Electronic Supplementary Material (ESI) for Organic & Biomolecular Chemistry

SUPPORTING INFORMATION

E-factor minimized hydrophosphonylation of aldheydes catalyzed by polystyryl-BEMP under solvent-free conditions

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CONTENTS

Experimental Section

Aldehydes **1a**, **1c**, **1f**, **1h**, and **1k** were distilled before using. All other chemicals were purchased and used without any further purification. All ^{1}H NMR and ^{13}C NMR spectra were recorded at 200 MHz or 400 MHz, and at 50.3 or 100.6 MHz respectively, using a Bruker DRX-ADVANCE 200 MHz and a Bruker DRX-ADVANCE 400 MHz spectrometers. The deuterated solvent used was $CDCl_3$, and TMS was employed as internal standard. Chemical shifts were reported in ppm and coupling constants in hertz. Thin Layer Chromatography analyses were carried out on silica gel on aluminum plates and UV and/or $KMnO_4$ were used as revealing systems.

Compounds **3a**,[1] **3b**,[2] **3c**,[2] **3d**,[3] **3e**,[2] **3f**,[4] **3g**,[2] **3h**,[5] **3i**,[6] **3j**,[1] **3k**,[2] **3l**,[7] **3m**,[8] and **4l**[9] are known compounds, product **4m** is a new compound.

References

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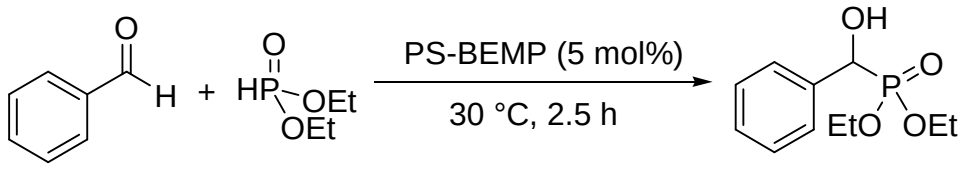
Typical procedure for PS-BEMP-catalyzed hydrophosphorylation of aldehydes under solvent-free conditions (batch procedure)



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

In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), benzaldehyde (**1a**) (0.051 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 2.5 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl-1-hydroxy-1-phenylmethylphosphonate (**3a**) as a white solid (0.122 g, 0.5 mmol, 99% yield).

PS-BEMP-catalyzed hydrophosphorylation of benzaldehyde (1a) under solvent-free conditions (cyclic continuous-flow reactor procedure)

Benzaldehyde (**1a**) (5.1 mL, 50 mmol) and **2** (6.5 mL, 50 mmol) were charged into a glass column functioning as a reservoir and PS-BEMP (1.1 g, 2.5 mmol, 2.2 mmol/g) was charged into a glass column. The reaction mixture was continuously pumped through the catalyst at 30 °C for 2.5 h until complete conversion to **3a** was achieved. At this point, the pump was left to run in order to recover the reaction mixture into the reservoir. Then MeOH (3 x 2 mL) was introduced into the system, cyclically pumped (10 min) trough the catalyst and then collected into the reservoir. After the evaporation of the solvent product **3a** was obtained in pure form as a white solid (12.2 g, 99% yield).

Recycling catalyst procedure

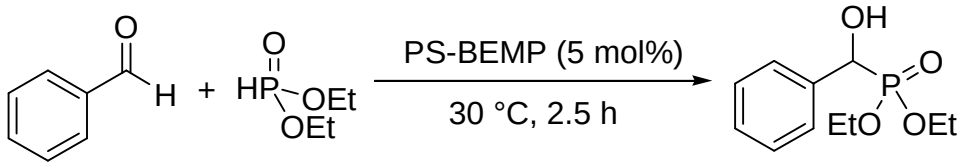
The catalyst into the column coming from the MeOH washing, was dried by flowing nitrogen and reused following the cyclic-mode flow procedure.

E-factor calculation (Waste produced (g)/ Product (g))

Batch conditions:
E-factor = [0.053 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.122 g (product)] / 0.122 g (product) = **13.0**

Cyclic continuous flow conditions:
E-factor = [5.3 g (aldehyde) + 6.9 g (diethylphosphite) + 1.1 g (PS-BEMP) + 4.75 g (MeOH) – 12.2 g (product)] / 12.2 g (product) = **0.48**

Chem. Name	**Diethyl-1-hydroxy-1-phenylmethylphosphonate** (**3a**)
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 6415-6419



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

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), benzaldehyde (**1a**) (0.051 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 2.5 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl-1-hydroxy-1-phenylmethylphosphonate (**3a**) (0.122 g, 99% yield).

E-factor = [0.053 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.122 g (product)] / 0.122 g (product) = **13.0**

Mol Formula	$C_{11}H_{17}O_4P$ (MM 244.22)	**m.p.**	82-83 °C (white solid)

TLC R_f (Eluent): 0.16 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 54.10; H, 7.02; found C, 54.07; H, 7.27.

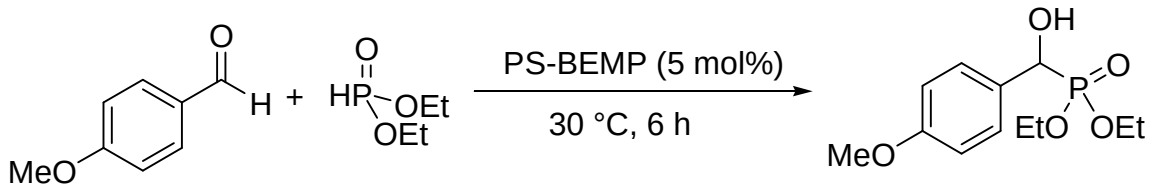
^{1}H NMR 400 MHz $CDCl_3$

δ value	No. H	Mult.	j value/Hz
1.18-1.40	6	*m*	
3.90-4.20	4	*m*	
5.02	1	*d*	10.8
7.22-7.40	3	*m*	
7.49	2	*d*	7.2

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.2, 16.2, 62.9 (*d*, $j_{P\text{-}C}$= 7.2 Hz), 63.2 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 70.5 (*d*, $j_{P\text{-}C}$= 159.8 Hz), 127.0 (*d*, $j_{P\text{-}C}$= 5.7 Hz), 127.8 (*d*, $j_{P\text{-}C}$= 2.7 Hz), 128.0 (*d*, $j_{P\text{-}C}$= 1.7 Hz), 136,7.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 25.4.

Chem. Name	**Diethyl-1-hydroxy-1-(4'-methoxyphenyl)methylphosphonate (3b)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 2864-2870



1b **2** **3b**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 4-methoxybenzaldehyde (**1b**) (0.061 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 ml, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 6 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(4'-methoxyphenyl)methylphosphonate (**3b**) (0.136 g, 99% yield).

E-factor = [0.068 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.136 g (product)] / 0.136 g (product) = **11.7**

Mol Formula	$C_{12}H_{19}O_5P$ (MM 274.25)	**m.p.**	120-122 °C (white solid)

TLC R_f (Eluent): 0.21 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 52.55; H, 6.98; found C, 52.76; H, 7.01.

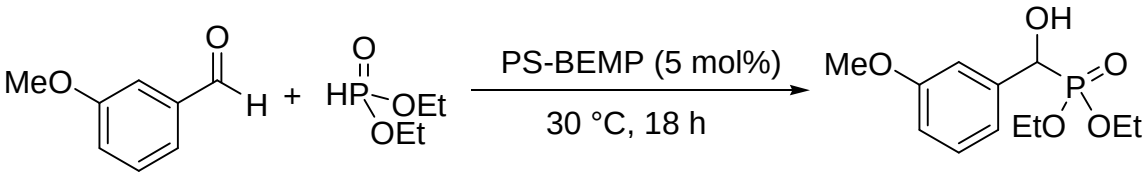
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.20	3	*t*	7.0
1.25	3	*t*	7.0
3.79	3	*s*	
3.91-4.10	4	*m*	
4.93	1	*d*	10.4
4.90-5.10	1	*bs*	
6.86	2	*d*	8.4
7.39	2	*dd*	2.0, 8.4

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.2, 16.2 (*d*, $j_{P\text{-}C}$= 3.1 Hz), 55.0, 62.8 (*d*, $j_{P\text{-}C}$= 7.2 Hz), 63.1, 70.0 (*d*, $j_{P\text{-}C}$= 161.8 Hz), 113.4, 128.4 (*d*, $j_{P\text{-}C}$= 6.0 Hz), 128.8, 159.2

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 25.8.

Chem. Name	**Diethyl-1-hydroxy-1-(3'-methoxyphenyl)methylphosphonate (3c)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 2864-2870



1c **2** **3c**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 3-methoxybenzaldehyde (**1c**) (0.061 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 18 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(3'-methoxyphenyl)methylphosphonate (**3c**) (0.135 g, 98% yield).

E-factor = [0.068 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.135 g (product)] / 0.135 g (product) = **11.8**

Mol Formula	$C_{12}H_{19}O_5P$ (MM 274.2)	**m.p.**	Light brown oil

TLC R_f (Eluent): 0.21 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 52.55; H, 6.98; found C, 52.36; H, 6.94.

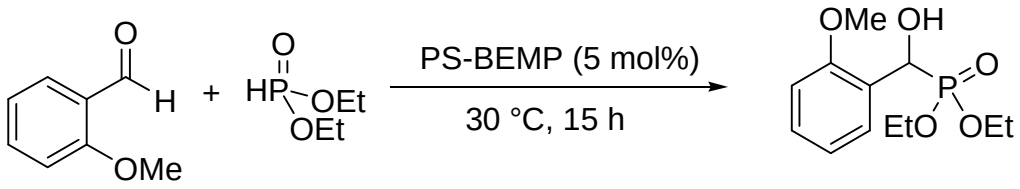
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.24	3	*t*	7.0
1.28	3	*t*	7.0
3.82	3	*s*	
3.92-4.20	4	*m*	
5.00	1	*d*	11.2
6.86	1	*d*	8.8
7.00-7.10	2	*m*	
7.20-7.32	1	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.2, 16.2, 55.1, 62.9 (*d*, $j_{P\text{-}C}$= 7.1 Hz), 63.2 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 70.5 (*d*, $j_{P\text{-}C}$= 159.8 Hz), 112.3 (*d*, $j_{P\text{-}C}$= 5.4 Hz), 113.7 (*d*, $j_{P\text{-}C}$= 2.5 Hz), 119.4 (*d*, $j_{P\text{-}C}$= 5.6 Hz), 129.0, 138.3, 159.3.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 25.2.

Chem. Name	**Diethyl 1-hydroxy-1-(2'-methoxyphenyl)methylphosphonate (3d)**
Lit. Ref.	*J. Org. Chem.* **2010**, *75*, 7498-7501



1d **2** **3d**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 2-methoxybenzaldehyde (**1c**) (0.068 g, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 15 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(2'-methoxyphenyl)methylphosphonate (**3d**) (0.132 g, 96% yield)..

E-factor = [0.068 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.132 g (product)] / 0.132 g (product) = **12.1**

Mol Formula	$C_{12}H_{19}O_5P$ (MM 274.25)	**m.p.**	57-60 °C (white solid)

TLC R_f (Eluent): 0.19 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 52.55; H, 6.98; found C, 52.29; H, 6.94.

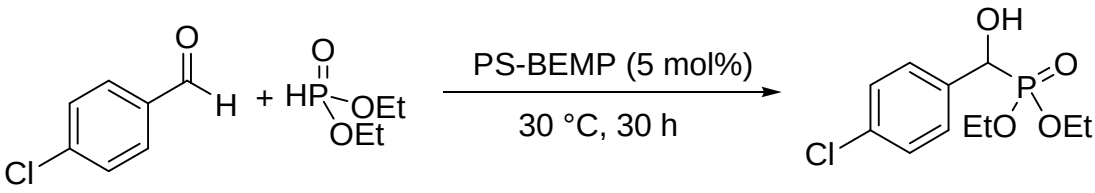
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.18	3	*t*	7.0
1.32	3	*t*	7.0
3.87	3	*s*	
3.88-4.25	4	*m*	
5.38	1	*d*	12.4
6.90	1	*d*	8.4
7.00	1	*t*	7.4
7.20-7.40	1	*m*	
7.50	1	*d*	7.6

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.1 (*d*, j_{P-C}= 5.8 Hz), 16.2 (*d*, j_{P-C}= 6.0 Hz), 55.3, 62.6 (*d*, j_{P-C}= 6.8 Hz), 62.9 (*d*, j_{P-C}= 6.9 Hz), 64.7 (*d*, j_{P-C}= 161.5 Hz), 110.2, 120.5 (*d*, j_{P-C}= 2.0 Hz), 125.2, 128.5 (*d*, j_{P-C}= 4.7 Hz), 128.9, (*d*, j_{P-C}= 2.6 Hz) 156.4 (*d*, j_{P-C}= 6.2 Hz)

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 26.3.

Chem. Name	**Diethyl-1-hydroxy-1-(4'-chlorophenyl)methylphosphonate (3e)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 2864-2870



1e **2** **3e**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 4-chlorobenzaldehyde (**1e**) (0.070 g, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 30 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(4'-chlorophenyl)methylphosphonate (**3e**) (0.137 g, 98% yield)..

E-factor = [0.070 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.137 g (product)] / 0.137 g (product) = **11.6**

Mol Formula	$C_{11}H_{16}ClO_4P$ (MM 278.67)	**m.p.**	69-71 °C (white solid)

TLC R_f (Eluent): 0.14 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 47.41; H, 5.79; found C, 47.31; H, 5.76.

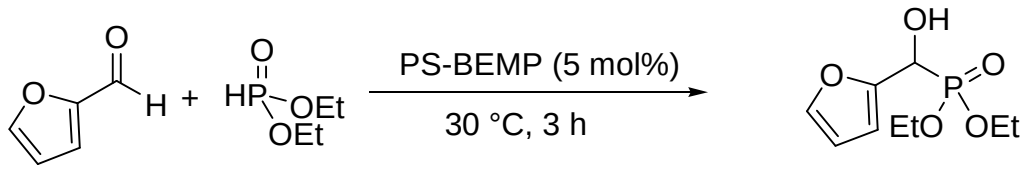
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.17-1.31	6	*m*	
3.90-4.08	4	*m*	
4.96	1	*d*	11.2
5.15-5.50	1	*bs*	
7.20-7.30	2	*m*	
7.30-7.45	2	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.1, 16.2, 62.9 (*d*, $j_{P\text{-}C}$= 7.3 Hz), 63.2 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 69.7 (*d*, $j_{P\text{-}C}$= 161.8 Hz), 128.0, 128.3 (*d*, $j_{P\text{-}C}$= 5.4 Hz), 133.4 (*d*, $j_{P\text{-}C}$= 3.5 Hz), 135.6.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 24.9.

Chem. Name	**Diethyl-1-hydroxy-1-(furan-2'-yl)methylphosphonate (3f)**
Lit. Ref.	*Tetrahedron Lett.*, **2009**, *50*, 5241-5244



1f **2** **3f**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), furfural (**1f**) (0.041 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 3 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(furan-2'-yl)methylphosphonate (**3f**) (0.116 g, 99% yield).

E-factor = [0.048 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.116 g (product)] / 0.116 g (product) = **13.7**

Mol Formula	$C_9H_{15}O_5P$ (MM 234.19)	**m.p.**	Brown oil

TLC R_f (Eluent): 0.21 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 46.16; H, 6.46; found C, 46.49; H, 6.49.

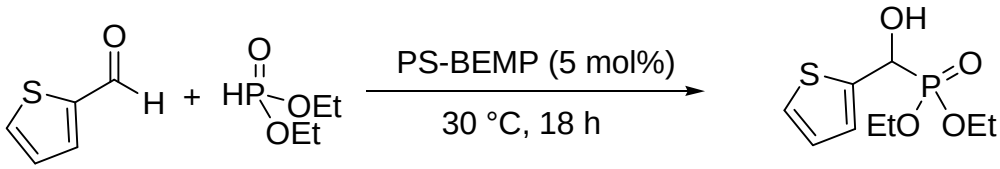
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.18	3	*t*	7.0
1.24	3	*t*	7.0
3.93-4.12	4	*m*	
4.12-4.60	1	*bs*	
4.96	1	*d*	13.6
6.31	1	*s*	
6.45	1	*s*	
7.35	1	*s*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.1, 16.2 (*d*, $j_{P\text{-}C}$= 5.4 Hz), 63.1 (*d*, $j_{P\text{-}C}$= 6.8 Hz), 63.3 (*d*, $j_{P\text{-}C}$= 6.5 Hz), 64.3 (*d*, $j_{P\text{-}C}$= 168.0 Hz), 109.0 (*d*, $j_{P\text{-}C}$= 5.9 Hz), 110.5, 142.4, 150.1.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 23.5

Chem. Name	**Diethyl-1-hydroxy-1-(thiophen-2'-yl)methylphosphonate (3g)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 2864-2870



1g **2** **3g**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 2-thiophenecarbaldehyde (**1g**) (0.047 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 18 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(thiophen-2'-yl)methylphosphonate (**3g**) (0.120 g, 96% yield).

E-factor = [0.056 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.120 g (product)] / 0.120 g (product) = **13.3**

Mol Formula	$C_9H_{15}O_4PS$ (MM 250.25)	**m.p.**	31-32 °C (brown solid)

TLC R_f (Eluent): 0.22 (ETP/AcOEt 1/1)

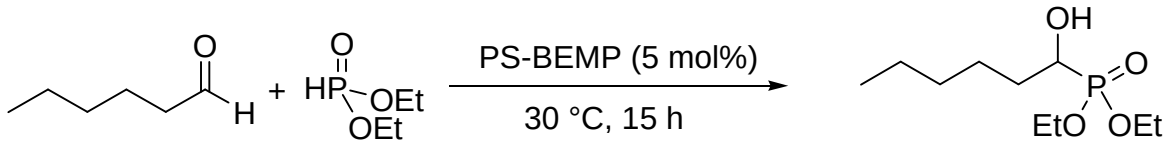
Elemental Analysis: Calcd.: C, 43.20; H, 6.04; S, 12.81; found C, 43.03; H, 6.15; S, 12.79.

^{1}H NMR 400 MHz $CDCl_3$	**δ value**	**No. H**	**Mult.**	**j value/Hz**
	1.24-1.38	6	*m*	
	4.02-4.18	4	*m*	
	5.23	1	*d*	10.8
	7.01	1	*t*	4.0
	7.19	1	*d*	2.0
	7.31	1	*t*	4.2

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.2, 16.3, 63.2 (*d*, $j_{P\text{-}C}$= 7.1 Hz), 63.6 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 66.7 (*d*, $j_{P\text{-}C}$= 167.8 Hz), 125.4 (*d*, $j_{P\text{-}C}$= 2.9 Hz), 125.9 (*d*, $j_{P\text{-}C}$= 7.5 Hz), 126.6, 139.7.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 23.6.

Chem. Name	**Diethyl-1-hydroxyhexylphosphonate (3h)**
Lit. Ref.	*Russ. J. Gen.Chem.* **2010**, *80*, 1718-1719



1h **2** **3h**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), hexanal (**1h**) (0.061 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 15 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxyhexylphosphonate (**3h**) (0.118 g, 0.5 mmol, 99% yield).

E-factor = [0.050 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.118 g (product)] / 0.118 g (product) = **13.5**

Mol Formula	$C_{10}H_{23}O_4P$ (MM 238.26)	**m.p.**	Colorless oil

TLC R_f (Eluent): 0.23 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 50.41; H, 9.73; found C, 50.55; H, 9.61.

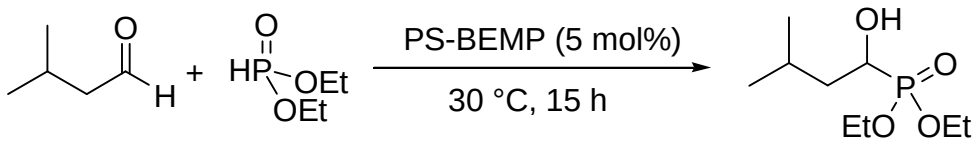
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
0.81	3	*t*	6.8
1.15-1.40	11	*m*	
1.50-1.70	3	*m*	
3.70-3.85	1	*m*	
4.04-4.20	4	*m*	
4.40-4.55	1	*bs*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 13.8, 16.3, 16.3, 22.4, 25.3 (*d*, $j_{P\text{-}C}$= 13.3 Hz), 31.2, 31.4, 62.2 (*d*, $j_{P\text{-}C}$= 7.1 Hz), 62.4 (*d*, $j_{P\text{-}C}$= 7.0 Hz), 67.5 (*d*, $j_{P\text{-}C}$= 160.6 Hz)

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 29.6.

Chem. Name	**Diethyl-1-hydroxy-3-methylbutylphosphonate (3i)**
Lit. Ref.	*Tetrahedron: Asymmetry*, **1994**, *5*, 1965-1972



1i **2** **3i**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), isovaleraldehyde (**1i**) (0.054 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 15 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-3-methylbutylphosphonate (**3i**) (0.109 g, 97% yield).

E-factor = [0.043 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.109 g (product)] / 0.109 g (product) = **14.6**

Mol Formula	$C_9H_{21}O_4P$ (MM 224.23)	**m.p.**	Colorless oil

TLC R_f (Eluent): 0.27 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 48.21; H, 9.44; found C, 48.47; H, 9.56.

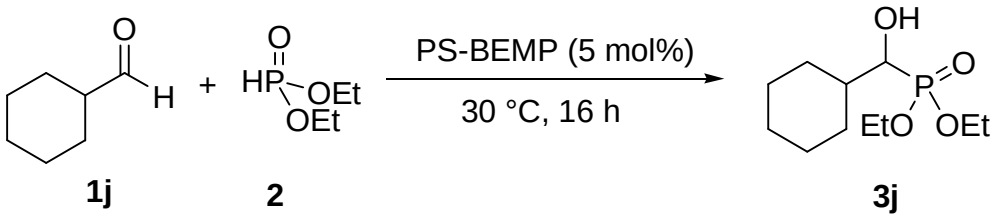
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
0.92	3	*d*	6.8
0.97	3	*d*	6.8
1.32-1.40	6	*m*	
1.45-1.55	1	*m*	
1.60-1.75	1	*m*	
1.85-2.00	1	*m*	
3.92-3.97	1	*m*	
4.10-4.25	4	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.3, 16.4, 20.9, 23.3, 23.8 (*d*, $j_{P\text{-}C}$= 14.0 Hz), 39.8, 62.3 (*d*, $j_{P\text{-}C}$= 7.0 Hz), 62.4 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 65.6 (*d*, $j_{P\text{-}C}$= 161.5 Hz).

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 29.7.

Chem. Name	**Diethyl-cyclohexyl(hydroxy)methylphosphonate (3j)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 6415-6419



1j **2** **3j**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), cycloehexanecarboxyaldehyde (**1j**) (0.061 mL, 0.5 mmol), diethyl phosphite (**2a**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 16 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl cyclohexyl(hydroxy)methylphosphonate (**3j**) (0.120 g, 96% yield).

E-factor = [0.056 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.120 g (product)] / 0.120 g (product) = **13.3**

Mol Formula	$C_{11}H_{23}O_4P$ (MM 250.27)	**m.p.**	Colorless oil

TLC R_f (Eluent): 0.25 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 52.79; H, 9.26; found C, 52.57; H, 9.39.

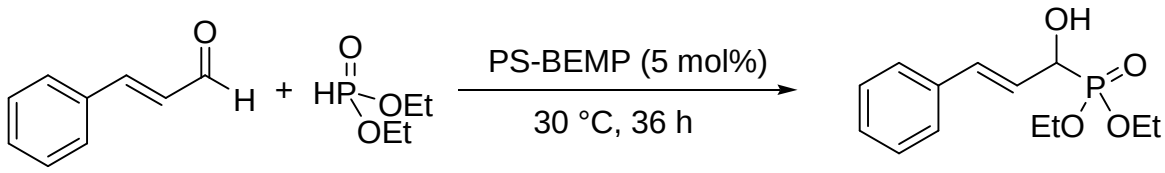
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.00-1.38	11	*m*	
1.60-1.90	5	*m*	
2.00	1	*d*	12.4
2.36	1	*bs*	
3.60-3.70	1	*m*	
4.10-4.25	4	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.3, 16.4, 25.8, 26.0, 26.1, 27.7 (*d*, $j_{P\text{-}C}$= 7.4 Hz), 29.7 (*d*, $j_{P\text{-}C}$= 8.8 Hz), 39.6, 62.2 (*d*, $j_{P\text{-}C}$= 6.8 Hz), 62.3 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 72.3 (*d*, $j_{P\text{-}C}$= 156.7 Hz).

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 29.0.

Chem. Name	**(*E*)-Diethyl-1-hydroxy-3-phenylallylphosphonate (3k)**
Lit. Ref.	*Tetrahedron,* **2008**, *64*, 2864-2870



1k **2** **3k**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), cinnamaldehyde (**1k**) (0.063 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 36 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give (*E*)-diethyl 1-hydroxy-3-phenylallylphosphonate (**3k**) (0.130 g, 96% yield).

E-factor = [0.066 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.130 g (product)] / 0.130 g (product) = **12.3**

Mol Formula	$C_{13}H_{19}O_4P$ (MM 270.26)	**m.p.**	97-98 °C (pale yellow solid)

TLC R_f (Eluent): 0.15 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 57.77; H, 7.09; found C, 55.56; H, 7.16.

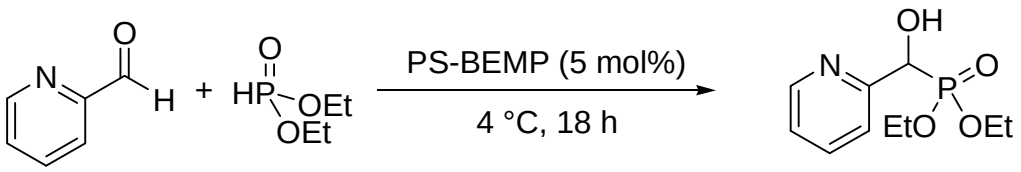
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.34	6	*dd*	2.3, 7.0
4.10-4.30	4	*m*	
4.67	1	*dd*	4.8, 12.8
6.32	1	*dt*	5.7, 15.9
6.78	1	*dd*	4.2, 15.8
7.20-7.28	2	*m*	
7.33	2	*t*	7.4
7.40	2	*d*	7.6

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.4, 16.5, 63.0 (*d*, $j_{P\text{-}C}$= 7.2 Hz), 63.3 (*d*, $j_{P\text{-}C}$= 7.0 Hz), 69.3 (*d*, $j_{P\text{-}C}$= 162.0 Hz), 124.2 (*d*, $j_{P\text{-}C}$= 3.7 Hz), 126.6, 127.7, 128.5, 132.1, 136.5.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 25.4.

Chem. Name	**Diethyl 1-hydroxy-1-(pyridin-2'-yl)methylphosphonate (3l)**
Lit. Ref.	*Heteroatom Chem.* **2007**, *18*, 347-353



1l **2** **3l**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 2-pyridinecarboxaldehyde (**1l**) (0.047 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 4 °C for 18 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(pyridin-2'-yl)methylphosphonate (**3l**) (0.115 g, 94% yield).

E-factor = [0.054 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.115 g (product)] / 0.115 g (product) = **13.9**

Mol Formula	$C_{10}H_{16}NO_4P$ (MM 245.21)	**m.p.**	Pale yellow oil

TLC R_f (Eluent): 0.23 (DCM/MeOH 99/1)

Elemental Analysis: Calcd.: C, 48.98; H, 6.58; N, 5.71; found C, 49.30; H, 6.67; N, 5.74.

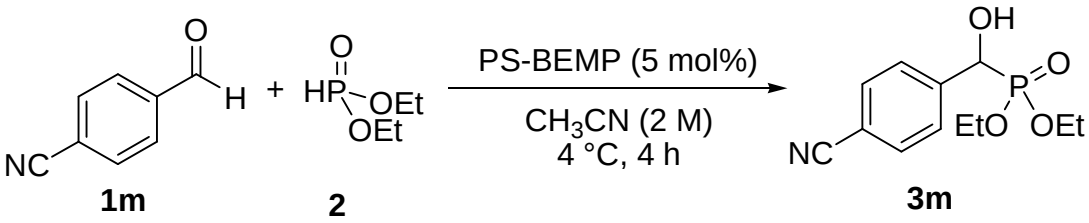
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.18	3	*t*	7.2
1.35	3	*t*	7.0
3.92-4.09	2	*m*	
4.10-4.30	2	*m*	
5.11	1	*d*	10.8
5.20-5.30	1	*bs*	
7.20-7.30	1	*m*	
7.55	1	*d*	8.0
7.70-7.74	1	*m*	
8.58	1	*d*	4.8

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.1 (*d*, $j_{P\text{-}C}$= 5.7 Hz), 16.2 (*d*, $j_{P\text{-}C}$= 5.8 Hz), 62.8 (*d*, $j_{P\text{-}C}$= 7.0 Hz), 63.1 (*d*, $j_{P\text{-}C}$= 6.8 Hz), 69.9 (*d*, $j_{P\text{-}C}$= 160.7 Hz), 122.1 (*d*, $j_{P\text{-}C}$= 3.2 Hz), 122.8, 136.5, 147.8, 154.0.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 23.5.

Chem. Name	**Diethyl-1-hydroxy-1-(4'-cyanoyphenyl)methylphosphonate (3m)**
Lit. Ref.	*Organometallics* **2009**, *28*, 6206-6212



METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 4-cyanobenzaldehyde (**1m**) (0.066 g, 0.5 mmol) were suspended in acetonitrile (0.25 mL). Then, diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) was added and the resulting mixture was left under stirring at 4 °C. After 4 hours (monitored by TLC), the PS-BEMP was filtered with a buchner funnel and washed with 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1'-hydroxy-1-(4-cyanoyphenyl)methylphosphonate (**3m**) (0.129 g, 96% yield).

E-factor = [0.066 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 0.79 (ACN) + 0.79 g (MeOH) – 0.129 g (product)] / 0.129 g (product) = **12.4**

Mol Formula	$C_{12}H_{16}NO_4P$ (MM269.23)	**m.p.**	Colorless oil

TLC R_f (Eluent): 0.18 (ETP/AcOEt 1/1)

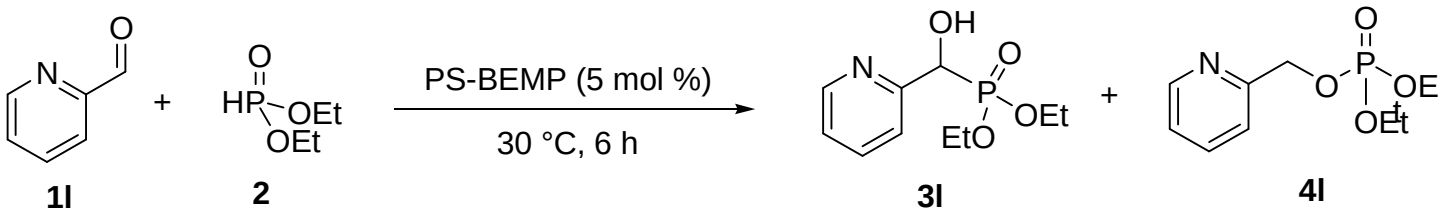
Elemental Analysis: Calcd.: C, 53.53; H, 5.99; N, 5.20; found C, 53.67; H, 5.82; N, 5.27.

^{1}H NMR 400 MHz $CDCl_3$	**δ value**	**No. H**	**Mult.**	**j value/Hz**
	1.26	6	*dd*	8.2, 15.4
	4.00-4.20	4	*m*	
	5.11	1	*d*	12.0
	7.55-7.75	4	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 16.3, 63.2 (*d*, $j_{P\text{-}C}$= 7.4 Hz), 63.8 (*d*, $j_{P\text{-}C}$= 7.1 Hz), 70.1 (*d*, $j_{P\text{-}C}$= 158.9 Hz), 111.5, 118.7, 127.6 (*d*, $j_{P\text{-}C}$= 5.0 Hz), 131.8, 142.4.

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 23.9.

Chem. Name	**Diethyl-1-hydroxy-1-(pyridin-2'-yl)methylphosphonate (3l)** **Diethyl pyrydin-2'-ylmethyl phosphate (4l)**
Lit. Ref.	*Inorg. Chim. Acta* **2005**, *358,* 2464-2472



1l **2** **3l** **4l**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 2-pyridinecarboxaldehyde (**1l**) (0.047 mL, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 6 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl 1-hydroxy-1-(pyridin-2'-yl)methylphosphonate (**3l**) and diethyl pyrydin-2'-ylmethyl phosphate (**4l**) as an inseparable mixture (0.120 g, 98% yield, **3l**/**4l** 40/60).

E-factor = [0.054 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.120 g (product)] / 0.120 g (product) = **13.3**

Mol Formula	$C_{10}H_{16}NO_4P$ (MM 245.21)	**m.p.**	Pale yellow oil

TLC R_f (Eluent): 0.23 (DCM/MeOH 99/1)

Elemental Analysis: Calcd.: C, 48.98; H, 6.58; N, 5.71; found C, 49.60; H, 6.71; N, 5.29.

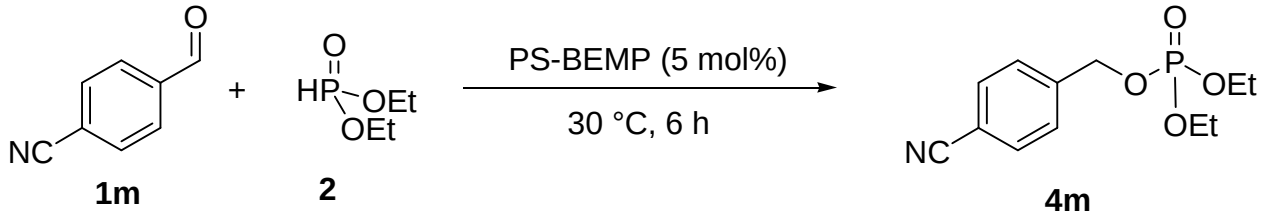
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.19	3 (**3l**)	*t*	7.0
1.34	3 (**3l**) + 6 (**4l**)	*m*	
3.93-4.12	2 (**3l**)	*m*	
4.12-4.30	2 (**3l**) + 4 (**4l**)	*m*	
5.12	1 (**3l**)	*d*	10.8
5.17	2 (**4l**)	*d*	8.0
7.21-7.28	1 (**3l**) + 1 (**4l**)	*m*	
7.51	1 (**4l**)	*d*	8.0
7.57	1 (**3l**)	*d*	7.6
7.72-7.80	1 (**3l**) + 1 (**4l**)	*m*	
8.58-8.65	1 (**3l**) + 1 (**4l**)	*m*	

^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 15.7, 15.8, 16.0, 16.1 (*d*, $j_{P\text{-}C}$= 6.1 Hz), 62.7 (*d*, $j_{P\text{-}C}$= 6.9 Hz), 63.0 (*d*, $j_{P\text{-}C}$= 6.8 Hz), 63.7, 63.7, 68.8 (*d*, $j_{P\text{-}C}$= 5.2 Hz), 70.0 (*d*, $j_{P\text{-}C}$= 160.8 Hz), 120.9, 122.0, 122.7, 122.7, 136.4, 136.6, 147.7, 148.8, 154.1, 155.6 (*d*, $j_{P\text{-}C}$= 8.6 Hz).

^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 3.0, 23.4.

Chem. Name	**Diethyl-(4-cyanophenyl)methyl phosphate (4m)**
Lit. Ref.	



1m **2** **4m**

METHOD:
In a screw capped vial equipped with a magnetic stirrer, PS-BEMP (0.011 g, 0.025 mmol, 2.2 mmol/g), 4-cyanobenzaldehyde (**1m**) (0.066 g, 0.5 mmol), diethyl phosphite (**2**) (0.065 mL, 0.5 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C for 6 hours (monitored by TLC). Then, methanol (1.0 mL) was added, the mixture was stirred for 5 minutes, the PS-BEMP was filtered with a buchner funnel and washed with additional 1.0 mL of methanol. The solvent was evaporated under vacuum to give diethyl (4-cyanophenyl)methyl phosphate (**4m**) (0.133 g, 99% yield).

E-factor = [0.066 g (aldehyde) + 0.069 g (diethylphosphite) + 0.011 g (PS-BEMP) + 1.58 g (MeOH) – 0.133 g (product)] / 0.133 g (product) = **12.0**

Mol Formula	$C_{12}H_{16}NO_4P$ (MM 269.23)	**m.p.**	Colorless oil

TLC R_f (Eluent): 0.17 (ETP/AcOEt 1/1)

Elemental Analysis: Calcd.: C, 53.53; H, 5.99; N, 5.20; found C, 53.84; H, 5.86; N, 5.28.

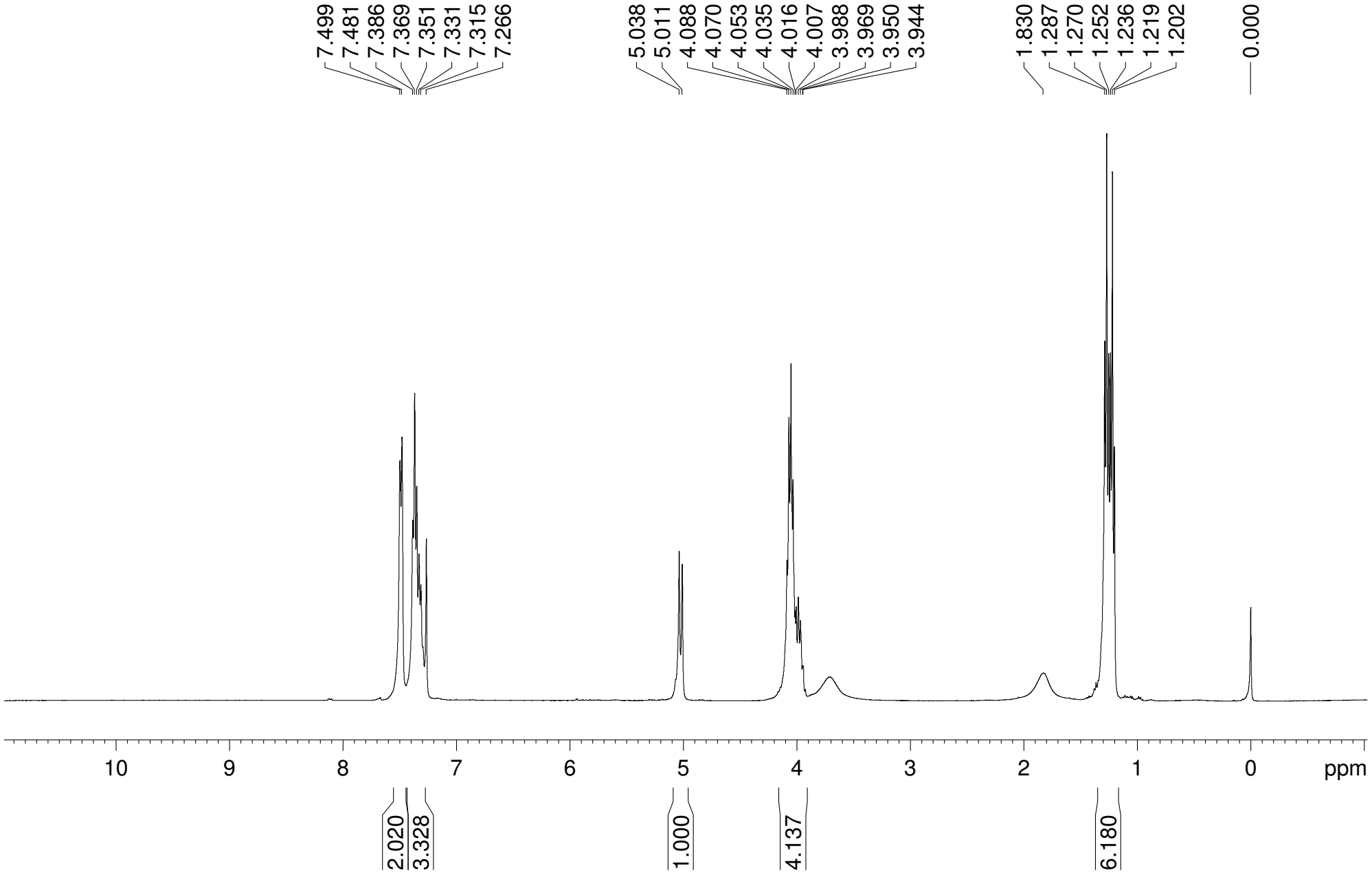
^{1}H NMR 400 MHz $CDCl_3$

δ value	**No. H**	**Mult.**	**j value/Hz**
1.33	6	*t*	7.0
4.10-4.20	4	*m*	
5.12	2	*d*	8.0
7.50	2	*d*	8.0
7.67	2	*d*	8.0

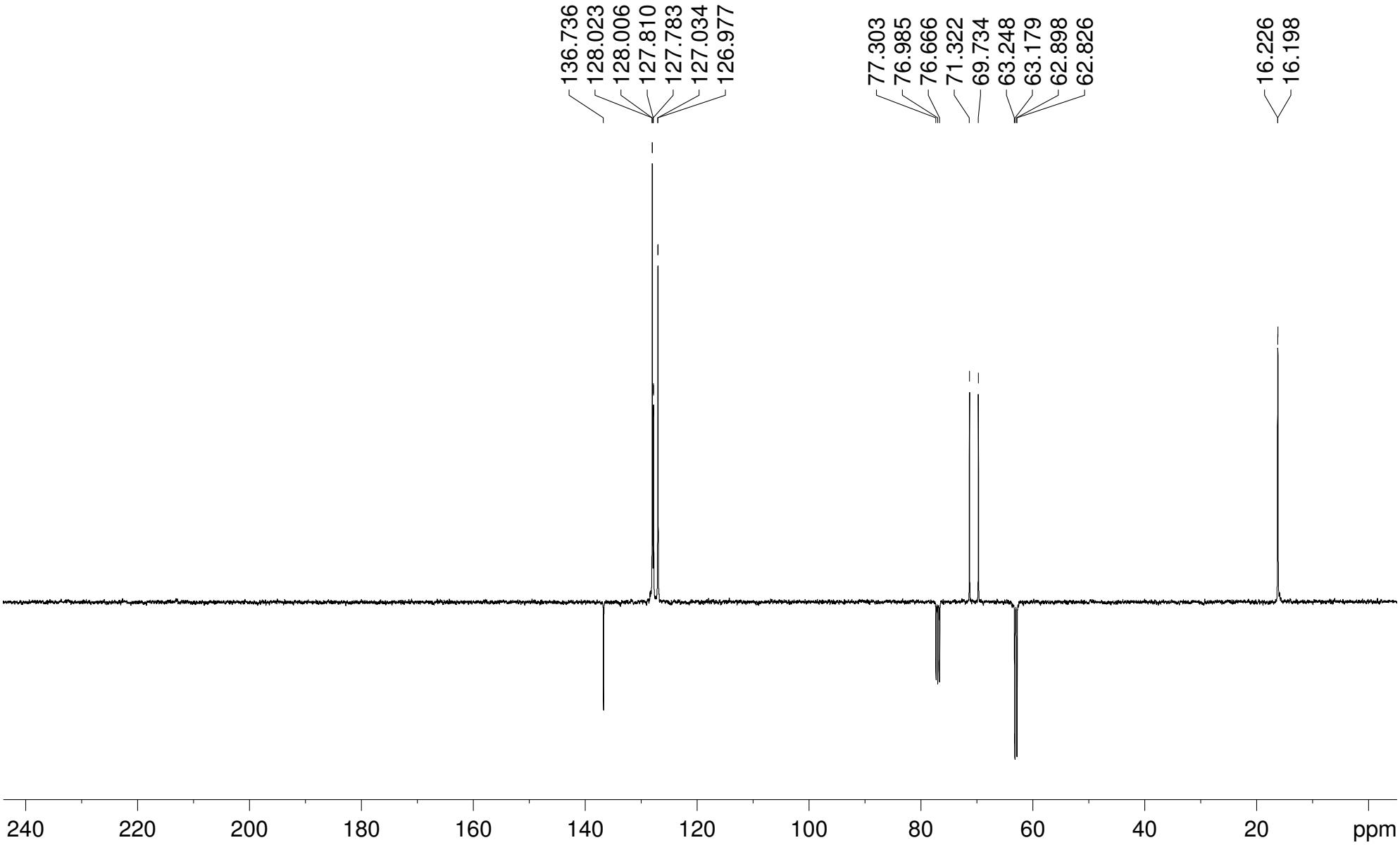
^{13}C NMR (100.6 MHz, $CDCl_3$) δ : 15.7, 15.8, 63.8 (*d*, $j_{P\text{-}C}$= 5.8 Hz), 67.3 (*d*, $j_{P\text{-}C}$= 5.0 Hz), 111.7, 118.2, 127.5, 132.0, 141.0 (*d*, $j_{P\text{-}C}$= 7.0 Hz).

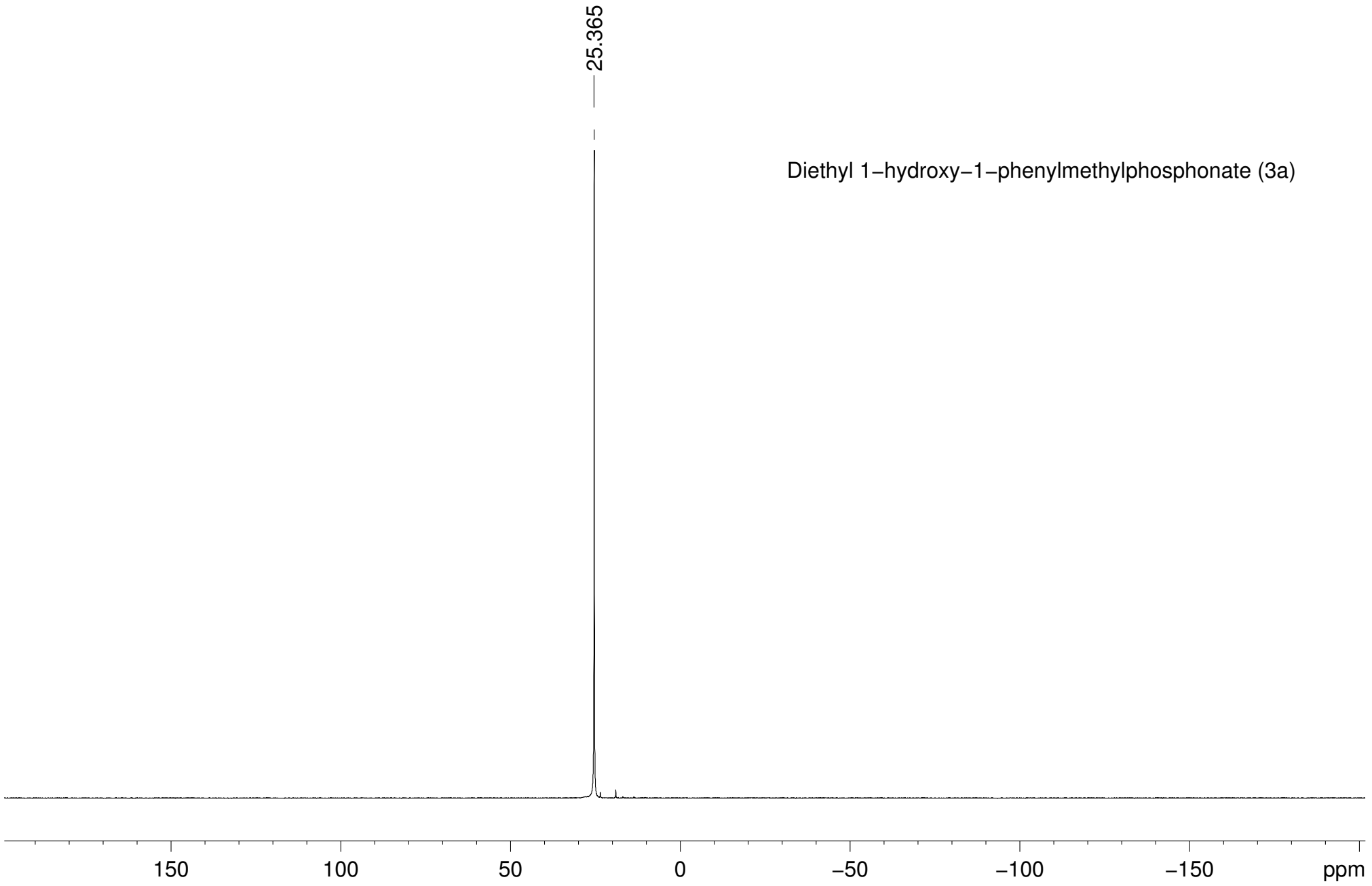
^{31}P NMR (161.9 MHz, $CDCl_3$) δ : 3.1.

Diethyl 1–hydroxy–1–phenylmethylphosphonate (3a)

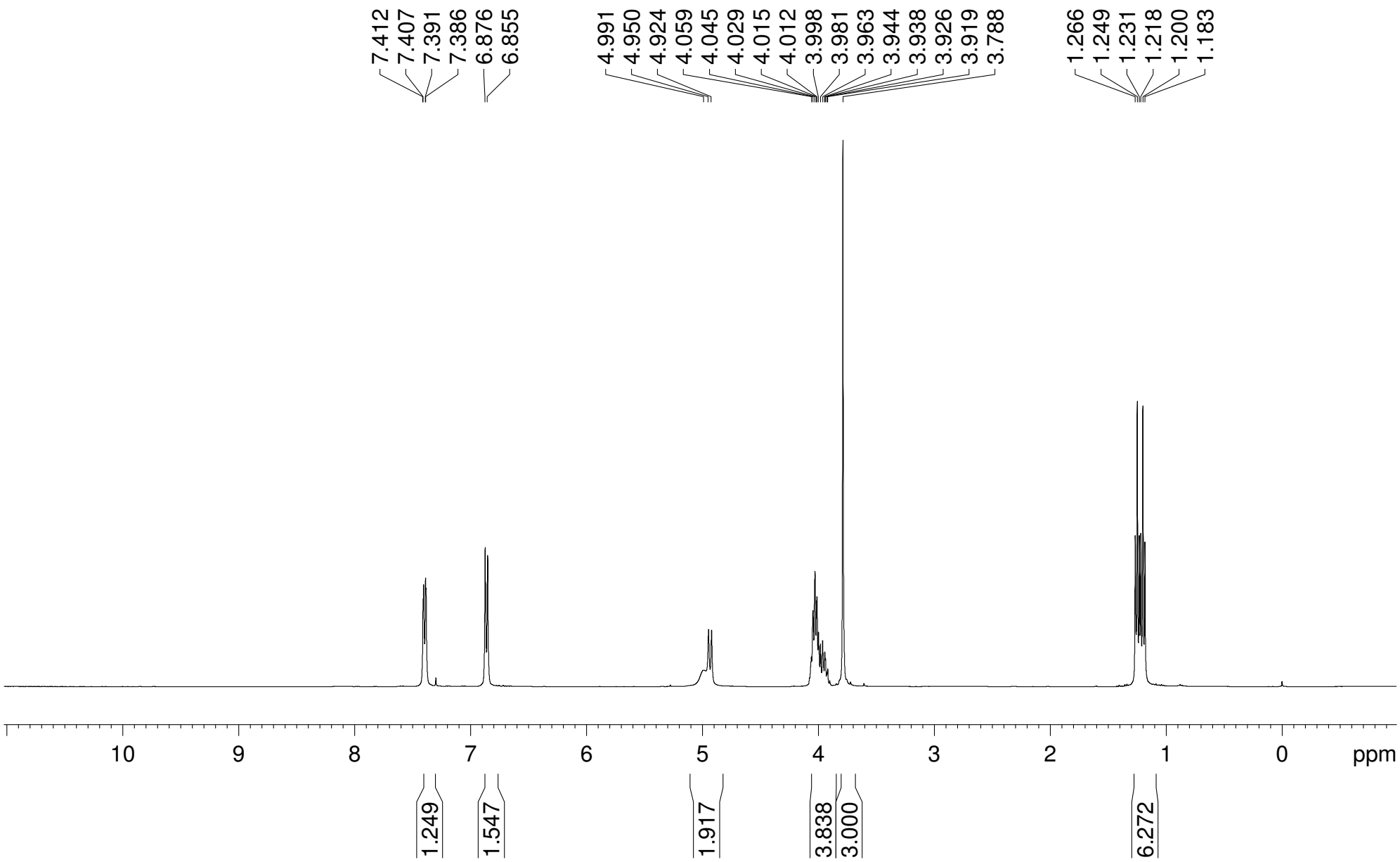


Diethyl 1−hydroxy−1−phenylmethylphosphonate (3a)

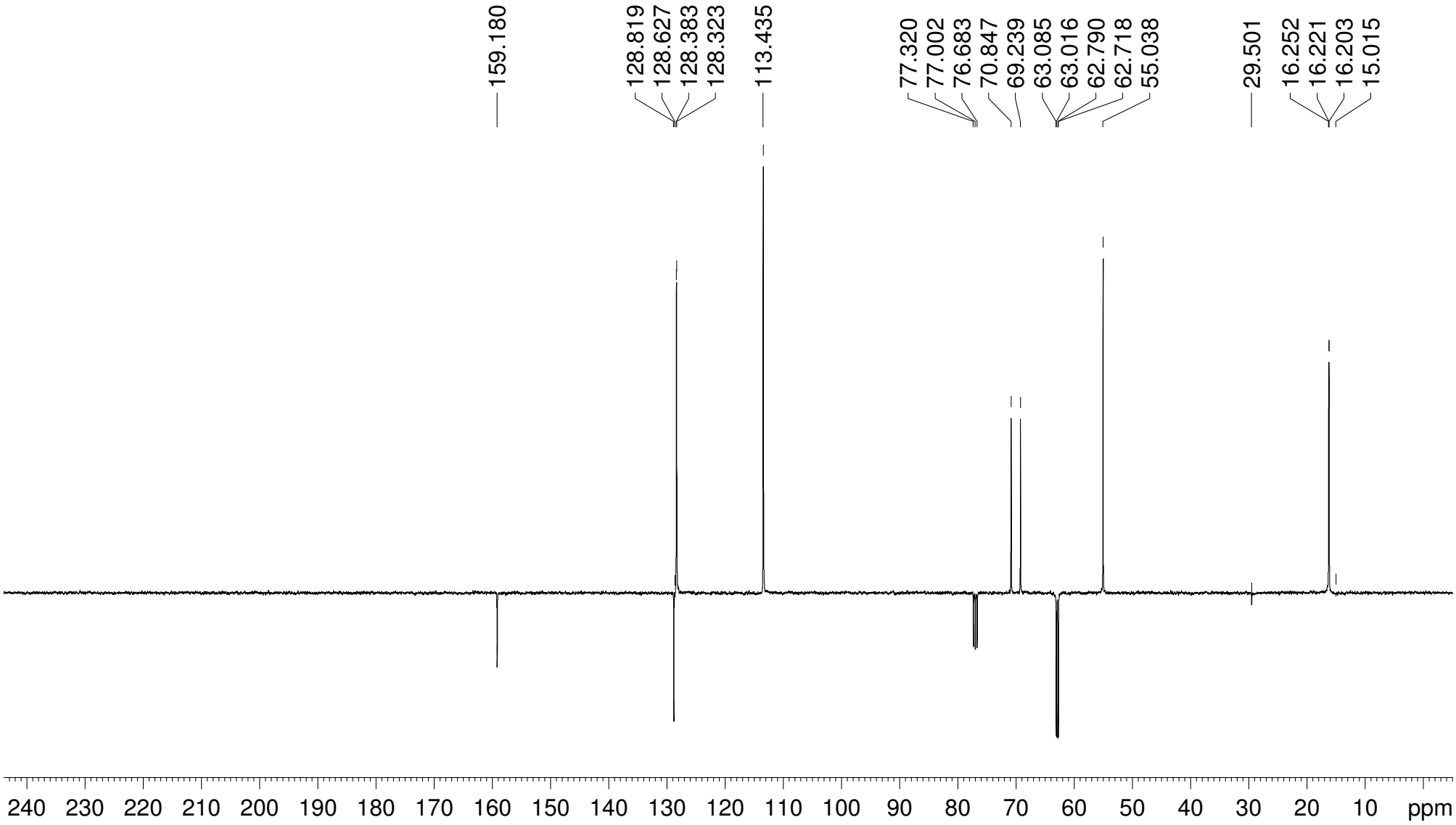


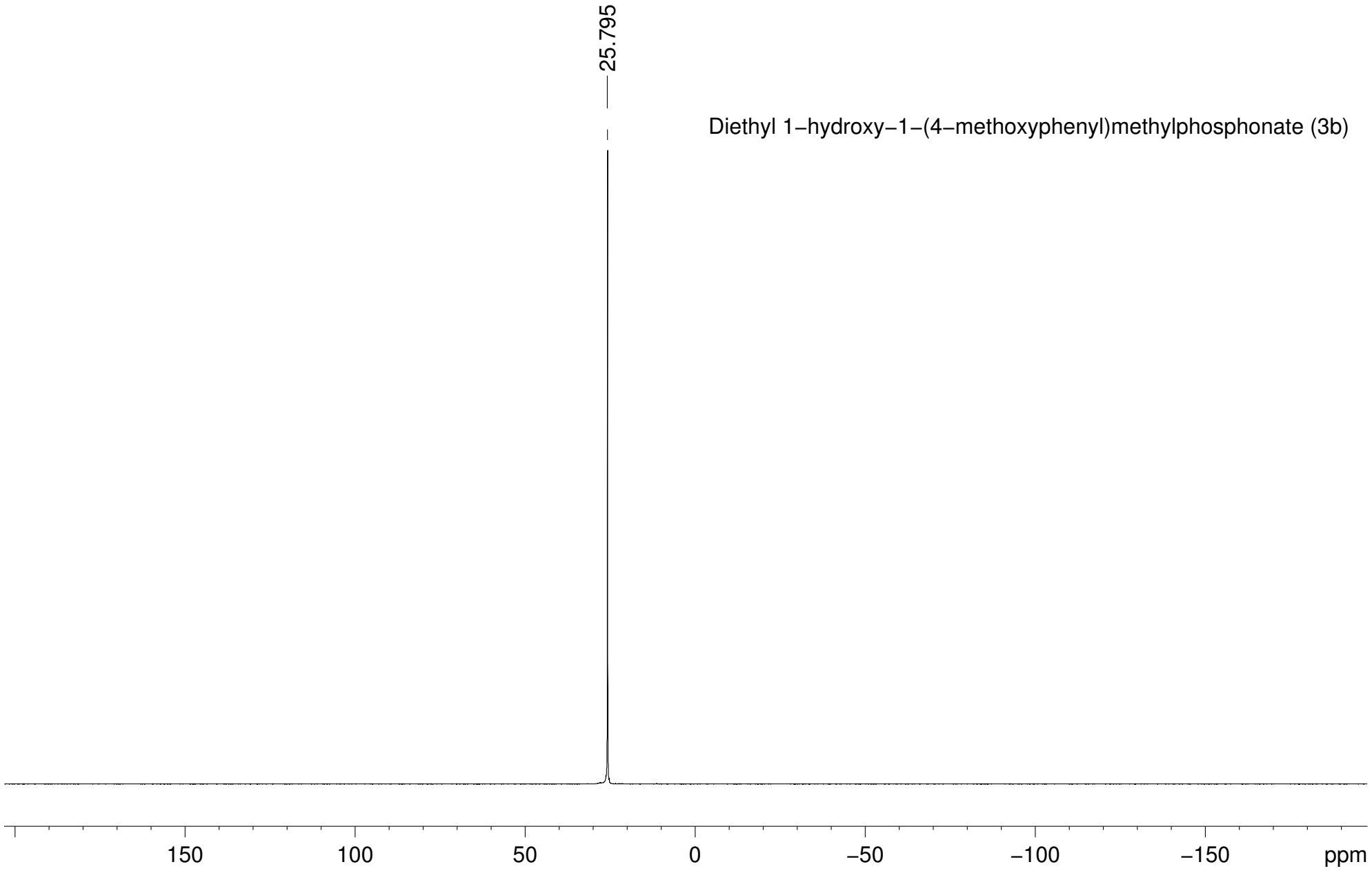


Diethyl 1–hydroxy–1–(4–methoxyphenyl)methylphosphonate (3b)

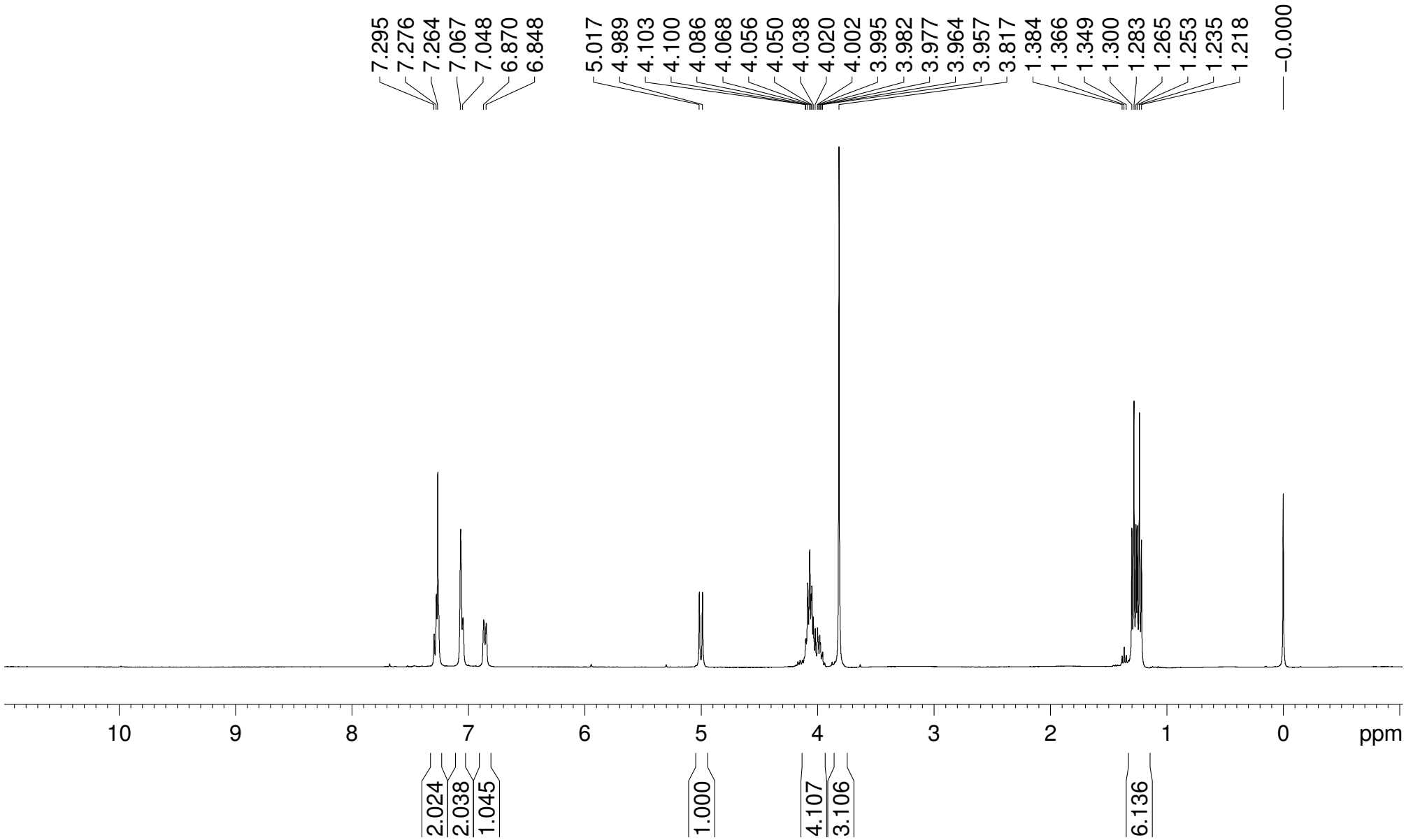


Diethyl 1–hydroxy–1–(4–methoxyphenyl)methylphosphonate (3b)

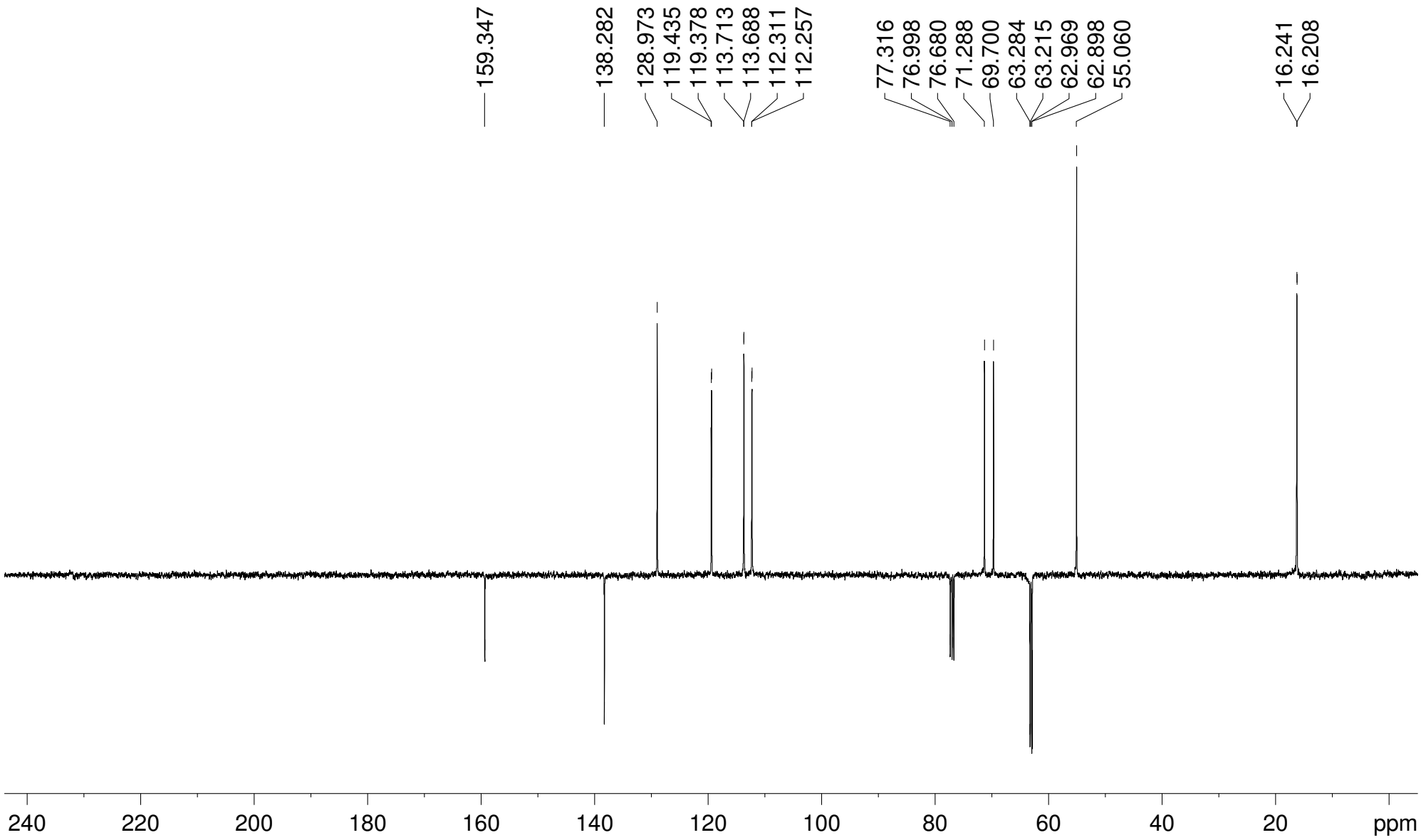


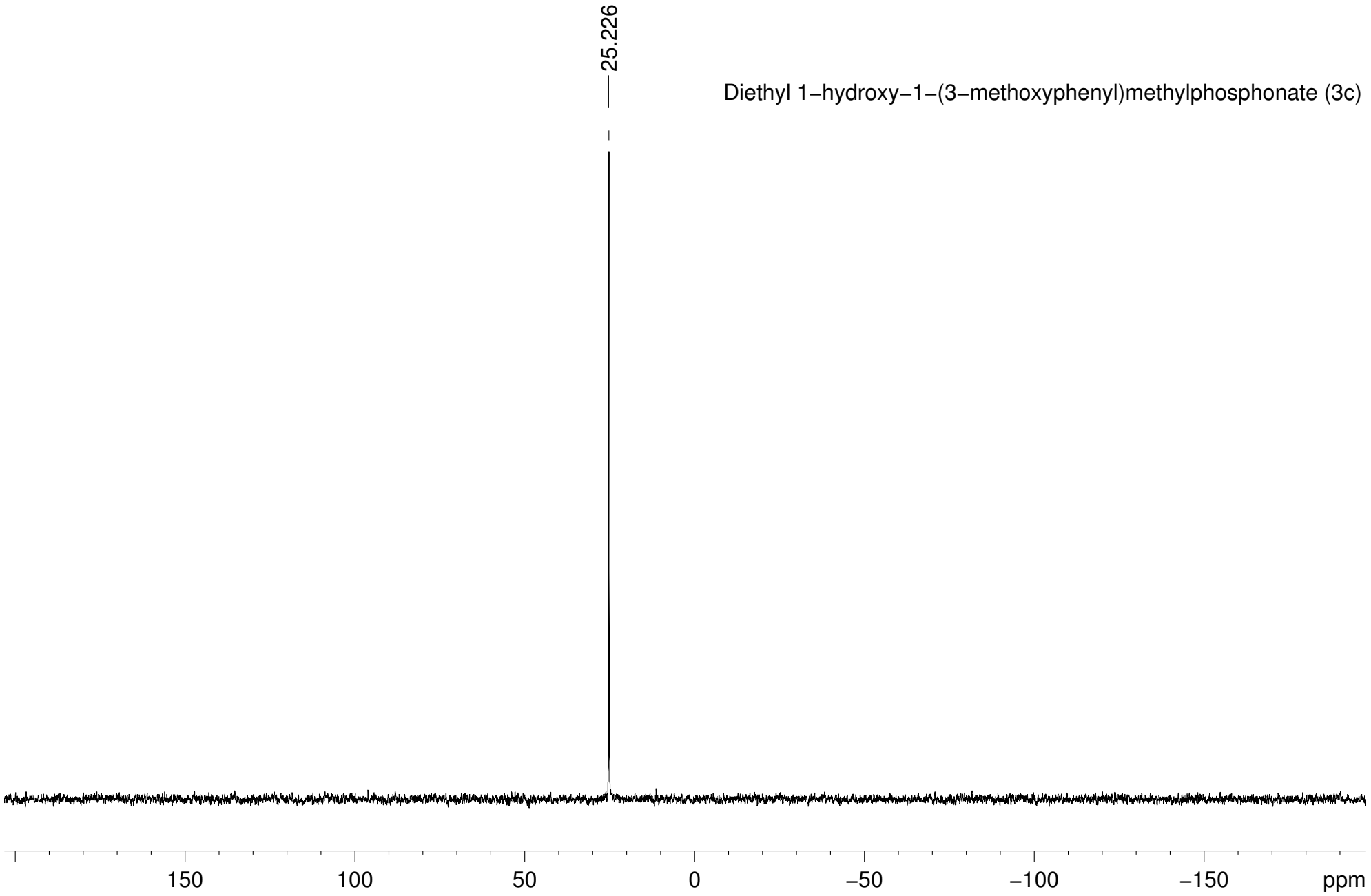


Diethyl 1–hydroxy–1–(3–methoxyphenyl)methylphosphonate (3c)

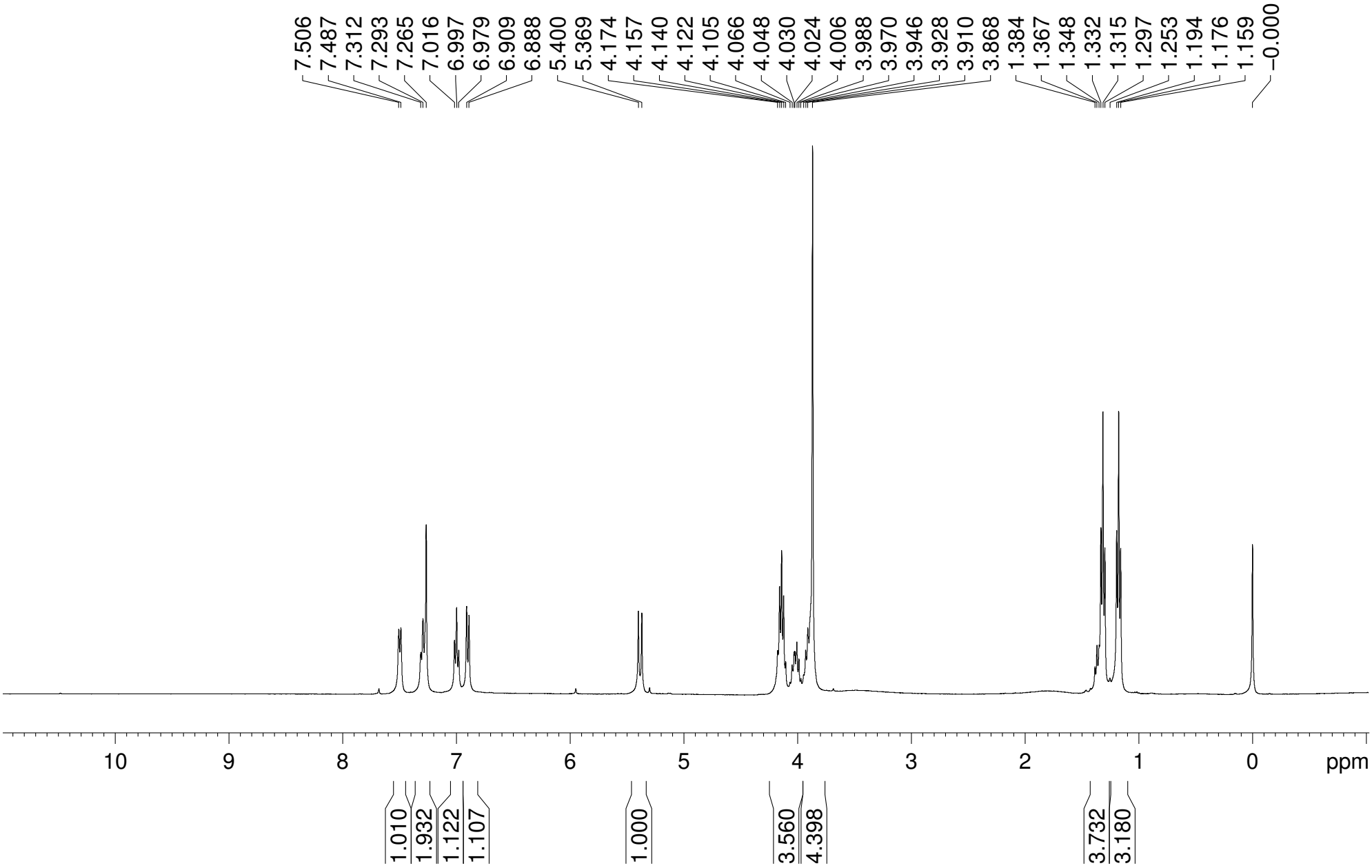


Diethyl 1–hydroxy–1–(3–methoxyphenyl)methylphosphonate (3c)

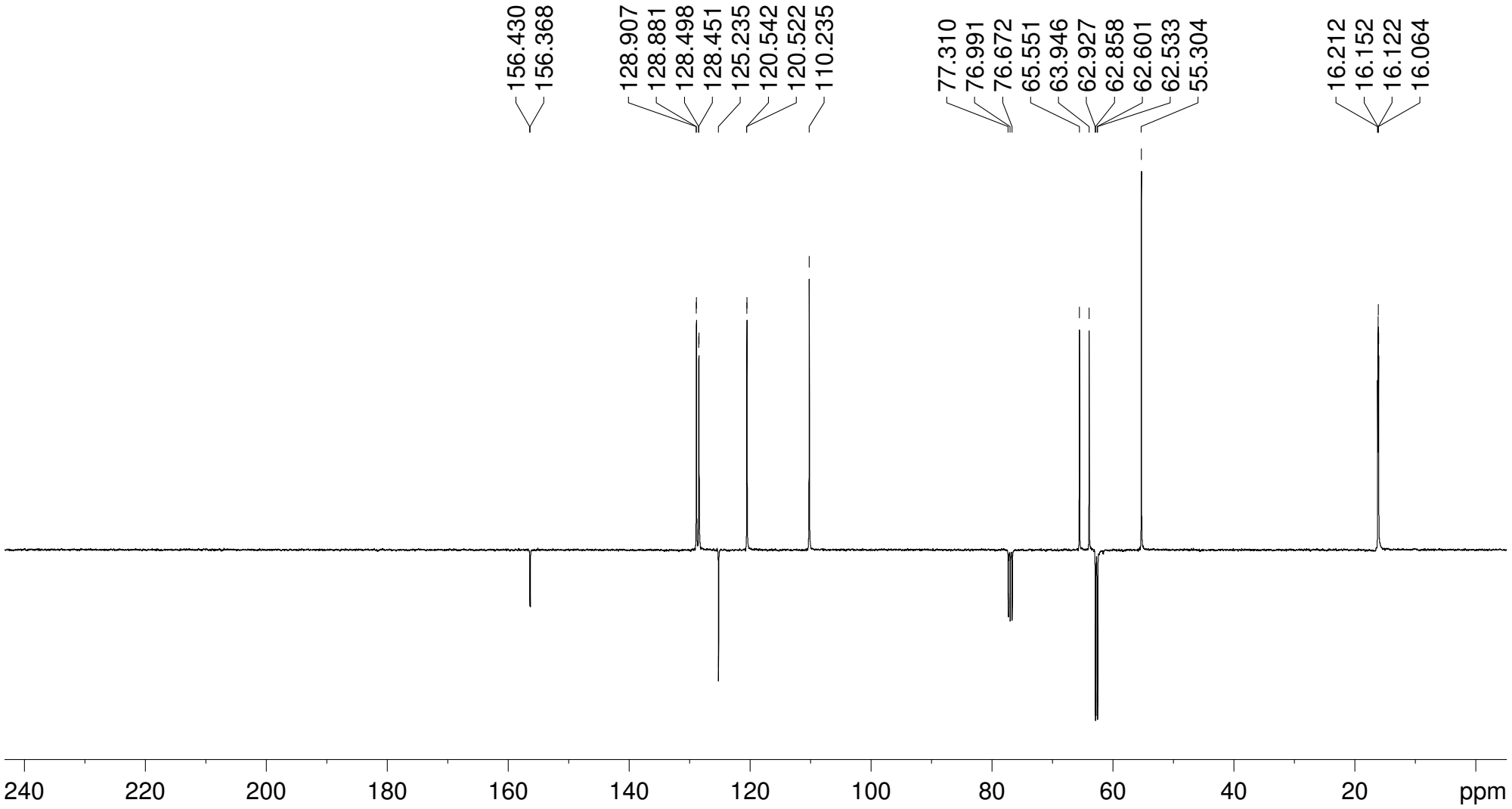


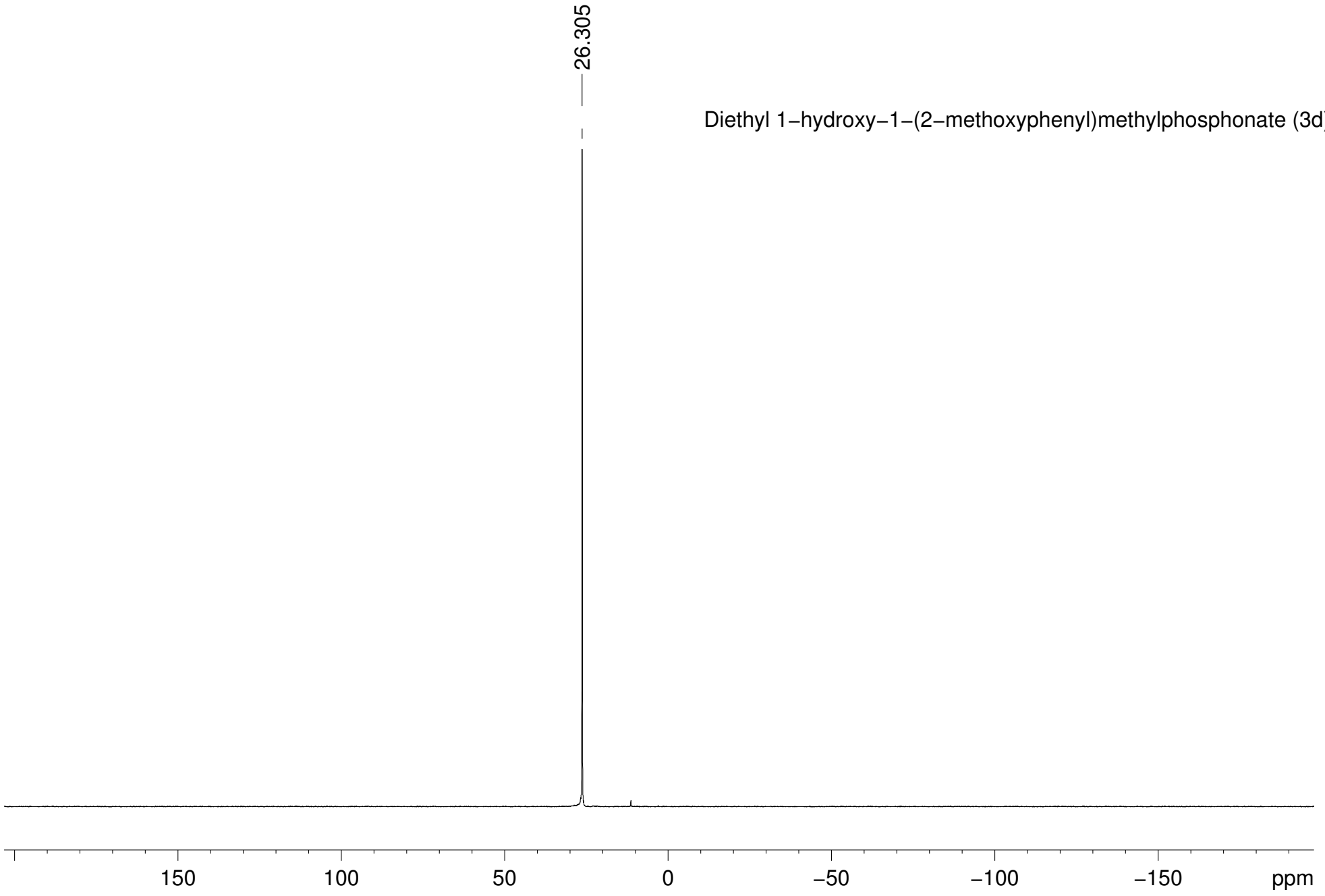


Diethyl 1–hydroxy–1–(2–methoxyphenyl)methylphosphonate (3d)

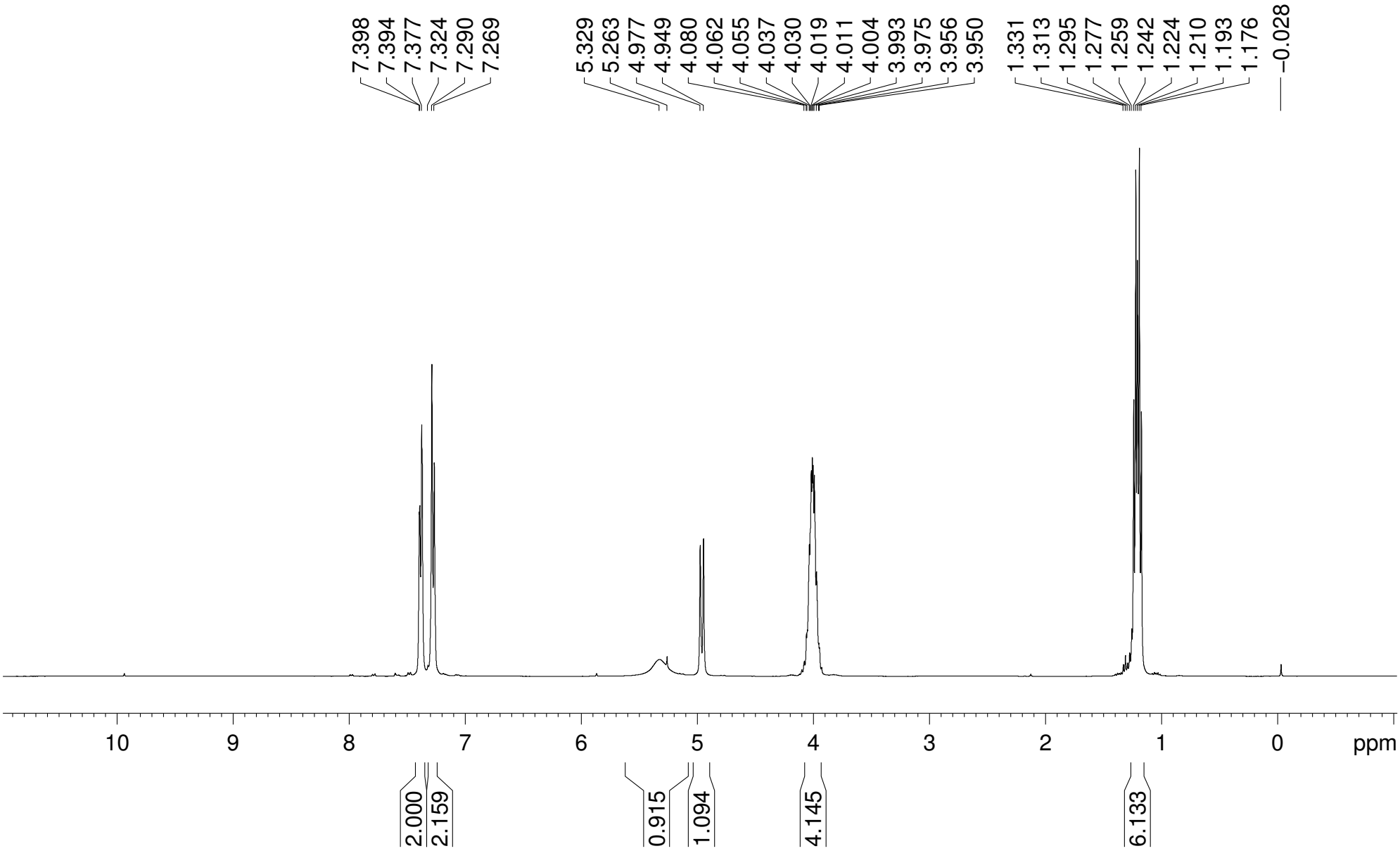


Diethyl 1–hydroxy–1–(2–methoxyphenyl)methylphosphonate (3d)

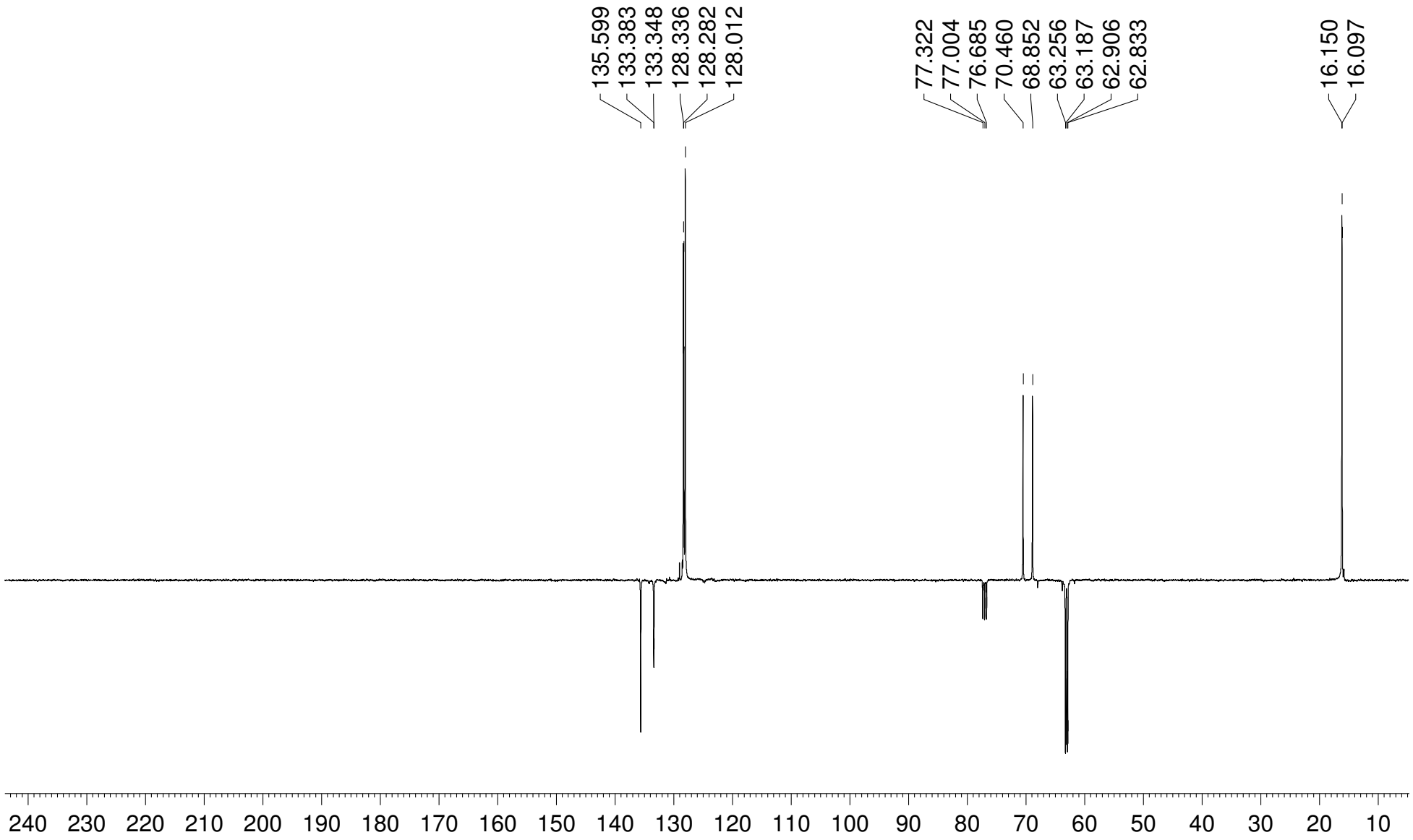


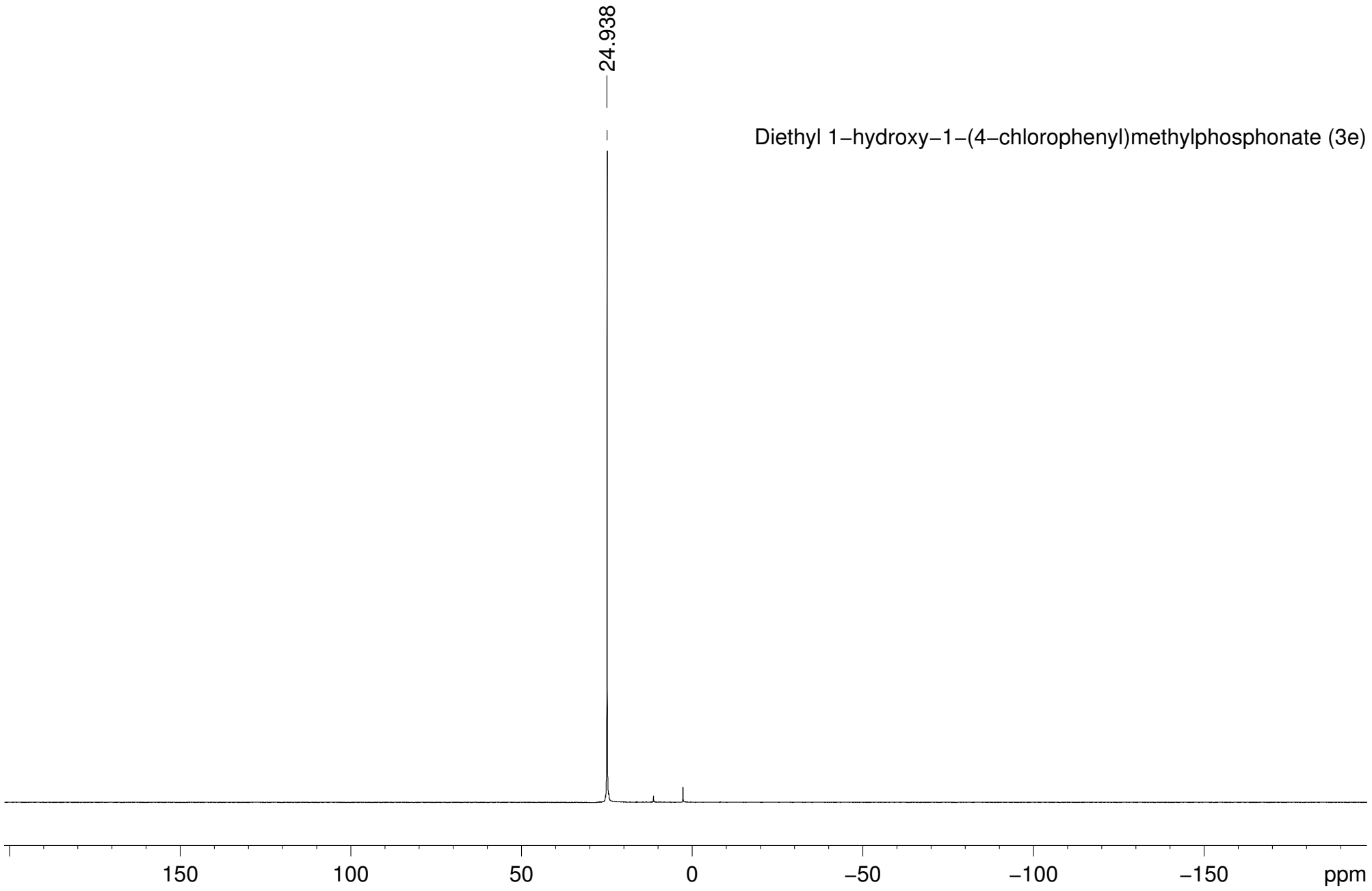


Diethyl 1–hydroxy–1–(4–chlorophenyl)methylphosphonate (3e)

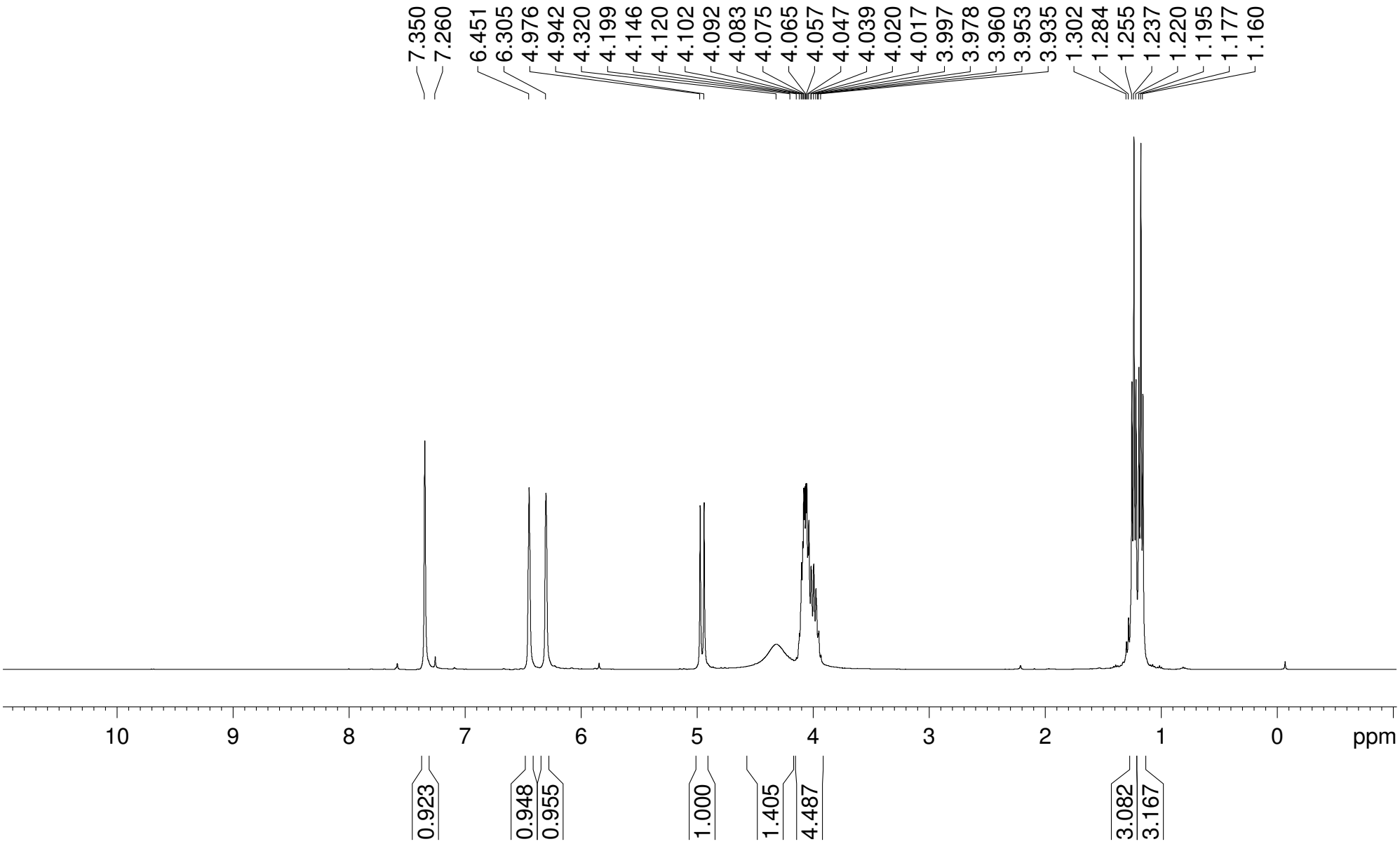


Diethyl 1–hydroxy–1–(4–chlorophenyl)methylphosphonate (3e)

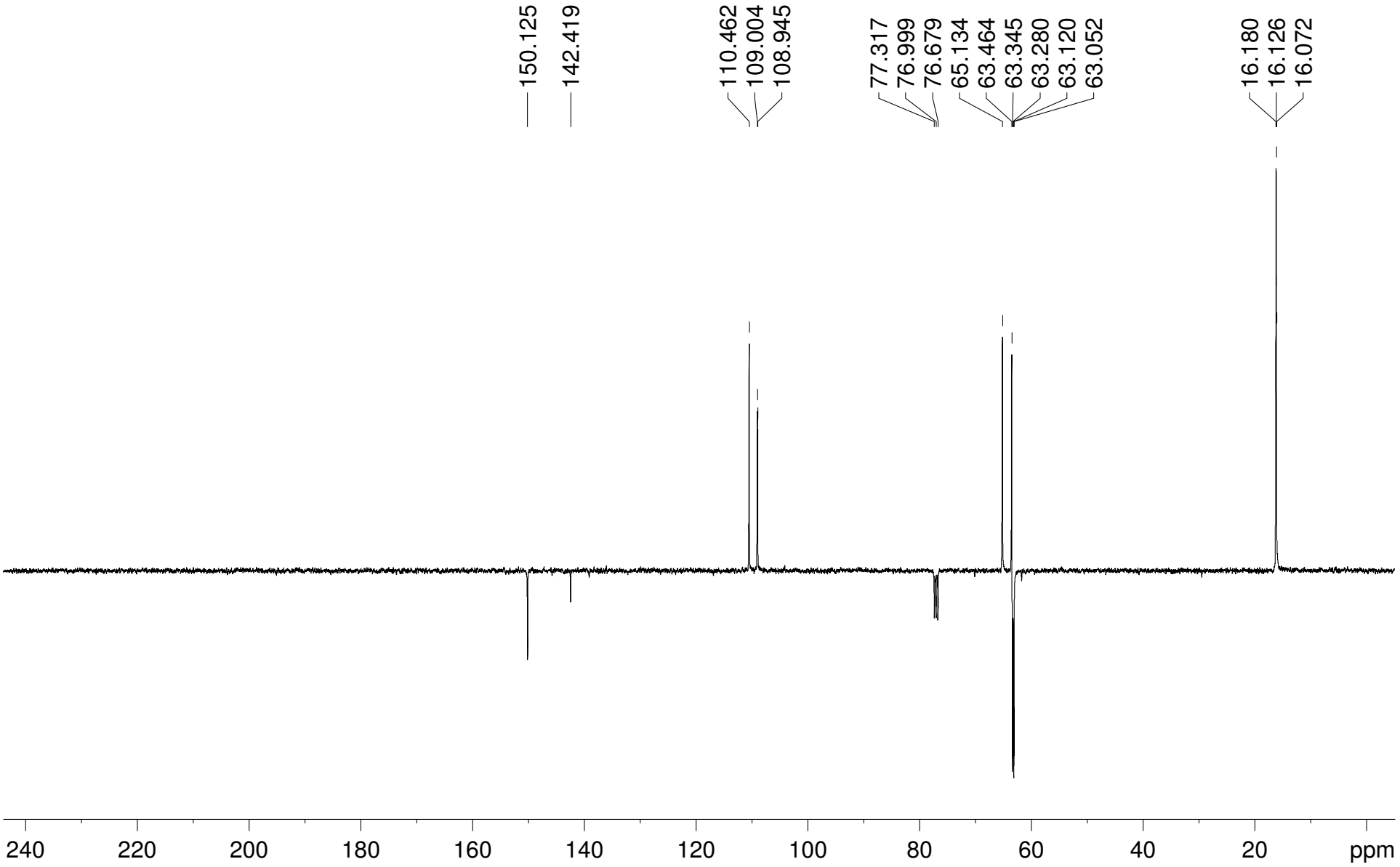


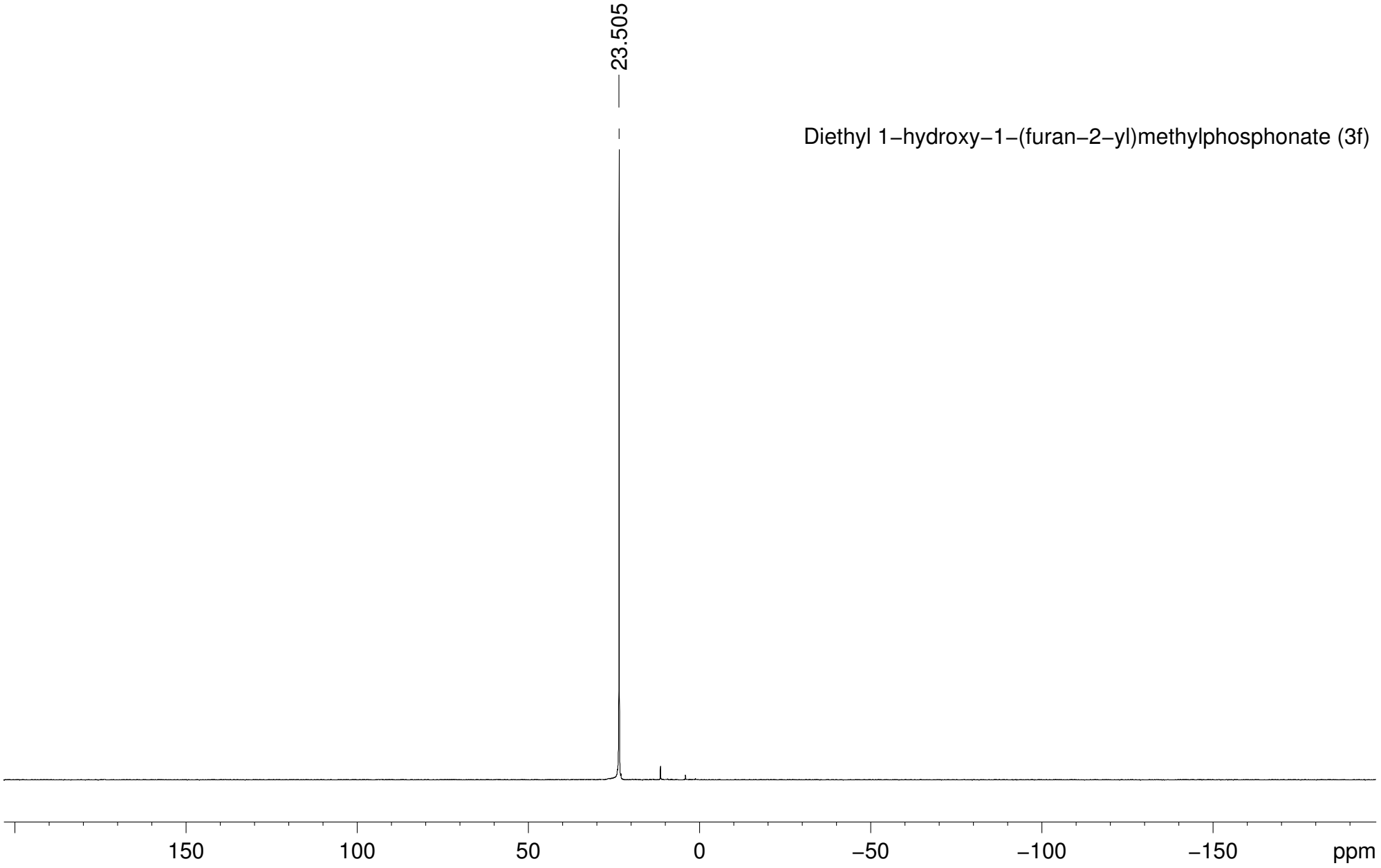


Diethyl 1–hydroxy–1–(furan–2–yl)methylphosphonate (3f)

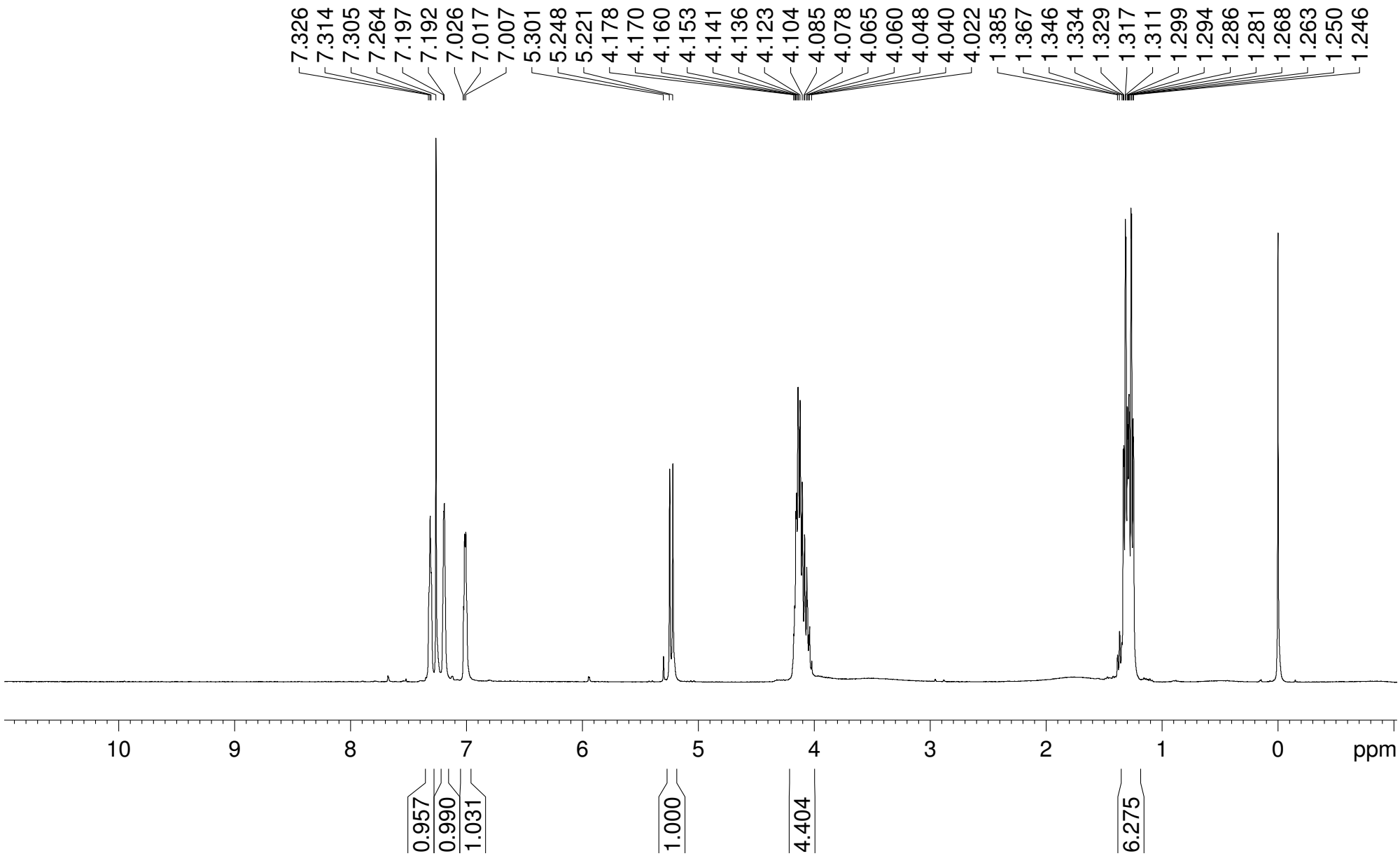


Diethyl 1–hydroxy–1–(furan–2–yl)methylphosphonate (3f)

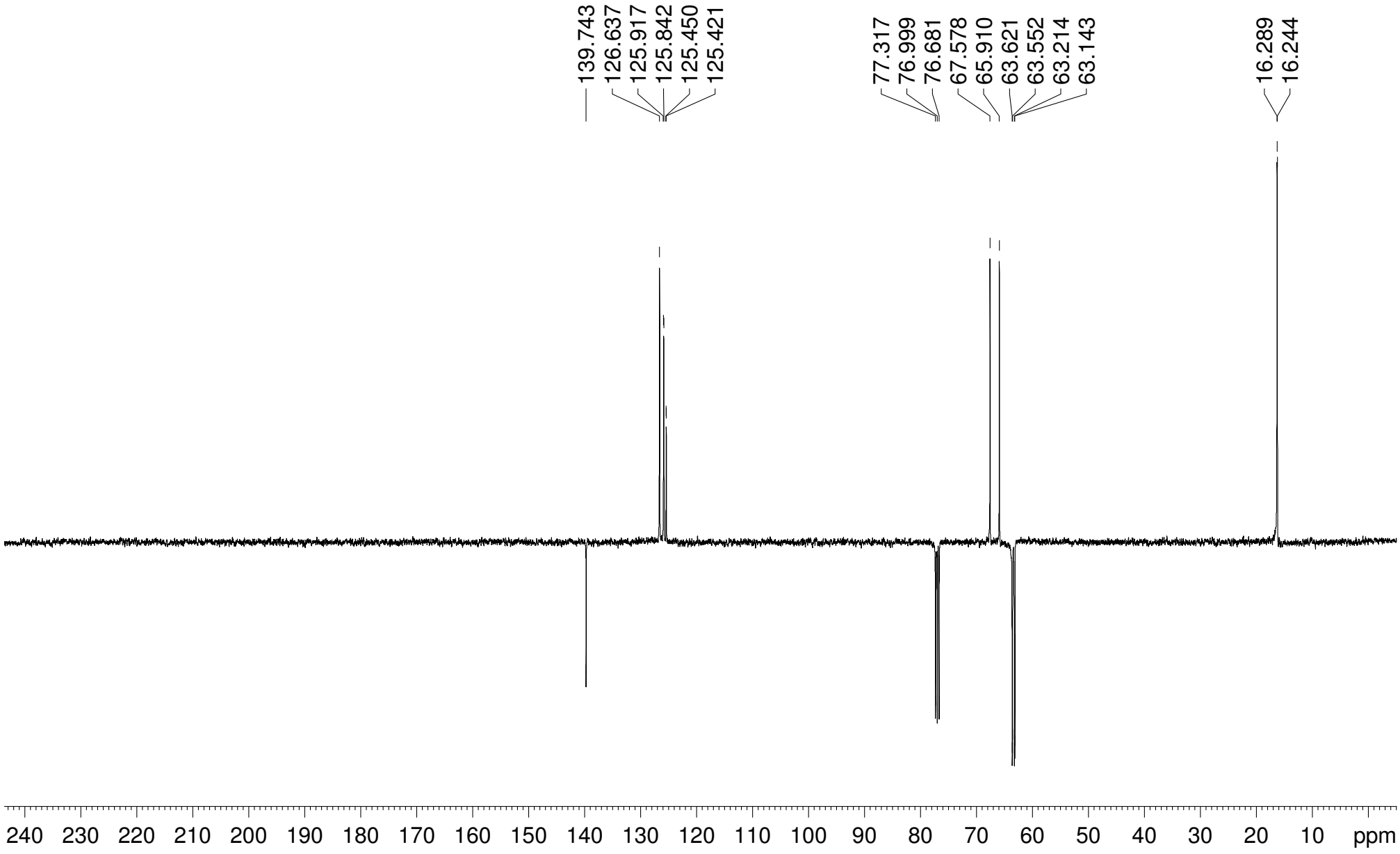


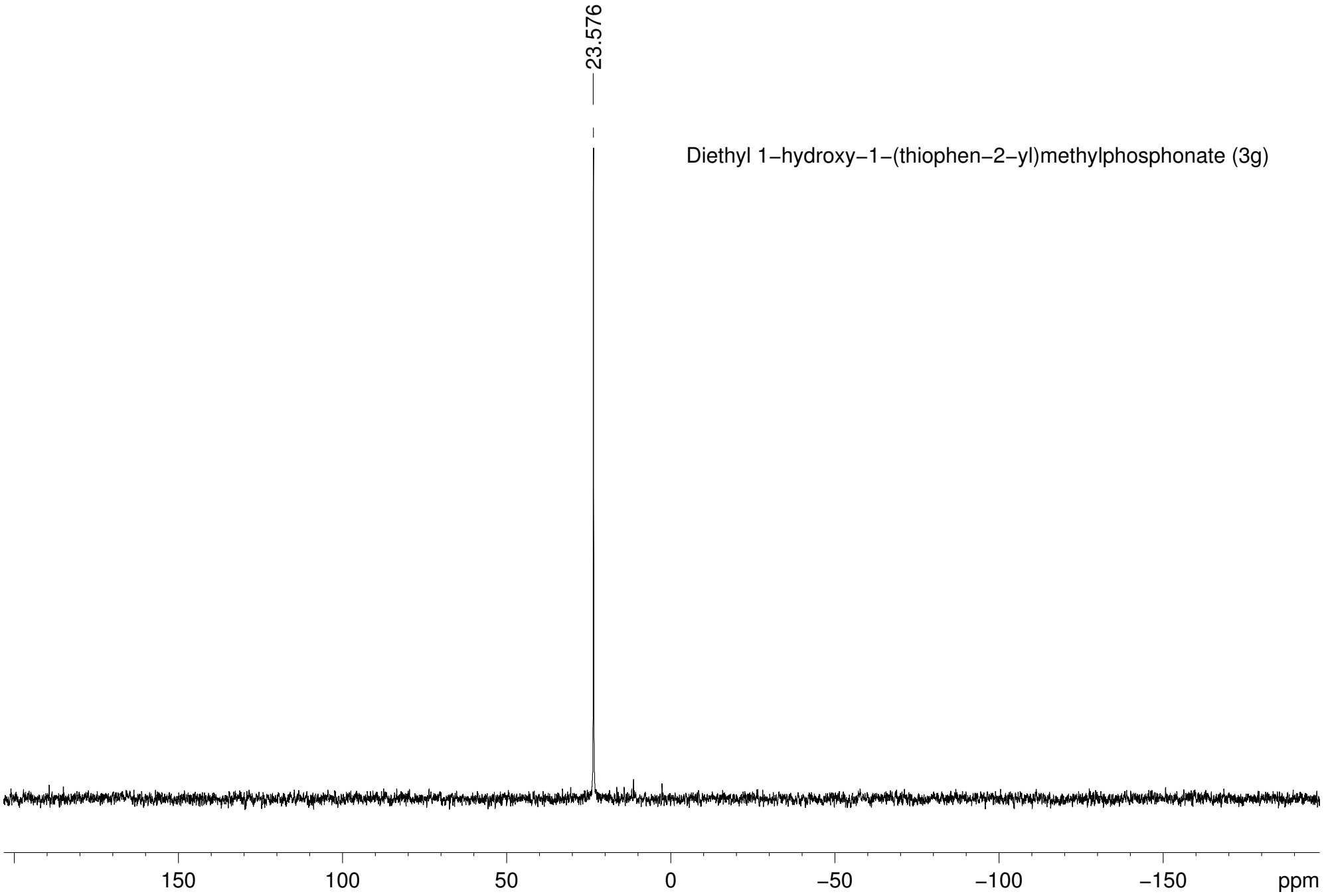


Diethyl 1–hydroxy–1–(thiophen–2–yl)methylphosphonate (3g)

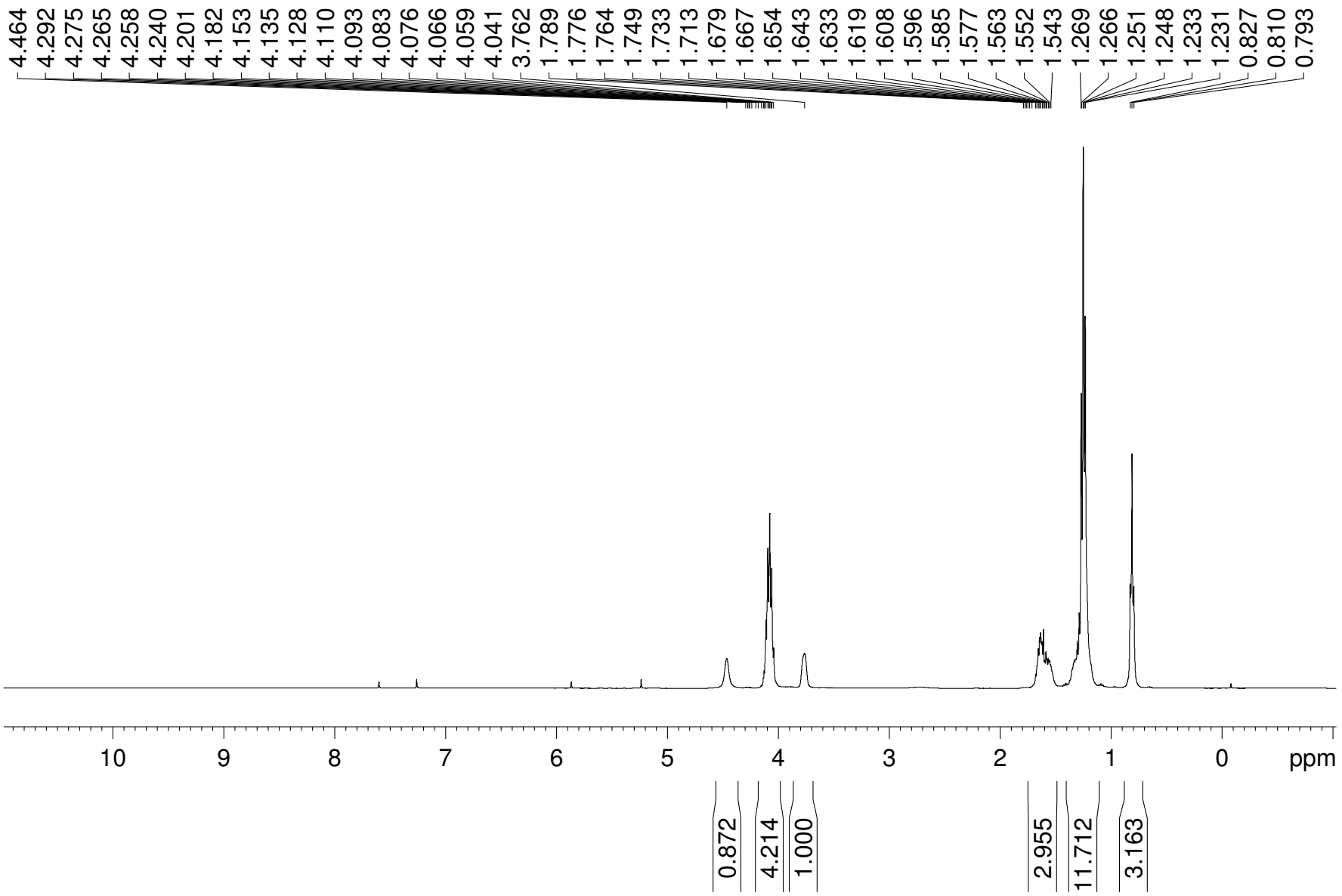


Diethyl 1–hydroxy–1–(thiophen–2–yl)methylphosphonate (3g)

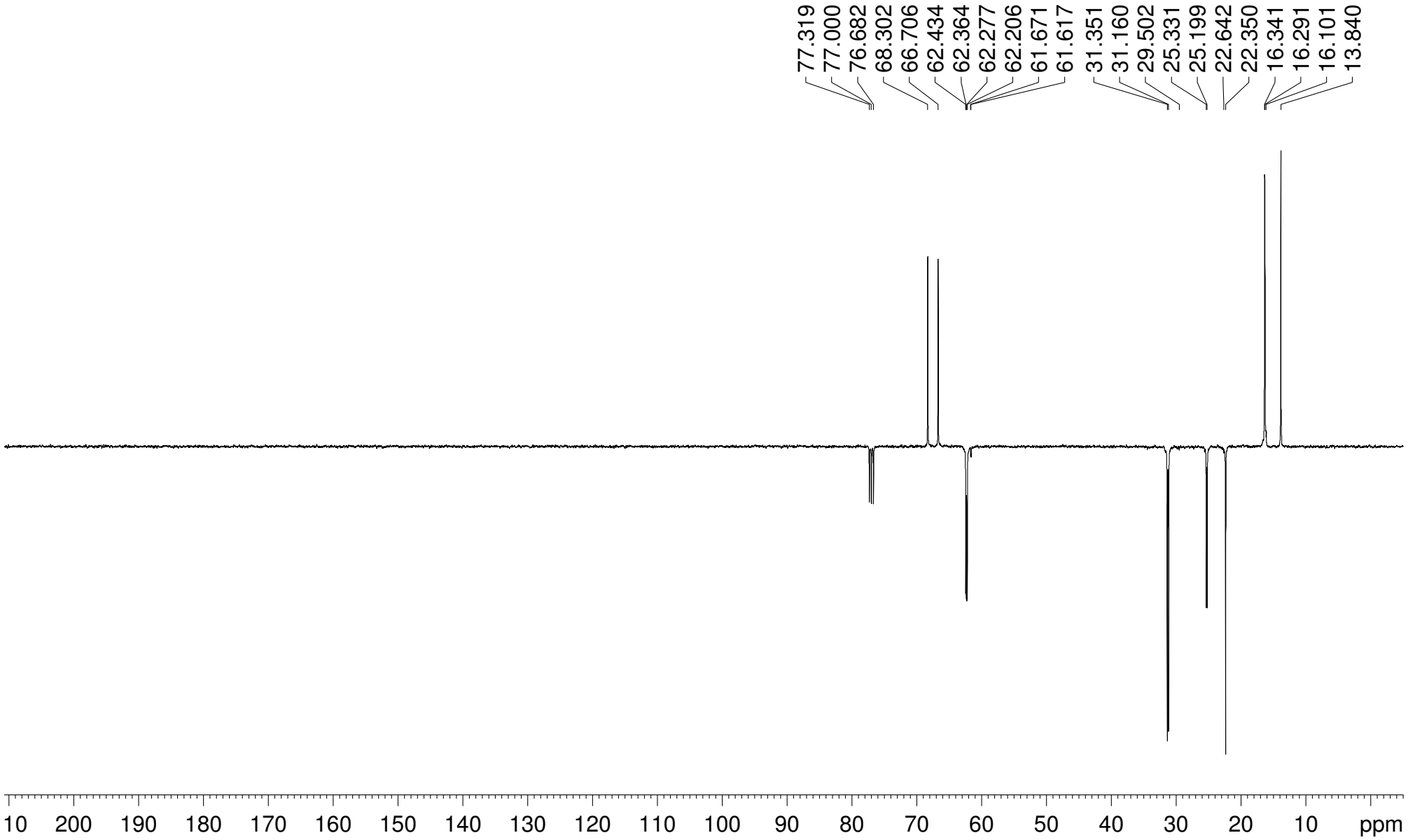


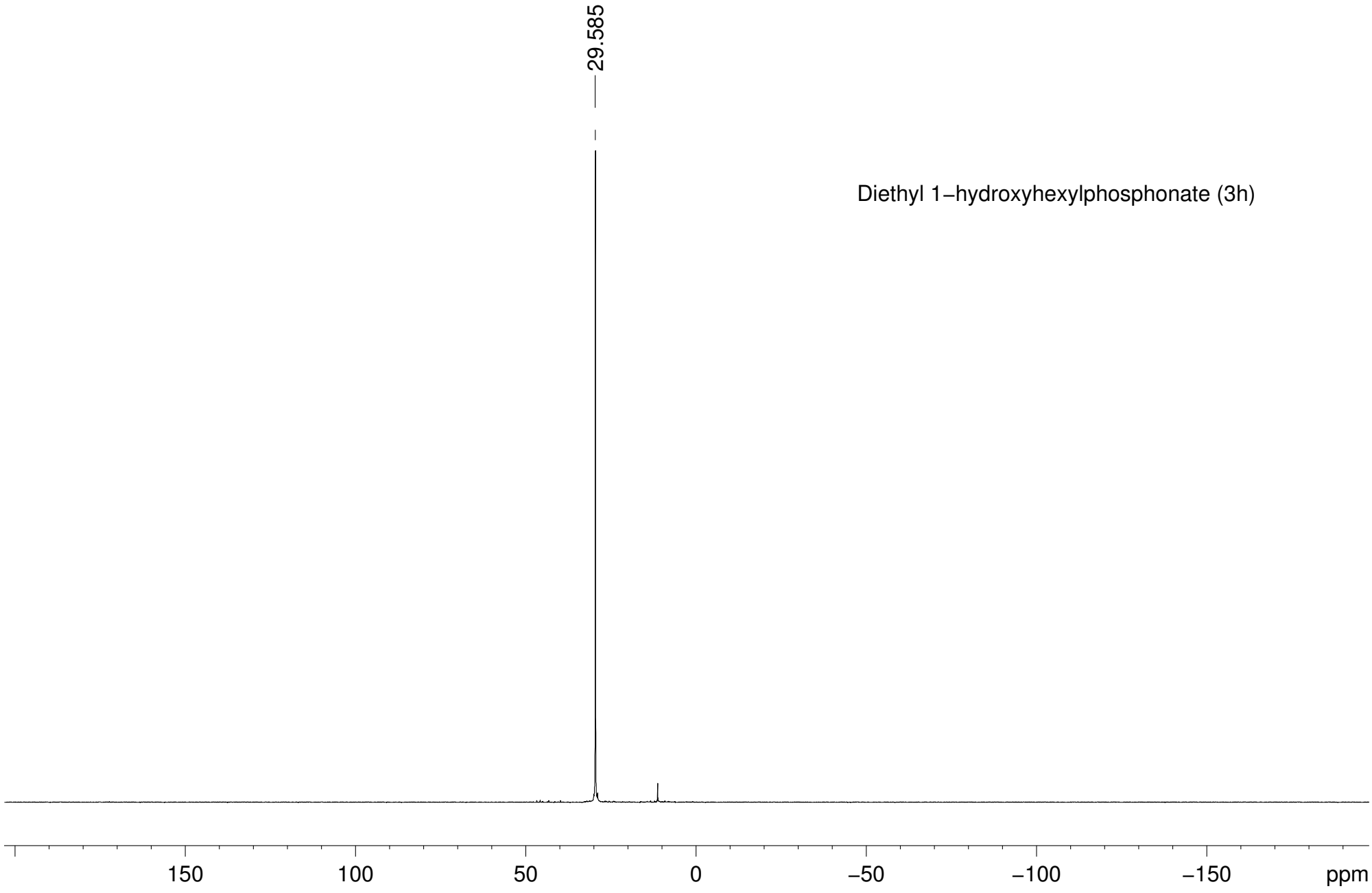


Diethyl 1–hydroxyhexylphosphonate (3h)

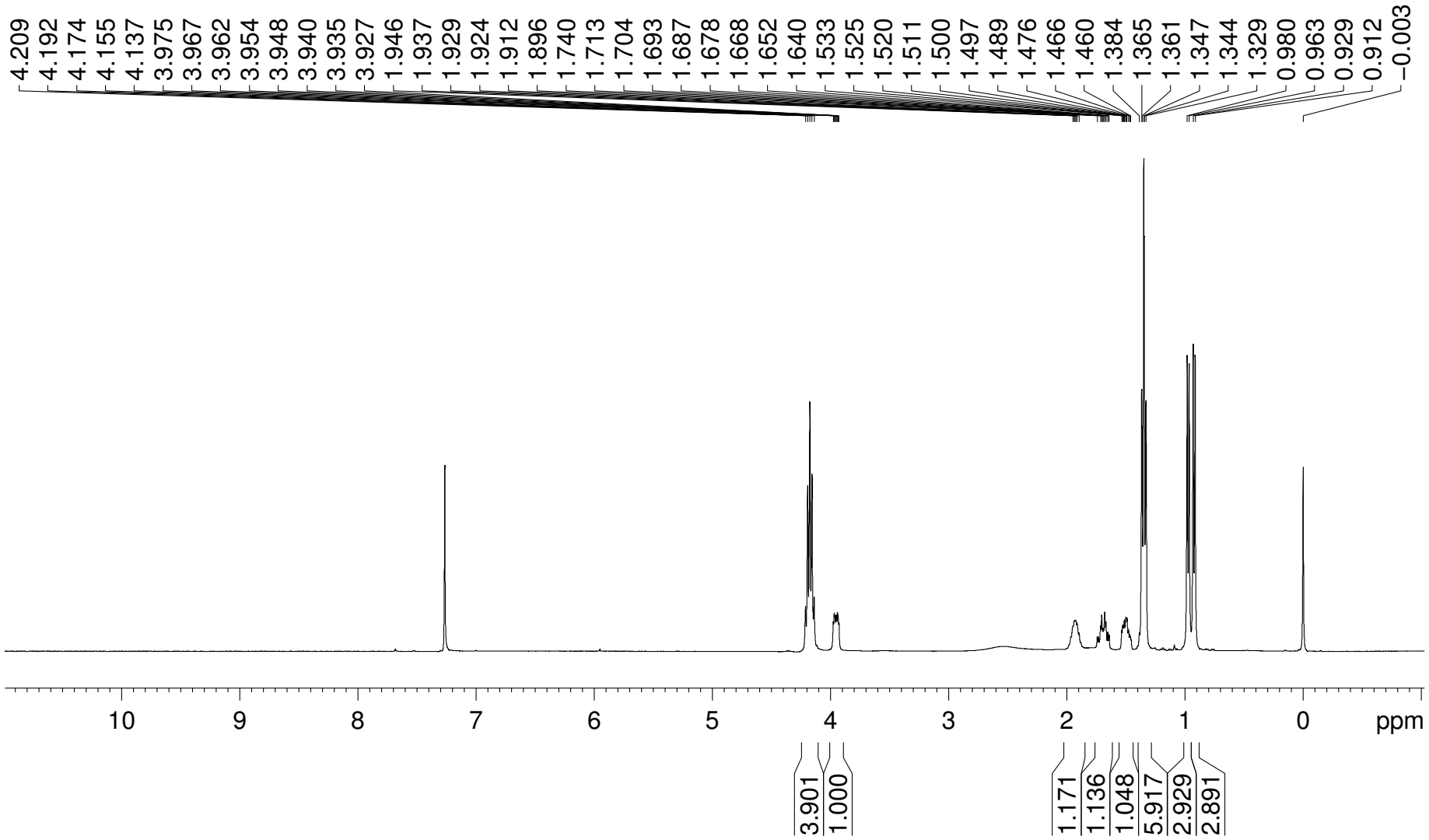


Diethyl 1–hydroxyhexylphosphonate (3h)

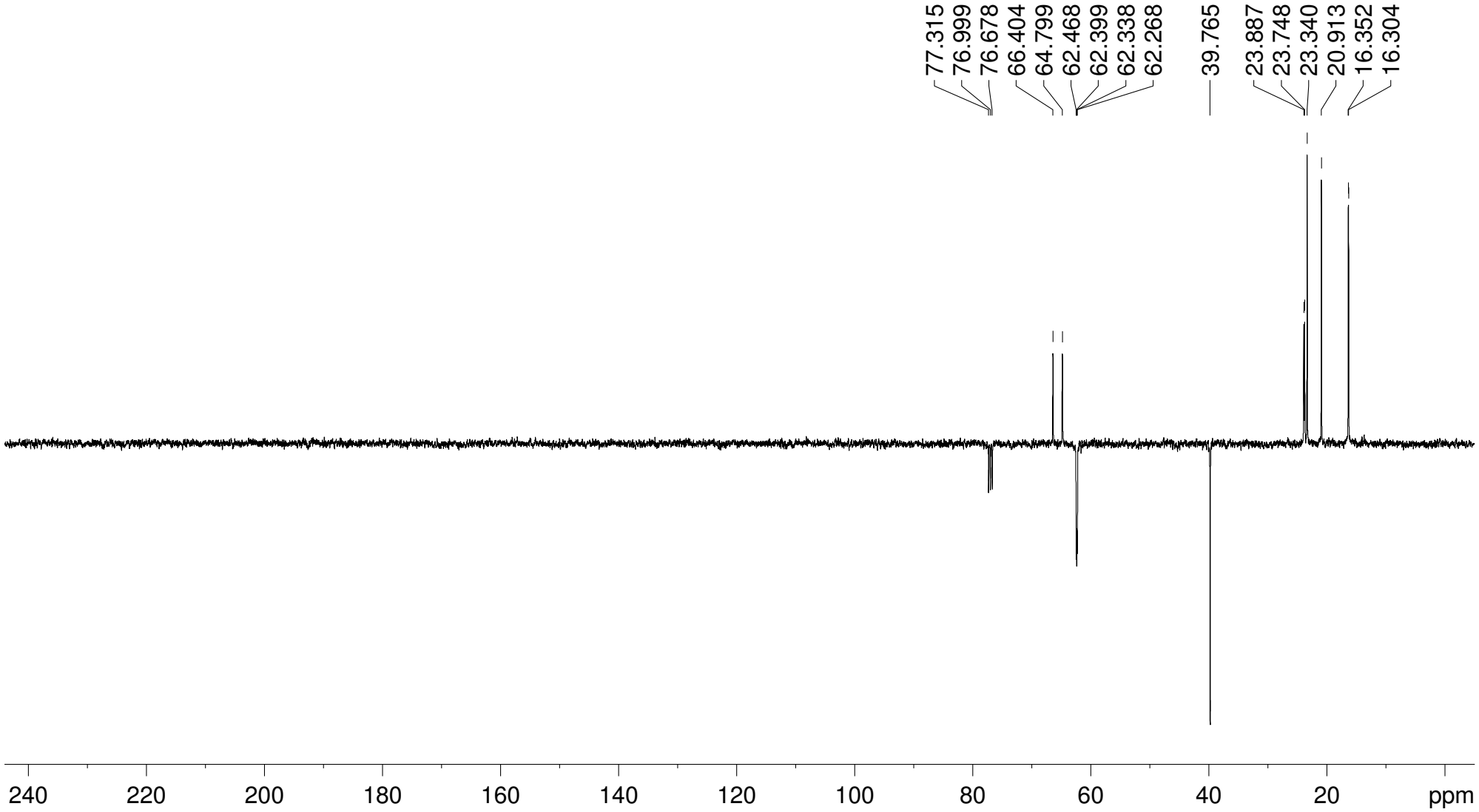


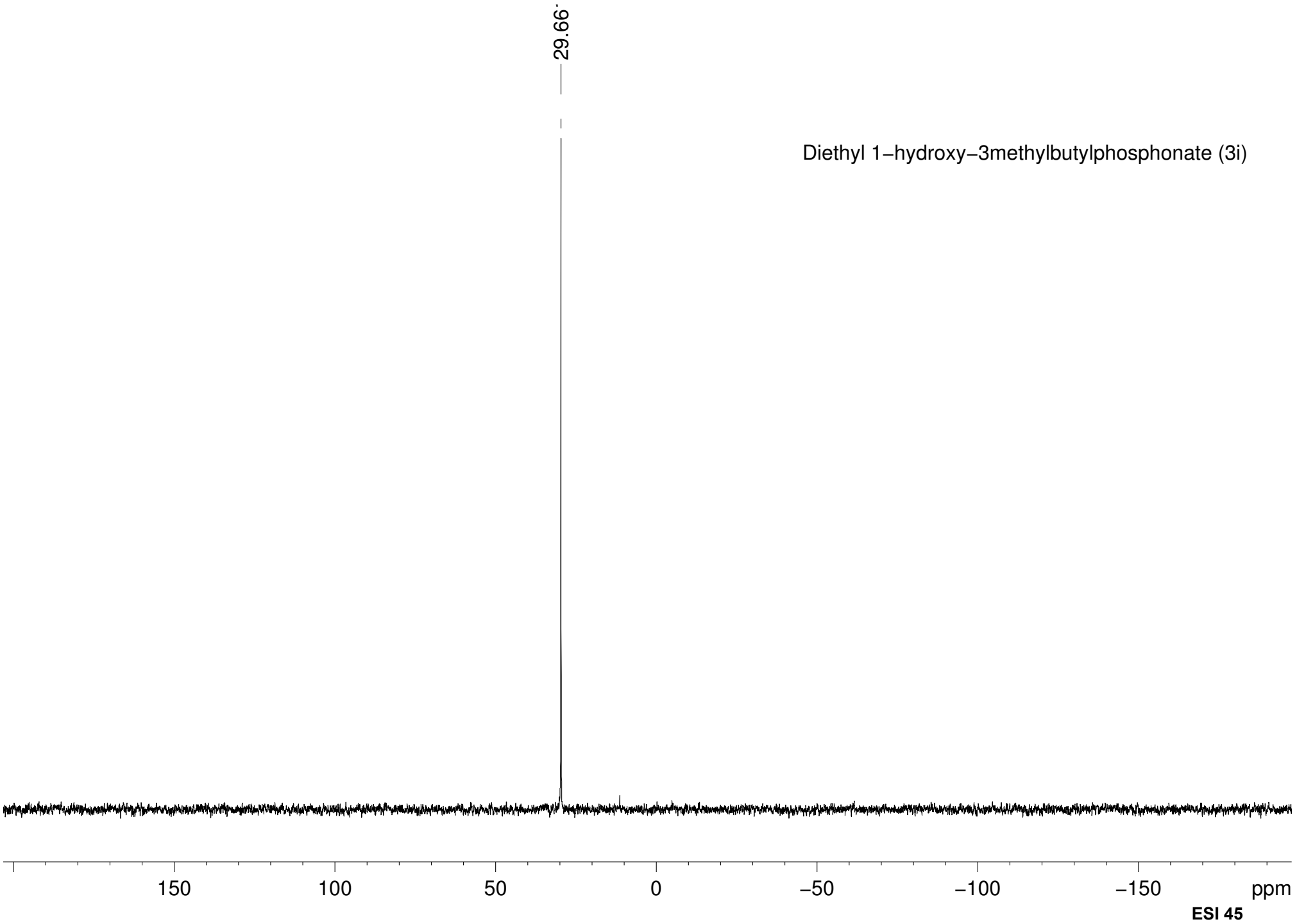


Diethyl 1–hydroxy–3methylbutylphosphonate (3i)

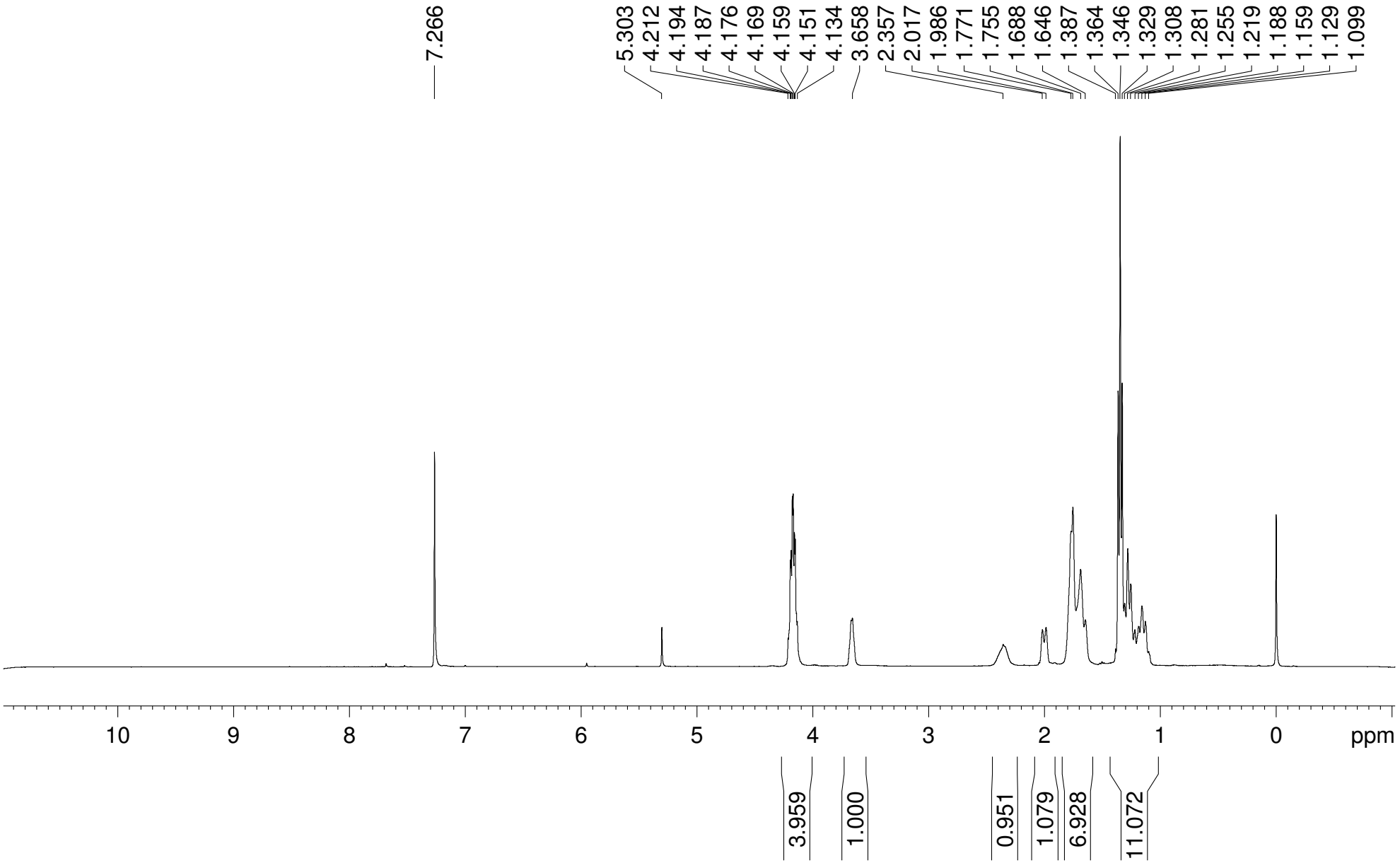


Diethyl 1−hydroxy−3methylbutylphosphonate (3i)

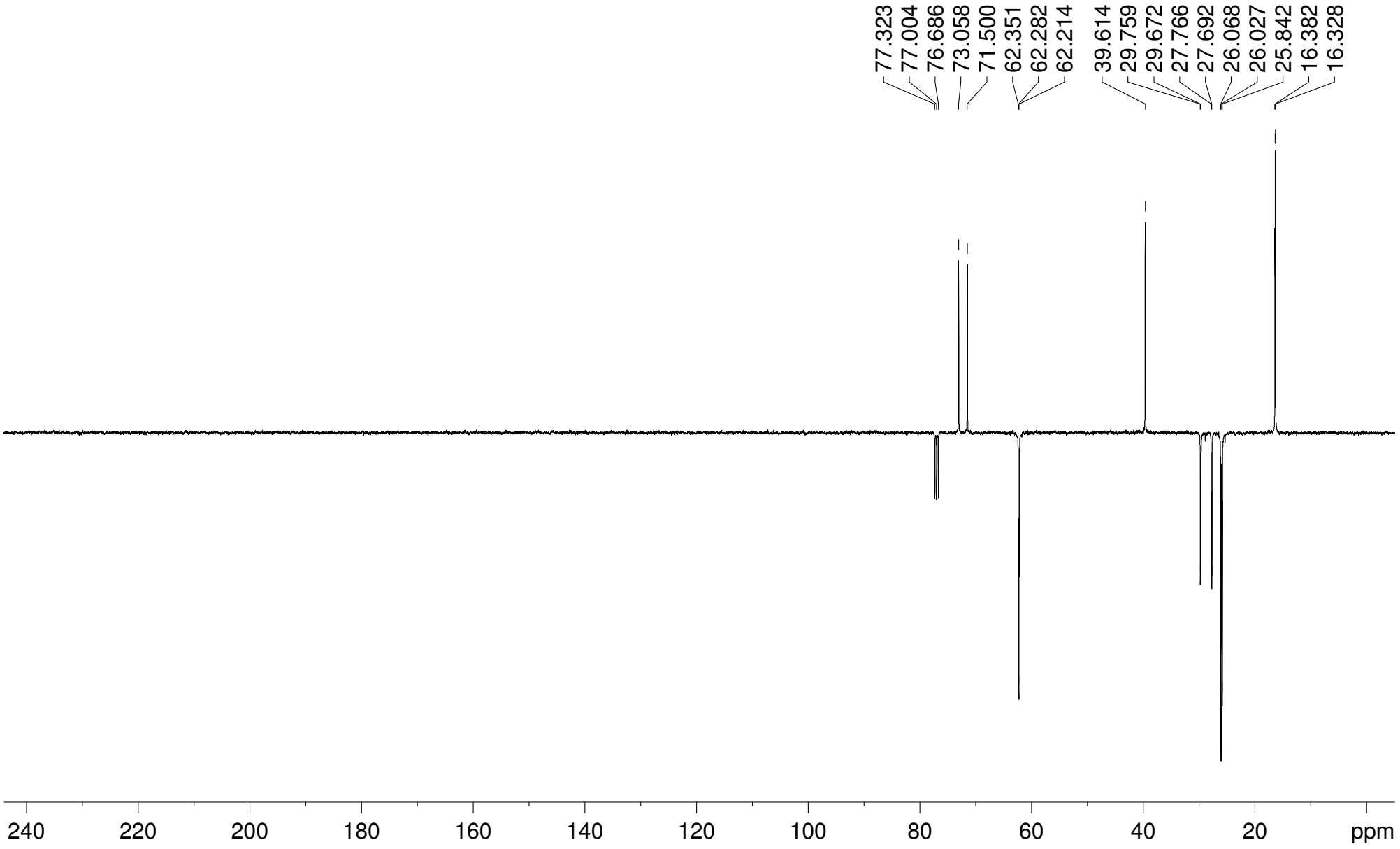


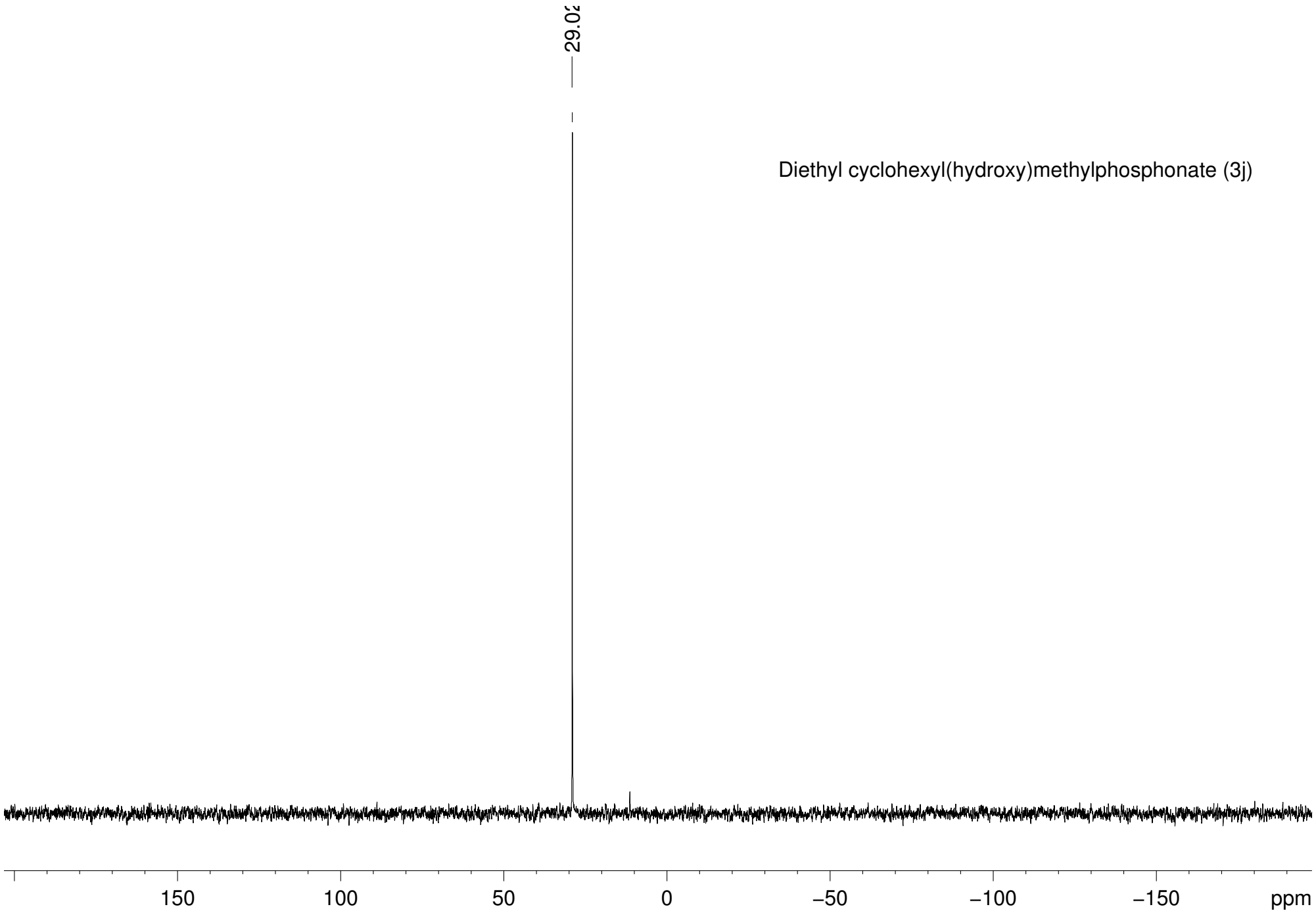


Diethyl cyclohexyl(hydroxy)methylphosphonate (3j)

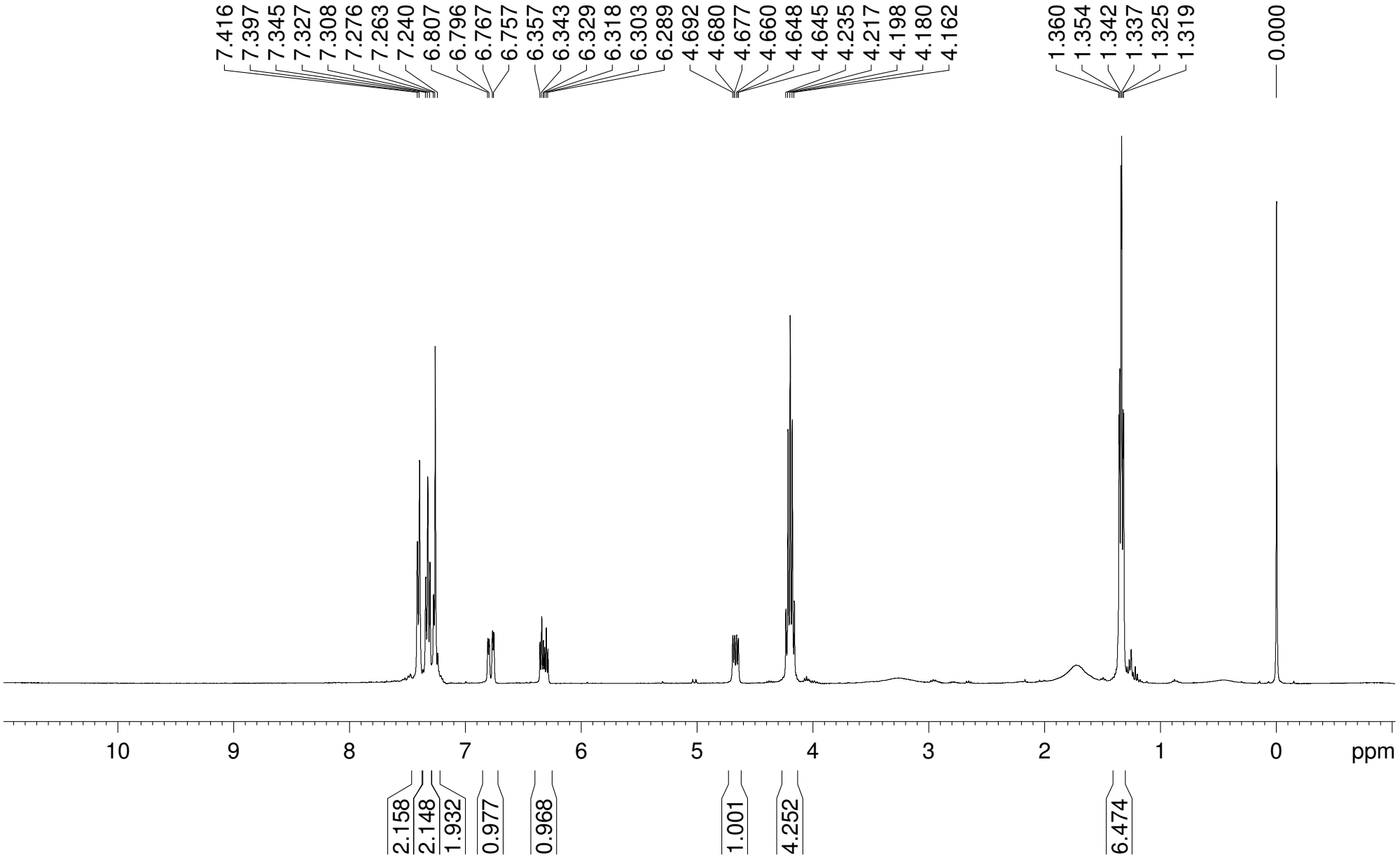


Diethyl cyclohexyl(hydroxy)methylphosphonate (3j)

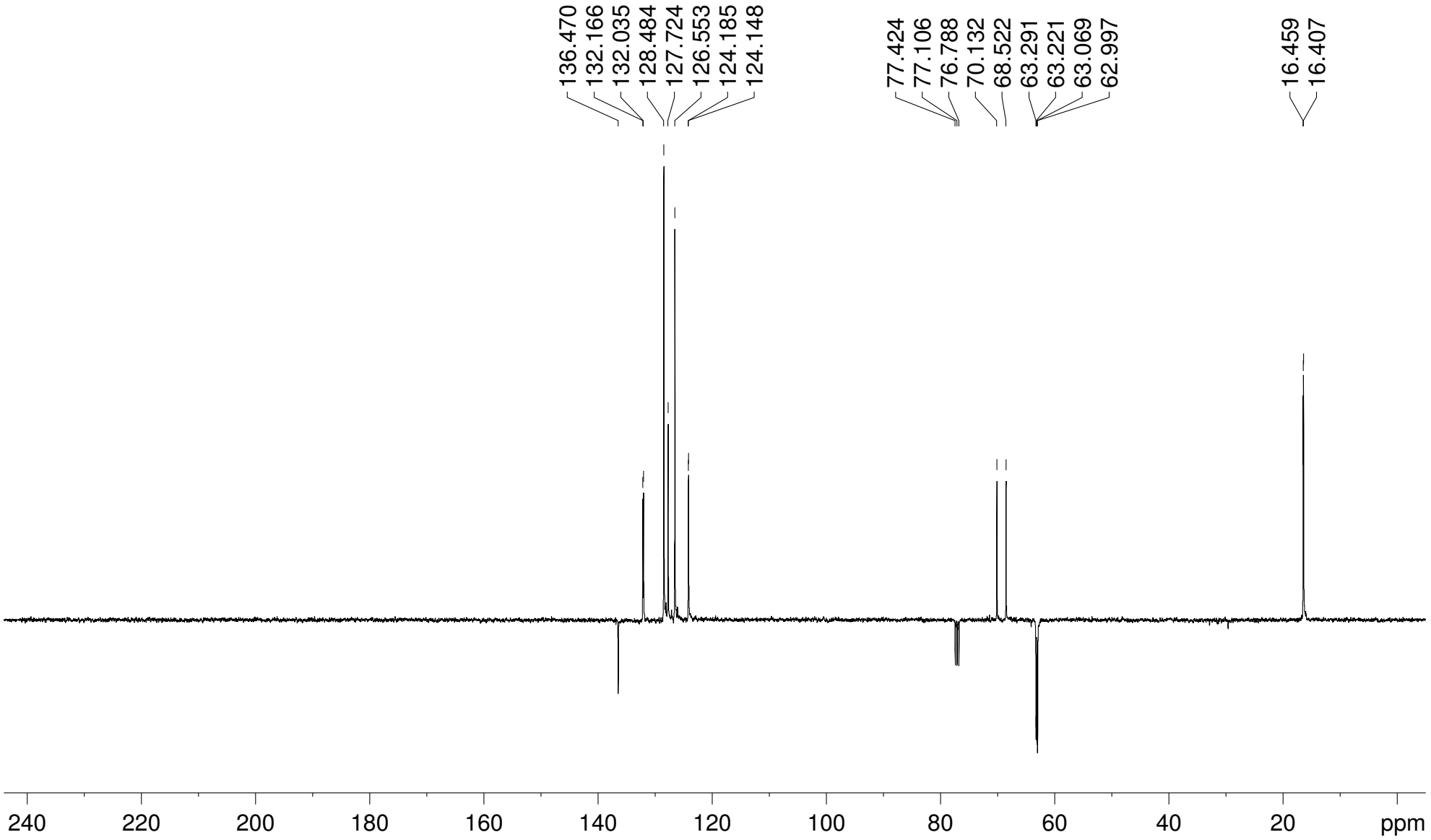


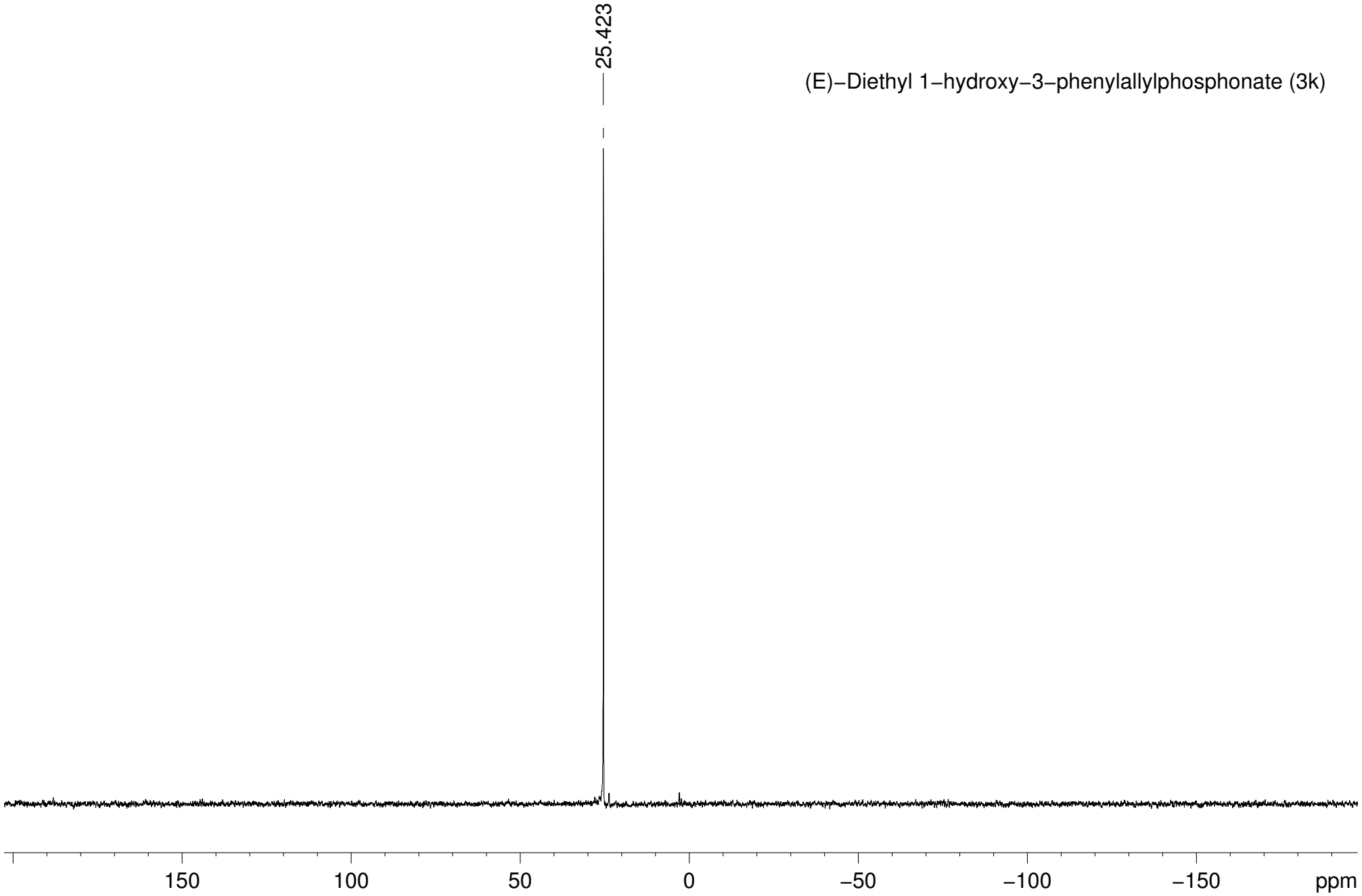


(E)−Diethyl 1−hydroxy−3−phenylallylphosphonate (3k)

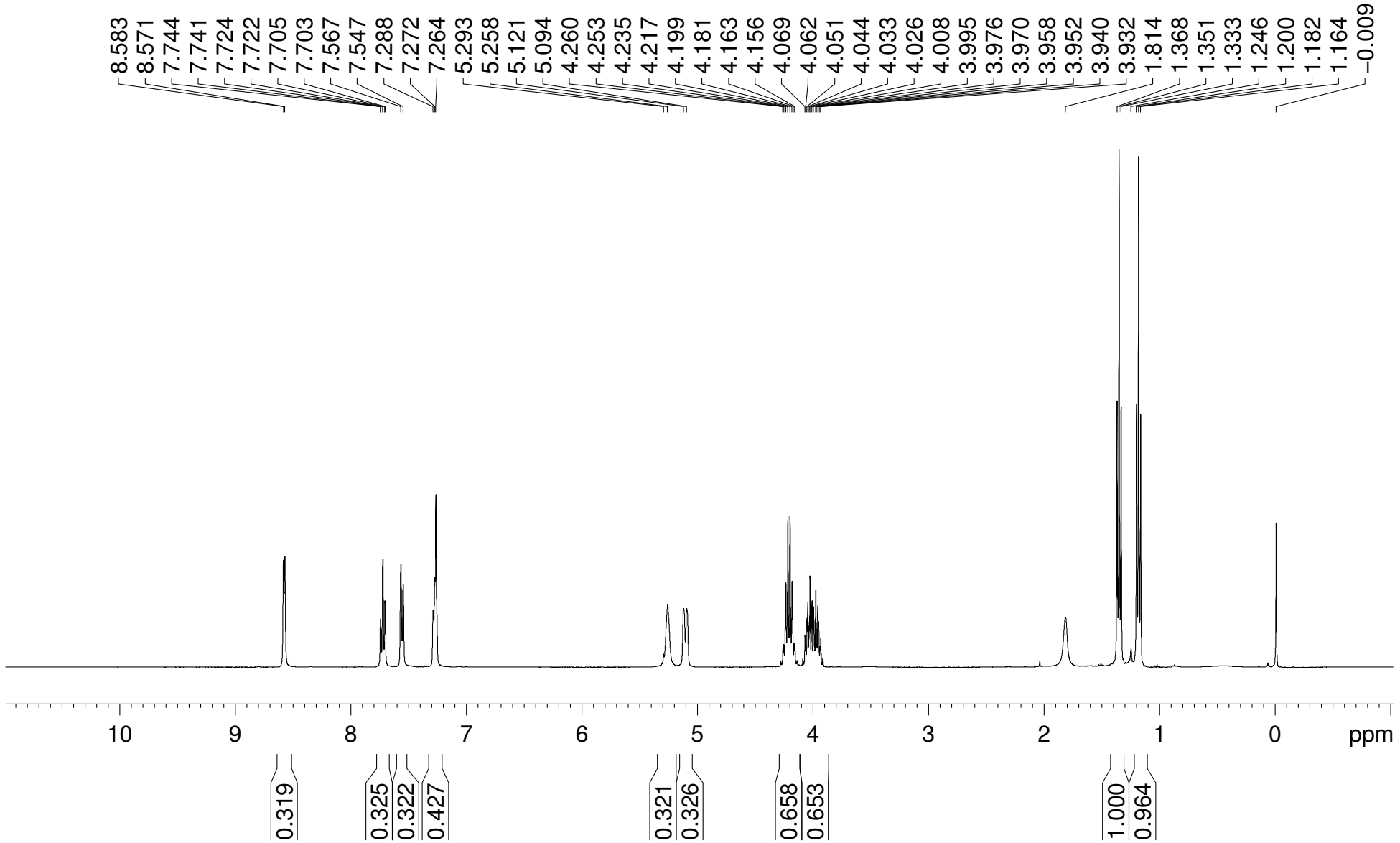


(E)−Diethyl 1−hydroxy−3−phenylallylphosphonate (3k)

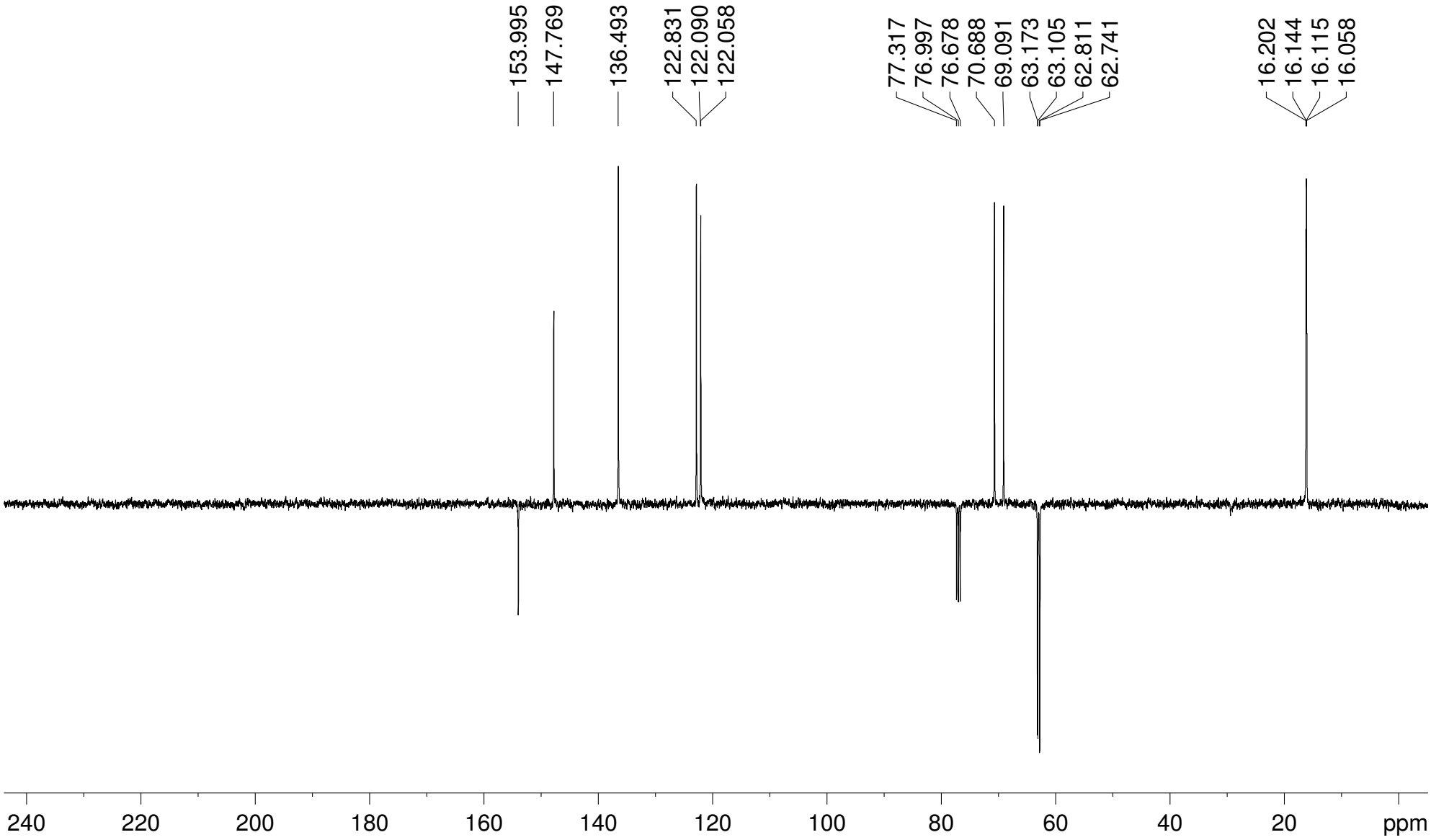


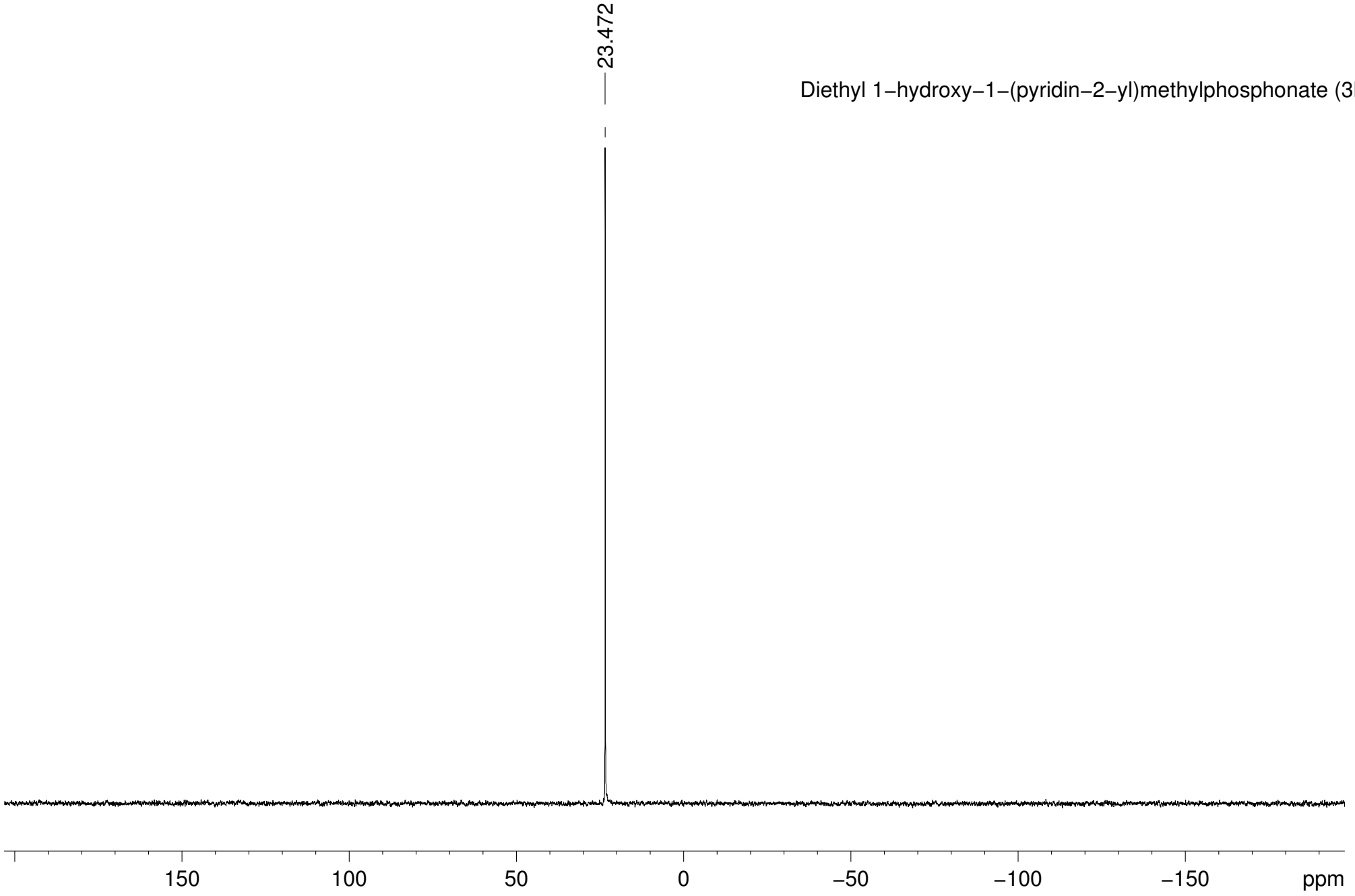


Diethyl 1–hydroxy–1–(pyridin–2–yl)methylphosphonate (3l)

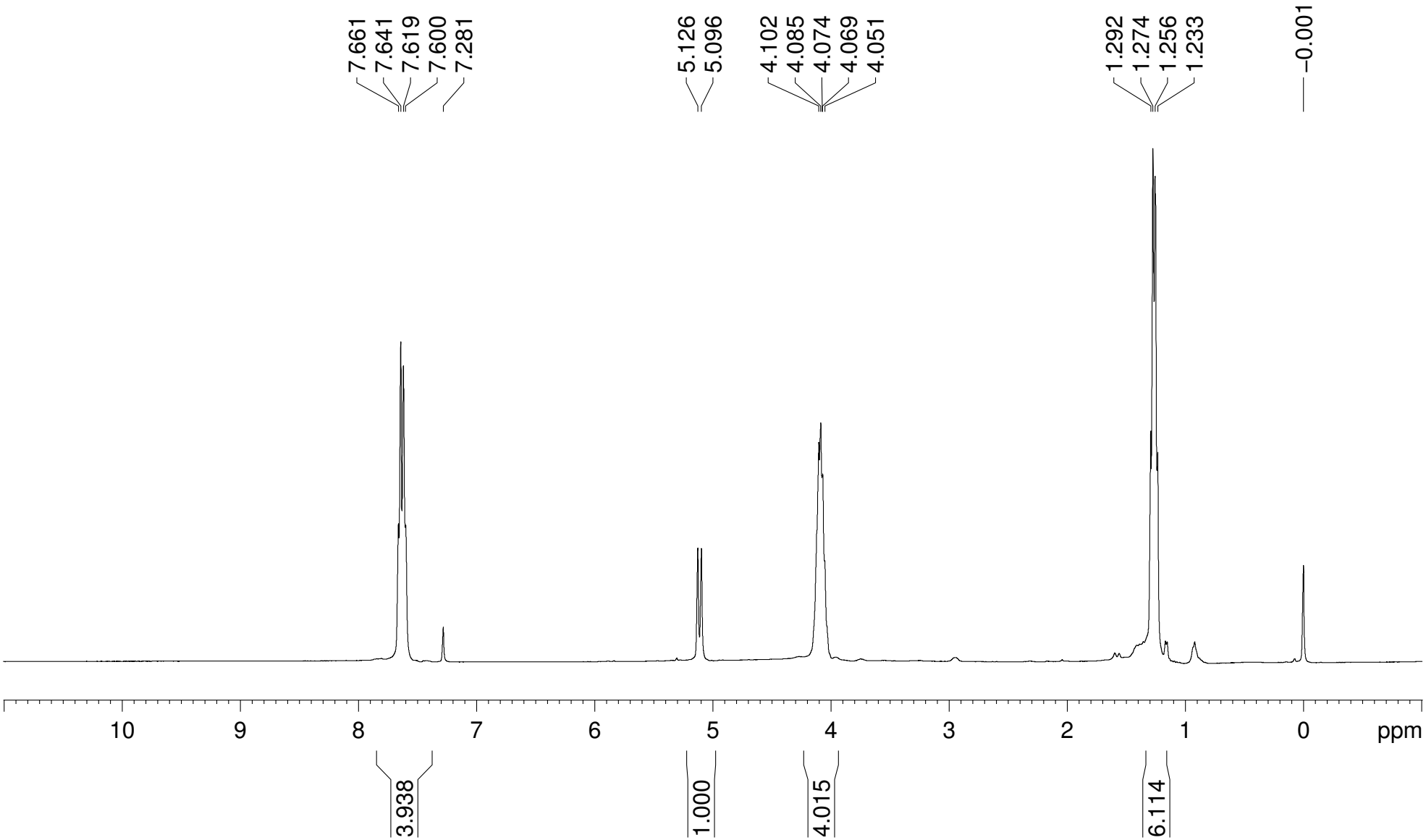


Diethyl 1–hydroxy–1–(pyridin–2–yl)methylphosphonate (3l)

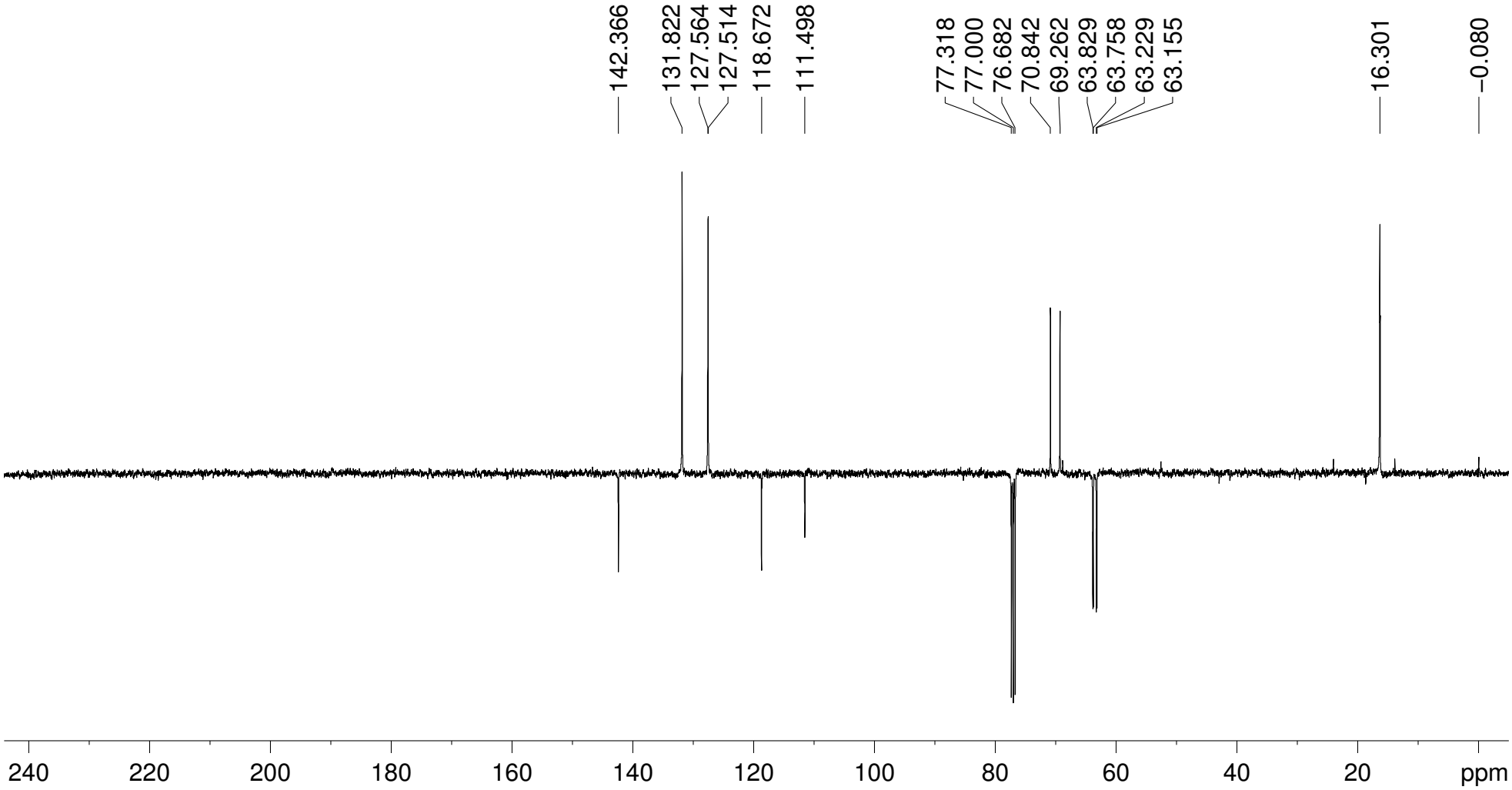




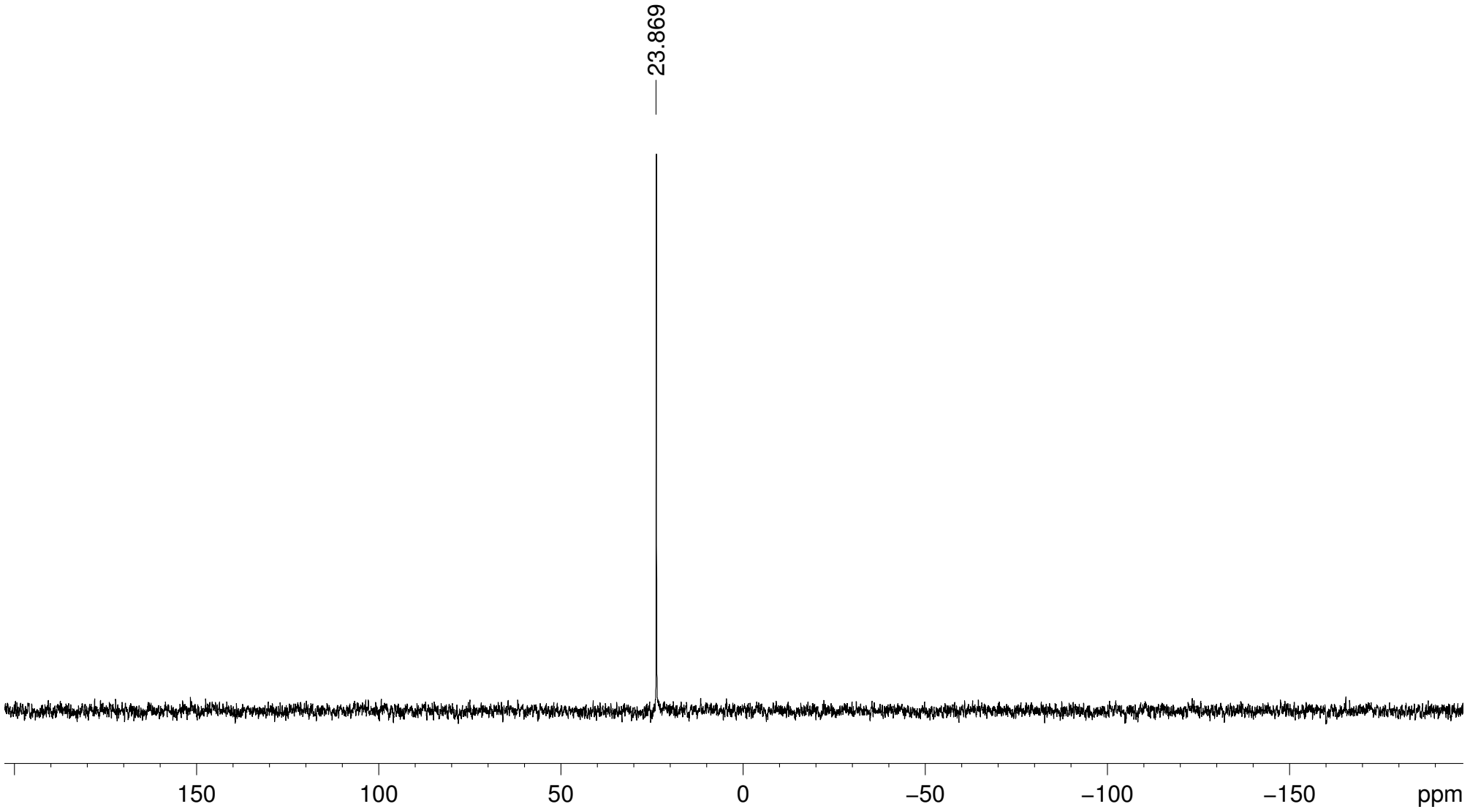
Diethyl 1–hydroxy–1–(4–cyanoyphenyl)methylphosphonate (3m)



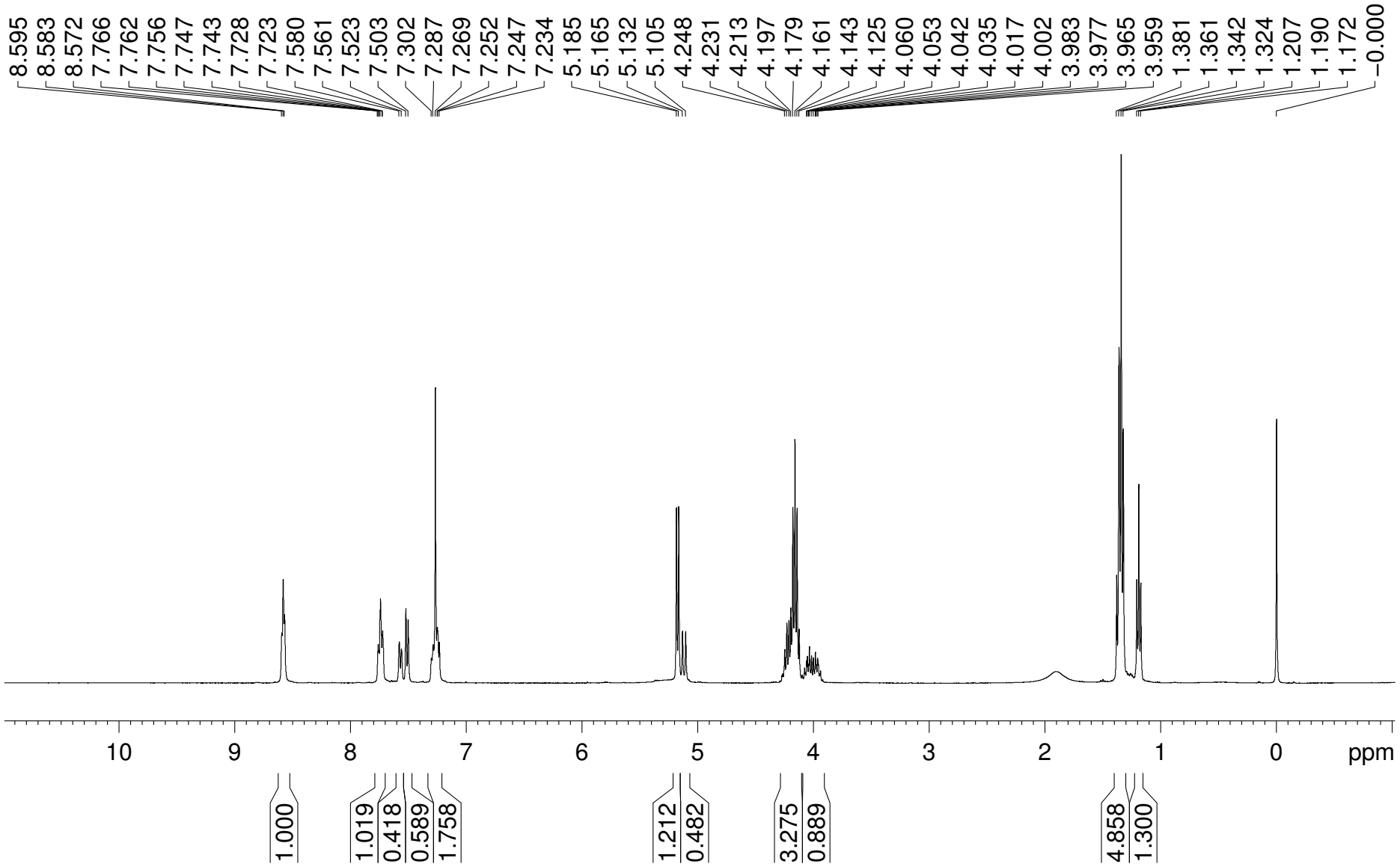
Diethyl 1–hydroxy–1–(4–cyanoyphenyl)methylphosphonate (3m)



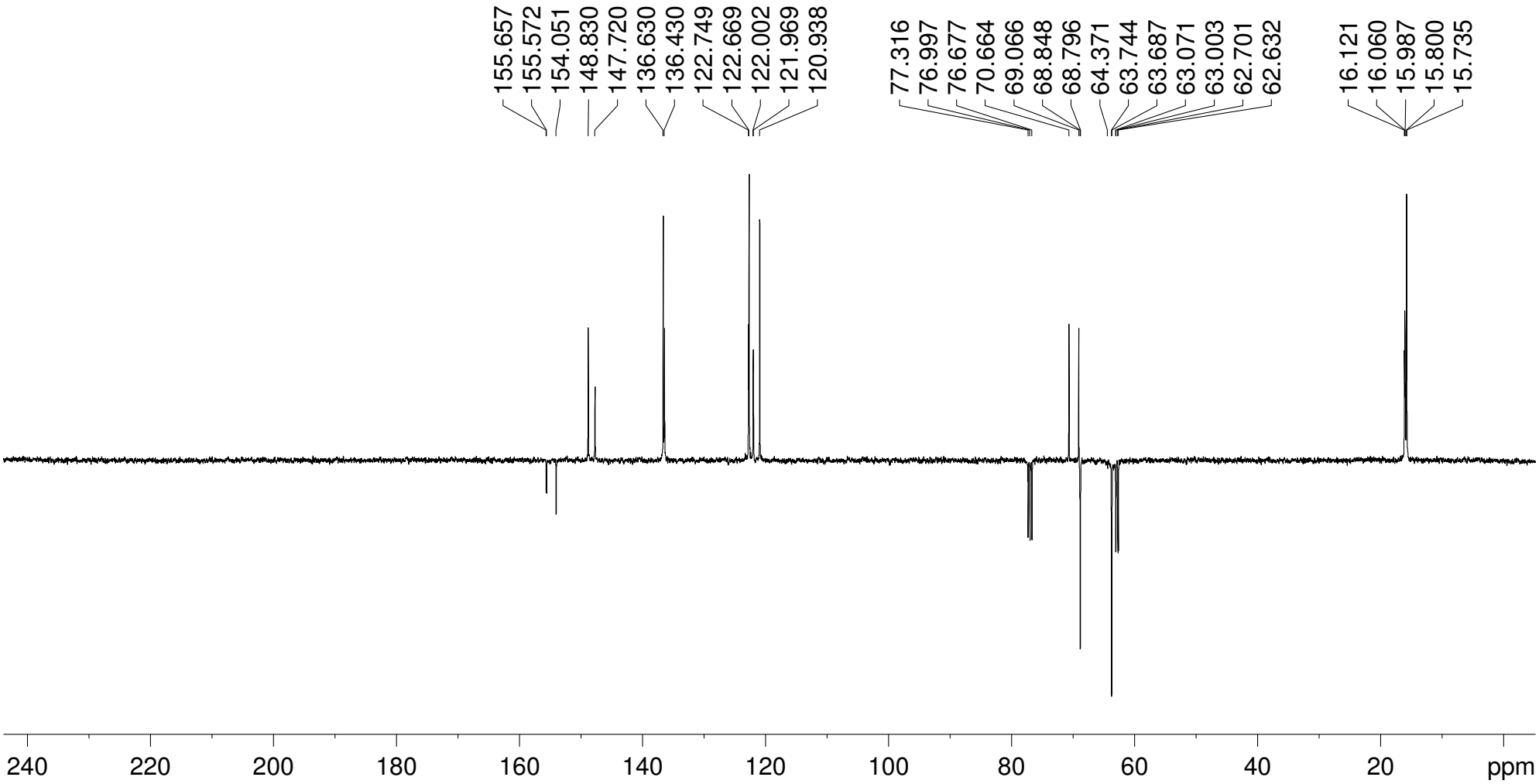
Diethyl 1–hydroxy–1–(4–cyanoyphenyl)methylphosphonate (3m)

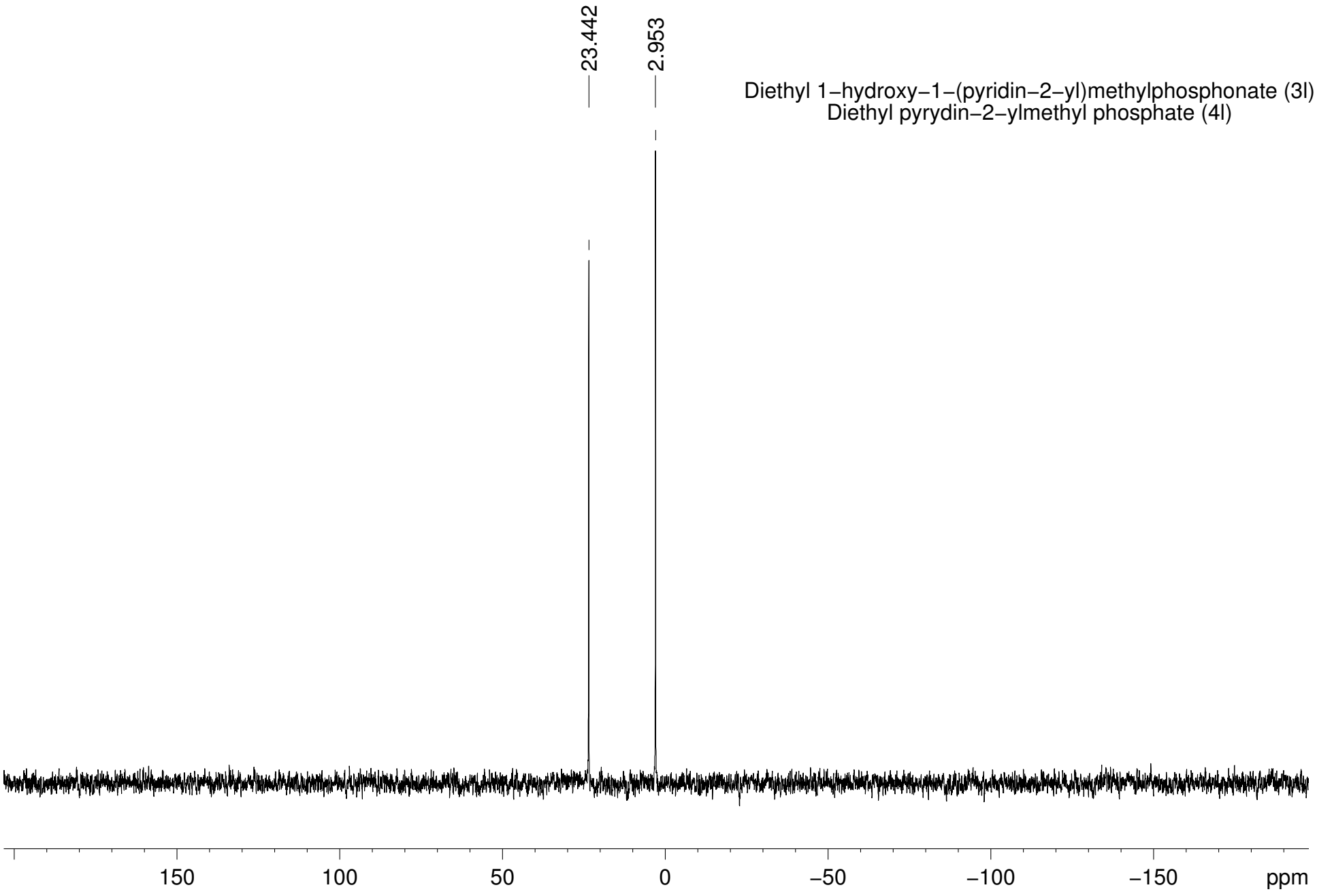


Diethyl 1–hydroxy–1–(pyridin–2–yl)methylphosphonate (3l)
Diethyl pyrydin–2–ylmethyl phosphate (4l)



Diethyl 1–hydroxy–1–(pyridin–2–yl)methylphosphonate (3l)
Diethyl pyrydin–2–ylmethyl phosphate (4l)





Diethyl (4–cyanophenyl)methyl phosphate (4m)