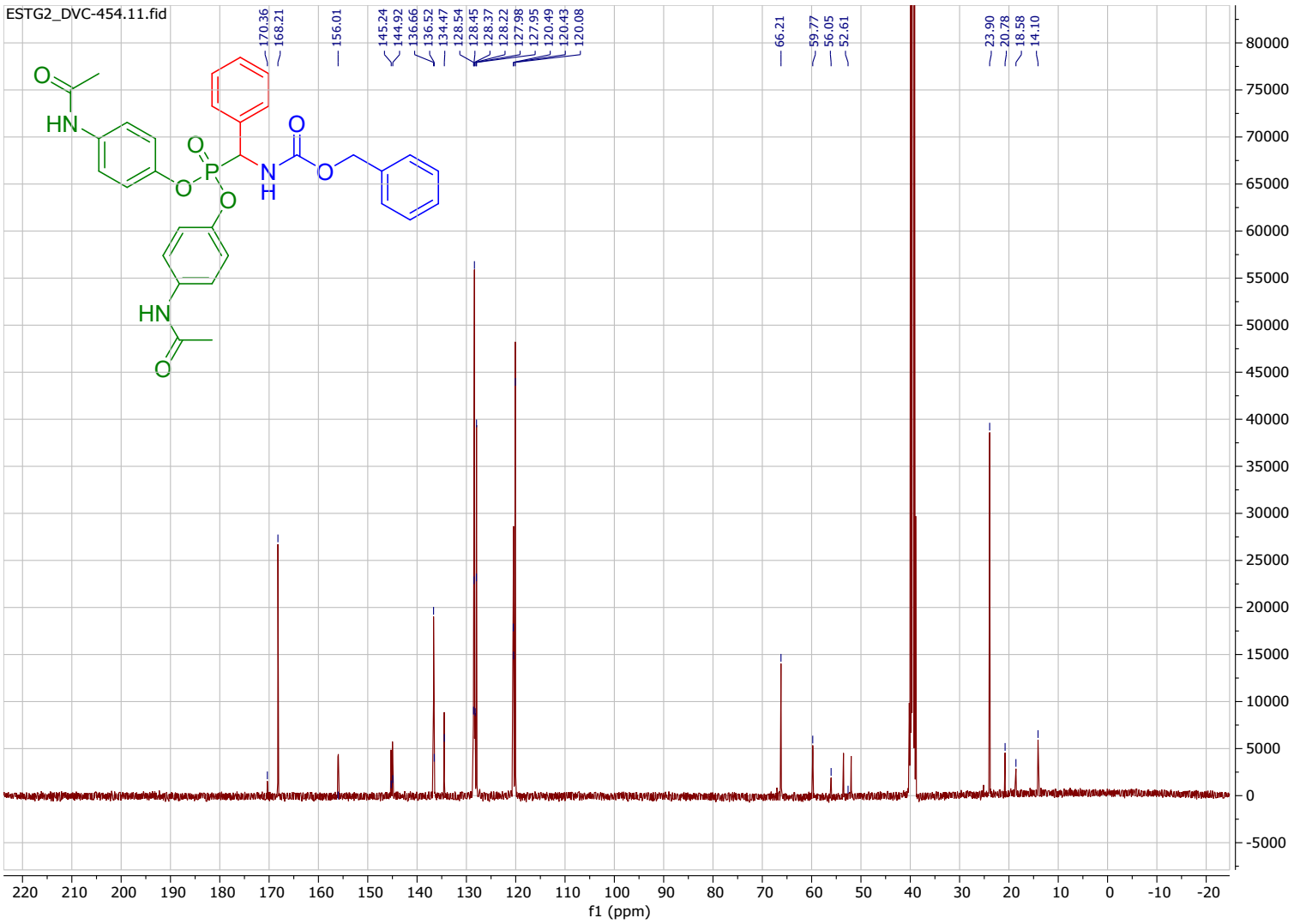


^{1}H NMR spectrum of compound **17**

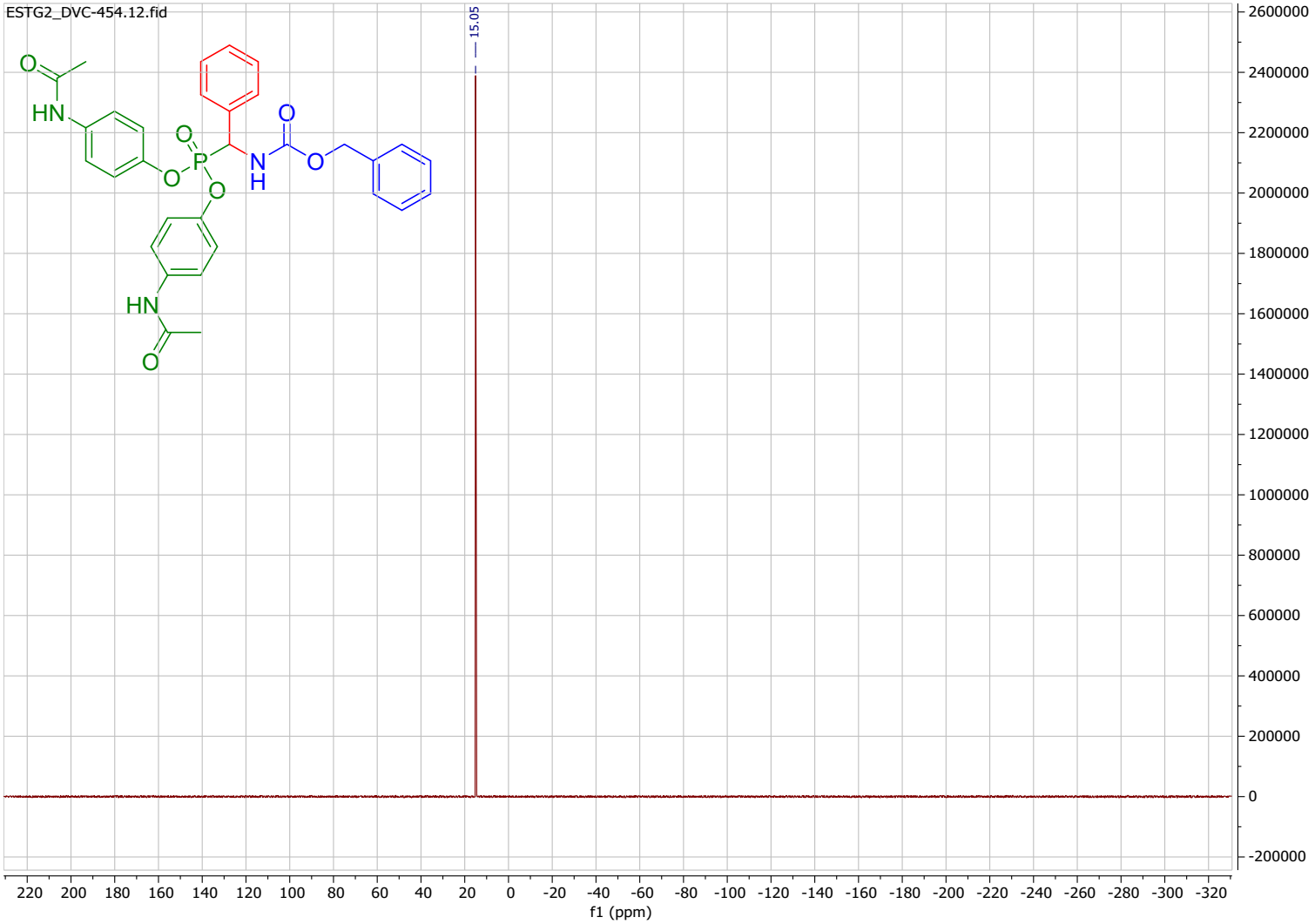
Comment [DC]: Update figure



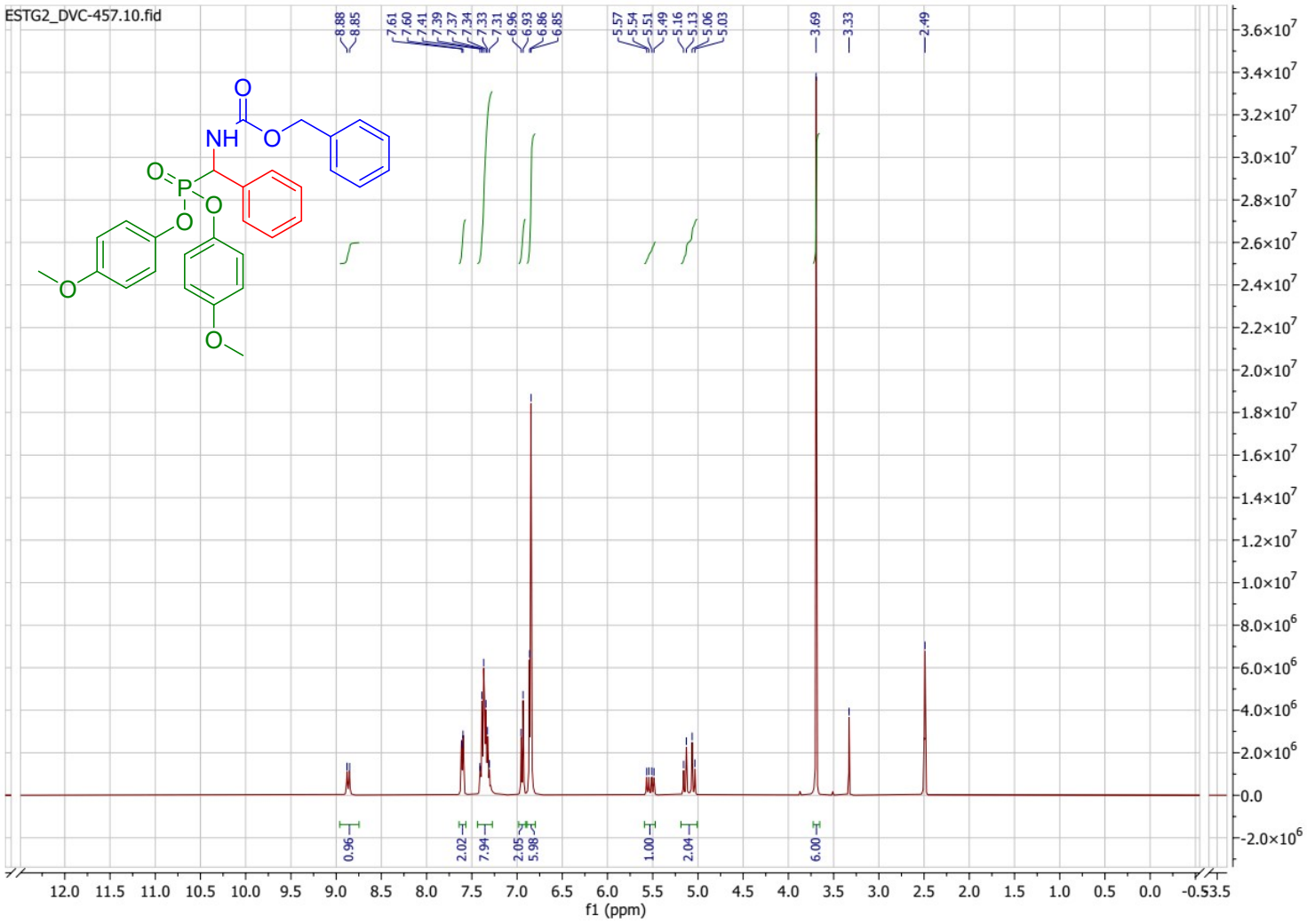
^{13}C NMR spectrum of compound **17** (without ^{31}P decoupling)



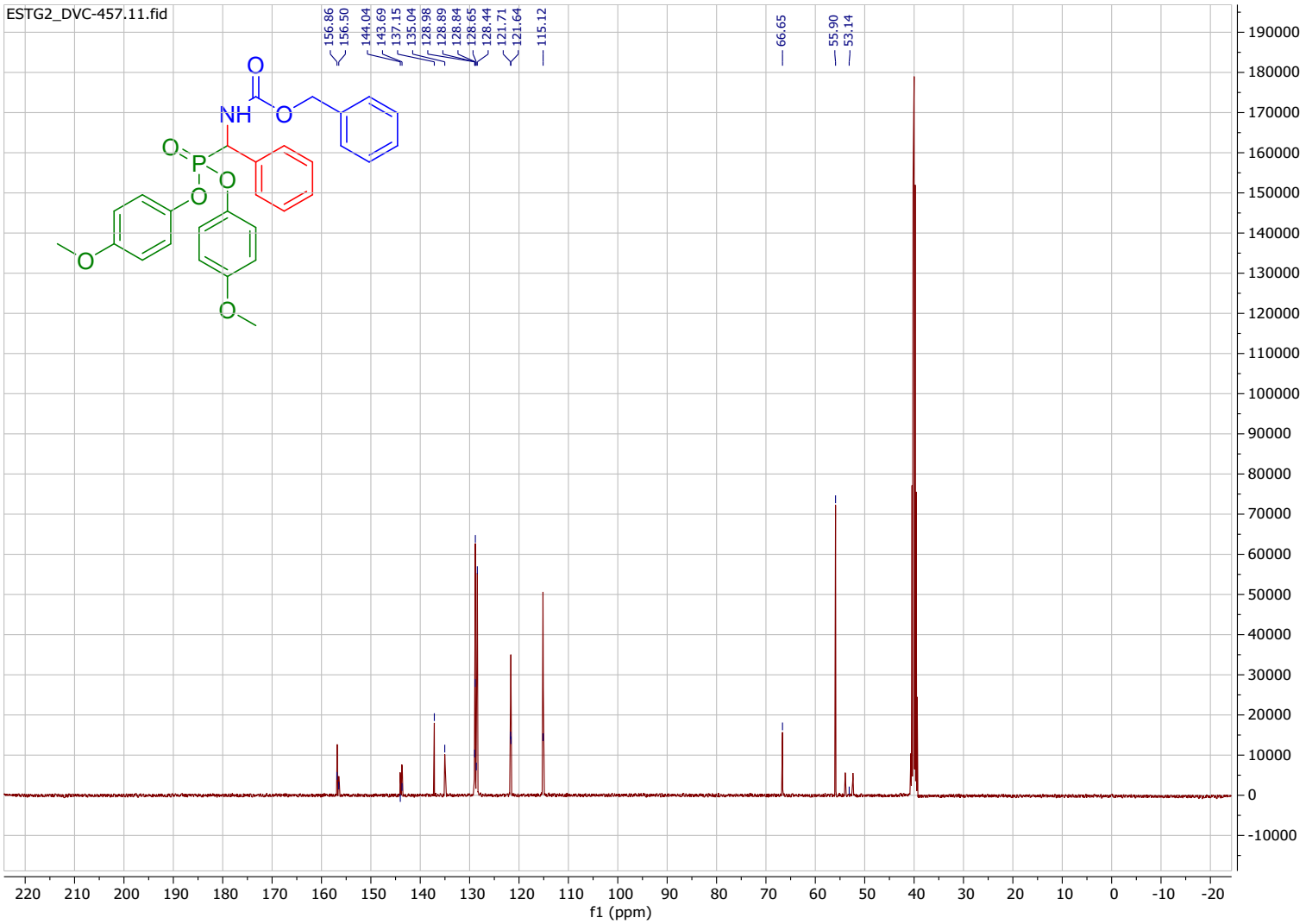
^{31}P NMR spectrum of compound **17**



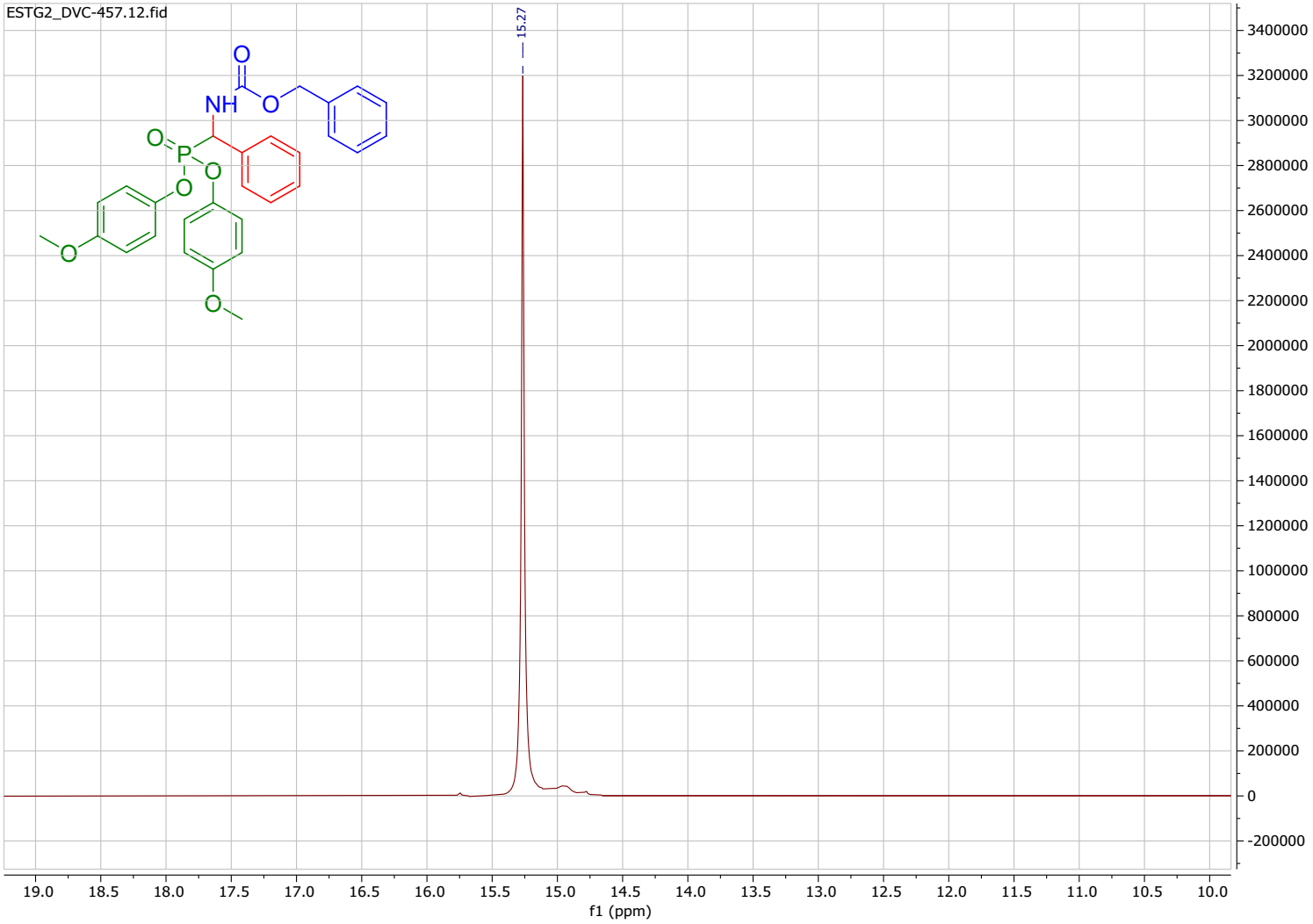
[1]H NMR spectrum of compound **18**



^{13}C NMR spectrum of compound **18** (without ^{31}P decoupling)

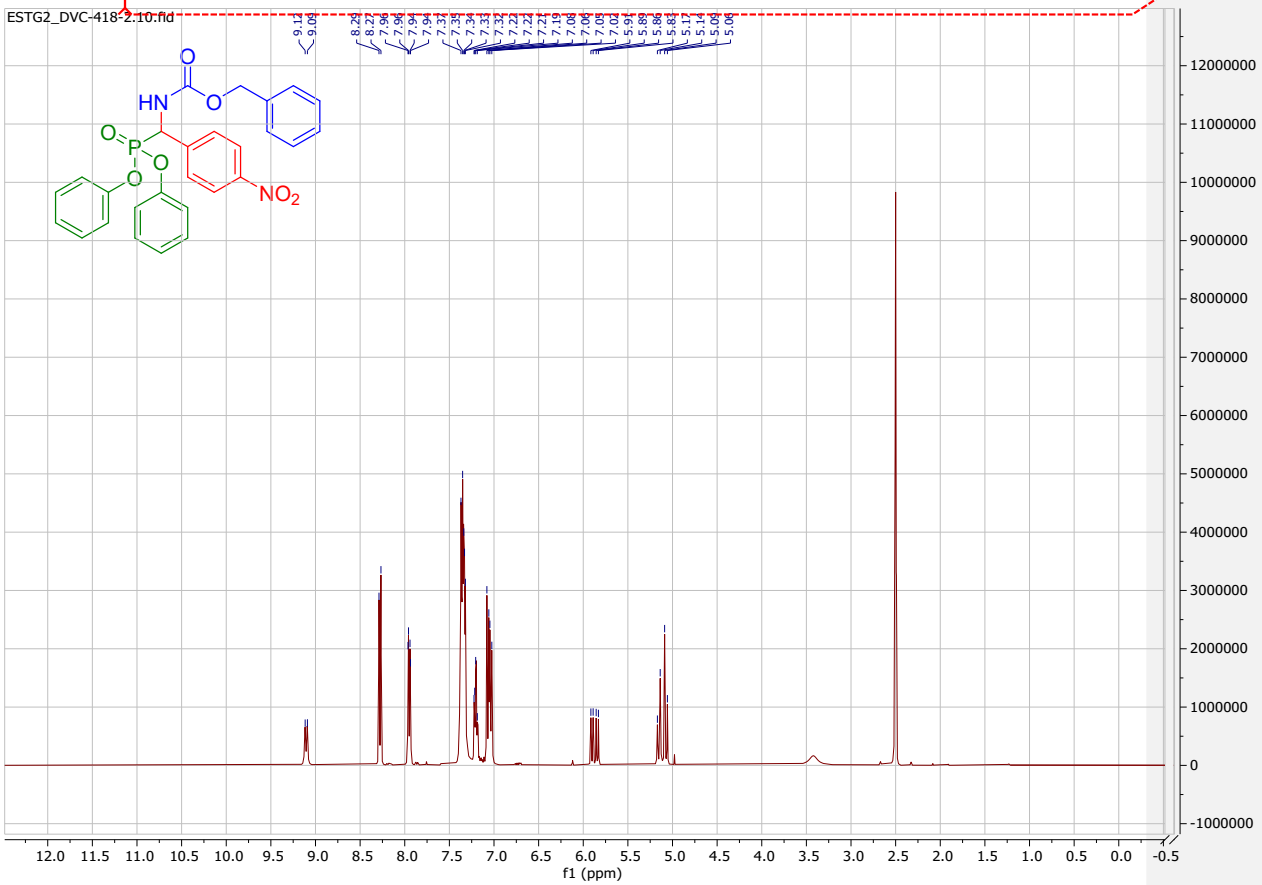


^{31}P NMR spectrum of compound **18**

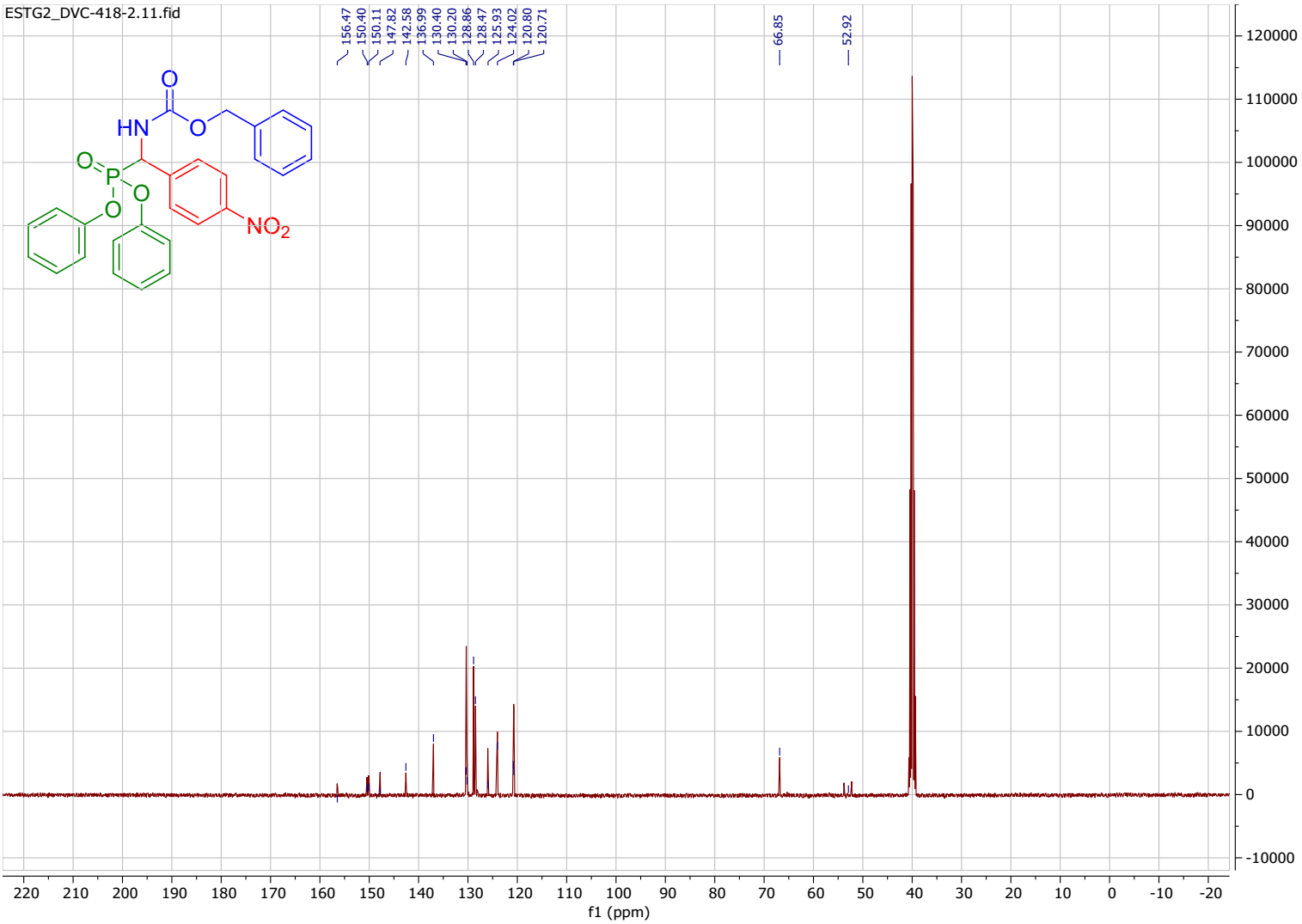


^{1}H NMR spectrum of compound **19**

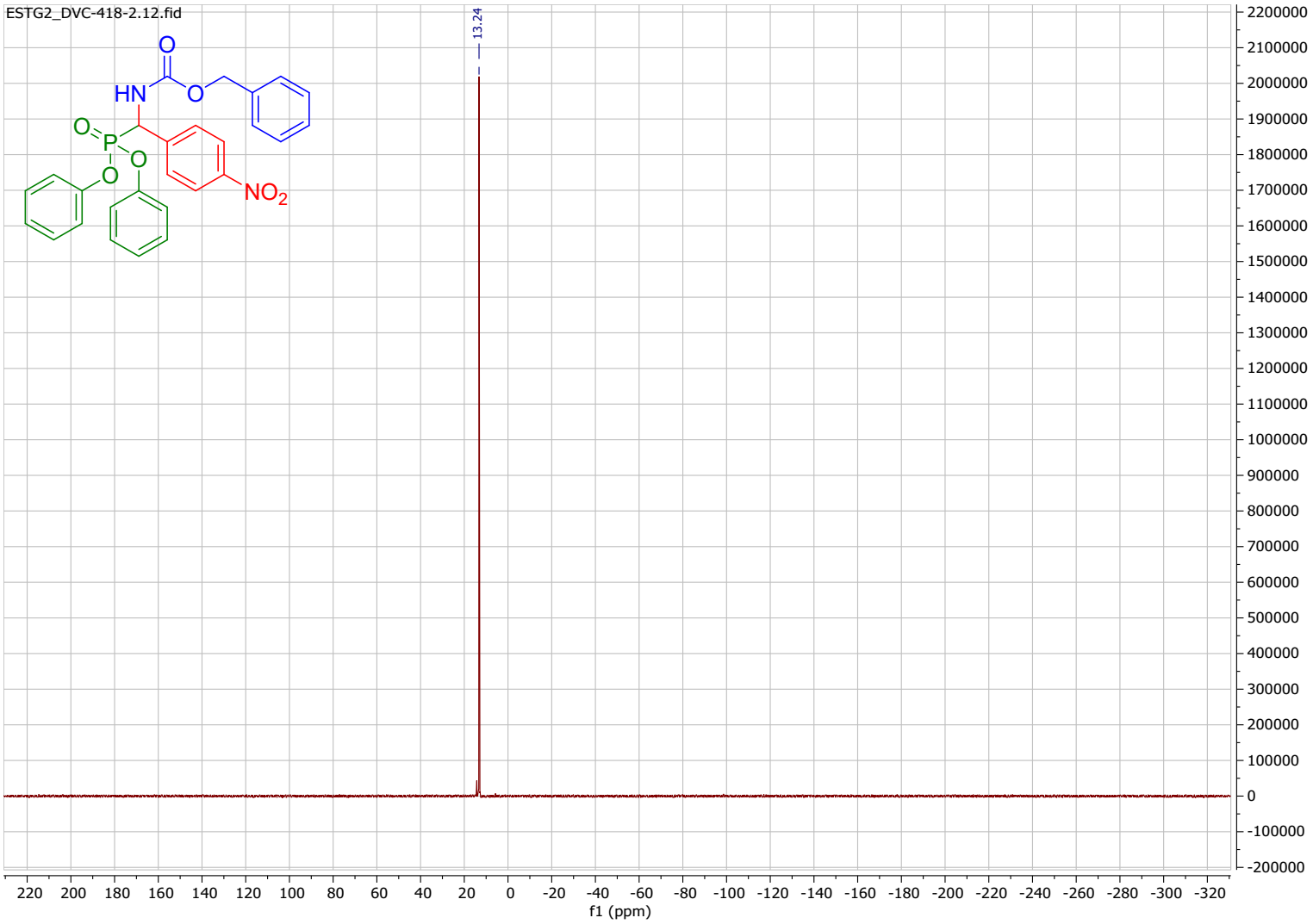
Comment [DC]: Update figure



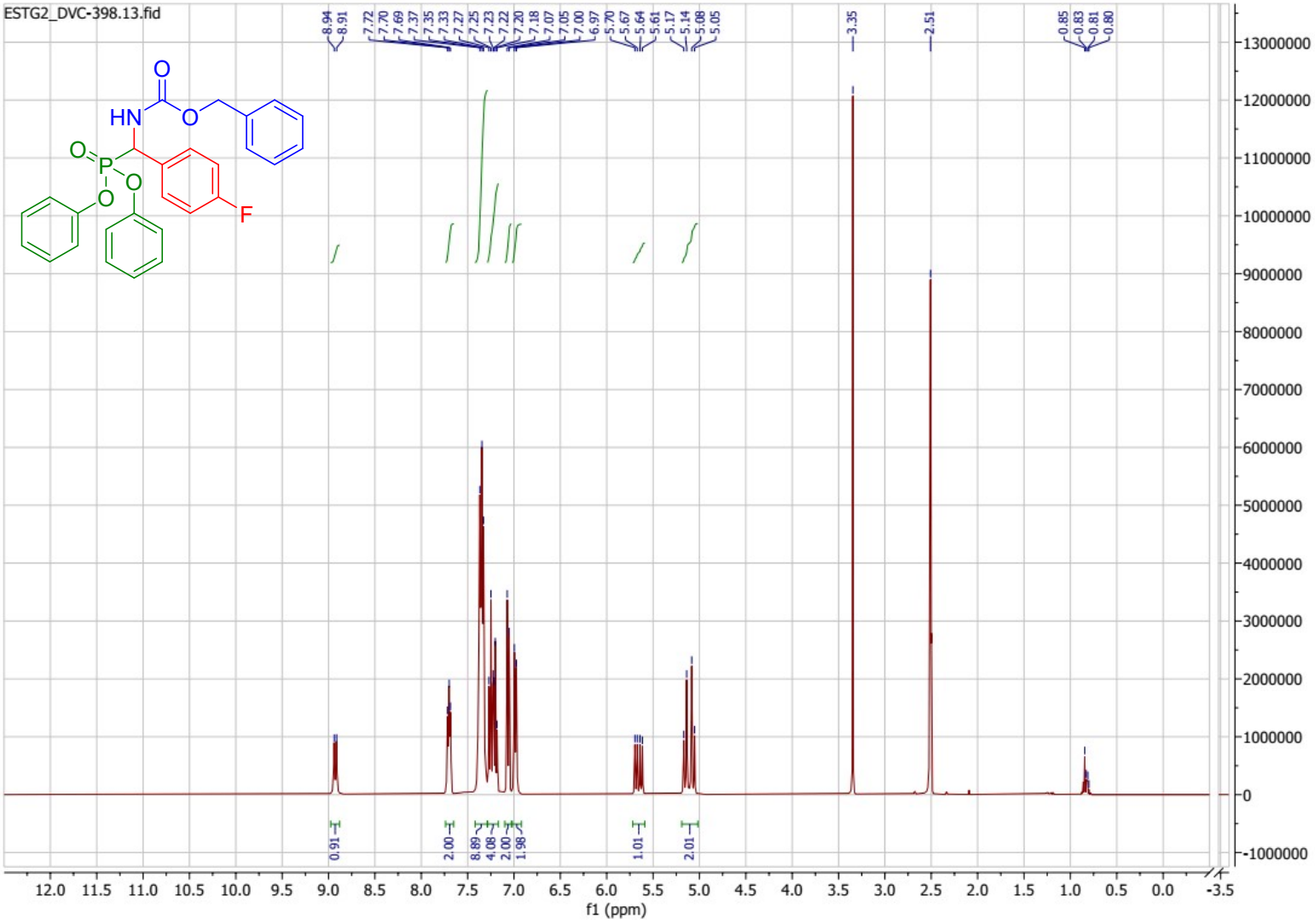
^{13}C NMR spectrum of compound **19** (without $^{3\,1}P$ decoupling)



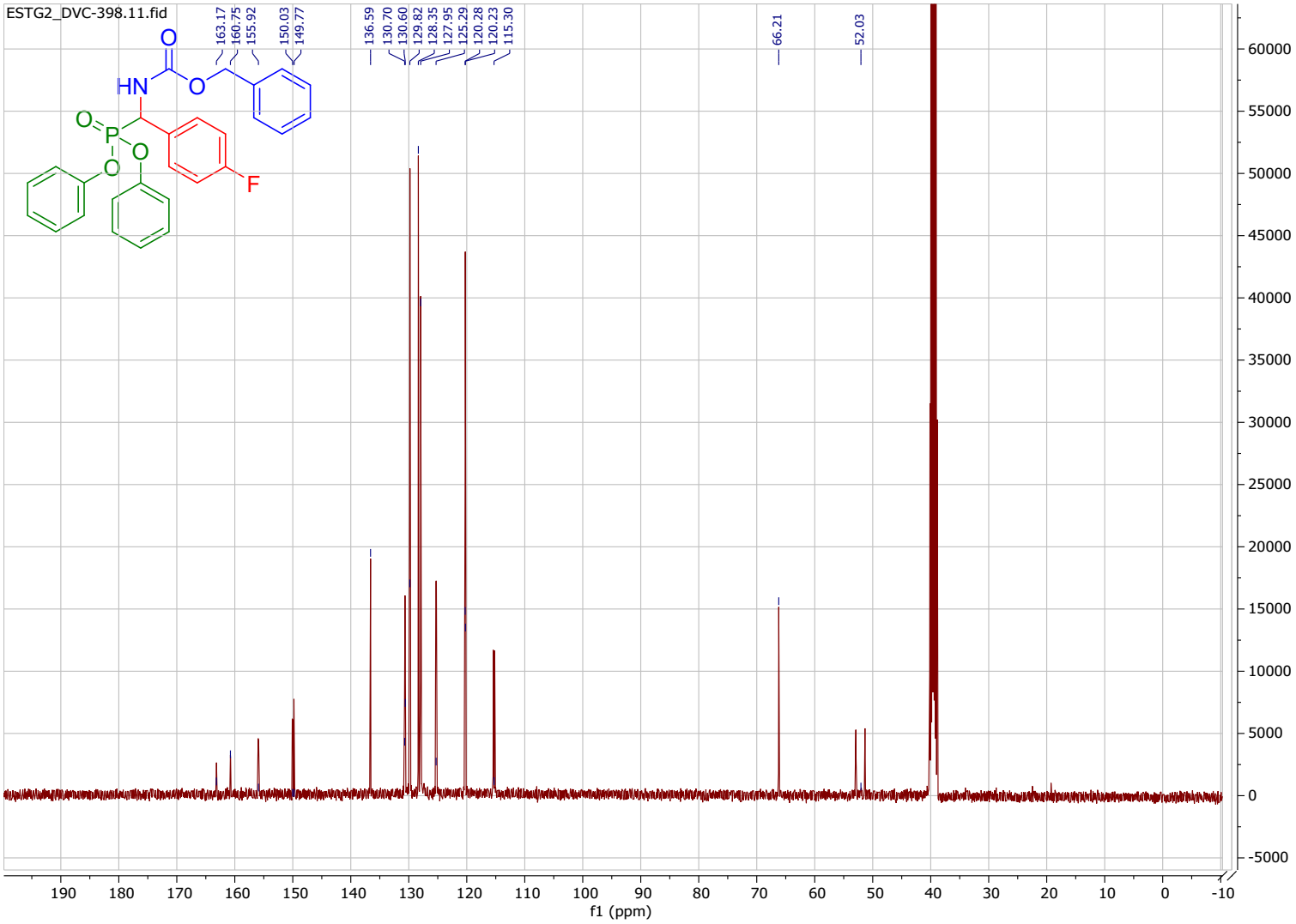
^{31}P-NMR spectra of compound **19**



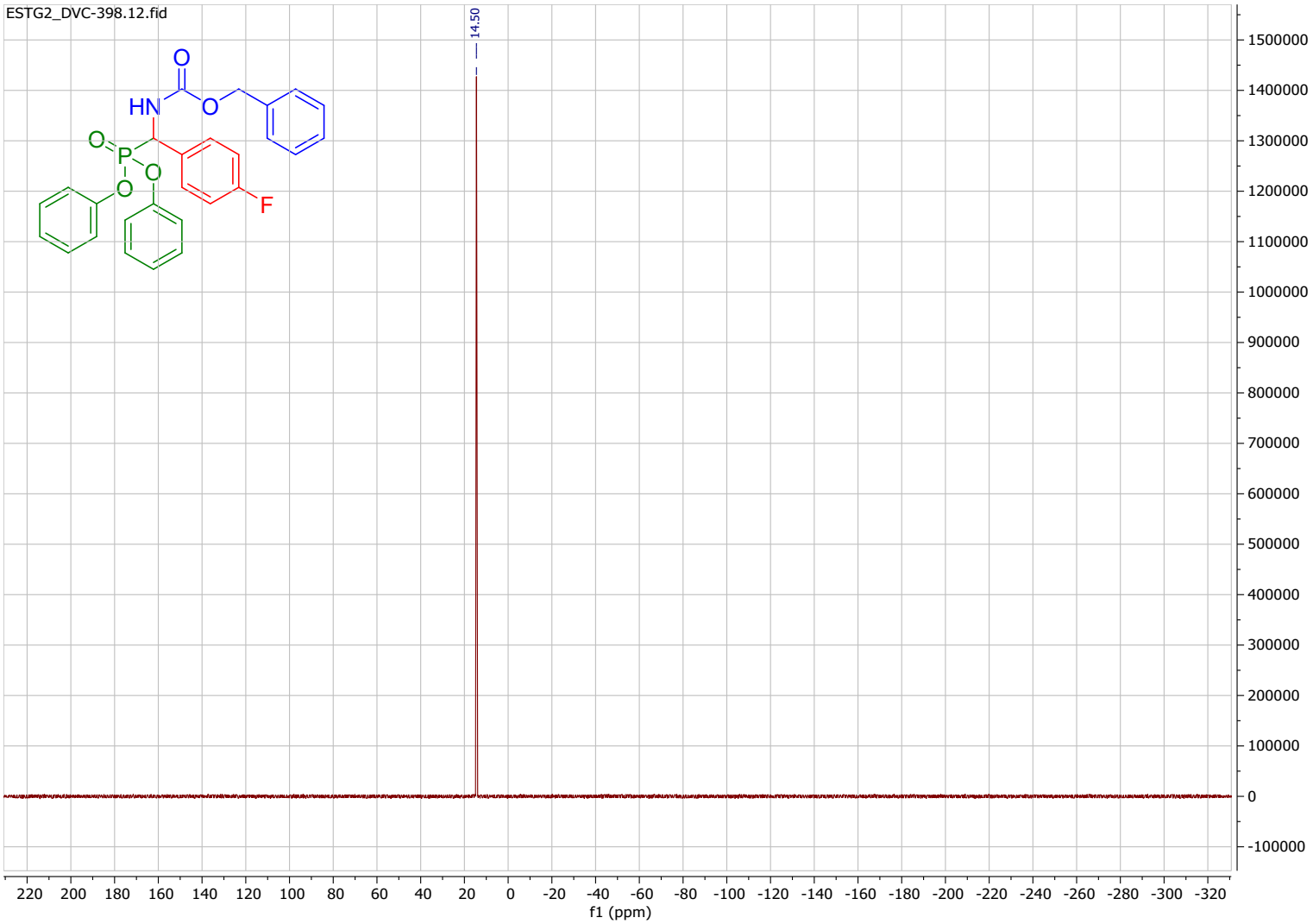
^{1}H-NMR spectra of compound **20**



^{13}C-NMR spectra of compound **20** (without ^{31}P decoupling)

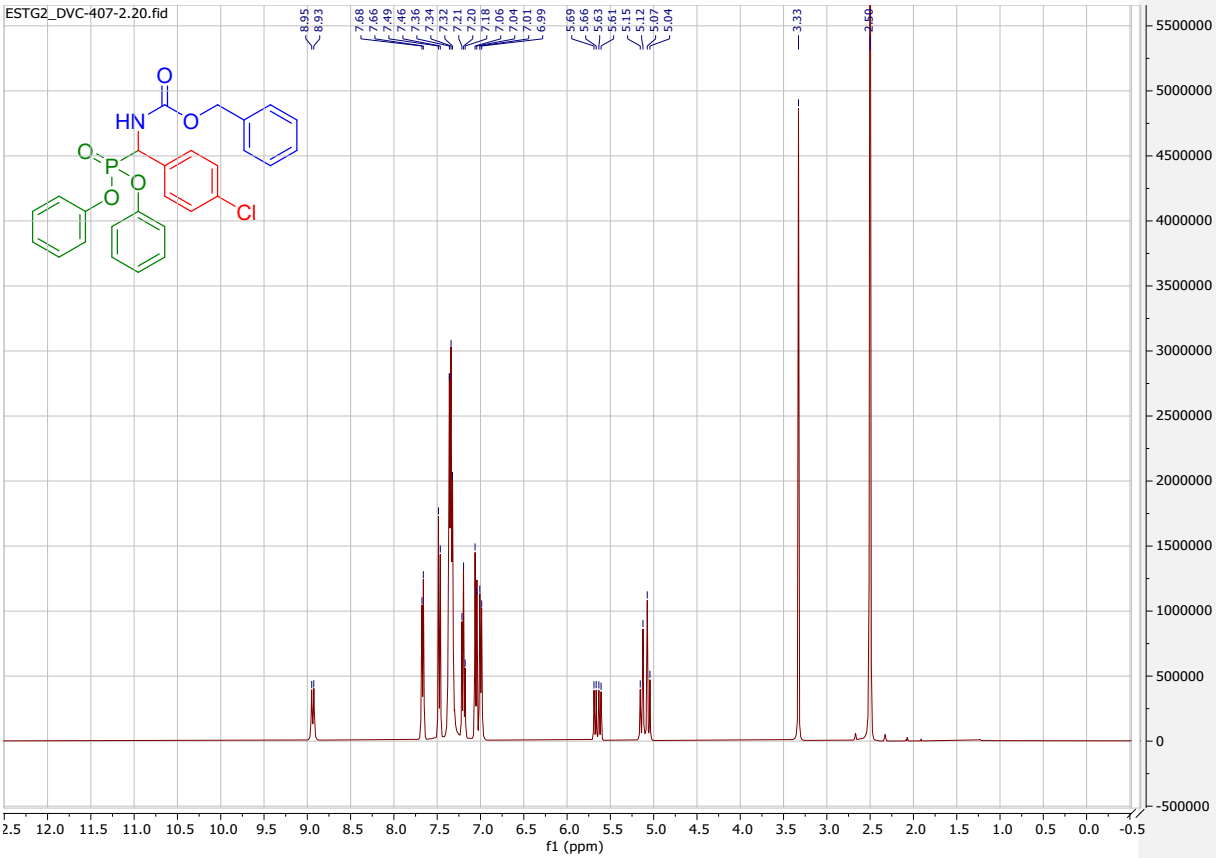


^{31}P-NMR spectra of compound **20**



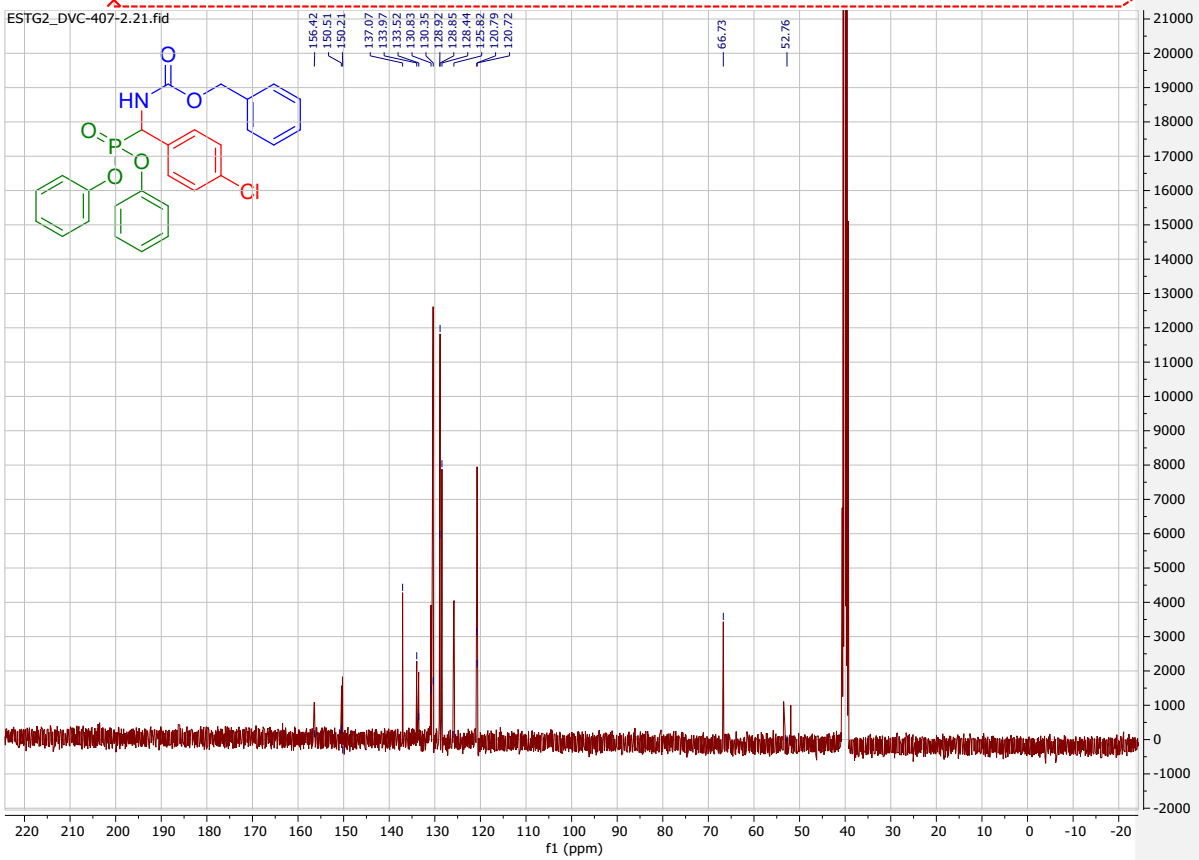
^{1}H-NMR spectra of compound **21**

Comment [DC]: Update figure

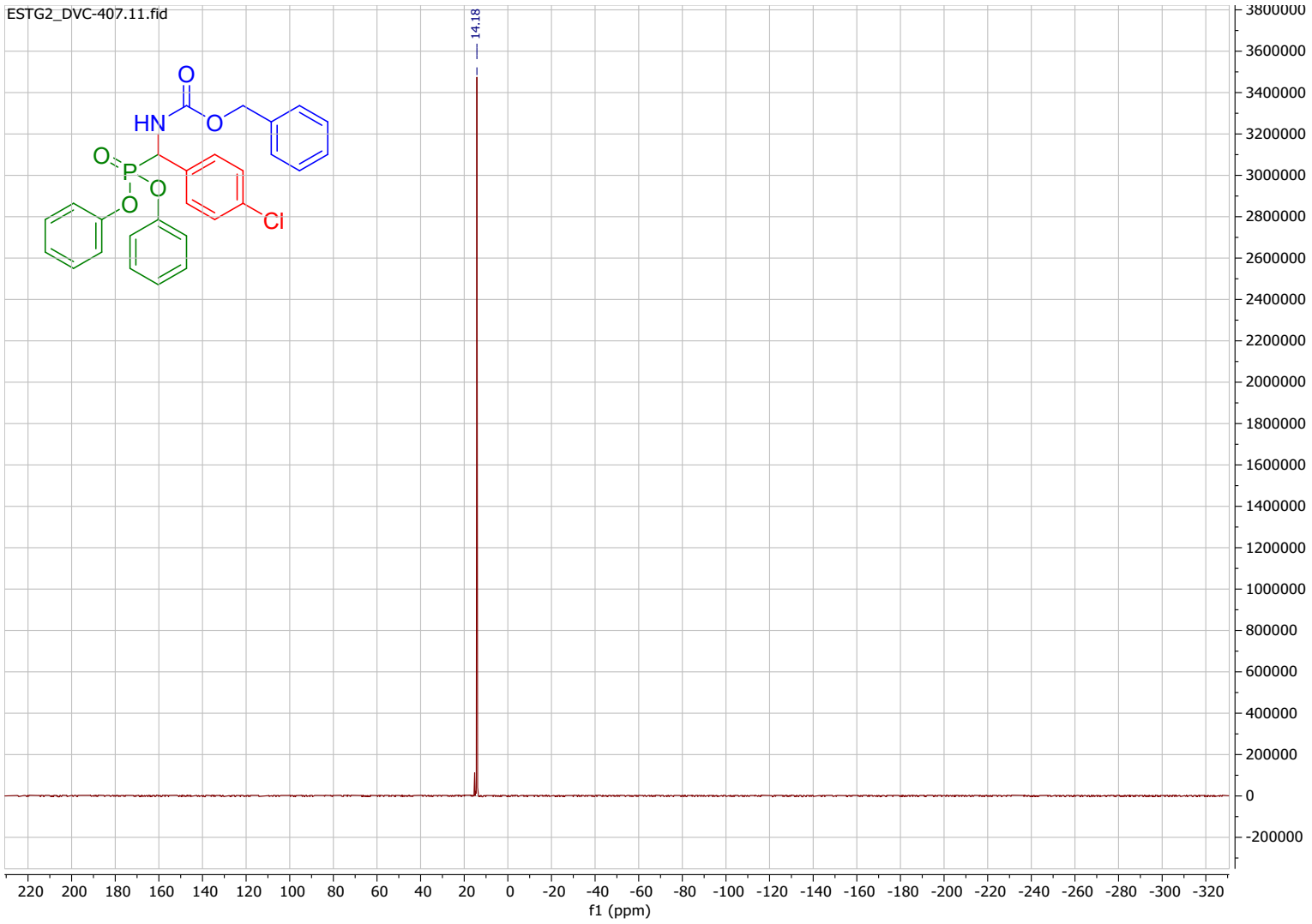


^{13}C-NMR spectra of compound **21** (without ^{31}P decoupling)

Comment [DC]: Update figure

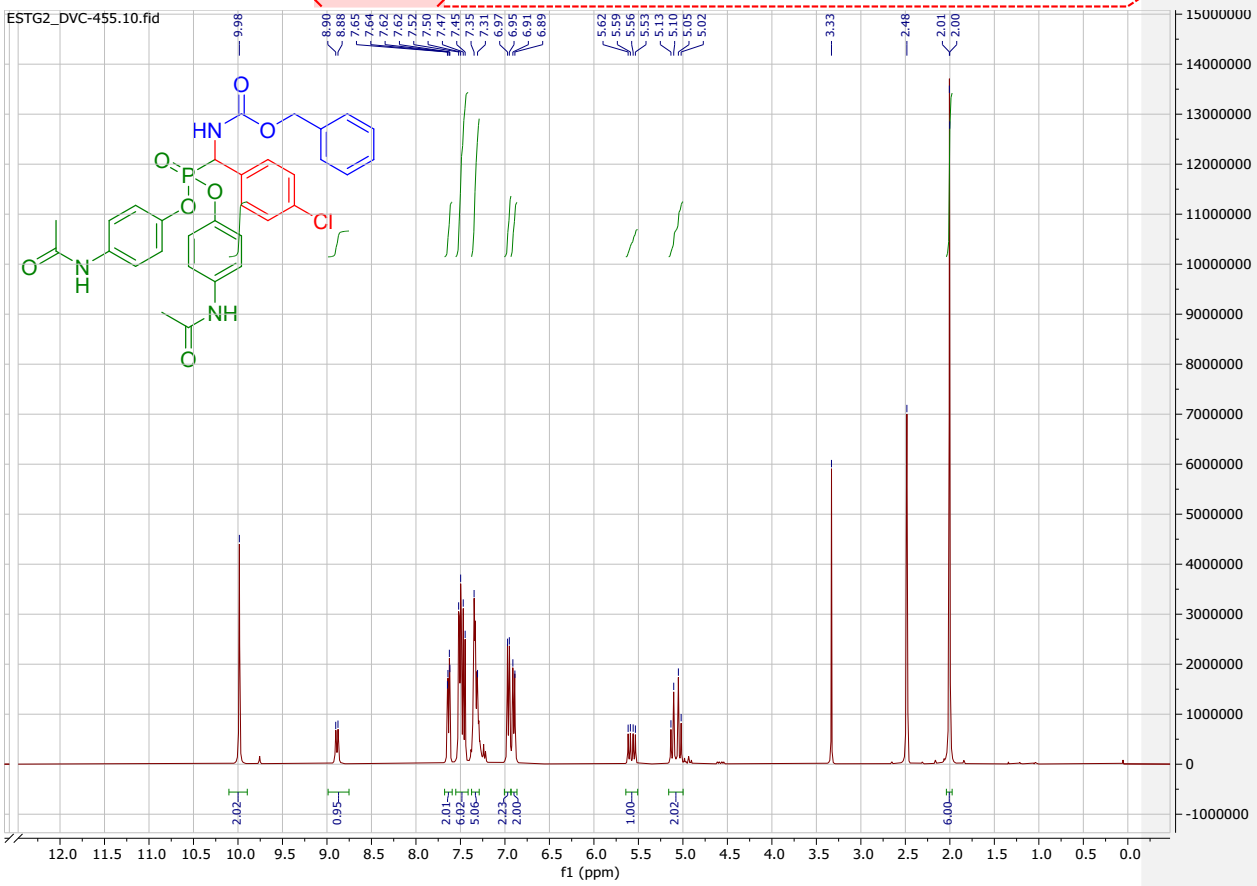


^{31}P-NMR spectra of compound **21**

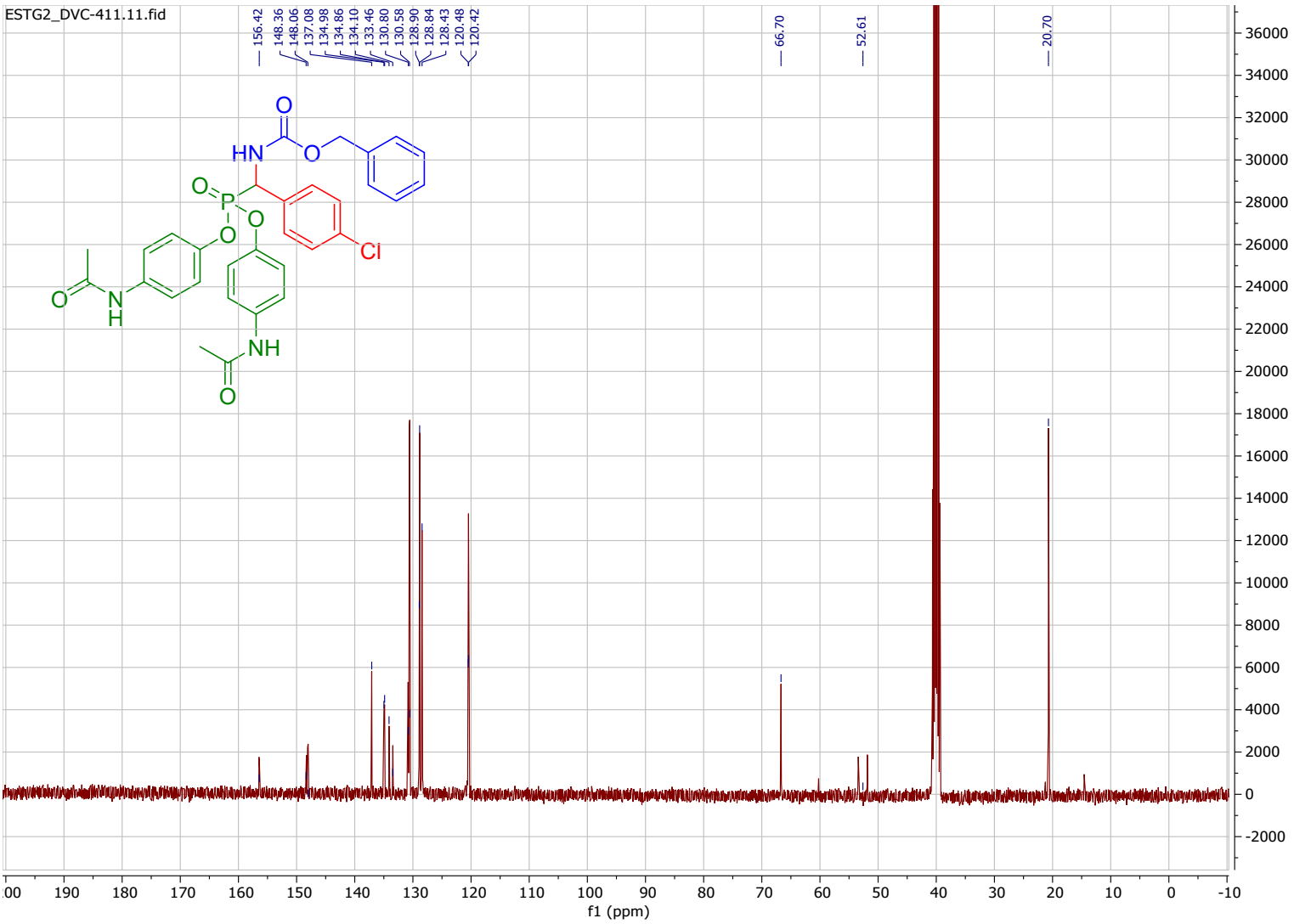


^{1}H-NMR spectra of compound **22**

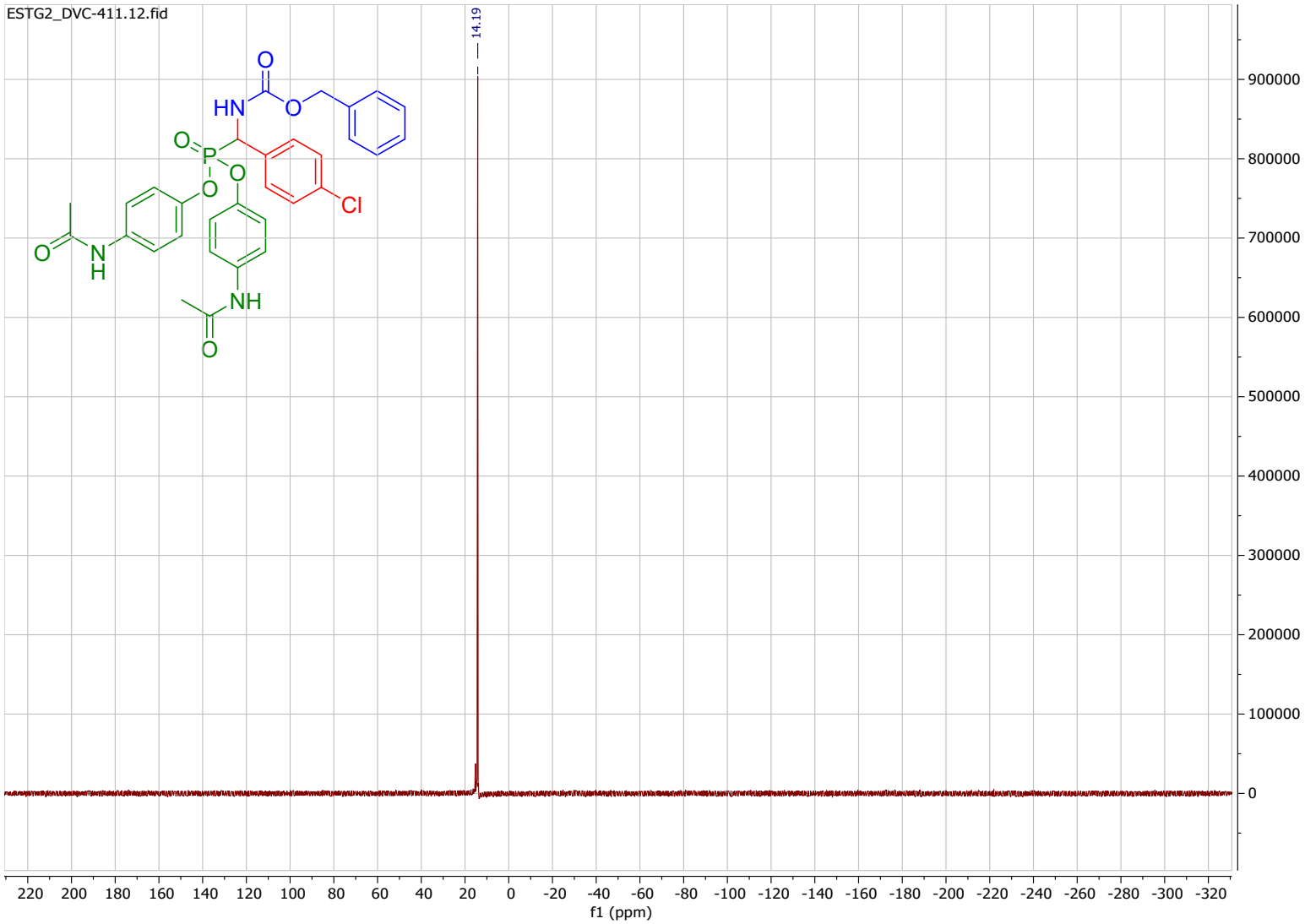
Comment [DC]: Update picture



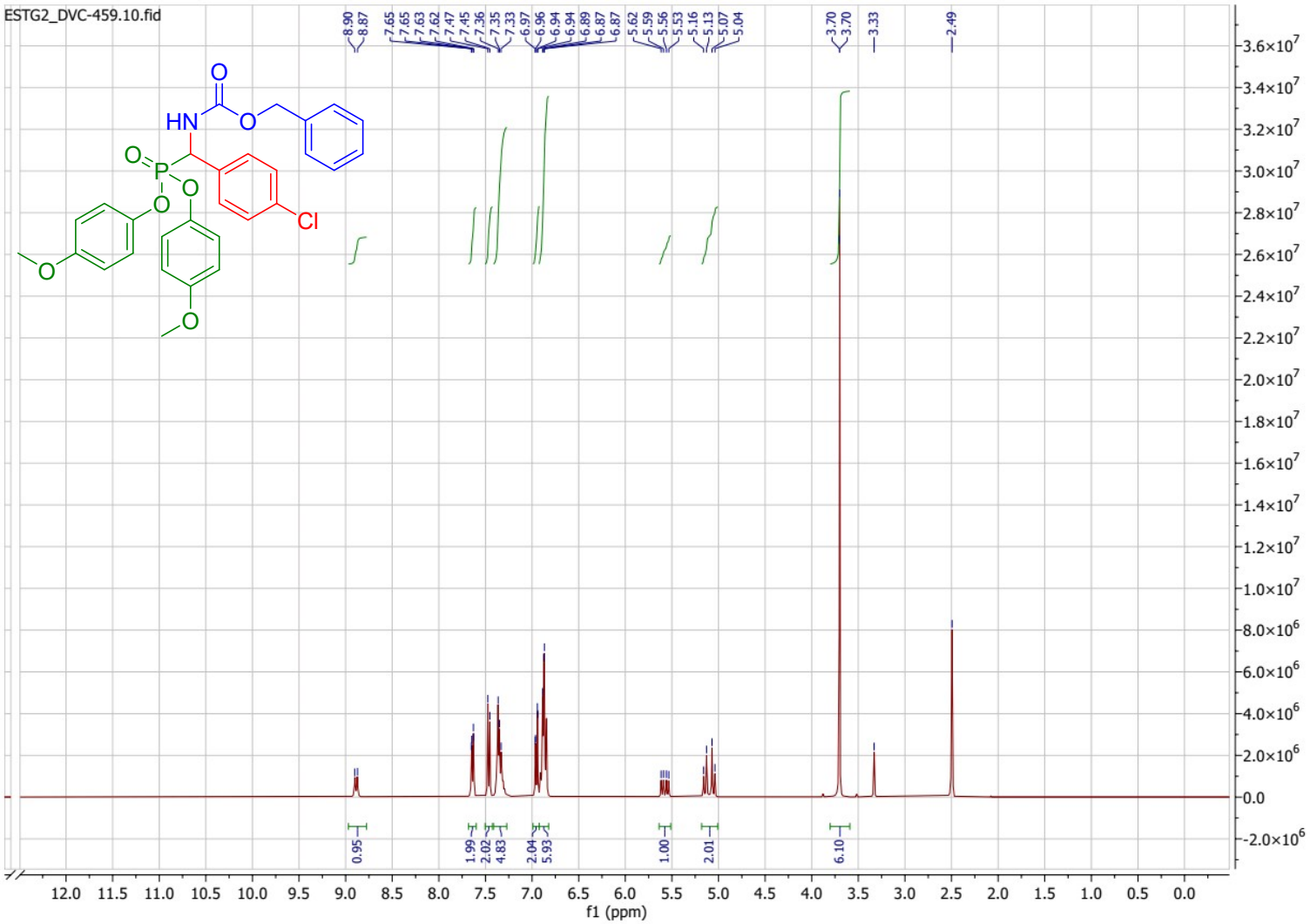
^{13}C-NMR spectra of compound **22** (without ^{31}P decoupling)



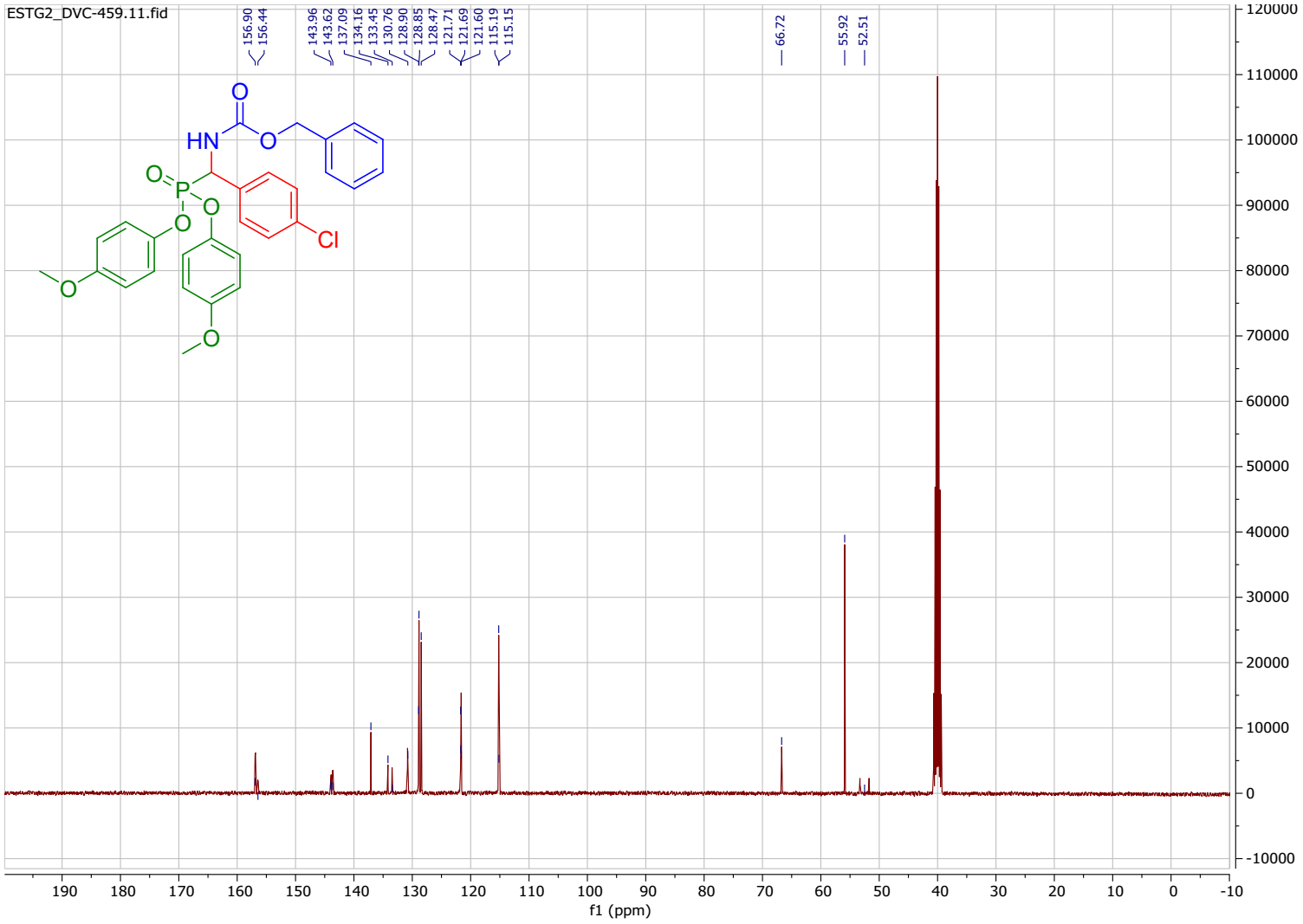
^{31}P-NMR spectra of compound **22**



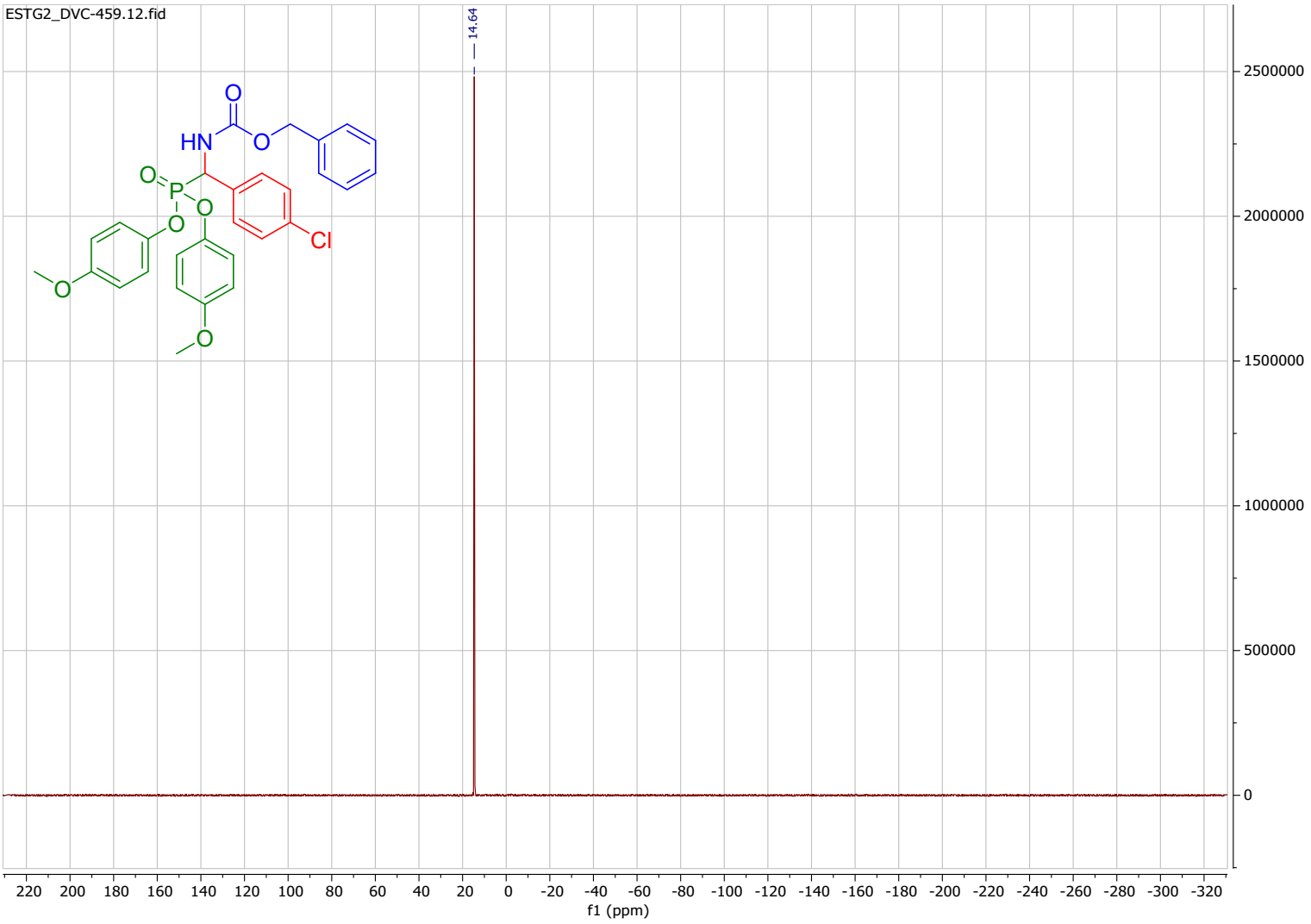
[1]H-NMR spectra of compound **23**



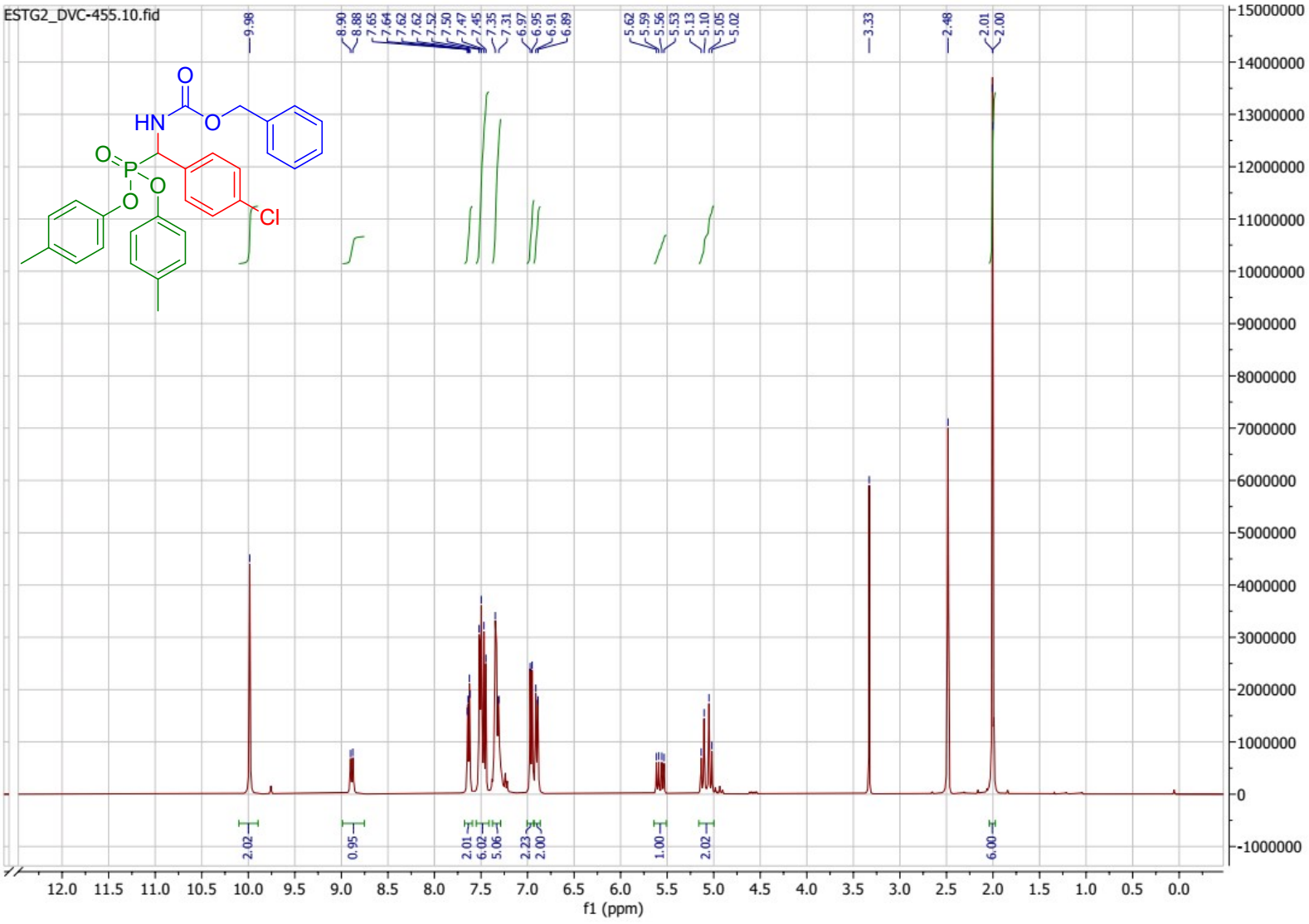
^{13}C-NMR spectra of compound **23** (without ^{31}P decoupling)



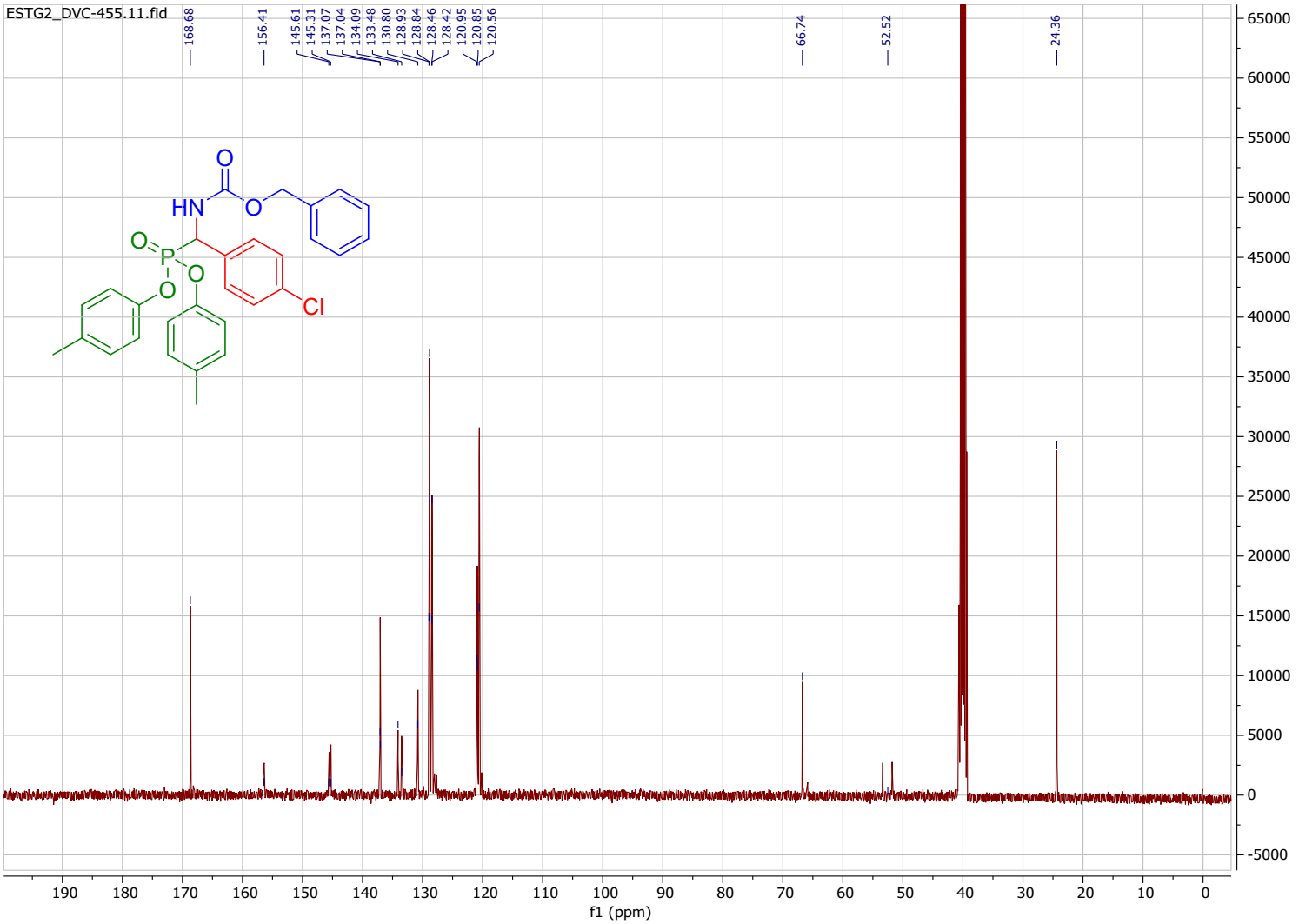
^{31}P-NMR spectra of compound **23**



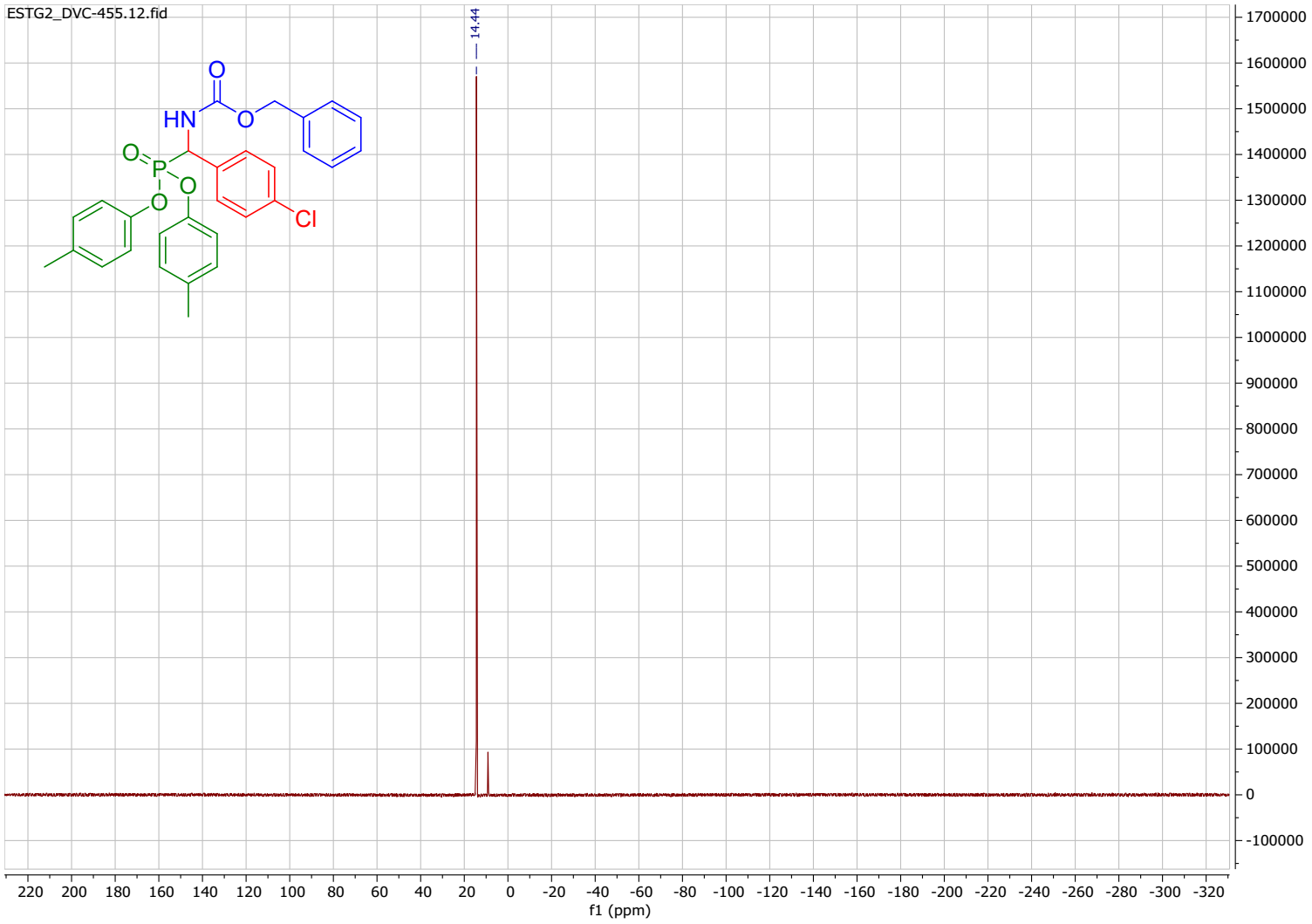
[1]H-NMR spectra of compound **24**



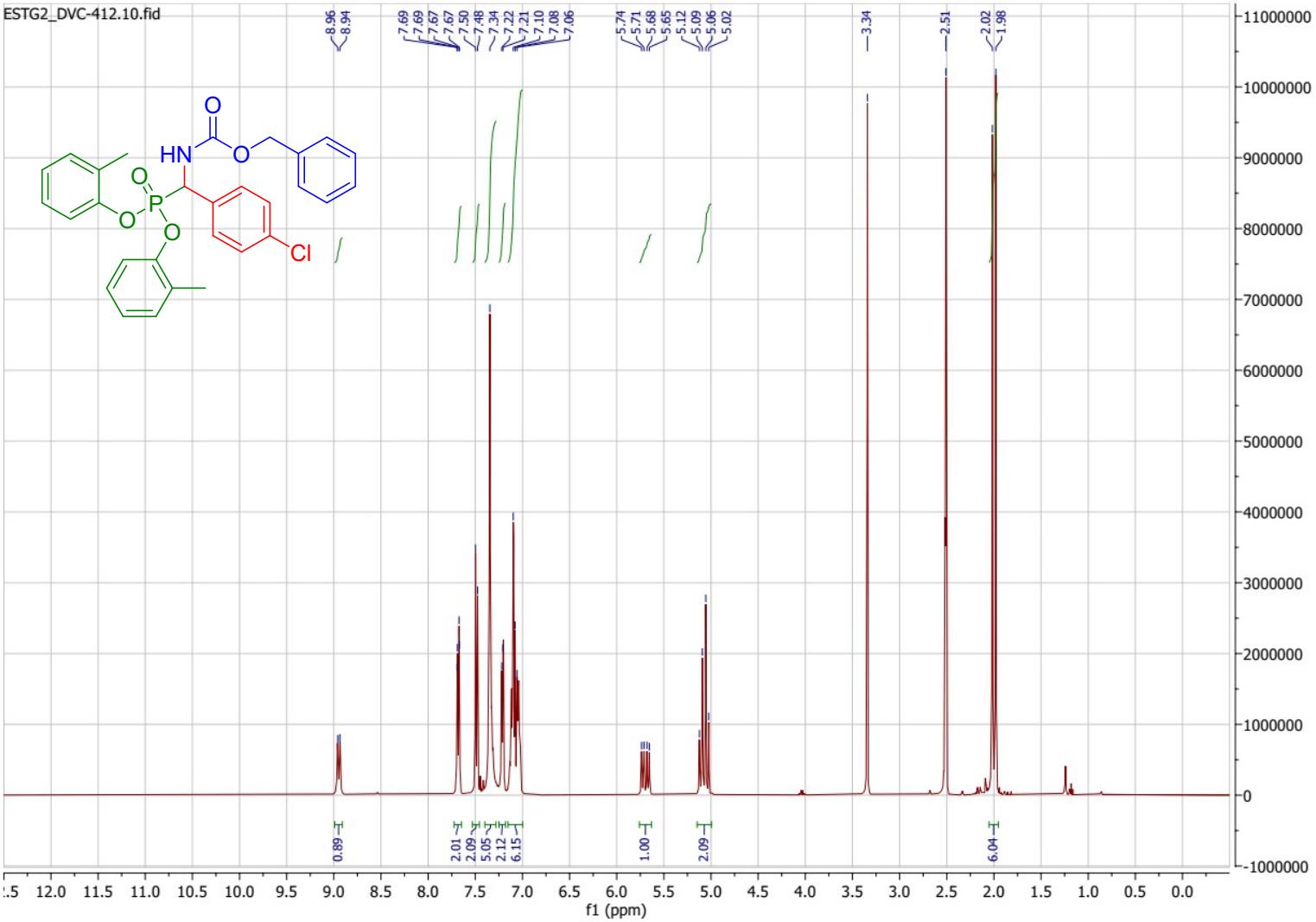
^{13}C-NMR spectra of compound **24** (without ^{31}P decoupling)



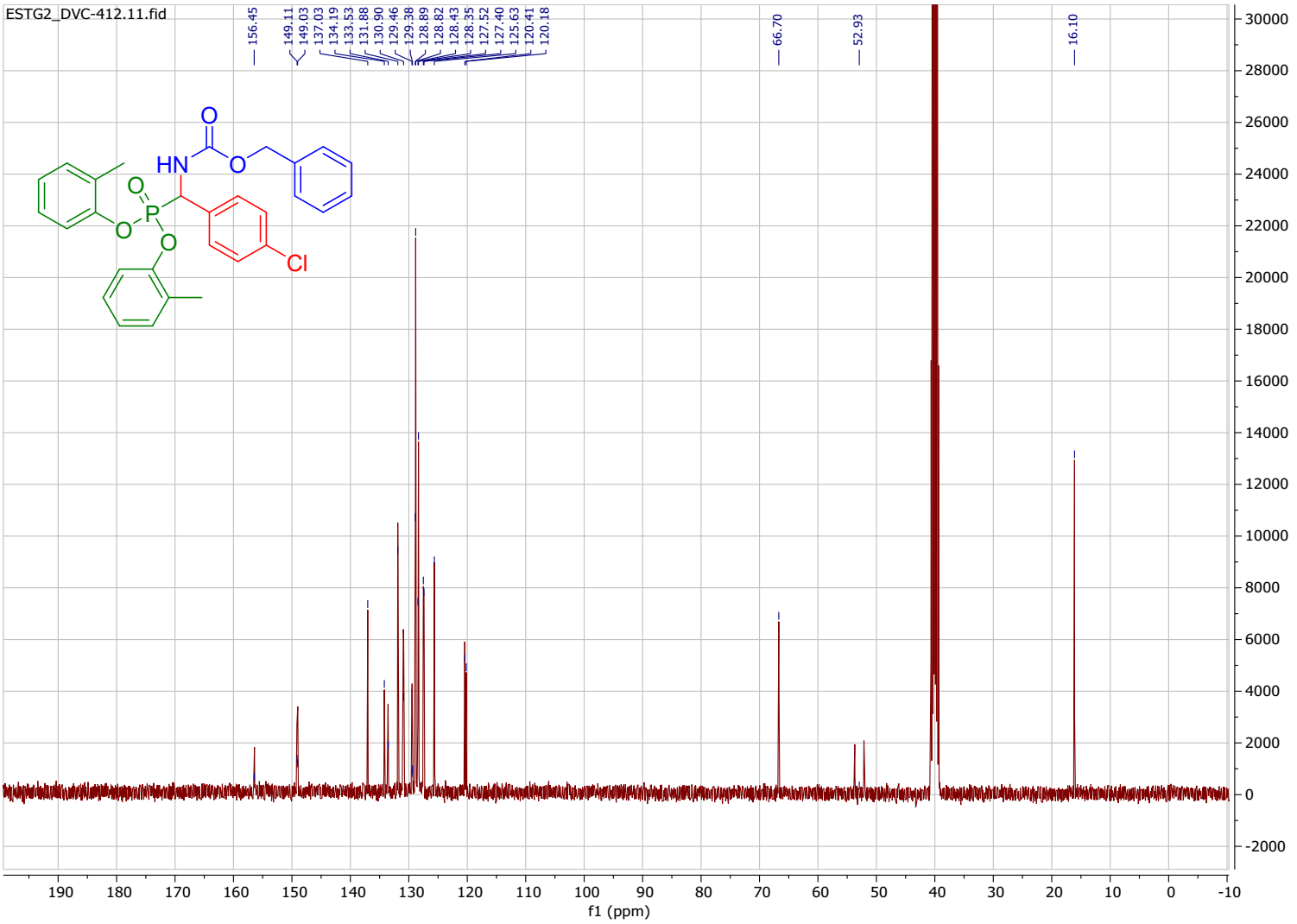
^{31}P-NMR spectra of compound **24**



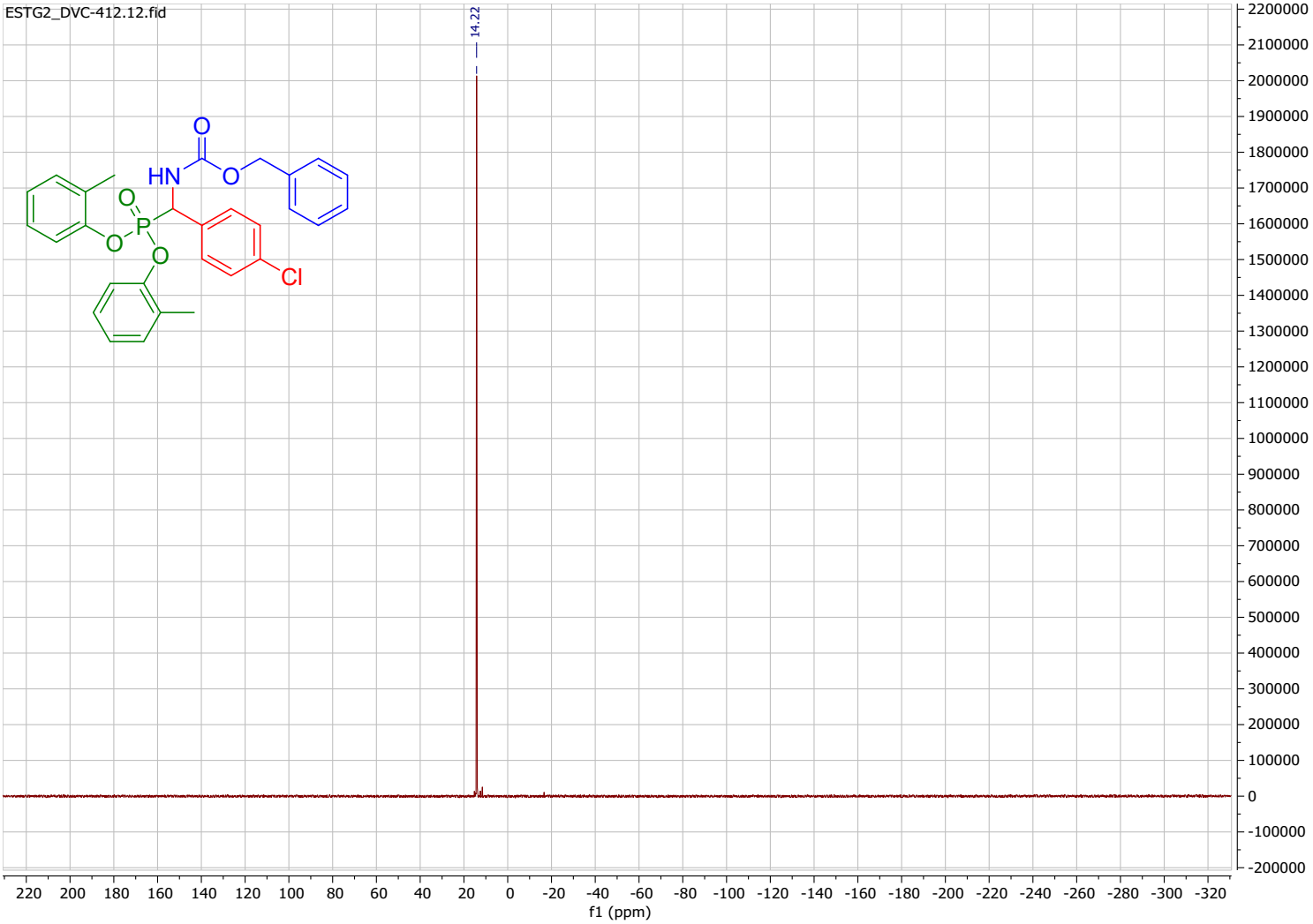
^{1}H-NMR spectra of compound **25**



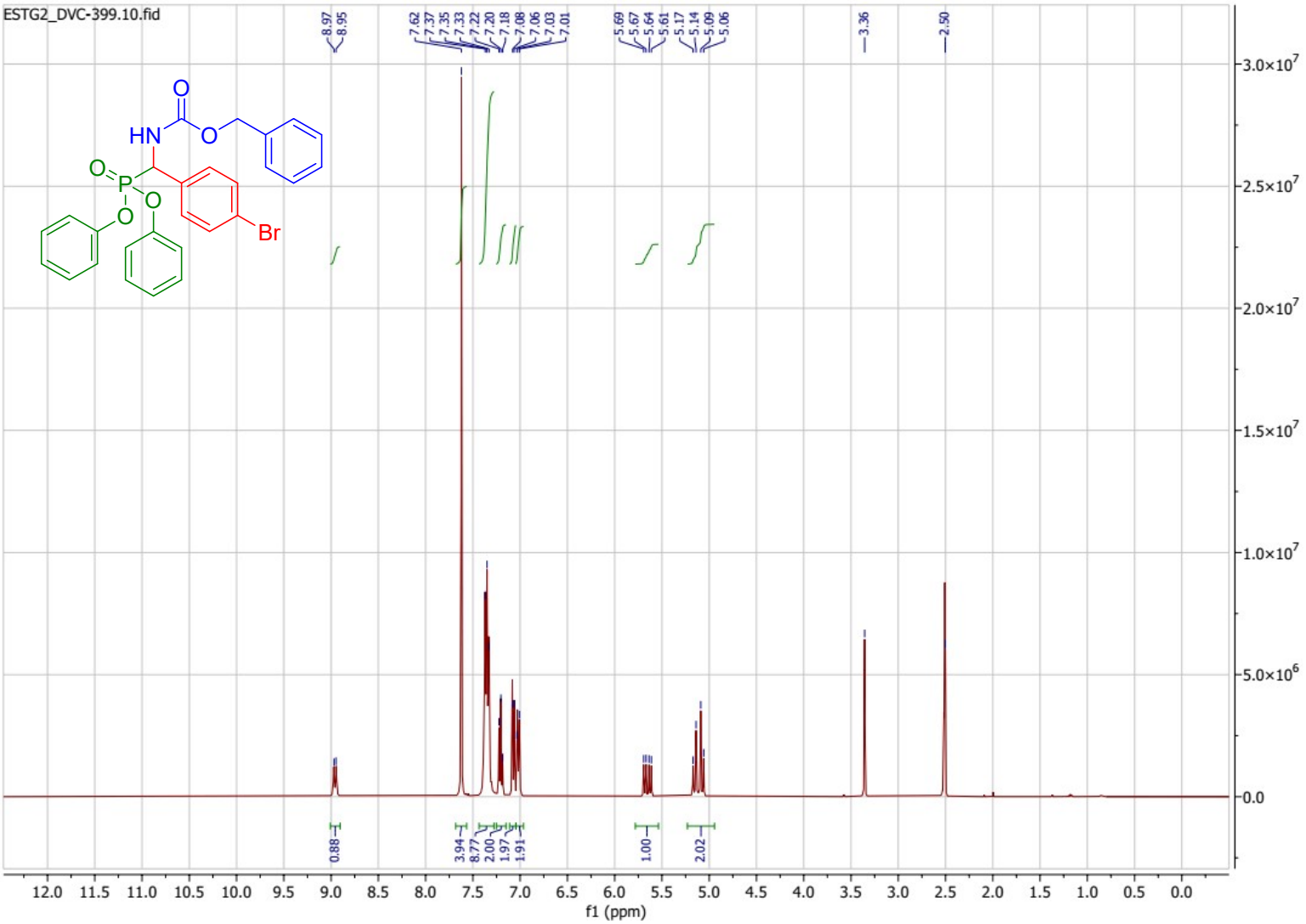
^{13}C-NMR spectra of compound **25** (without ^{31}P decoupling)



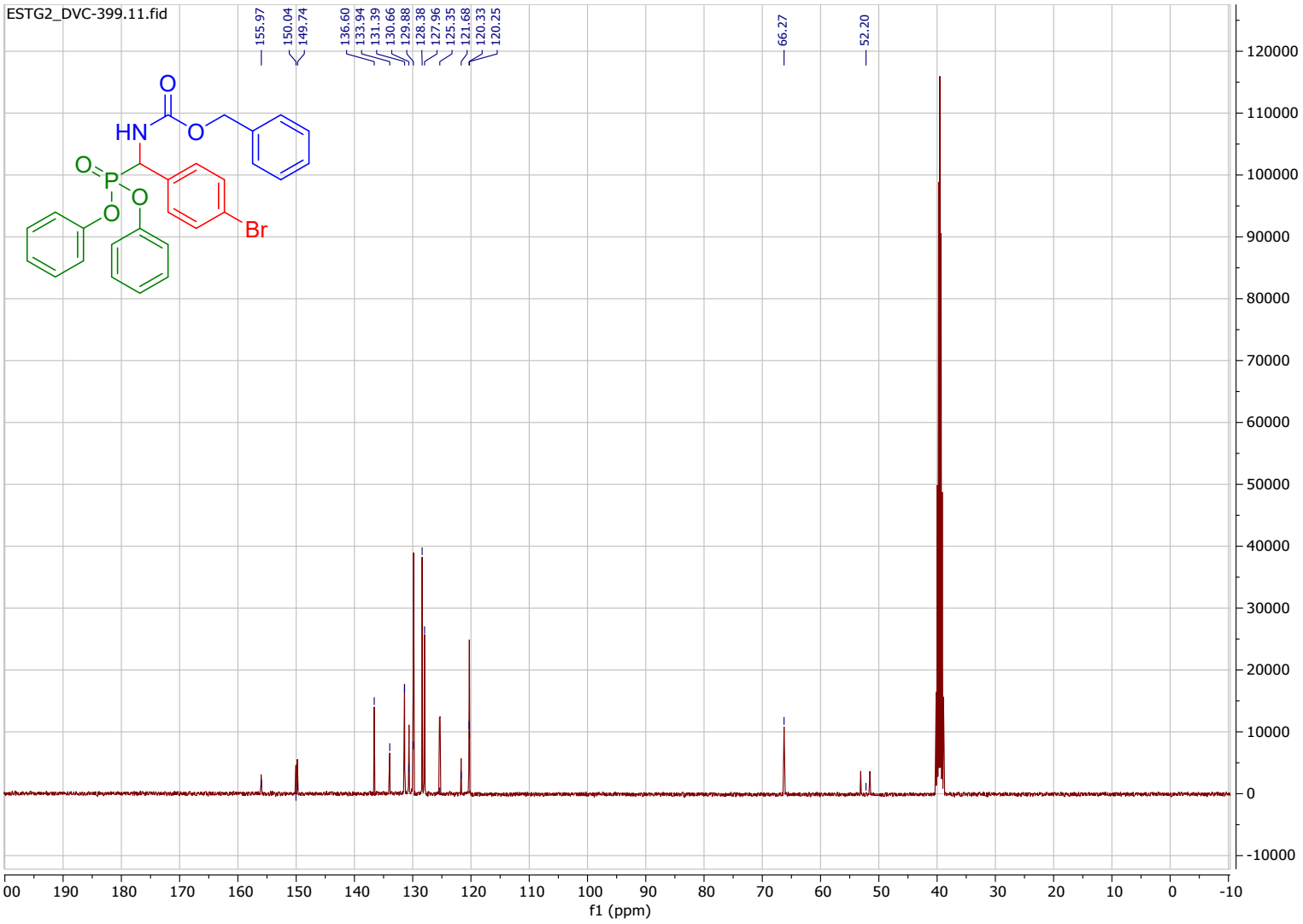
^{31}P-NMR spectra of compound **25**



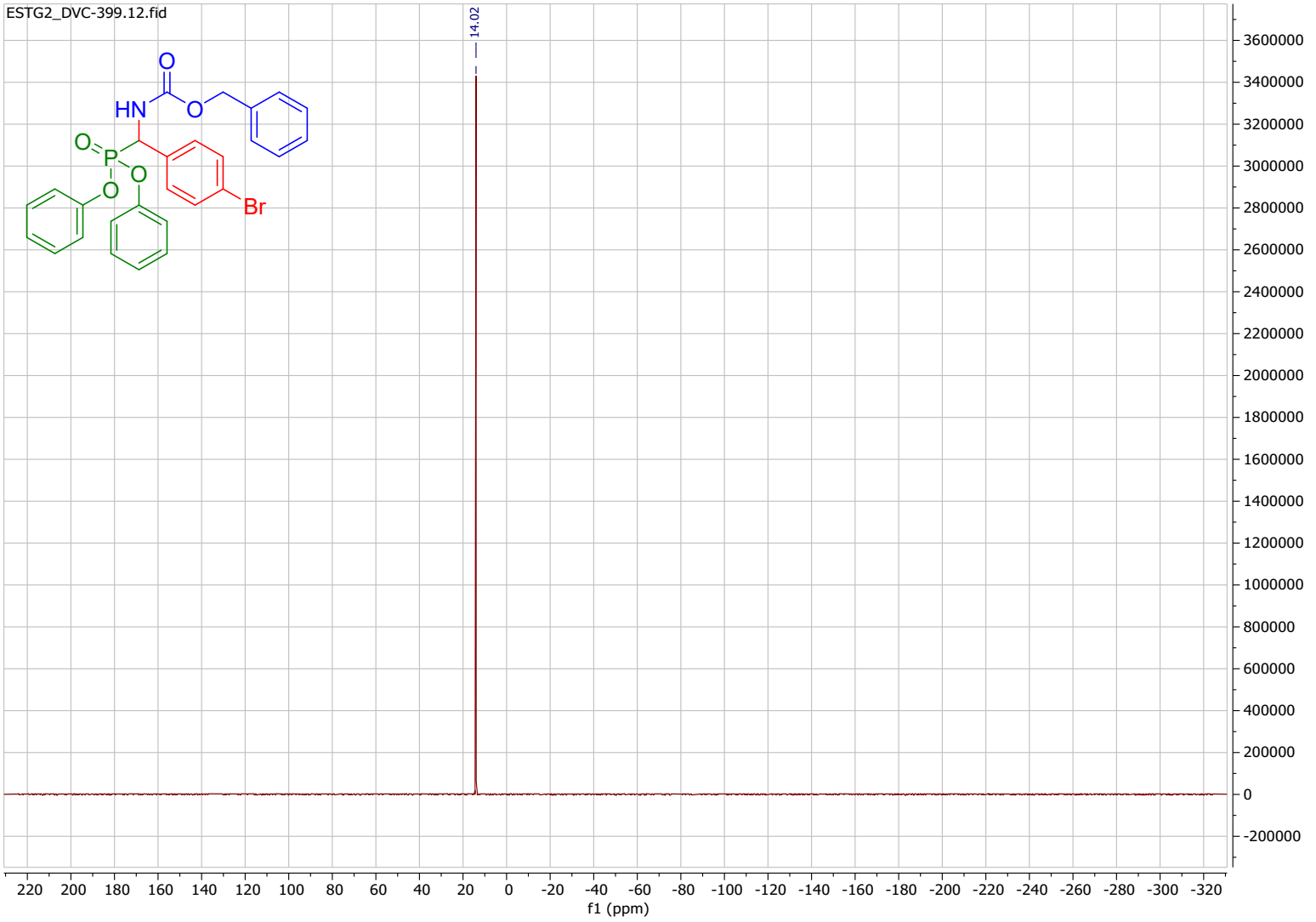
[1]H-NMR spectra of compound **26**



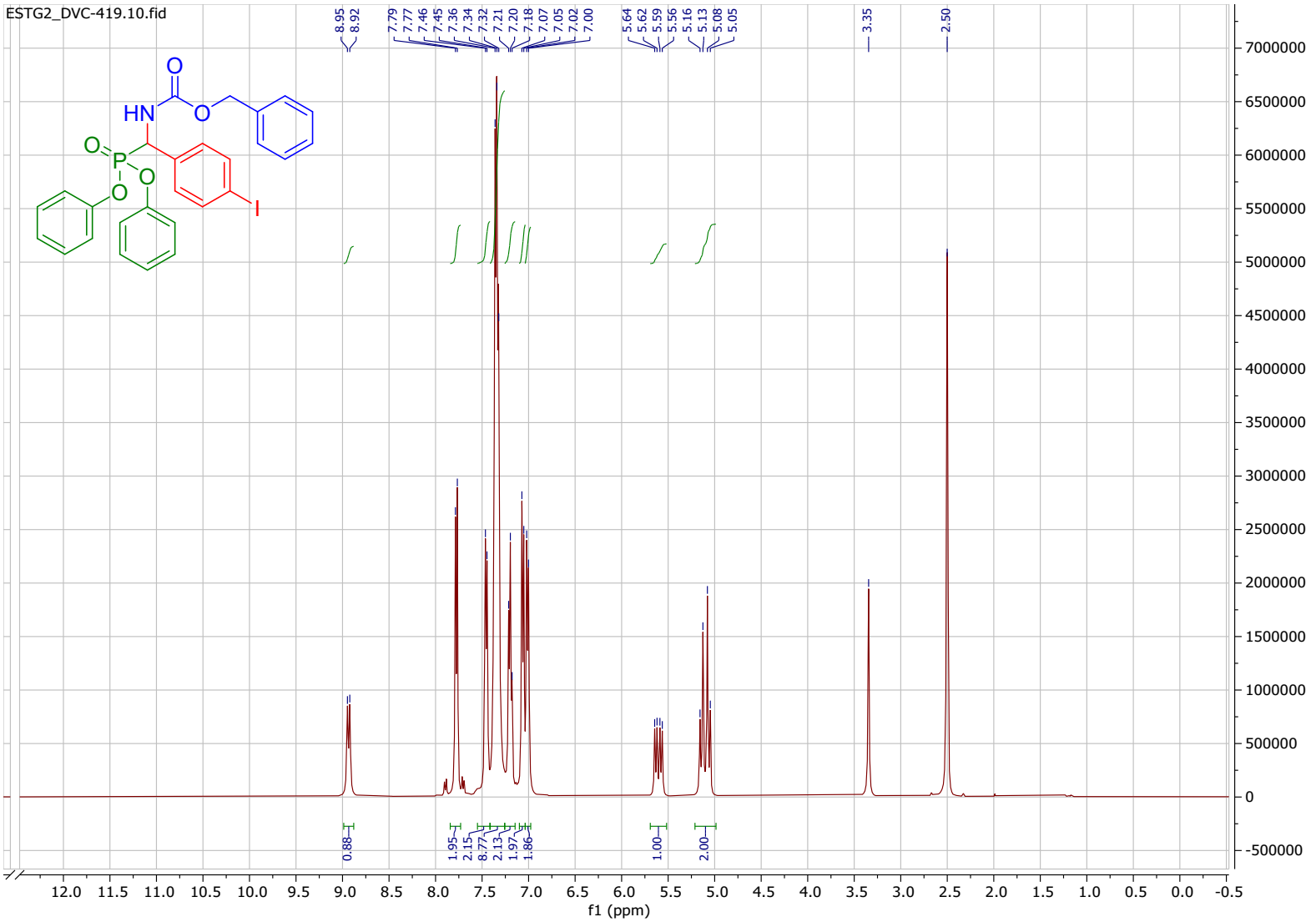
^{13}C-NMR spectra of compound **26** (without ^{31}P decoupling)



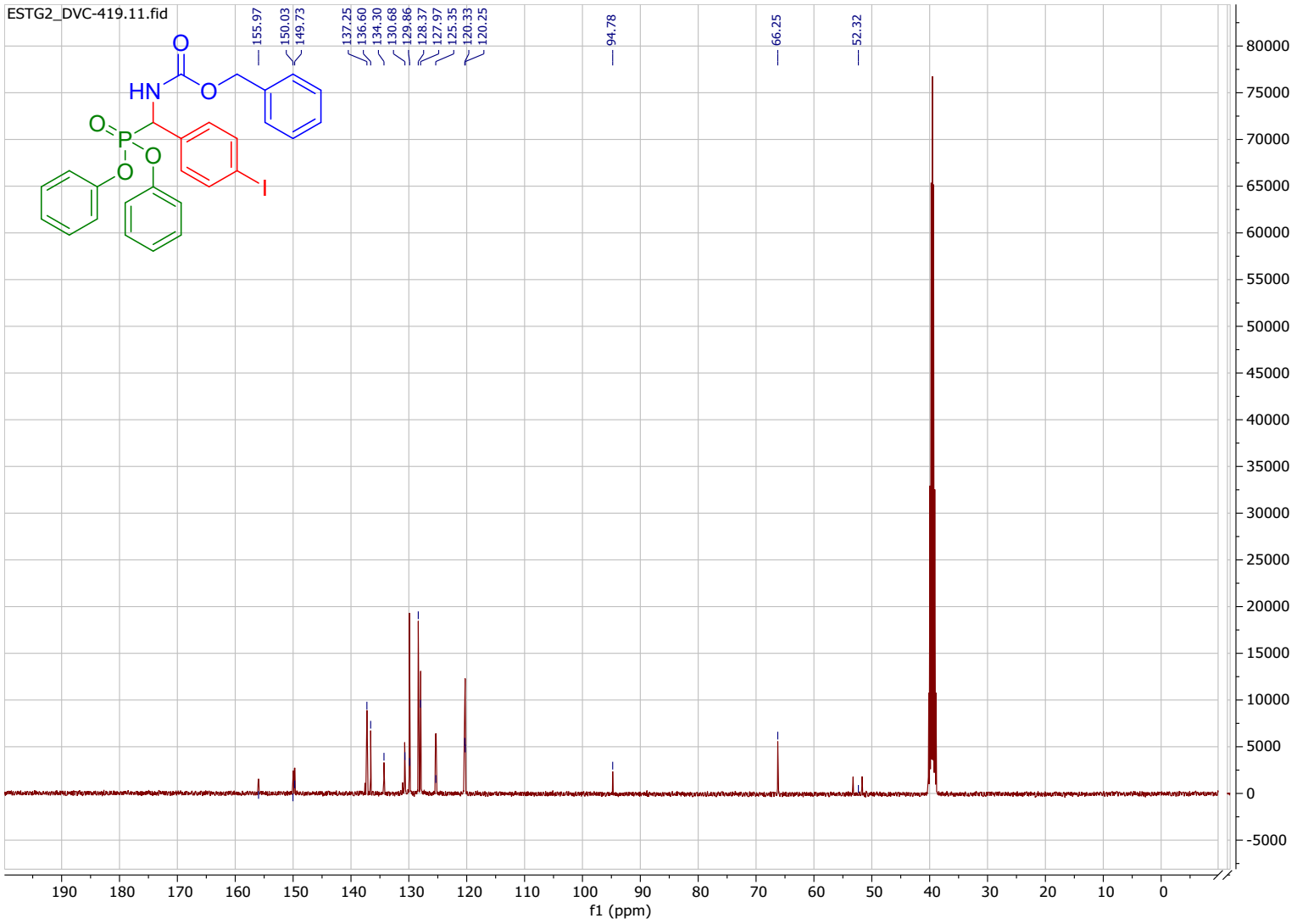
^{31}P-NMR spectra of compound **26**



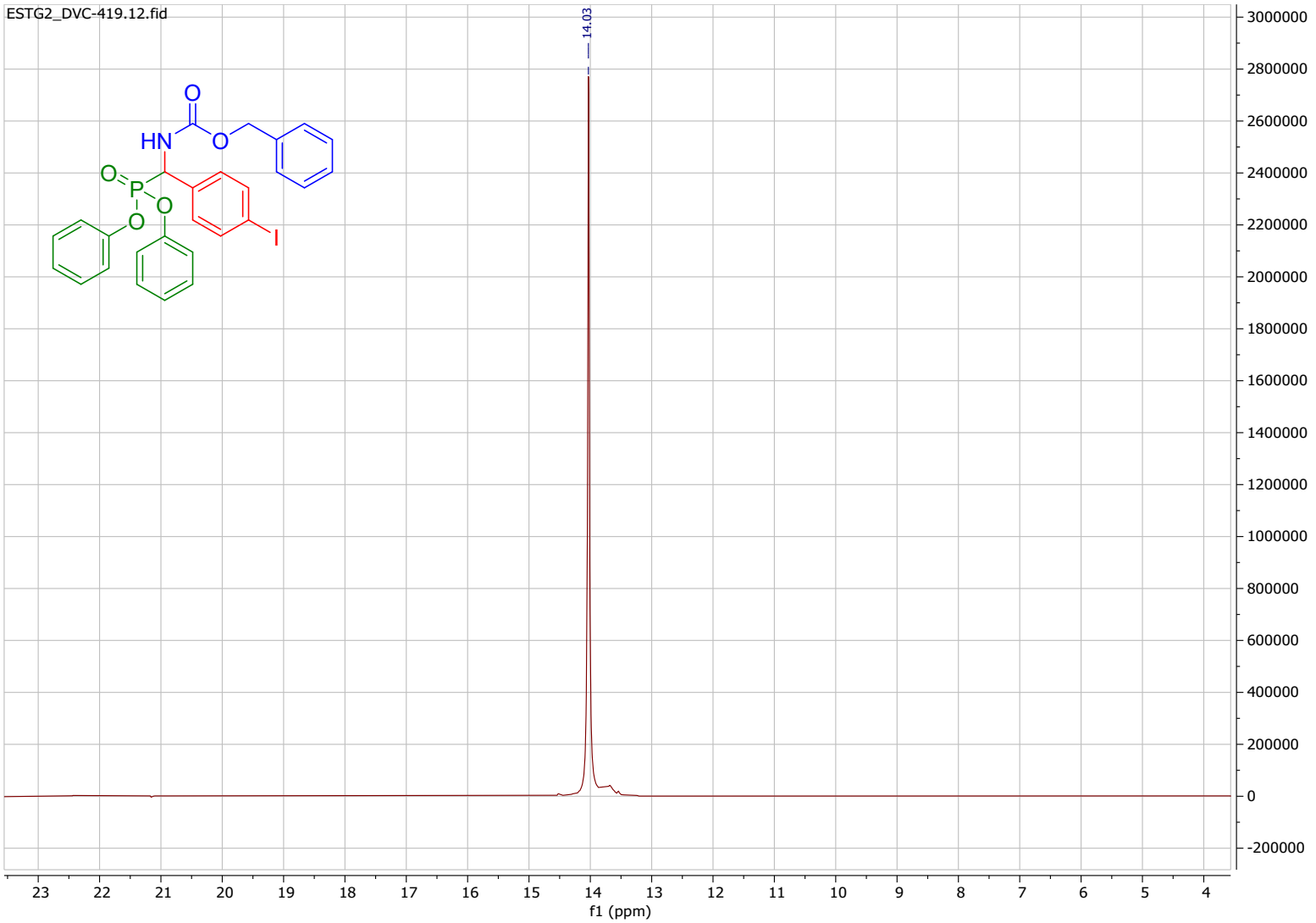
[1]H-NMR spectra of compound **27**



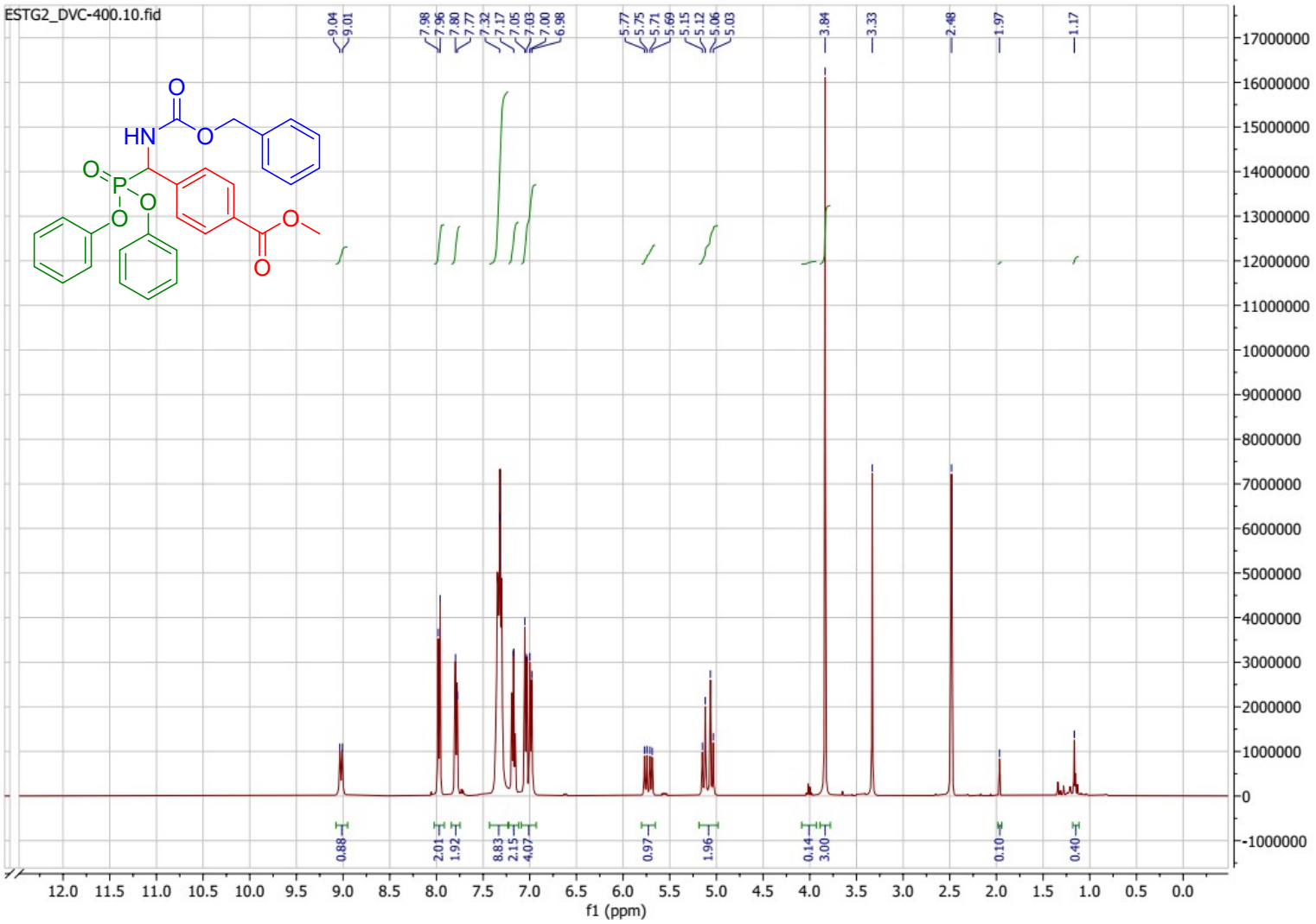
^{13}C-NMR spectra of compound **27** (without ^{31}P decoupling)



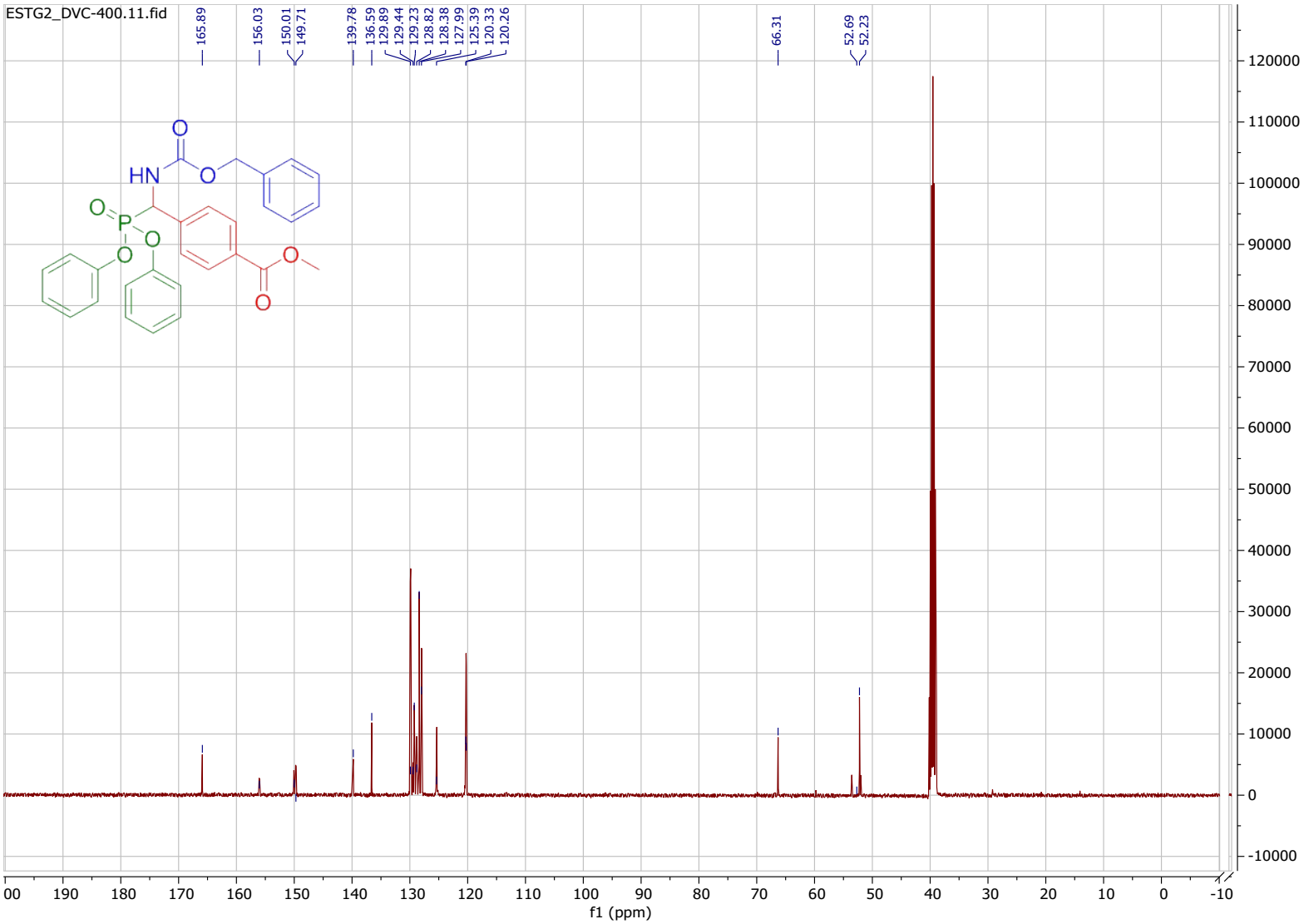
^{31}P-NMR spectra of compound **27**



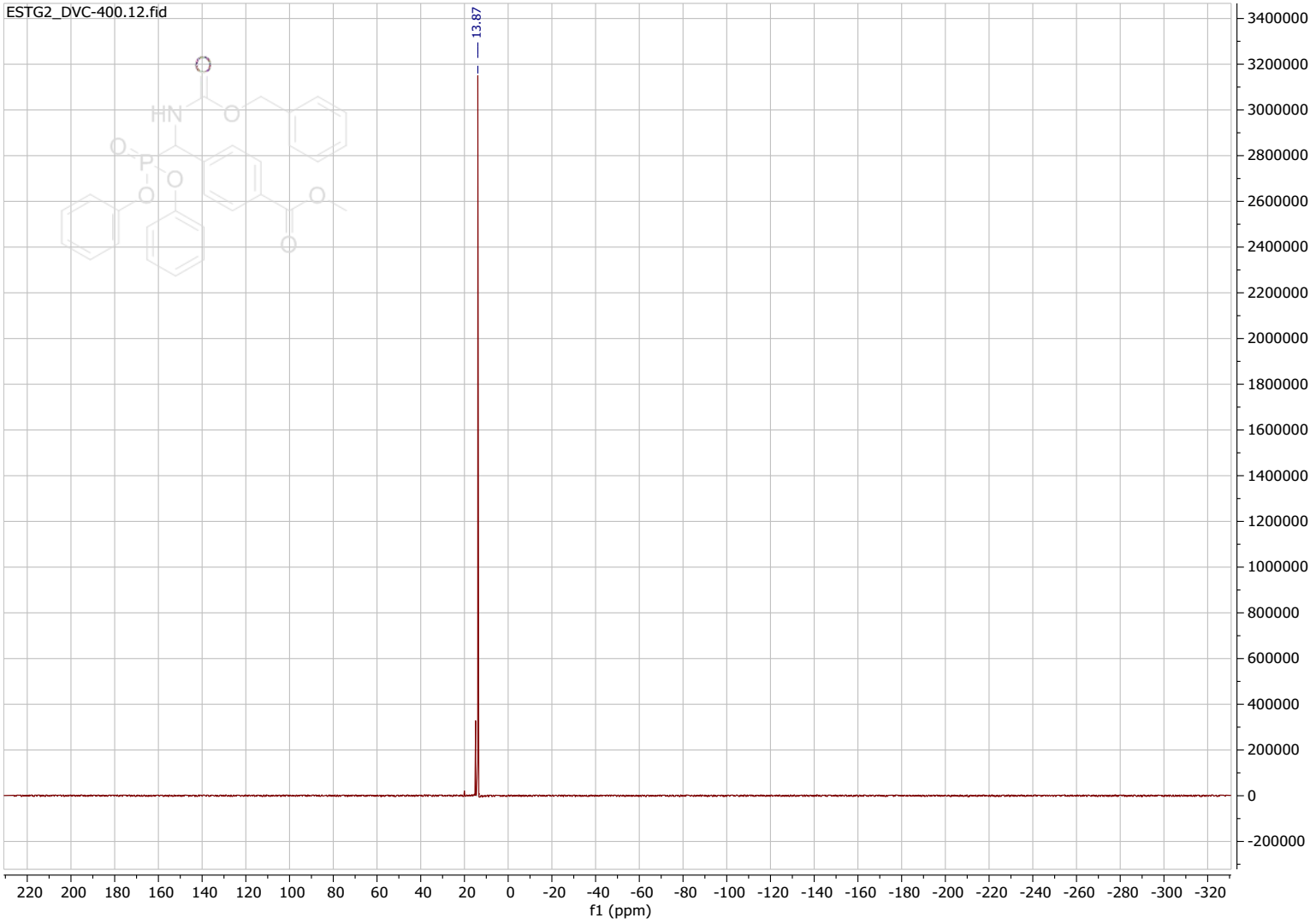
^{1}H-NMR spectra of compound **28**



^{13}C-NMR spectra of compound **28** (without ^{31}P decoupling)

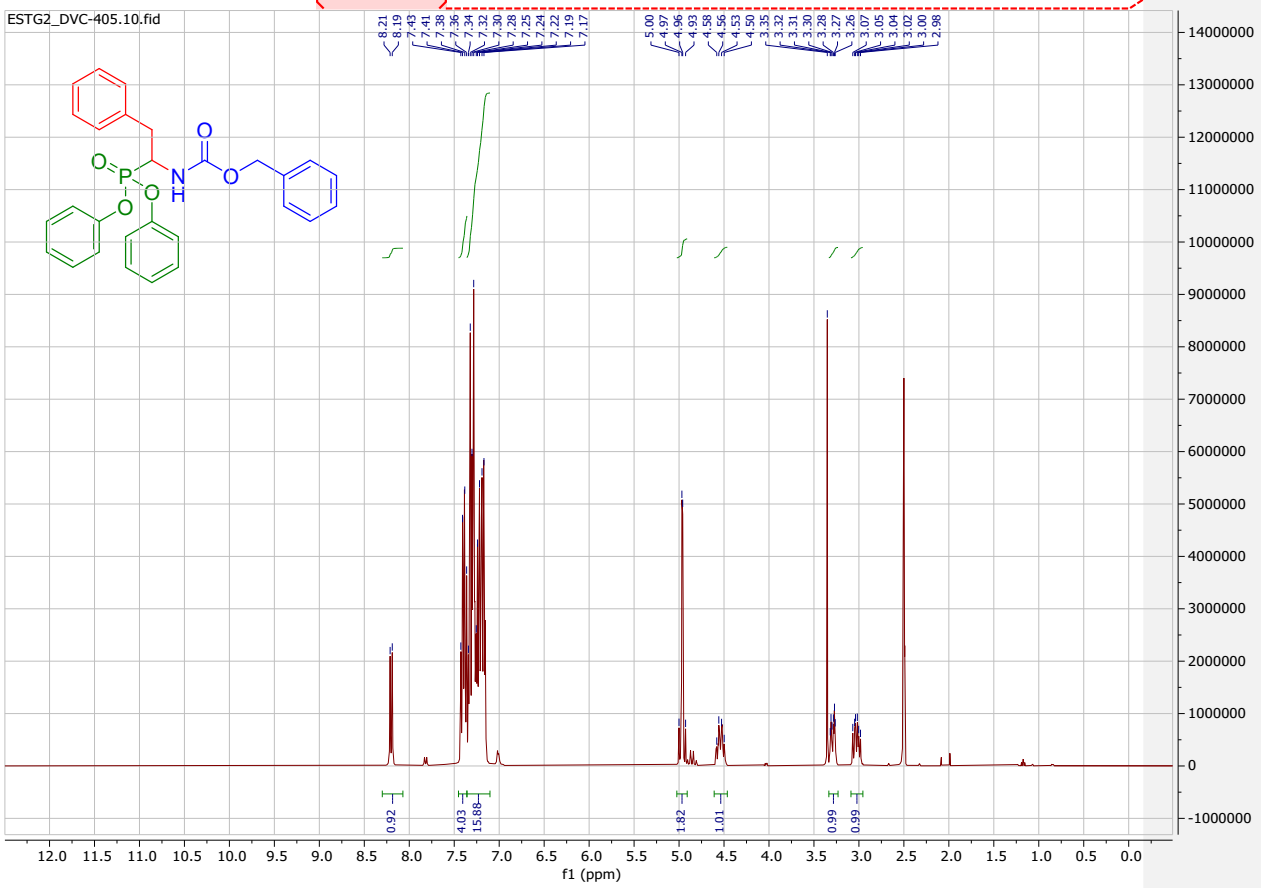


^{31}P-NMR spectra of compound **28**

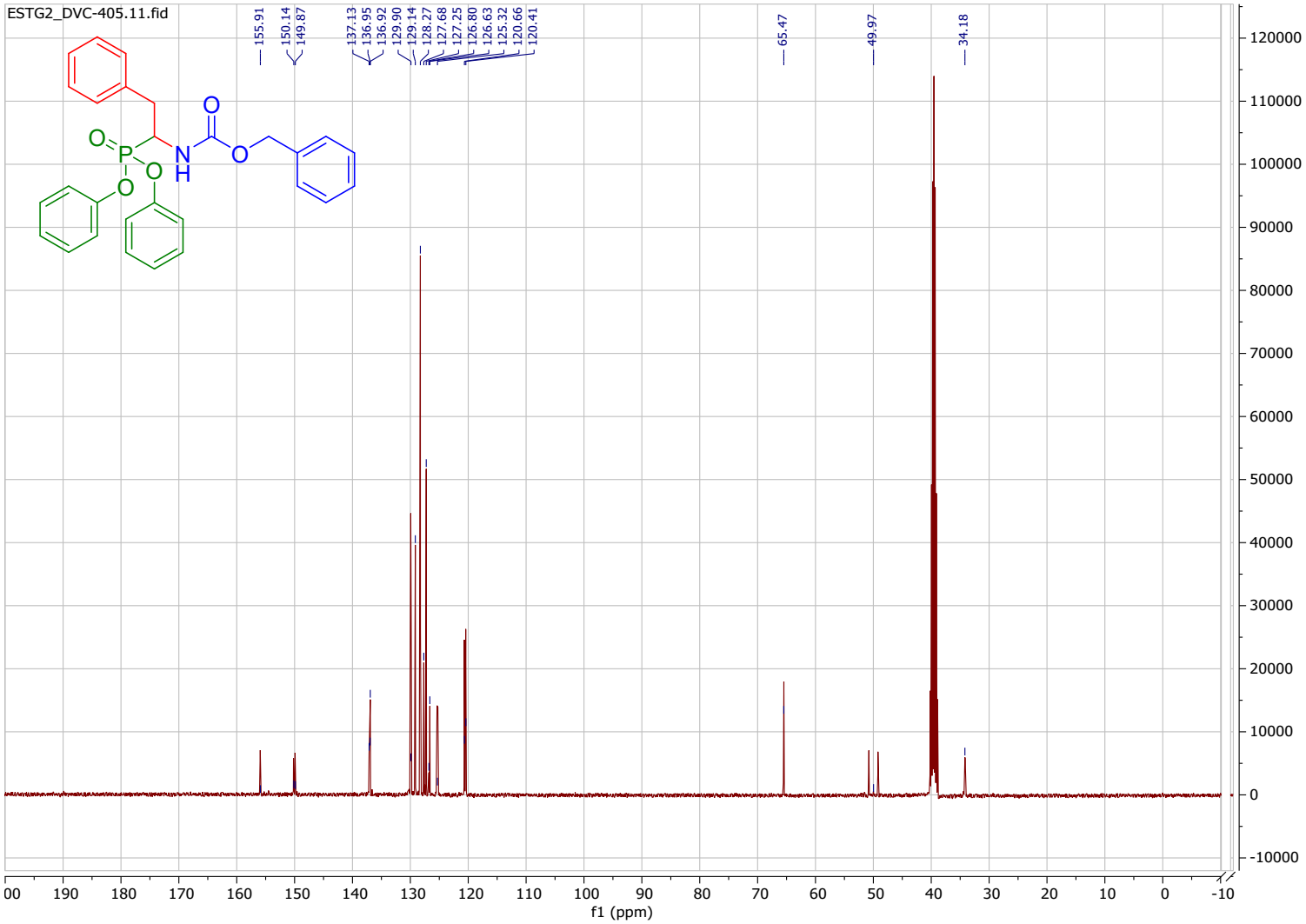


^{1}H-NMR spectra of compound **29**

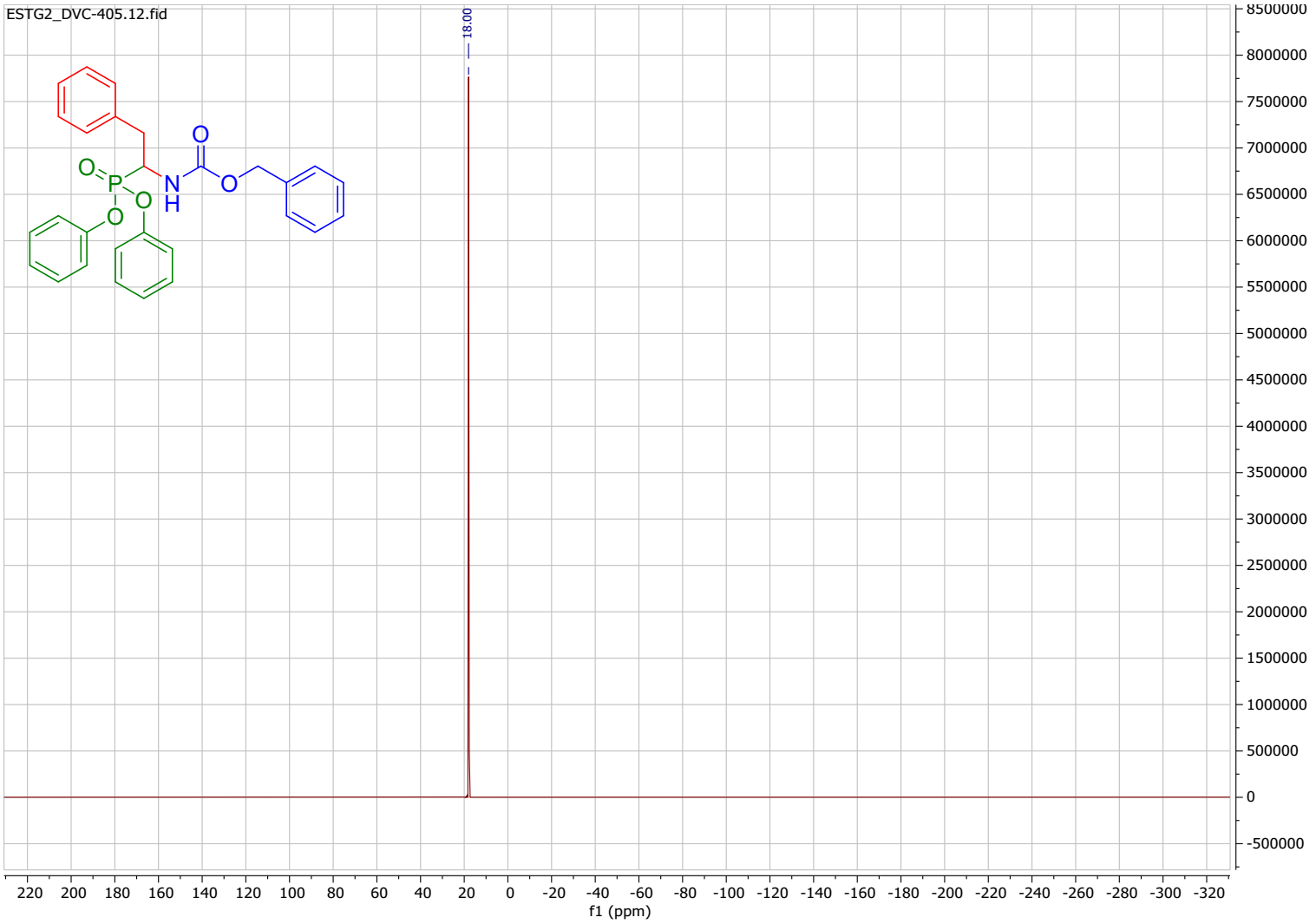
Comment [DC]: Update figure



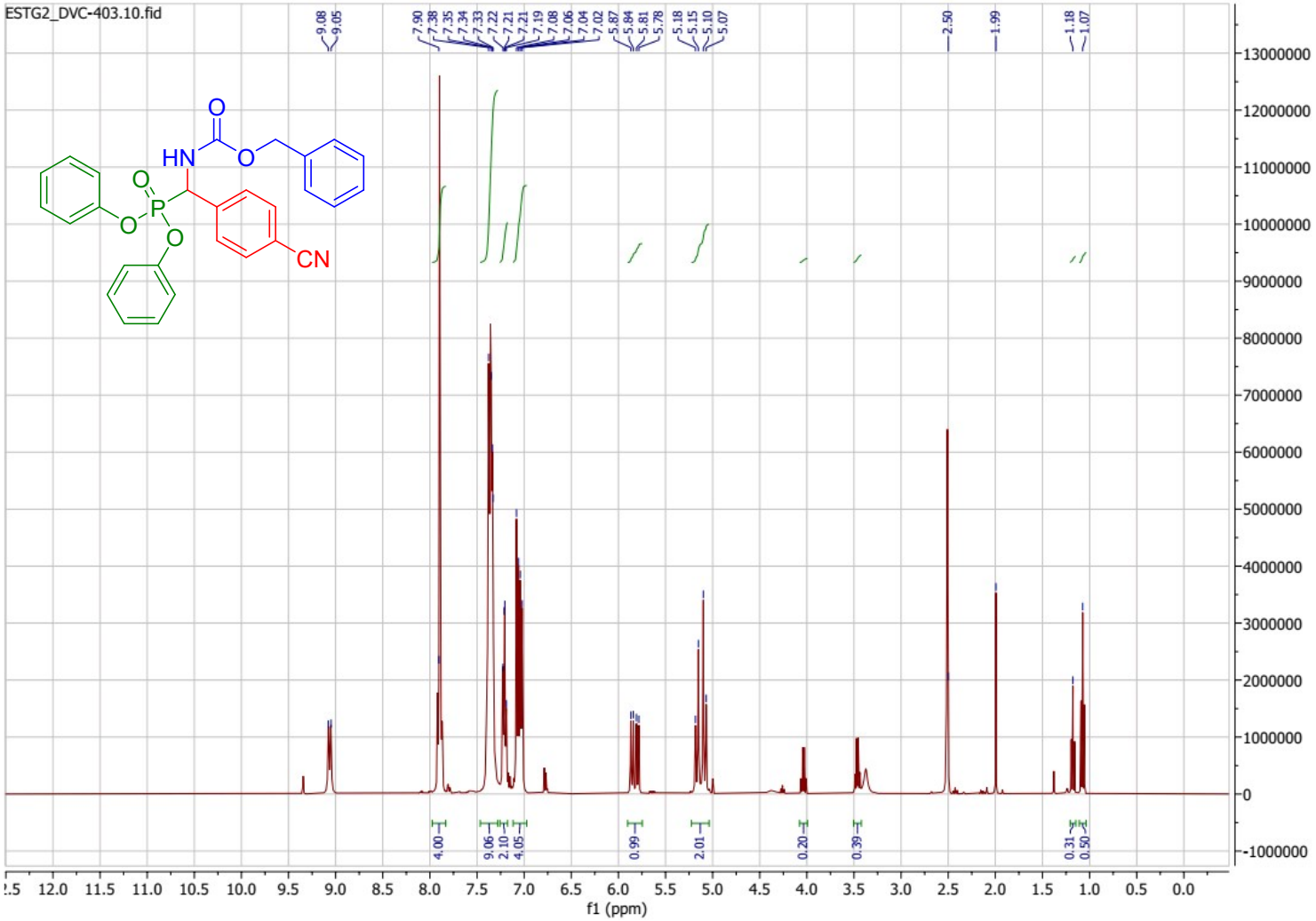
^{13}C-NMR spectra of compound **29** (without ^{31}P decoupling)



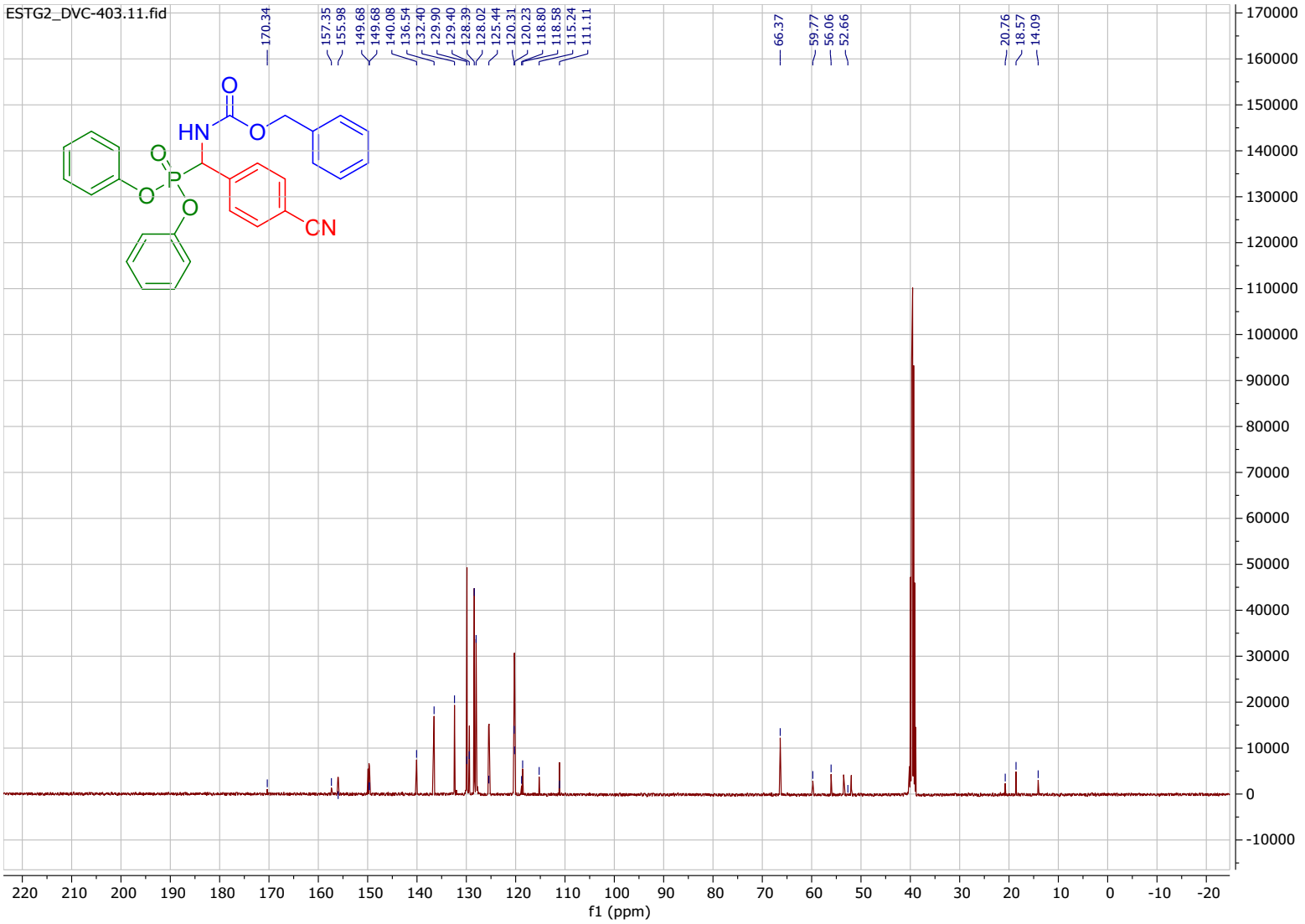
^{31}P-NMR spectra of compound **29**



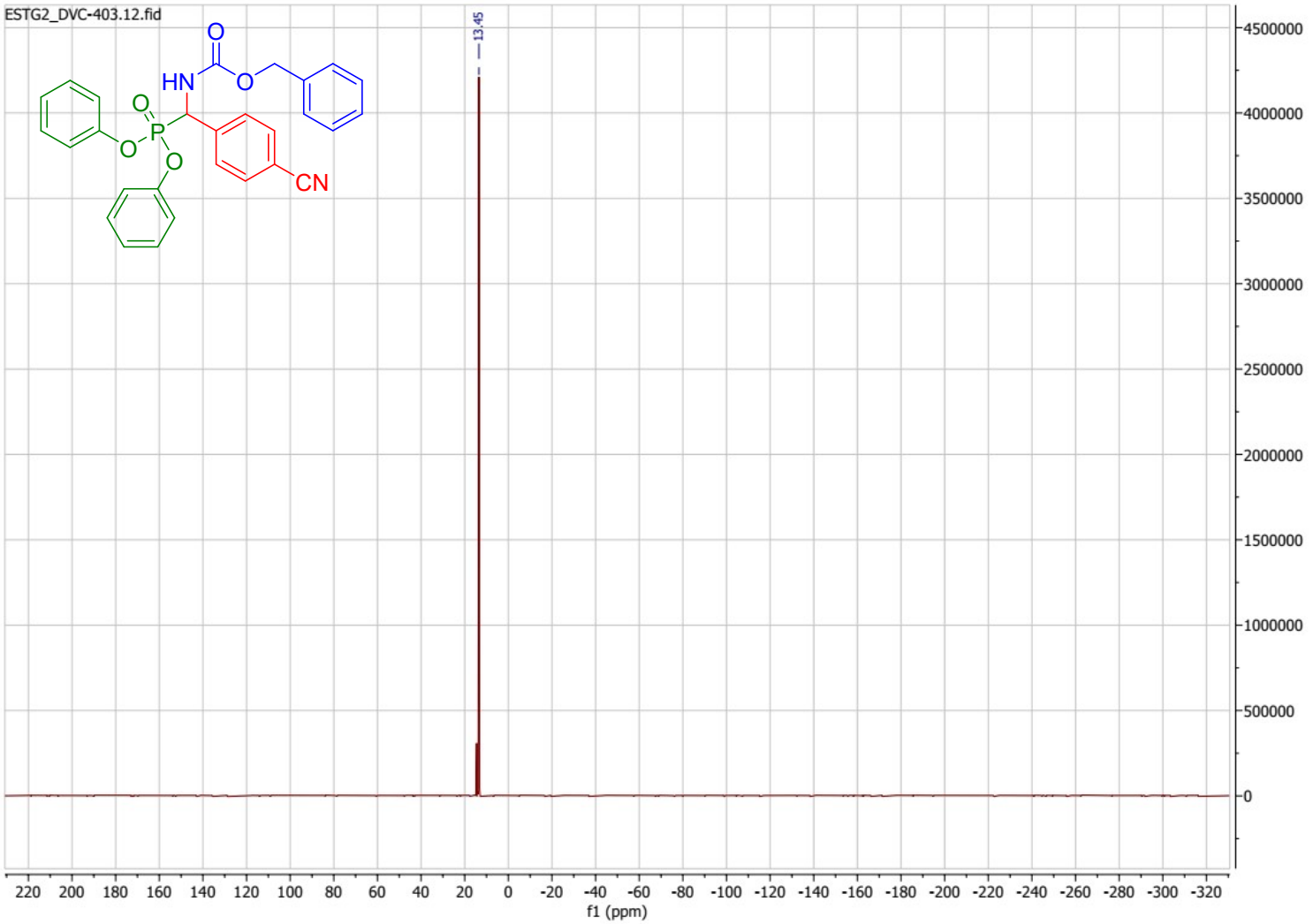
[1]H-NMR spectra of compound **30**



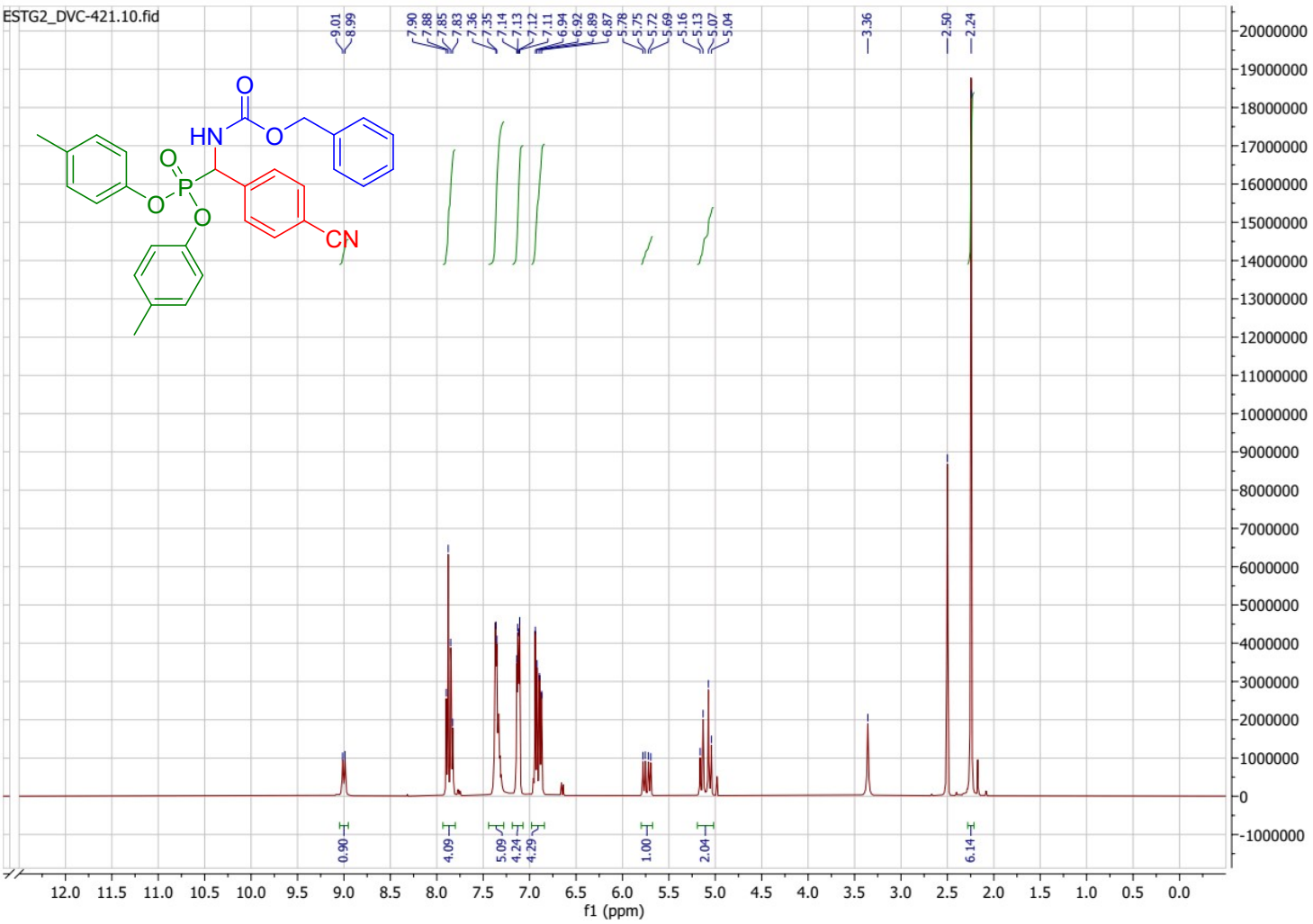
^{13}C-NMR spectra of compound **30** (without ^{31}P decoupling)



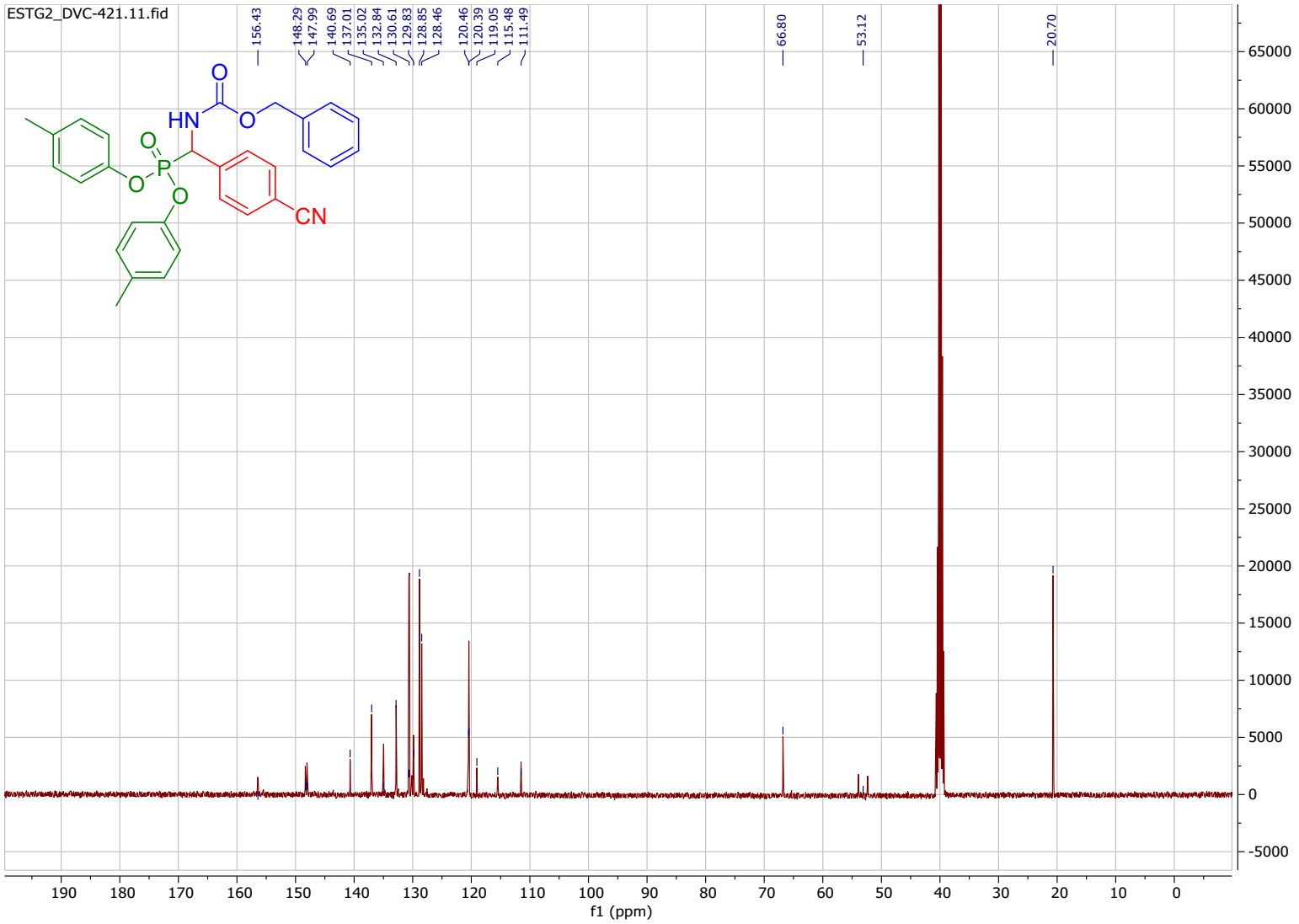
^{31}P-NMR spectra of compound **30**



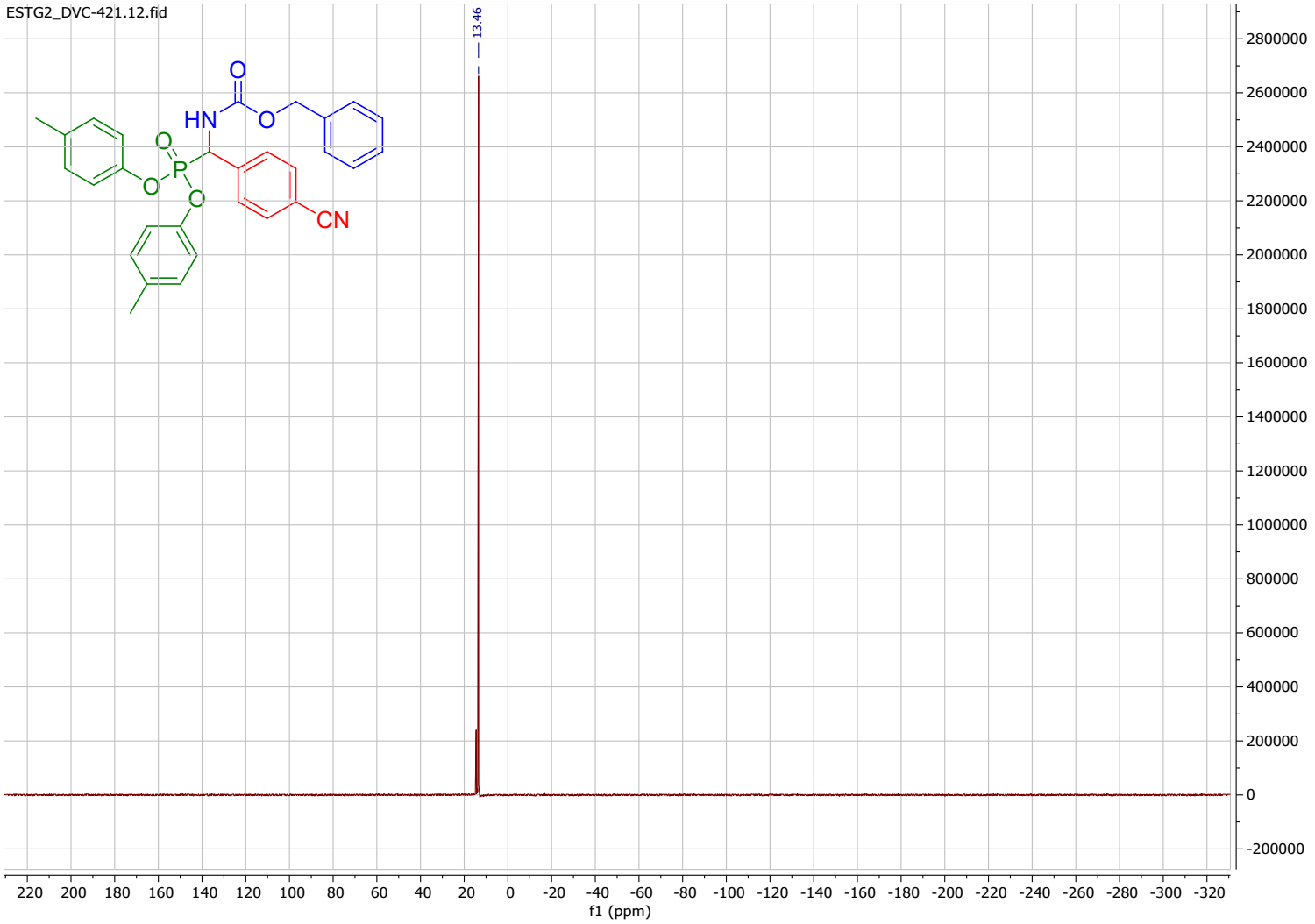
[1]H-NMR spectra of compound **31**



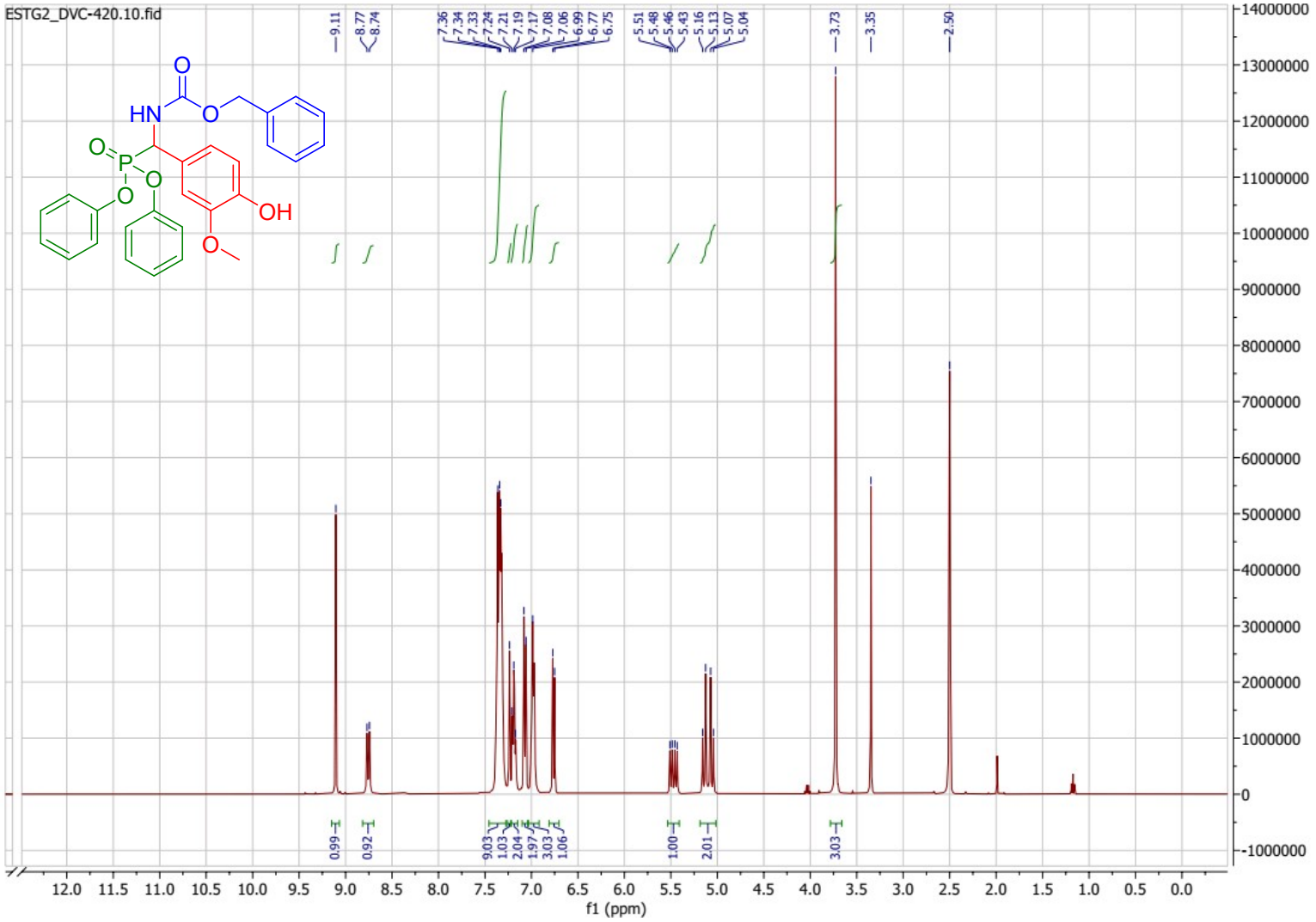
^{13}C-NMR spectra of compound **31** (without ^{31}P decoupling)



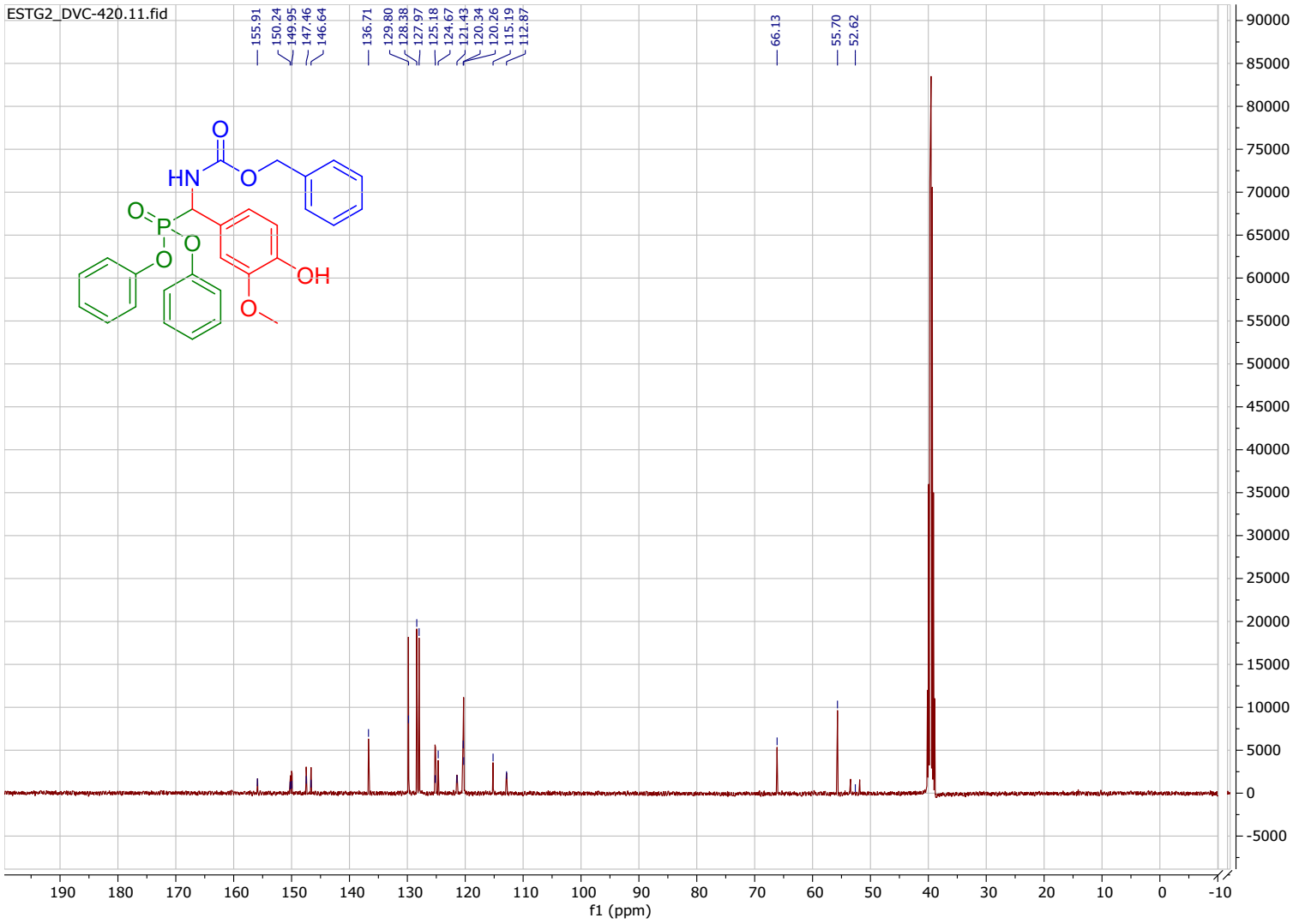
^{31}P-NMR spectra of compound **31**



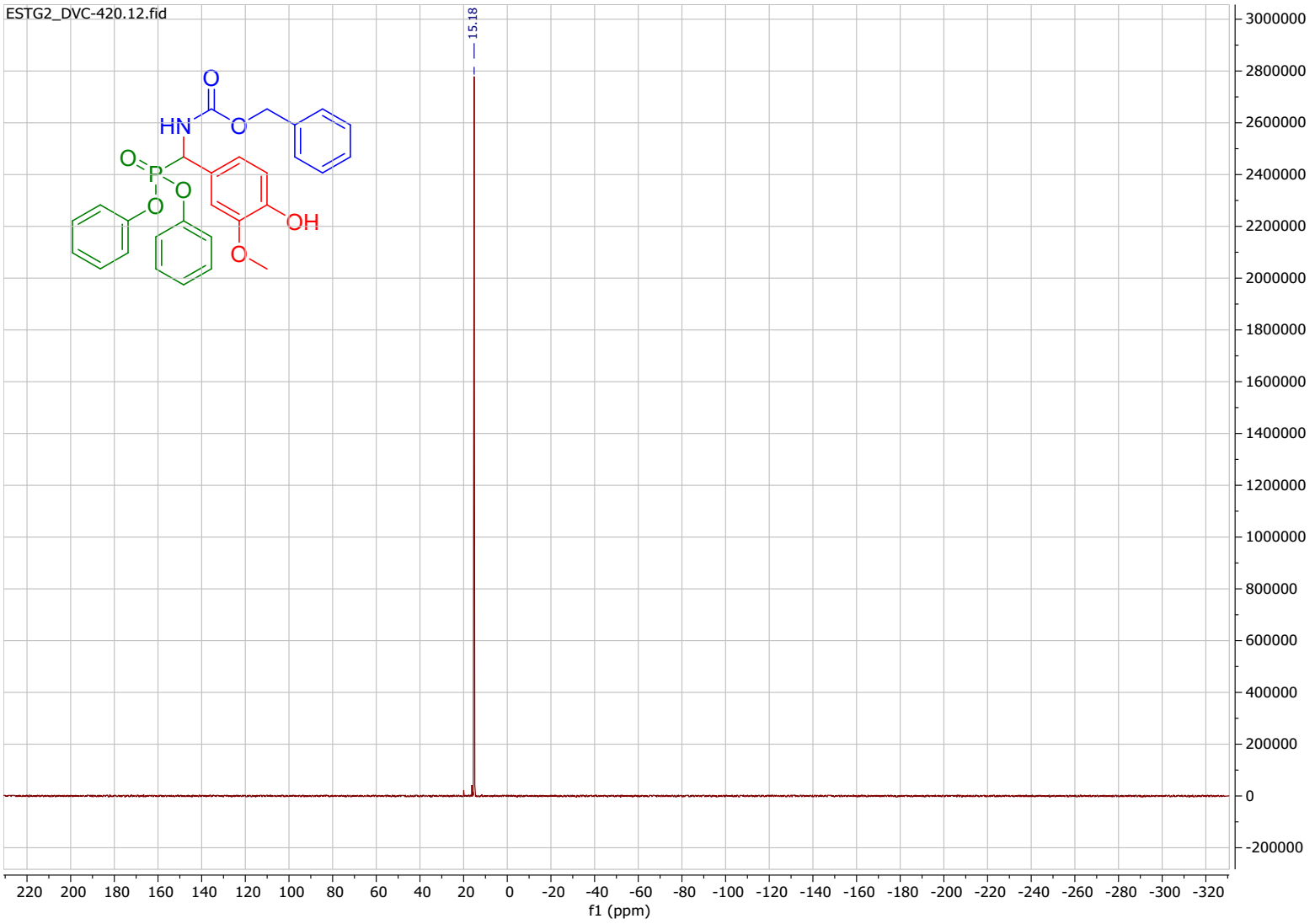
[1]H-NMR spectra of compound **32**



^{13}C-NMR spectra of compound **32** (without ^{31}P decoupling)

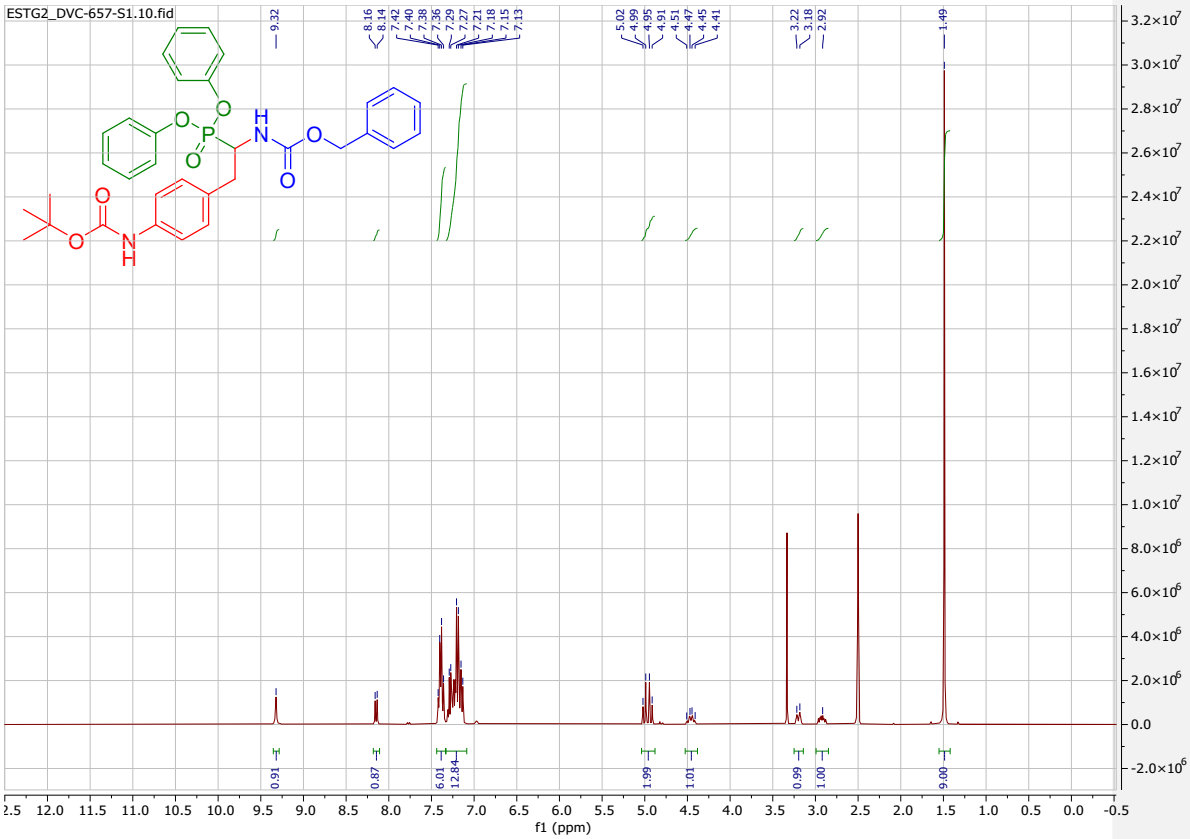


^{31}P-NMR spectra of compound **32**

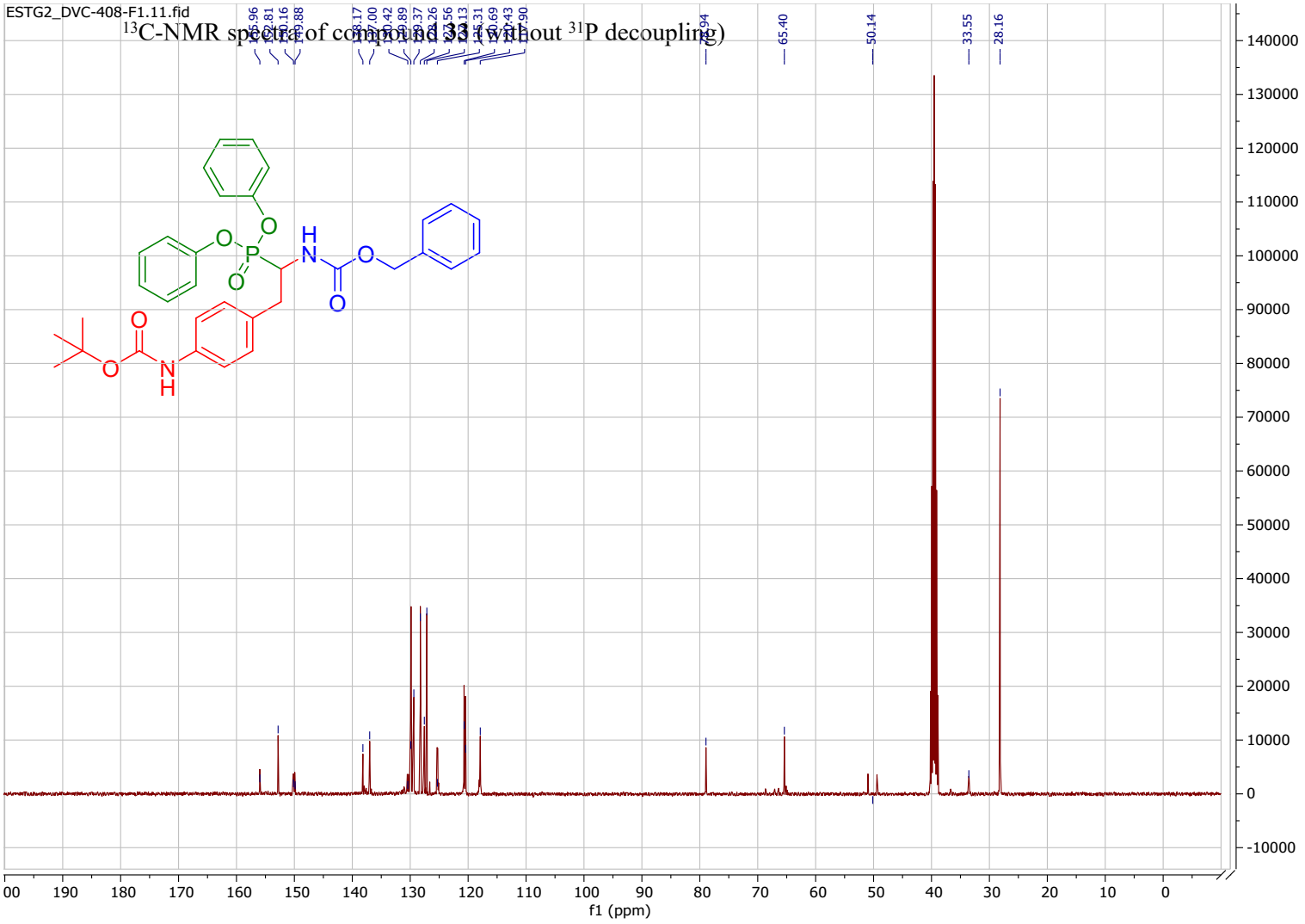


^{1}H-NMR spectra of compound **33**

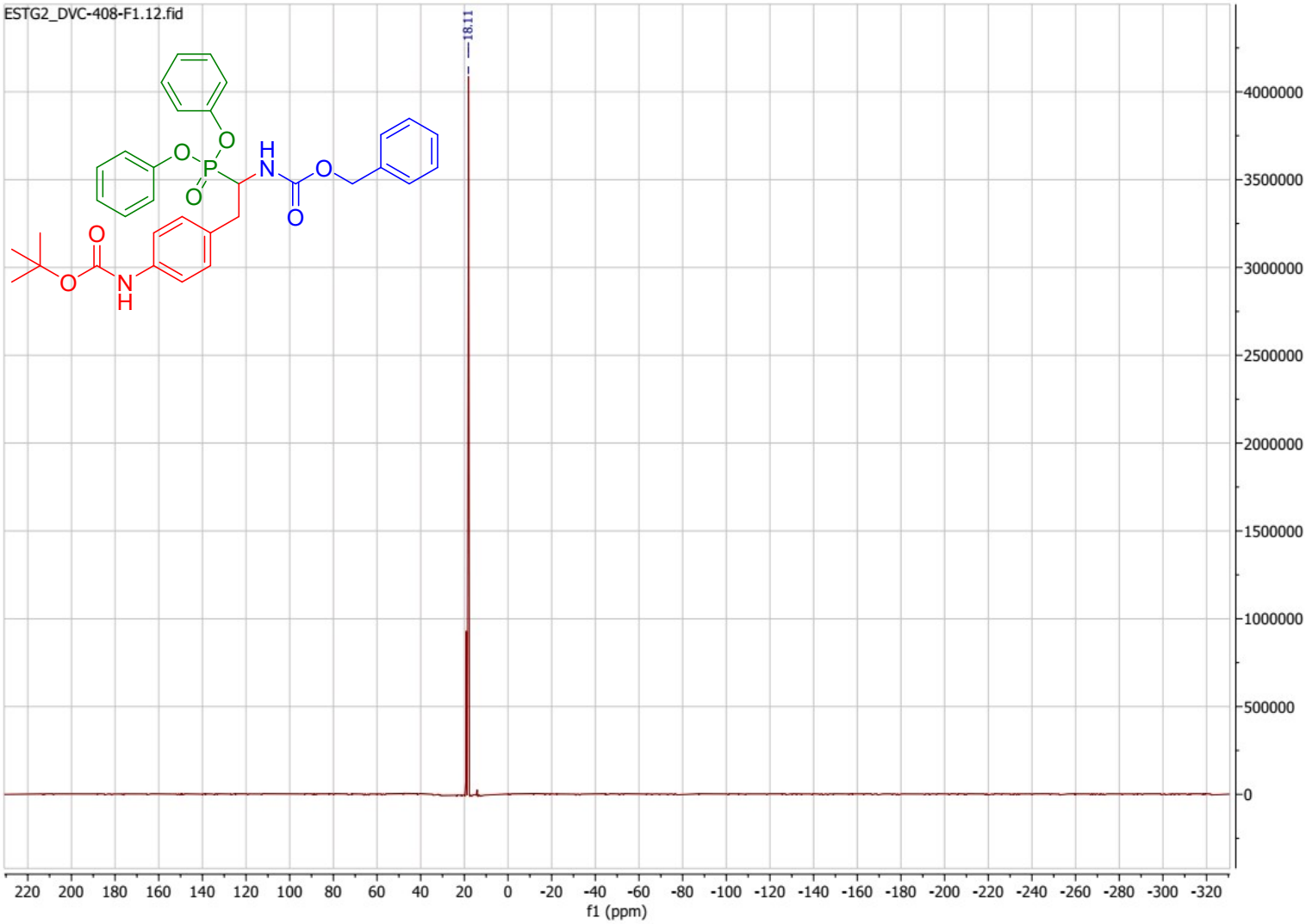
Comment [DC]: Updated figure



^{13}C-NMR spectra of compound **33** (without ^{31}P decoupling)

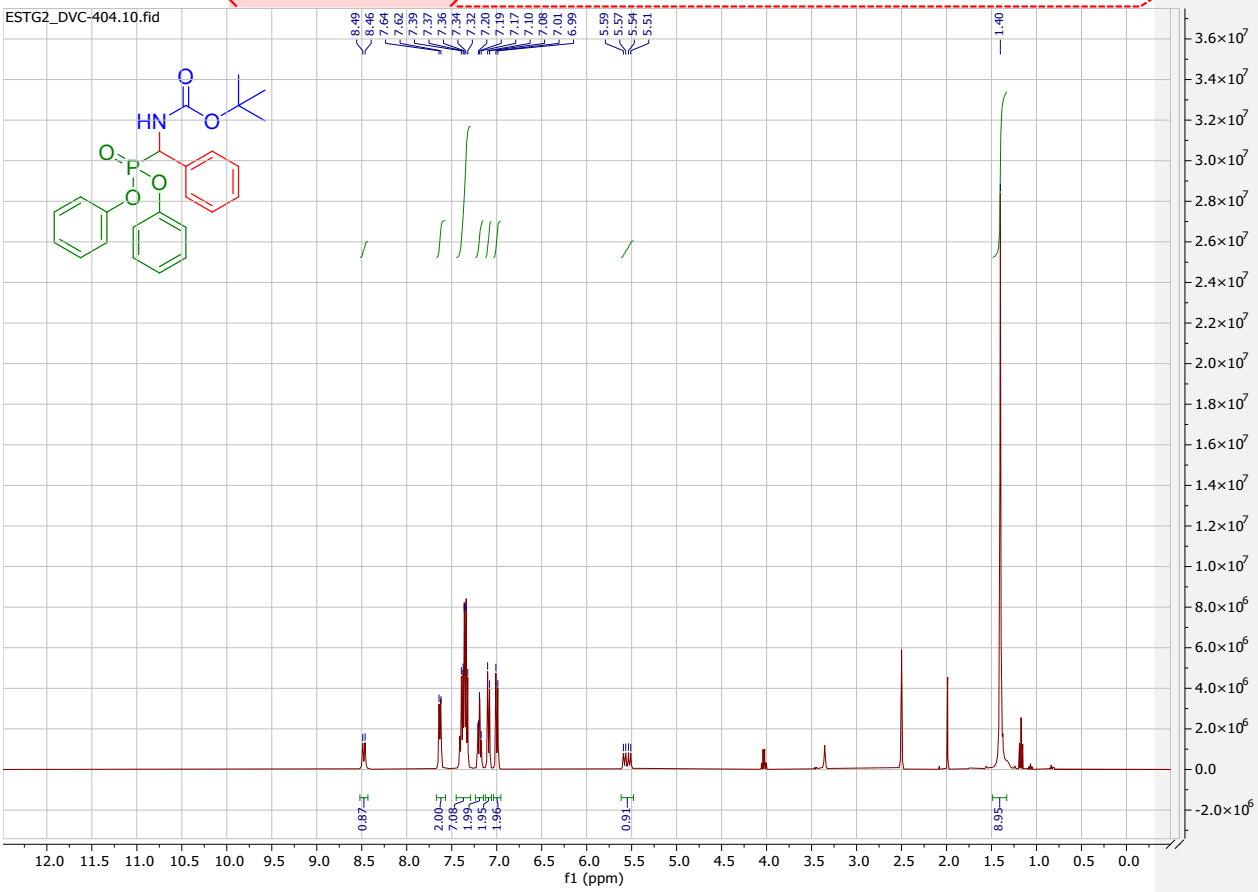


^{31}P-NMR spectra of compound **33**

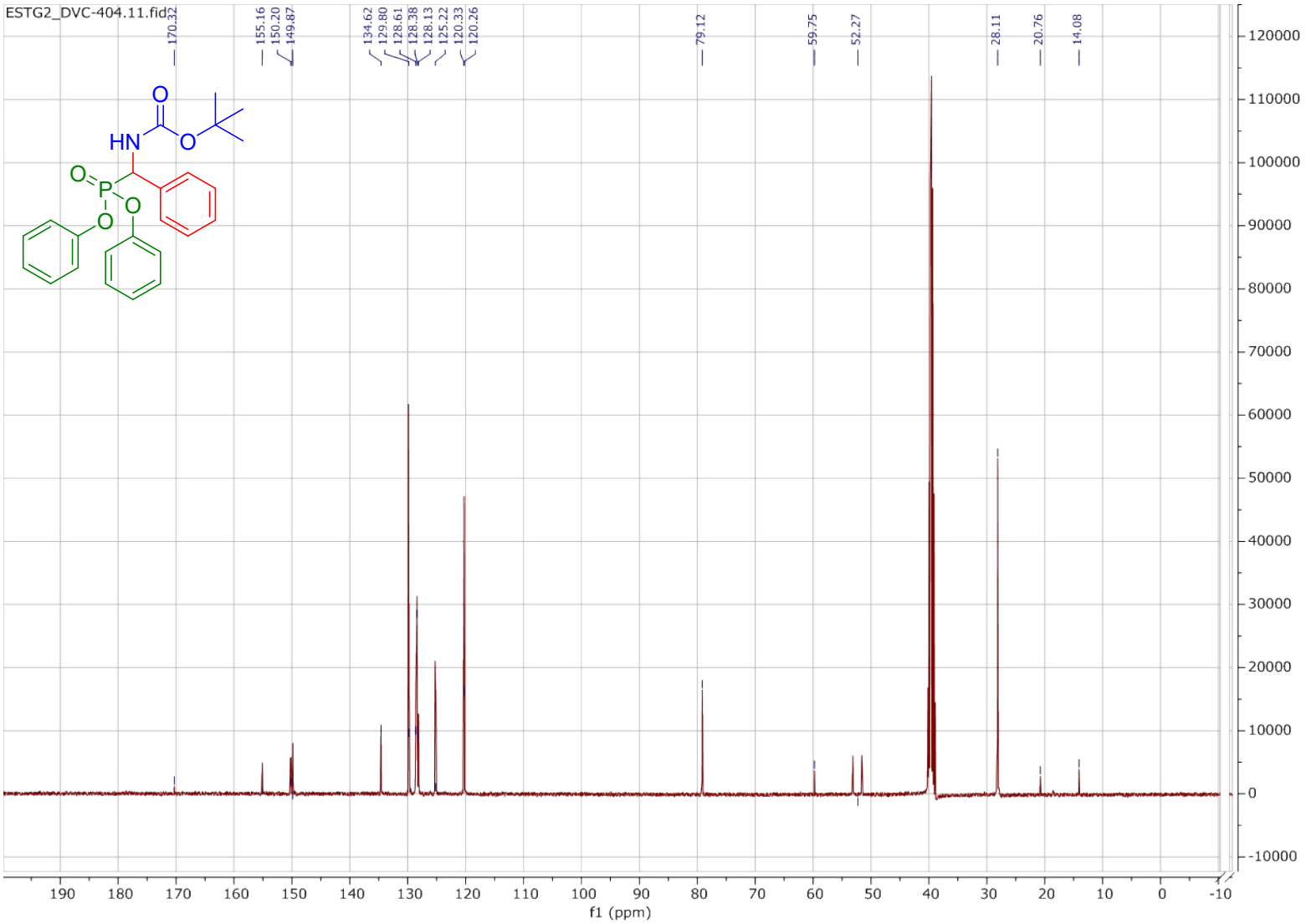


^{1}H-NMR spectra of compound **34**

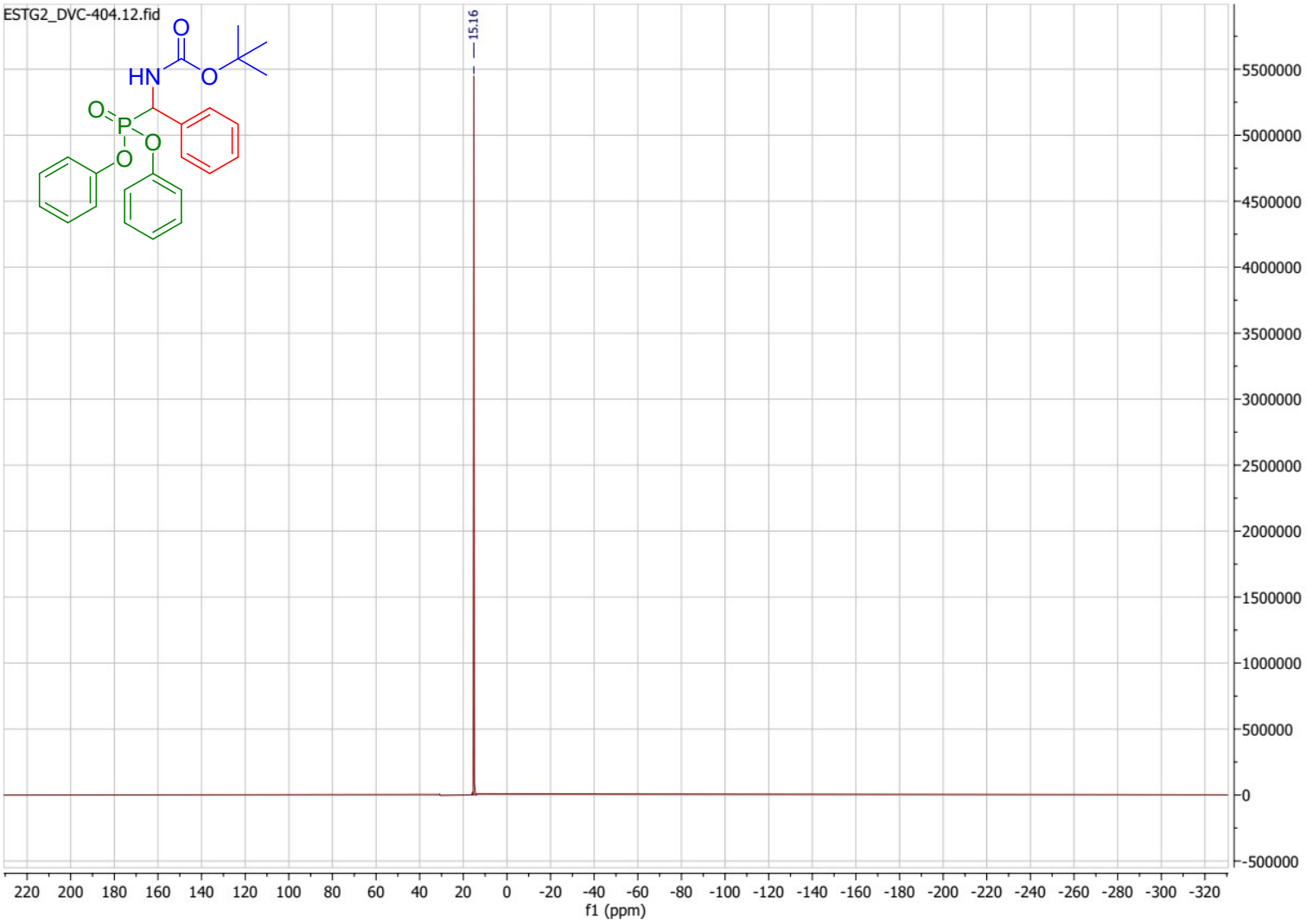
Comment [DC]: Updated figure



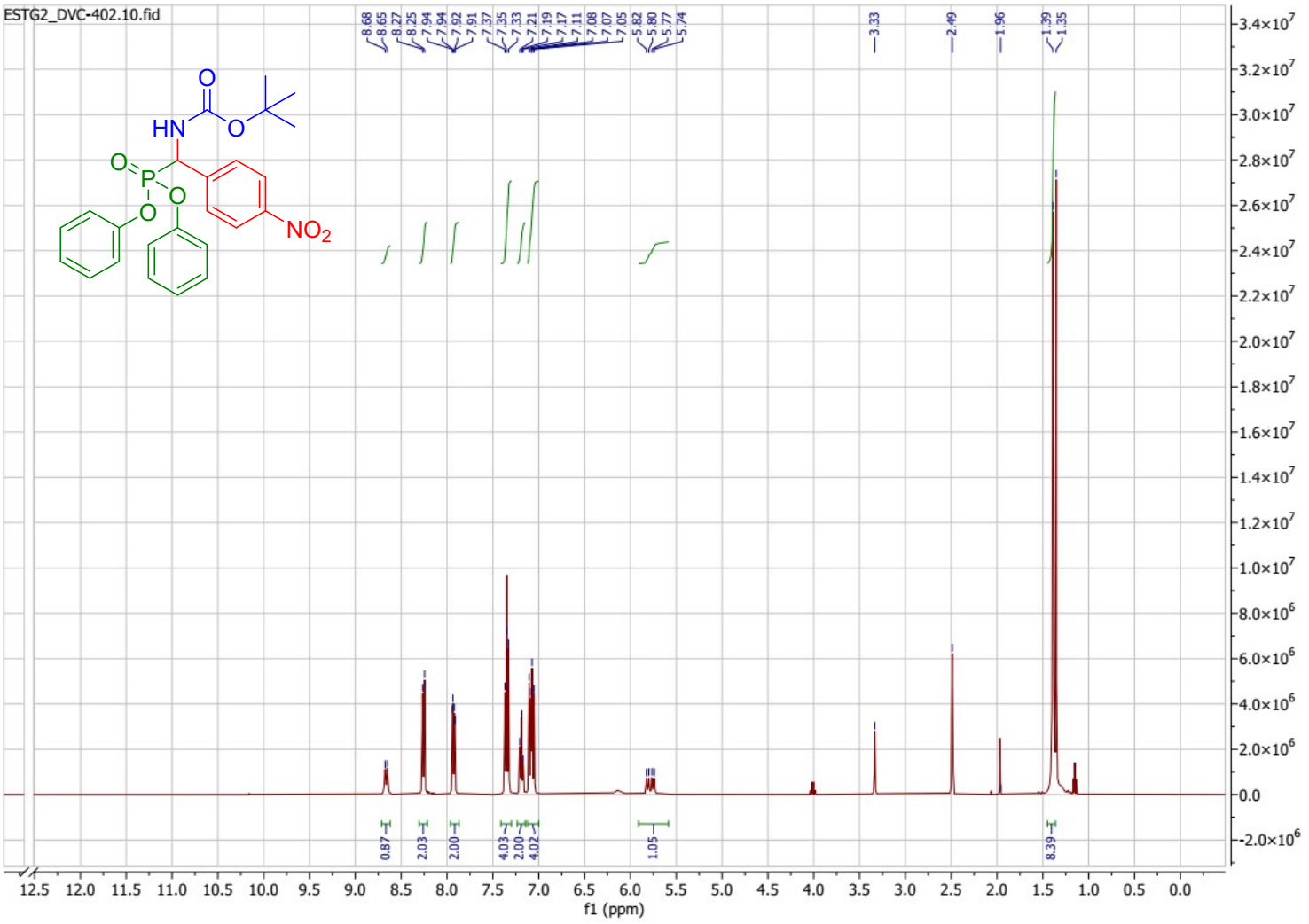
^{13}C-NMR spectra of compound **34** (without ^{31}P decoupling)



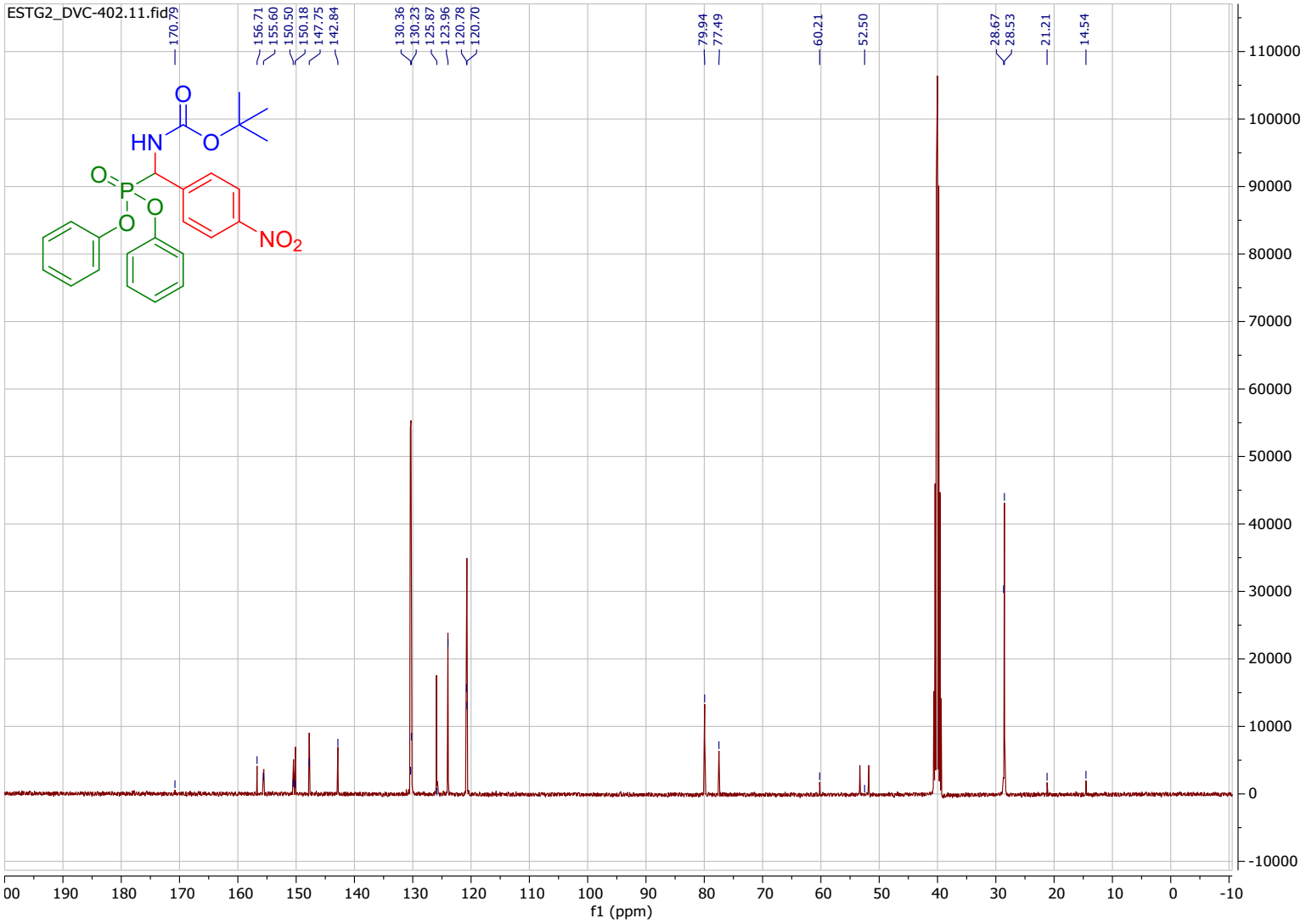
^{31}P-NMR spectra of compound **34**



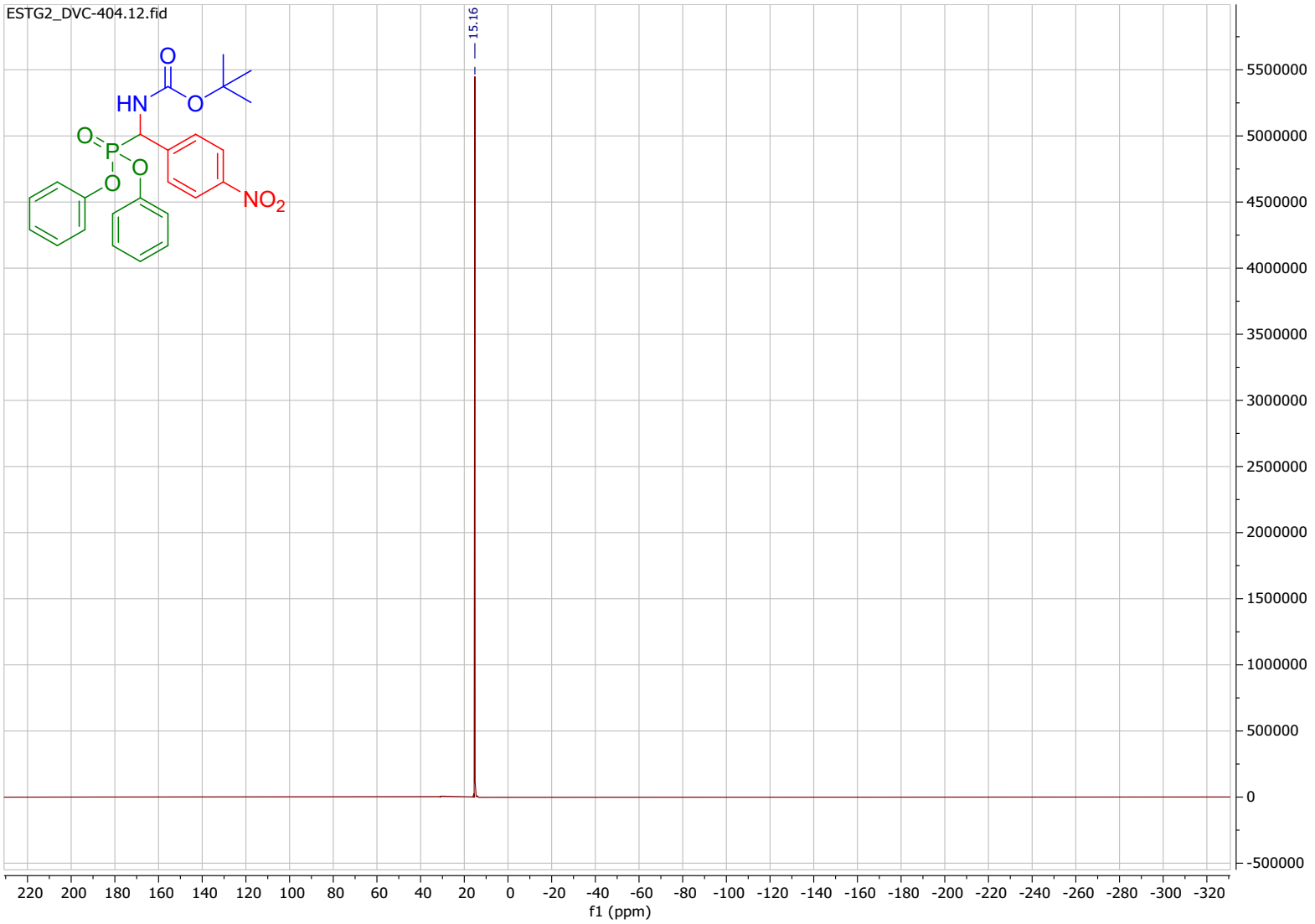
[1]H-NMR spectra of compound **35**



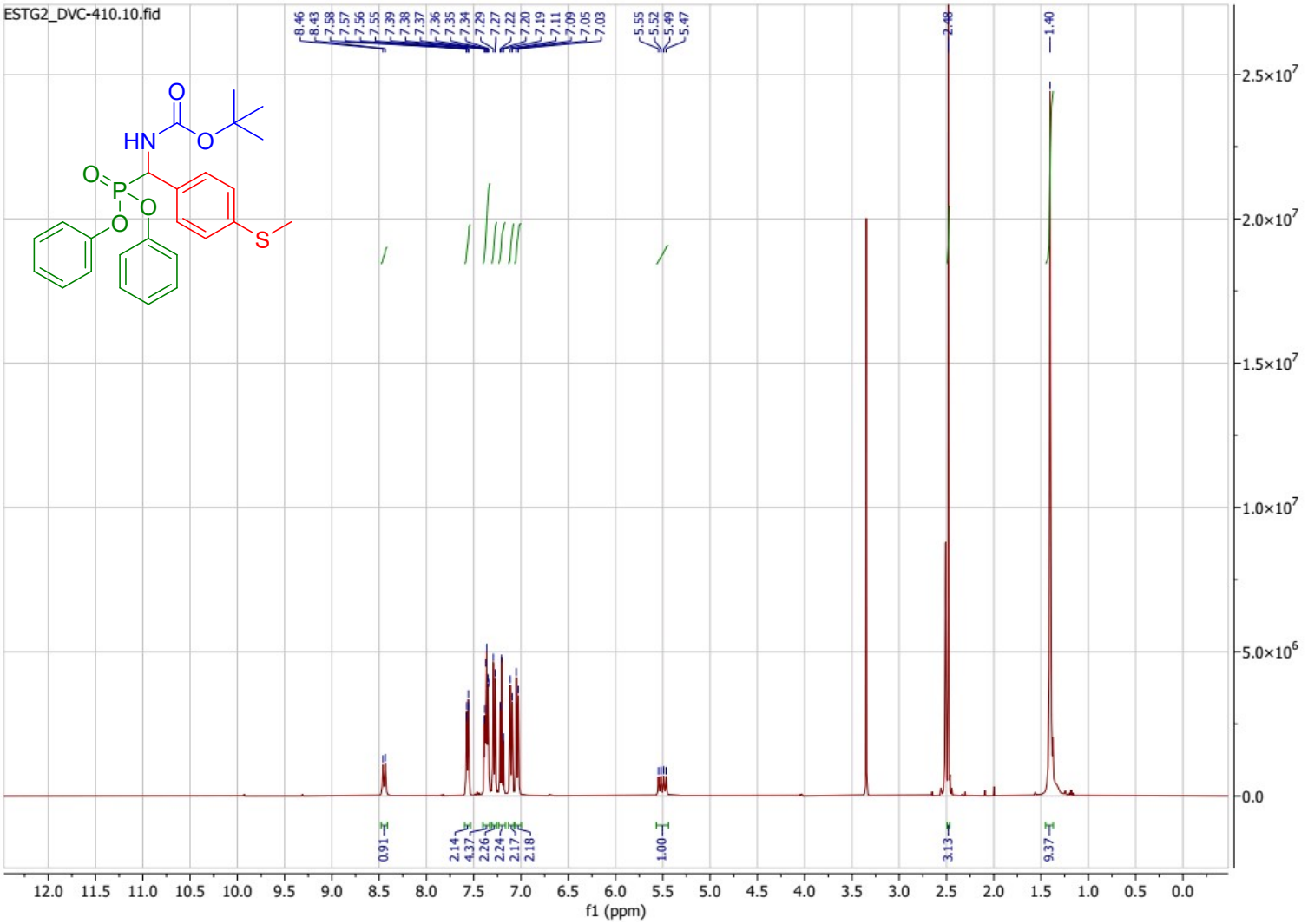
^{13}C-NMR spectra of compound **35** (without ^{31}P decoupling)



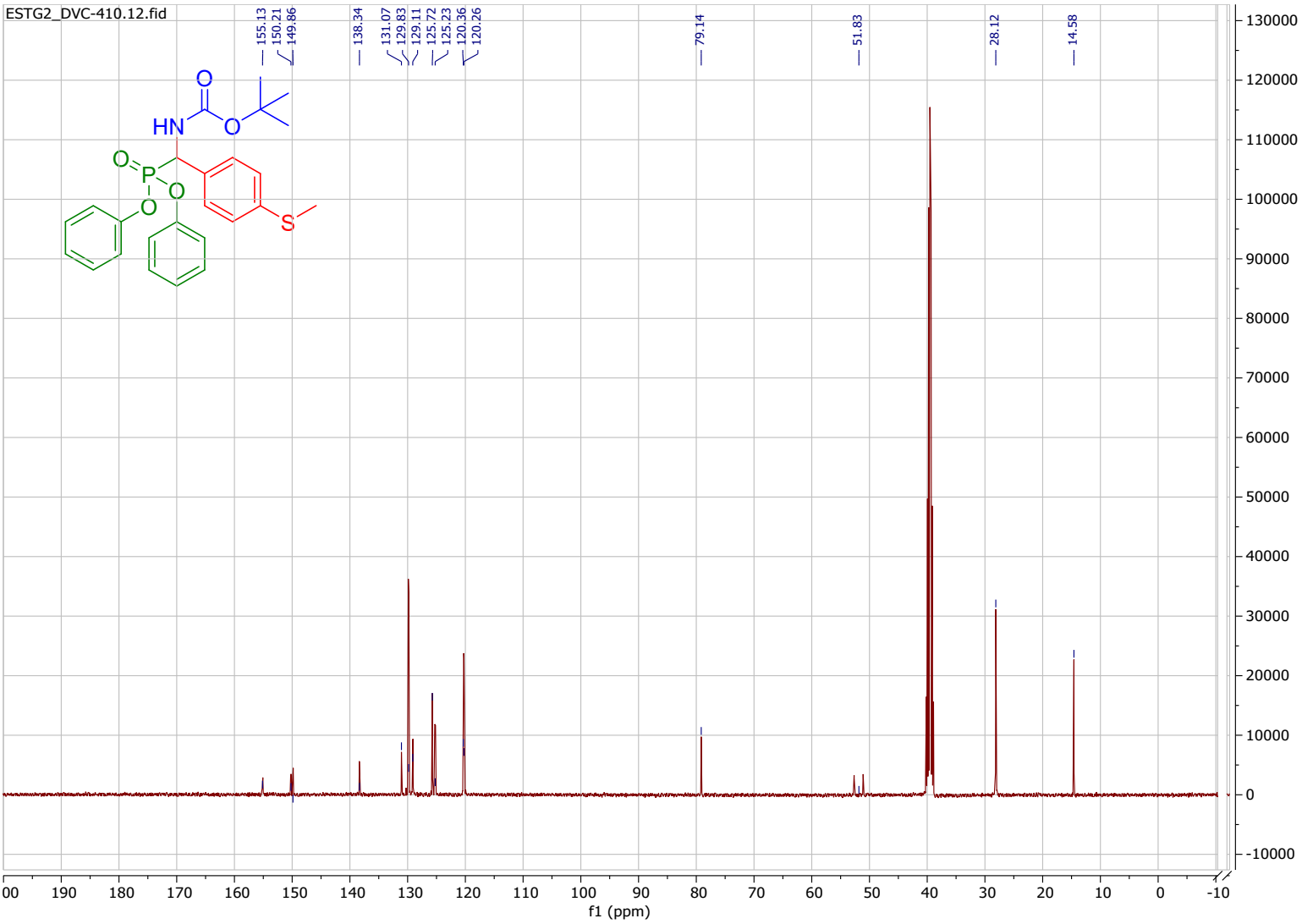
^{31}P-NMR spectra of compound **35**



[1]H-NMR spectra of compound **36**



^{13}C-NMR spectra of compound **36** (without ^{31}P decoupling)



^{31}P-NMR spectra of compound **36**