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Zhenguo Huang

University of Wollongong, zhenguo@uow.edu.au

Hima K. Lingam

Ohio State University

Xuenian Chen

The Ohio State University

Spencer Porter

University of Wollongong, sp733@uowmail.edu.au

Aijun Du

University Of Queensland

See next page for additional authors

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Abstract

Boron–nitrogen containing compounds with high hydrogen contents as represented by ammonia borane (NH₃BH₃) have recently attracted intense interest for potential hydrogen storage applications. One such compound is [(NH₃)₂BH₂]₃B₃H₈ with a capacity of 18.2 wt% H. Two safe and efficient synthetic routes to [(NH₃)₂BH₂]₃B₃H₈ have been developed for the first time since it was discovered 50 years ago. The new synthetic routes avoid a dangerous starting chemical, tetraborane (B₄H₁₀), and afford a high yield. Single crystal X-ray diffraction analysis reveals N–H₂...H₂–B dihydrogen interactions in the [(NH₃)₂BH₂]₃B₃H₈·18-crown-6 adduct. Extended strong dihydrogen bonds were observed in pure [(NH₃)₂BH₂]₃B₃H₈ through crystal structure solution based upon powder X-ray analysis. Pyrolysis of [(NH₃)₂BH₂]₃B₃H₈ leads to the formation of hydrogen gas together with appreciable amounts of volatile boranes below 160 °C.

Keywords

analysis, b₃h₈, 2bh₂, nh₃, structural, studies, synthesis, decomposition, thermal

Disciplines

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Authors

Zhenguo Huang, Hima K. Lingam, Xuenian Chen, Spencer Porter, Aijun Du, Patrick M. Woodard, Sheldon Shore, and Ji-Cheng Zhao

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ARTICLE TYPE

Synthesis, structural analysis, and thermal decomposition studies of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$

Zhanguo Huang,^{#,†,*} Hima K. Lingam,[‡] Xuenian Chen,^{†,‡} Spencer Porter,[#] Aijun Du,^{\$} Patrick M. Woodard,[‡] Sheldon G. Shore^{†,‡,*} and Ji-Cheng Zhao^{†,*}

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Boron-nitrogen containing compounds with high hydrogen contents as represented by ammonia borane (NH_3BH_3) have recently attracted intense interest for potential hydrogen storage applications. One such compound is $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ with a capacity of 18.2 wt.% H. Two safe and efficient synthetic routes to $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ have been developed for the first time since it was discovered 50 years ago. The new synthetic routes avoid a dangerous starting chemical, tetraborane (B_4H_{10}), and afford a high yield. Single crystal X-ray diffraction analysis reveals $\text{N}-\text{H}^{\delta+} \cdots \text{H}^{\delta-}-\text{B}$ dihydrogen interactions in the $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ -18-crown-6 adduct. Extended strong dihydrogen bonds were observed in pure $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ through crystal structure solution based upon powder X-ray analysis. Pyrolysis of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ leads to the formation of hydrogen gas together with appreciable amounts of volatile boranes below 160 °C.

Introduction

Hydrogen would be an ideal energy carrier because of its high gravimetric energy density, pollution-free end product (water), and high energy efficiency via fuel cell¹ if an effective way to store it could be developed.¹⁻³ To this end, solid-state hydrogen storage materials have attracted significant attention as they can potentially store H_2 safely and efficiently.¹⁻⁴ In addition to experimental investigations, theoretical calculations have been employed to aid the exploration of hydrogen storage materials and to help explain hydrogen absorption and desorption.⁵ There exists strong interest in boron containing compounds for hydrogen storage since they normally possess high hydrogen contents (19.6 wt.% H in NH_3BH_3 ,^{6,7} 14.8 wt.% H in $\text{Mg}(\text{BH}_4)_2$,^{8,9} 7.7 wt.% in $\text{Li}_2\text{B}_{12}\text{H}_{12} \cdot 7\text{NH}_3$ ¹⁰). In addition to exploring new compounds, researchers have also studied some

existing boron compounds such as $\text{AlB}_4\text{H}_{11}$ (13.5 wt.% H),¹¹ $\text{NH}_3\text{B}_3\text{H}_7$ (17.8 wt.% H)¹², and $[(\text{NH}_3)_2\text{BH}_2]\text{BH}_4$ ¹³, which have received scattered attention due to the lack of facile syntheses. For example, the synthesis of $\text{AlB}_4\text{H}_{11}$ requires diborane (B_2H_6), which is highly flammable and consequently necessitates high quality vacuum apparatus and strong experience.^{11,14} To make a compound interesting for hydrogen storage, its synthetic ease and availability are apparently of great importance.

We have recently reported facile syntheses of unsolvated NaB_3H_8 ¹⁵ and $\text{NH}_4\text{B}_3\text{H}_8$ ¹⁶. These new methods avoid highly flammable compounds such as B_2H_6 and pentaborane (B_5H_9) and effectively simplify the reaction setup, thus enabling studies of these compounds for hydrogen storage and other applications in a typical laboratory. Hydrolysis studies show that upon addition of catalysts, both compounds release more than 7 wt.% hydrogen.^{16,17}

B_3H_8^- has recently been observed during the thermal decomposition of $\text{Mg}(\text{BH}_4)_2$.¹⁸ Dehydrogenation of $\text{Mg}(\text{BH}_4)_2$ leads to a highly selective formation of magnesium triborane, $\text{Mg}(\text{B}_3\text{H}_8)_2$. This process is reversible at 250 °C under 120 atm H_2 . As the authors noted, this is the first example of a reversible, solid-state rehydrogenation of a borohydride occurring below 350 °C. Studying B_3H_8^- can potentially lead to more options in the search of hydrogen storage materials beyond ammonia borane and borohydrides. In addition, it has provided fundamental understanding of the mechanisms of thermal decomposition and regeneration, as evidenced by the case of $\text{Mg}(\text{BH}_4)_2$.

During the search for boron compounds with high hydrogen capacity, diammoniate of tetraborane, $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$, attracts our attention since it has a high hydrogen content of 18.2 wt.%.

[†]Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA. Fax: 1 614 2921537; Tel: 1 614 2929462 E-mail: zhao.199@osu.edu.

[#]Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, NSW, 2522, Australia. E-mail: zhenguo@uow.edu.au

^{\$}Centre for Computational Molecular Science, Australian Institute of Bioengineering and Nanotechnology, The University of Queensland, QLD 4072, Brisbane, Australia

[‡]Department of Chemistry, The Ohio State University, Columbus, OH, 43210, USA. Fax: 1 614 2921685; Tel: 1 614 2926000 E-mail: shore.1@osu.edu.

[†] Electronic Supplementary Information (ESI) available: crystal structure analysis, mass spectra of the gaseous decomposition products. CCDC 909679 & 909680 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. See DOI: 10.1039/b000000x/.

However, the only available syntheses of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ involves handling of tetraborane (B_4H_{10}), which is highly volatile and inflames violently upon contact with air.^{19,20} Furthermore, B_4H_{10} is not commercially available and its synthesis remains complex and challenging.²¹ Studies on this compound have been sparse since its discovery 50 years ago. The few publications to date provide limited information with respect to its crystal structure and properties. Herein, we report 1) safe and efficient syntheses of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$; 2) crystal structure; and 3) hydrogen release properties via thermal decomposition.

Experimental Section

General Procedures

All manipulations were carried out on a high vacuum line or in a glove box filled with high purity nitrogen. Tetrahydrofuran (THF) was dried over sodium/benzophenone and was freshly distilled prior to use. Ammonia (Matheson) was distilled from sodium immediately prior to use. Nuclear magnetic resonance (NMR) spectra were obtained on a Bruker Avance DPX 250 NMR. ^{11}B NMR spectra were obtained at 80.3 MHz and externally referenced to $\text{BF}_3\cdot\text{OEt}_2$ in C_6D_6 at 0.00 ppm. ^1H NMR spectra were obtained at 250.1 MHz and referenced to CD_3CN . Unsolvated NaB_3H_8 was prepared following the procedure recently developed in our lab.¹⁵ All other starting materials were used as received from Sigma Aldrich.

Syntheses of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$

Two routes have been developed to synthesize this compound. For the first method, in a reaction flask, 6 mmol NH_4Cl was dissolved in 20 mL liquid NH_3 . 60 mL $\text{THF}\cdot\text{BH}_3$ (1M) was then added into the flask. After 45 min stirring, NH_3 was removed and THF was condensed into the same flask. White powders (~ 400 mg) were obtained after filtering. The powders were then reacted with 4.5 mmol unsolvated NaB_3H_8 in liquid NH_3 for ~20 min. After removing NH_3 , THF was used to extract the desired products (~380 mg) (yield 95%). ^{11}B NMR (THF): BH_2 : δ -13.2 ppm, B_3H_8^- , δ -29.9 ppm; ^1H NMR (CD_3CN): BH_2 , δ 1.9 ppm, NH_3 , δ 4.3 ppm; B_3H_8^- , δ 0.2 ppm.

For the second method, 1.05 g (9.5 mmol) of $(\text{CH}_3)_2\text{S}\cdot\text{BH}_2\text{Cl}$ was added to 20 mL of toluene in a reaction flask inside a dry box. NH_3 gas was then bubbled through the solution for 20 min at room temperature with constant stirring. Removing solvent under dynamic vacuum results in white powders (~ 780 mg). The powder was then reacted with 9.5 mmol unsolvated NaB_3H_8 in liquid NH_3 for ~20 min. After removing NH_3 , THF was used to extract the desired products (~ 790 mg) (yield 95%).

X-ray Crystallography

Single crystal X-ray analysis

X-ray quality single crystals of the $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8\cdot 18\text{-crown-6}$ adduct were grown from a 1:1 (molar ratio) mixture of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ and 18-crown-6 in THF. Single crystal X-ray diffraction data were collected on a Nonius Kappa CCD diffractometer which employs graphite-monochromated $\text{Mo K}\alpha$ radiation ($\lambda = 0.71073 \text{ \AA}$). Due to the sensitivity of the compound, single crystals were picked up from the mother solution in a nitrogen filled glove box and stored in Fomblin oil until data collection. A single crystal coated with Fomblin oil was

mounted on the tip of a glass fiber. Unit cell parameters were obtained by indexing the peaks in the first 10 frames and refined by employing the whole data set. All frames were integrated and corrected for Lorentz and polarization effects using the DENZO-SMN package.²² Absorption correction for the structure was accounted for using SCALEPACK.²² The structure was solved by direct methods using the SHELXTL-97 (full-matrix least-squares refinements) structure solution package.²³ All nonhydrogen atoms were located and refined anisotropically. Hydrogen atoms on boron and nitrogen atoms were located and refined isotropically, and other hydrogen atom positions were calculated by assuming standard geometries.

Powder X-ray analysis

Powder X-ray diffraction data were collected on a Bruker D8 Advance X-ray powder diffractometer at room temperature, which employs a Ge 111 Vario monochromator at the X-ray tube with $\text{Cu K}\alpha 1$ radiation ($\lambda = 1.5406 \text{ \AA}$). Due to the sensitivity to air and moisture, samples were ground and loaded into 1 mm Lindeman glass capillaries in an argon glove box.

The powder pattern was indexed in Topas Pro (Bruker AXS; Karlsruhe, Germany)²⁴ and the result indicates that $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ crystallizes in a orthorhombic unit cell ($Z = 4$). Possible solutions were modelled and geometry optimized in CASTEP (Accelrys, Inc; San Diego, California, USA) where the lowest energy lattices were prioritized as structure solution candidates. Calculation details are provided in ESI. Based upon the bond lengths and angles in $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8\cdot 18\text{-crown-6}$ adduct, rigid bodies of B_3H_8^- and $[(\text{NH}_3)_2\text{BH}_2]^+$ were constructed in Topas. Simulated annealing determined the orientations of these two subunits within the unit cell. Rietveld refinement yielded the best fit in $P2_12_12_1$. Atomic positions were determined by the rigid body framework. Thermal parameters for like atoms within a subunit were refined together while hydrogens were fixed at a reasonable value. Refinement details and crystallographic parameters are provided in ESI.

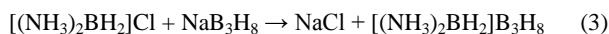
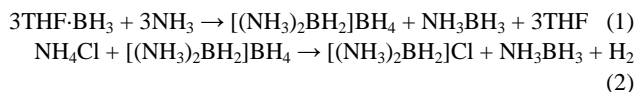
Thermal decomposition studies

Thermal stability of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ was studied using a Mettler Toledo high-pressure differential scanning calorimeter (DSC27HP) in an argon filled glove box with a ramp rate of $5 \text{ }^\circ\text{C}/\text{min}$. Thermogravimetric analysis (TGA) was performed on a Perkin Elmer TGA 7 analyzer. Powder was sealed in an aluminium pan in the glove box and the lid was pierced twice right before positioning the pan onto the TGA holder. The powder was heated to $400 \text{ }^\circ\text{C}$ at a heating rate of $5 \text{ }^\circ\text{C}/\text{min}$ under an Ar flow of $40 \text{ cm}^3/\text{min}$. The pressure of the DSC chamber is 1 atmosphere during the study. In a separate experiment, 2 mmol $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ was loaded into a 50 mL flask that was connected to a vacuum line, where another 50 mL flask filled with 10 mL anhydrous THF was also attached. The THF was cooled to liquid nitrogen temperature, so it was solidified, before the flask was opened to dynamic vacuum. After 10 min of dynamic evacuation, the flask with the sample was slowly heated up to $200 \text{ }^\circ\text{C}$. The gaseous decomposition products (except for H_2) were condensed into the flask cooled by liquid nitrogen. The condensed products were then analysed using ^{11}B NMR spectroscopy. The high sensitivity of ^{11}B allows for an easy and accurate identification of these B containing products. The

gaseous decomposition products were also studied using a mass spectrometer (ThermoStar GSD 320, Pfeiffer Vacuum), which is coupled with a thermogravimetric analyzer (TGA/DSC 1, Mettler Toledo). The amount of H₂ was semi-quantified via vacuum fractionation through a calibrated vacuum line. Detailed procedure can be found in Ref. 16.

Results and Discussions

For the first route, the synthesis can be illustrated in three steps as described in equations 1, 2, and 3. First, NH₃ reacts with THF·BH₃ to form [(NH₃)₂BH₂]BH₄ and NH₃BH₃, a well-known reaction since 1960s.^{25,26} [(NH₃)₂BH₂]BH₄ then reacts with NH₄Cl to produce [(NH₃)₂BH₂]Cl.^{27,28}



In the second method, NH₃ reacts with (CH₃)₂S·BH₂Cl to form the ionic compound [(NH₃)₂BH₂]Cl, which then reacts with NaB₃H₈ according to equation 3.



For the synthesis, unsolvated NaB₃H₈ is prepared based on the route developed in our lab.¹⁵ It should be mentioned that solvated NaB₃H₈ can also be used for the last step; i.e., an alternative mercury-free synthetic route to NaB₃H₈ can be employed.^{29,30} Thus, the two new synthetic routes to [(NH₃)₂BH₂]B₃H₈ avoid dangerous starting materials and are much safer to carry out. The overall yield is also high, close to 95 % based on NaB₃H₈. The ¹¹B NMR spectrum (Fig. 1 top) of [(NH₃)₂BH₂]B₃H₈ in THF clearly indicates the purity of the desired product, with resonance only associated with BH₂ and B₃H₈⁻ present in the spectrum. The ¹H NMR spectrum (Fig. 1 bottom) further proves the success of this synthesis, as evidenced by the resonances associated with NH₃, BH₂ and B₃H₈⁻.

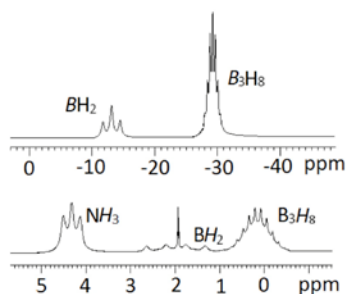


Fig. 1 ¹¹B NMR spectrum of [(NH₃)₂BH₂]B₃H₈ in THF (top) and ¹H NMR spectrum in CD₃CN (bottom).

Crystal Structure

(NH₃)₂BH₂B₃H₈·18-crown-6

Table 1 lists crystallographic data of the [(NH₃)₂BH₂]B₃H₈·18-

crown-6 adduct. This compound shows a separate ion pair structure (Fig. 2). One NH₃ connects to the crown ether by three N–H···O hydrogen bonds between the hydrogen of the NH₃ and the oxygen of the ether. In this structure, the closest N–H^{δ+}···H^{δ-}–B distance is around 2.1 Å. This distance is very close to the sum of van der Waals radii between two hydrogen atoms, 2.4 Å, indicative of weak N–H^{δ+}···H^{δ-}–B dihydrogen interaction that is commonly found in B and N containing compounds such as NH₃B₃H₇¹², NH₃BH₃³¹, and NH₃BH₂NH₂BH₃³².

Table 1. Crystallographic information of [(NH₃)₂BH₂]B₃H₈·18-crown-6

empirical formula	C ₁₂ H ₄₀ B ₄ N ₂ O ₆
crystal system	Triclinic
space group	<i>P</i> -1
<i>Z</i>	2
<i>a</i> (Å)	8.0619(16)
<i>b</i> (Å)	10.828(2)
<i>c</i> (Å)	12.983(3)
<i>a</i> (deg)	77.64(3)
<i>β</i> (deg)	85.11(3)
<i>γ</i> (deg)	83.07(3)
<i>V</i> (Å ³)	1096.9(4)
<i>T</i> (K)	180
<i>D</i> _{calcd} (g·cm ⁻³)	1.065
<i>μ</i> (mm ⁻¹)	0.077
no. reflns collected	5041
no. unique reflns	281
R1 [<i>I</i> > 2σ(<i>I</i>)] ^a	0.0380
wR2(all data) ^b	0.1064

$$^a R_1 = \sum ||F_o| - |F_c|| / \sum |F_o| \quad ^b wR_2 = [\sum w(F_o^2 - F_c^2)^2 / \sum w(F_o^2)^2]^{1/2}$$

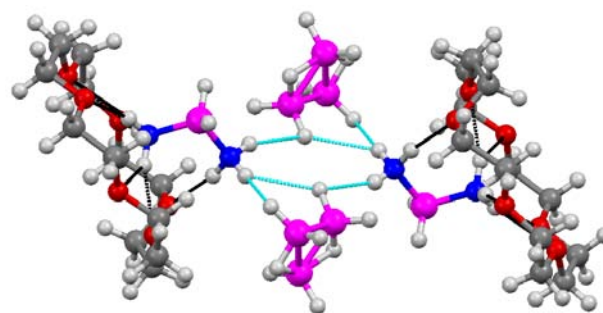


Fig. 2 Structure of [(NH₃)₂BH₂]B₃H₈·18-crown-6. Black dotted lines indicate N–H···O hydrogen bonds; light blue dotted line denotes intermolecular N–H^{δ+}···H^{δ-}–B interactions. B: Magenta, N: blue, H: light grey, O: red, C: dark grey.

Pure [(NH₃)₂BH₂]B₃H₈

The existence of crown ether affects the packing of B₃H₈⁻ and [(NH₃)₂BH₂]⁺ and thus this adduct does not reflect the true bonding nature in pure [(NH₃)₂BH₂]B₃H₈. Efforts made to obtain solvent free [(NH₃)₂BH₂]B₃H₈ single crystals have been unsuccessful. Therefore, structure solutions based on powder X-

ray diffraction analysis combined with first-principles calculations have been carried out. Fig. 3 shows the powder XRD pattern and the Rietveld refinement results. Refinement details are provided in ESI. $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ crystallizes in a $P2_12_12_1$ unit cell ($Z = 4$) with $a = 8.2202(3)$ Å, $b = 9.2554(4)$ Å, $c = 9.3847(4)$ Å. The pure compound possesses extensive strong $\text{N}-\text{H}^{\delta+}\cdots\text{H}^{\delta-}-\text{B}$ interactions (Fig. 4), as evidenced by distances ranging from 1.9 to 2.2 Å, shorter than the sum of van der Waals radii between two hydrogen atoms, 2.4 Å. Similar to $\text{NH}_3\text{B}_3\text{H}_7$ ¹² and NH_3BH_3 ³¹, these extended dihydrogen bond interactions are believed to be the main force for molecule packing.

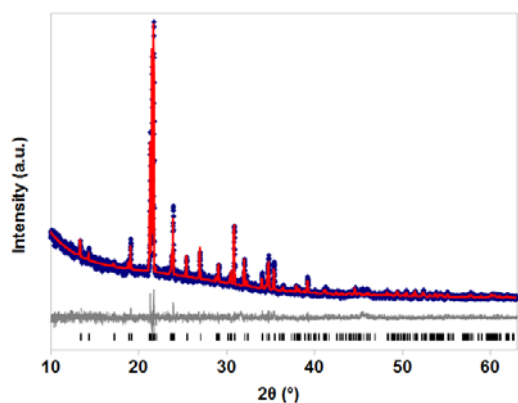


Fig. 3 XRD pattern of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ and the Rietveld refinement result. Blue: raw data points. Red: calculated profile. Grey: difference curve. Black vertical tick marks are indexed Bragg reflections for $P2_12_12_1$.

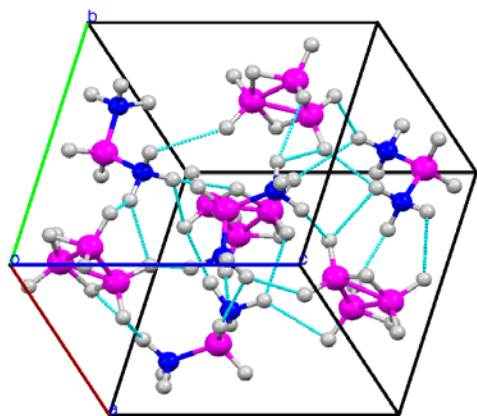


Fig. 4 Crystal view showing intermolecular $\text{N}-\text{H}^{\delta+}\cdots\text{H}^{\delta-}-\text{B}$ interactions (indicated by dotted lines) in the pure solid $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$. B: Magenta, N: blue, H: light grey.

Thermal decomposition

$[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ has a high hydrogen content of 18.2 wt.%. DSC and TGA results (Fig. 5) collectively indicate that decomposition takes place simultaneously at 100 °C and finishes at around 160 °C, with a total weight loss of 40 wt.%. The peaks at 60 °C and 30 °C are likely due to phase changes. When the sample was subject to heating from 20 °C to 70 °C and cooling from 70 °C to 20 °C, then another heating from 20 °C to 400 °C, two endothermic peaks at 60 °C overlap and a sharp exothermic peak appeared at around 30 °C. XRD analysis carried out under

inert atmosphere (due to the hygroscopic nature of the compound) at various temperatures combined with DFT calculations might help elucidate the details of this change in the crystal structure. The decomposition gaseous products were trapped and dissolved in THF at about -78 °C. The NMR analysis of the gaseous products (Fig. 6) indicates the presence of B_2H_6 , B_5H_9 and $\text{B}_3\text{N}_3\text{H}_6$, which are also found during the decomposition of $\text{NH}_4\text{B}_3\text{H}_8$.¹⁶ In addition to these volatile borane species, appreciable amounts of NH_3 is also detected via mass analysis during the decomposition of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ (ESI). Approximately 15 wt.% of the weight loss is due to hydrogen evolution, as determined by the vacuum fractionation.

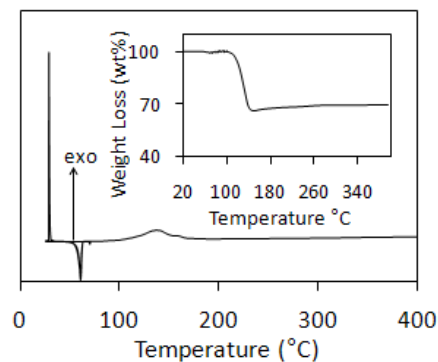


Fig. 5 DSC and TGA curves of $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ (5 °C/min).

It is widely accepted that the strong $\text{N}-\text{H}^{\delta+}\cdots\text{H}^{\delta-}-\text{B}$ interaction contributes to the formation of H_2 .³³⁻³⁶ In both NH_3BH_3 and $[(\text{NH}_3)_2\text{BH}_2]\text{BH}_4$, where strong dihydrogen interactions exist and the ratio of these two types of H atoms is 1:1, the neat thermal decomposition yields fairly high purity H_2 with only traces of NH_3 , B_2H_6 , and $\text{B}_3\text{N}_3\text{H}_6$.^{37,38} Unlike these two compounds, the ratio is 3:5 for $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$, so the extra hydridic H atoms likely contribute to the formation of undesired boron hydrides, especially B_2H_6 and B_5H_9 . The thermal decomposition shows that the existence of protonic H on N atoms seems to suppress the formation of these boranes and facilitate the formation of H_2 , considering that the total 70 wt.% weight loss with 10 wt.% H_2 for $\text{NH}_4\text{B}_3\text{H}_8$ (3 : 6 of $\text{H}^{\delta+} : \text{H}^{\delta-}$), compared to the total 40 wt.% weight loss with 15 wt.% H_2 from $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ (3 : 5 of $\text{H}^{\delta+} : \text{H}^{\delta-}$).

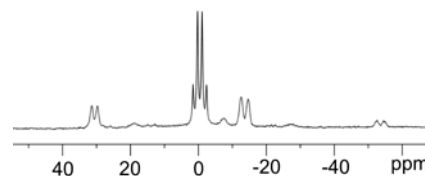


Fig. 6 ^{11}B NMR spectrum of gaseous products from $[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$ dissolved in THF. B_2H_6 (exists as $\text{THF}\cdot\text{BH}_3$, δ 0 ppm), B_5H_9 (δ -13.9, -53.8 ppm), and $\text{B}_3\text{N}_3\text{H}_6$ (δ 30.8 ppm) were observed.

Conclusions

Two safe and efficient synthetic methods were developed to diammoniate of tetraborane ($[(\text{NH}_3)_2\text{BH}_2]\text{B}_3\text{H}_8$). These new methods avoid the employment of highly flammable B_4H_{10} and thus effectively simplify the reaction setup. Calculated crystal

structure indicates strong N–H^{δ+}...H^{δ-}–B interactions in the pure [(NH₃)₂BH₂]B₃H₈, as evidenced by the short distances ranging from 1.9 to 2.2 Å, smaller than the sum of van der Waals radii between two hydrogen atoms, 2.4 Å. This is in contrast to NH₄B₃H₈, where the shortest N–H^{δ+}...H^{δ-}–B distances are closer to 2.4 Å. Thermal decomposition reveals that more H₂, and less B₂H₆, B₅H₉, and B₃N₃H₆ are released from [(NH₃)₂BH₂]B₃H₈ than NH₄B₃H₈. This is likely due to the improvement in the H^{δ+} : H^{δ-} ratio from 3 : 6 for NH₄B₃H₈ to 3 : 5 for [(NH₃)₂BH₂]B₃H₈. The hydrogen evolution via thermal decomposition is thus unlikely to meet the requirement for hydrogen storage. Solid state nuclear magnetic resonance will be carried out in the future to elucidate the heat of reaction as well as mechanisms in the pathway.

Boron-nitrogen-hydrogen compounds have been investigated for hydrogenation and catalytic conversion due to their high hydrogen content and strong reducing capability.³⁵ [(NH₃)₂BH₂]B₃H₈ may be suitable for such applications, and the reported synthesis will greatly facilitate future explorations of these applications.

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