SUPPORTING INFORMATION:

An Open-flask Synthesis of Amine-boranes via Tandem Amine-Ammonium Salt Equilibration-Metathesis

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Contents:

Experimental Section

- **General Information:**

^{11}B, ^{1}H, and ^{13}C NMR spectra were recorded at room temperature, on a Varian INOVA 300 MHz NMR spectrophotometer. Chemical shifts (δ values) are reported in parts per million relative to $BF_3.Et_2O$ for ^{11}B NMR respectively. Data are reported as: δ value, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, p=pentet, h=hextet, m=multiplet, br=broad) and integration. Tetrahydrofuran (THF, ACS grade containing 0.004% water and 0.025% BHT) was purchased from Fisher-Scientific. Sodium borohydride (SBH, powder, purity >99% by hydride estimation[1]) was purchased in bulk from Dow Chemical Co. (Rohm and Haas). Ammonium fluoride (98%, Sigma-Aldrich), ammonium chloride (ACS reagent, Mallinckrodt), ammonium formate (97%, Sigma-Aldrich), ammonium sulfate (ACS reagent, Mallinckrodt), and ammonium carbonate (ACS reagent, Sigma-Aldrich) were purchased from the respective commercial sources and powdered prior to use. All of the amines used were purchased from commercial sources. Liquid amines were distilled while solid amines were used without any purification. All of the amine-boranes (**2a-2k**) synthesized have been reported in prior literature.[2,3,4,5]

- **General procedure for the preparation of amine-boranes (2a-2k):**

SBH (0.19 gms, 5 mmol) and powdered ammonium sulfate (0.33 gms, 2.5 mmol) were transferred to a 25 mL dry round bottom flask, fitted with a water-cooled reflux condenser. The corresponding amine (**1a-1f, 1j-1k**, 5 mmol) or diamine (**1g-1i**, 2.5 mmol) was charged into the reaction flask followed by addition of THF (5 mL) at rt. The heterogeneous reaction mixture was brought to reflux, under vigorous stirring. Reaction progress was monitored by ^{11}B NMR spectroscopy (**Note:** A drop of anhydrous DMSO is added to the reaction aliquot before running the NMR experiment). Upon completion of the reaction (6-8 h), the reaction was cooled to rt, filtered through celite, and washed with THF. Removal of solvent *in vacuo* yielded the corresponding amine-borane.

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[1] Brown, H. C. *Organic Syntheses Via Boranes*, Wiley: New York, **1975**, Chapter 9.
[2] **2a,2c,2e-2i:** Ramachandran, P. V.; Kulkarni, A. S.; Pfeil, M. A.; Dennis, J. D.; Willits, J. D.; Heister, S. D.; Son, S. F.; Pourpoint, T. L. *Chem. Eur. J.* **2014**, *20*, 16869.
[3] **2b:** Hutchins, R. O.; Learn, K.; Nazer, B.; Pytlewski, D.; Pelter, A. *Org. Prep. Proced. Int.* **1984**, *16*, 335.
[4] **2d**,**2j**: Ramachandran, P. V.; Kulkarni, A. S. *RSC Adv.* **2014**, *4*, 26207.
[5] **2k**: Kawase, Y.; Yamagishi, T.; Kutsuma, T.; Zhibao, H.; Yamamoto, Y.; Kimura, T.; Nakata, T.; Kataoka, T.; Yokomatsu, T. *Org. Process Res. Dev.* **2012**, *16*, 495.

- **Procedure for the large-scale preparation of TEAB (2a):**

Caution:

Ammonia - Toxic, corrosive.

Hydrogen - Highly flammable.

The reaction was carried out in a well-ventilated hood with the reaction vessel outlet directly leading into the hood exhaust due to the hazards associated with escaping ammonia and the liberation of large quantities of hydrogen.

Sodium borohydride (37.9 gms, 1 mol) and powdered ammonium sulfate (66.1 gms, 0.5 mol) were transferred to a 3-necked 3 L dry round bottom flask, fitted with water-cooled reflux condensers. *N,N,N*-Triethylamine (**1a**, 139.4 mL, 1 mol) was charged into the flask, followed by THF (1 L) at rt. The heterogeneous reaction mixture was brought to reflux, under vigorous stirring. Upon completion of the reaction (6 h), as monitored by ^{11}B NMR spectroscopy, the reaction was cooled to rt, filtered through celite, and washed with THF. Removal of solvent *in vacuo* yielded **2a** as a colorless liquid (103.5 g, 90%). Hydride analysis revealed **2a** to be 97% pure. ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 2.79 (qd, J = 7.4, 1.7 Hz, 6H), 1.19 (td, J = 7.3, 1.7 Hz, 9H), 2.10 – 0.9 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 52.2, 8.6.; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -13.95 (q, J = 96.0 Hz).

- **General procedure for hydride analysis of amine-boranes (Hydrolysis reaction):**

An aqueous solution of amine-borane (2 mmol in 1 mL H_2O) was transferred to a round bottom flask with a septum inlet fitted with a connecting tube. The connecting tube was attached to an analytical gas burette filled with $CuSO_4$ solution. A solution of $RuCl_3$ (4.2 mg, 1 mol% in 2 mL H_2O) was syringed into the vial, all at once. The hydrogen generated was measured using the analytical gas burette. The temperature of the reaction was maintained at 25˚C.

Characterization of amine-boranes:

Triethylamine-borane (2a):

Colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 2.79 (qd, *J* = 7.4, 1.7 Hz, 6H), 1.19 (td, *J* = 7.3, 1.7 Hz, 9H), 2.10 – 0.9 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 52.2, 8.6.; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -13.95 (q, *J* = 96.0 Hz).

***tert*-Butylamine-borane (2b):**

White solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 3.81 (s, 2H), 1.22 (s, 9H), 2.0 – 0.7 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 51.9, 26.8; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -23.35 (q, *J* = 93.9 Hz).

Cyclohexylamine-borane (2c):

White Solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 3.59 (s, 2H), 2.72 (tdt, *J* = 10.4, 7.7, 3.0 Hz, 1H), 2.22 – 2.09 (m, 2H), 1.86 – 1.57 (m, 3H), 1.42 – 1.06 (m, 5H)), 0.90 - 2.05 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 56.8, 32.2, 25.2, 24.4; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -20.88 (q, *J* = 95.0 Hz).

***N*,*N*-Diisopropylamine-borane (2d):**

Colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 3.39 – 3.11 (m, 3H), 1.28 (ddd, *J* = 6.7, 5.1, 1.8 Hz, 12H), 0.70 - 2.00 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 51.9, 18.9, 20.9; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -21.76 (q, *J* = 96.0 Hz).

Morpholine-borane (2e):

White Solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 4.38 (s, 1H), 3.95 – 3.75 (m, 2H), 3.53 (t, J = 12.3 Hz, 2H), 3.03 (d, J = 13.5 Hz, 2H), 2.83 – 2.63 (m, 2H), 1.5 (br q, 3H, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 64.5, 50.8; ^{11}B NMR (96 MHz, $CDCl_3$) δ -15.47 (q, J = 97.2 Hz).

***N*-Ethylpiperidine-borane (2f):**

Colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 3.03 – 2.80 (m, 4H), 2.80 – 2.67 (m, 2H), 1.94 – 1.78 (m, 2H), 1.70 – 1.49 (m, 4H), 1.27 (t, J = 7.2 Hz, 3H), 2.10 – 0.95 (br q, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 57.4, 54.6, 22.7, 20.3, 8.8; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -13.01 (q, J = 97.0 Hz).

1,2-Diaminoethane-bisborane (2g):

Purification involved washing the product with isopropanol and water.

White Solid.

^{1}H NMR (300 MHz, DMSO-d_6) δ (ppm): 5.25 (s, 4H), 2.61 (s, 4H), 2.11 – 0.23 (br s, 6H, BH_3); ^{13}C NMR (75 MHz, DMSO-d_6) δ (ppm): 45.8; ^{11}B NMR (96 MHz, THF) δ (ppm): -19.29 (q, J = 95.0 Hz).

Piperazine-bisborane (2h):

White solid.

^{1}H NMR (300 MHz, DMSO-d_6) δ (ppm): 6.19 (s, 2H), 3.20 – 2.77 (m, 4H), 2.75 - 2.42 (m, 4H), 2.15 – 0.62 (br q, 6H); ^{13}C NMR (75 MHz, DMSO-d_6) δ (ppm): 49.9; ^{11}B NMR (96 MHz, DMSO-d_6) δ (ppm): -10.30 (q, J = 95.0 Hz).

_N,N_-Dimethylpiperazine-bisborane (2i):

White solid. A mixture of diastereomers (from ^{11}B NMR analysis).

^{1}H NMR (300 MHz, DMSO-d_6) δ(ppm): 3.22 – 2.68 (m), 2.69 – 2.45 (m), 2.46 – 2.30 (m), 2.22 (d, J = 1.7 Hz), 2.15 – 0.79 (br, BH_3); ^{13}C NMR (75 MHz, DMSO-d_6) δ (ppm): 54.0, 53.7; ^{11}B NMR (96 MHz, THF) δ (ppm): -9.97 (q), -11.89 (q). The two quartets are merged, which are separated into two singlets upon ^{1}H-^{11}B decoupling.

Pyridine-borane (2j):

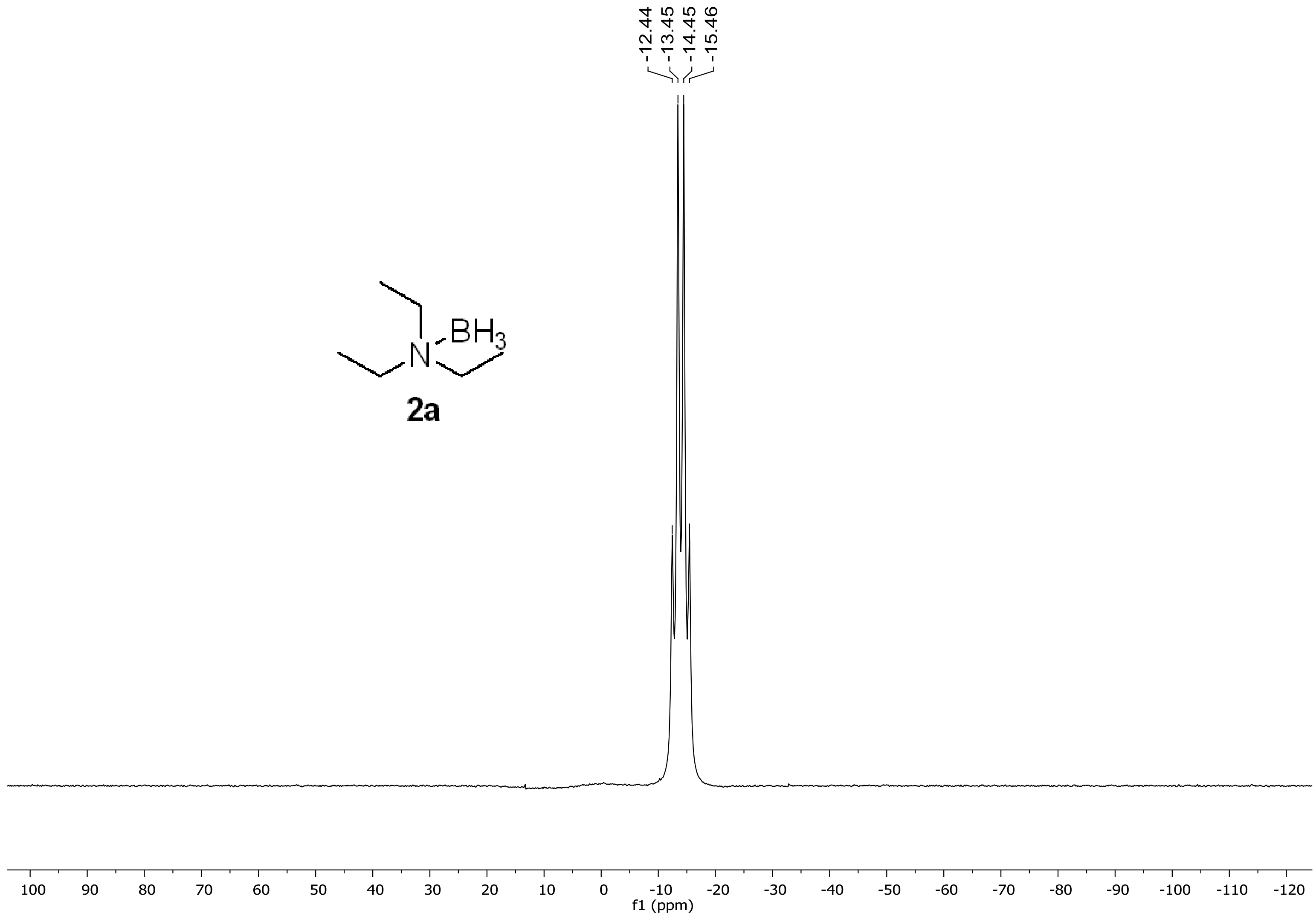
Colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 8.57 (d, J = 5.5 Hz, 2H), 7.95 (td, J = 7.7, 1.6 Hz, 1H), 7.59 – 7.48 (m, 2H), 2.62 (q, J = 96 Hz, 3H, BH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 146.8, 138.8, 125.0; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -12.57 (q, J = 97.7 Hz).

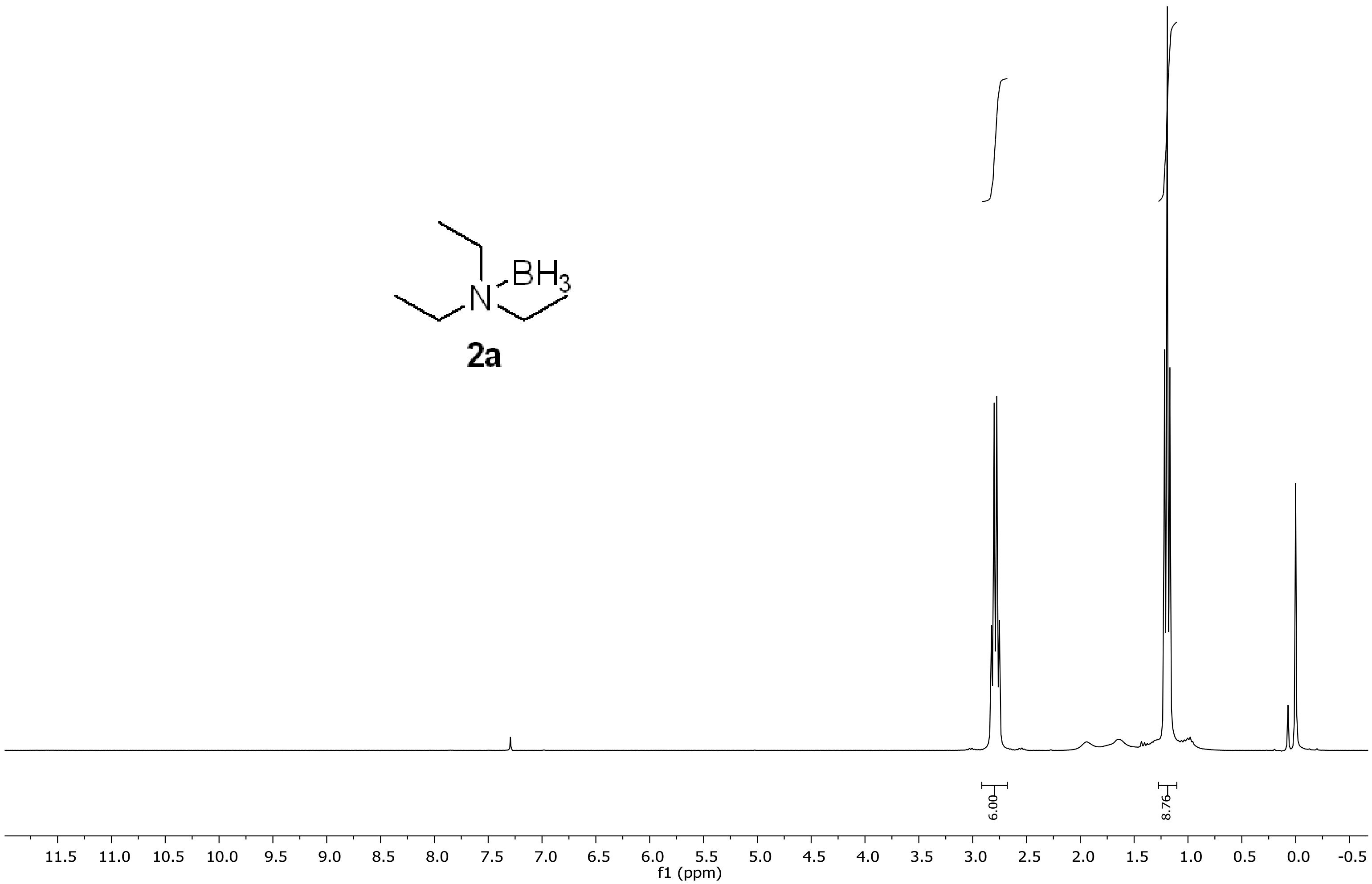
2-Picoline-borane (2k):

White solid.

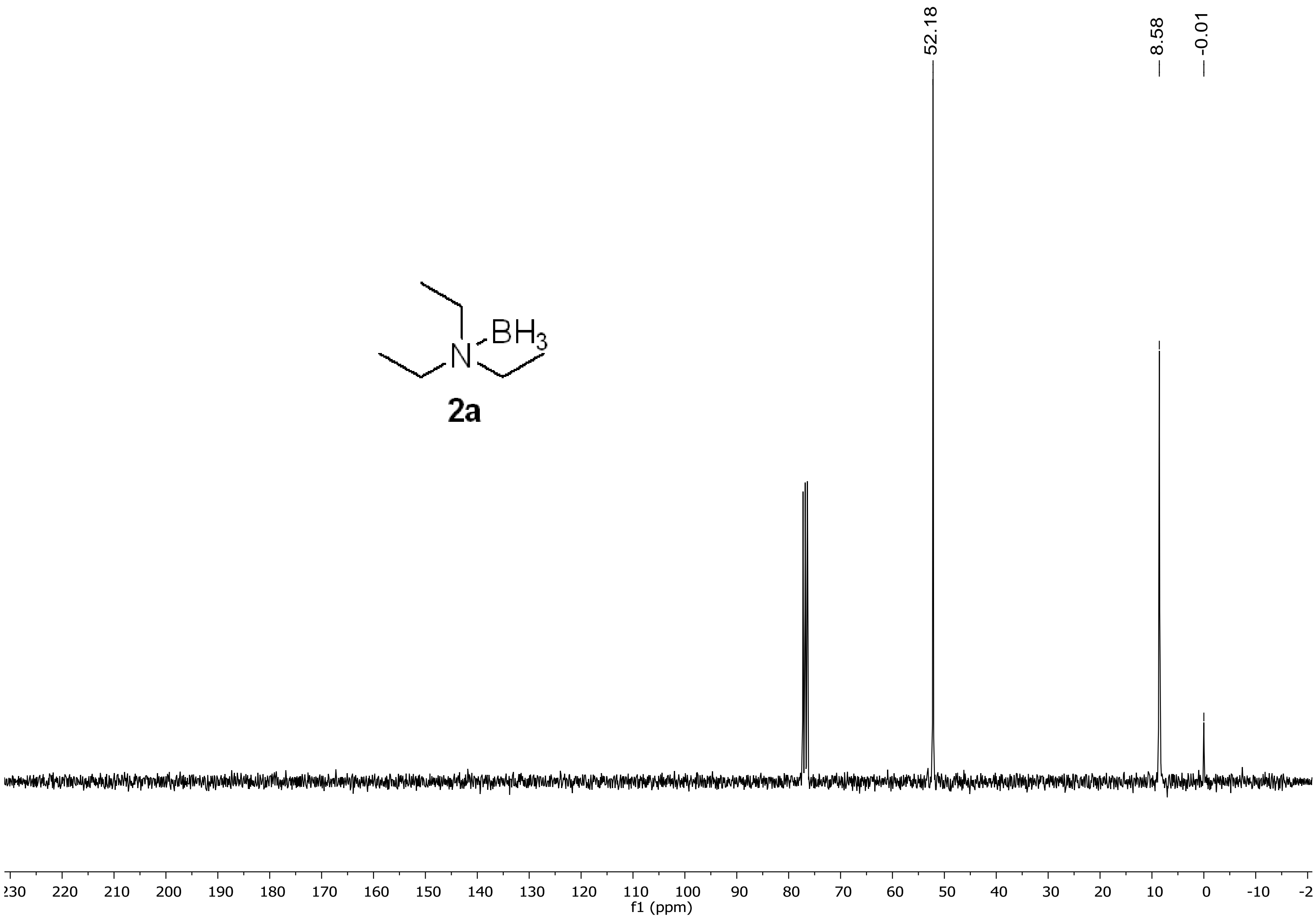
^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 8.72 (d, J = 6 Hz, 1H), 7.89 – 7.72 (m, 1H), 7.36 (dd, J = 7.7, 1.4 Hz, 1H), 7.28 (ddd, J = 7.7, 6.1, 1.7 Hz, 1H), 3.10 – 1.80 (br q, BH_3), 2.75 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.2, 148.2, 139.0, 126.3, 122.0, 22.5; ^{11}B NMR (96 MHz, $CDCl_3$) δ (ppm): -14.22 (q, J = 97.9 Hz).



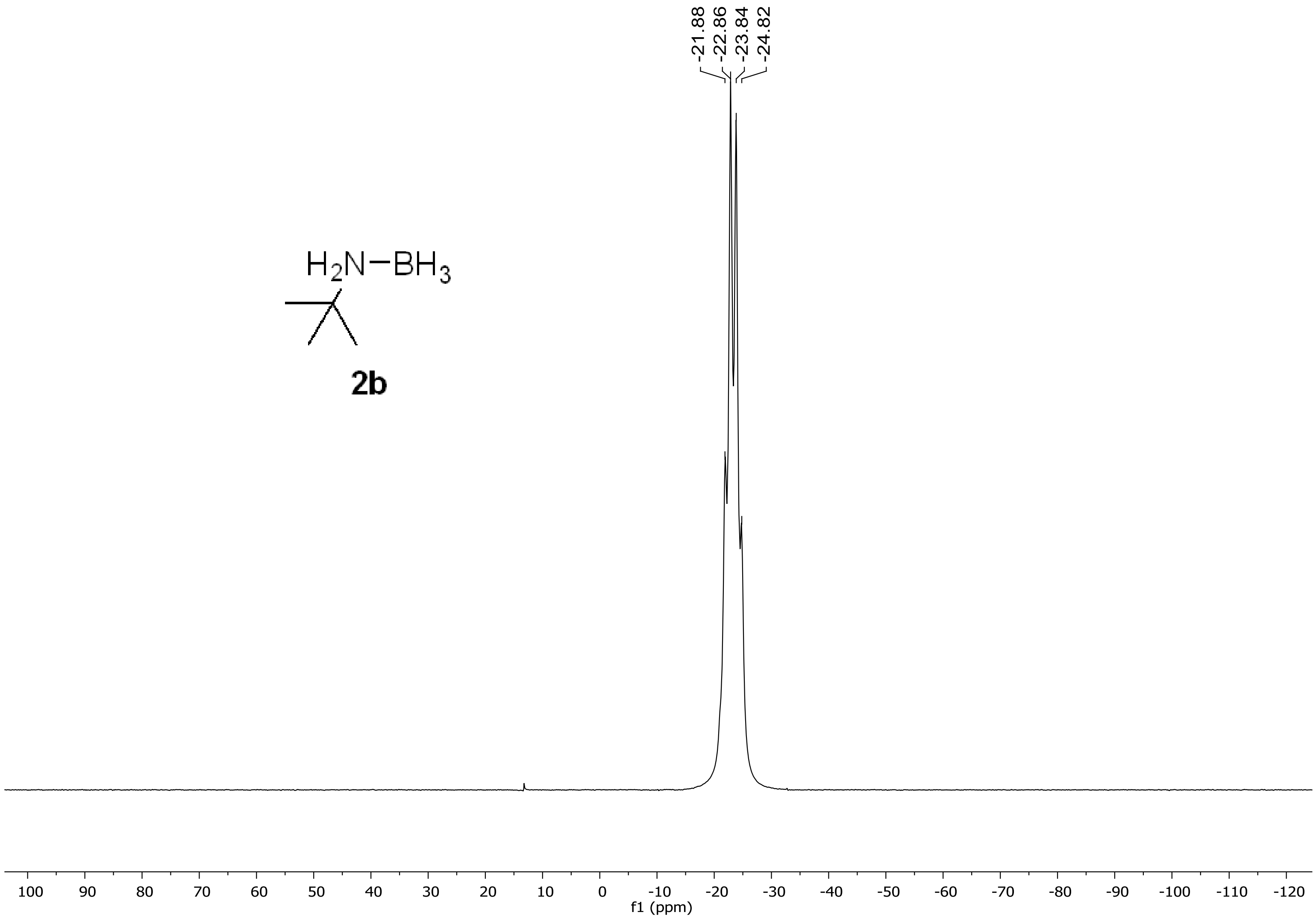
^{11}B NMR (96 MHz, $CDCl_3$) Triethylamine-borane (**2a,** Entry 1)



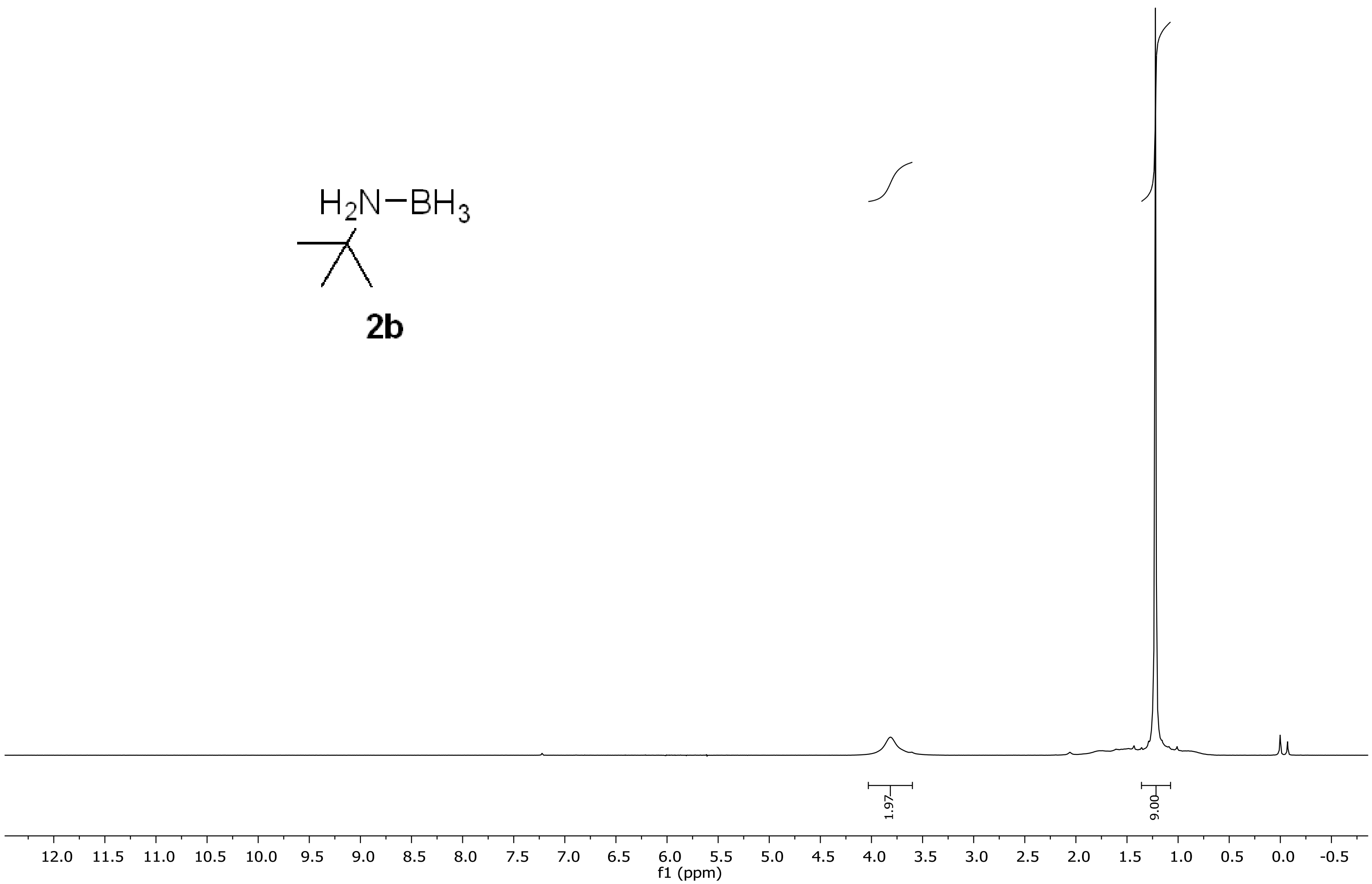
[1]H NMR (300 MHz, $CDCl_3$) Triethylamine-borane (**2a,** Entry 1)



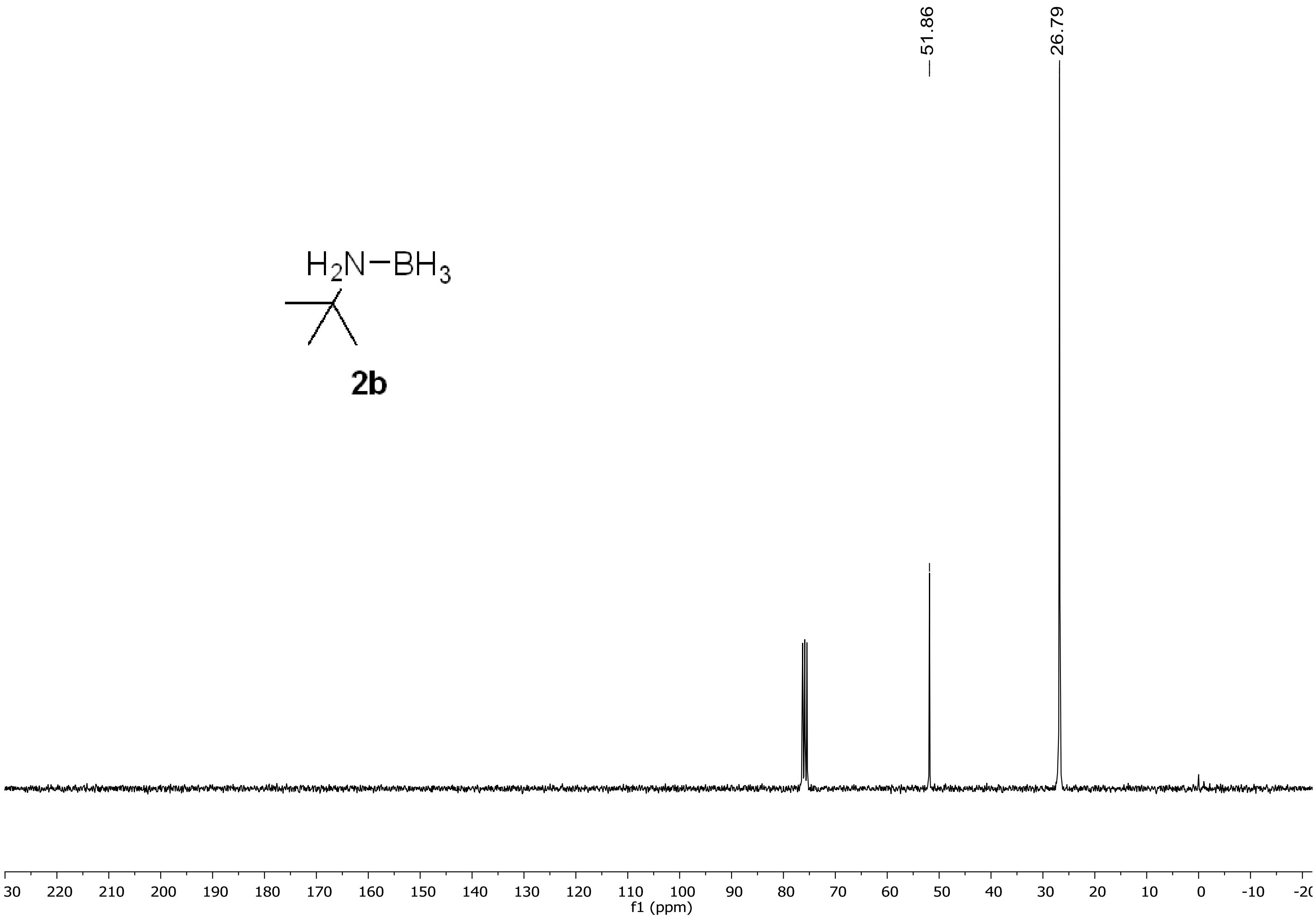
^{13}C NMR (75 MHz, $CDCl_3$) Triethylamine-borane (**2a,** Entry 1)



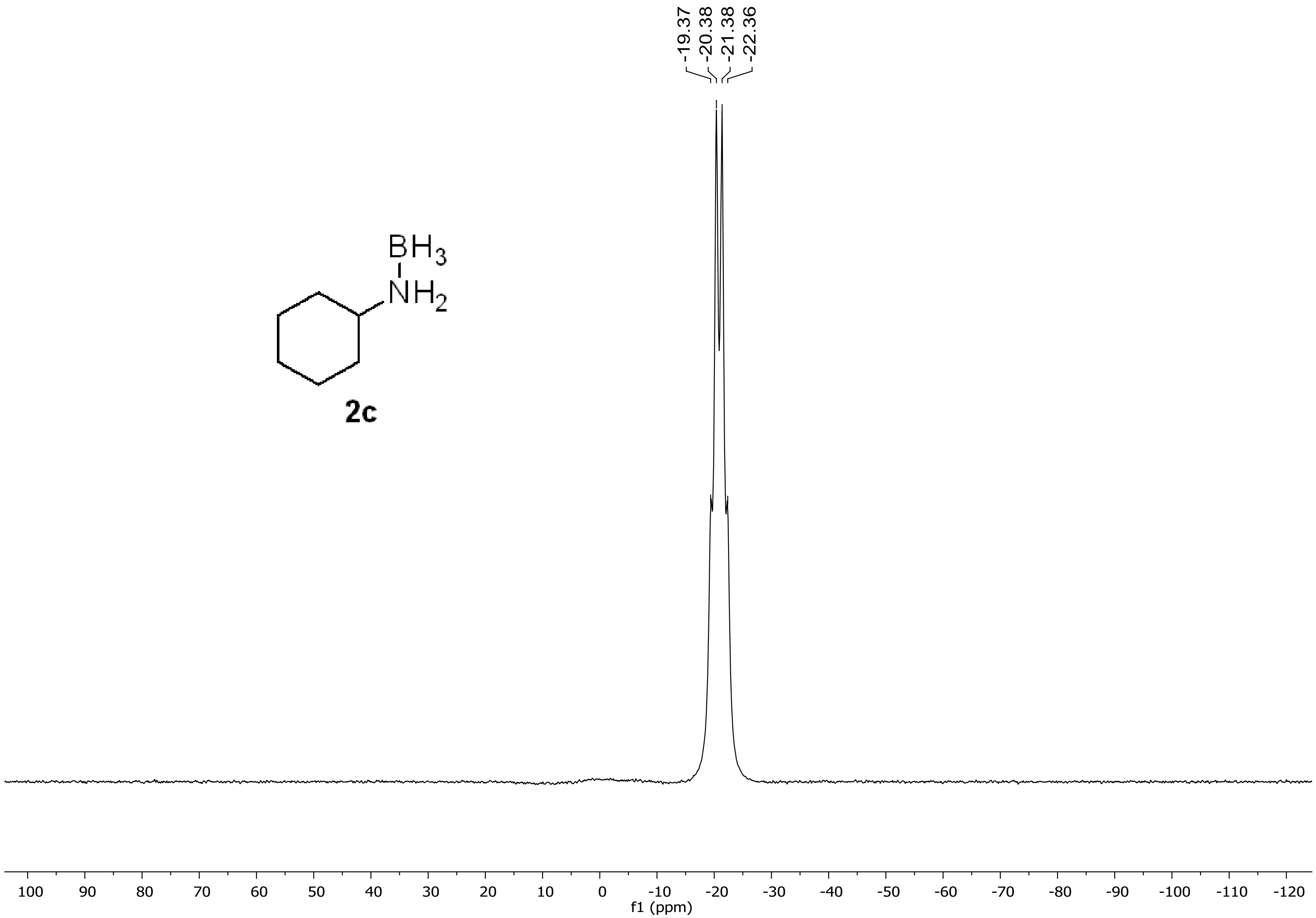
^{11}B NMR (96 MHz, $CDCl_3$) *tert*-Butylamine-borane (**2b,** Entry 2)



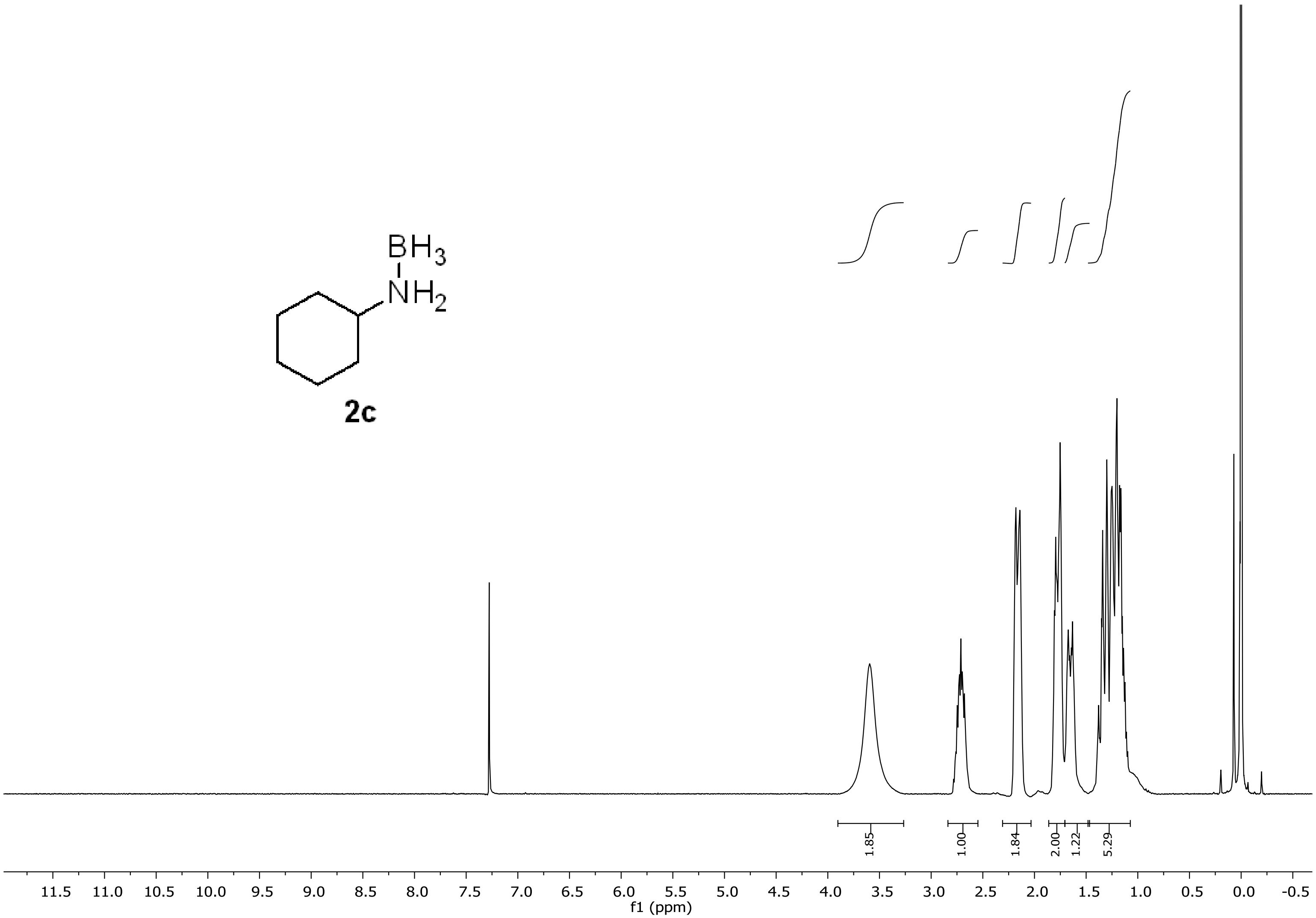
^{1}H NMR (300 MHz, $CDCl_3$) *tert*-Butylamine-borane (**2b,** Entry 2)



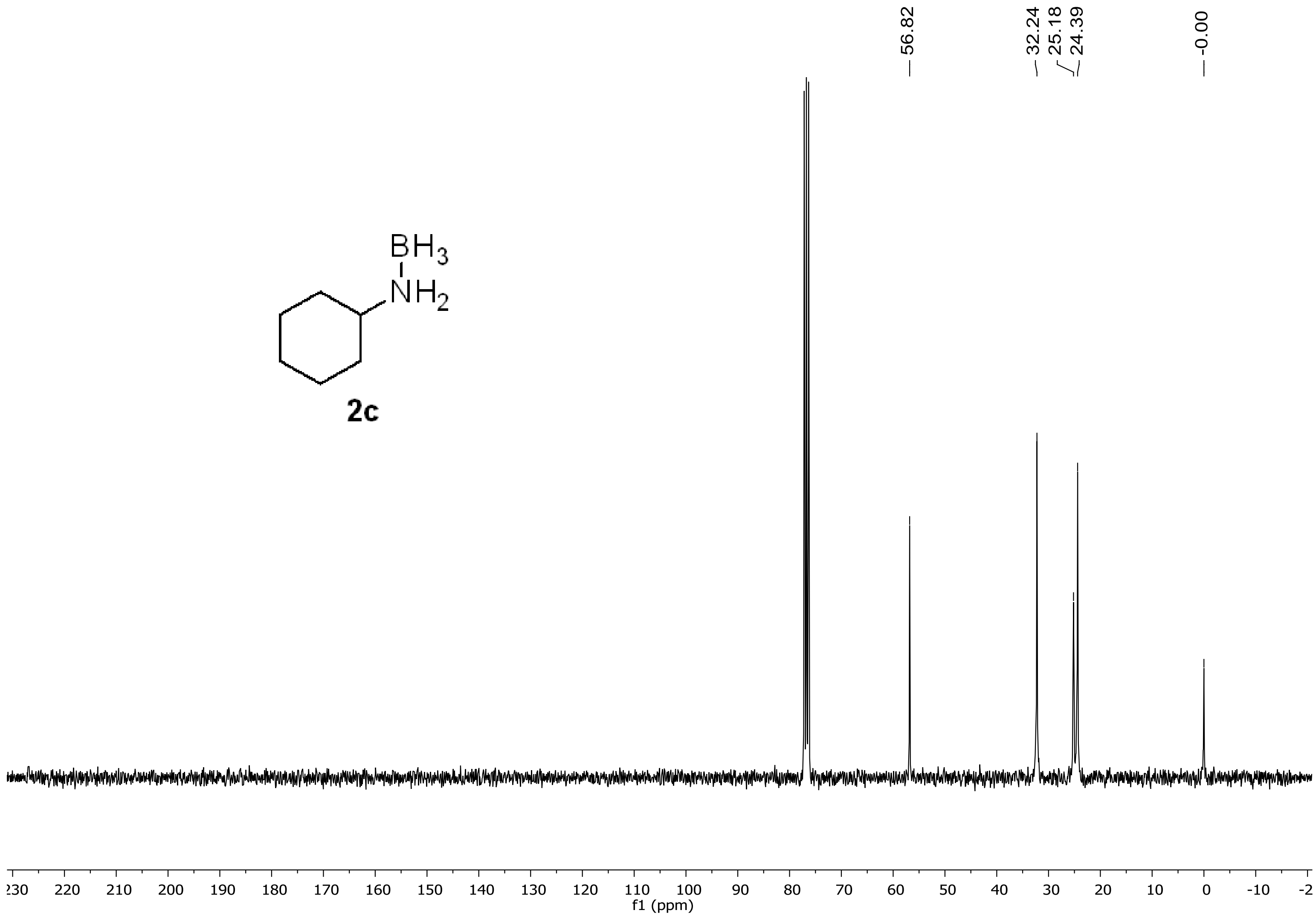
^{13}C NMR (75 MHz, $CDCl_3$) *tert*-Butylamine-borane (**2b,** Entry 2)



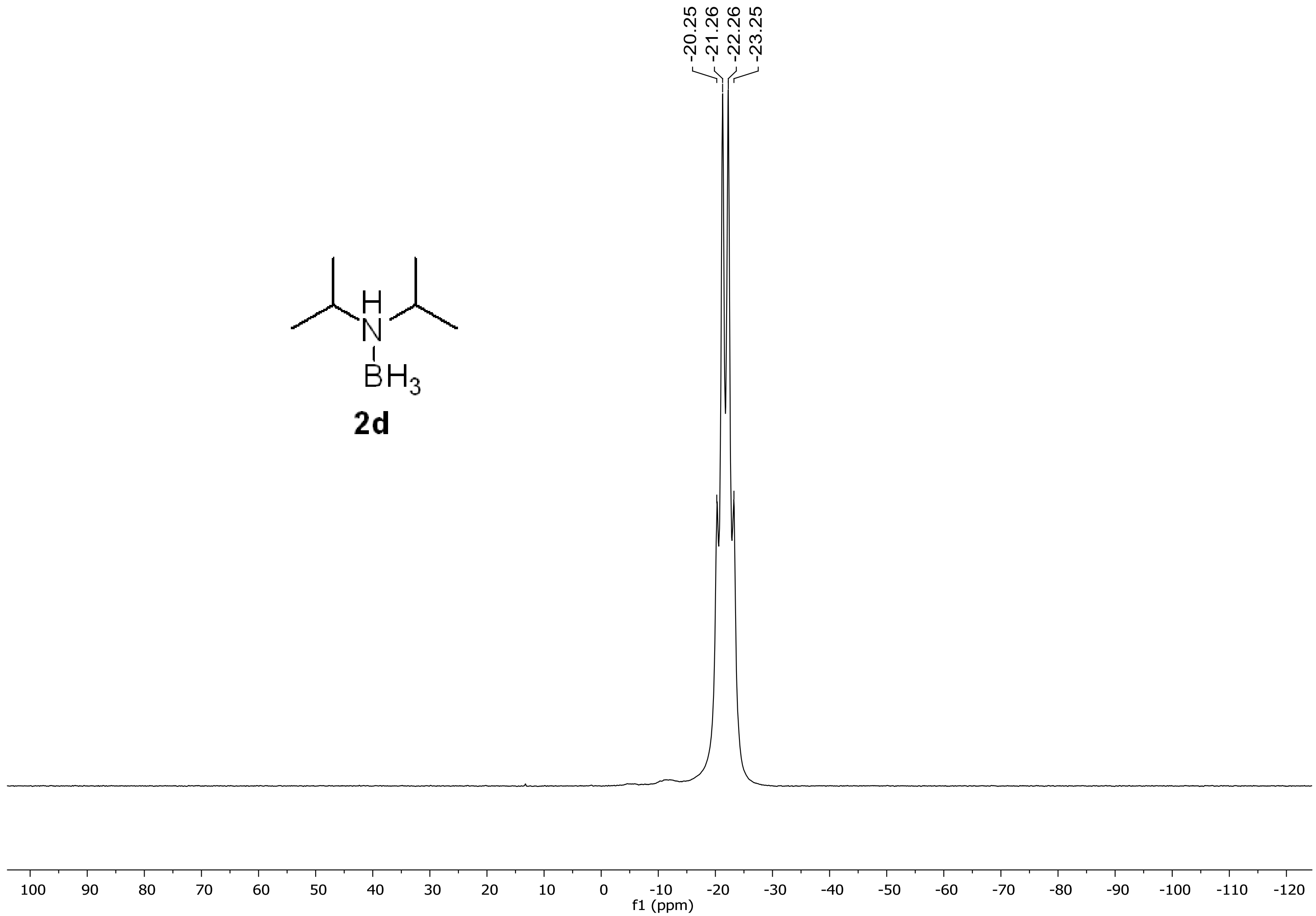
[11]B NMR (96 MHz, $CDCl_3$) Cyclohexylamine-borane (**2c,** Entry 3)



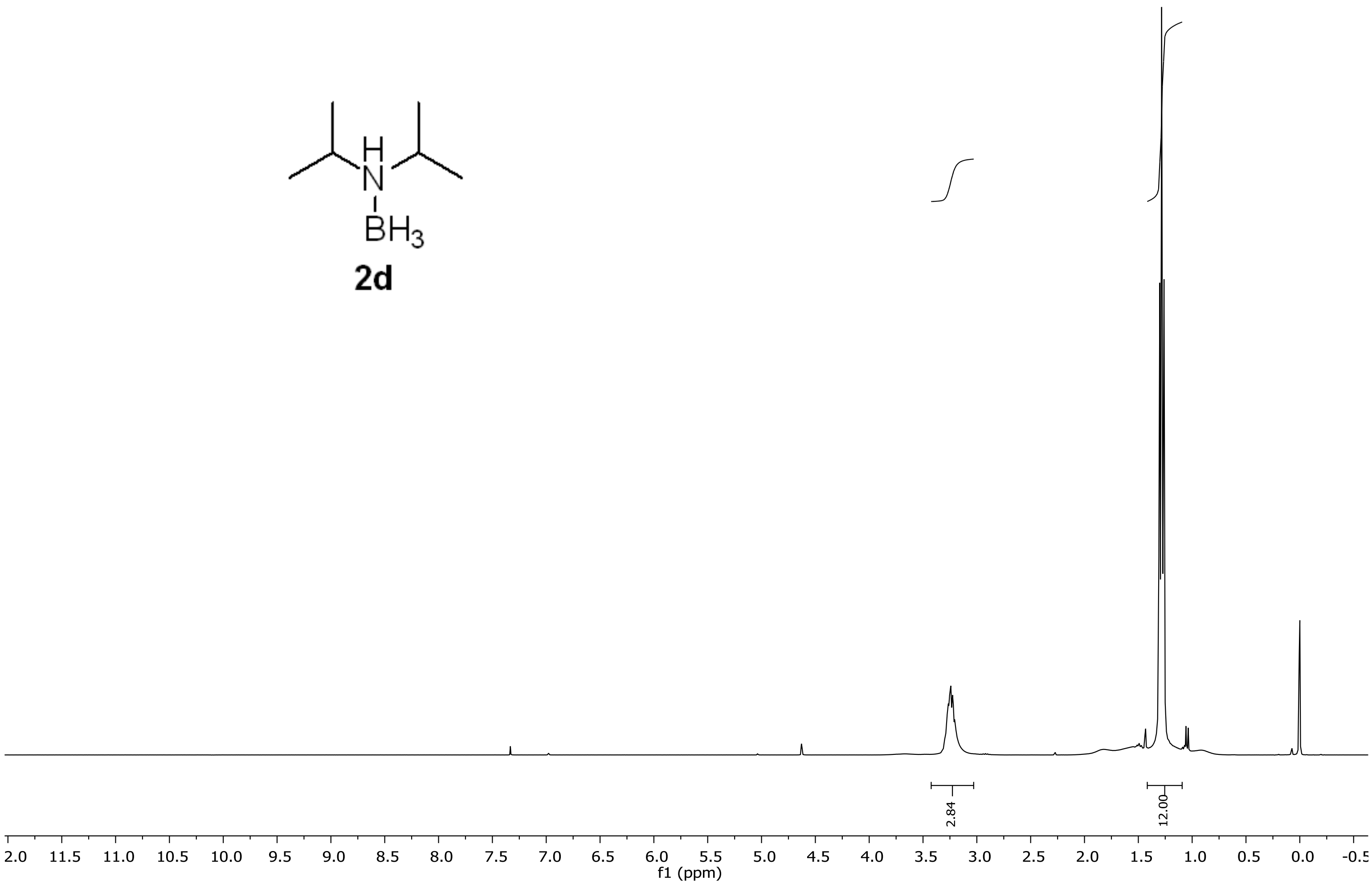
[1]H NMR (300 MHz, $CDCl_3$) Cyclohexylamine-borane (**2c,** Entry 3)



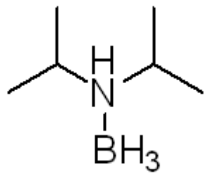
^{13}C NMR (75 MHz, $CDCl_3$) Cyclohexylamine-borane (**2c,** Entry 3)



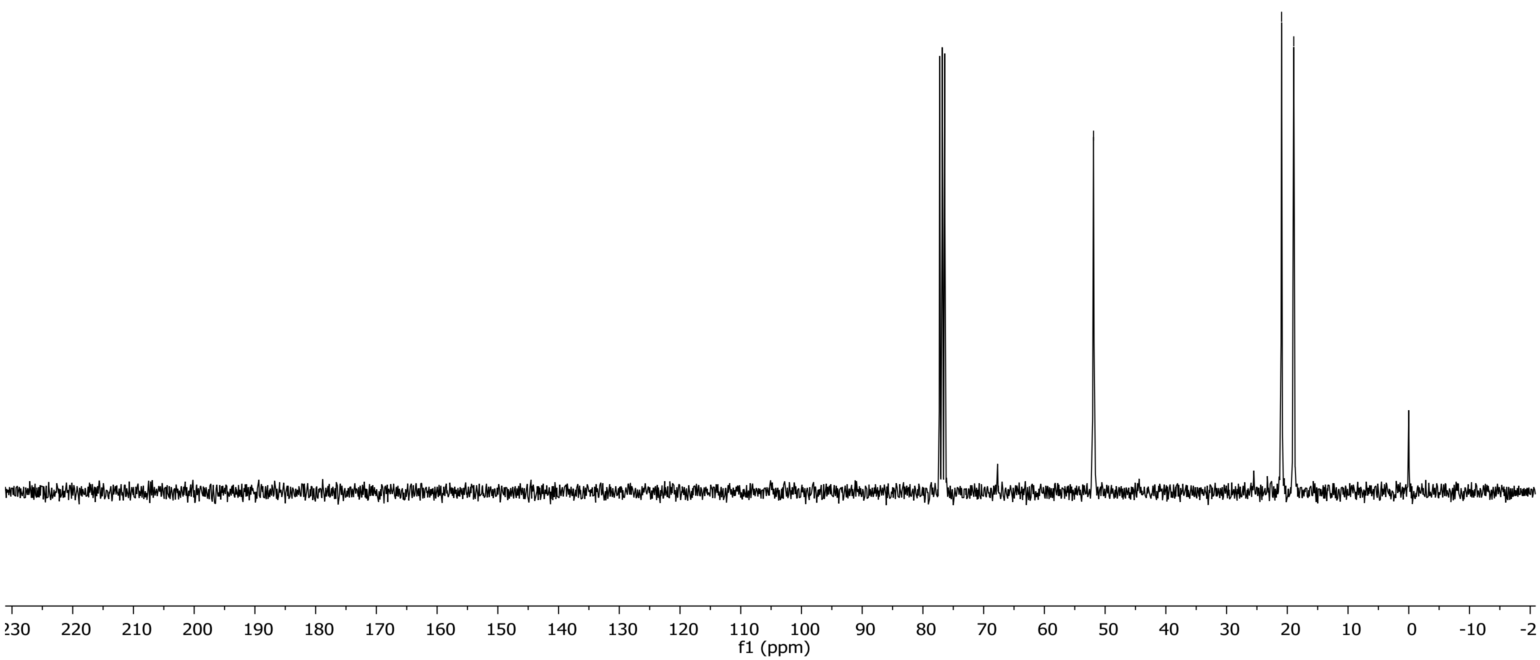
^{11}B NMR (96 MHz, $CDCl_3$) *N*,*N*-Diisopropylamine-borane (**2d,** Entry 4)



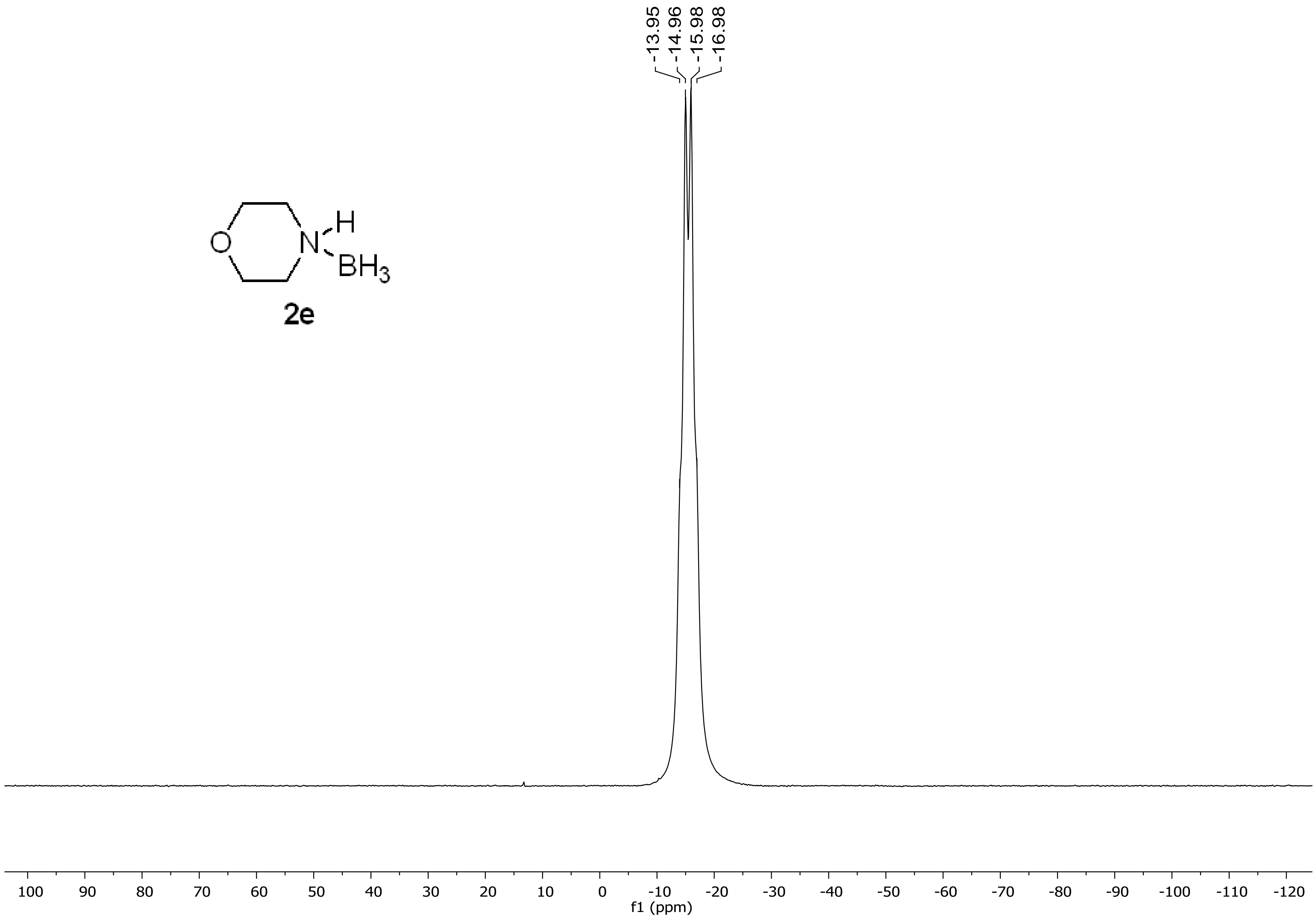
^{1}H NMR (300 MHz, $CDCl_3$) *N*,*N*-Diisopropylamine-borane (**2d,** Entry 4)



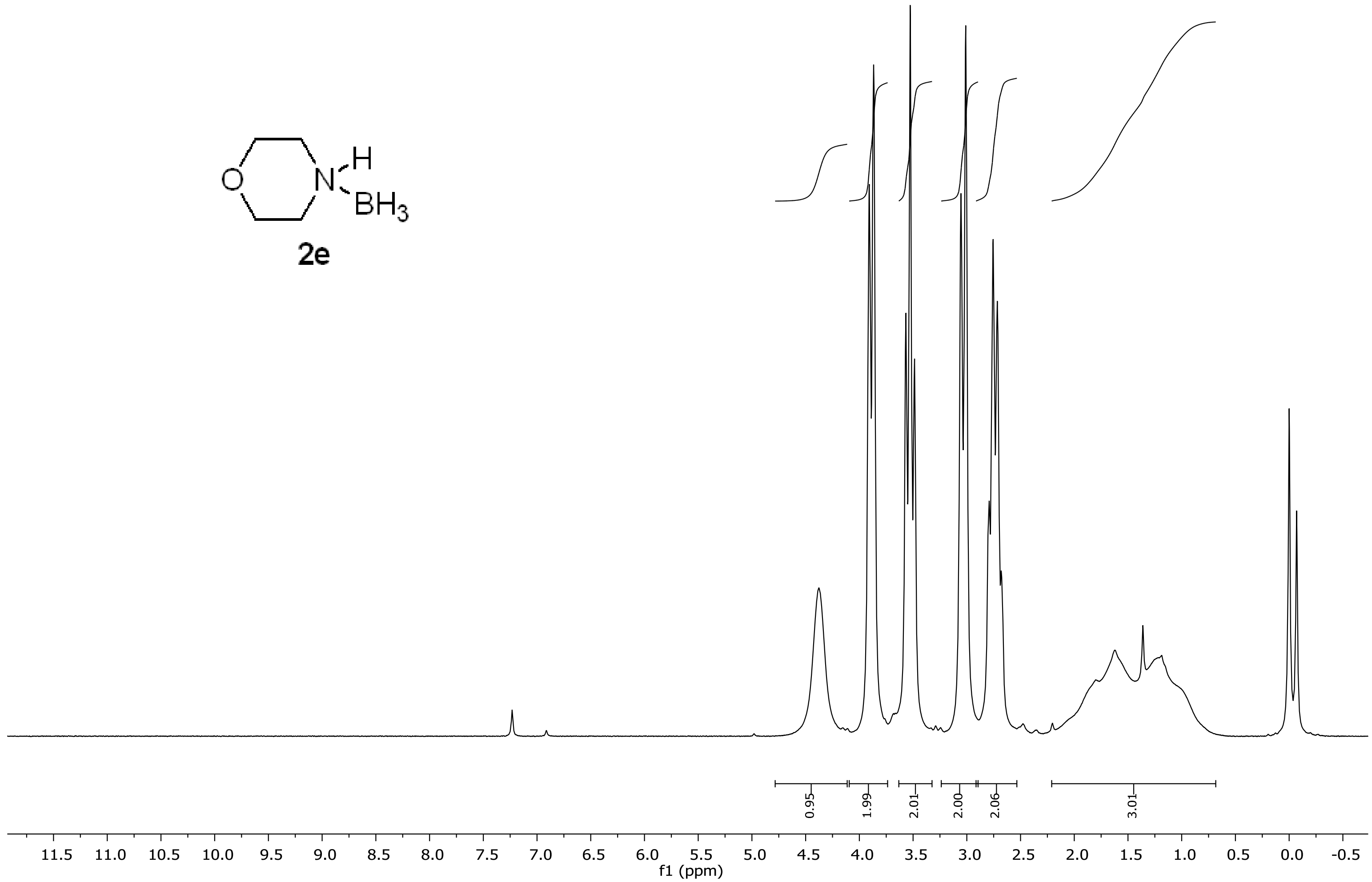
2d



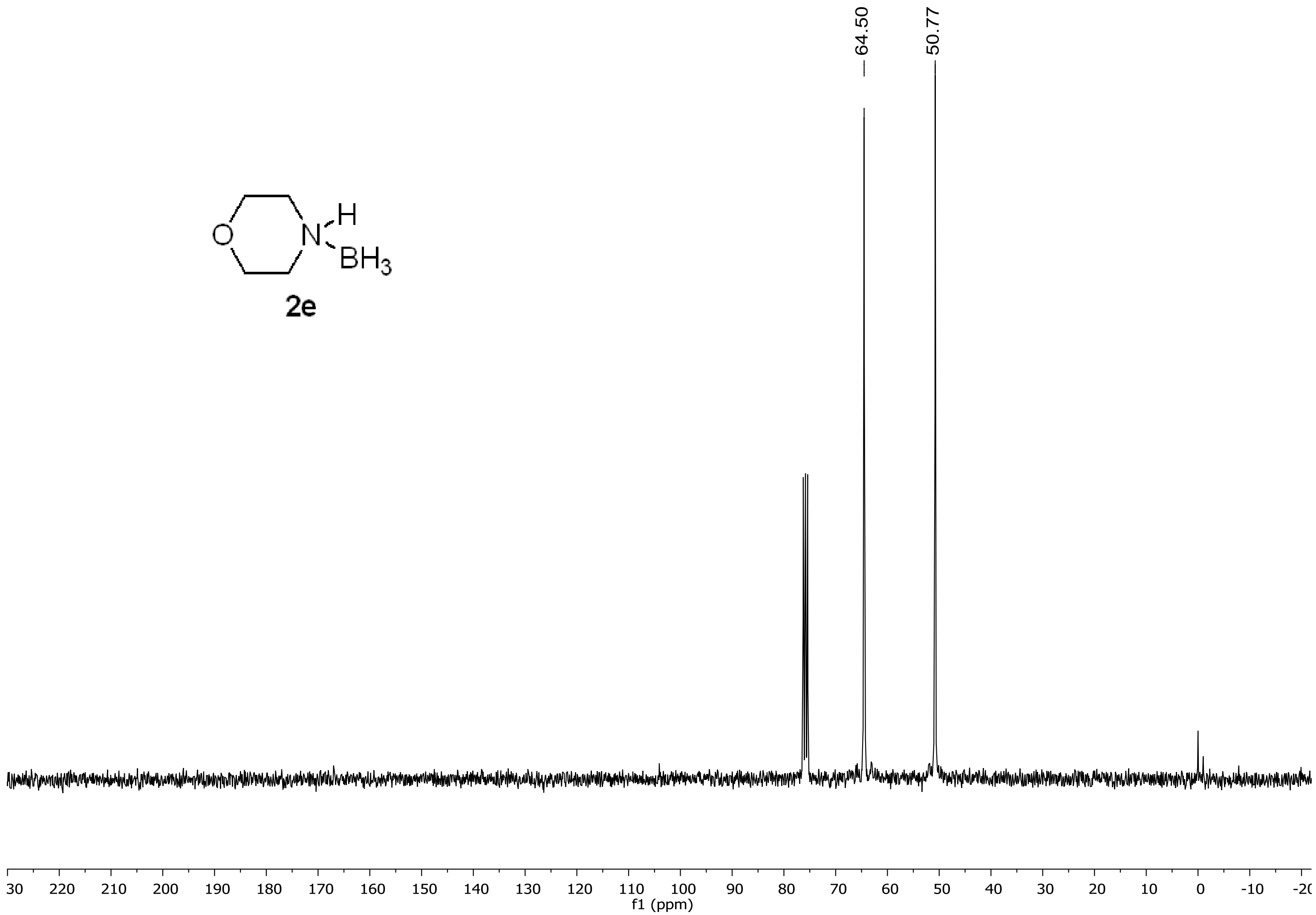
^{13}C NMR (75 MHz, $CDCl_3$) *N*,*N*-Diisopropylamine-borane (**2d,** Entry 4)



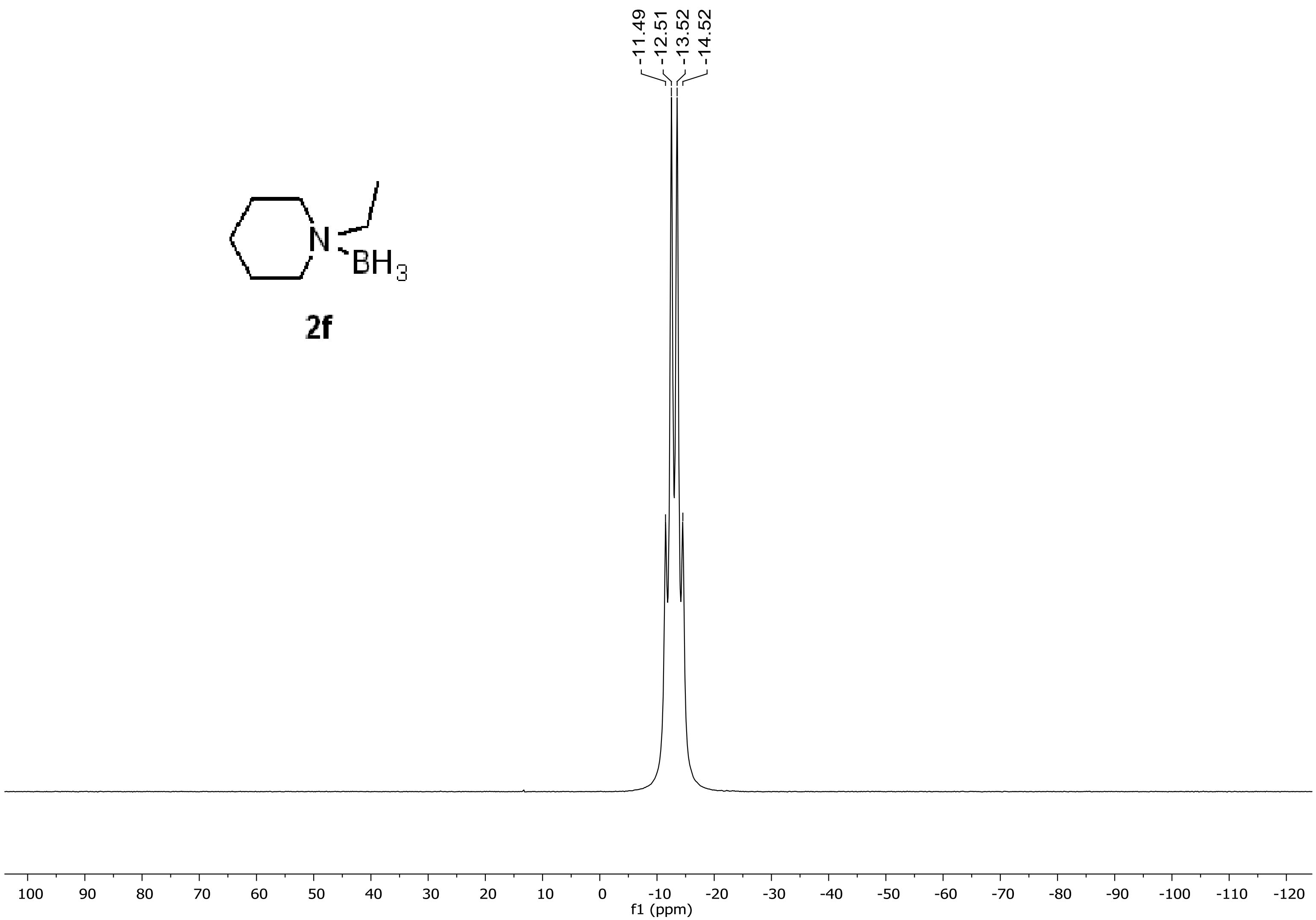
^{11}B NMR (96 MHz, $CDCl_3$) Morpholine-borane (**2e,** Entry 5)



^{1}H NMR (300 MHz, $CDCl_3$) Morpholine-borane (**2e,** Entry 5)

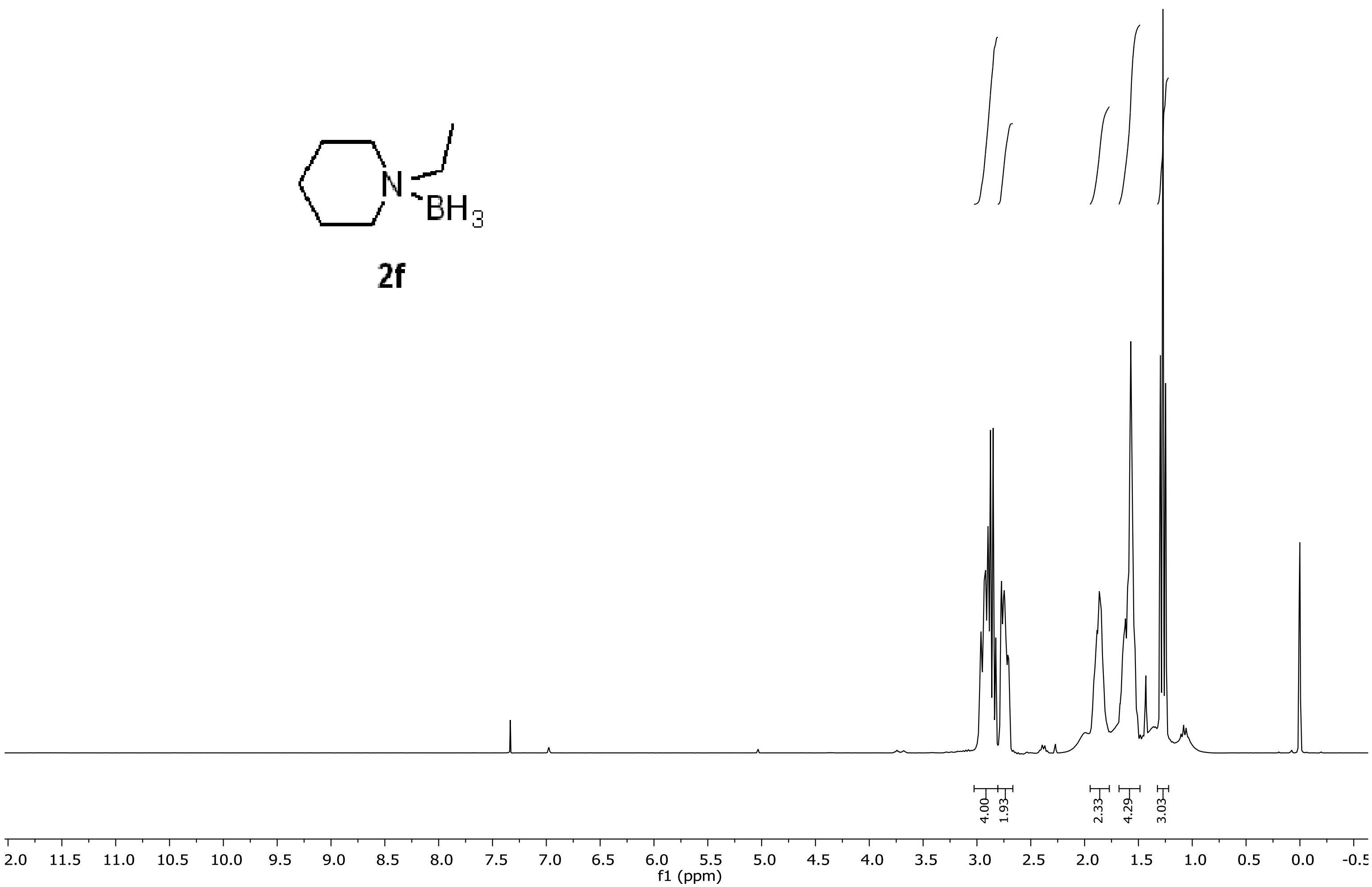


^{13}C NMR (75 MHz, $CDCl_3$) Morpholine-borane (**2e,** Entry 5)

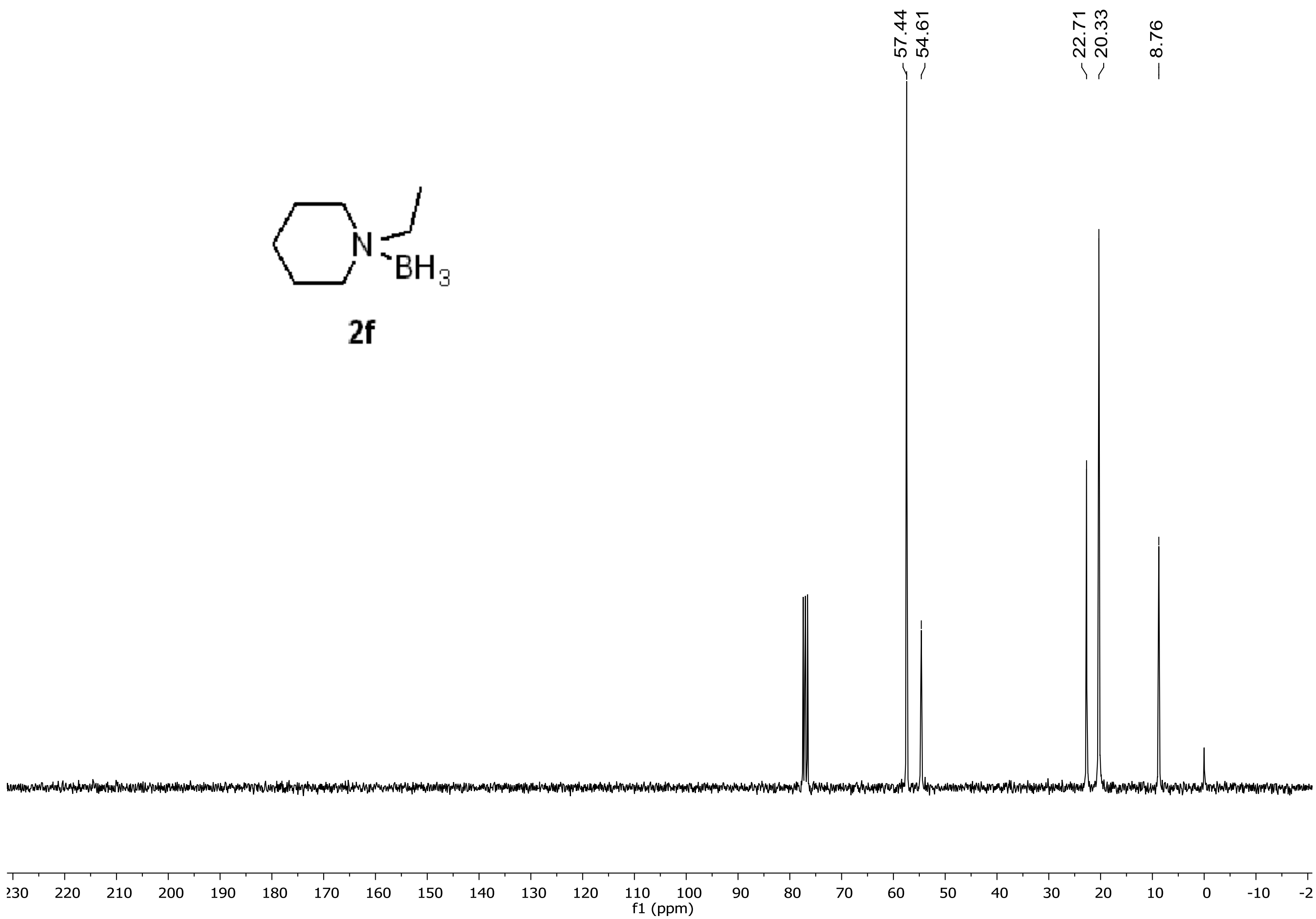


2f

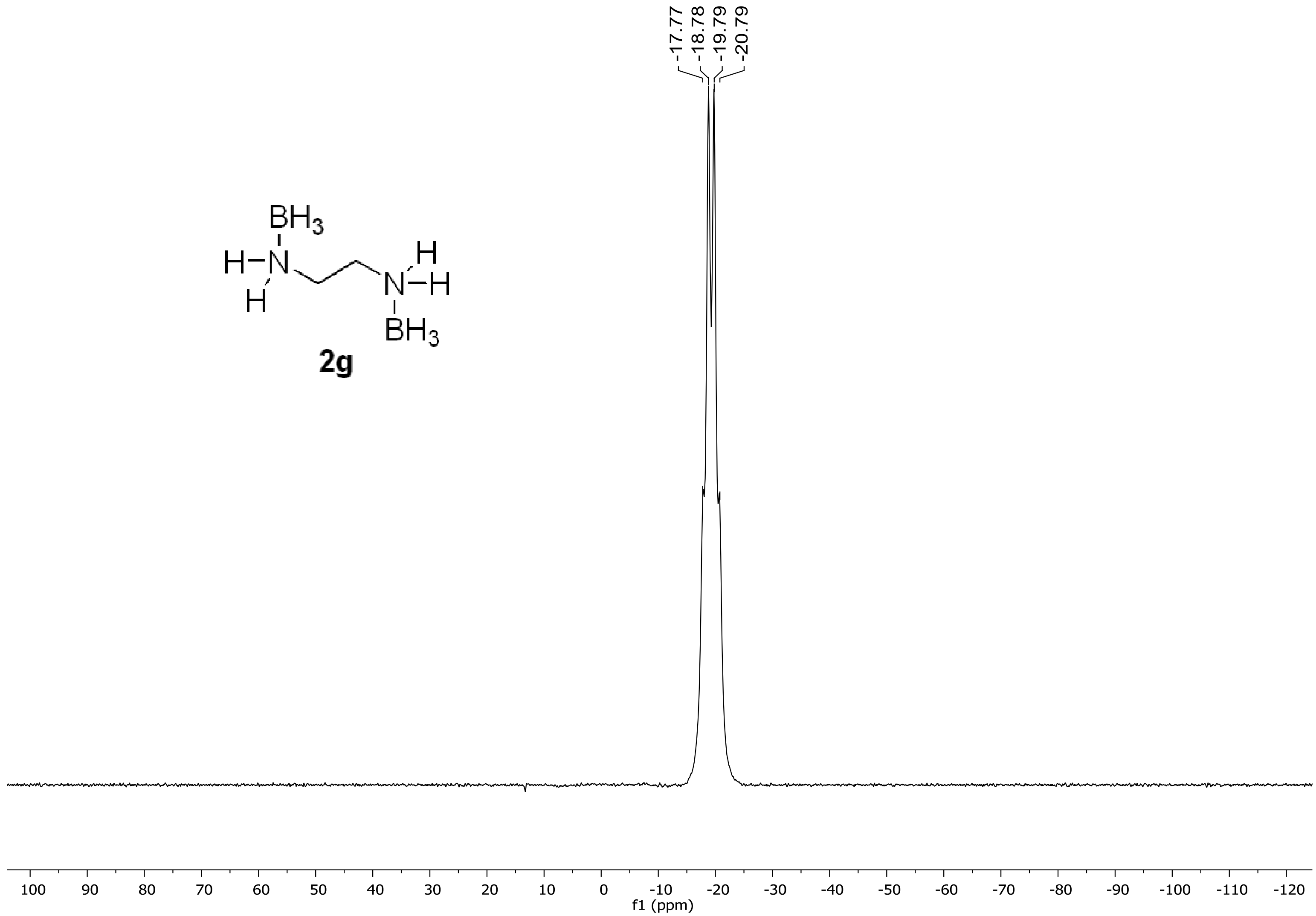
^{11}B NMR (96 MHz, $CDCl_3$) *N*-Ethylpiperidine-borane (**2f,** Entry 6)



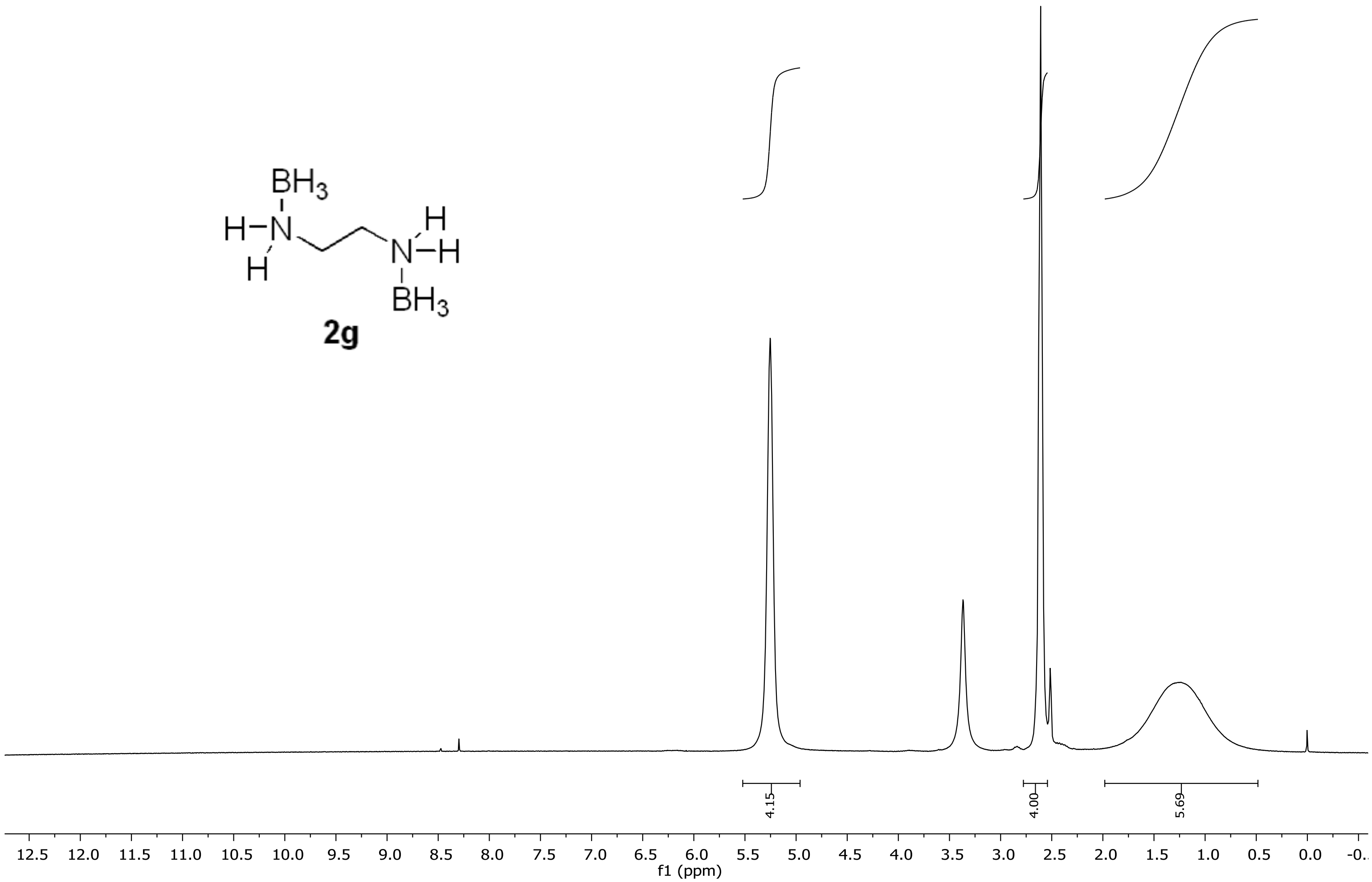
^{1}H NMR (300 MHz, $CDCl_3$) *N*-Ethylpiperidine-borane (**2f,** Entry 6)



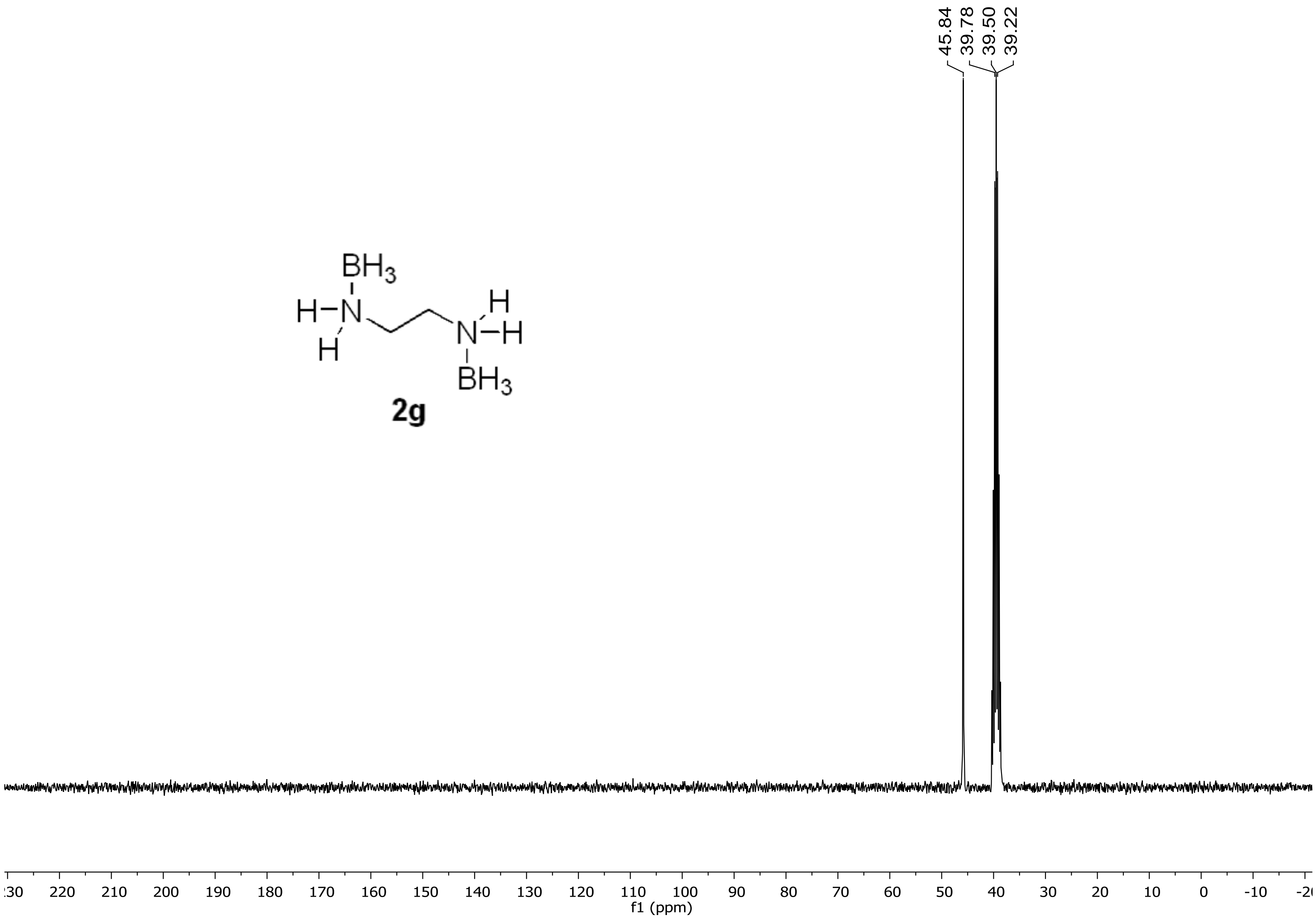
^{13}C NMR (75 MHz, $CDCl_3$) *N*-Ethylpiperidine-borane (**2f,** Entry 6)



[11]B NMR (96 MHz, THF) 1,2-Diaminoethane-bisborane (**2g,** Entry 7)

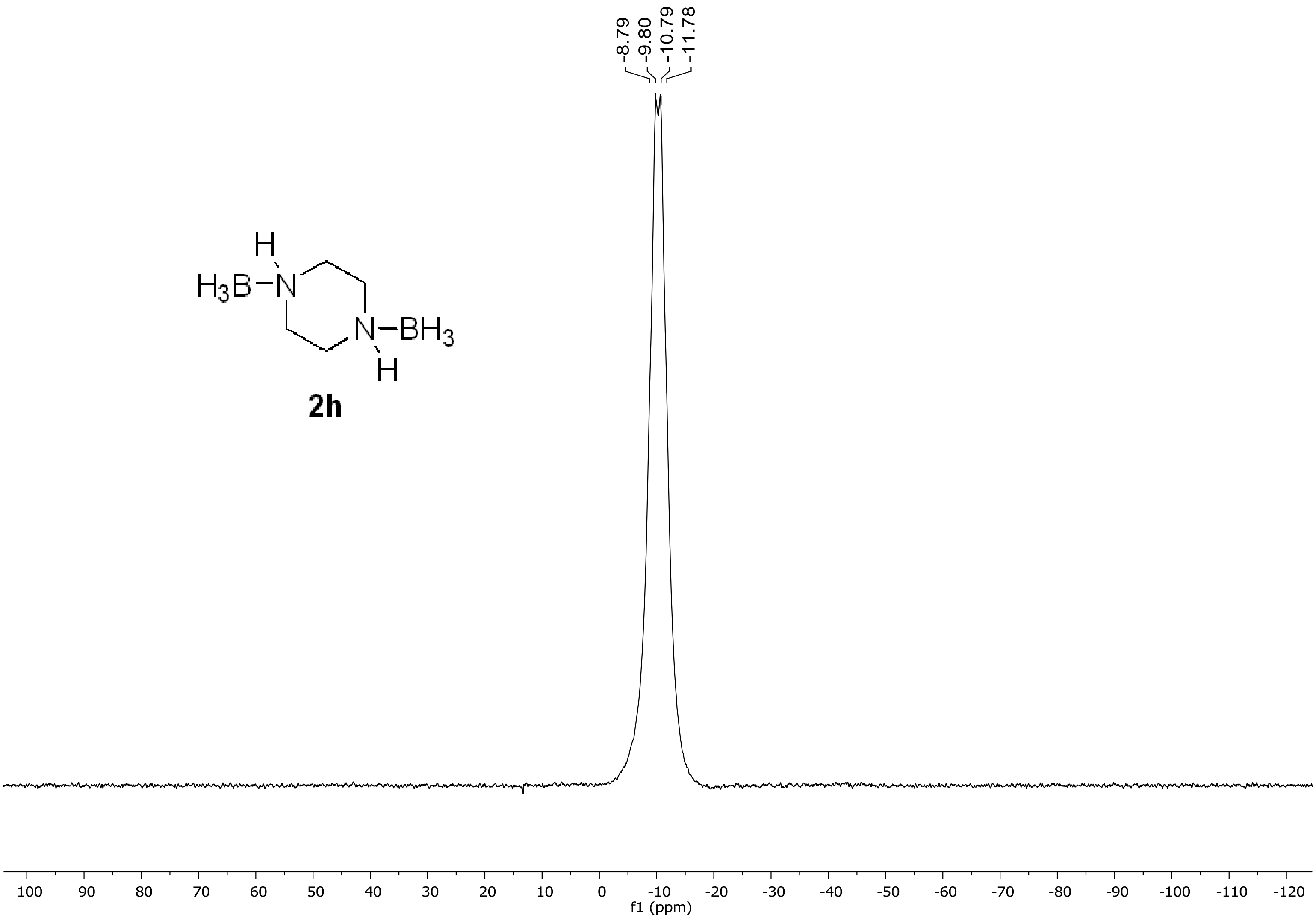


^{1}H NMR (300 MHz, DMSO-d_6) 1,2-Diaminoethane-bisborane (**2g,** Entry 7)

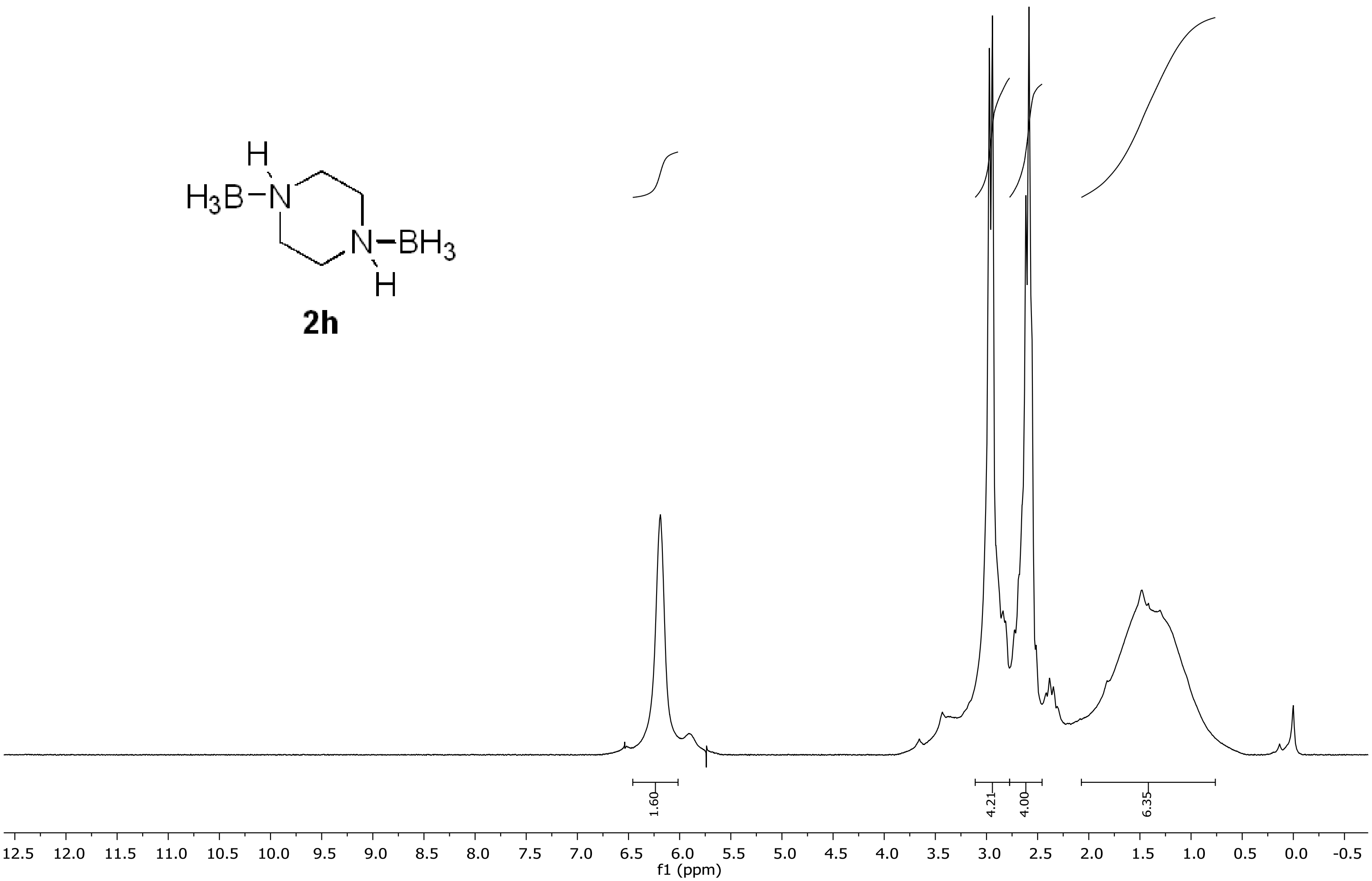


2g

^{13}C NMR (75 MHz, DMSO-d_6) 1,2-Diaminoethane-bisborane (**2g,** Entry 7)

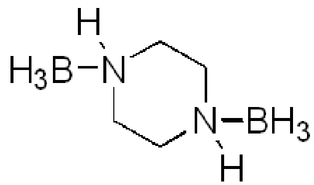


^{11}B NMR (96 MHz, DMSO-d_6) Piperazine-bisborane (**2h,** Entry 8)

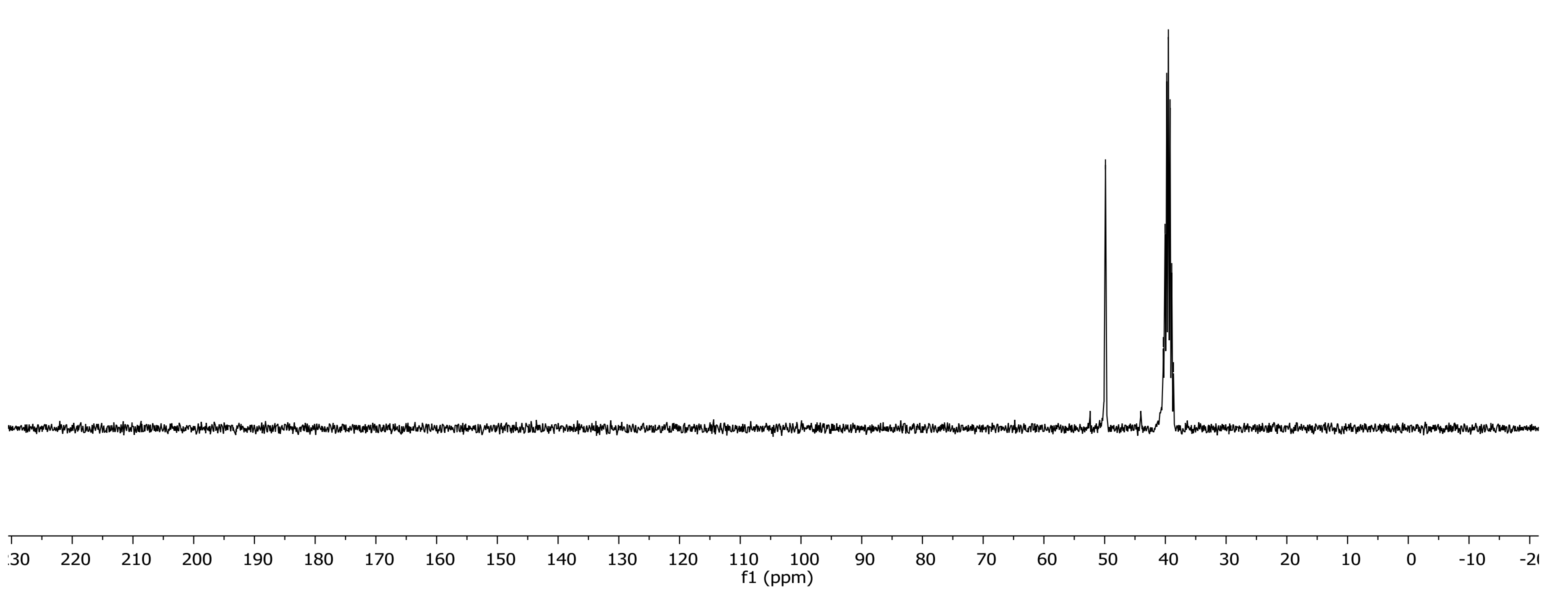


2h

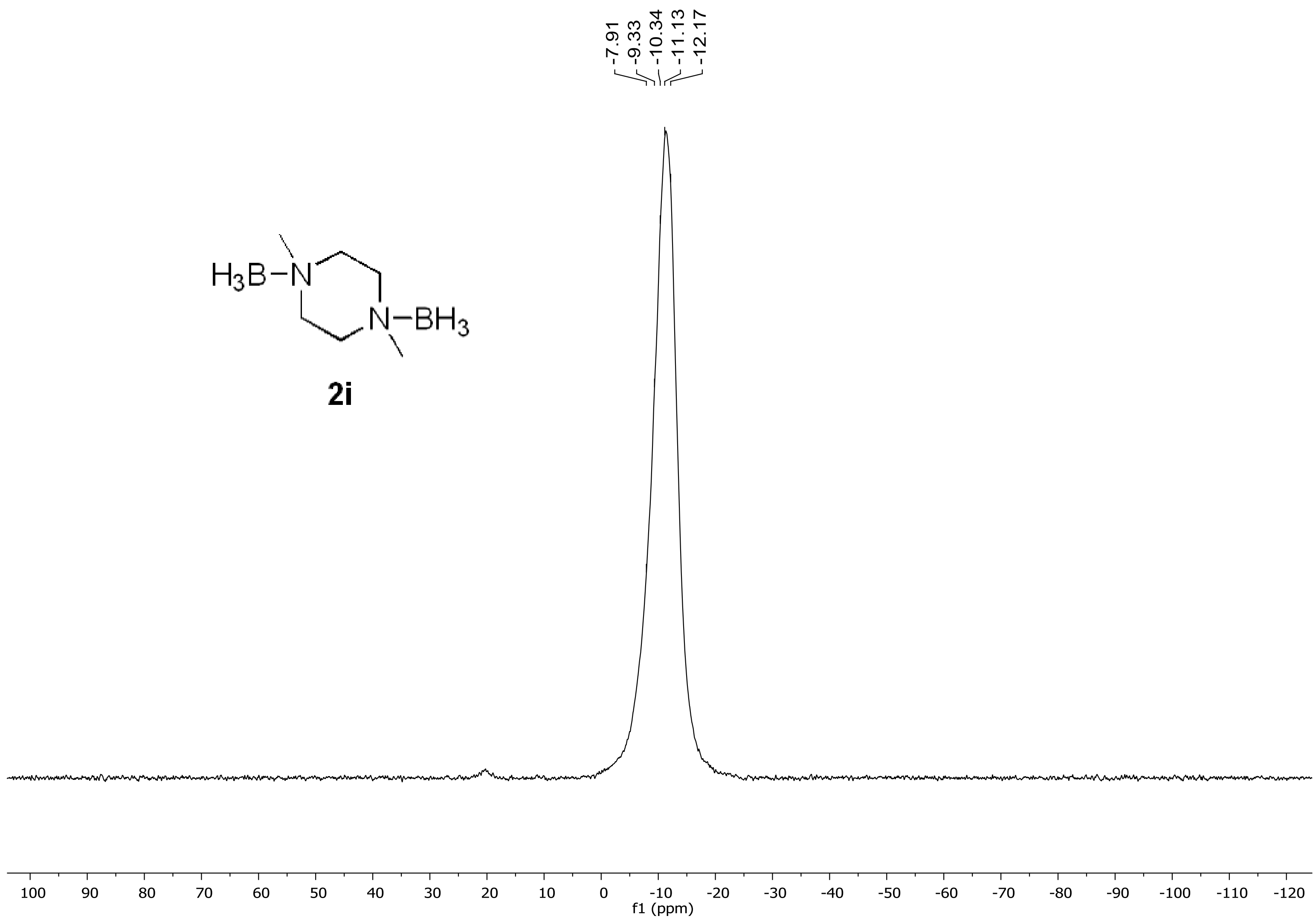
[1]H NMR (300 MHz, DMSO-d_6) Piperazine-bisborane (**2h,** Entry 8)



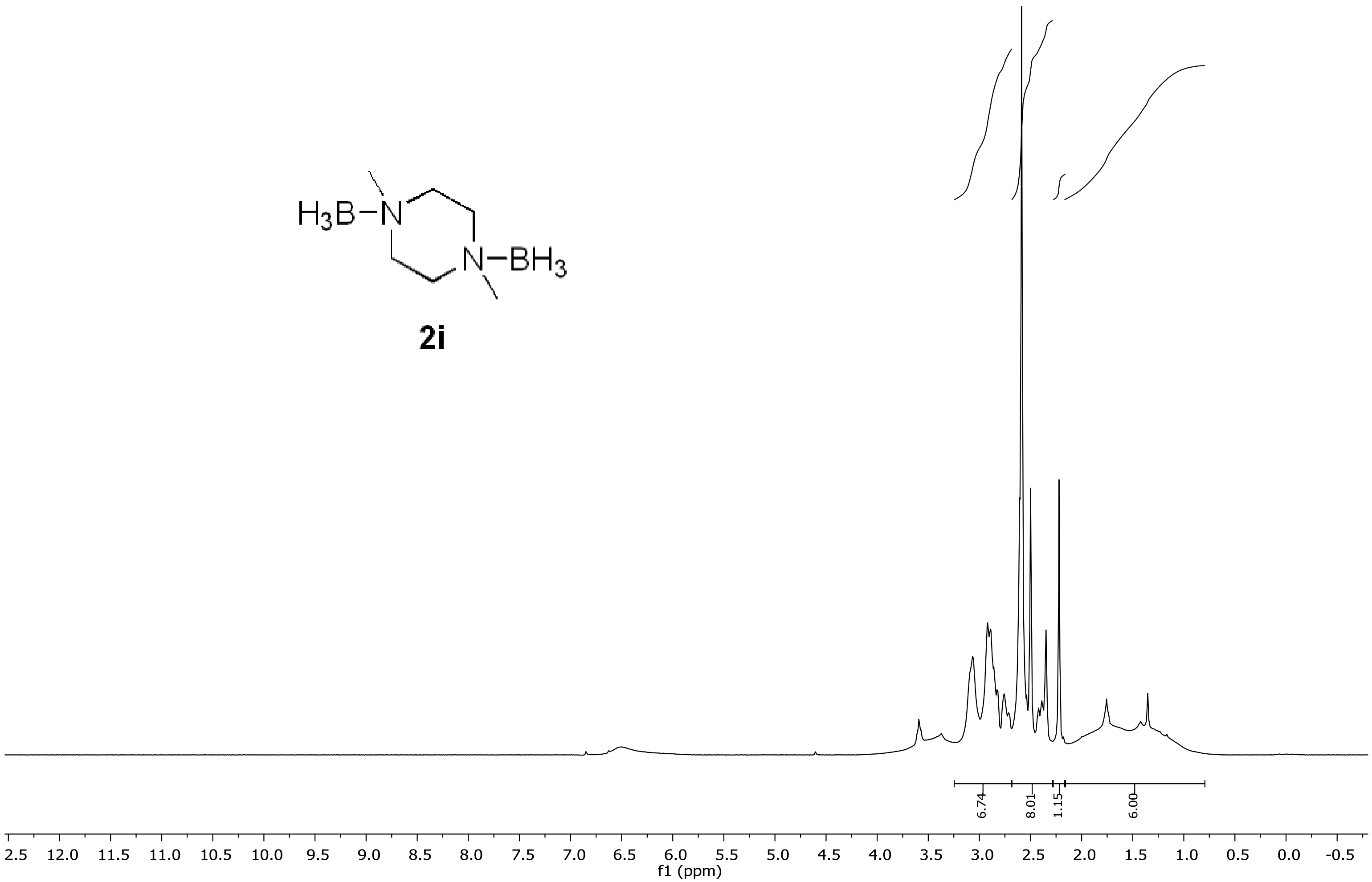
2h



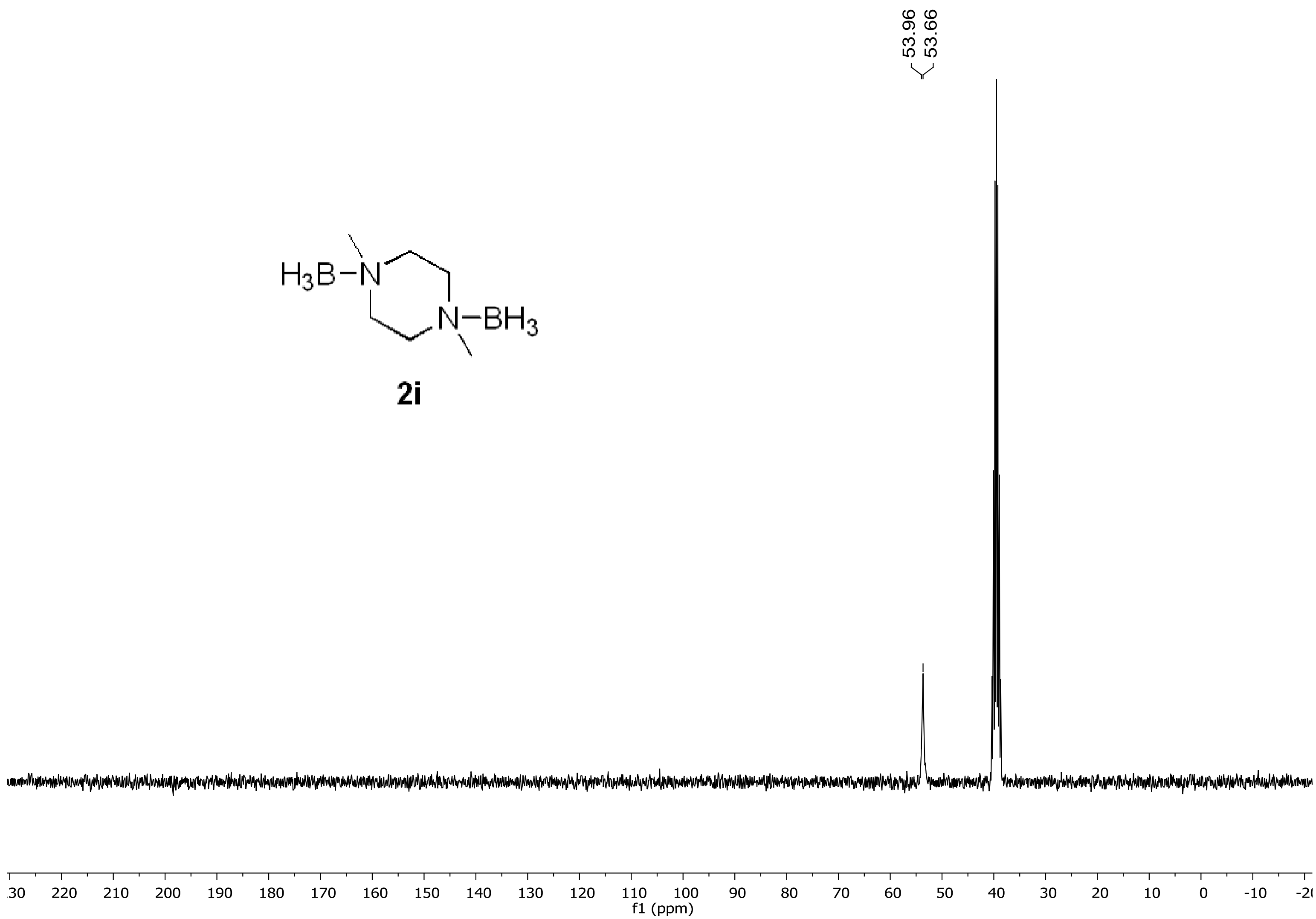
^{13}C NMR (75 MHz, DMSO-d_6) Piperazine-bisborane (**2h,** Entry 8)



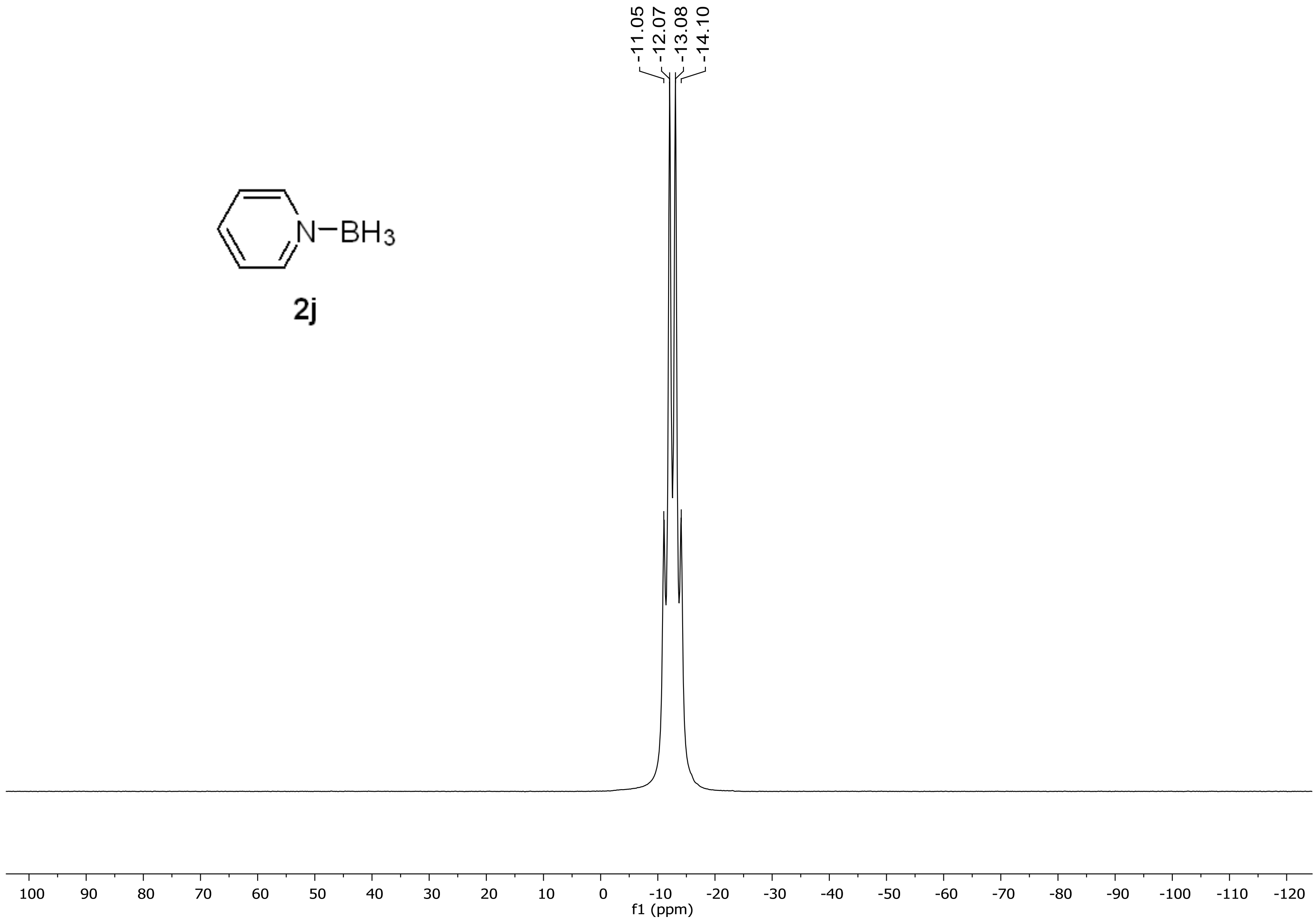
[11]B NMR (96 MHz, THF) *N*,*N*-Dimethylpiperazine-bisborane (**2i,** Entry 9)



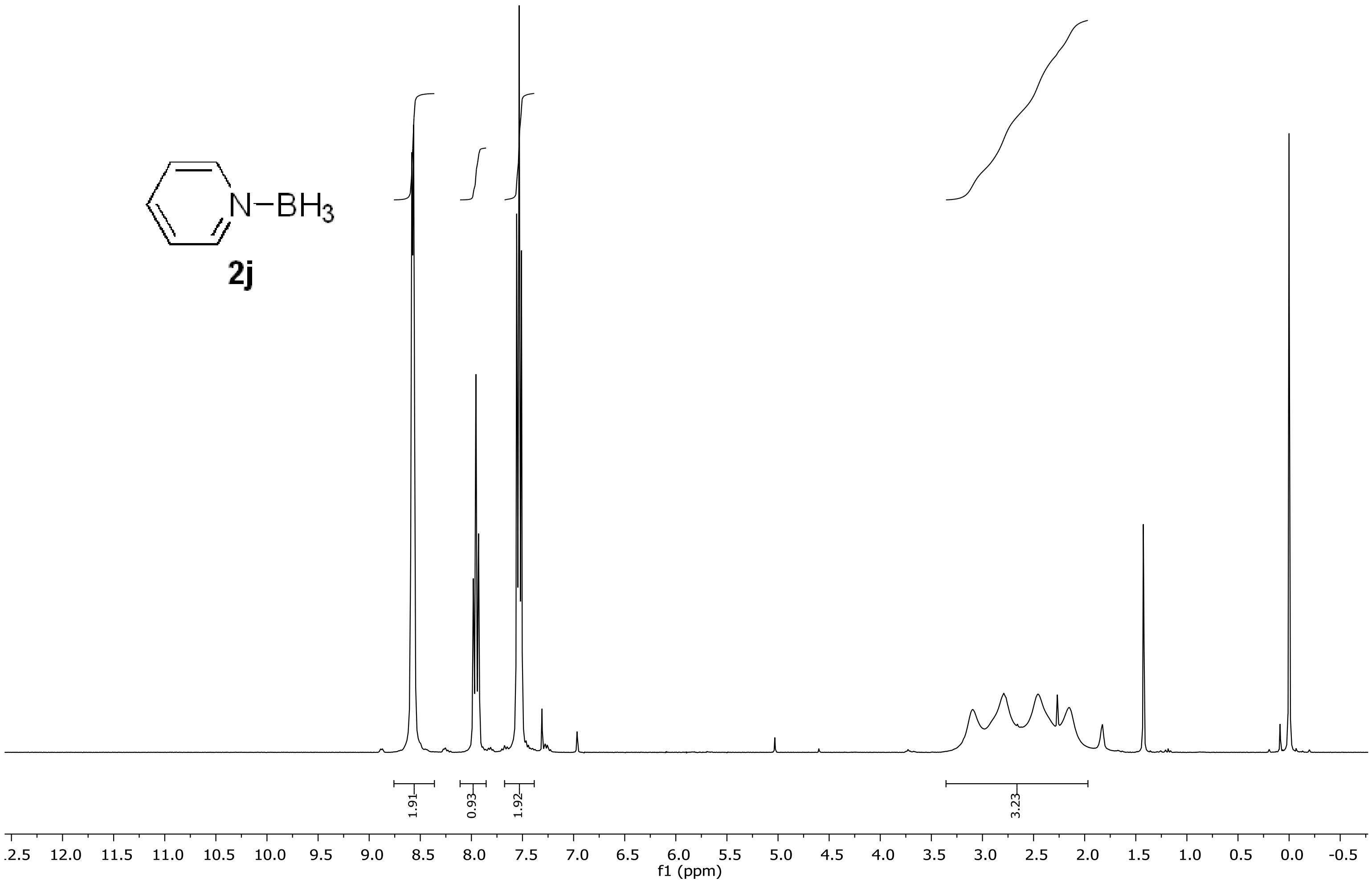
^{1}H NMR (300 MHz, DMSO-d_6) *N*,*N*-Dimethylpiperazine-bisborane (**2i,** Entry 9)



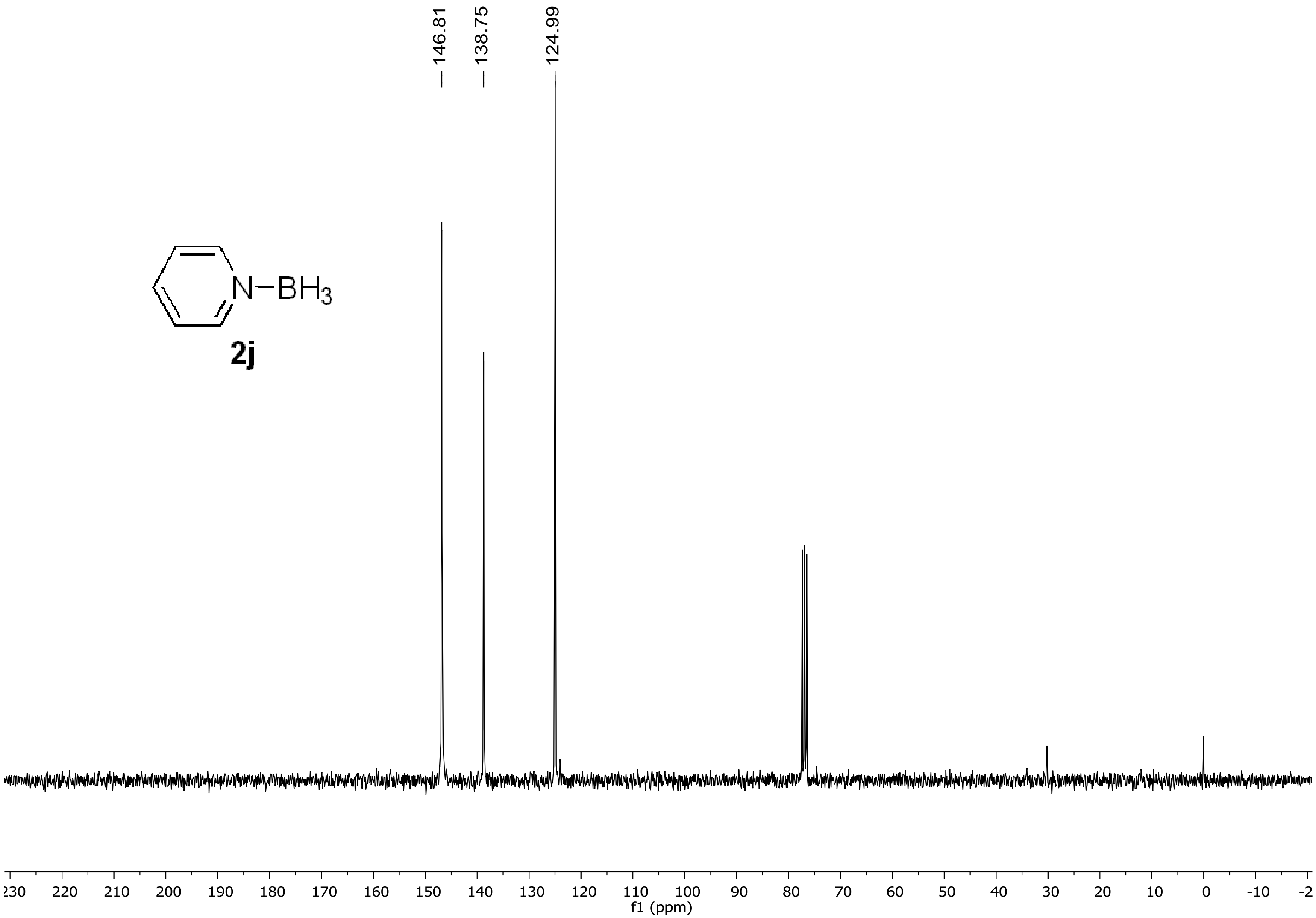
^{13}C NMR (75 MHz, DMSO-d_6) *N*,*N*-Dimethylpiperazine-bisborane (**2i,** Entry 9)



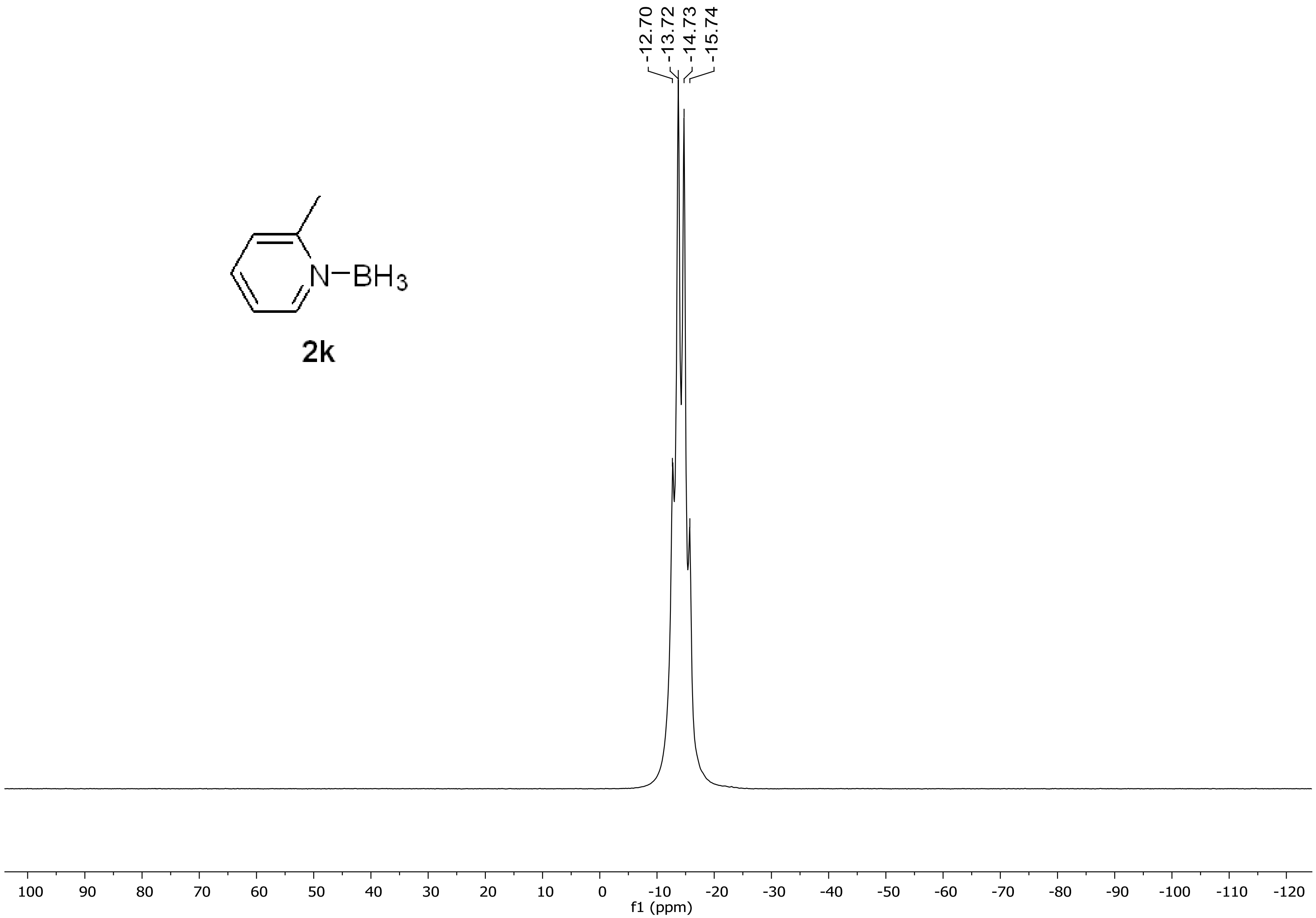
^{11}B NMR (96 MHz, $CDCl_3$) Pyridine-borane (**2j,** Entry 10)



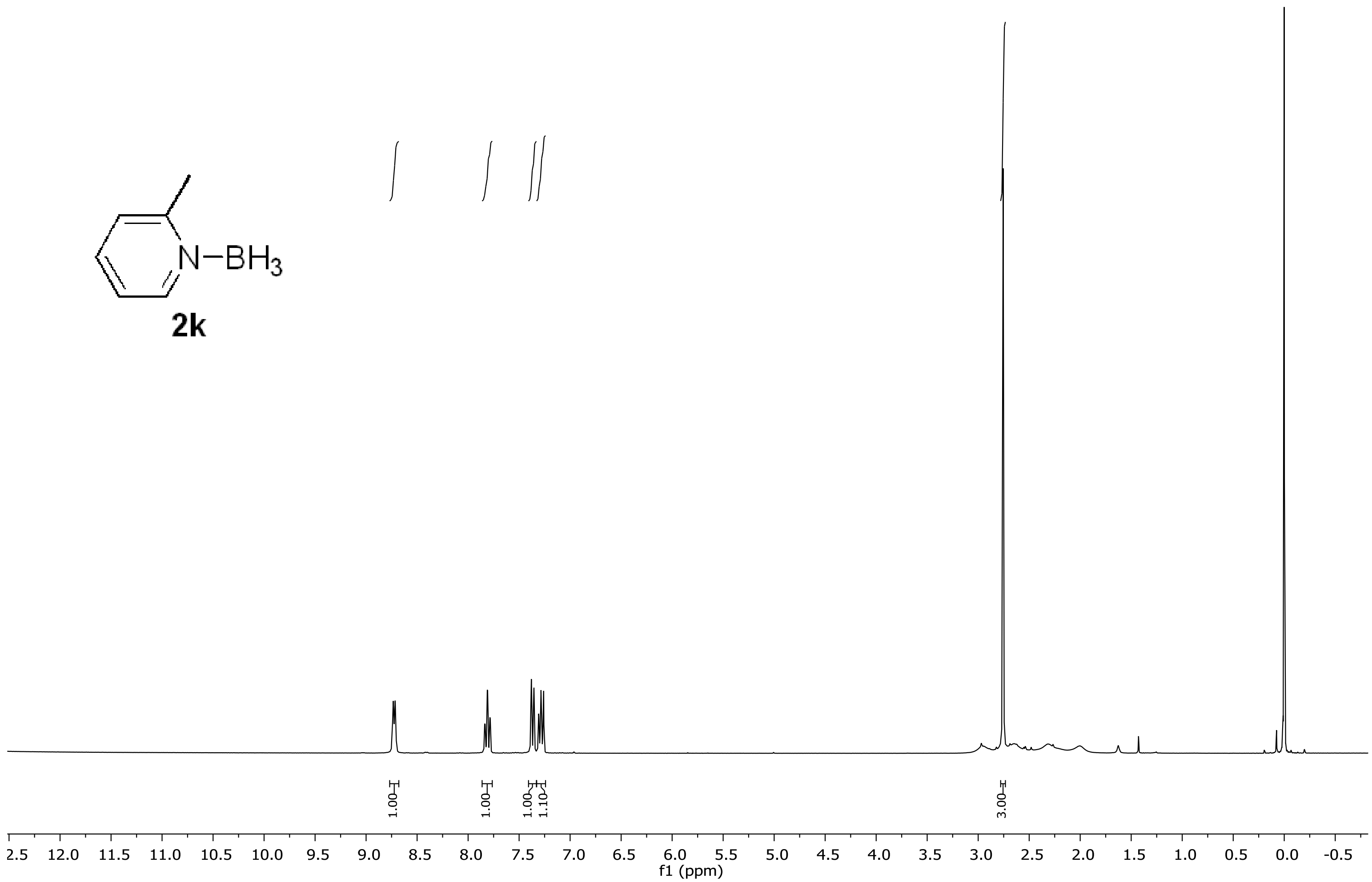
^{1}H NMR (300 MHz, $CDCl_3$) Pyridine-borane (**2j,** Entry 10)



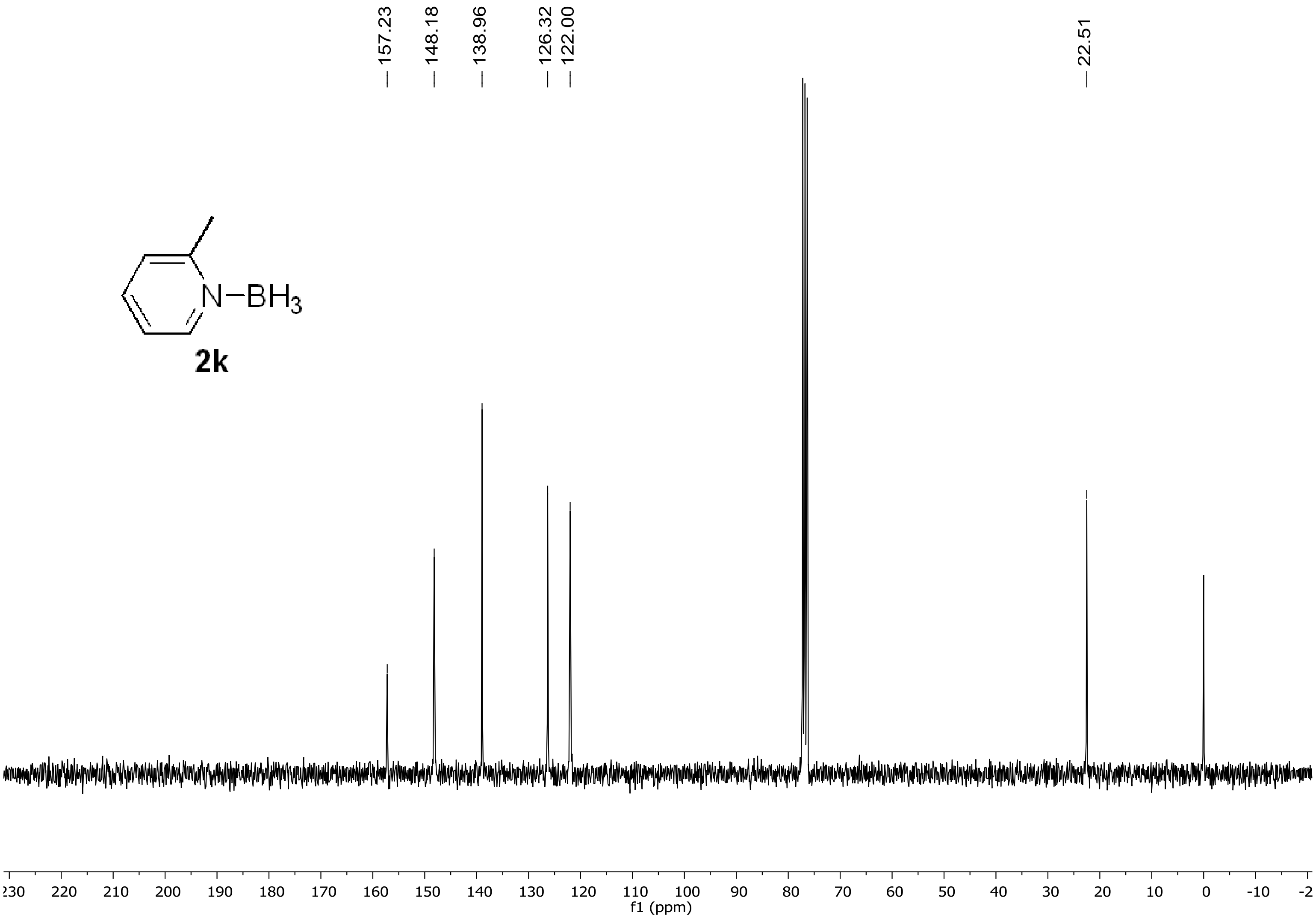
^{13}C NMR (75 MHz, $CDCl_3$) Pyridine-borane (**2j,** Entry 10)



^{11}B NMR (96 MHz, $CDCl_3$) 2-Picoline-borane (**2k,** Entry 11)



[1]H NMR (300 MHz, $CDCl_3$) 2-Picoline-borane (**2k,** Entry 11)



^{13}C NMR (75 MHz, $CDCl_3$) 2-Picoline-borane (**2k,** Entry 11)