

Cu(II)-catalyzed cross-dehydrogenative coupling reaction of *N'*-acyl arylhydrazines and phosphites

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1. General information

All the commercial reagents were used as such without further purification. All solvents were used as commercial anhydrous grade without further purification. The flash column chromatography was carried out over silica gel (200-300 mesh). ^1H , ^{13}C and ^{31}P NMR spectra were recorded on a Bruker Avance 400 MHz spectrometer. Chemical shifts in ^1H NMR spectra are reported in parts per million (ppm) downfield from the internal standard Me_4Si (TMS). Chemical shifts in ^{13}C NMR spectra are reported relative to the central line of the chloroform signal ($\delta = 77.0$ ppm). Peaks were labeled as singlet (s), doublet (d), triplet (t), quartet (q), and multiplet (m). High resolution mass spectra were obtained with a Shimadzu LCMS-IT-TOF mass spectrometer. Analytical TLC was performed using EM separations percolated silica gel 0.2 mm layer UV 254 fluorescent sheets. **1a-t** and **1s-w** were synthesized according to literature methods.^{1,2}

2. Preparation of *N'*-aryl acylhydrazines **1r**, **1x** and **1y**

2-Bromo-*N'*-phenylbenzohydrazide (1r). To a solution of 2-bromobenzoic acid (0.8 g, 4.0 mmol) in DMF (10 mL) was added EDC·HCl (0.85 g, 4.4 mmol) and HOBt (0.59 g, 4.4 mmol), then phenylhydrazine (0.44 g, 4.0 mmol) was added and the reaction mixture was stirred at ambient temperature under nitrogen atmosphere for 24 h. The mixture was poured into H_2O (150 mL) and extracted with EtOAc (30 mL \times 3). The organic phases were combined and washed with saturated NaHCO_3 (30 mL \times 2) and saturated NaCl (30 mL \times 1) respectively, dried over Na_2SO_4 . The solution was concentrated *in vacuo* and purified by column chromatography on silica gel (eluting with 3:1 to 1:1 petroleum ether/ethyl acetate) to give **1r** as white solid (1.08 g, 93% yield, mp: 194-196 °C); ESI-MS (m/z): 291.2 $[\text{M}+\text{H}]^+$; ^1H NMR (400 MHz, CDCl_3) δ : 7.82 (s, 1H), 7.64 (d, $J = 7.9$ Hz, 1H), 7.60 (d, $J = 7.5$ Hz, 1H), 7.40 (t, $J = 7.5$ Hz, 1H), 7.34 (t, $J = 7.6$ Hz, 1H), 7.27 (dd, $J = 10.3$, 5.1 Hz, 2H), 6.96 (dd, $J = 18.1$, 7.8 Hz, 3H), 6.36 (d, $J = 3.7$ Hz, 1H); ^{13}C NMR (100 MHz, $\text{DMSO}-d_6$) δ : 167.6, 149.6, 137.9, 133.4, 131.9, 129.7, 129.2, 128.2, 119.7, 119.1, 112.8; HRMS (ESI) calcd. for $\text{C}_{13}\text{H}_{12}\text{BrN}_2\text{O}$ $[\text{M}+\text{H}]^+$: 291.0127, found: 291.0133.

tert-Butyl 2-(3,5-dimethylphenyl)hydrazinecarboxylate (1x). To a solution of (3,5-dimethylphenyl)hydrazine hydrochloride (1.0 g, 5.81 mmol) in dry dichloromethane (20 mL) was added Boc_2O (1.25 g, 5.81 mmol) at 0 °C. The resultant solution was then stirred at reflux for 3 h. Removing the reaction solvent afforded a colorless solid, which was washed with hexane and dried *in vacuo* to give **1x** as white solid (1.21 g, 88% yield, mp: 90-92 °C); ESI-MS (m/z): 237.2 $[\text{M}+\text{H}]^+$; ^1H NMR (400 MHz, CDCl_3) δ : 7.16 (t, $J = 8.1$ Hz, 1H), 6.90-6.82 (m, 2H), 6.76-6.69 (m, 1H), 6.38 (s, 1H), 1.55 (s, 6H), 1.49 (s, 9H); ^{13}C NMR (100 MHz, CDCl_3) δ : 156.4, 148.4, 146.8, 138.9, 138.0, 122.8, 110.9, 85.2, 81.1, 28.2 (d, $J = 9.8$ Hz), 27.4, 21.4 (d, $J = 11.3$ Hz); HRMS (ESI) calcd. for $\text{C}_{13}\text{H}_{21}\text{N}_2\text{O}_2$ $[\text{M}+\text{H}]^+$: 237.1597, found: 237.1562.

***N'*-Methyl-*N'*-phenylbenzohydrazide (1y).**³ Freshly cut Na (0.11 g, 4.72 mmol) was added to absolute ethanol (5.0 mL) to obtain a clear solution. Then *N'*-phenylbenzohydrazide (**1a**, 1.0 g, 4.72 mmol) was added to the clear solution, followed by the addition of CH_3I (0.81 g, 5.66 mmol). The resulting solution was kept at reflux for 24 h. The solution was concentrated and the residue

was dissolved in EtOAc (30 mL), washed with water and dried over Na₂SO₄. The solution was concentrated *in vacuo* and purified by column chromatography on silica gel (eluting with 3:1 petroleum ether/ethyl acetate) to afford **1e** as white solid (0.69 g, 65% yield); ESI-MS (*m/z*): 237.2 [M+H]⁺; ¹H NMR (400 MHz, CDCl₃) δ: 7.91 (s, 1H), 7.87-7.82 (m, 2H), 7.56 (t, *J* = 7.4 Hz, 1H), 7.47 (t, *J* = 7.5 Hz, 2H), 7.30-7.24 (m, 3H), 6.89 (dd, *J* = 14.5, 7.6 Hz, 3H), 3.30 (s, 3H).

3. Typical procedure for the Cu(II)-catalyzed CDC reaction

To a mixture of *N'*-aryl acylhydrazine (0.3 mmol), Cu(OAc)₂·H₂O (0.03 mmol), AgNO₃ (0.06 mmol), NMO (0.6 mmol) and MS 4Å (30 mg) in DMSO (2.0 mL) was added diisopropyl phosphonate (0.6 mmol), the resulting mixture was stirred at ambient temperature for 12-24 h. After completion of the reaction (indicated by TLC), the mixture was quenched with saturated NaCl solution, extracted with EtOAc, and dried over Na₂SO₄. The crude product was purified by flash column chromatography to provide the corresponding product **3a-x**.

Diisopropyl (2-benzoyl-1-phenylhydrazinyl)phosphonate (3a). White solid; mp: 166-167 °C; ¹H NMR (400 MHz, DMSO-*d*₆) δ: 10.88 (s, 1H), 7.97-7.92 (m, 2H), 7.62 (m, 1H), 7.54 (dd, *J* = 10.2, 4.6 Hz, 2H), 7.33-7.26 (m, 2H), 7.22 (d, *J* = 7.8 Hz, 2H), 6.99 (t, *J* = 7.2 Hz, 1H), 4.94 (s, 1H), 4.70 (s, 1H), 1.29 (d, *J* = 6.1 Hz, 6H), 1.12 (s, 6H); ¹³C NMR (100 MHz, DMSO-*d*₆) δ: 166.3, 143.3 (d, *J* = 13.2 Hz), 132.5, 132.0, 128.6, 128.5, 127.6, 122.2, 117.0 (d, *J* = 2.0 Hz), 71.4 (d, *J* = 10.1 Hz), 23.6, 23.3; ³¹P NMR (162 MHz, CDCl₃) δ: 0.15; HRMS (ESI) calcd. for C₁₉H₂₆N₂O₄P [M+H]⁺: 377.1625, found: 377.1627.

Diisopropyl (2-benzoyl-1-(4-fluorophenyl)hydrazinyl)phosphonate (3b). White solid; mp: 143-144 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.76 (s, 1H), 7.88-7.81 (m, 2H), 7.44 (dd, *J* = 10.7, 4.1 Hz, 1H), 7.34 (m, 4H), 7.00-6.91 (m, 2H), 4.88 (m, 2H), 1.35 (d, *J* = 5.7 Hz, 6H), 1.24 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 160.6, 158.2, 139.3 (d, *J* = 12.7 Hz), 131.9 (d, *J* = 18.8 Hz), 128.2, 127.6, 121.9 (d, *J* = 6.5 Hz), 115.3, 73.2 (d, *J* = 5.7 Hz), 23.7 (dd, *J* = 20.3, 4.9 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: 0.24; HRMS (ESI) calcd. for C₁₉H₂₅FN₂O₄P [M+H]⁺: 395.1530, found: 395.1547.

Diisopropyl (2-benzoyl-1-(4-chlorophenyl)hydrazinyl)phosphonate (3c). White solid; mp: 148-150 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.29 (s, 1H), 7.85 (d, *J* = 7.7 Hz, 2H), 7.48 (t, *J* = 7.4 Hz, 1H), 7.36 (t, *J* = 7.6 Hz, 2H), 7.27 (d, *J* = 8.5 Hz, 2H), 7.22 (d, *J* = 9.0 Hz, 2H), 4.88 (dd, *J* = 12.4, 6.2 Hz, 2H), 1.36 (d, *J* = 6.1 Hz, 6H), 1.25 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 141.9 (d, *J* = 13.2 Hz), 132.0, 131.9, 128.7, 128.6, 128.3, 127.7, 120.1 (d, *J* = 2.2 Hz), 73.4 (d, *J* = 5.6 Hz), 23.7 (dd, *J* = 18.4, 4.9 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: -0.25; HRMS (ESI) calcd. for C₁₉H₂₅ClN₂O₄P [M+H]⁺: 411.1235, found: 411.1245.

Diisopropyl (2-benzoyl-1-(4-bromophenyl)hydrazinyl)phosphonate (3d). White solid; mp: 160-161 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.06 (s, 1H), 7.88-7.82 (m, 2H), 7.50 (dd, *J* = 11.8, 4.4 Hz, 1H), 7.38 (t, *J* = 8.3 Hz, 4H), 7.23-7.19 (m, 2H), 4.88 (dd, *J* = 12.6, 6.2 Hz, 2H), 1.37 (d, *J* = 6.2 Hz, 6H), 1.25 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 142.4 (d, *J* = 13.2 Hz), 132.0, 131.9, 131.6, 128.3, 127.7, 120.3 (d, *J* = 2.4 Hz), 116.1, 73.4 (d, *J* = 5.6 Hz), 23.7 (dd, *J* = 17.9, 4.9 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: -0.18; HRMS (ESI) calcd. for C₁₉H₂₅BrN₂O₄P [M+H]⁺: 455.0730, found: 455.0731.

Diisopropyl (2-benzoyl-1-(3-chlorophenyl)hydrazinyl)phosphonate (3e). White solid; mp: 156-157 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.46 (s, 1H), 7.91-7.84 (m, 2H), 7.47 (t, *J* = 7.4 Hz, 1H), 7.39-7.31 (m, 3H), 7.24-7.15 (m, 2H), 7.03-6.98 (m, 1H), 4.89 (d, *J* = 5.7 Hz, 2H), 1.37 (d, *J* = 6.1 Hz, 6H), 1.25 (d, *J* = 6.0 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 144.5 (d, *J* = 13.4 Hz), 134.4, 131.9, 131.8, 129.7, 128.3, 127.7, 123.2, 118.5, 116.5, 73.5 (d, *J* = 5.7 Hz), 23.7 (dd, *J* = 17.9, 4.8 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: -0.59; HRMS (ESI) calcd. for C₁₉H₂₅ClN₂O₄P [M+H]⁺: 411.1235, found: 411.1242.

Diisopropyl (2-benzoyl-1-(2-chlorophenyl)hydrazinyl)phosphonate (3f). White solid; mp: 96-98 °C; ¹H NMR (400 MHz, CDCl₃) δ: 8.47 (s, 1H), 7.87 (d, *J* = 7.8 Hz, 1H), 7.78-7.74 (m, 2H), 7.52 (dd, *J* = 8.5, 6.3 Hz, 1H), 7.45-7.37 (m, 3H), 7.31 (dd, *J* = 7.6, 1.4 Hz, 1H), 7.21 (td, *J* = 7.7, 1.5 Hz, 1H), 4.84 (dq, *J* = 12.5, 6.2 Hz, 2H), 1.37 (d, *J* = 6.1 Hz, 6H), 1.27 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 166.3, 139.1 (d, *J* = 13.1 Hz), 132.6, 132.1, 132.0, 130.1, 128.7, 128.7, 127.4, 127.3, 73.0 (d, *J* = 5.8 Hz), 23.9 (d, *J* = 3.0 Hz), 23.6 (d, *J* = 6.8 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: 0.12; HRMS (ESI) calcd. for C₁₉H₂₅ClN₂O₄P [M+H]⁺: 411.1235, found: 411.1245.

Diisopropyl (2-benzoyl-1-(4-methoxyphenyl)hydrazinyl)phosphonate (3g). White solid; mp: 124-125 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.26 (s, 1H), 7.86-7.79 (m, 2H), 7.46 (t, *J* = 7.4 Hz, 1H), 7.35 (dd, *J* = 12.3, 5.4 Hz, 4H), 6.81 (d, *J* = 9.0 Hz, 2H), 4.88 (dq, *J* = 12.5, 6.2 Hz, 2H), 3.76 (s, 3H), 1.34 (d, *J* = 6.2 Hz, 6H), 1.24 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 156.7, 136.4 (d, *J* = 12.8 Hz), 132.4, 131.8, 128.3, 127.6, 123.1 (d, *J* = 2.2 Hz), 114.0, 72.9 (d, *J* = 5.7 Hz), 55.5, 23.8 (dd, *J* = 23.3, 5.0 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: 0.79; HRMS (ESI) calcd. for C₂₀H₂₈N₂O₅P [M+H]⁺: 407.1730, found: 407.1738.

Diisopropyl (2-benzoyl-1-(4-nitrophenyl)hydrazinyl)phosphonate (3h). Brown solid; mp: 125-128 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.19 (s, 1H), 8.16 (d, *J* = 9.2 Hz, 2H), 7.90-7.85 (m, 2H), 7.53 (dd, *J* = 10.5, 4.4 Hz, 1H), 7.43-7.35 (m, 4H), 4.91 (s, 2H), 1.40 (t, *J* = 5.8 Hz, 6H), 1.27 (d, *J* = 6.4 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.1, 148.9 (d, *J* = 13.0 Hz), 142.6, 132.5, 131.4, 128.6, 127.6, 124.9, 116.5, 74.2 (d, *J* = 4.8 Hz), 23.7 (dd, *J* = 20.7, 4.6 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: -1.44; HRMS (ESI) calcd. for C₁₉H₂₅N₃O₆P [M+H]⁺: 422.1475, found: 422.1487.

Diisopropyl (1-benzoyl-2-(4-nitrophenyl)hydrazinyl)phosphonate (3h'). White solid; mp: 121-123 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.72 (s, 1H), 8.19 (d, *J* = 9.3 Hz, 2H), 7.89-7.82 (m, 2H), 7.45-7.40 (m, 3H), 7.20-7.15 (m, 2H), 4.80 (dq, *J* = 12.5, 6.2 Hz, 2H), 1.38 (d, *J* = 6.2 Hz, 6H), 1.28 (d, *J* = 6.2 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 149.5, 140.5, 137.1 (d, *J* = 11.1 Hz), 131.0, 130.1, 128.5, 126.3, 126.1, 112.1, 75.3 (d, *J* = 6.3 Hz), 23.5 (dd, *J* = 19.9, 5.0 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: -7.59; HRMS (ESI) calcd. for C₁₉H₂₅N₃O₆P [M+H]⁺: 422.1475, found: 422.1484.

Diisopropyl (2-benzoyl-1-(3,5-dimethylphenyl)hydrazinyl)phosphonate (3i). White solid; mp: 161-162 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.04 (s, 1H), 7.89 (d, *J* = 7.2 Hz, 2H), 7.49 (t, *J* = 7.3 Hz, 1H), 7.39 (t, *J* = 7.4 Hz, 2H), 6.97 (s, 2H), 6.68 (s, 1H), 4.88 (dd, *J* = 12.5, 6.1 Hz, 2H), 2.26 (s, 6H), 1.35 (d, *J* = 6.1 Hz, 6H), 1.24 (d, *J* = 6.1 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.0, 143.0 (d, *J* = 12.5 Hz), 138.2, 132.4, 131.8, 130.0, 128.3, 127.7, 125.4, 117.0, 73.0 (d, *J* = 5.5 Hz), 23.8 (d, *J* = 3.5 Hz), 23.6 (d, *J* = 6.2 Hz), 21.5; ³¹P NMR (162 MHz, CDCl₃) δ: -0.41; HRMS (ESI) calcd. for C₂₁H₃₀N₂O₄P [M+H]⁺: 405.1938, found: 405.1942.

Diisopropyl (2-benzoyl-1-(6-chloropyridin-2-yl)hydrazinyl)phosphonate (3j). White solid; mp: 120-122 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.34 (s, 1H), 7.93-7.88 (m, 2H), 7.56-7.48 (m, 2H), 7.44-7.36 (m, 2H), 7.15 (d, *J* = 8.2 Hz, 1H), 6.93 (t, *J* = 7.2 Hz, 1H), 5.05-4.94 (m, 2H), 1.36 (d, *J* = 6.1 Hz, 6H), 1.28 (d, *J* = 5.7 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 167.1, 155.5, 155.4, 148.6, 140.2, 132.0, 128.4, 127.8, 117.7, 108.9, 74.0, 24.4-23.4 (m); ³¹P NMR (162 MHz, CDCl₃) δ: -2.63; HRMS (ESI) calcd. for C₁₈H₂₄ClN₃O₄P [M+H]⁺: 412.1187, found: 412.1202.

Diisopropyl (2-(4-methoxybenzoyl)-1-phenylhydrazinyl)phosphonate (3l). White solid; mp: 181-182 °C; ¹H NMR (400 MHz, CDCl₃) δ: 9.26 (s, 1H), 7.86 (d, *J* = 8.8 Hz, 2H), 7.33 (d, *J* = 7.9 Hz, 2H), 7.29-7.22 (m, 2H), 7.02 (t, *J* = 7.3 Hz, 1H), 6.84 (d, *J* = 8.8 Hz, 2H), 4.90 (d, *J* = 6.0 Hz, 2H), 3.83 (s, 3H), 1.34 (d, *J* = 6.1 Hz, 6H), 1.22 (d, *J* = 6.0 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 166.6, 162.4, 143.2 (d, *J* = 13.0 Hz), 129.6, 128.7, 124.5, 123.2, 118.7 (d, *J* = 2.3 Hz), 113.5, 73.0 (d, *J* = 5.5 Hz), 55.4, 23.8 (d, *J* = 3.7 Hz), 23.6 (d, *J* = 6.1 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: 0.14; HRMS (ESI) calcd. for C₂₀H₂₈N₂O₅P [M+H]⁺: 407.1730, found: 407.1735.

Diisopropyl (2-(4-hydroxybenzoyl)-1-phenylhydrazinyl)phosphonate (3m). White solid; mp: 180-182 °C; ¹H NMR (400 MHz, DMSO-*d*₆) δ: 10.64 (s, 1H), 10.16 (s, 1H), 7.82 (d, *J* = 8.6 Hz, 2H), 7.28 (t, *J* = 7.8 Hz, 2H), 7.19 (d, *J* = 8.1 Hz, 2H), 6.97 (t, *J* = 7.2 Hz, 1H), 6.87 (d, *J* = 8.6 Hz, 2H), 4.95 (d, *J* = 5.3 Hz, 1H), 4.69 (d, *J* = 5.7 Hz, 1H), 1.24-1.29 (m, 6H), 1.16-1.07 (m, 6H); ¹³C NMR (100 MHz, DMSO-*d*₆) δ: 166.4, 161.3, 144.0 (d, *J* = 13.9 Hz), 130.1, 128.9, 123.5, 122.4, 117.3, 115.4, 71.9, 71.7, 23.9 (d, *J* = 32.7 Hz), 23.4-23.3 (m); ³¹P NMR (162 MHz, DMSO-*d*₆) δ: -0.97; HRMS (ESI) calcd. for C₁₉H₂₆N₂O₅P [M+H]⁺: 393.1574, found: 393.1597.

Diisopropyl (2-(4-bromobenzoyl)-1-phenylhydrazinyl)phosphonate (3n). White solid; mp: 176-177 °C; ¹H NMR (400 MHz, CDCl₃) δ: 10.21 (s, 1H), 7.76 (d, *J* = 8.4 Hz, 2H), 7.41 (d, *J* = 8.3 Hz, 2H), 7.31 (d, *J* = 8.2 Hz, 2H), 7.29-7.22 (m, 2H), 7.02 (t, *J* = 7.1 Hz, 1H), 4.90 (s, 2H), 1.34 (d, *J* = 5.8 Hz, 6H), 1.22 (d, *J* = 5.4 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 166.0, 143.0 (d, *J* = 12.7 Hz), 131.3, 130.7, 129.4, 128.7, 126.6, 123.5, 118.8 (d, *J* = 2.2 Hz), 73.3 (d, *J* = 5.7 Hz), 23.7 (dd, *J* = 20.1, 4.9 Hz); ³¹P NMR (162 MHz, CDCl₃) δ: 0.29; HRMS (ESI) calcd. for C₁₉H₂₅BrN₂O₄P [M+H]⁺: 455.0730, found: 455.0745.

Diisopropyl (2-(4-aminobenzoyl)-1-phenylhydrazinyl)phosphonate (3o). White solid; mp: 125-126 °C; ¹H NMR (400 MHz, DMSO-*d*₆) δ: 10.39 (s, 1H), 7.67 (d, *J* = 8.6 Hz, 2H), 7.26 (t, *J* = 7.9 Hz, 2H), 7.18 (d, *J* = 8.0 Hz, 2H), 6.96 (t, *J* = 7.2 Hz, 1H), 6.59 (d, *J* = 8.6 Hz, 2H), 5.76 (s, 2H), 4.94 (s, 1H), 4.69 (s, 1H), 1.27 (d, *J* = 6.0 Hz, 6H), 1.11 (d, *J* = 7.4 Hz, 6H); ¹³C NMR (100 MHz, DMSO-*d*₆) δ: 166.5, 152.9, 144.2 (d, *J* = 14.4 Hz), 129.8, 128.9, 122.3, 119.2, 117.3, 113.0, 71.9, 71.6, 24.2, 23.8; ³¹P NMR (162 MHz, DMSO-*d*₆) δ: -0.51; HRMS (ESI) calcd. for C₁₉H₂₇N₃O₄P [M+H]⁺: 392.1734, found: 392.1732.

Diisopropyl (2-(4-nitrobenzoyl)-1-phenylhydrazinyl)phosphonate (3p). Yellow solid; mp: 169-170 °C; ¹H NMR (400 MHz, CDCl₃) δ: 10.70 (s, 1H), 8.10-8.03 (m, 4H), 7.34-7.24 (m, 4H), 7.05 (t, *J* = 7.1 Hz, 1H), 4.91 (d, *J* = 5.5 Hz, 2H), 1.36 (d, *J* = 5.9 Hz, 6H), 1.24 (d, *J* = 5.7 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ: 164.8, 149.6, 142.7 (d, *J* = 12.4 Hz), 137.3, 129.0, 128.8, 123.8, 123.2, 118.9 (d, *J* = 2.1 Hz), 73.6 (d, *J* = 5.9 Hz), 23.7 (m); ³¹P NMR (162 MHz, CDCl₃) δ: 0.11; HRMS (ESI) calcd. for C₁₉H₂₅N₃O₆P [M+H]⁺: 422.1475, found: 422.1479.

Diisopropyl (2-(3-nitrobenzoyl)-1-phenylhydrazinyl)phosphonate (3q). Yellow solid; ¹H NMR

(400 MHz, CDCl₃) δ : 10.98 (s, 1H), 8.72 (s, 1H), 8.25 (d, $J = 7.7$ Hz, 1H), 8.20 (d, $J = 8.1$ Hz, 1H), 7.42 (t, $J = 8.0$ Hz, 1H), 7.32 (d, $J = 8.2$ Hz, 2H), 7.29-7.22 (m, 2H), 7.03 (t, $J = 7.2$ Hz, 1H), 4.94 (s, 2H), 1.37 (t, $J = 7.7$ Hz, 6H), 1.25 (d, $J = 16.9$ Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ : 164.7, 148.1, 142.4 (d, $J = 12.5$ Hz), 133.6, 133.5, 129.5, 128.9, 126.5, 124.1, 122.8, 119.1, 119.1, 74.1 (d, $J = 5.9$ Hz), 23.8 (d, $J = 3.7$ Hz), 23.5 (d, $J = 5.9$ Hz); ³¹P NMR (162 MHz, CDCl₃) δ : -0.10; HRMS (ESI) calcd. for C₁₉H₂₄N₃O₆PNa [M+Na]⁺: 444.1295, found: 444.1282.

Diisopropyl (2-(2-bromobenzoyl)-1-phenylhydrazinyl)phosphonate (3r). White solid; mp: 96-98 °C; ¹H NMR (400 MHz, CDCl₃) δ : 7.91 (s, 1H), 7.69 (d, $J = 7.2$ Hz, 1H), 7.64 (d, $J = 7.8$ Hz, 1H), 7.41 (dd, $J = 14.9, 7.8$ Hz, 3H), 7.33 (dd, $J = 12.7, 7.0$ Hz, 3H), 7.08 (t, $J = 7.3$ Hz, 1H), 4.89 (dd, $J = 12.1, 6.0$ Hz, 2H), 1.39 (t, $J = 7.0$ Hz, 6H), 1.25 (d, $J = 6.1$ Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ : 167.4, 142.6 (d, $J = 11.9$ Hz), 135.7, 133.4, 131.8, 130.0, 128.8, 127.5, 123.5, 119.9, 118.7, 73.1 (d, $J = 5.0$ Hz), 23.9 (d, $J = 3.1$ Hz), 23.6 (d, $J = 5.8$ Hz); ³¹P NMR (162 MHz, CDCl₃) δ : -0.44; HRMS (ESI) calcd. for C₁₉H₂₅BrN₂O₄P [M+H]⁺: 455.0730, found: 455.0742.

Diisopropyl (2-acetyl-1-phenylhydrazinyl)phosphonate (3s). White solid; mp: 123-125 °C; ¹H NMR (400 MHz, CDCl₃) δ : 8.94 (s, 0.80H), 7.80 (s, 0.20H), 7.33 (dt, $J = 15.8, 8.1$ Hz, 1H), 7.28-7.23 (m, 4H), 7.12 (t, $J = 6.8$ Hz, 0.23H), 7.02 (m, 0.81H), 4.83 (s, 1.54H), 4.71 (m, 0.46H), 2.09 (s, 2.35H), 2.05 (s, 0.65H), 1.34 (dd, $J = 10.5, 6.2$ Hz, 6H), 1.26 (d, $J = 6.1$ Hz, 1.18H), 1.18 (d, $J = 6.1$ Hz, 4.86H); ¹³C NMR (100 MHz, CDCl₃) δ : 170.2, 142.8 (d, $J = 12.7$ Hz), 129.0, 128.7, 124.5, 123.2, 120.0, 118.2, 73.1, 23.8, 23.5 (d, $J = 6.2$ Hz), 20.9; ³¹P NMR (162 MHz, CDCl₃) δ : 0.43; HRMS (ESI) calcd. for C₁₄H₂₃N₂O₄PNa [M+Na]⁺: 337.1288, found: 337.1272.

tert-Butyl 2-(diisopropoxyphosphoryl)-2-phenylhydrazinecarboxylate (3t). White solid; mp: 105-107 °C; ¹H NMR (400 MHz, CDCl₃) δ : 7.33-7.24 (m, 4H), 7.03 (t, $J = 6.5$ Hz, 1H), 6.77 (s, 1H), 4.87-4.71 (m, 2H), 1.47 (d, $J = 16.8$ Hz, 9H), 1.37 (d, $J = 6.2$ Hz, 6H), 1.21 (d, $J = 6.1$ Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ : 155.5, 143.6, 128.7, 123.3, 118.5, 81.3, 72.6, 28.2, 23.5-23.8 (m), 23.5; ³¹P NMR (162 MHz, MeOD) δ : -0.13; HRMS (ESI) calcd. for C₁₇H₂₉N₂O₅PNa [M+Na]⁺: 395.1706, found: 395.1722.

tert-Butyl 2-(diisopropoxyphosphoryl)-2-(4-fluorophenyl)hydrazinecarboxylate (3u). White solid; mp: 81-83 °C; ¹H NMR (400 MHz, CDCl₃) δ : 7.33-7.24 (m, 2H), 6.97 (t, $J = 8.6$ Hz, 2H), 6.67 (s, 1H), 4.78 (s, 2H), 1.48 (s, 9H), 1.36 (d, $J = 6.1$ Hz, 6H), 1.23 (d, $J = 6.0$ Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ : 155.4, 139.5, 121.2, 115.5, 115.3, 81.5, 72.5, 28.2, 23.8 (d, $J = 3.5$ Hz), 23.6 (d, $J = 5.1$ Hz); ³¹P NMR (162 MHz, MeOD) δ : -0.44; HRMS (ESI) calcd. for C₁₇H₂₈FN₂O₅PNa [M+Na]⁺: 413.1612, found: 413.1625.

tert-Butyl 2-(4-chlorophenyl)-2-(diisopropoxyphosphoryl)hydrazinecarboxylate (3v). White solid; mp: 75-76 °C; ¹H NMR (400 MHz, CDCl₃) δ : 7.26 (s, 1H), 7.24 (s, 3H), 6.63 (s, 1H), 4.79 (s, 2H), 1.49 (s, 9H), 1.37 (d, $J = 6.2$ Hz, 6H), 1.23 (d, $J = 6.2$ Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ : 155.3, 128.7, 119.4, 100.0, 81.3, 73.0, 28.2, 23.6-23.8 (m); ³¹P NMR (162 MHz, MeOD) δ : -1.60; HRMS (ESI) calcd. for C₁₇H₂₈ClN₂O₅PNa [M+Na]⁺: 429.1317, found: 429.1325.

tert-Butyl 2-(4-bromophenyl)-2-(diisopropoxyphosphoryl)hydrazinecarboxylate (3w). Brown solid; ¹H NMR (400 MHz, CDCl₃) δ : 7.38 (d, $J = 8.9$ Hz, 2H), 7.20 (t, $J = 5.9$ Hz, 2H), 6.61 (s, 1H), 4.78 (s, 2H), 1.49 (s, 9H), 1.37 (d, $J = 6.2$ Hz, 6H), 1.23 (d, $J = 6.1$ Hz, 6H); ¹³C NMR (100 MHz, DMSO-*d*₆) δ : 143.4, 131.0, 122.2, 115.7, 113.6, 73.0 (d, $J = 5.4$ Hz), 70.3 (d, $J = 4.9$ Hz),

26.5, 21.9 (d, $J = 17.7$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : -1.59; HRMS (ESI) calcd. for $\text{C}_{17}\text{H}_{28}\text{BrN}_2\text{O}_5\text{PNa}$ $[\text{M}+\text{Na}]^+$: 473.0811, found: 473.0835.

tert-Butyl 2-(diisopropoxyphosphoryl)-2-(3,5-dimethylphenyl)hydrazinecarboxylate (3x). White solid; mp: 91-94 °C; ^1H NMR (400 MHz, CDCl_3) δ : 6.93 (s, 2H), 6.69 (s, 1H), 6.59 (s, 1H), 4.79 (s, 2H), 2.28 (s, 6H), 1.49 (s, 9H), 1.37 (d, $J = 6.1$ Hz, 6H), 1.24 (t, $J = 6.4$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ : 155.4, 143.3 (d, $J = 13.0$ Hz), 138.3, 125.2, 116.5, 81.3, 72.6, 28.2, 23.9, 23.7 (dd, $J = 25.5, 4.9$ Hz), 21.5; ^{31}P NMR (162 MHz, MeOD) δ : -0.55; HRMS (ESI) calcd. for $\text{C}_{19}\text{H}_{33}\text{N}_2\text{O}_5\text{PNa}$ $[\text{M}+\text{Na}]^+$: 423.2019, found: 423.2030.

Diethyl (2-benzoyl-1-phenylhydrazinyl)phosphonate (3y). White solid; mp: 140-141 °C; ^1H NMR (400 MHz, CDCl_3) δ : 9.81 (s, 1H), 7.89-7.81 (m, 2H), 7.44 (t, $J = 7.4$ Hz, 1H), 7.36 (d, $J = 7.9$ Hz, 2H), 7.31 (dd, $J = 12.4, 4.8$ Hz, 2H), 7.26 (t, $J = 4.1$ Hz, 2H), 7.05 (t, $J = 7.3$ Hz, 1H), 4.31-4.20 (m, 4H), 1.26 (t, $J = 6.9$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ : 166.9, 142.9 (d, $J = 12.9$ Hz), 132.0, 131.9, 128.9, 128.3, 127.6, 123.8, 119.2 (d, $J = 2.1$ Hz), 64.1 (d, $J = 5.4$ Hz), 16.0 (d, $J = 7.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 2.43; HRMS (ESI) calcd. for $\text{C}_{17}\text{H}_{21}\text{N}_2\text{O}_4\text{PNa}$ $[\text{M}+\text{Na}]^+$: 371.1131, found: 371.1144.

Diisopropyl (1-phenylhydrazinyl)phosphonate (4). Brown oil; ^1H NMR (400 MHz, CDCl_3) δ : 7.48 (d, $J = 8.1$ Hz, 2H), 7.32-7.24 (m, 2H), 7.02 (t, $J = 7.3$ Hz, 1H), 4.68 (dq, $J = 12.5, 6.2$ Hz, 2H), 4.56-4.17 (m, 2H), 1.37 (d, $J = 6.0$ Hz, 6H), 1.24 (d, $J = 6.1$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ : 145.1 (d, $J = 13.2$ Hz), 128.6, 122.7, 119.3 (d, $J = 2.5$ Hz), 72.1 (d, $J = 5.7$ Hz), 23.7 (dd, $J = 24.8, 4.8$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : -2.68; HRMS (ESI) calcd. for $\text{C}_{12}\text{H}_{22}\text{N}_2\text{O}_3\text{P}$ $[\text{M}+\text{H}]^+$: 273.1363, found: 273.1368.

4. X-ray structure of 3t

The single crystal of **3t** was prepared from hexane.

Identification code	zjq-150203-4	
Empirical formula	C ₁₇ H ₂₉ N ₂ O ₅ P	
Formula weight	372.40	
Temperature	100 K	
Wavelength	1.54184 Å	
Crystal system	Triclinic	
Space group	P -1	
Unit cell dimensions	a = 9.7307 (6) Å	α = 68.269 (5)°.
	b = 10.8147 (5) Å	β = 72.364 (6)°.
	c = 11.1682 (8) Å	γ = 69.847 (5)°.
Volume	1003.97 (11) Å ³	
Z	2	
μ	1.453 mm ⁻¹	
F(000)	401.9	
Crystal size	0.2×0.05×0.05 mm ³	
Theta range for data collection	8.7 to 143.2°	
Index ranges	-10 ≤ h ≤ 11, -8 ≤ k ≤ 13, -13 ≤ l ≤ 13	
Reflections collected	7674	
Independent reflections	3778 [R _{int} = 0.0223, R _{sigma} = 0.0262]	
Data / restraints / parameters	3778 / 0 / 232	
Goodness-of-fit on F ²	1.052	
Final R indices [I > 2sigma (I)]	R ₁ = 0.0326, wR ₂ = 0.0819	
R indices (all data)	R ₁ = 0.0365, wR ₂ = 0.0854	
Largest diff. peak and hole	0.39 and -0.41 e.Å ⁻³	

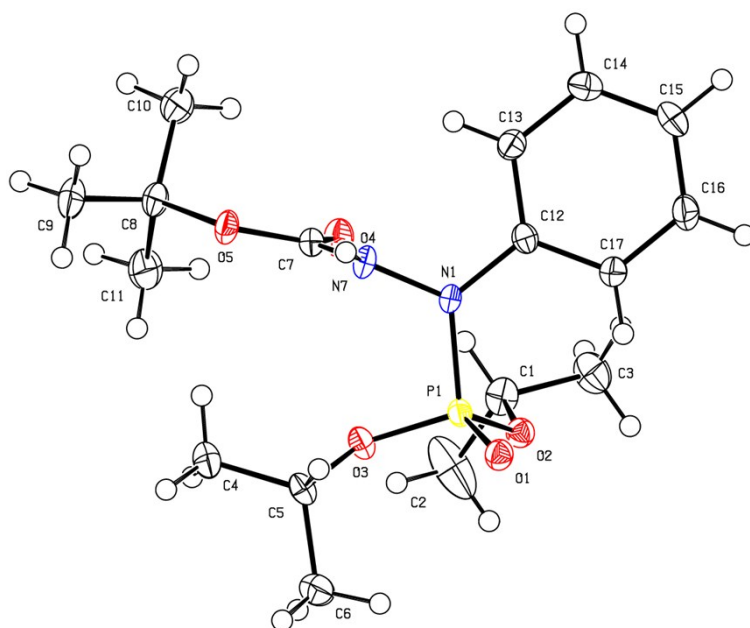


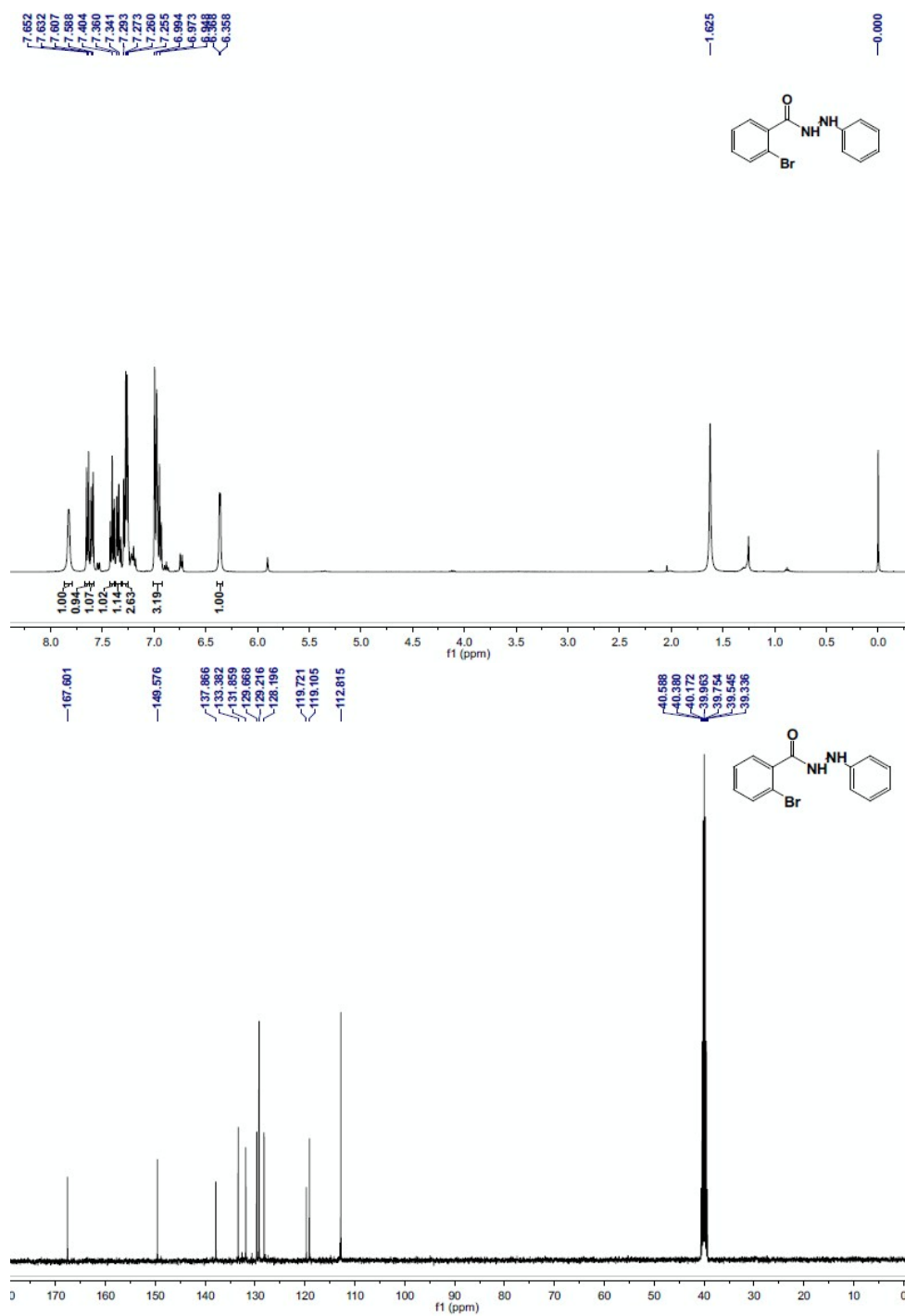
Figure 1. X-ray crystal structure of **3t**.

5. References

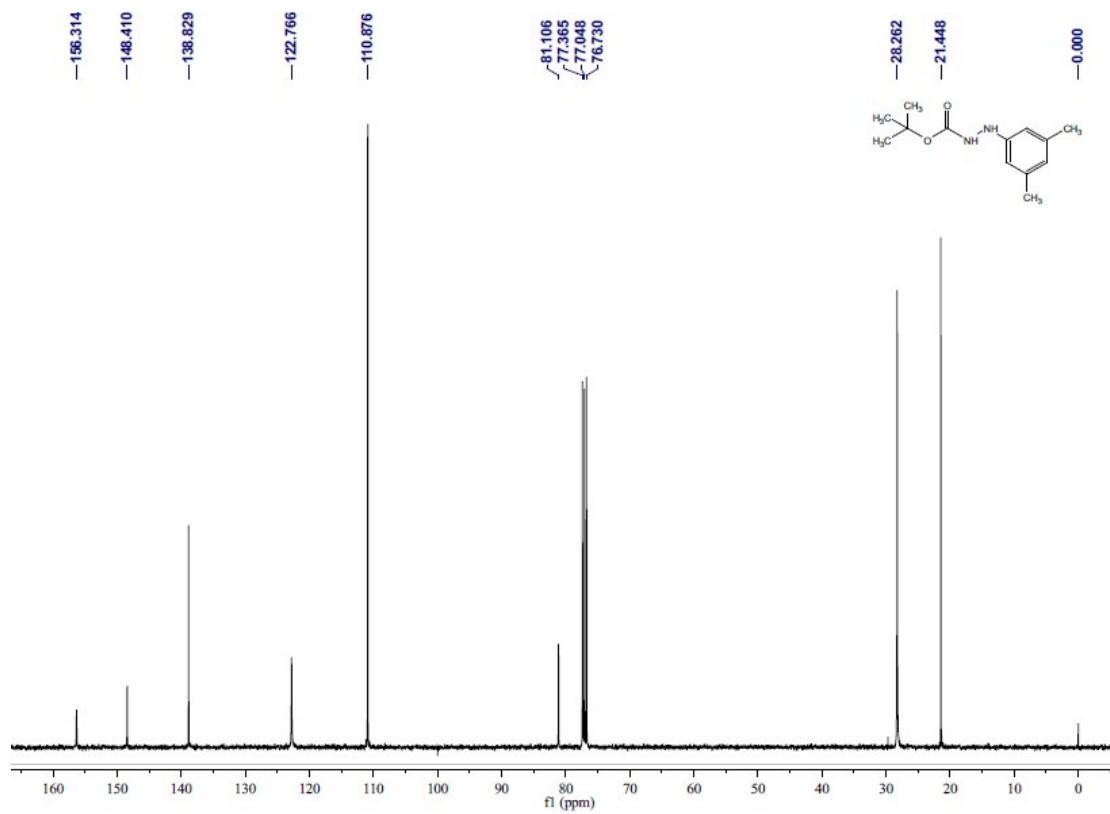
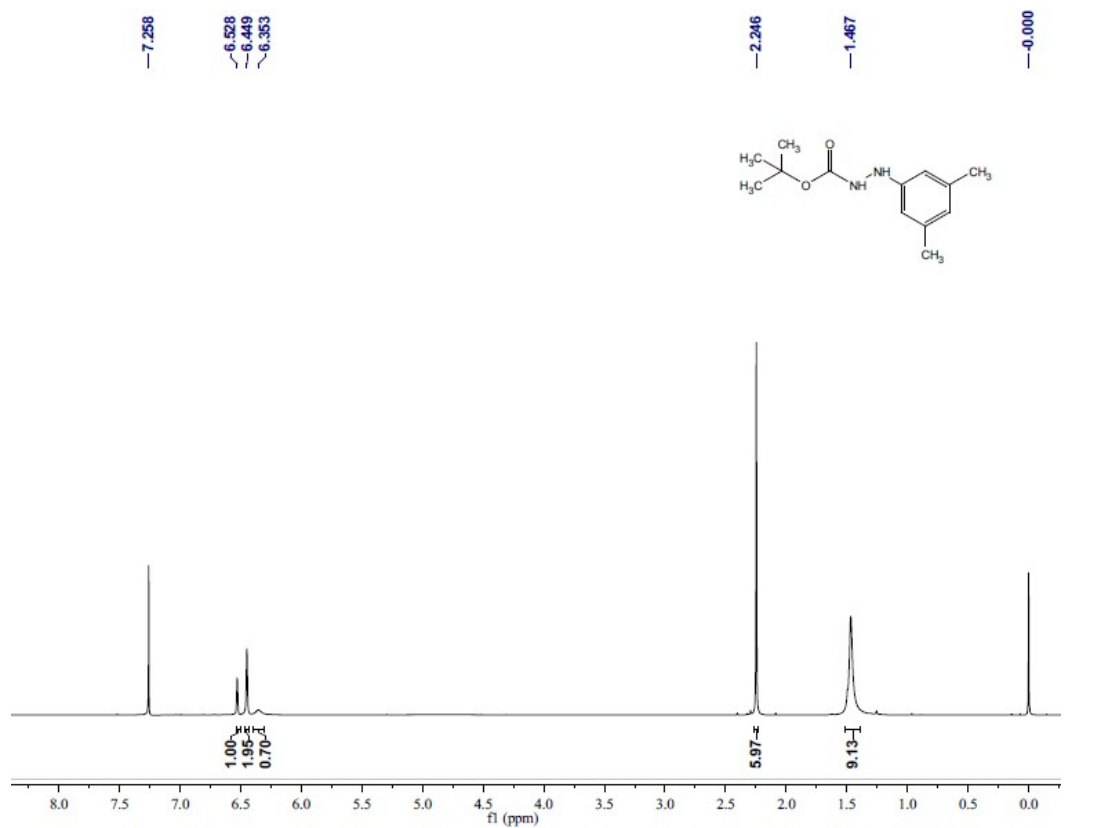
1. J.-Q. Zhang, G.-B. Huang, J. Weng, G. Lu and A. S. C. Chan, *Org. Biomol. Chem.*, 2015, **13**, 2055-2063.
2. (a) L. A. Carpino, P. H. Terry and P. J. Crowley, *J. Org. Chem.*, 1961, **26**, 4336-4340. (b) H. Jasch, S. B. Hoefling and M. R. Heinrich, *J. Org. Chem.*, 2012, **77**, 1520-1532.
3. S. Han, Y. Shin, S. Sharma, N. K. Mishra, J. Park, M. Kim, M. Kim, J. Jang and I. S. Kim, *Org. Lett.*, 2014, **16**, 2494-2497.

6. ^1H , ^{13}C and ^{31}P NMR spectra

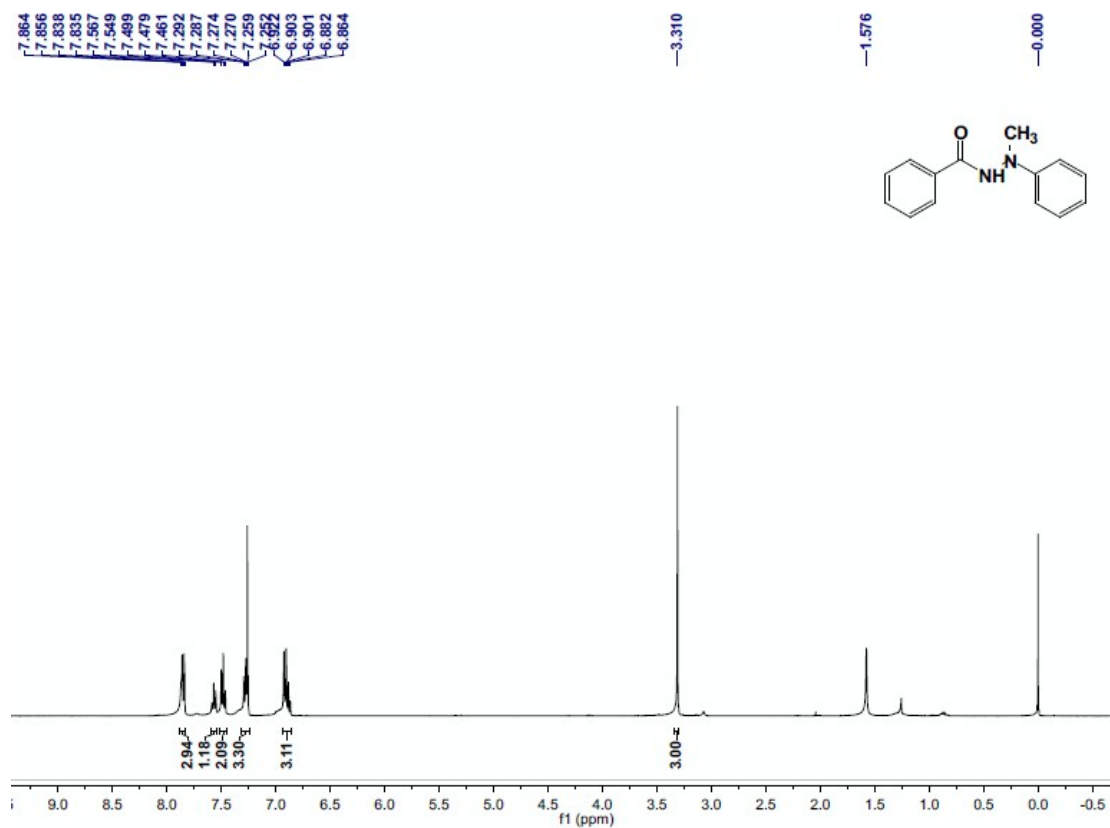
2-Bromo- N' -phenylbenzohydrazide (**1r**)



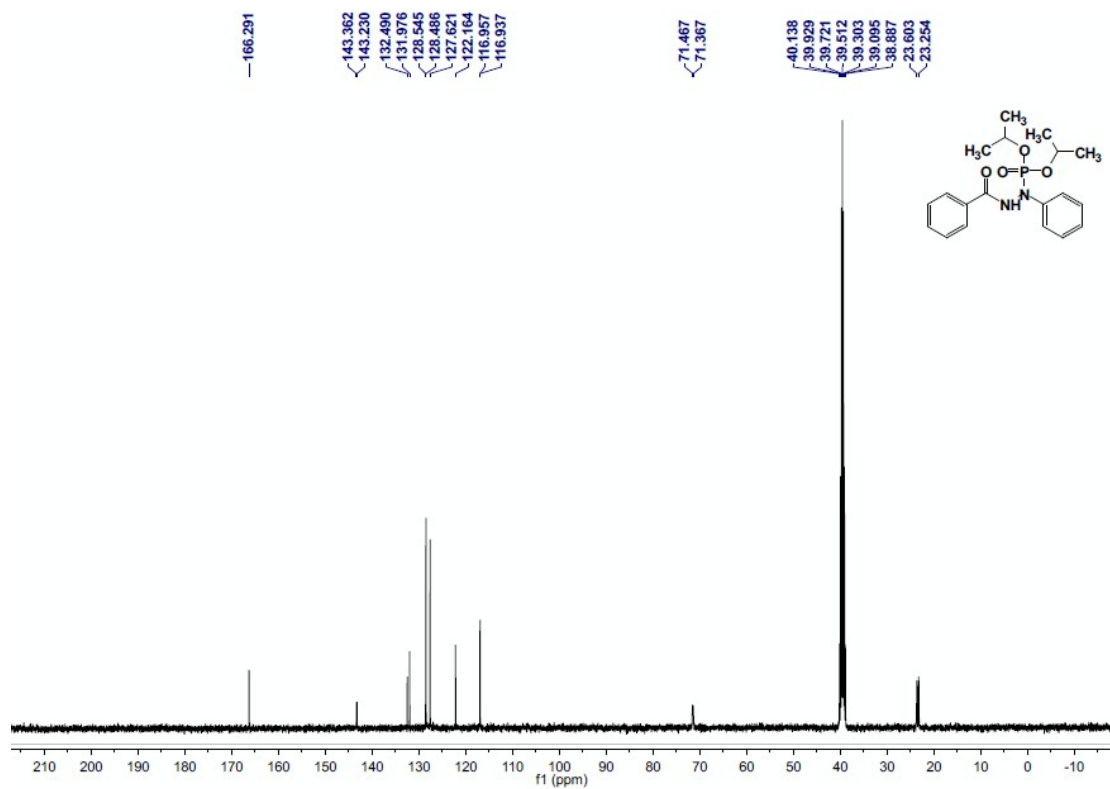
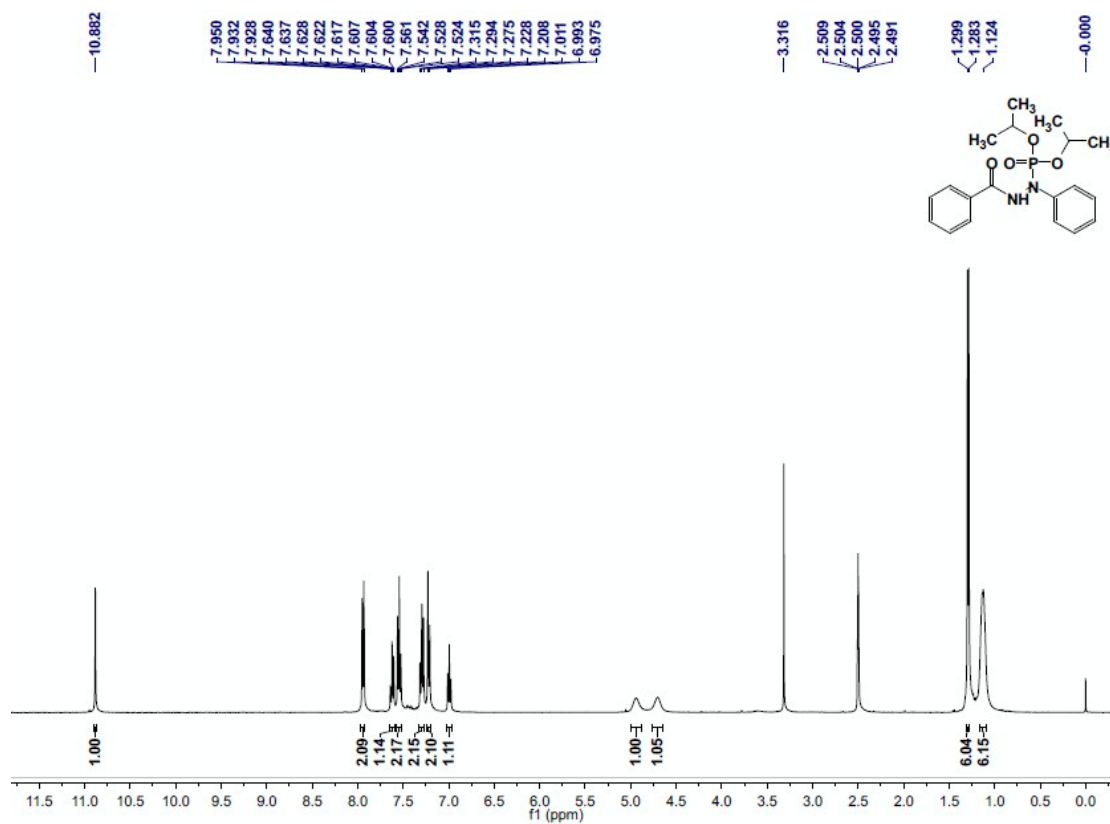
tert-Butyl 2-(3,5-dimethylphenyl)hydrazinecarboxylate (**1x**)

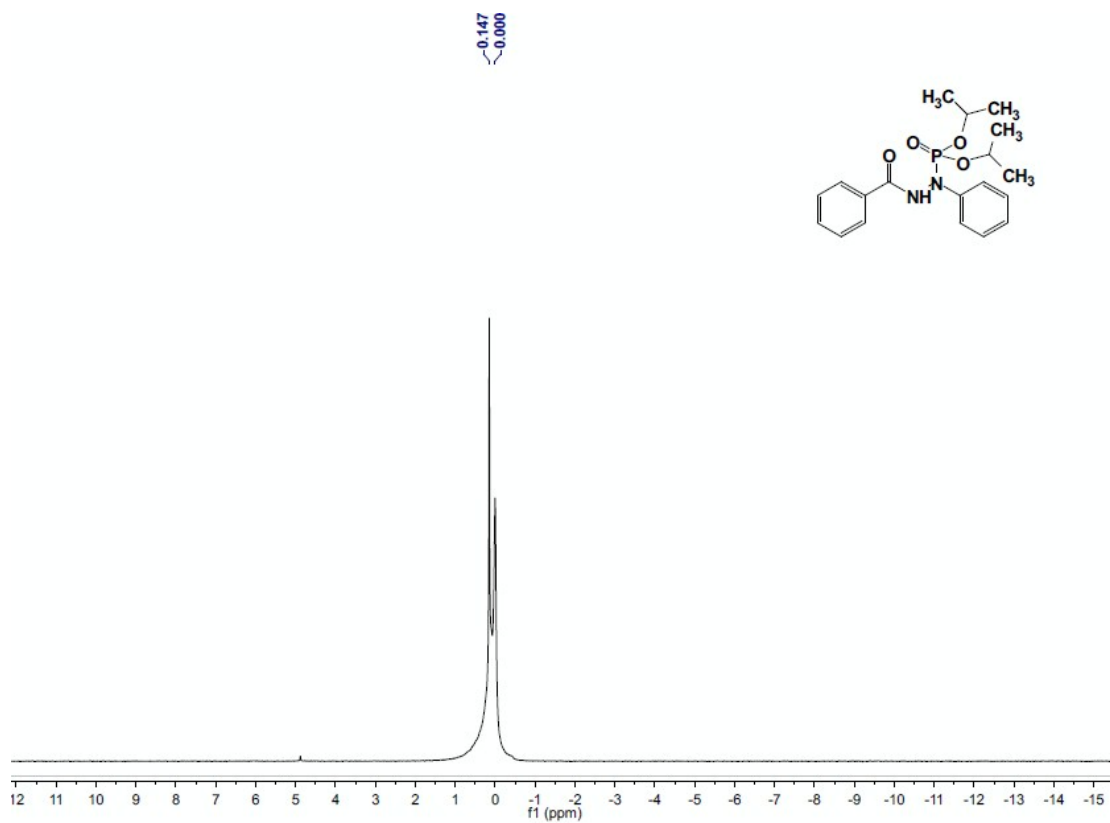


N'-Methyl-*N'*-phenylbenzohydrazide (**1y**)

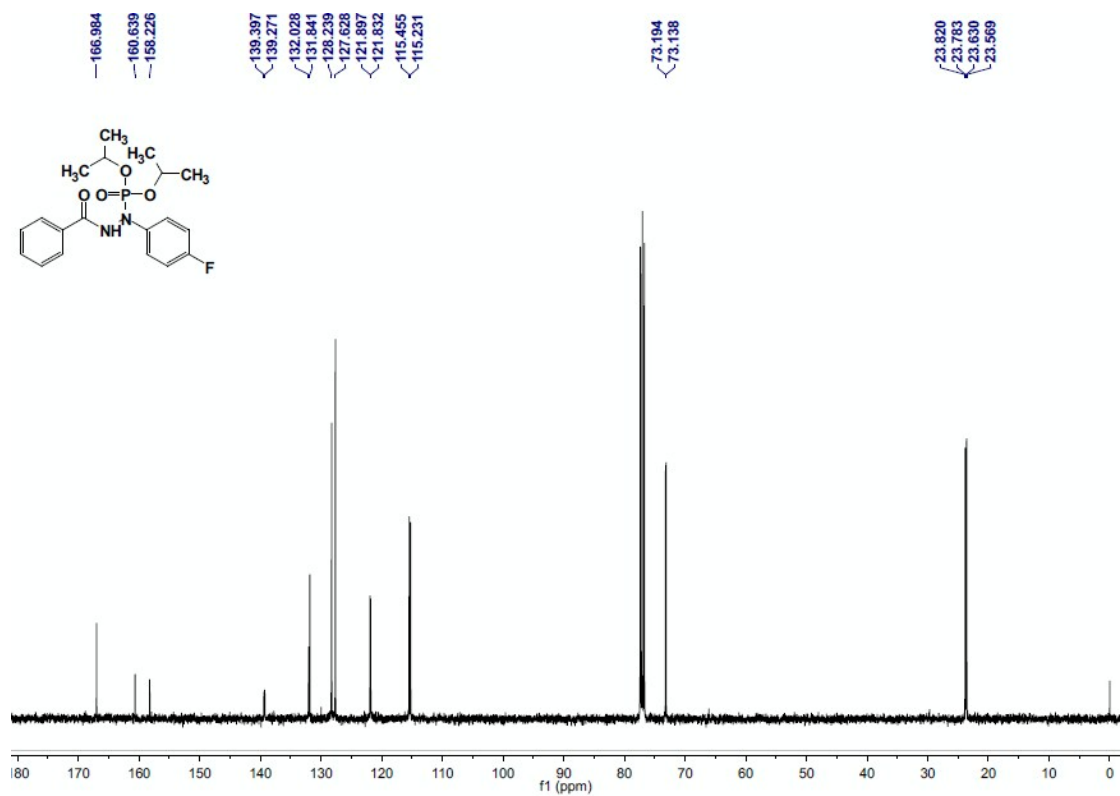
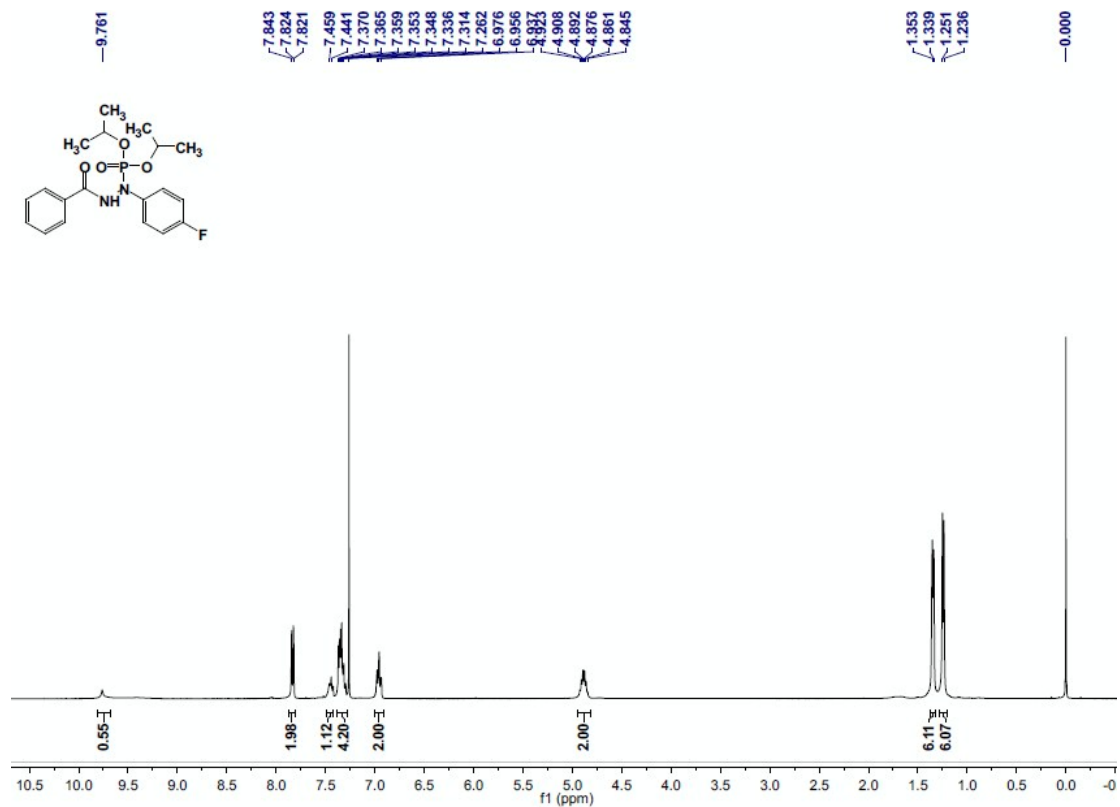


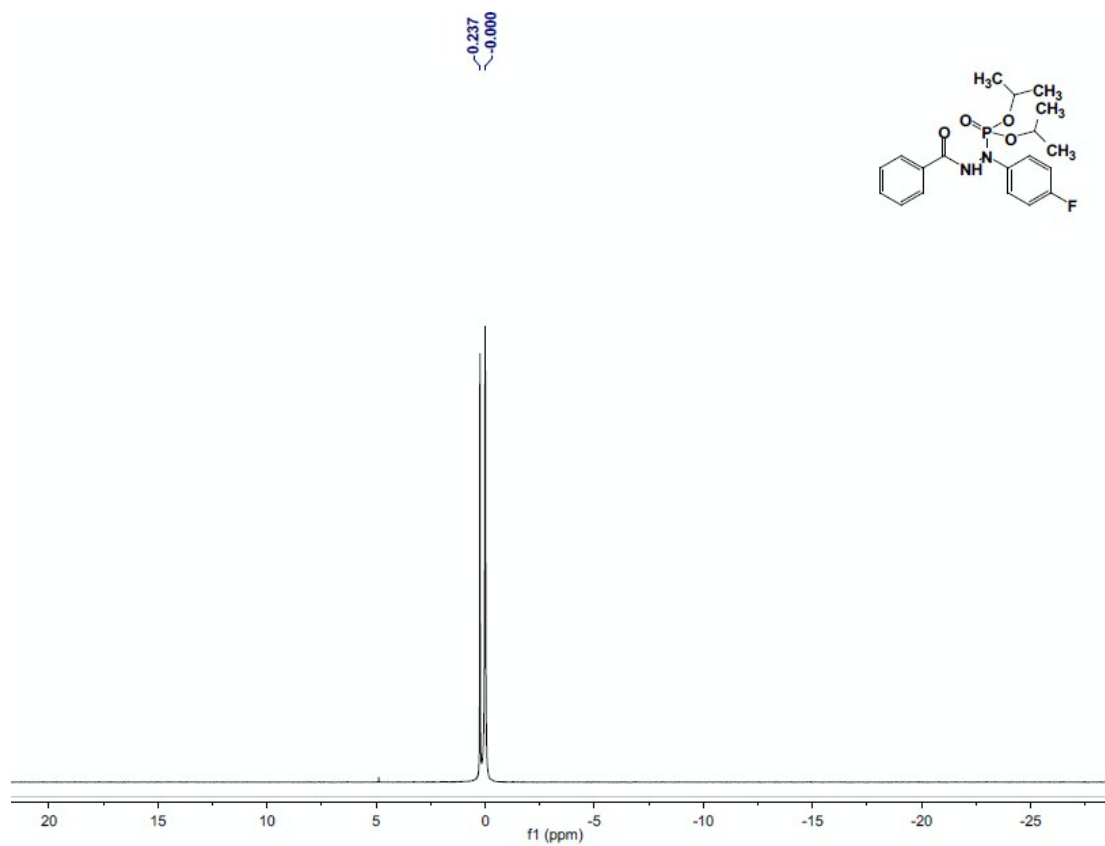
Diisopropyl (2-benzoyl-1-phenylhydrazinyl)phosphonate (3a)



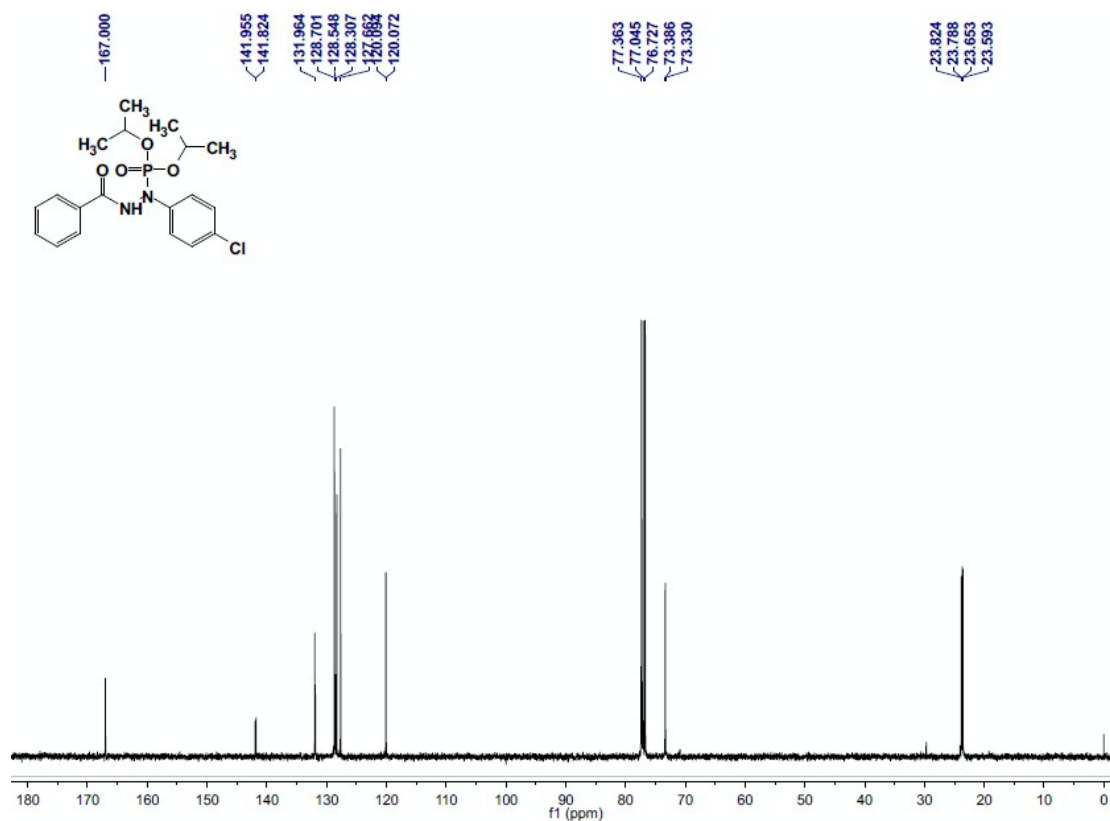
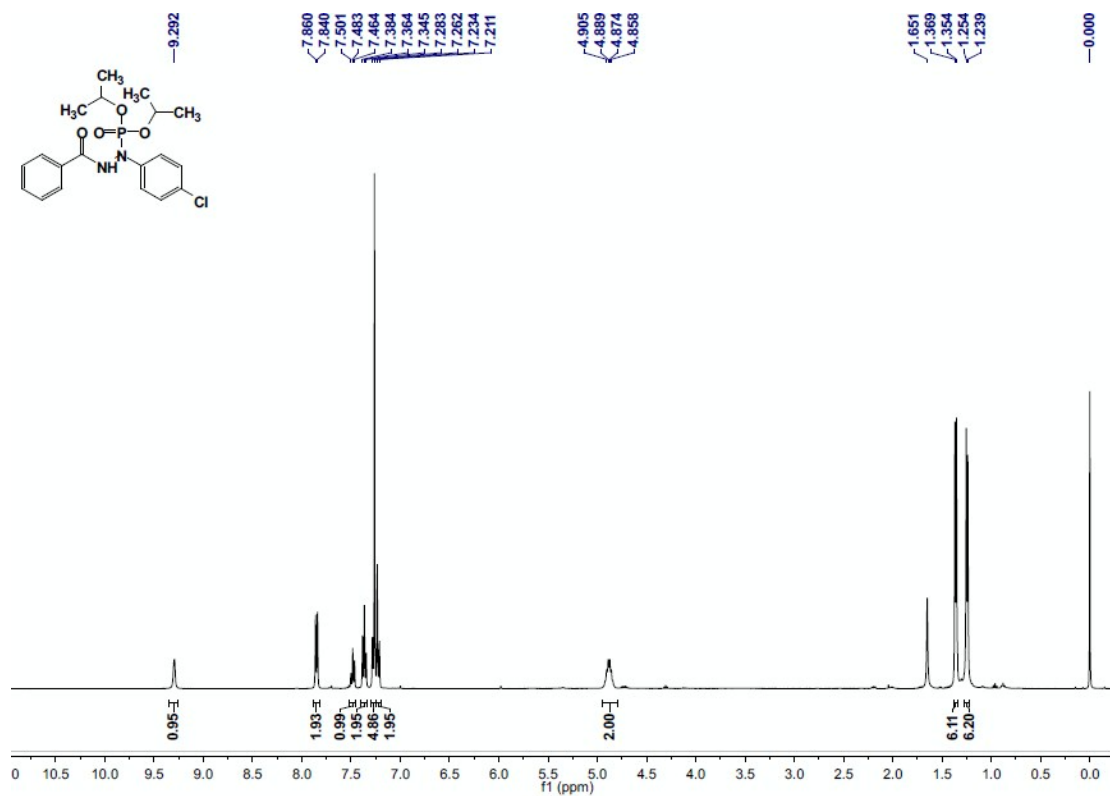


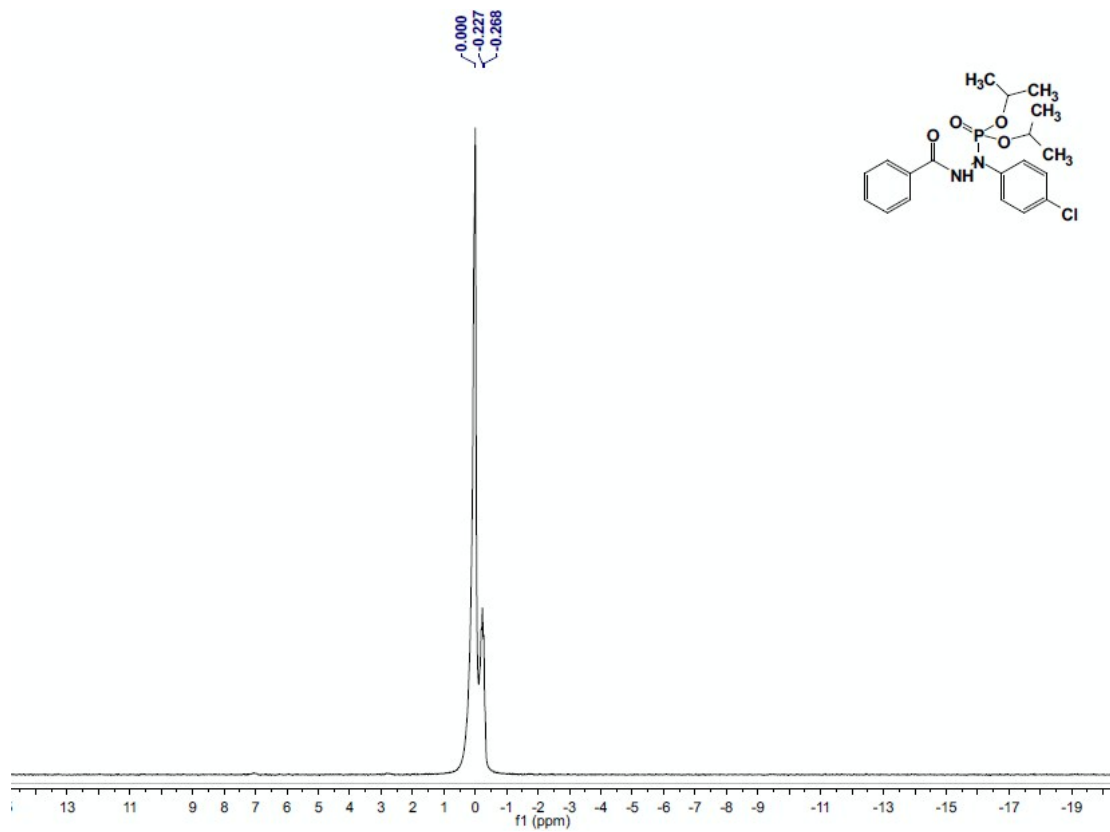
Diisopropyl (2-benzoyl-1-(4-fluorophenyl)hydrazinyl)phosphonate (3b)



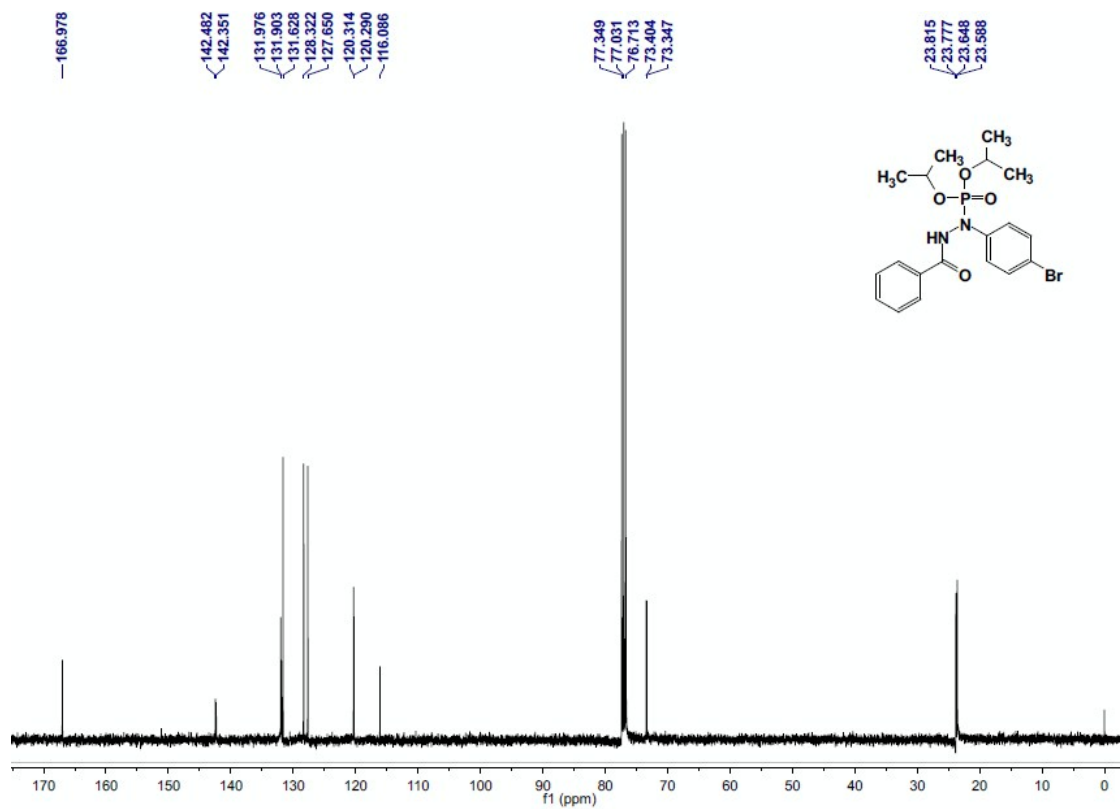
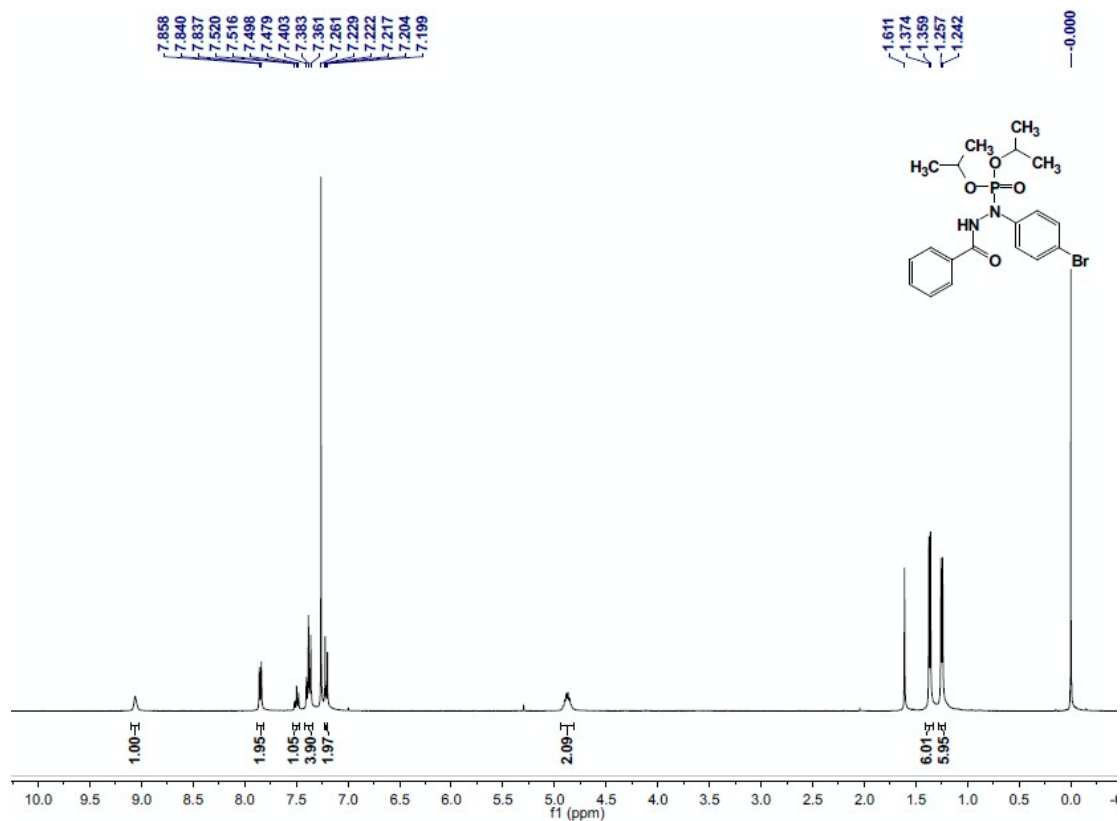


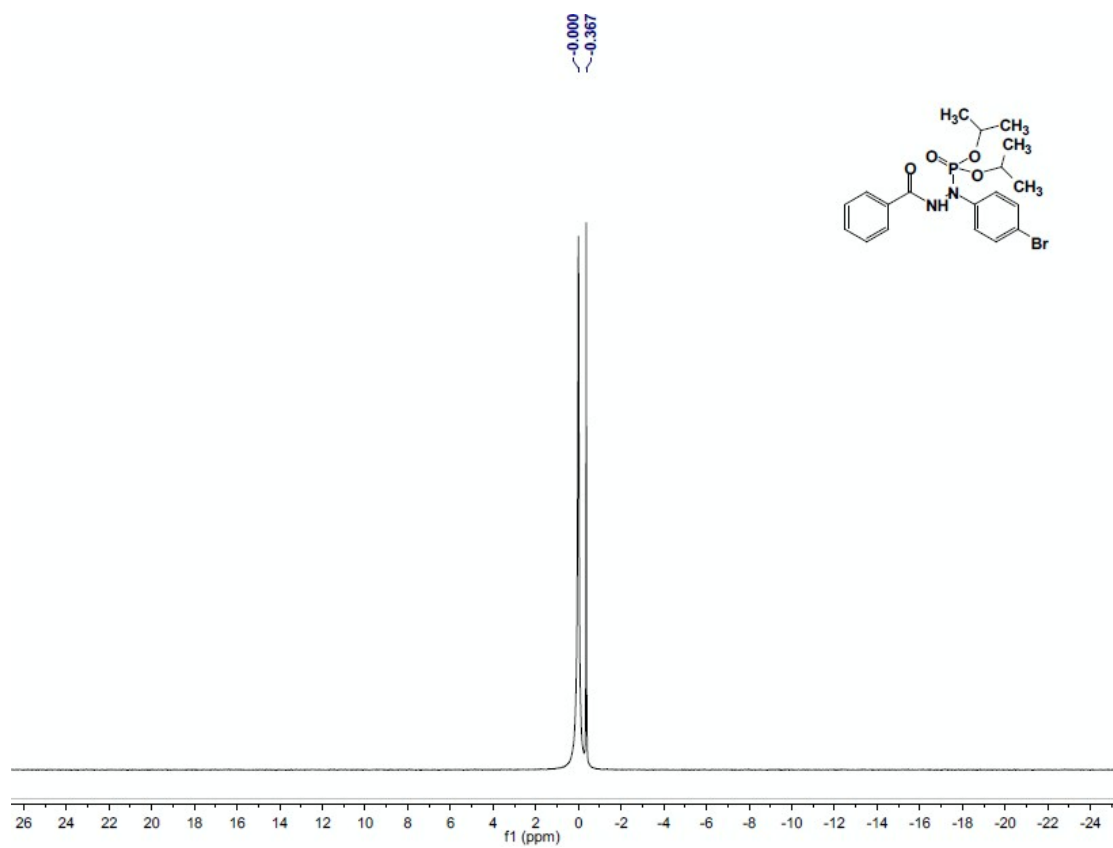
Diisopropyl (2-benzoyl-1-(4-chlorophenyl)hydrazinyl)phosphonate (3c)



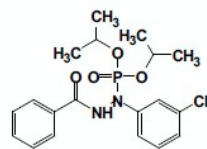
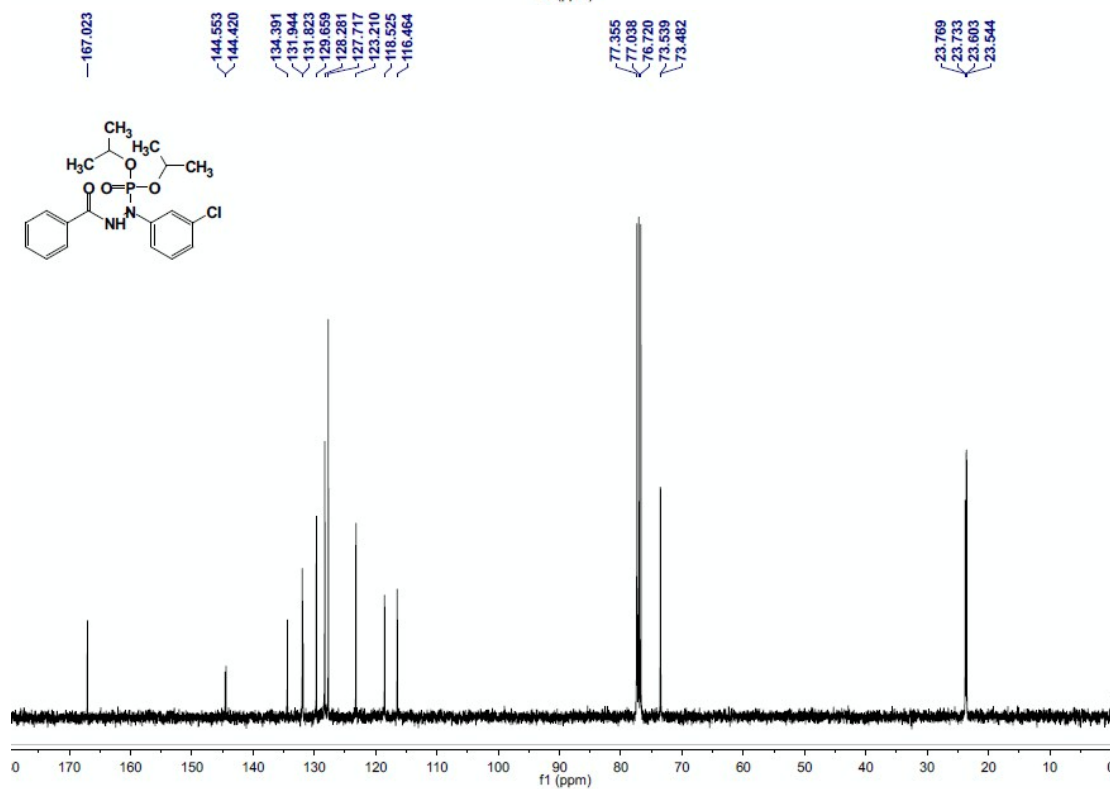
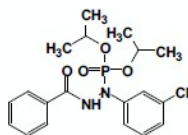
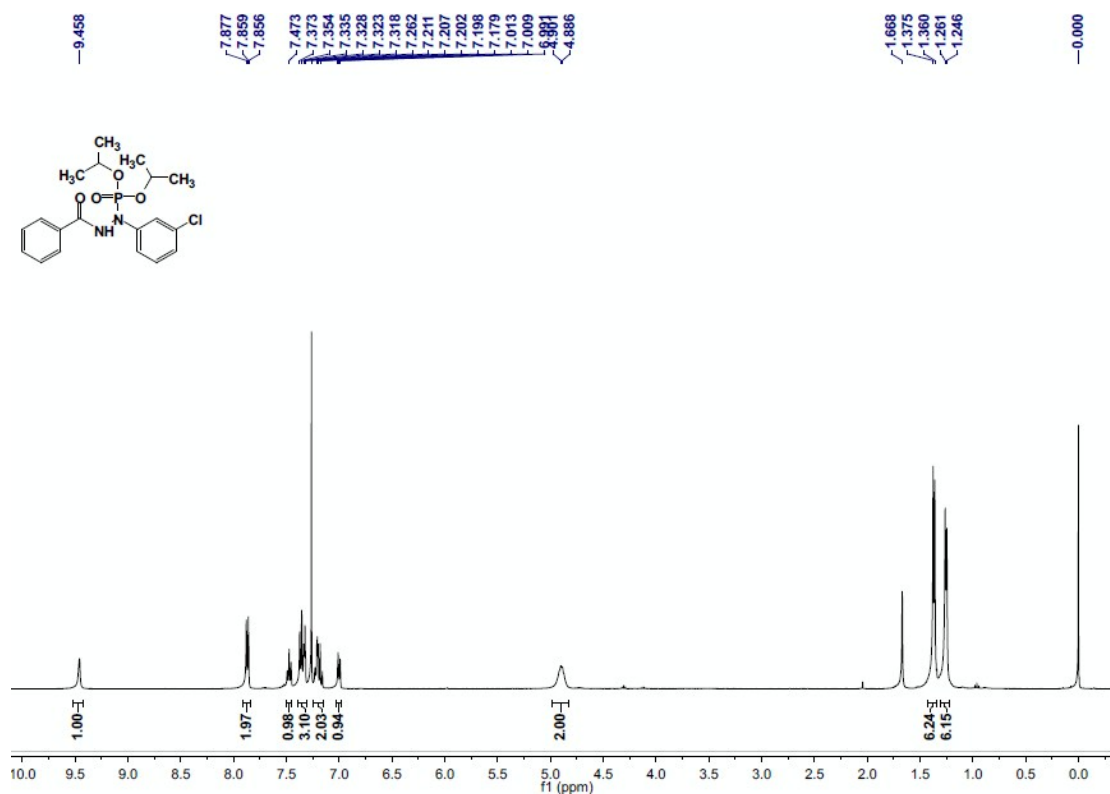


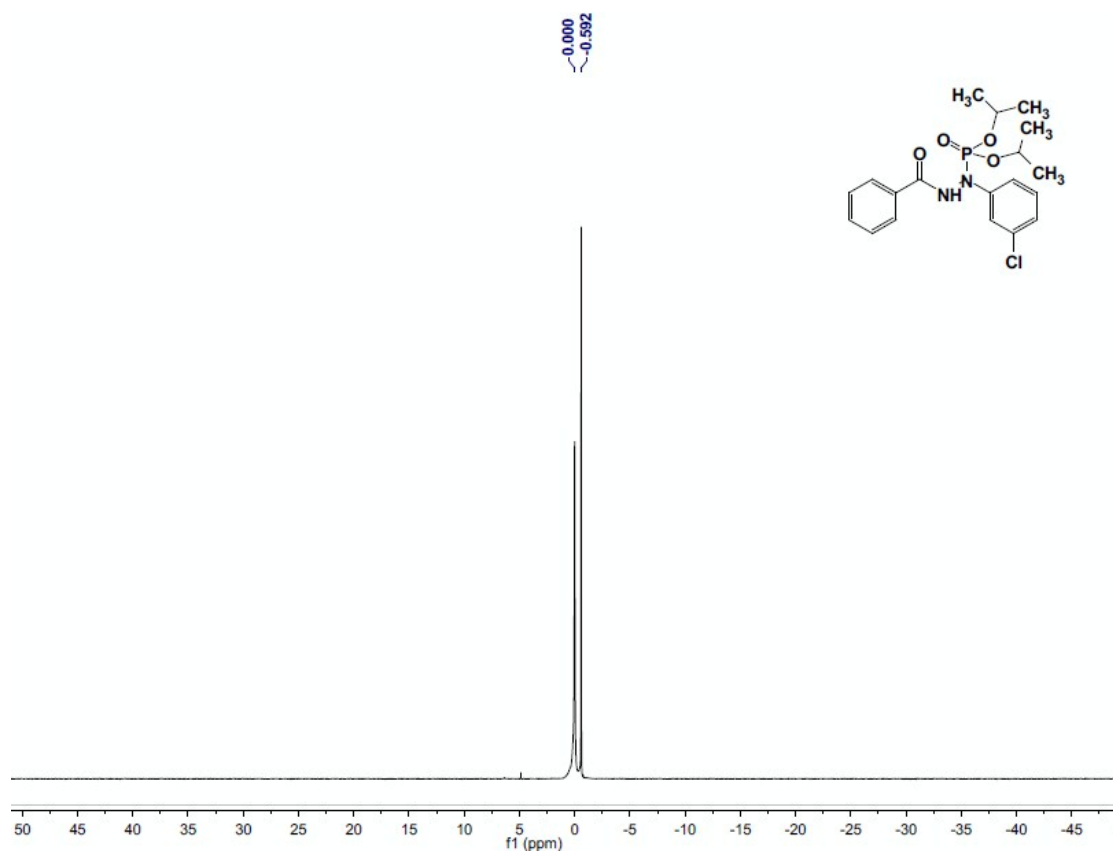
Diisopropyl (2-benzoyl-1-(4-bromophenyl)hydrazinyl)phosphonate (3d)



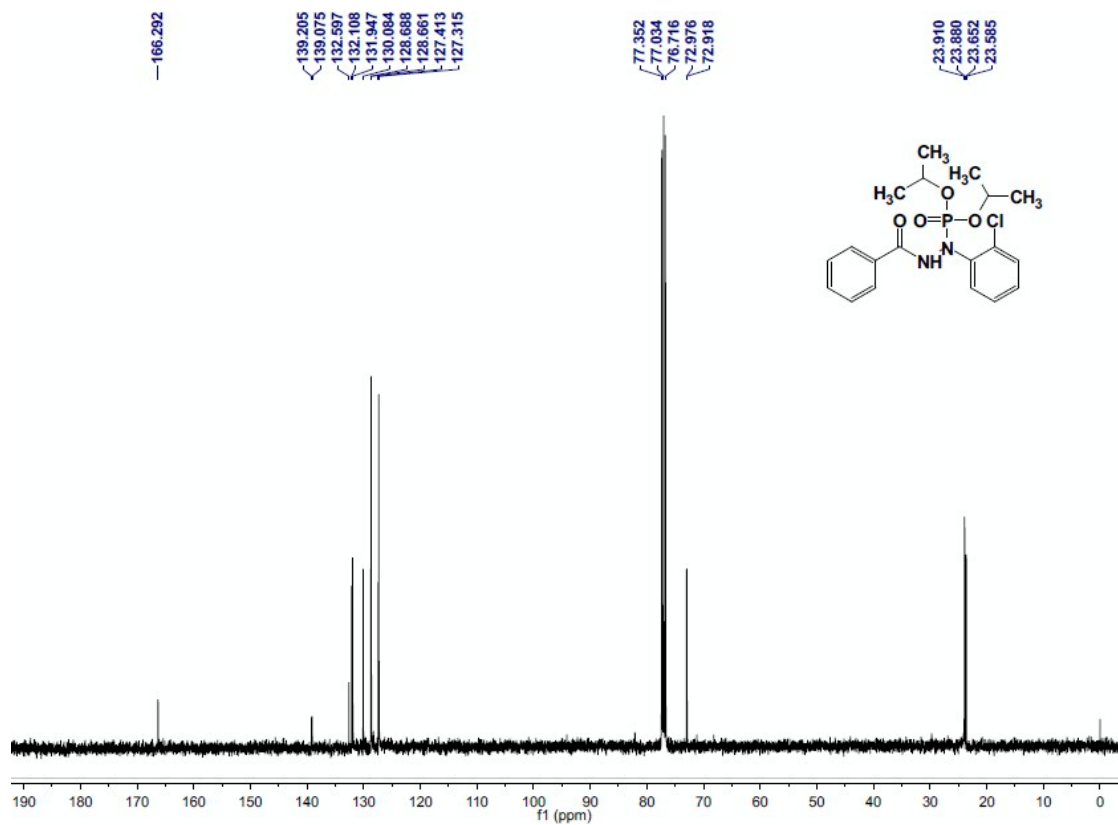
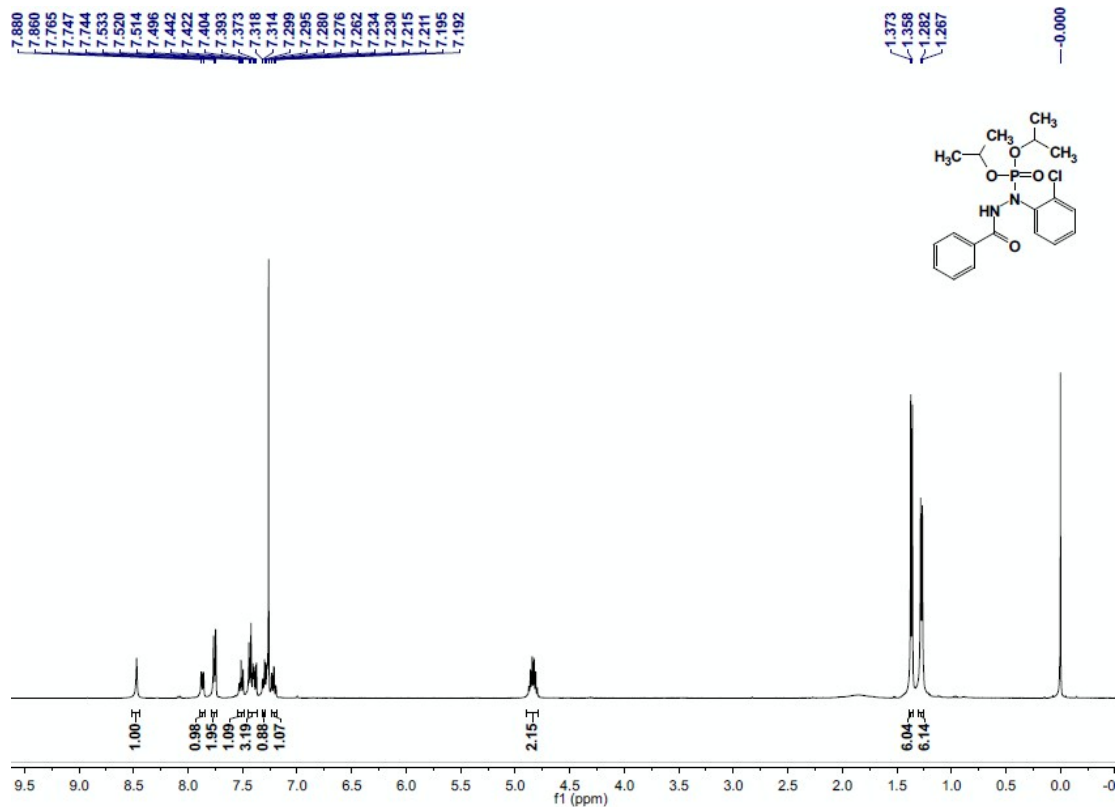


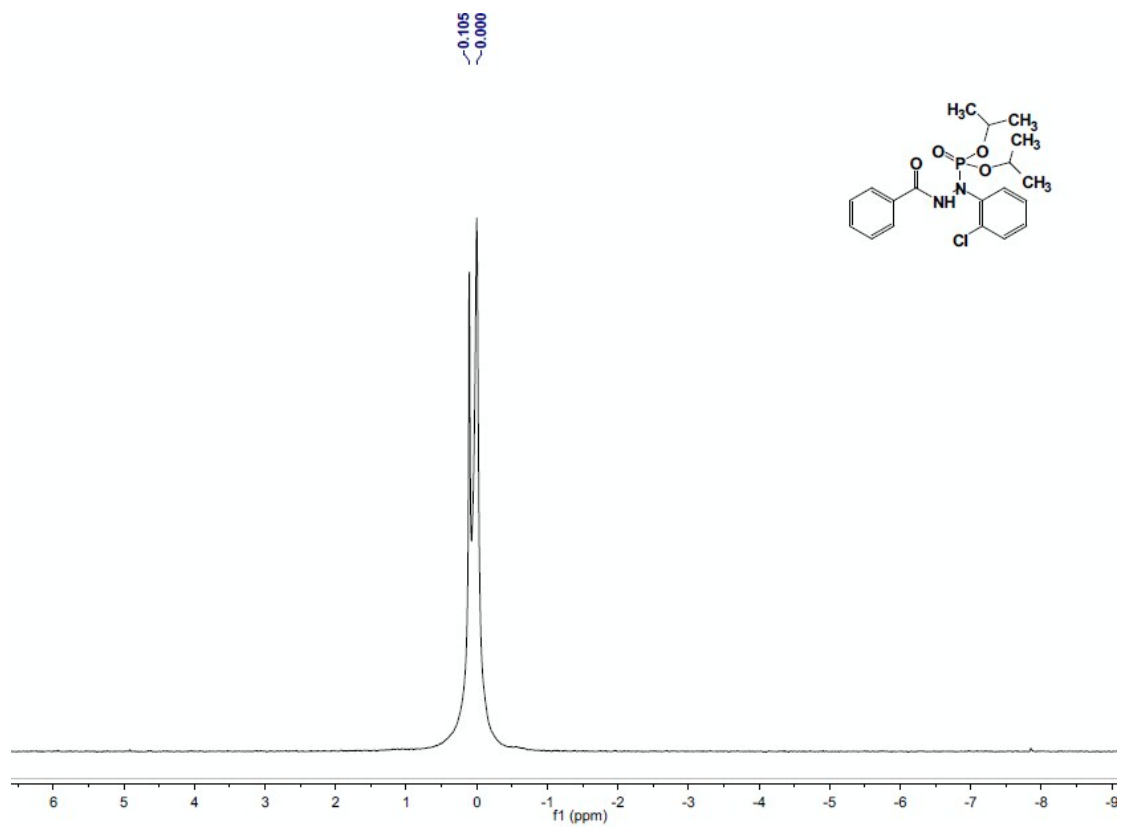
Diisopropyl (2-benzoyl-1-(3-chlorophenyl)hydrazinyl)phosphonate (3e)



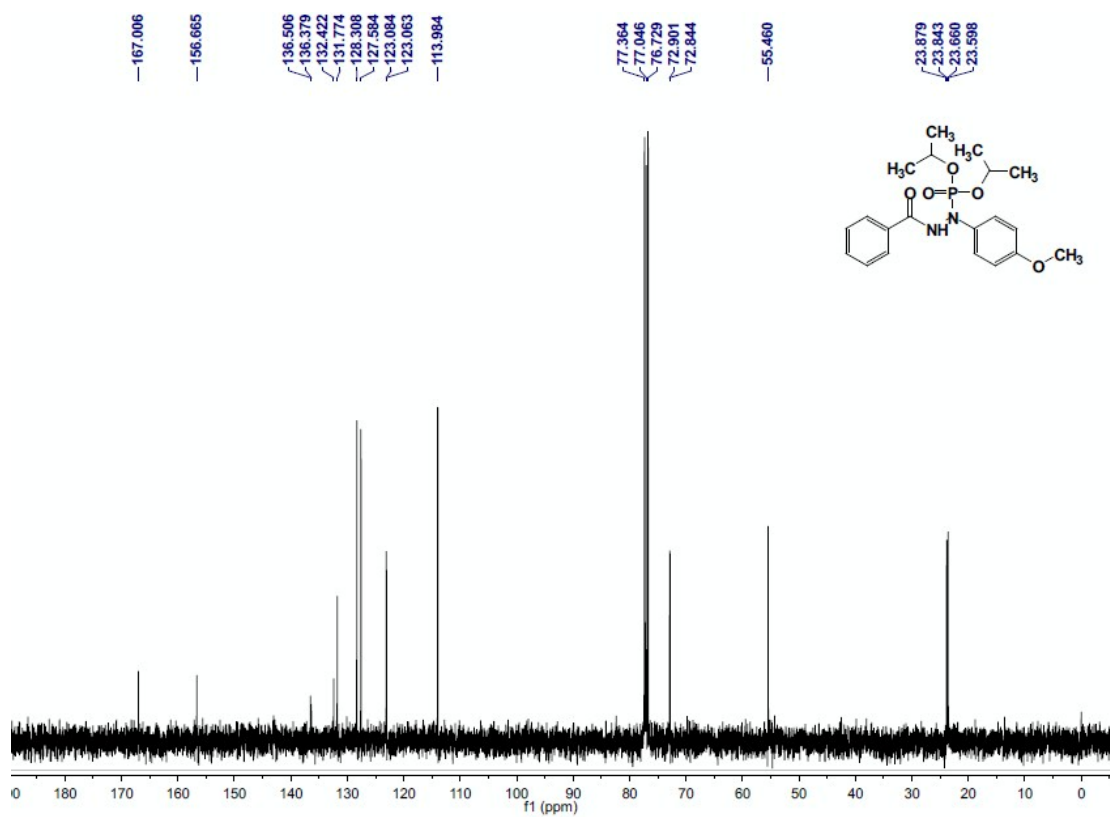
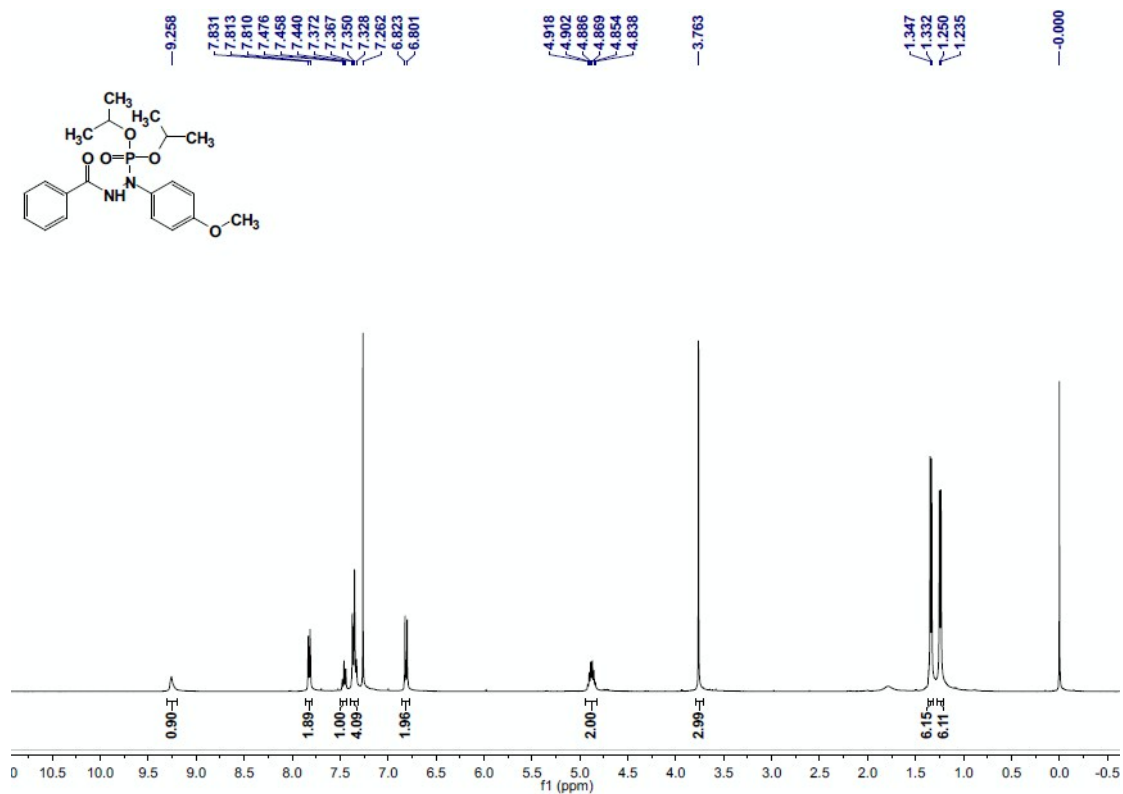


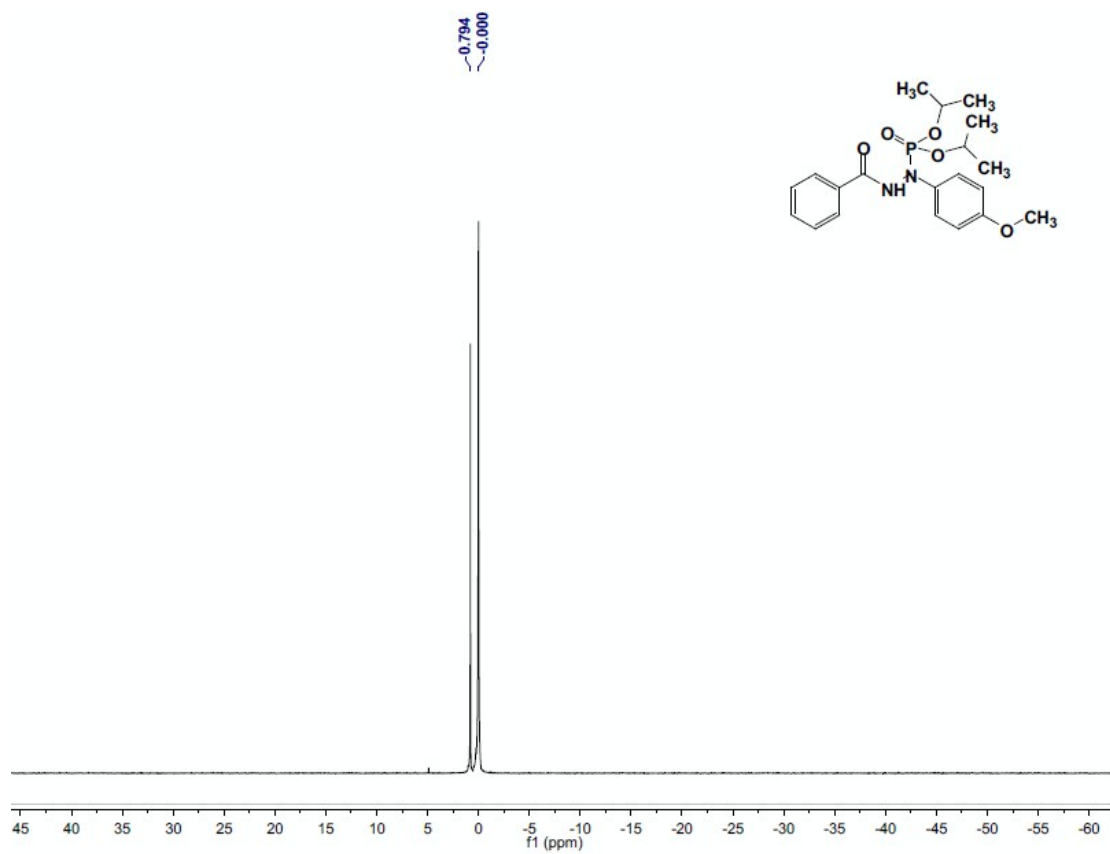
Diisopropyl (2-benzoyl-1-(2-chlorophenyl)hydrazinyl)phosphonate (3f)



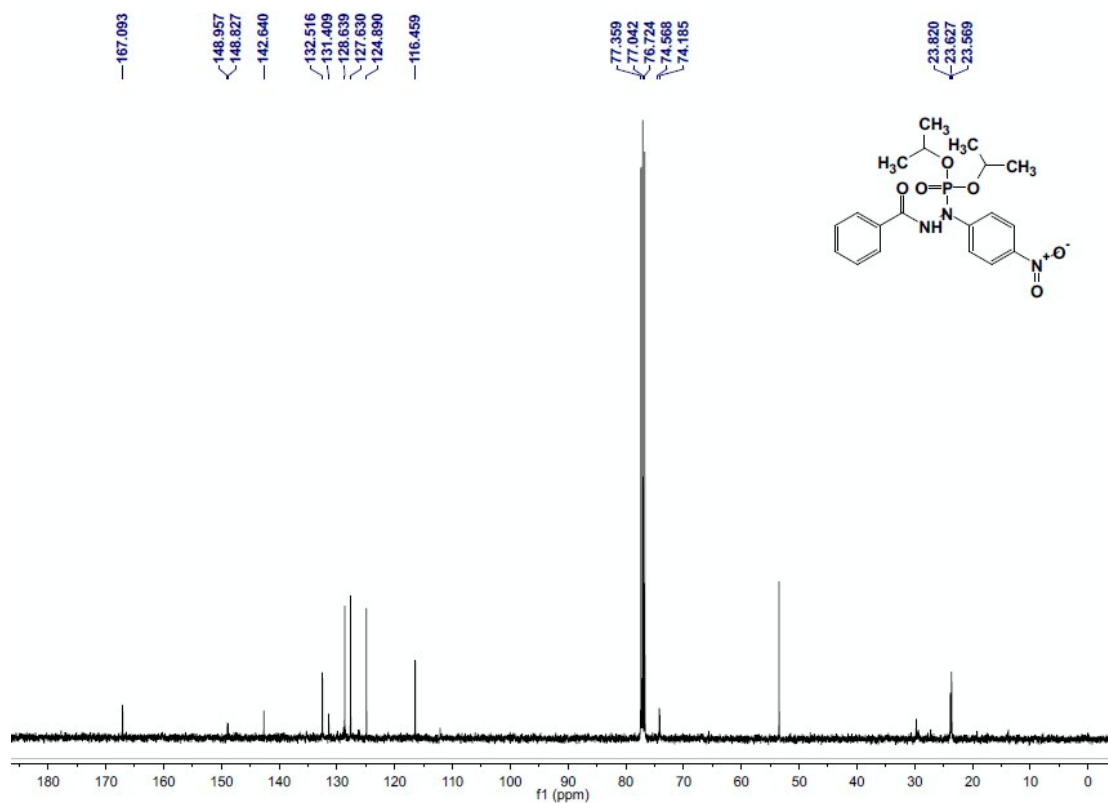
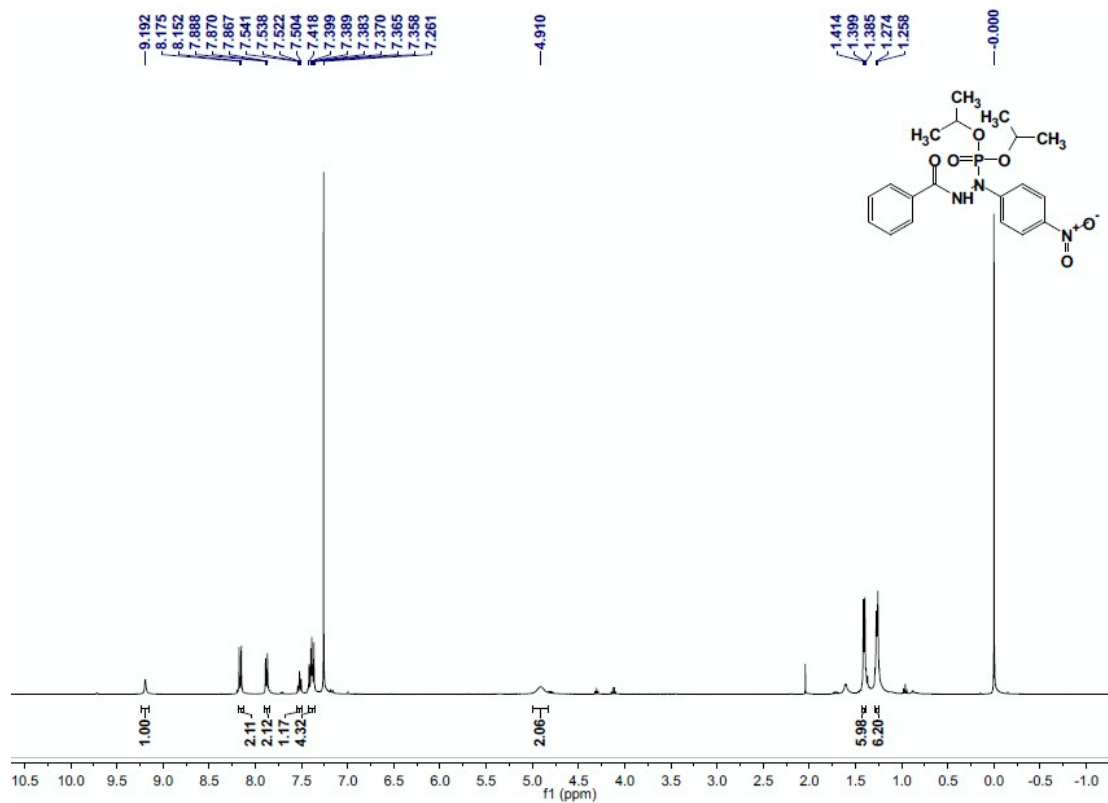


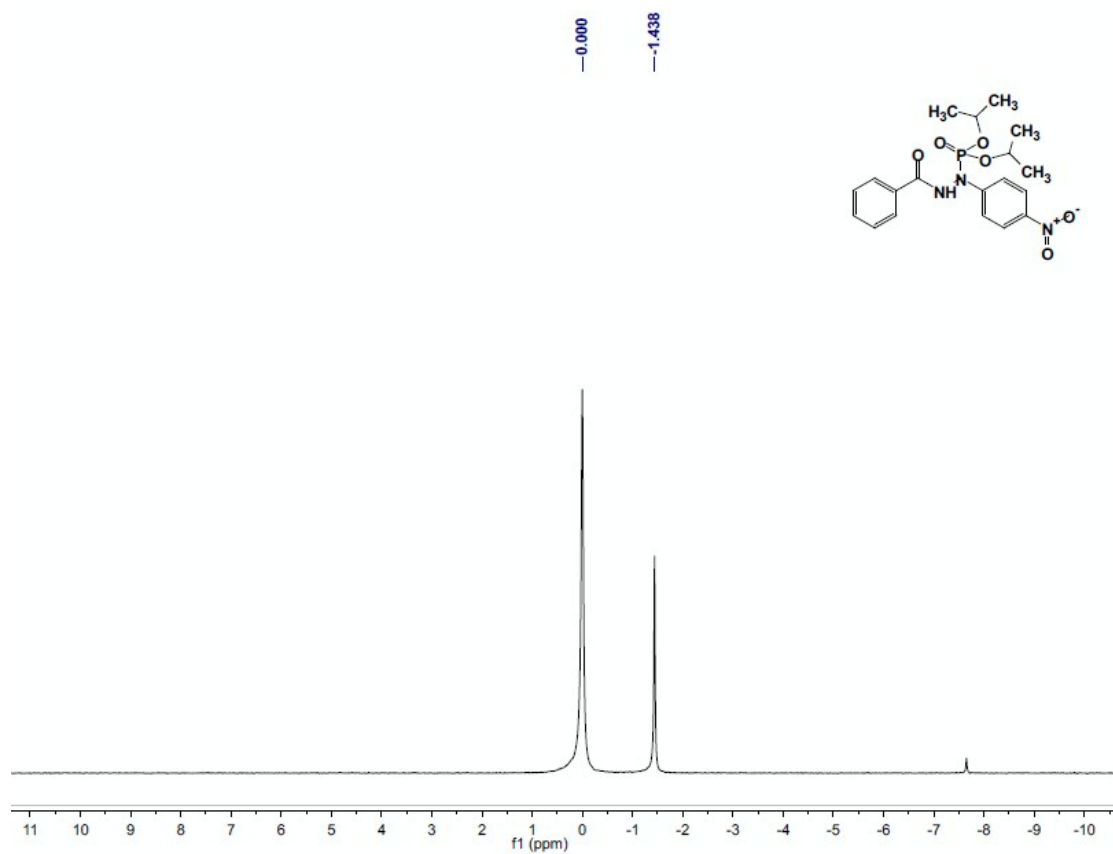
Diisopropyl (2-benzoyl-1-(4-methoxyphenyl)hydrazinyl)phosphonate (3g)



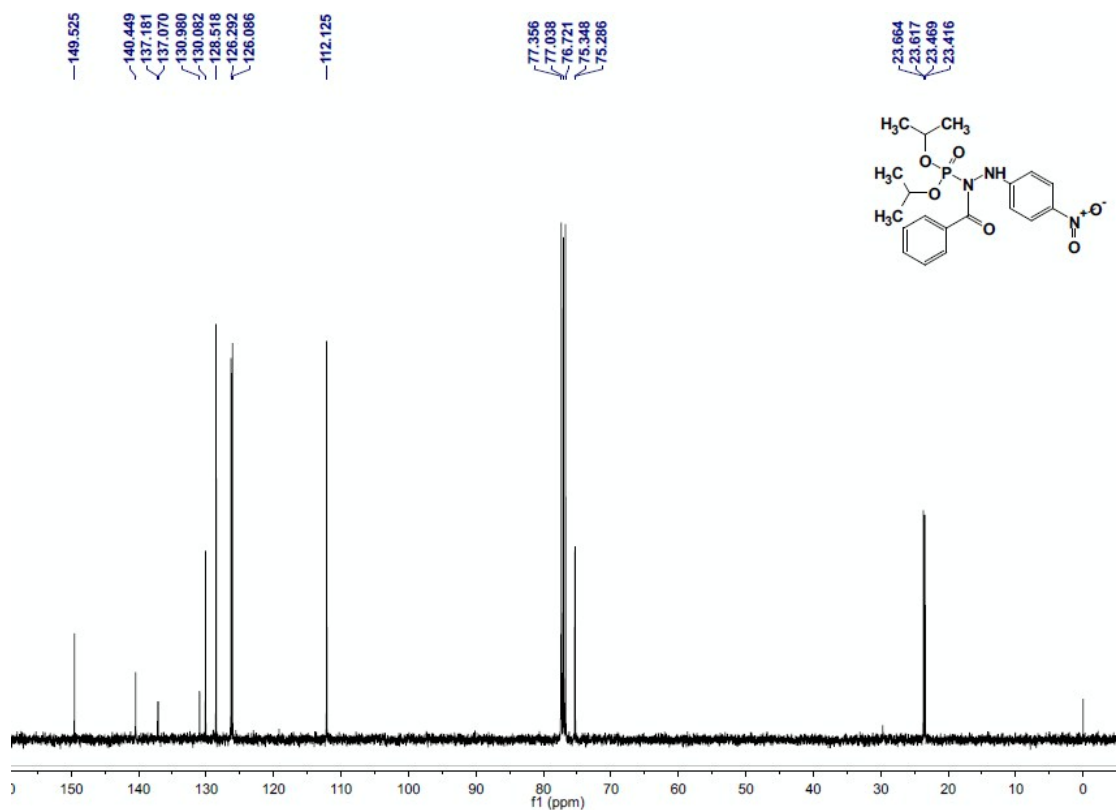
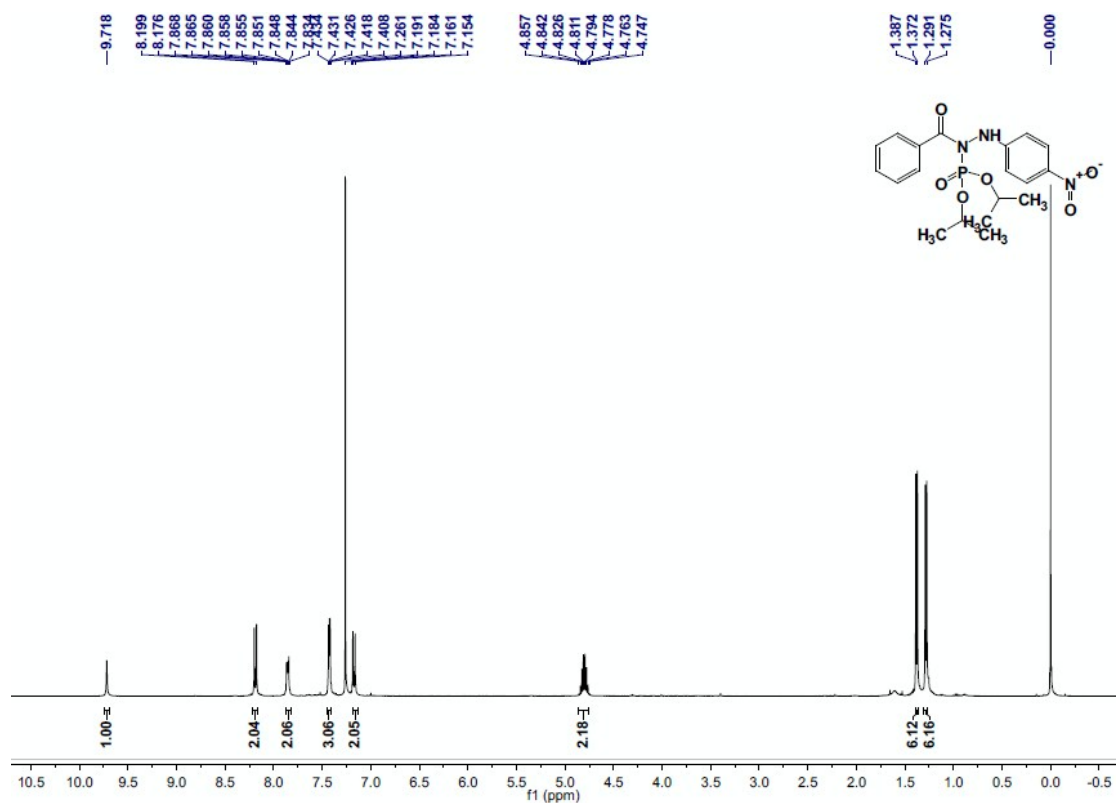


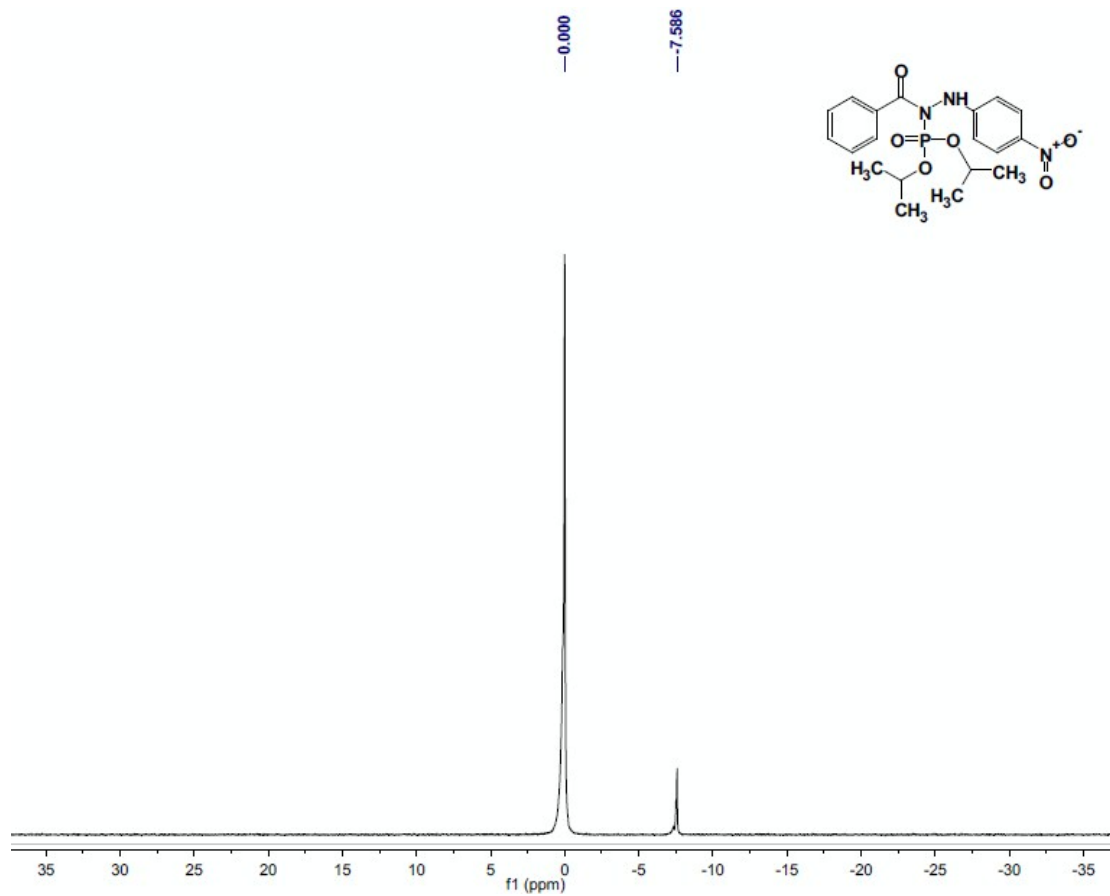
Diisopropyl (2-benzoyl-1-(4-nitrophenyl)hydrazinyl)phosphonate (3h)



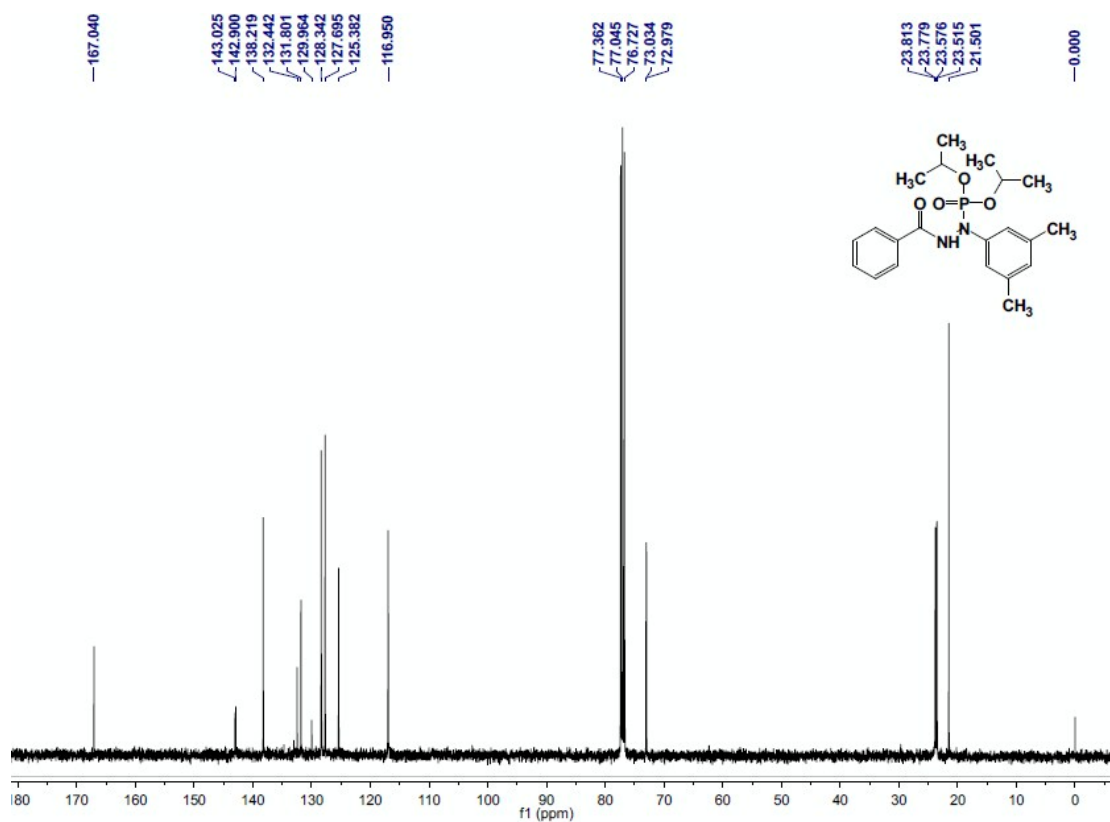
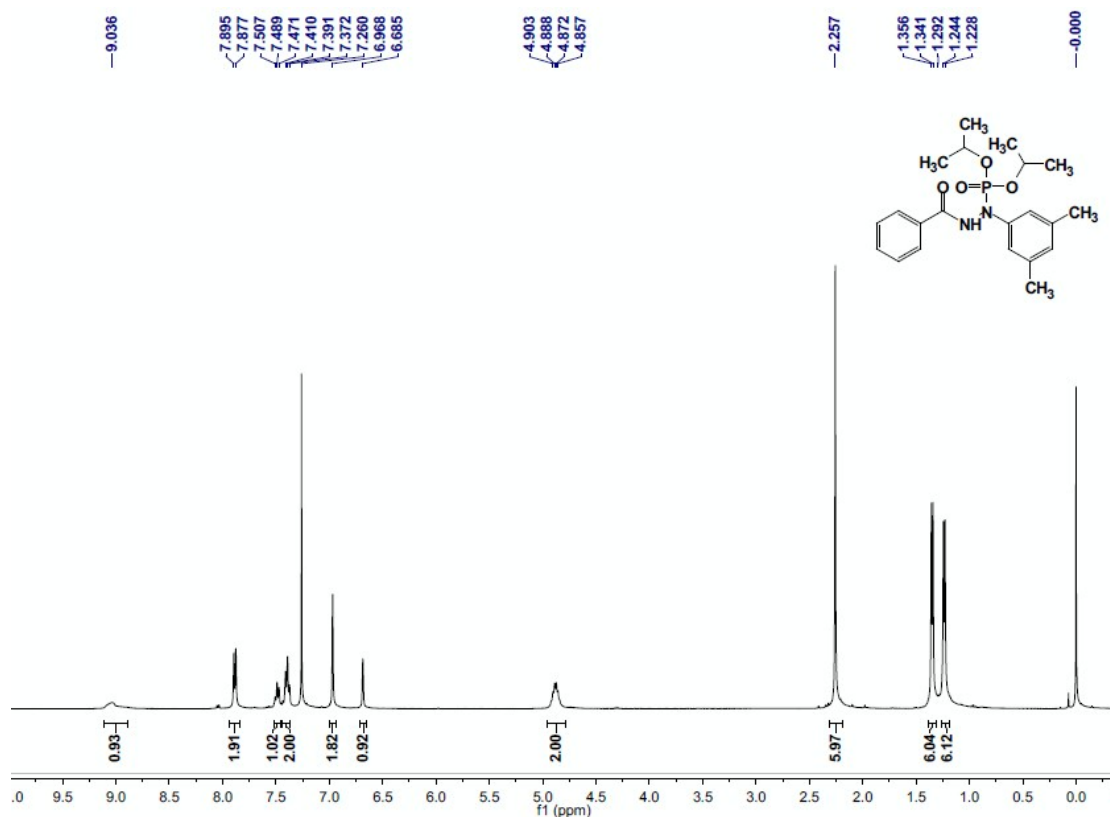


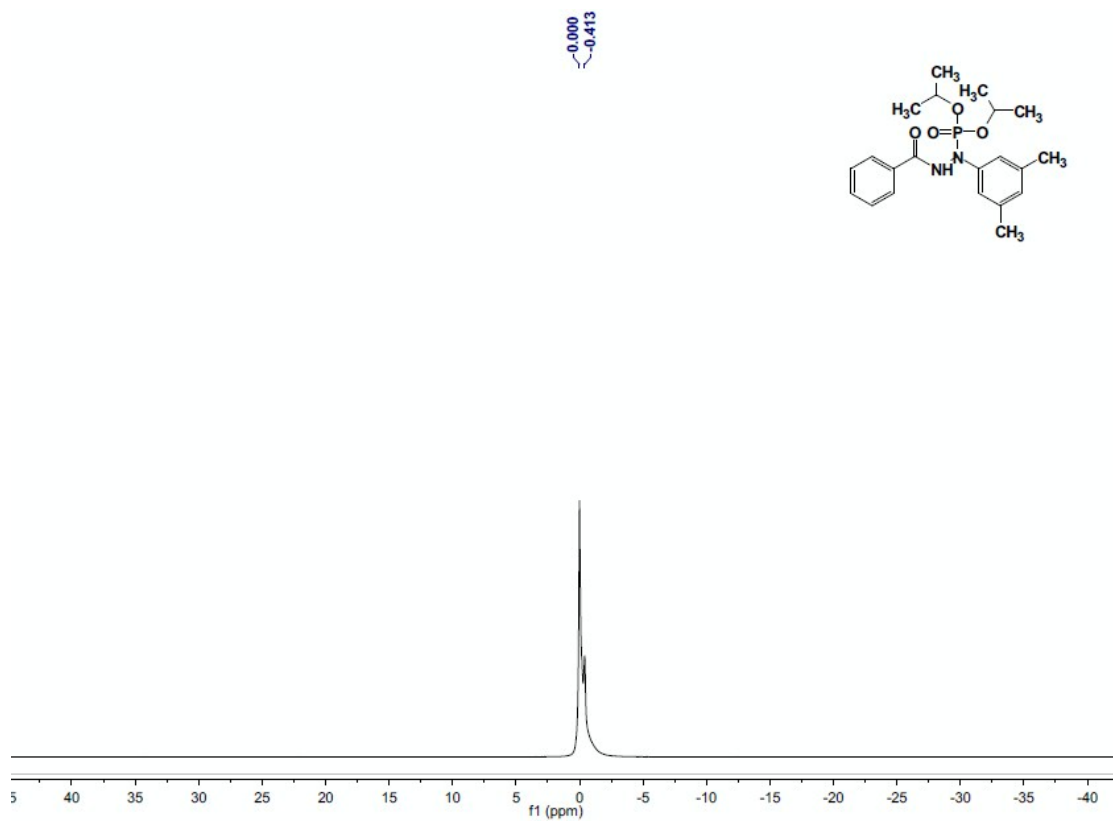
Diisopropyl (1-benzoyl-2-(4-nitrophenyl)hydrazinyl)phosphonate (3h')



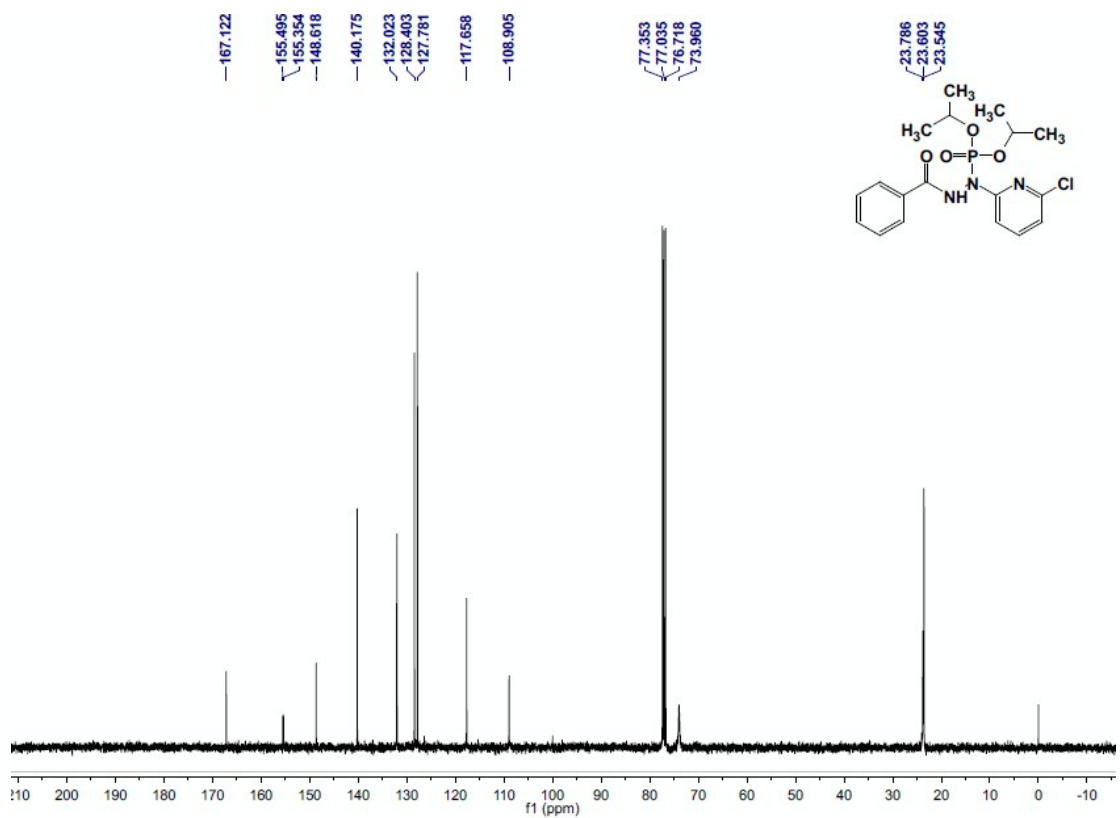
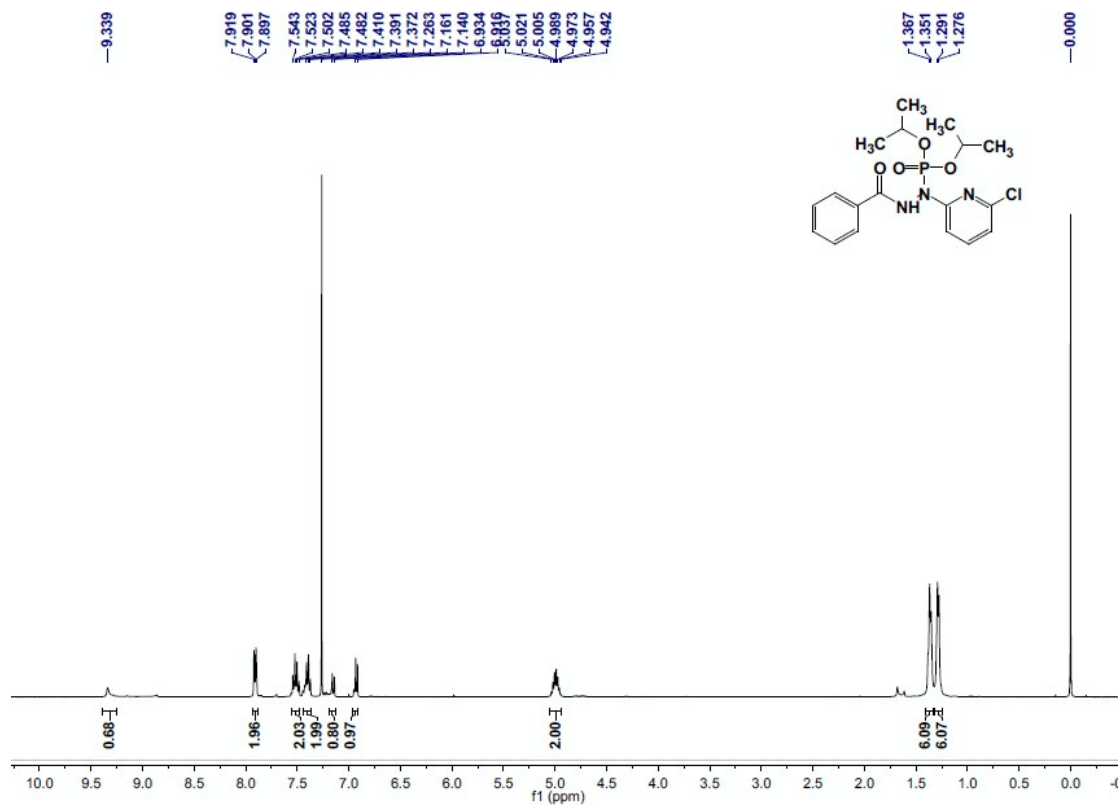


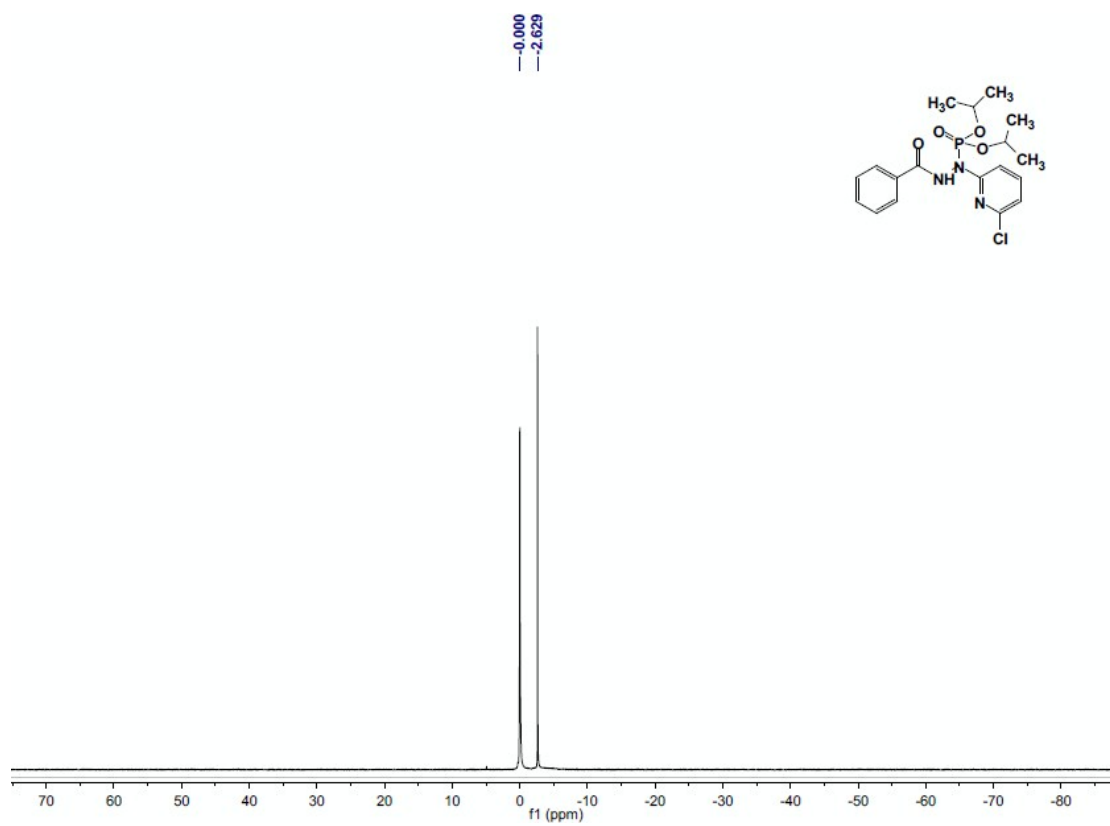
Diisopropyl (2-benzoyl-1-(3,5-dimethylphenyl)hydrazinyl)phosphonate (3i)



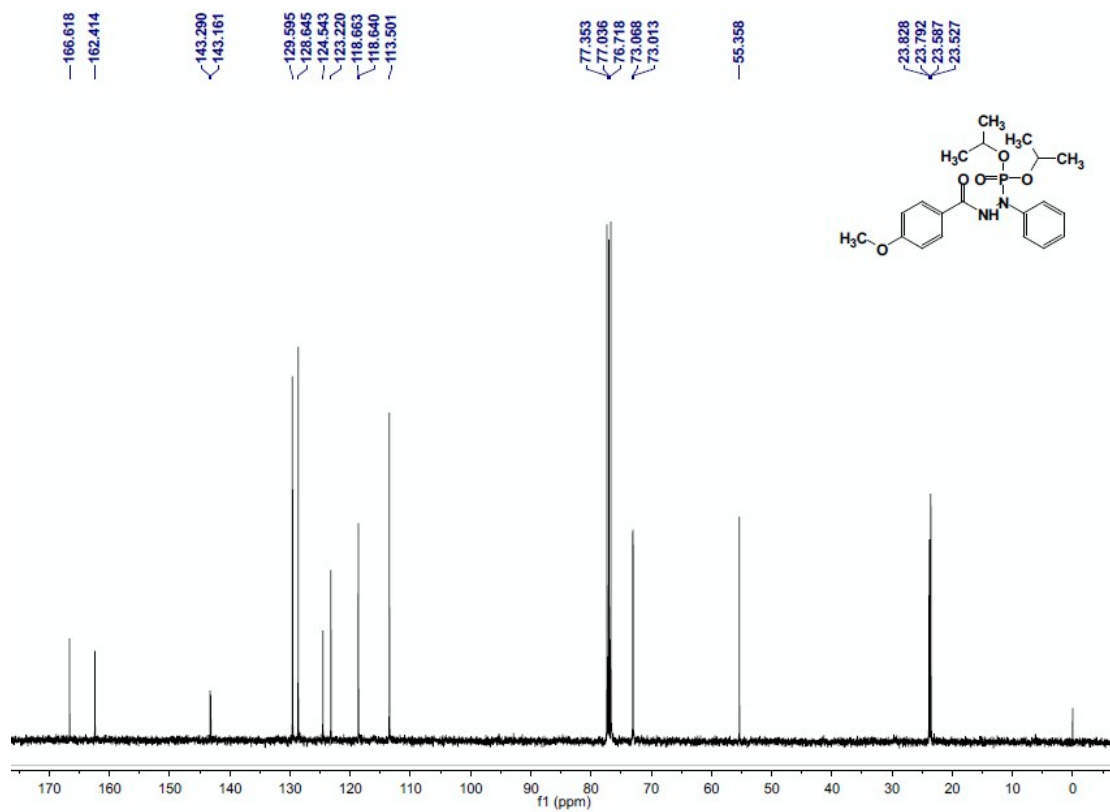
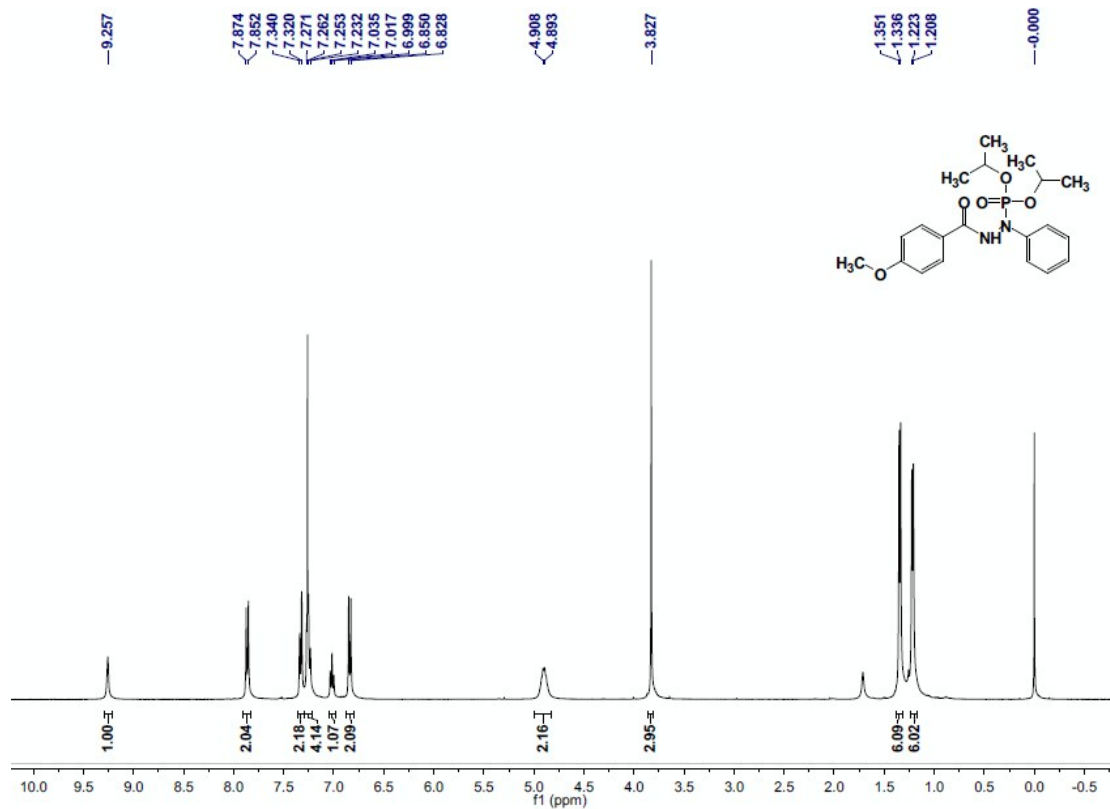


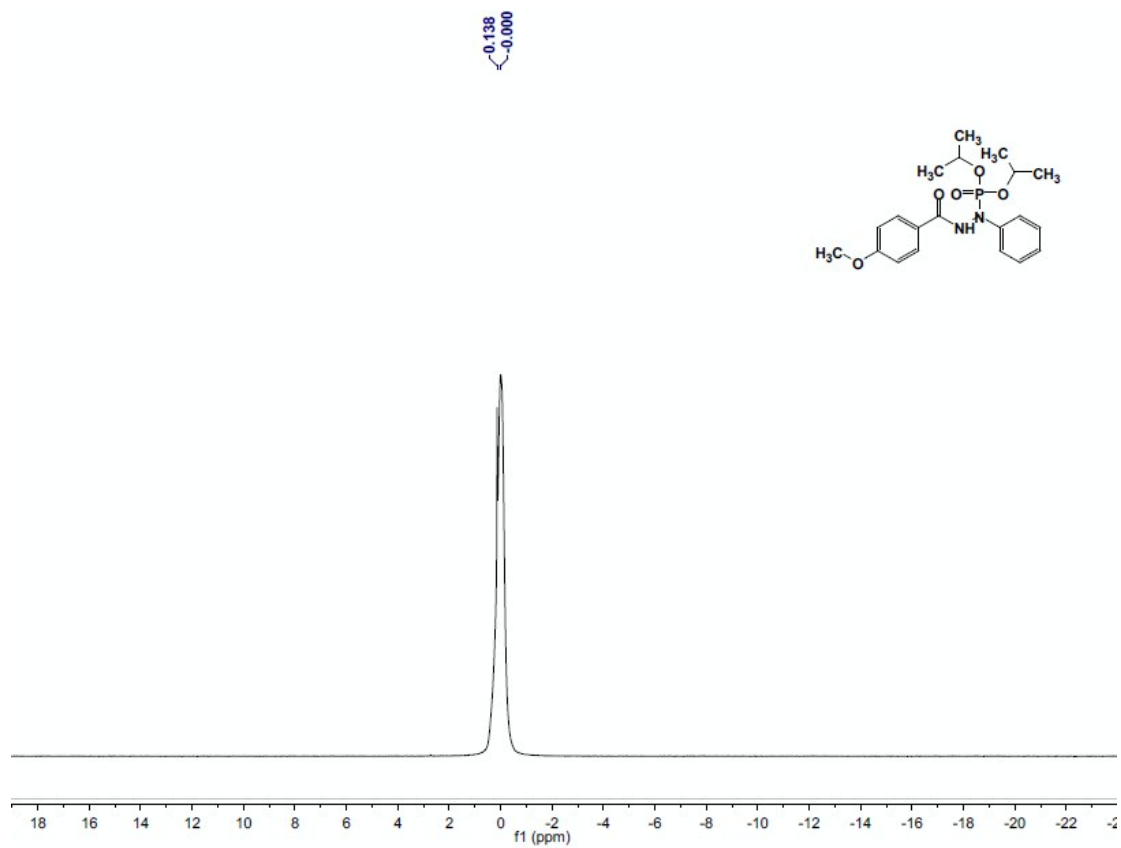
Diisopropyl (2-benzoyl-1-(6-chloropyridin-2-yl)hydrazinyl)phosphonate (3j)



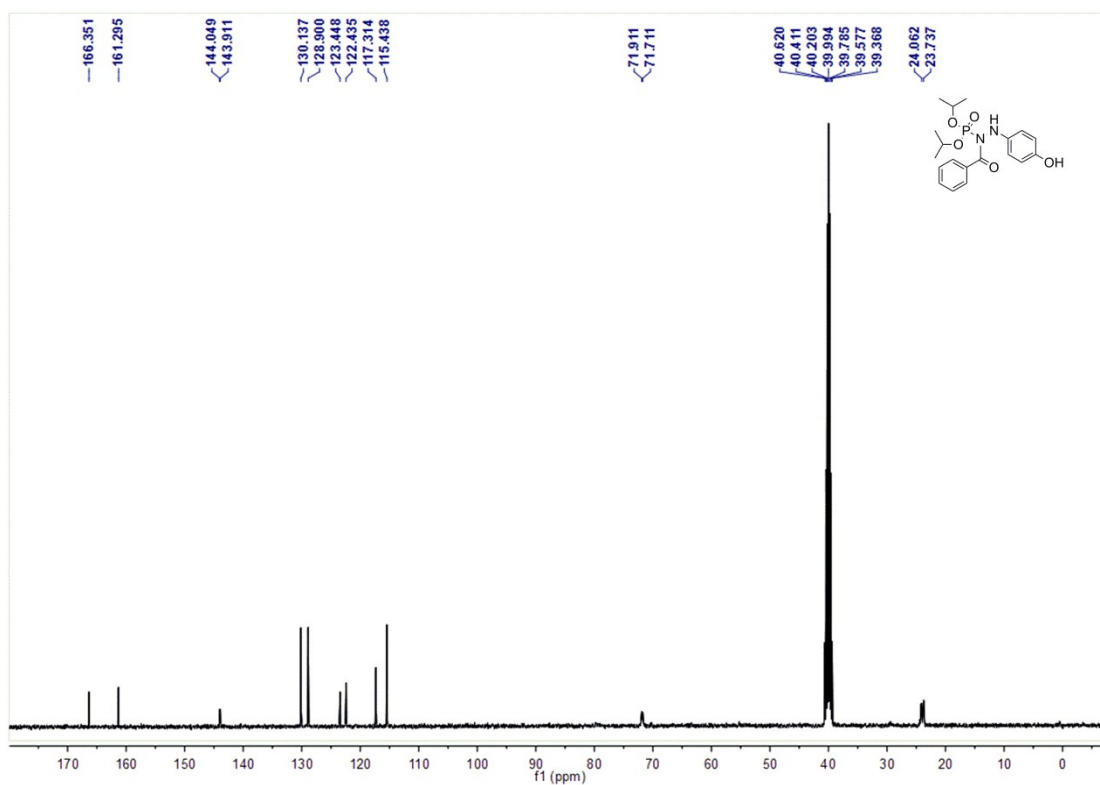
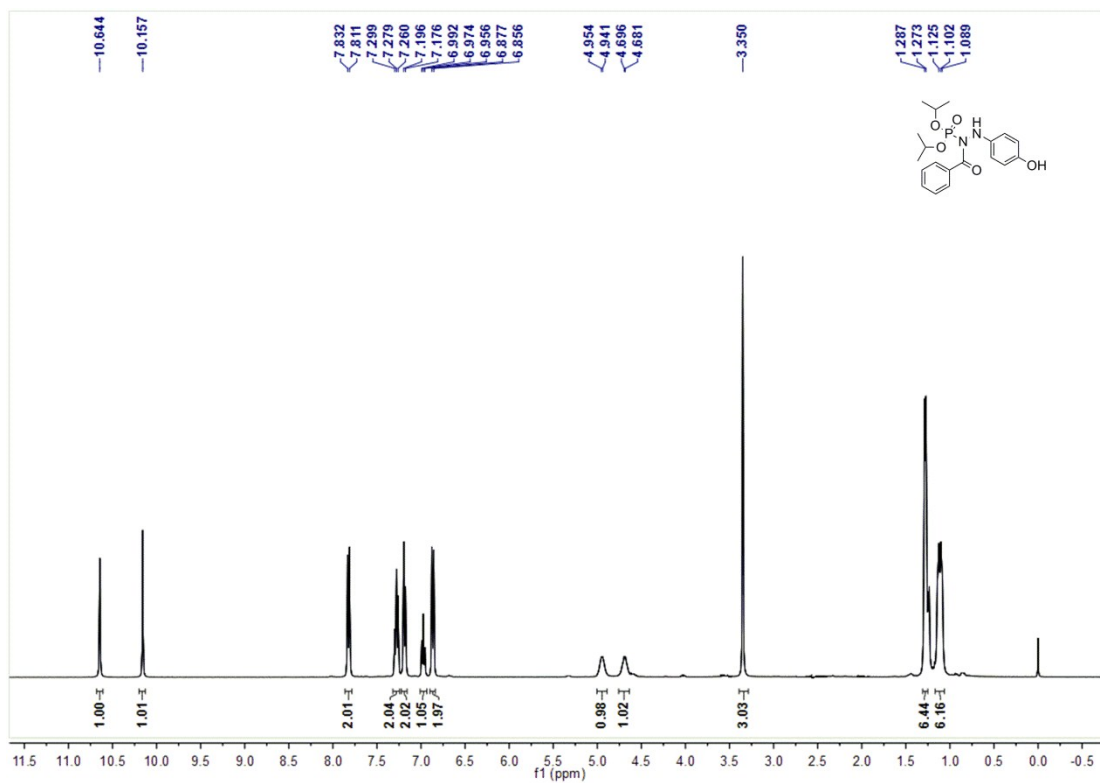


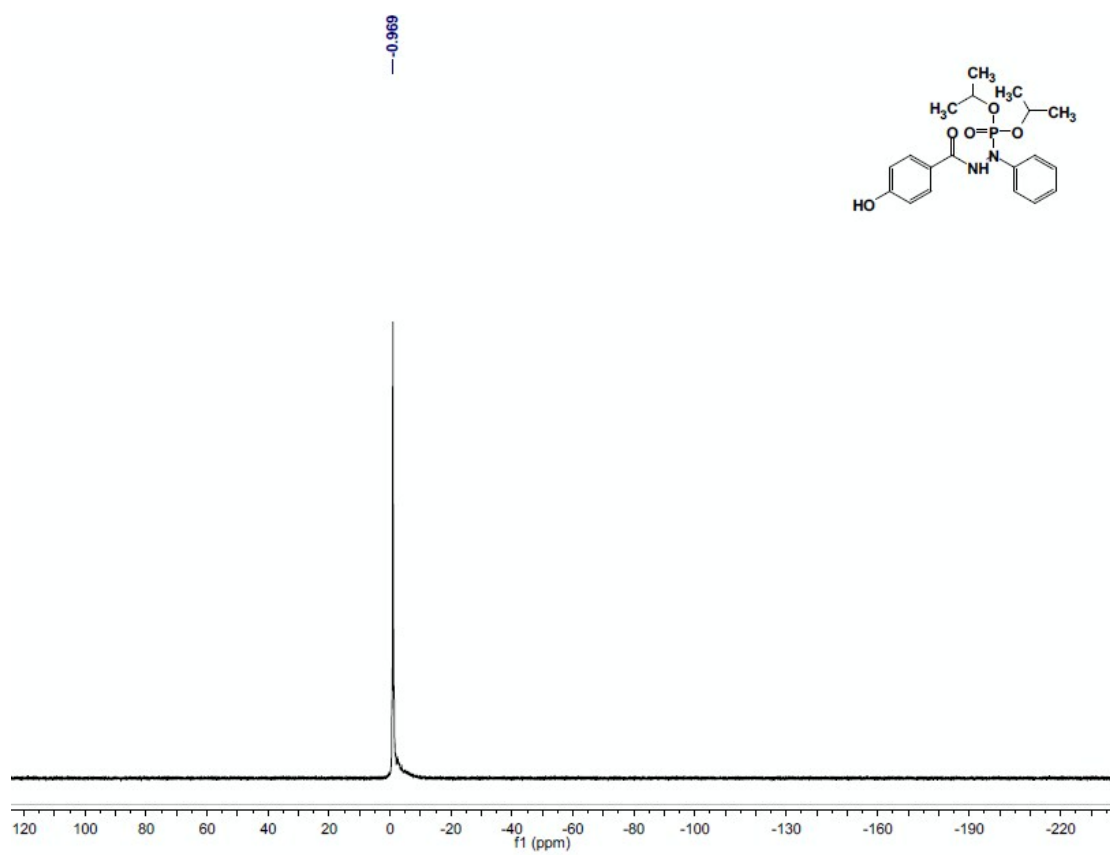
Diisopropyl (2-(4-methoxybenzoyl)-1-phenylhydrazinyl)phosphonate (3l)



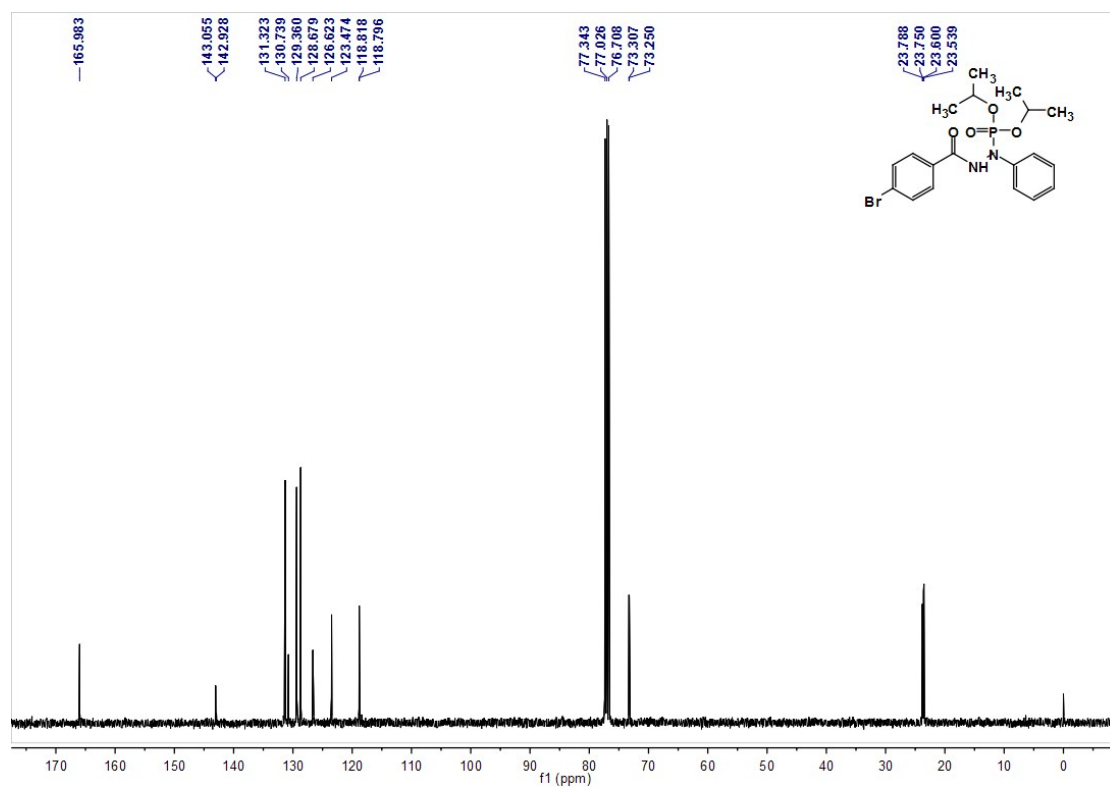
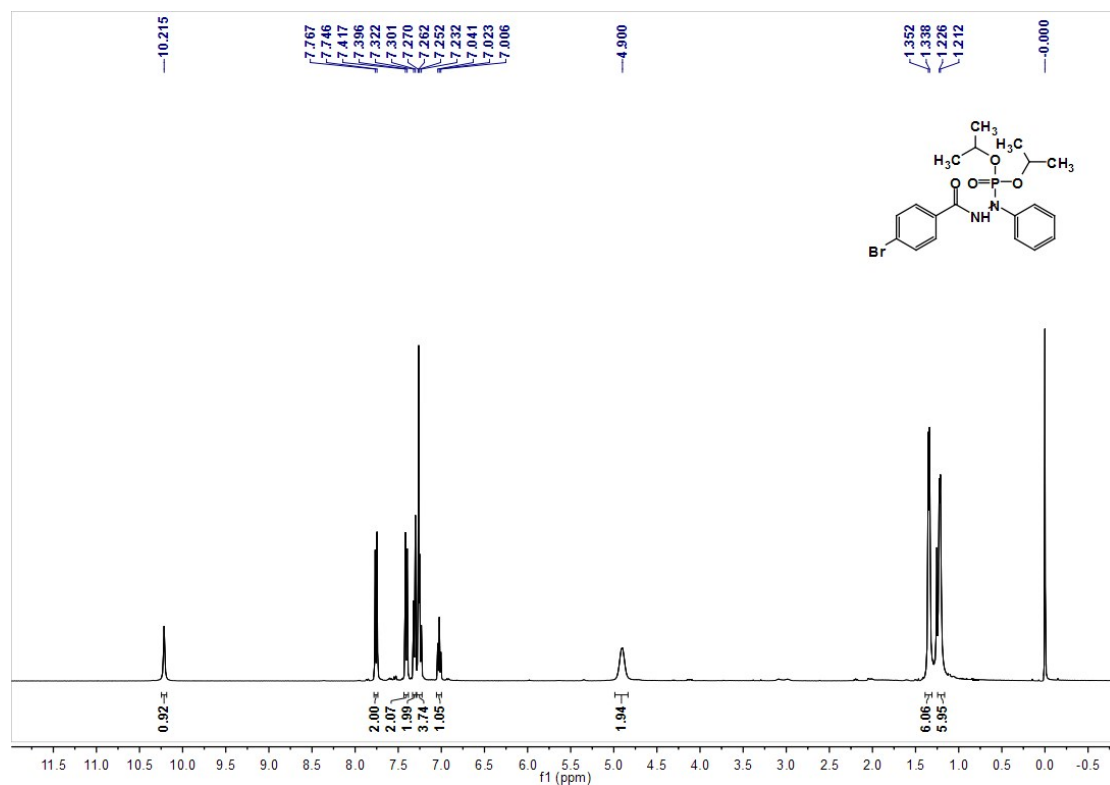


Diisopropyl (2-(4-hydroxybenzoyl)-1-phenylhydrazinyl)phosphonate (3m)

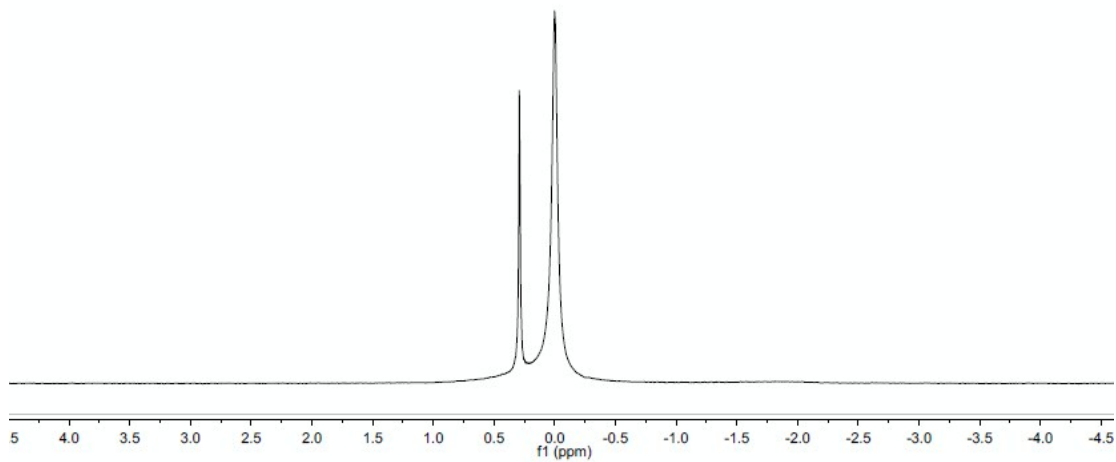
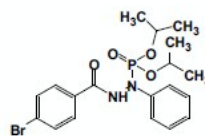




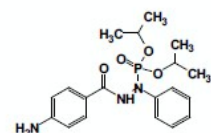
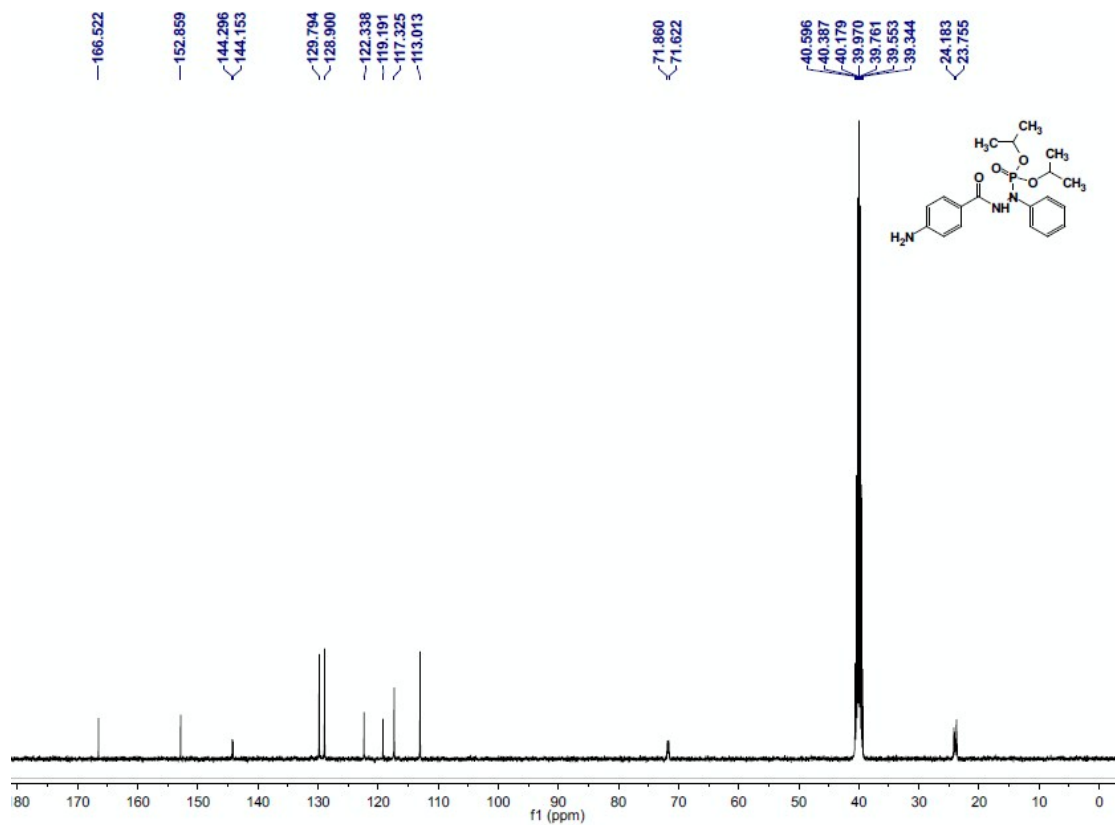
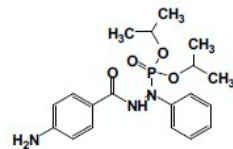
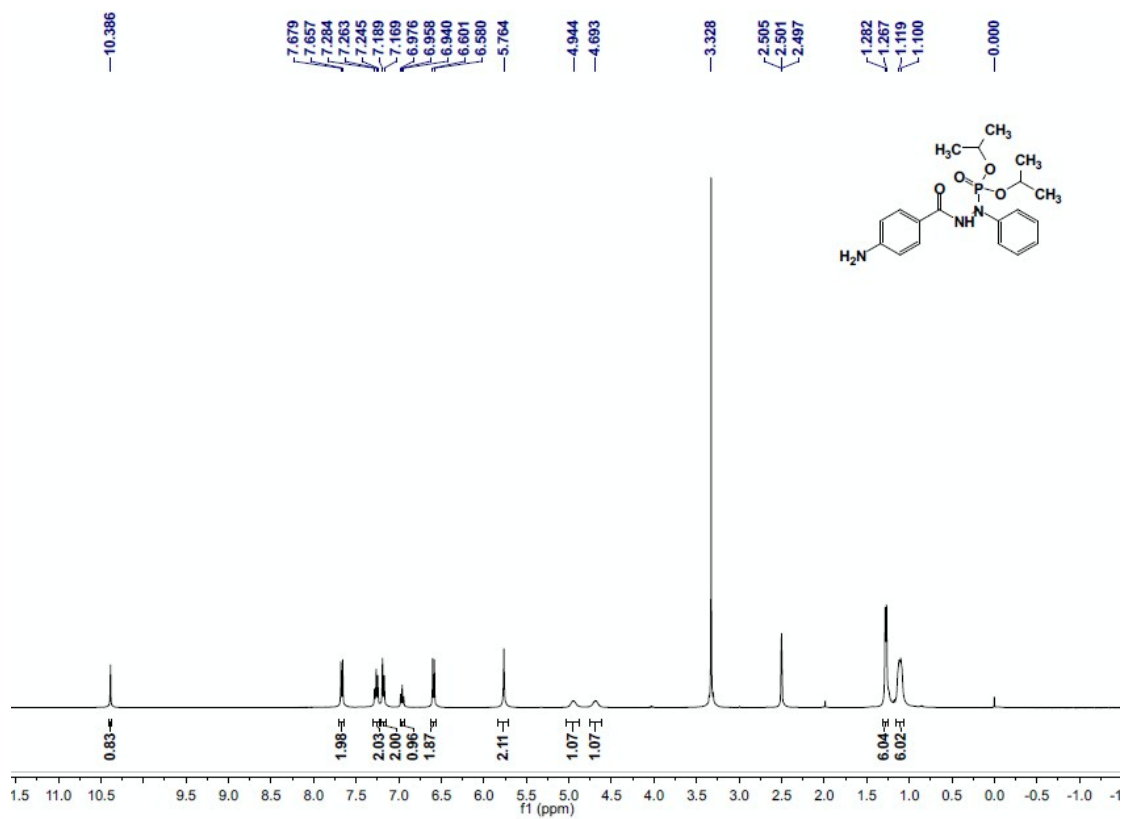
Diisopropyl (2-(4-bromobenzoyl)-1-phenylhydrazinyl)phosphonate (3n)

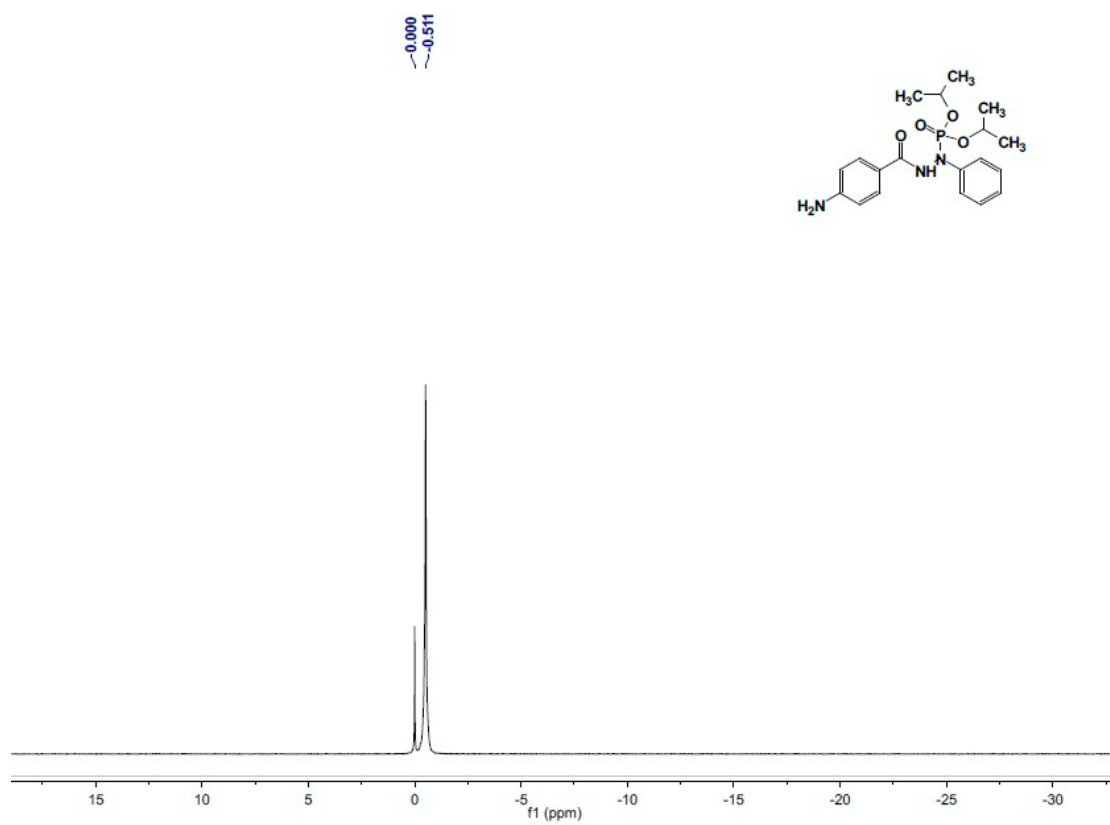


-0.290
-0.000

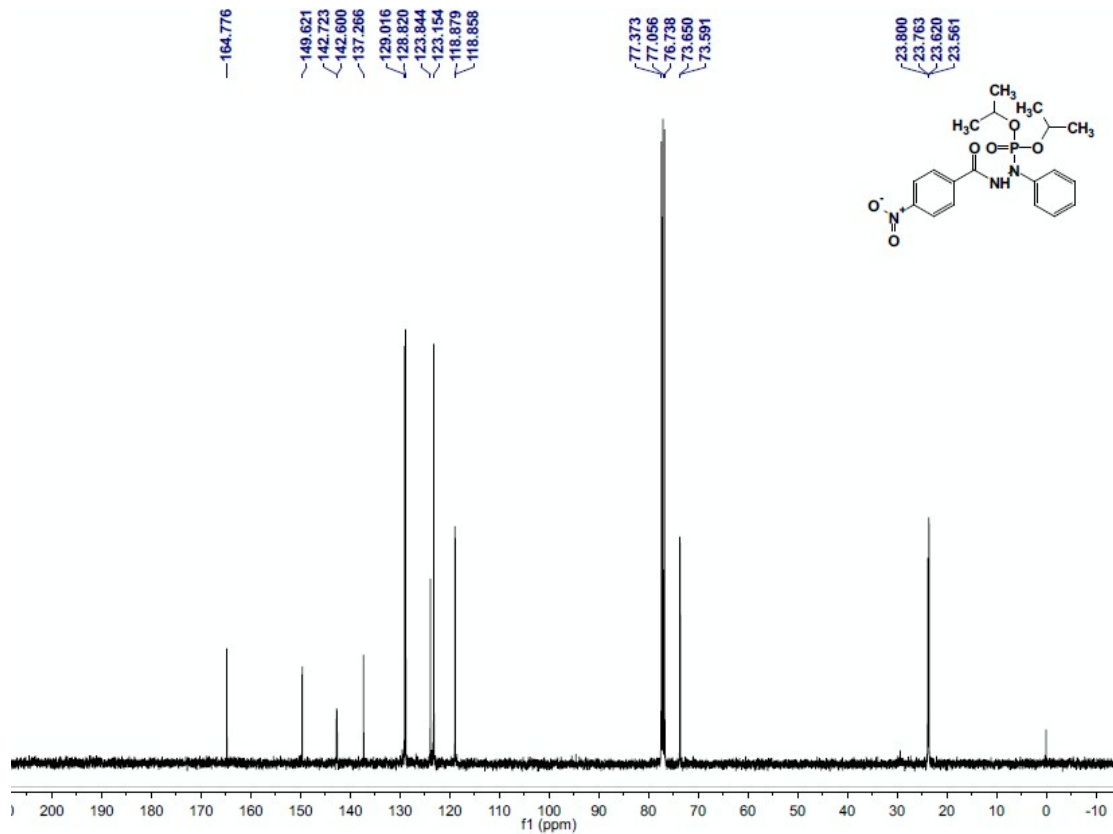
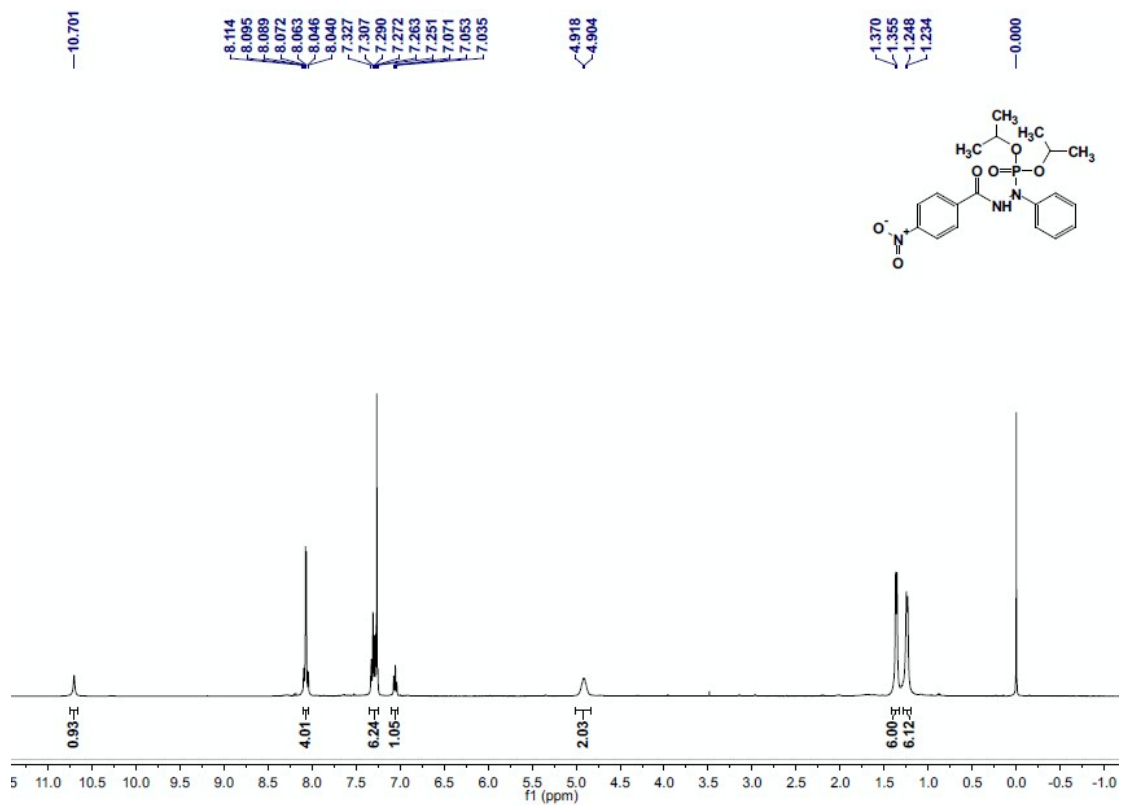


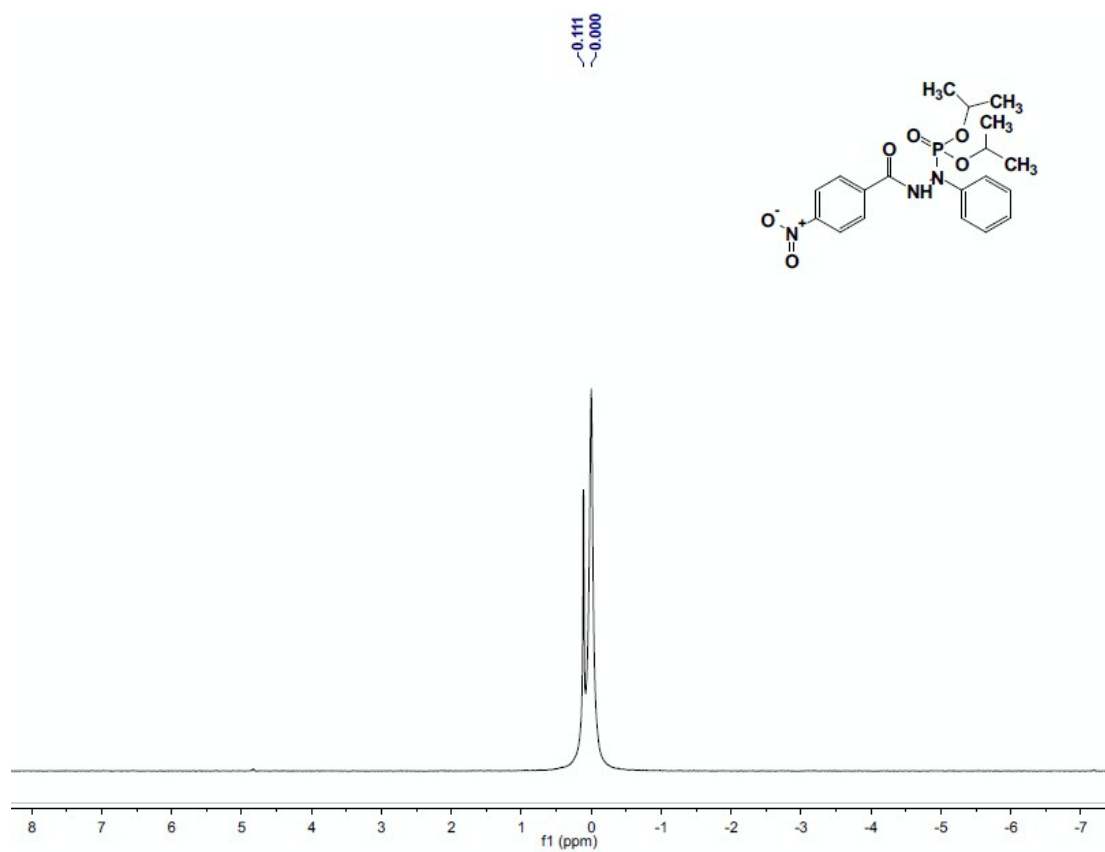
Diisopropyl (2-(4-aminobenzoyl)-1-phenylhydrazinyl)phosphonate (3o)



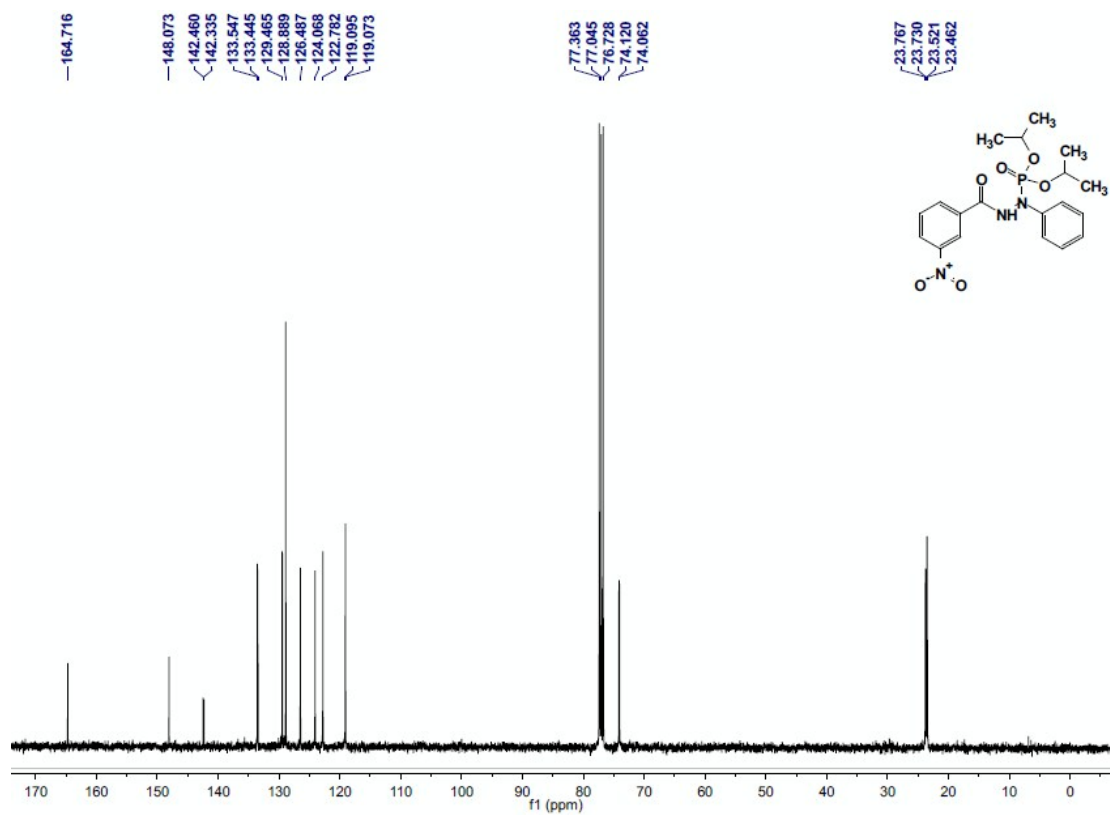
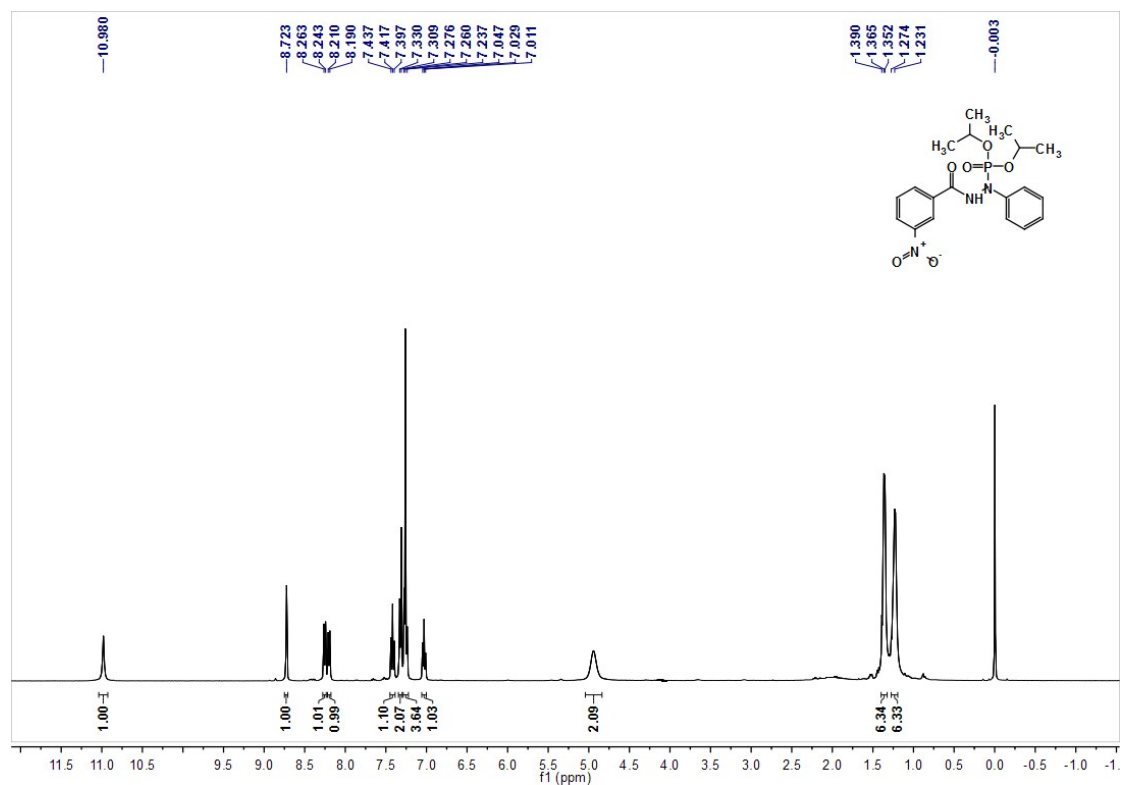


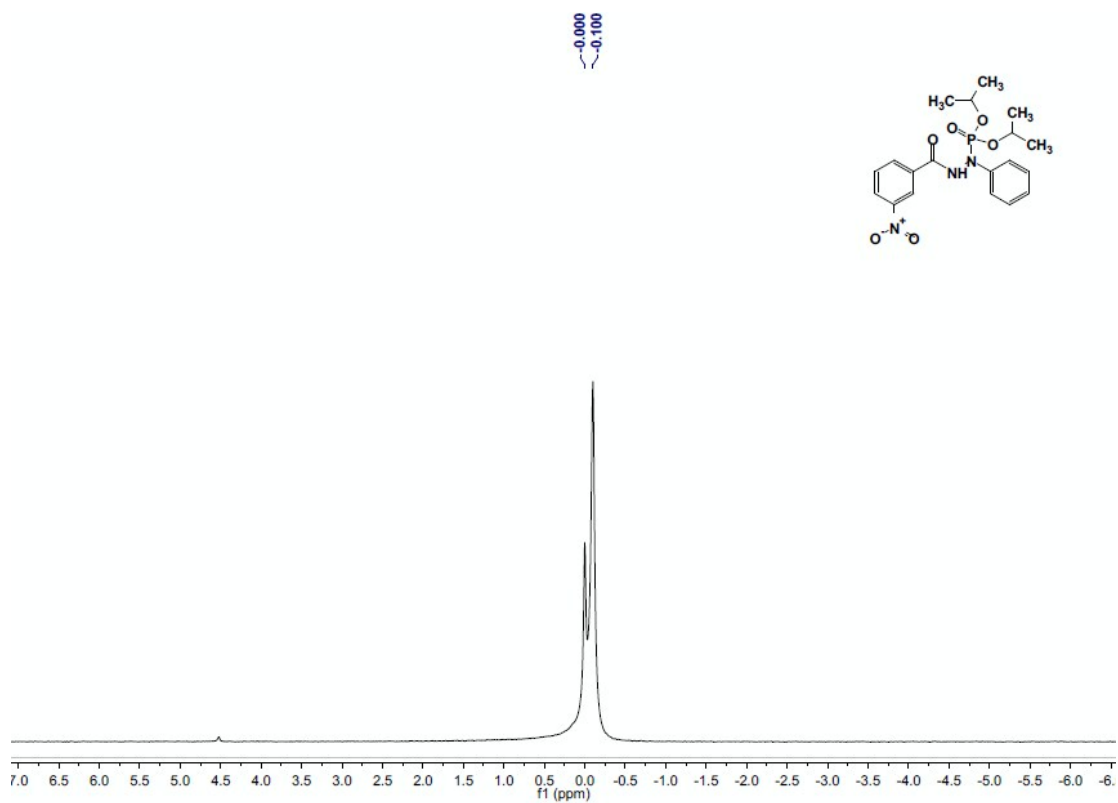
Diisopropyl (2-(4-nitrobenzoyl)-1-phenylhydrazinyl)phosphonate (3p)



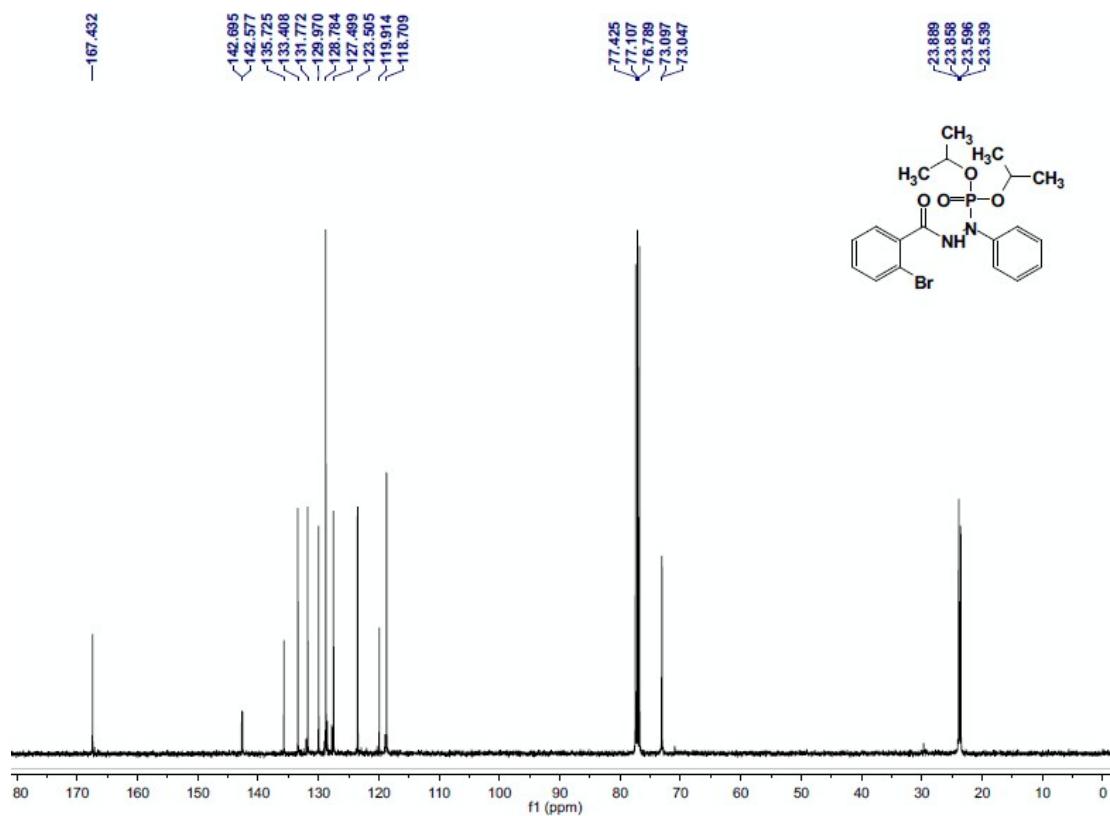
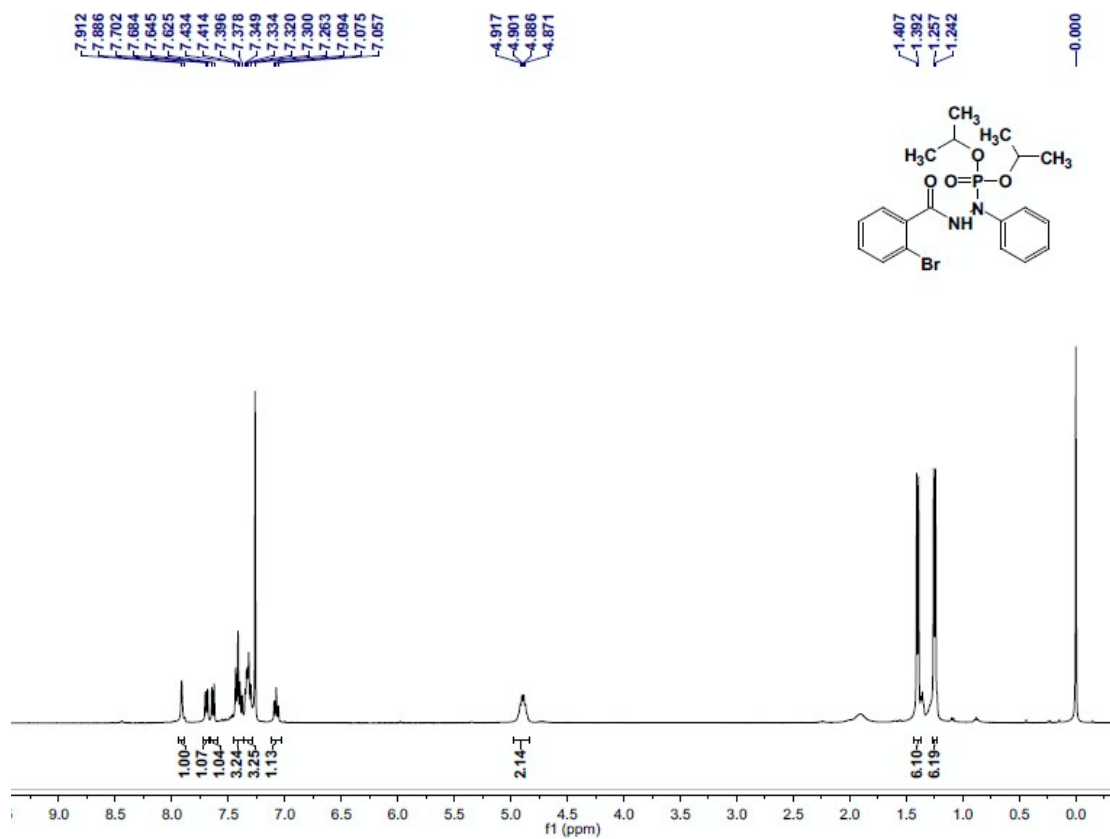


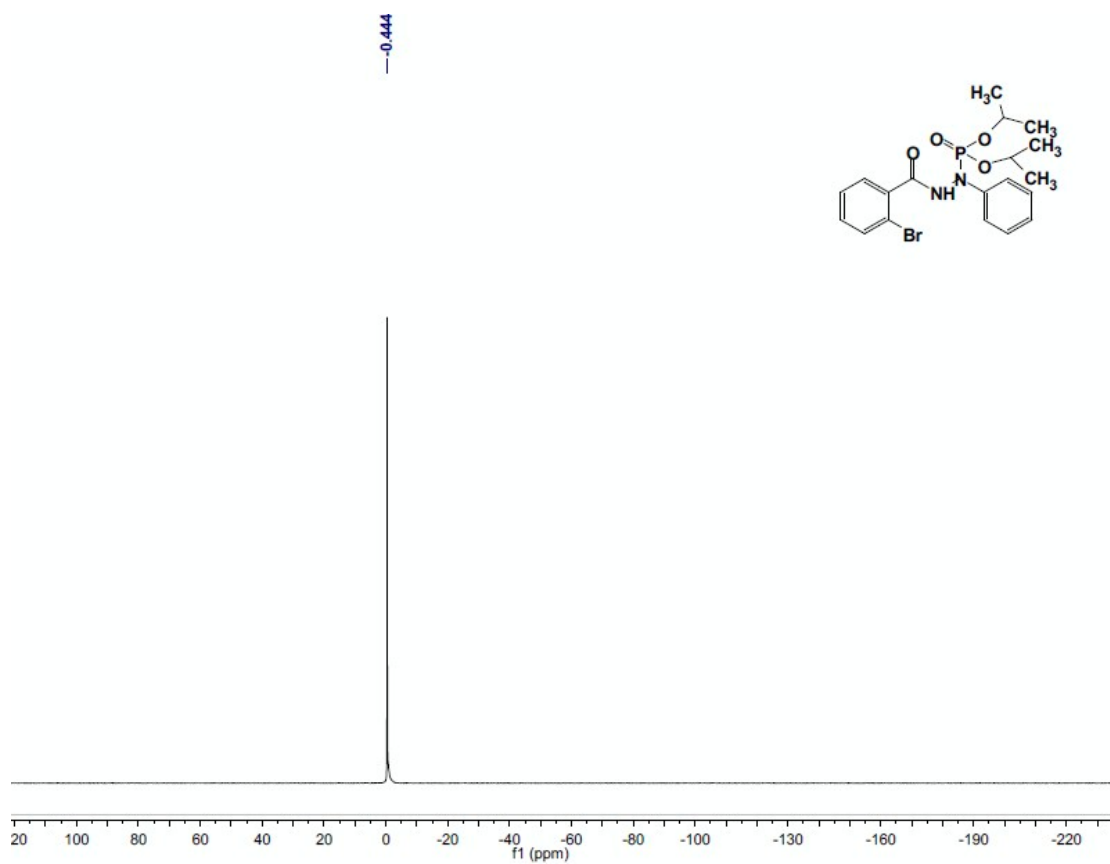
Diisopropyl (2-(3-nitrobenzoyl)-1-phenylhydrazinyl)phosphonate (3q)



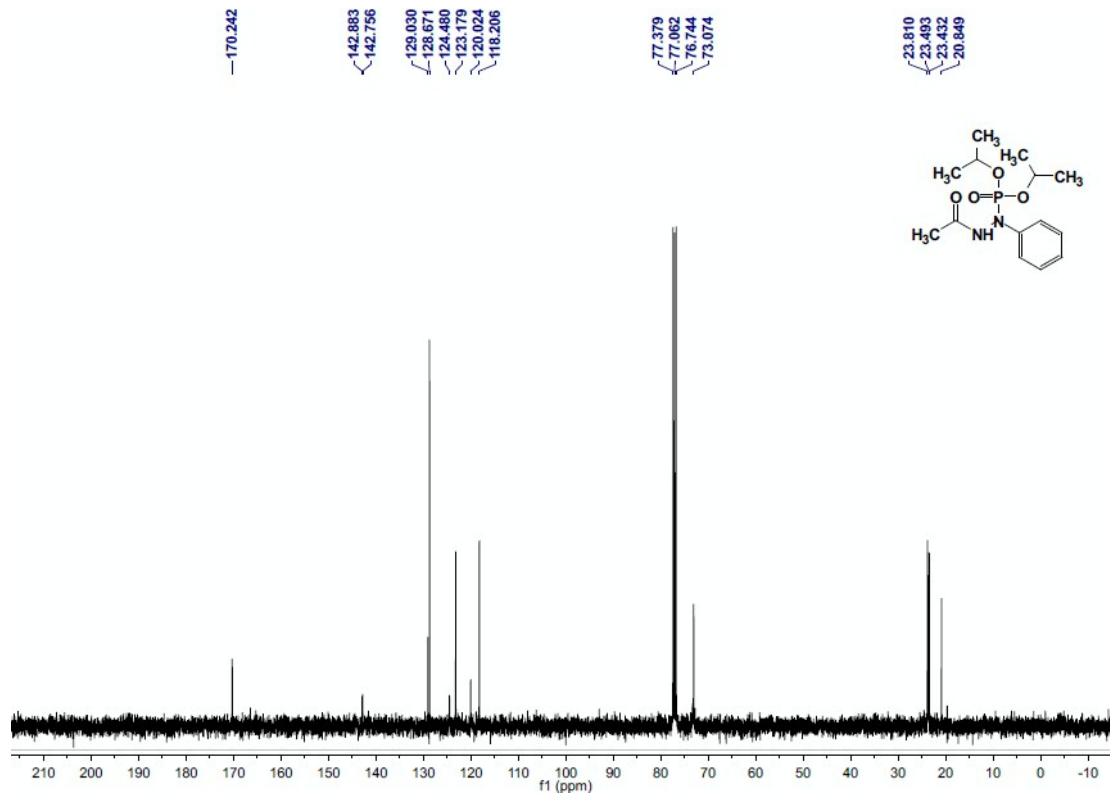
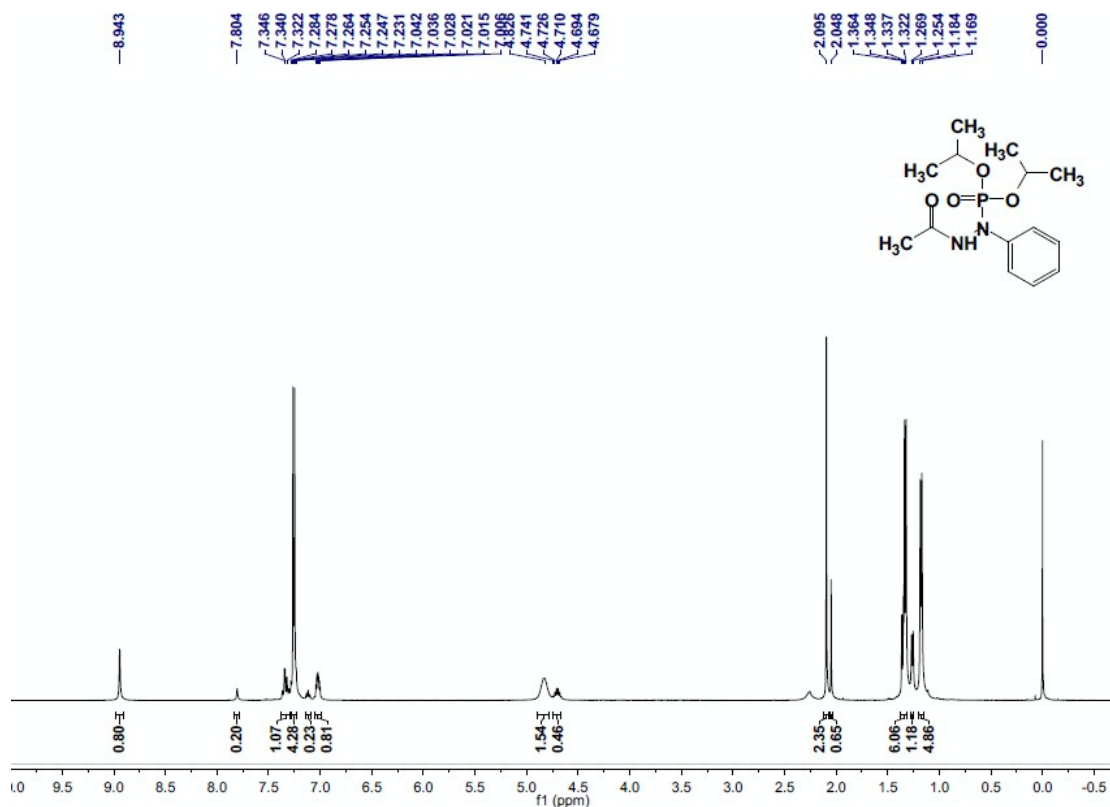


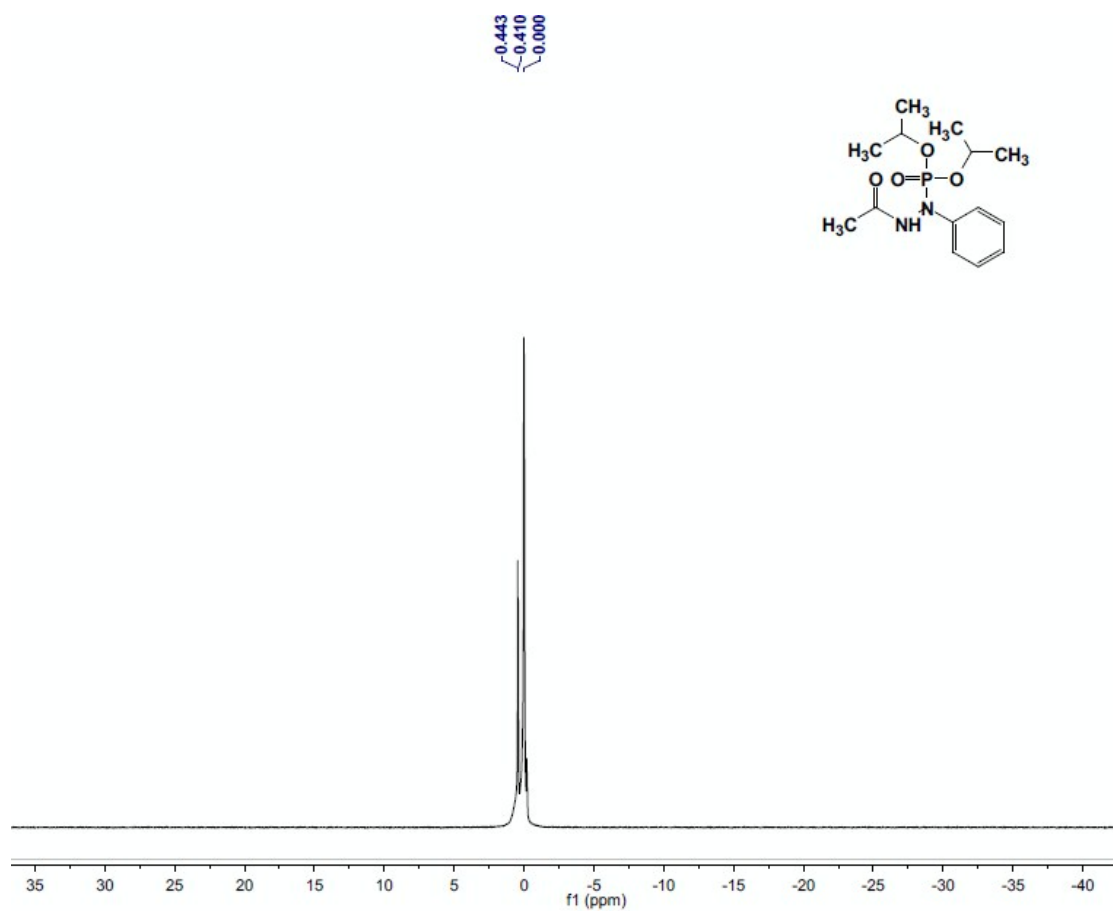
Diisopropyl (2-(2-bromobenzoyl)-1-phenylhydrazinyl)phosphonate (3r)



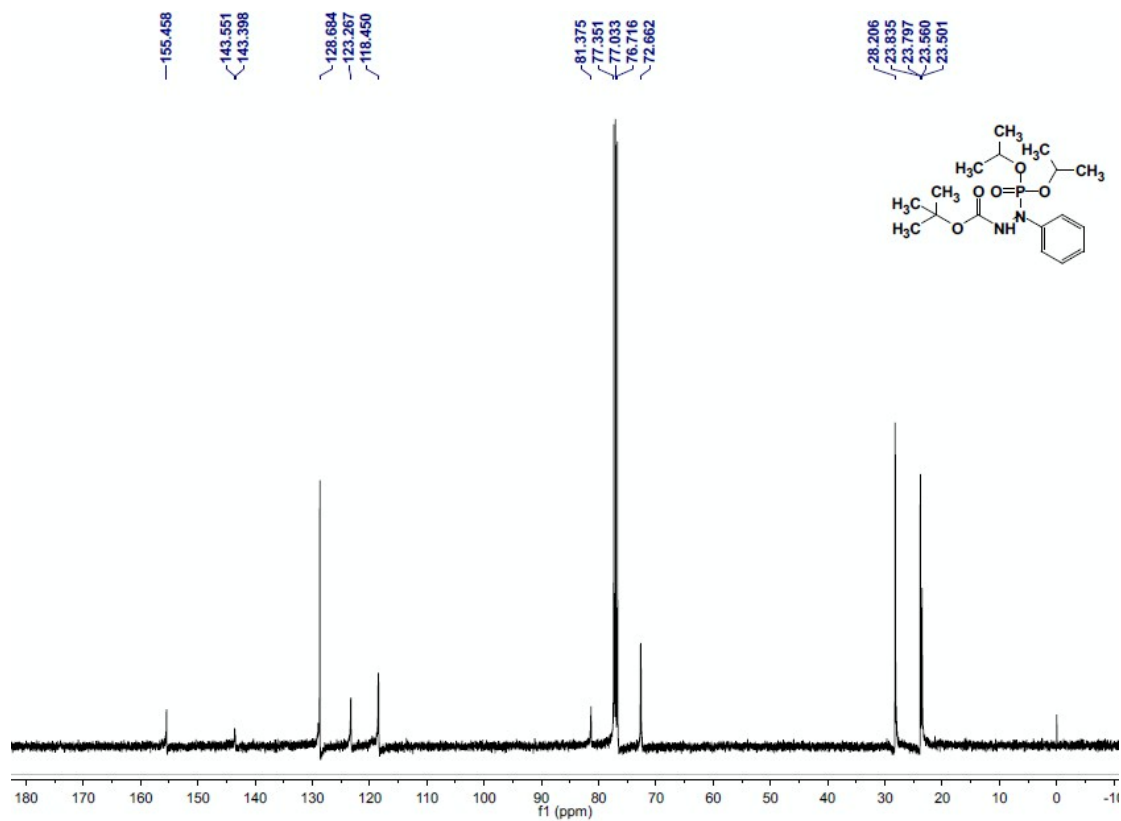
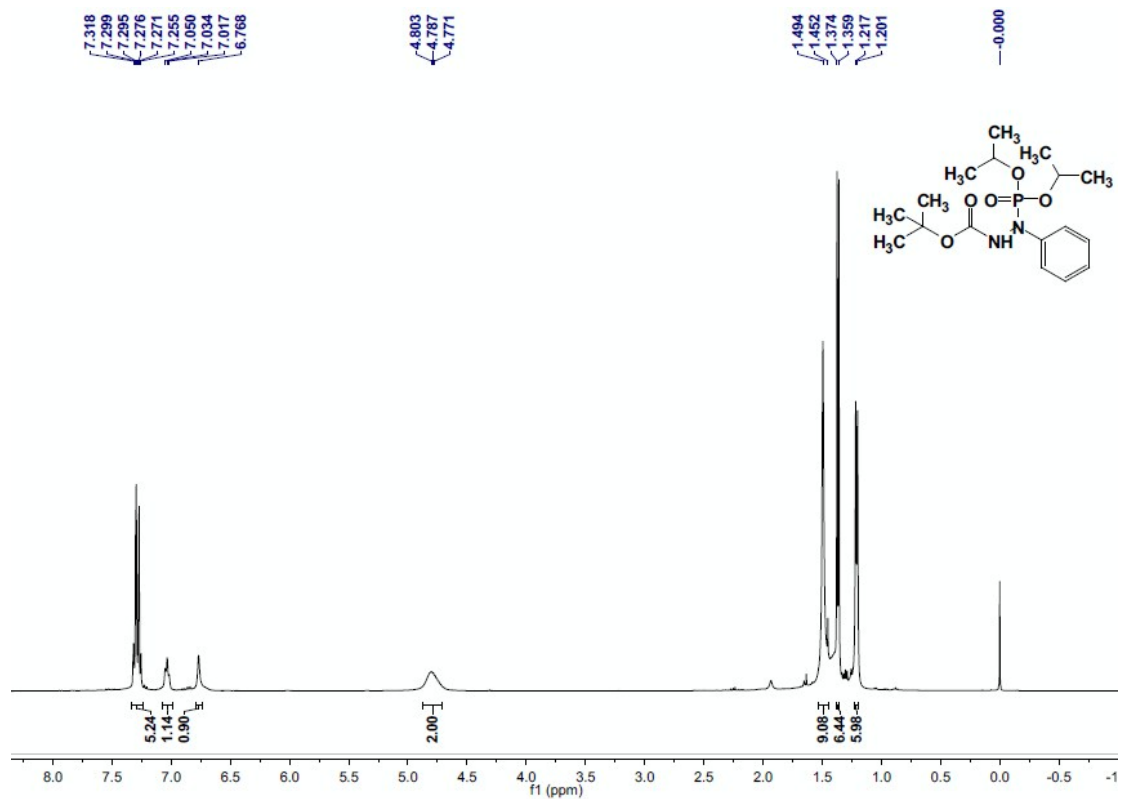


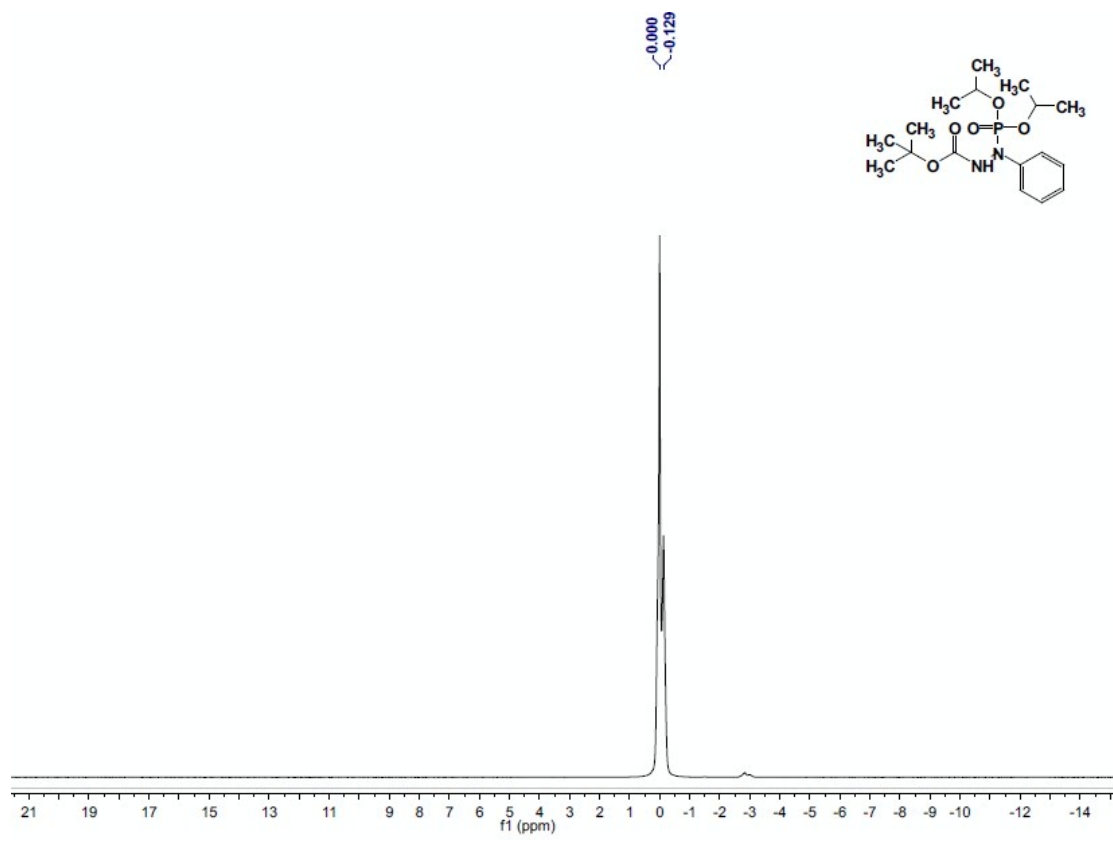
Diisopropyl (2-acetyl-1-phenylhydrazinyl)phosphonate (3s)



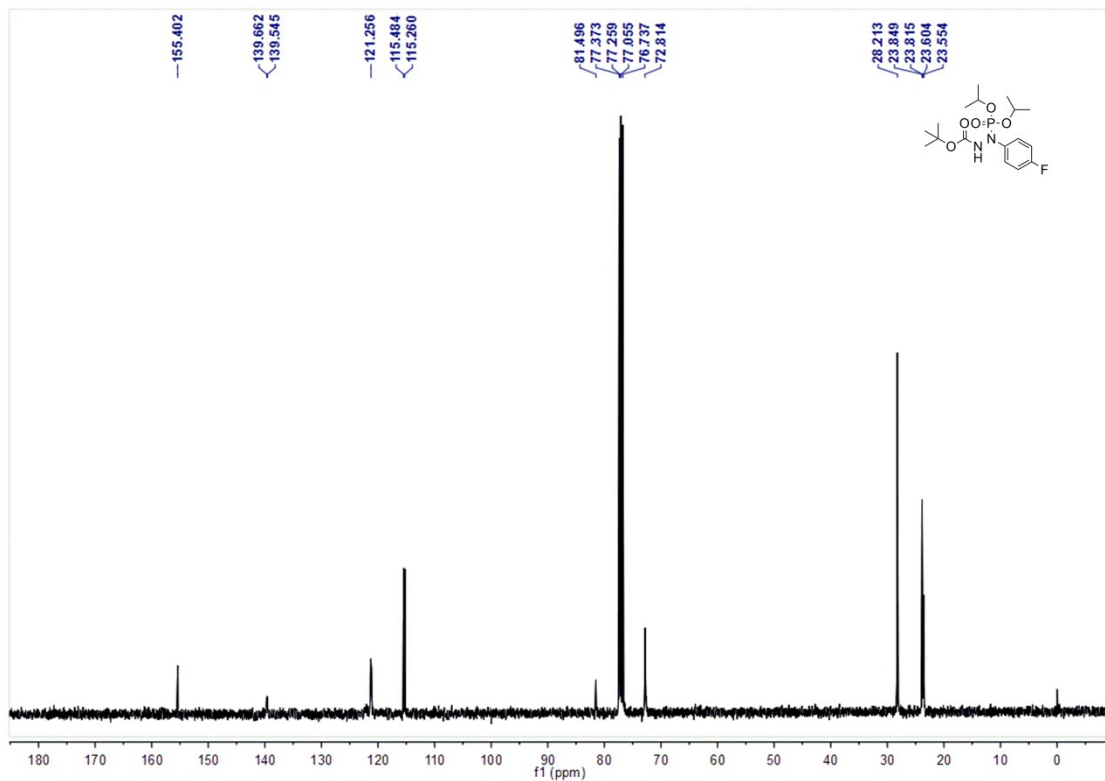
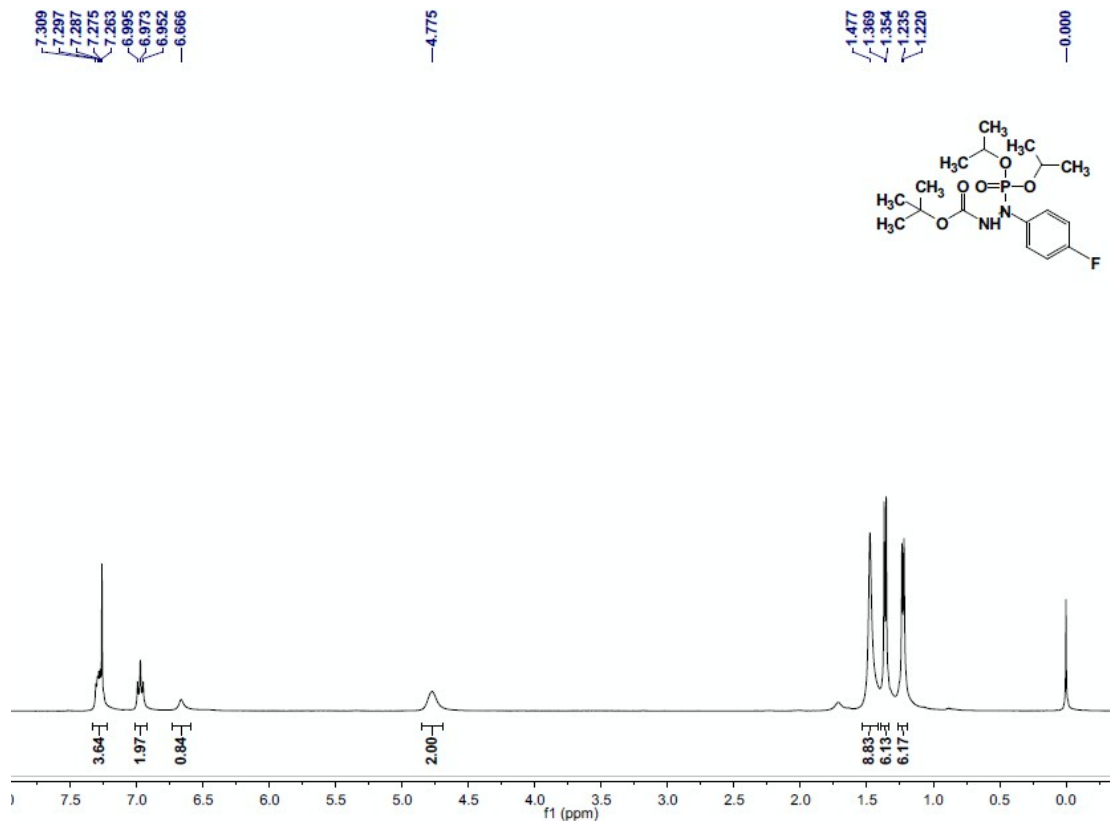


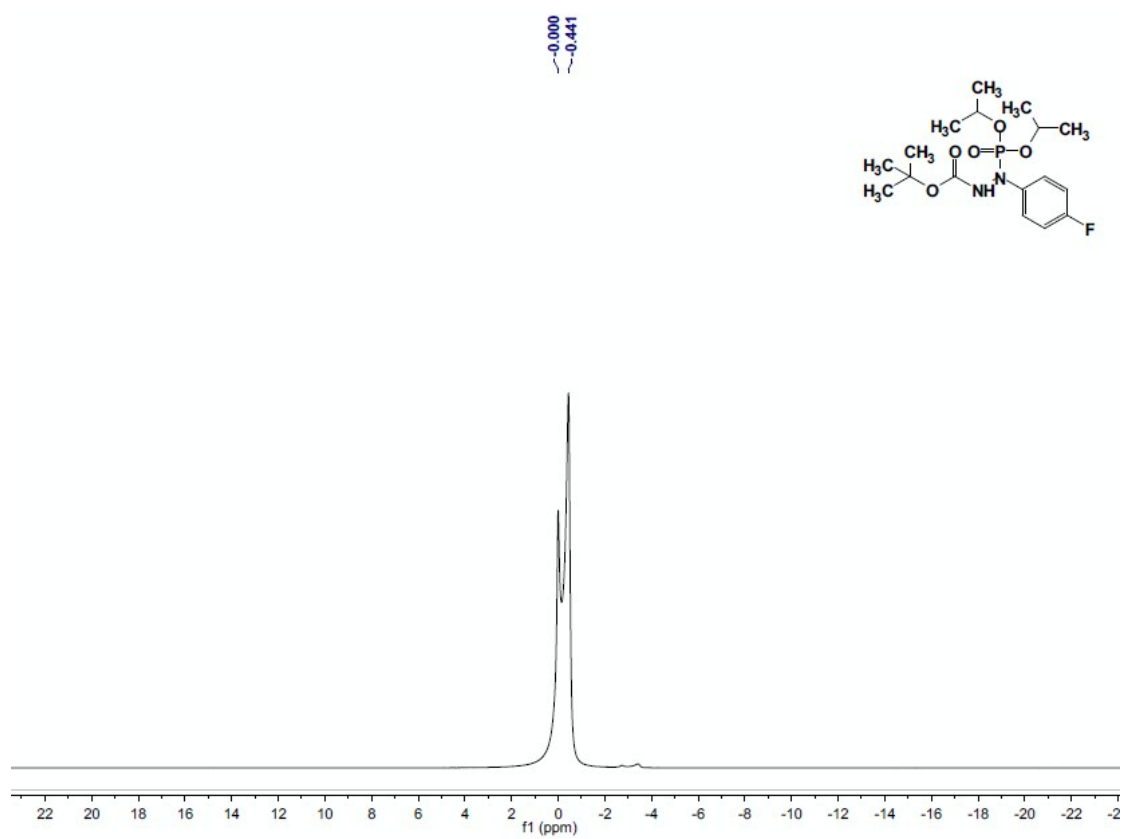
tert-Butyl 2-(diisopropoxyphosphoryl)-2-phenylhydrazinecarboxylate (3t)



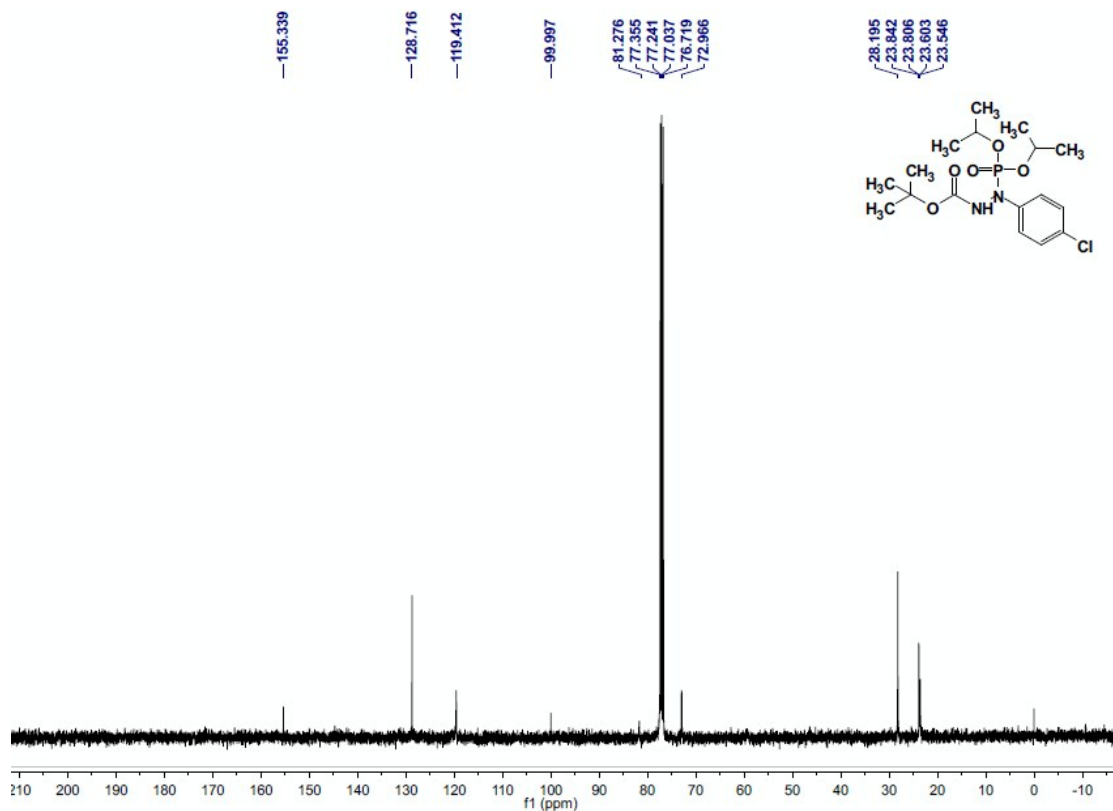
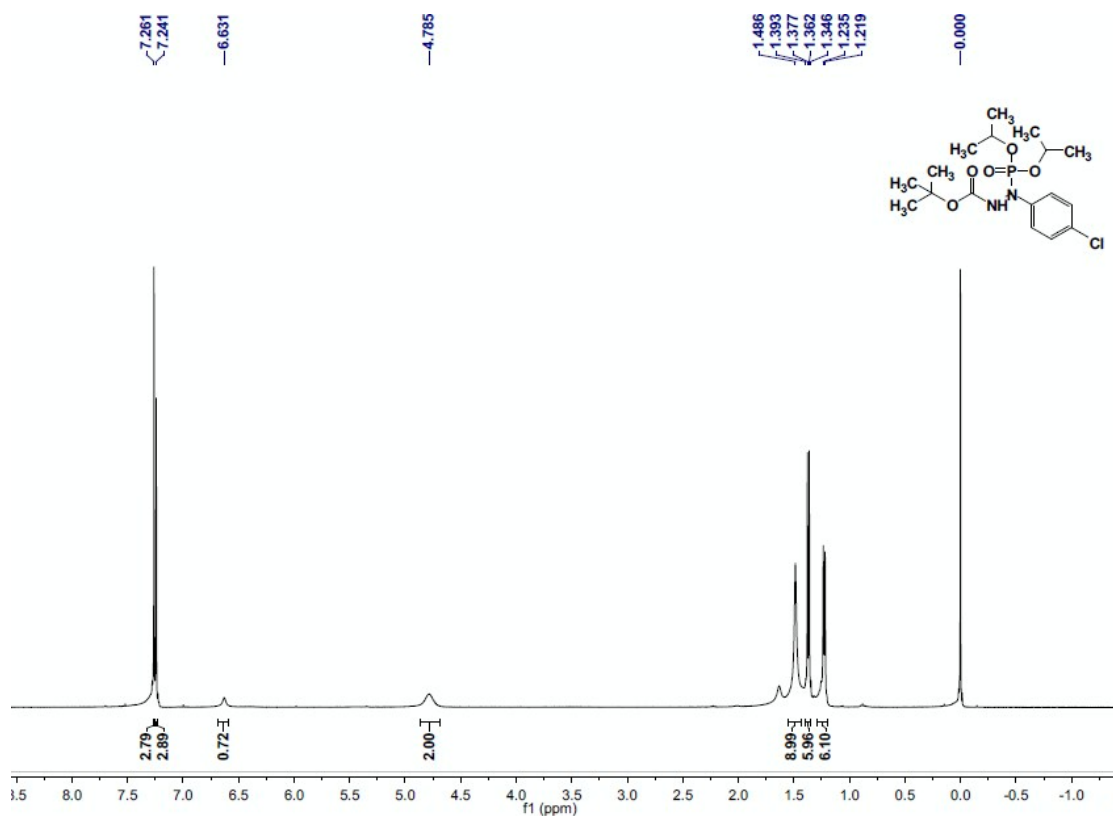


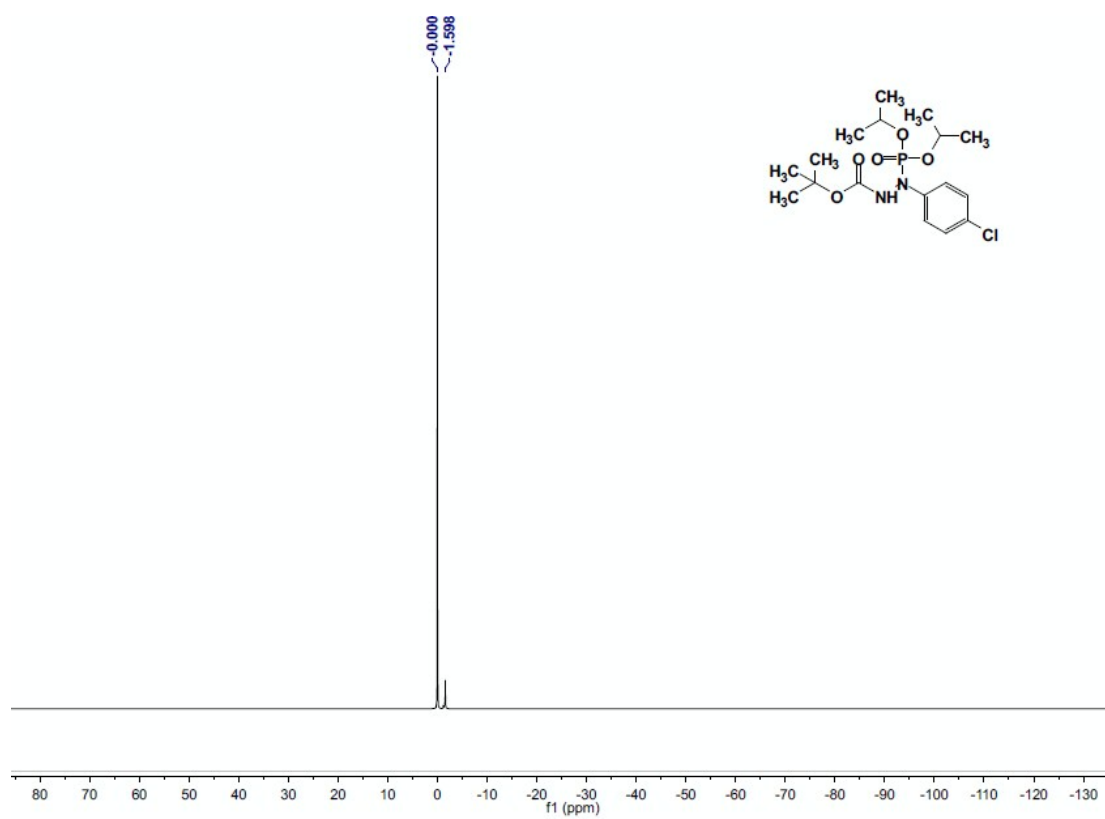
***tert*-Butyl 2-(diisopropoxyphosphoryl)-2-(4-fluorophenyl)hydrazinecarboxylate (3u)**



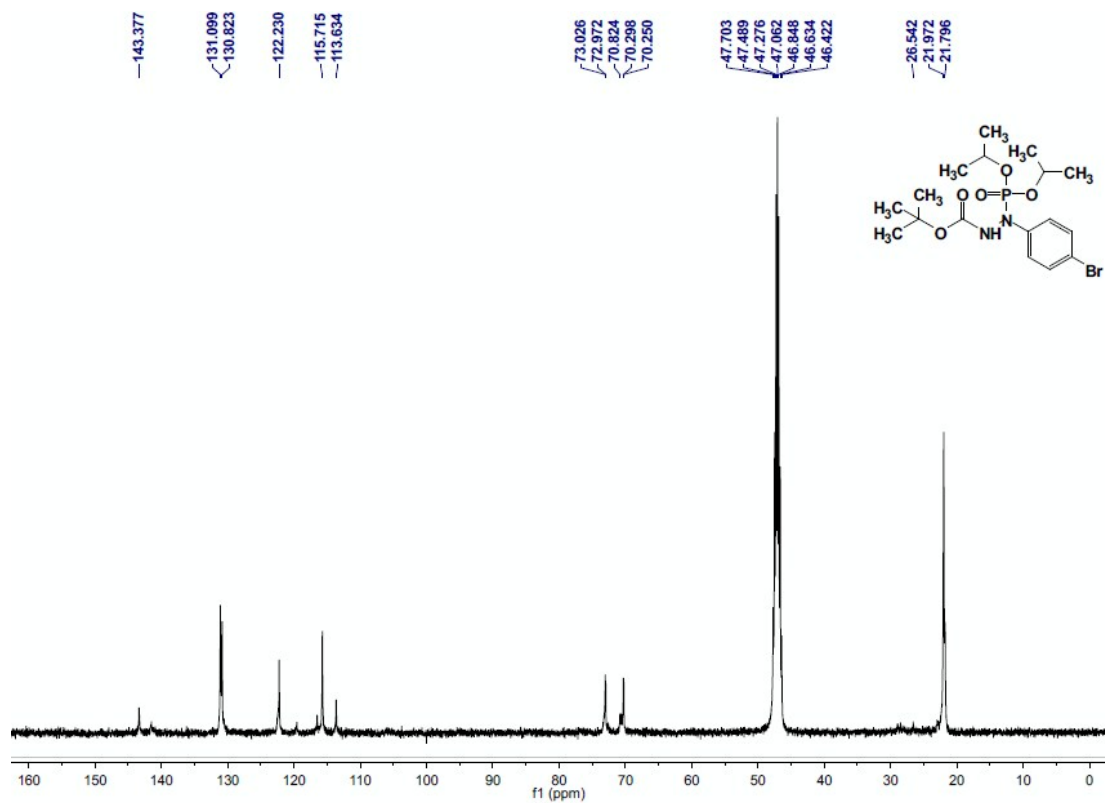
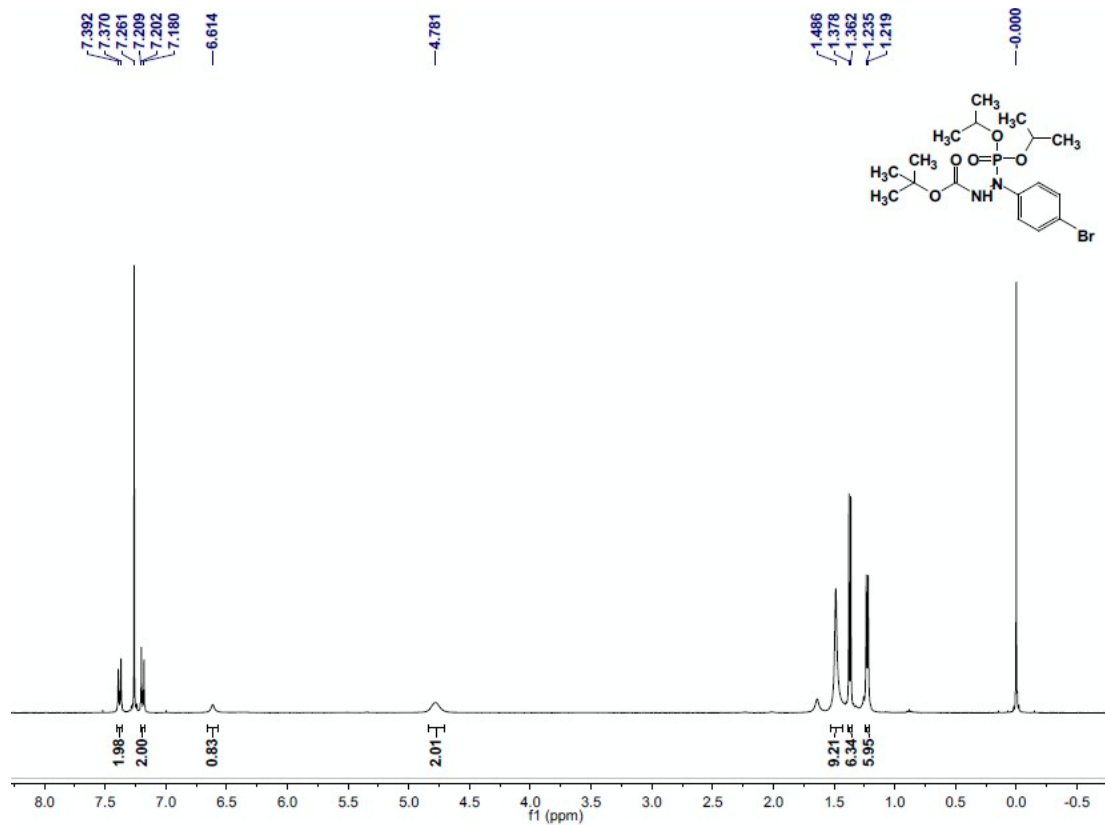


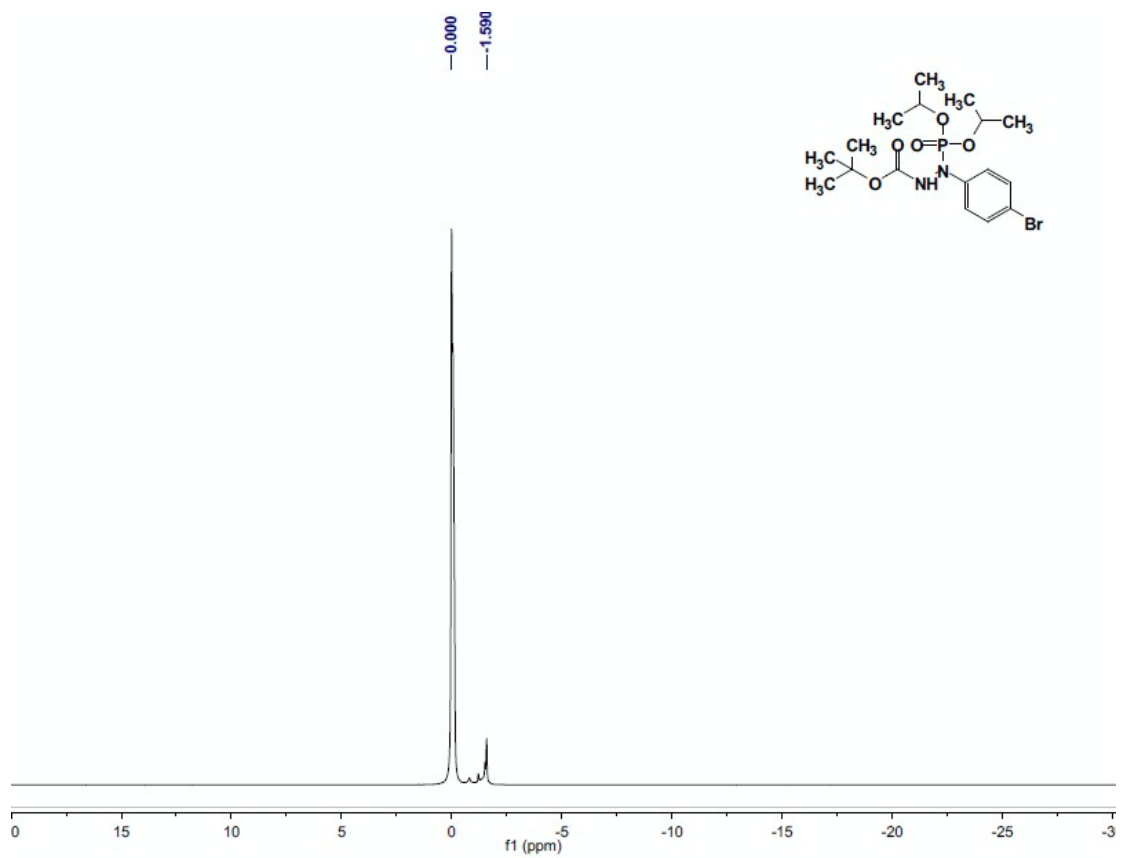
tert-Butyl 2-(4-chlorophenyl)-2-(diisopropoxyphosphoryl)hydrazinecarboxylate (**3v**)



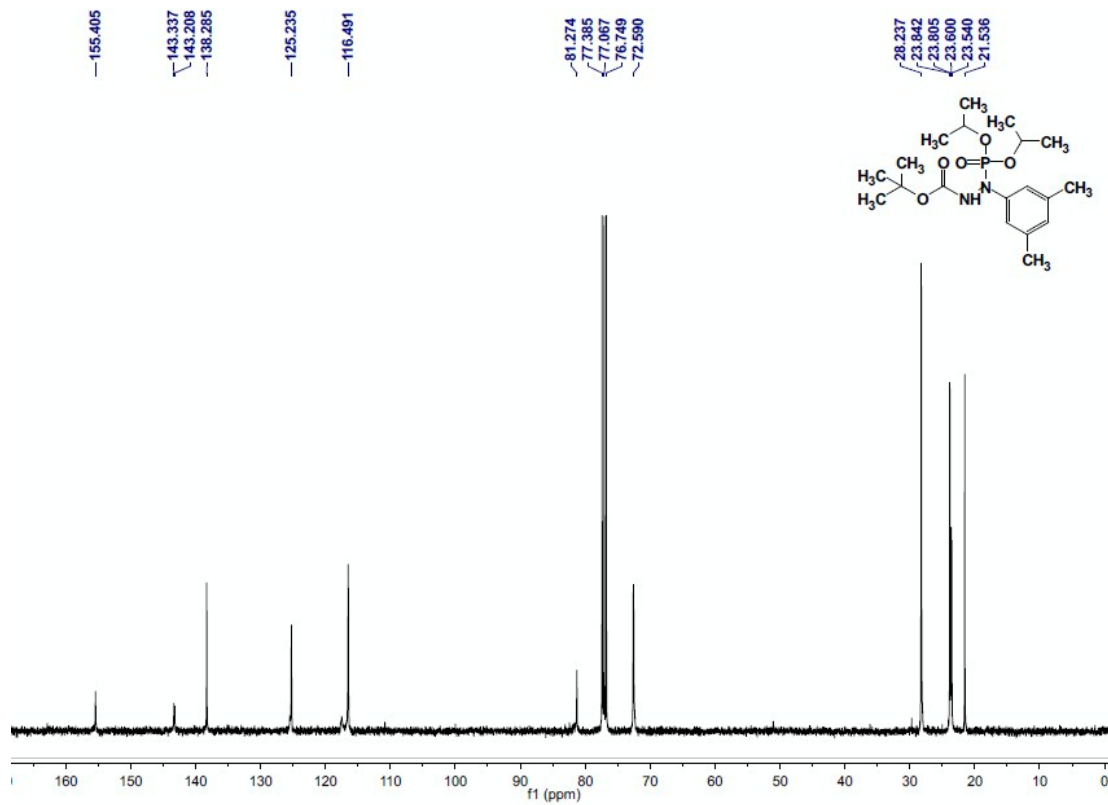
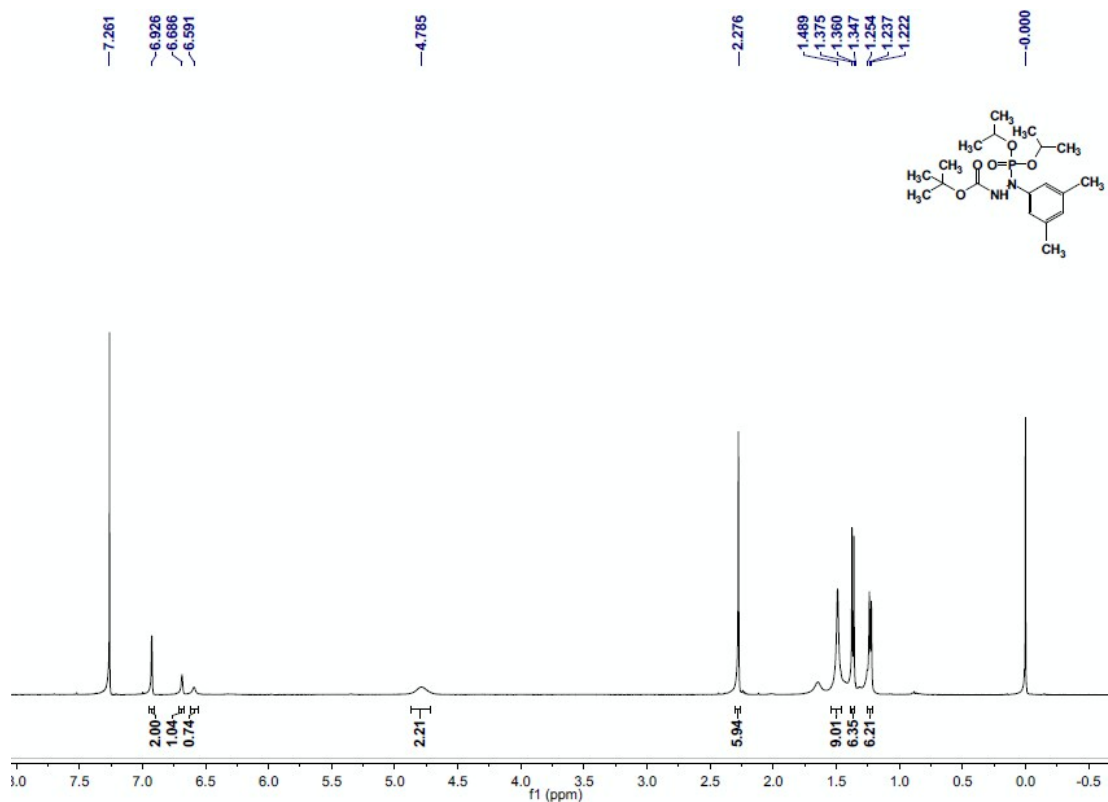


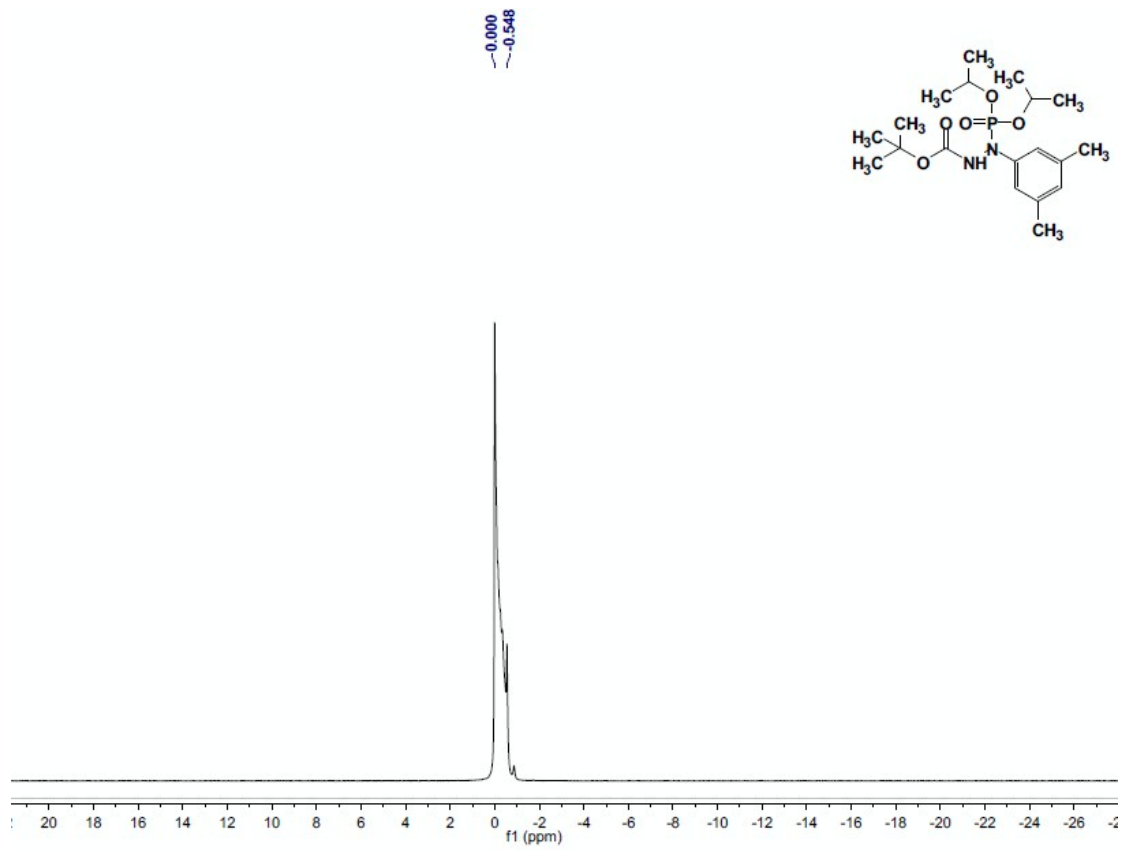
tert-Butyl 2-(4-bromophenyl)-2-(diisopropoxyphosphoryl)hydrazinecarboxylate (**3w**)



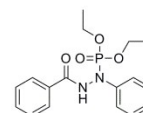
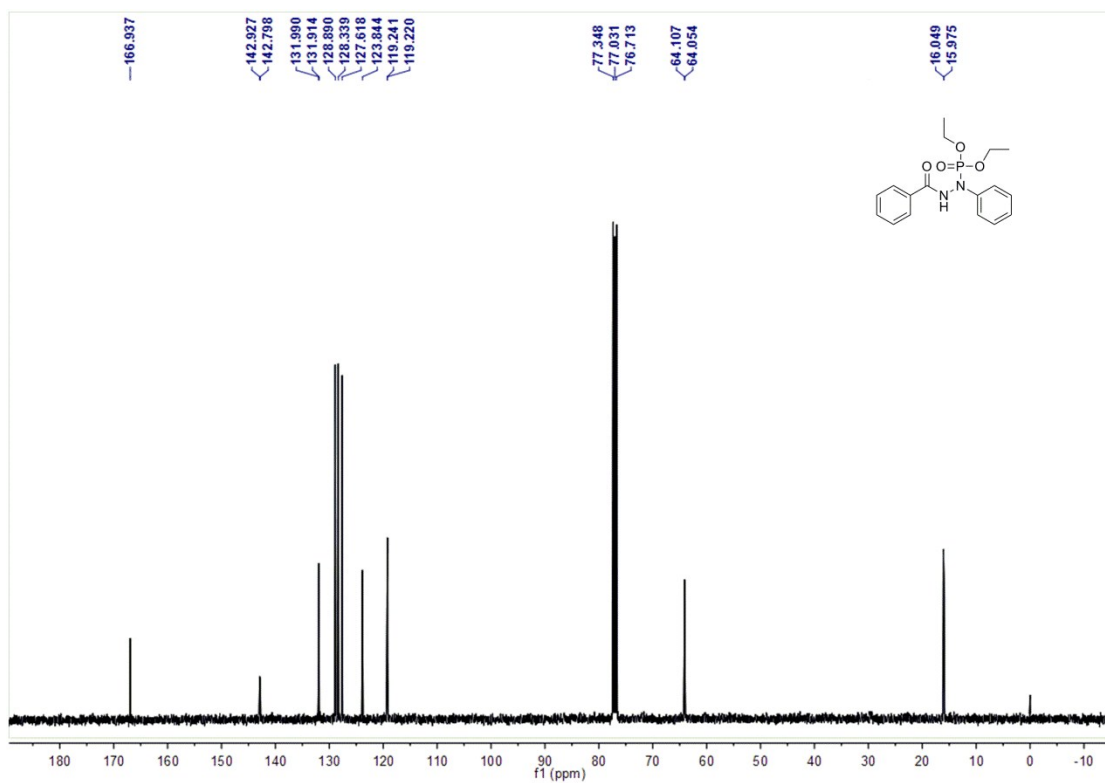
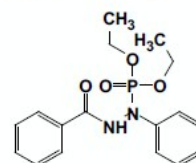
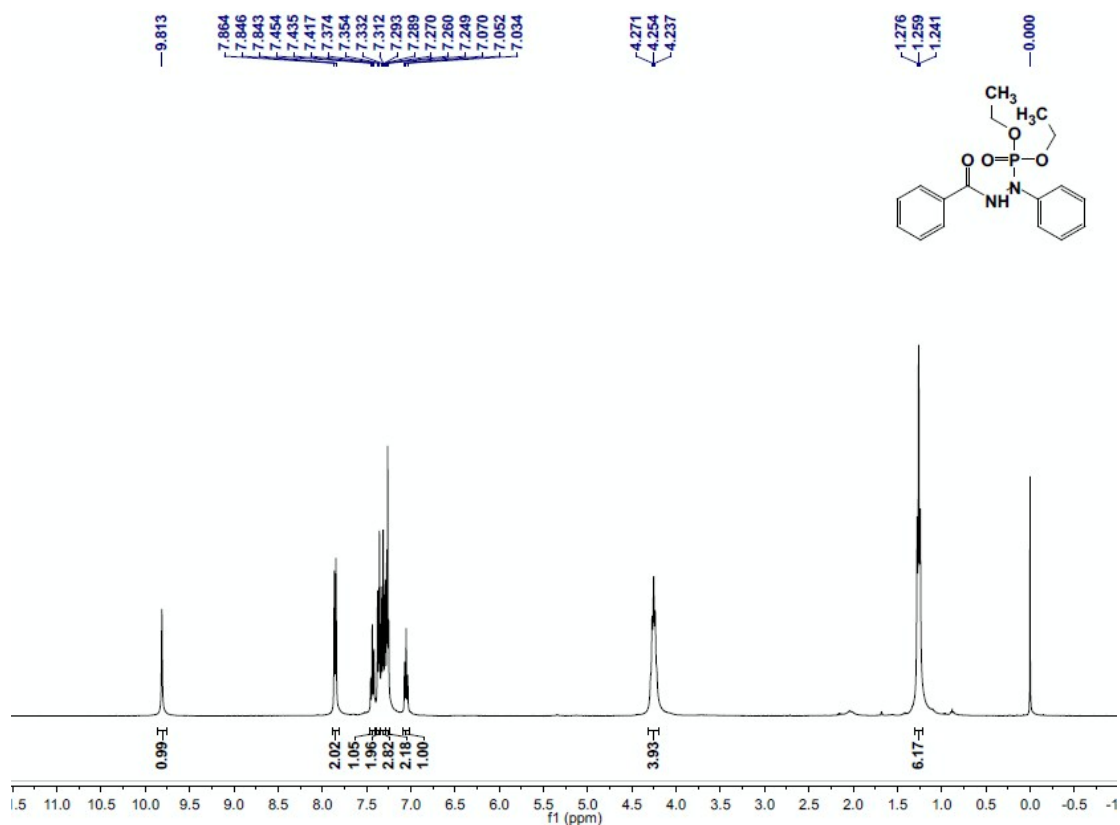


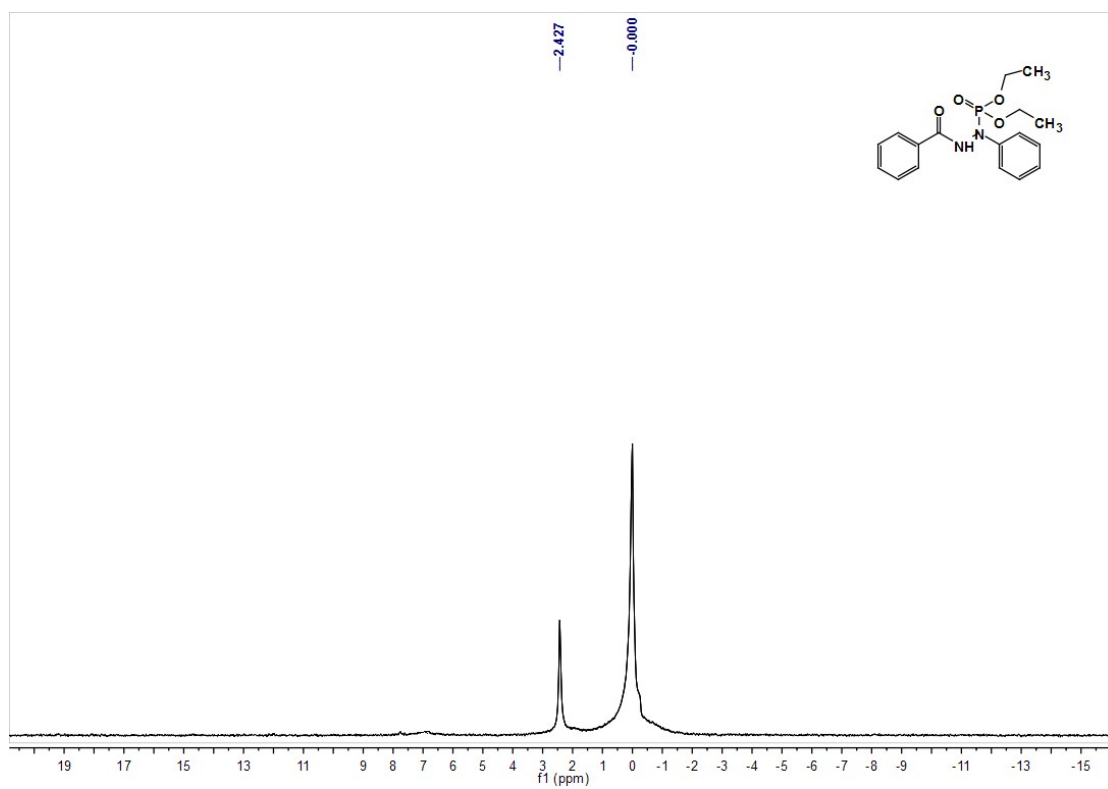
tert-Butyl 2-(diisopropoxyphosphoryl)-2-(3,5-dimethylphenyl)hydrazinecarboxylate
(3x)





Diethyl (2-benzoyl-1-phenylhydrazinyl)phosphonate (3y)





Diisopropyl (1-phenylhydrazinyl)phosphonate (4)

