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Supporting Information

Selective Hydrogenation of Nitriles to Primary Amines Catalyzed by a Novel Iron Complex

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General Procedure:

All experiments with metal complexes and phosphine ligands were carried out under an atmosphere of purified nitrogen in a Vacuum Atmospheres glovebox equipped with a MO 40-2 inert gas purifier or using standard Schlenk techniques under argon atmosphere. All solvents were reagent grade or better. Non-deuterated solvents were dried over sodium/benzophenoneketyl (tetrahydrofuran, n-pentane, 1,4-dioxane, diethylether and toluene), magnesium (MeOH, EtOH and isopropanol) and distilled under argon atmosphere. MeCN was purchased from Sigma Aldrich and was degassed and stored in the glove box. All solvents were degassed with argon and kept in the glove box over activated 4Å molecular sieves. Deuterated solvents were purchased from Aldrich, purged with argon and stored over activated 4Å molecular sieves in the glove box. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded using Bruker AMX-300 and AMX-400 NMR spectrometers. All spectra were recorded at 295 K, unless otherwise noted. ^{1}H NMR and ^{13}C{H} NMR chemical shifts are reported in ppm downfield from tetramethylsilane and referenced to the residual signals of an appropriate deuterated solvent. ^{31}P{H} NMR chemical shifts are reported in ppm downfield from H_3PO_4 and referenced to an external 85% solution of phosphoric acid in D_2O. NMR spectroscopy abbreviations: br, broad; s, singlet; d, doublet; m, multiplet. GCMS was carried out on HP 6890 (flame ionization detector and thermal conductivity detector) and HP 5973 (MS detector) instruments equipped with a 30 m column (Restek 5MS, 0.32 mm internal diameter) with a 5% phenylmethylsilicone coating (0.25 mm) and helium as carrier gas. Most of the commercially available reagents were used as received. Benzonitrile was dried and purified by distillation. Selected substrates (4-methylbenzonitrile, 3-methylbenzonitrile, 4-fluorobenzonitrile) were purified either by distillation or crystallization. All the products of the catalytic experiments are commercially available and were identified by comparison of the ^{1}H NMR spectra or by GC-MS spectra with those of the commercially available compounds. Elemental analyses were performed on a Thermo Finnigan Italia S.p.A-FlashEA 1112 CHN Elemental Analyzer.

Experimental:

Synthesis of Bis(2-diisopropylphosphinobenzyl)amine (1):

In an oven-dried Schlenk flask *n*BuLi (1.3g, 20.3 mmol, 3 equiv, 1.6 M in hexane) was added dropwise to a solution of bis(2-bromobenzyl)amine (2.4g, 6.7 mmol) in diethyl ether (90 mL) at -50 °C under an argon atmosphere. The reaction solution turned pink and was allowed to warm up to room temperature and stirred for 16 h, providing a red solution. The reaction mixture was again cooled to -50 °C and diisopropylchlorophosphine (3.1g, 20.2 mmol) was added dropwise while stirring for half an hour. The reaction mixture was stirred at room temperature for 12 h. Monitoring the reaction mixture at this point by $^{31}P\{^1H\}$ NMR showed two singlet signals at -5.4 and 85.4 ppm in a 2:1 ratio. Then the solvents and volatiles were removed in *vacuo* and 80 ml of dry toluene and 20 mL of degassed water were added to the sticky solid residue and the mixture was refluxed overnight under an argon atmosphere. The $^{31}P\{^1H\}$ NMR of an aliquot in toluene showed a sharp signal at -4.4 ppm, corresponding to the desired ligand **1**, and an aliquot in water showed a signal at 67.8 ppm corresponding to oxidized diisopropylphosphineoxide. The toluene portion was separated from the aqueous solution, dried over $MgSO_4$ and evaporated to dryness under reduced pressure to obtain a red viscous liquid (99% purity by ^{31}P NMR) which can be used without further purifications for complex synthesis. Yield: 2.1 g (74%).

^1H NMR ($CDCl_3$, 400 MHz): δ = 0.90 (dd, 12H, CH_3), 1.12 (dd, 12H, CH_3), 2.11 (m, 4H, CH), 2.35 (s, NH), 4.15 (d, J = 2 Hz, 2H, CH_2), 7.22 (td, 2H, Ar), 7.30 (td, 2H, Ar), 7.43 (m, 2H, Ar), 7.49 (m, 2H, Ar). ^{13}C-NMR ($CDCl_3$, 101 MHz): δ = 19.5 (d, J_{CP} = 10.6 Hz, CH_3), 20.2 (d, J_{CP} = 18.8 Hz, CH_3), 24.1 (d, J_{CP} = 12.3 Hz, CH), 52.1 (d, J_{CP} =23.7 Hz, CH_2), 126.2 (s, Ar), 128.7 (s, Ar), 129.03 (d, J_{CP} = 6.1 Hz, Ar), 132.3 (d, J_{CP} = 3.1 Hz, Ar), 134.2 (d, J_{CP} = 20.1 Hz, Ar), 147 (d, J_{CP} = 24.1 Hz, Ar). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 121 MHz): δ = -4.6 (s).

Preparation of Fe(1)Br_2 complex (2):

To a suspension of $FeBr_2$ (140 mg, 0.65 mmol) in 15 mL THF was added one equiv. of ligand **1** (280 mg, 0.65 mmol) under N_2 atmosphere and the reaction mixture was stirred at room temperature overnight. The obtained light green solution was filtered through celite and the solvent was removed in *vacuo*. The residue was washed twice with pentane (2x10 mL) and dried. Afterwards the product was extracted with acetonitrile and washed with pentane to afford **2** (252 mg) in 60% yield as a light green product. Crystals suitable for X-ray analysis were obtained by slow diffusion of pentane into a concentrated toluene solution of **2**. Anal. Calcd. for $C_{26}H_{41}Br_2FeNP_2$: C, 48.40; H, 6.41; N, 2.17. Found: C, 48.98; H, 5.99; N, 2.20; IR (thin film, NaCl) = 3387 cm^{-1}($\nu_{N\text{-}H}$); ESI-MS: m/z: 446.46 [monooxidised iPrPNP + H]$^+$ = $[C_{26}H_{41}NOP_2H]^+$.

Reaction of complex (2) with 1 equiv. KHMDS under CO:

A solution of **2** (30 mg, 0.046 mmol) in 0.5 mL THF was taken in a J Young NMR tube in glovebox. The tube was taken out from the glove box and the N_2 atmosphere was removed by a *freeze pump thaw* cycle. The tube was pressurised with 1 atm of CO. Then 1 equiv. KHMDS (9.2 mg) was added under CO atmosphere and the reaction mixture was kept at room temperature for 24 hours. Monitoring the reaction solution by $^{31}P\{^1H\}$ NMR showing the appearance of two doublet signals at 63 and 71 ppm ($^2J_{PP}$ = 90 Hz) along with a signal of free PNP ligand, indicating the formation of a diamagnetic complex of the type $Fe(PNP)(CO)_2Br$ with the coordination of both phosphorus atoms in a *cis* arrangement. $^{31}P\{^1H\}$ NMR (THF, 121 MHz): δ = 63 ppm (d, $^2J_{PP}$ = 90 Hz), 71 ppm (d, $^2J_{PP}$ = 90 Hz). IR (NaCl): 2009 cm-1 (ν_{CO}), 1959 cm^{-1} (ν_{CO}).

General procedure for nitrile hydrogenation:

For Table 1: 0.01 mmol of pre-catalyst **2** was dissolved in 2 mL THF and a solution of 0.01 mmol of $NaHBEt_3$ (1 M in THF) in 1 mL THF (according to Table 1) was added dropwise at room temperature while stirring. After stirring the reaction mixture for 20 min, the solvent was evaporated under vacuum. Then the specified amount of base (see Table 1) and 1 mmol of benzonitrile were added to the residue and the mixture was dissolved in 2 mL of THF and placed in a high pressure autoclave. The autoclave was pressurized with H_2 (see Table 1) and heated at 140 ºC (bath temperature) with stirring for the specified time. The reaction mixture was then cooled down in an ice bath and H_2 was vented off. The reaction products were analyzed by GC-MS using m-xylene as internal standard.

For Table 2 (entries 1,2,4,5,13,14 and 20): 0.01 mmol of pre-catalyst **2**, 0.01 mmol of $NaHBEt_3$ (1 M in THF), 0.03 mmol KHMDS and 1 mmol substrate were used, employing the same procedure as described above. Product yields were determined by either GC-MS or ^1H NMR using m-xylene or toluene internal standard.

For Table 2 (entries 3,11 and 15): 0.02 mmol of pre-catalyst **2**, dissolved in 2 mL THF and a solution of 0.02 mmol of $NaHBEt_3$ (1 M in THF) in 1 mL THF was added dropwise at room temperature while stirring. After stirring the reaction mixture for 20 min, the solvent was evaporated under vacuum for 2 h. Then 0.06 mmol of KHMDS and 1 mmol of substrate were added to the residue and the mixture was dissolved in 2 mL of THF and placed in a high pressure autoclave. The autoclave was take out of the glove box and pressurized with 60 bar H_2 and heated at 140 ºC (bath temperature) with stirring for the specified time. The reaction mixture was then cooled in an ice bath and H_2 was vented off. Product yields were determined by either GC-MS or ^1H NMR using m-xylene or toluene internal standard.

For Table 2 (entries 6-10, 12, 16-19): To a solution of 0.02 mmol of pre-catalyst **2**, in 2 mL THF was added 0.02 mmol of $NaHBEt_3$ (1 M in THF) in 1 mL THF dropwise at room temperature while stirring. The reaction mixture was kept for 20 min. The solvent was evaporated under vacuum and the residue was kept for drying for 2 h. Then 0.06 mmol of KHMDS and 0.4 mmol of substrate were added to the residue. The mixture was dissolved in 2 mL of THF (for entry 18; 2 mL toluene was used) and placed in a high pressure autoclave. The autoclave was take out from the glove box and pressurized with 60 bar H_2 and heated at 140 ºC (bath temperature) with stirring for the specified time. The reaction mixture was then cooled in an ice bath and H_2 was vented off. Product yields were determined by either GC-MS or ^1H NMR using m-xylene or toluene internal standard.

X-ray Crystal structure determination:

Crystal data were measured at 100 K on a Bruker Apex-II Kappa CCD diffractometer equipped with [λ(Mo-Kα) = 0.71073 Å] radiation, graphite monochromator and Mira Col optics. The data were processed with APEX-II collect package programs. Structures were solved by the AUTOSTRUCTURE module and refined with full-matrix least-squares refinement based on F2 with SHELXL-97. Full details can be found in the CIF files and Table S1.

Table S1: Crystal data summary of **2**.

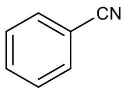
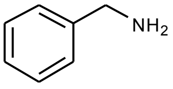
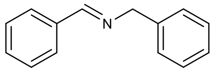
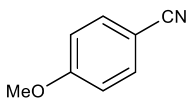
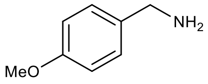
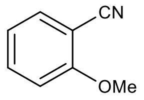
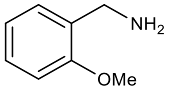
	2
CCDC	1419077
empirical formula	$C_{26} H_{41} Br_2 Fe N P_2$
formula weight (g·mol^{-1})	645.21
temperature (K)	100(2)
wavelength (Å)	0.71073
crystal system, space group	Orthorhombic, P2(1)2(1)2(1)
a (Å)	12.014(2)
b (Å)	15.518(3)
c (Å)	15.750(2)
α (deg)	90.00
β(deg)	90.00
γ (deg)	90.00
volume (Å^3)	2936.5(8)
Z, density (calcd) (Mg·m^{-3})	4, 1.459
abs coefficient (mm^{-1})	3.358
F(000)	1320
crystal size (mm^3)	0.12 x 0.10 x 0.06
θ range (deg) for data collection	2.59 to 26.37
reflections collected	20482
reflections unique	5954/ R_{int} = 0.0461
completeness to θ (%)	99.7

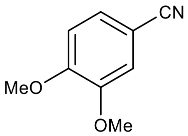
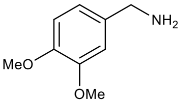
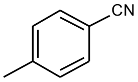
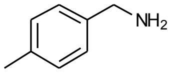
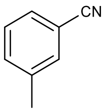
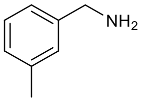
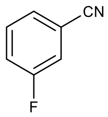
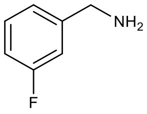
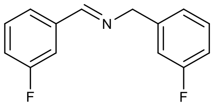
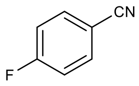
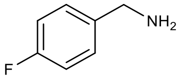
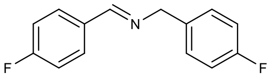
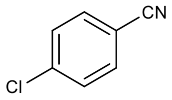
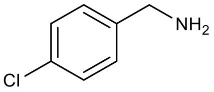
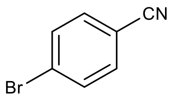
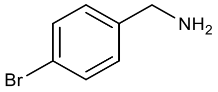
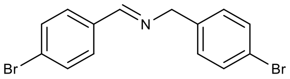
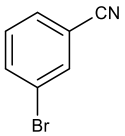
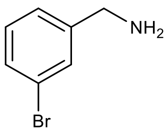
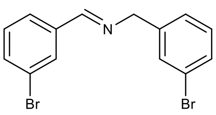
absorption correction	Semi-empirical from equivalents
max/min transmission	0.8239 and 0.6887
data / restraints / parameters	5954 / 0/ 301
goodness-of-fit on F^2	1.036
final R_1 and wR_2 indices [$I > 2\sigma(I)$]	0.0333, 0.0767
R_1 and wR_2 indices (all data)	0.0435, 0.0814
largest diff. peak and hole (e·Å^{-3})	1.254 and -0.435

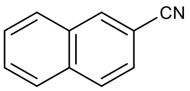
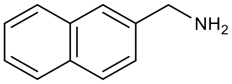
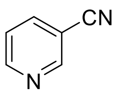
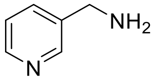
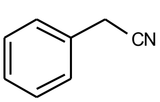
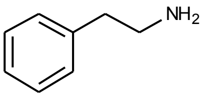
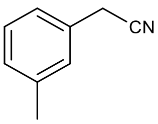
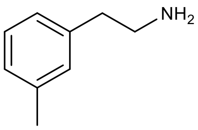
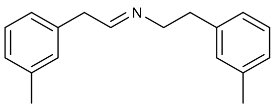
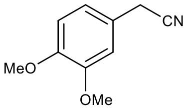
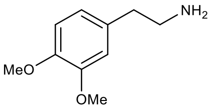
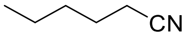
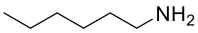
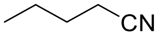
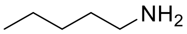
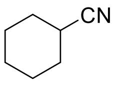
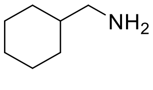
Table S2: Selected bond lengths and bond angles of **2**.

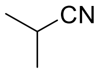
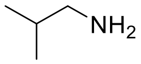
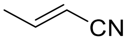
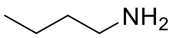
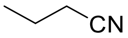
Bond lengths [Å]		Bond Angles [°]	
Br1-Fe1	2.3794(7)	N1-Fe1-Br1	106.16(9)
Br2-Fe1	2.3811(7)	N1-Fe1-Br2	105.26(9)
Fe1-N1	2.118(3)	Br1-Fe1-Br2	118.71(3)
Fe1-P1	2.4282(11)	N1-Fe1-P1	89.96(8)
N1-H1	0.88(4)	Br1-Fe1-P1	119.41(3)
		Br2-Fe1-P1	111.75(3)

Table S3: GC-MS data for the nitriles and hydrogenated amines and imines formed during hydrogenation of various nitriles using HP 6890 equipped with flame ionization and thermal conductivity detectors and HP 5973 (MS detector) instruments, equipped with a 30 m column (Restek 5MS, 0.32 mm internal diameter) with a 5% phenylmethylsilicone coating (0.25 mm) and helium as carrier gas with a flow rate of 1 ml/min):

Entry	Substrate	Primary amine	Secondary imine
1	 t_r = 6.256 min m/z = 103	 t_r = 6.885 min m/z = 107	 t_r = 14.896 min m/z = 195
2	 m/z = 133	 t_r = 10.702 m/z = 136/137	
3	 t_r = 10.881 min m/z = 133	 t_r = 10.334 min m/z = 137	

4	 t_r = 12.819 min m/z = 163	 t_r = 12.693 min m/z = 167	
5	 t_r = 8.454 min m/z = 114	 t_r = 8.660 min m/z = 121	
6	 t_r = 8.254 min m/z = 117	 t_r = 8.677 m/z = 121	
7	 t_r = 5.585 min m/z = 121	 t_r = 7.174 min m/z = 125	 t_r = 14.757 min m/z = 231
8	 t_r = 6.043 min m/z = 121	 t_r = 7.160 min m/z = 125	 t_r = 14.757 min m/z = 231
9	 t_r = 9.130 min m/z = 137	 t_r = 10.010 m/z = 141	
10	 t_r = 10.261 min m/z = 182	 t_r = 11.015 min m/z = 186	 t_r = 19.093 min m/z = 353
11	 t_r = 10.104 min m/z = 181	 t_r = 11.127 min m/z = 185	 t_r = 18.902 min m/z = 353

12	 t_r = 13.171 min m/z = 153	 t_r = 13.578 min m/z = 157	
13	 t_r = 9.147 min m/z = 104	 t_r = 8.614 min m/z = 108	
14	 t_r = 9.003 min m/z = 117	 t_r = 8.406 min m/z = 121	
15	 t_r = 10.250 min m/z = 131	 t_r = 9.803 min m/z = 135	 t_r = 17.258 min m/z = 251
16	 t_r = 13.655 min m/z = 177	 t_r = 13.370 min m/z = 181	
17	 t_r = 7.577 min m/z = 97	 t_r = 6.713 min m/z = 101	
18	 t_r = 4.906 min m/z = 82	 t_r = 3.899 min m/z = 87	
19	 t_r = 6.766 min m/z = 109	 t_r = 6.009 min m/z = 113	

20	 t_r = 2.282 min m/z = 69	 t_r = 2.057 min m/z = 73	
21	 t_r = 2.497 min m/z = 67	 t_r = 2.282 min m/z = 73	 t_r = 2.733 min m/z = 68

t_r = retention time

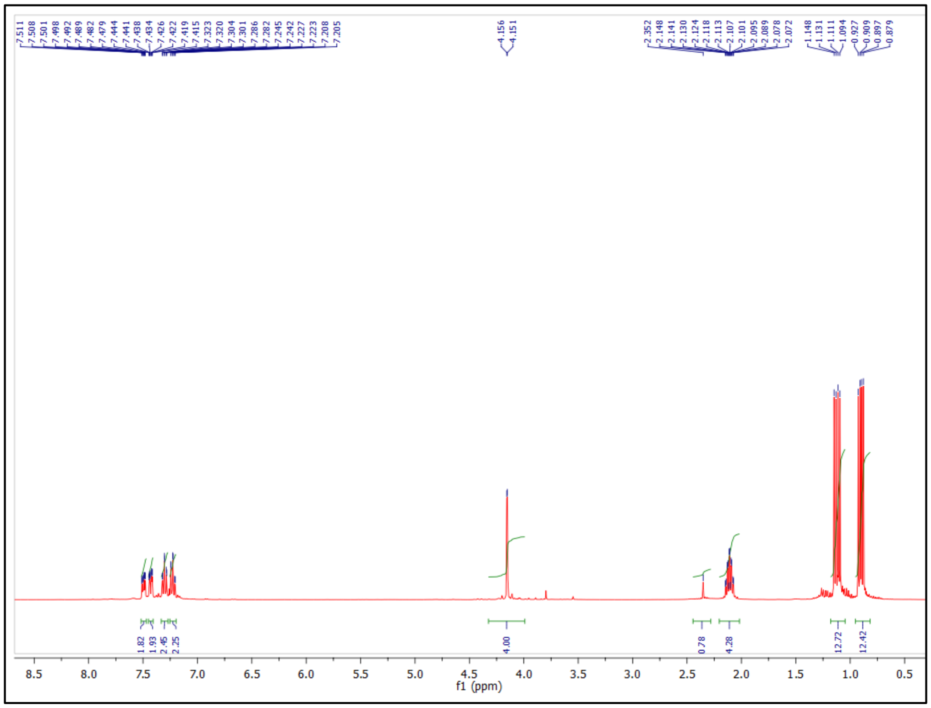


Figure S1: ^{1}H NMR spectrum of **1** in CDCl$_3$ at room temperature.

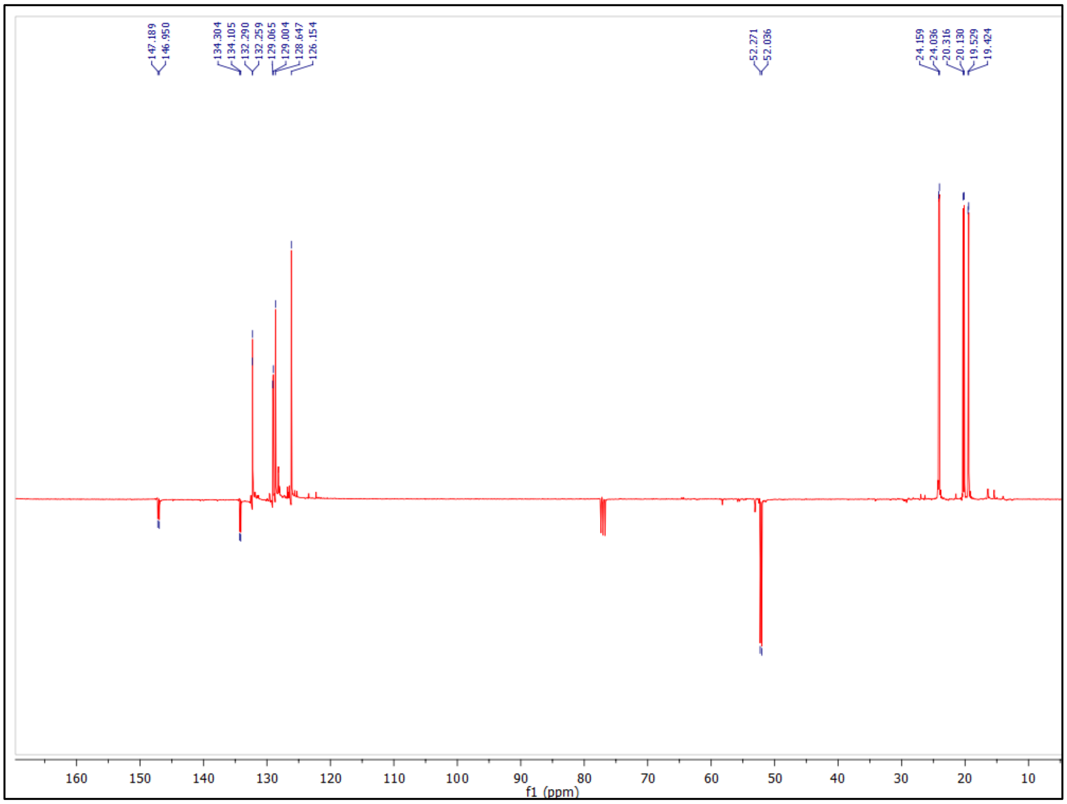


Figure S2: ^{13}CDEPTQ NMR spectrum of **1** in CDCl$_3$ at room temperature.

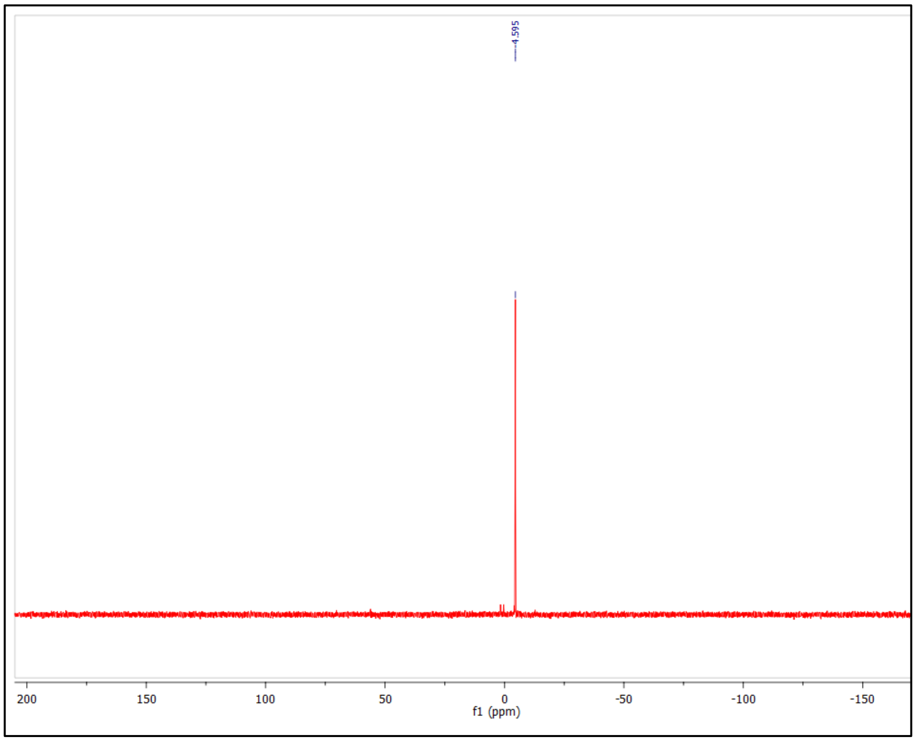


Figure S3: ^{31}P{^{1}H}NMR spectrum of **1** in CDCl$_3$ at room temperature.