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Ammonia-mediated, large-scale synthesis of ammonia borane

P. Veeraraghavan Ramachandran,[*] Hitesh Mistry, Ameya S. Kulkarni and Pravin D. Gagare
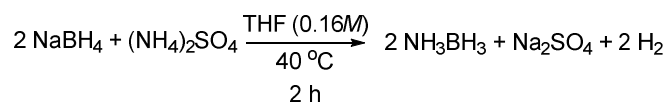
A simple, large-scale synthesis of ammonia borane from NaBH$_4$ and (NH$_4$)$_2$SO$_4$ at 0°C-rt in THF containing 5% NH$_3$ is described. The presence of ammonia is critical for the reaction to proceed and allows the reaction at high concentration and ambient temperature without the need for anhydrous solvent or inert atmosphere.
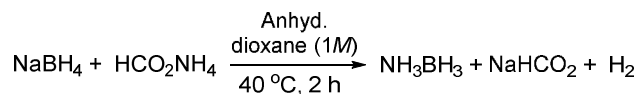
The simplest of the amine-boranes, ammonia-borane (AB) has attracted considerable attention, notably during the past decade, as an environmentally desirable carrier of hydrogen due to its stability, transportability and non-toxicity.[1] Recently, it has been examined as an additive to hypergolic ionic liquids as green rocket propulsion fuel.[2] Although the growth of hydrogen storage research involving AB has been phenomenal,[1] the current state of hydrogen storage processes are still either inadequate or impractical for widespread use. As part of our project involving AB for portable hydrogen storage applications, we required multi-kilogram quantities of AB to build fuel cell cartridges. We desperately needed a scale-up friendly synthesis of AB for our project to proceed. Herein, we report a practical, large-scale (10 mole) ambient temperature synthesis of AB in reagent-grade THF containing 5% dissolved NH$_3$, *without the need for anhydrous solvents, inert conditions* or any special apparatus. The synthesis is critically dependent on the presence of dissolved ammonia in the reaction medium. The details follow.

Since the seminal reports by Shore and Parry[3] detailing the preparation of AB from LiBH$_4$ (LBH) as well as from diammoniate of diborane (DADB), several protocols have been described in the literature.[1] Unfortunately, none of these are suitable for large-scale synthesis. For example, the dilution of the reaction medium (0.165 *M*) was a major drawback of our earlier synthesis from sodium borohydride (SBH) and ammonium sulfate in anhydrous THF (Scheme 1).[4] This was overcome with an improved synthesis using ammonium formate and SBH in 1 *M* anhydrous dioxane (Scheme 2). However, (i) the carcinogenicity of dioxane, (ii) the tedious removal of solvent for

recycling, and (iii) the cost of the anhydrous solvent again posed obstacles.

$$2\ NaBH_4 + (NH_4)_2SO_4 \xrightarrow[\substack{40\ ^oC \\ 2\ h}]{THF\ (0.16M)} 2\ NH_3BH_3 + Na_2SO_4 + 2\ H_2$$

Scheme 1. Synthesis of AB in dilute THF.

$$NaBH_4 + HCO_2NH_4 \xrightarrow[\substack{40\ ^oC,\ 2\ h}]{\substack{Anhyd. \\ dioxane\ (1M)}} NH_3BH_3 + NaHCO_2 + H_2$$

Scheme 2. AB synthesis in dioxane.

Autrey and co-workers recently reported the synthesis of AB *via* ether (THF)-mediated decomposition of the *in situ* generated ammonium borohydride (NH$_4$BH$_4$, ABH$_2$) in liquid ammonia at -78°C (scheme 3).[5,6] They also reported a modification of the above synthesis in a Hastelloy reactor at selected temperatures and pressures so as to maintain the liquid ammonia environment to produce ABH$_2$.[7] All of these procedures require the condensation of large quantities of ammonia,[8] anhydrous solvent, low temperature and/or a special apparatus, thus making the scale-up inconvenient.

$$NaBH_4 + NH_4Cl \xrightarrow[\substack{-78\ ^oC}]{liquid\ NH_3} NH_4BH_4 \xrightarrow{THF} NH_3BH_3 + H_2$$
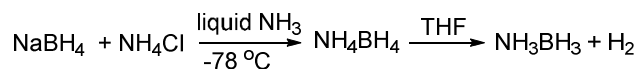
Scheme 3. AB synthesis via ABH$_2$ in liquid ammonia

More recently, Shore and coworkers reported a large-scale synthesis of AB from either borane-methyl sulfide (BMS) or borane-*N,N*-dimethylaniline *via* the nucleophilic displacement of the base with gaseous ammonia in anhydrous THF or toluene.[9] The former borane complex (BMS) is expensive, pyrophoric, has an obnoxious odor and is synthesized from SBH using corrosive BF$_3$-etherate. The

latter complex (*N,N*-dimethylaniline-borane) is prepared by passing gaseous diborane, generated in situ from SBH and I_2 in diglyme, through *N,N*-dimethylaniline in toluene. Generating B_2H_6 in large-scale caused a major safety concern.

The above mentioned processes are all carried out in dry solvents, under an inert atmosphere adding to the cost of AB. A safe, scalable, economical synthesis of AB under optimal conditions of temperature and pressure became our goal. If possible, we sought to achieve this in reagent-grade solvents at high concentration and in air. The metathesis of SBH with ammonium salts still remained the most attractive protocol for AB synthesis in terms of cost and convenience.

We began our project by targeting the concentration factor first. During our earlier synthesis of AB, we had observed that the reaction is slow in both THF and dioxane at ambient temperature and faster at 40 $^{\circ}$C, though the solubility of SBH in dioxane allowed increased concentration. Thus, increased solubility of the reagents/products in the solvent became a necessary condition to conduct reactions at higher concentration. Due to the excellent solubility of SBH[10] as well as AB[3b] in NH_3 and the capability of NH_3 to cleave DADB,[3a] we envisaged that adding NH_3 to THF[11] would aid the metathesis of SBH, without the need to form NH_4BH_4. Our expectation was that the presence of NH_3 would allow increased concentration of SBH in THF, resulting in an improved synthesis.

On the basis of earlier results, ammonium sulfate was selected as the salt and added to SBH in anhydrous THF (1*M*) at 0 $^{\circ}$C when we observed, expectedly, no reaction even after two hours (Figure 1(a)). We then examined our hypothesis, by the addition of 2.5% ammonia to anhydrous THF before the addition of the reagents. We were delighted to observe immediate gas evolution (presumably hydrogen). The ^{11}B NMR spectrum showed the formation of AB (δ -22 ppm, q), which proceeded to 97% completion after 4 h. Further reaction was extremely slow and we warmed the mixture to room temperature (rt), when the reaction was complete in 5 h (Figure 1.b). A simple filtration and removal of solvent provided 77% yield of pure AB, as was determined by hydride analysis (hydrolysis reaction). Thus, we achieved our first goal of preparing AB at increased concentration by using ammoniated THF.

Table 1: Synthesis of AB: Optimization of ammonium salts for the synthesis of AB in ammoniated THF.[a]

entry	Ammonium salt	Reaction condition	Isolated Yield, %
1	NH₄OAc	0 °C, 2 h, rt 2 h	70
2	NH₄F	0 °C, 2 h, rt 9 h	74
3	NH₄HCO₂	0 °C, 2 h, rt, 2.5 h	74
4	NH₄Cl	0 °C, 2 h, rt, 2 h	71
5	NH₄HCO₃	0 °C, 2 h, rt 2 h	75
6	NH₄HF₂	0 °C 2 h, rt 3 h	73
7	(NH₄)₃PO₄	0 °C 2 h, rt, >16 h	Incomplete
8	NH₄HSO₄	0 °C 2 h, rt 8 h	58
9	(NH₄)₂SO₄	0 °C, 4 h, rt 5 h	77
10	(NH₄)₂CO₃	0 °C, 4 h, rt 6 h	76

[a]The reaction was performed in THF containing 2.5% NH_3.

It is also noteworthy that THF is the solvent of choice, since this reaction, repeated in diethyl ether (Et_2O), was much slower, leaving considerable amounts of unreacted SBH even after 12 h.[12] With apprehension, we carried out the reaction in reagent-grade THF as

obtained commercially, without drying or distilling. The reaction yielded AB of same purity and yield as with anhydrous THF. Thus, we also realized our second goal; viz. the large-scale synthesis of AB in inexpensive, ordinary solvent.
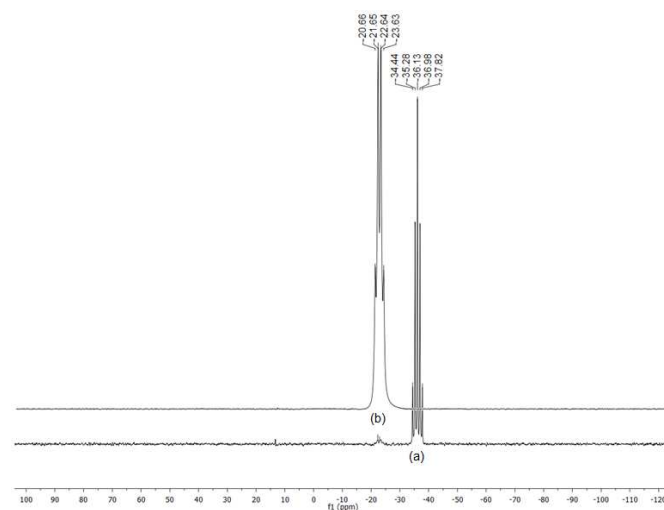
Figure 1. (a) ^{11}B NMR spectrum (in DMSO) of reaction mixture (SBH and $NH_4(SO_4)_2$ (1:1)) at 0 $^{\circ}$C after 2h in THF (1*M*). (b) ^{11}B NMR spectrum of AB prepared in THF (1*M*) containing 2.5% NH_3.

With two of our major goals achieved, we continued our optimization for the best condition and yields. A series of ammonium salts was then evaluated for the new synthesis of AB in ammoniated THF at 0 $^{\circ}$C-rt. Commercially available ammonium salts, such as ammonium carbonate, ammonium nitrate, ammonium chloride, ammonium fluoride, ammonium acetate, ammonium bicarbonate, ammonium carbamate, ammonium hydrogen fluoride, and ammonium hydrogen sulfate were treated with SBH in the presence of ammonia (Table 1).[13] As in the case of our earlier AB syntheses,[4] the best yields and purities of AB were obtained using ammonium sulfate (Table 1: entry 9). Indeed, powdering the ammonium sulfate accelerated the rate of the reaction and provided better yields. Any loss of dissolved ammonia was accompanied by a deceleration of the rate resulting in decreased yields.
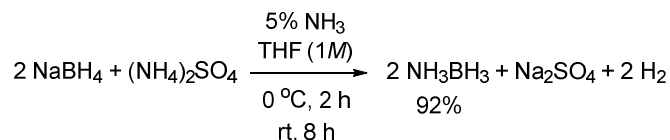
Table 2: Synthesis of AB: Optimization of reaction condition with $(NH_4)_2SO_4$.

entry	Molarity[a]	% NH₃	Reaction condition	Workup[b]	Yield[c]
1	1	2.5	0 °C, 4 h, rt, 5 h	A	77%
2	1	2.5	0 °C, 4 h, rt, 5 h	B	87%
3	1	2.5	rt, 15 h	B	70%
4	**1**	**5**	**0 °C, 2 h, rt, 8 h**	**B**	**92%**
5	1.5	5	0°C, 2 h, rt, 10 h	B	69%
6	2	5	0°C, 2 h, rt, 18 h	B	43%
7	2	10	0°C, 2 h, rt, 13 h	A	80%

[a]Molarity of SBH or ammonium salt in THF containing NH_3. [b]A: No addition of ammoniated THF prior to isolation. B: Additional 1M solution of NH_3 in THF was added to the reaction mixture prior to isolation. [c]Isolated yield.

Molar ratios of SBH to ammonium sulfate ranging from 1:0.5 to 1:1 were then examined. Although theoretically a 1:0.5 molar ratio should be sufficient for the metathesis, prolonged reaction time was necessary when less than 0.75 molar equivalent of ammonium sulfate was used. This resulted in the formation of 5-10% of an impurity at δ -9.5 ppm, probably due to the decomposition of AB. Optimal yield and purity was achieved when a 1:1 molar ratio of SBH to ammonium sulfate was used. The purity of the material was determined by ^{11}B NMR spectroscopy as well as *via* hydride estimation.

The reaction was further optimized using ammonium sulfate in ammoniated THF by varying the molarity, concentration of ammonia as well as the reaction temperature, and time. As can be seen from the representatives in Table 2,[13] the best results were achieved with 5% ammonia in THF v/v (entry 4) at 1*M* concentration with respect to SBH. Increasing the molarity of SBH resulted in an increase in reaction time and decreased yield of AB. Increasing the % of ammonia also did not improve the results due to the loss of the dissolved ammonia. Satisfactory yields were obtained when the reaction was carried out at 0°C and warmed to rt (Scheme 4). With the best protocol, we observed varying yields (70-85%) of the product AB from different batches. Upon investigation, we realized that the difference in yields was due to the loss of precipitated AB in the residue during filtration. We circumvented this problem by diluting the reaction medium with THF containing 1 *M* ammonia before the filtration (Table 2, workup B). This protocol was then carried out on a 10-mole scale to demonstrate the simplicity and effectiveness of our optimal process.

$$2\ NaBH_4 + (NH_4)_2SO_4 \xrightarrow[\substack{0\ ^oC,\ 2\ h \\ rt,\ 8\ h}]{\substack{5\%\ NH_3 \\ THF\ (1M)}} 2\ NH_3BH_3 + Na_2SO_4 + 2\ H_2$$
92%

Scheme 4. AB synthesis via displacement reaction

In a typical reaction procedure,[13] condensed liquid ammonia (500 mL) was transferred via cannula to 10 L reagent-grade THF contained in an indented 22 L three-neck round bottom flask fitted with an overhead stirrer, stopper, and a cold finger.[13] The flask was cooled in ice-water bath. Sodium borohydride (378.3 g, 10 mol) and powdered ammonium sulfate (1.32 Kg, 10 mol) were transferred to the reaction flask after addition of ammonia. The mixture was stirred carefully for 2 h at 0 °C and then at room temperature for 8 h. Upon completion of the reaction, as monitored by ^{11}B NMR spectroscopy, 1 *M* ammoniated THF solution (5 L) was added to the reaction mixture, stirred for 30 min, filtered through celite, and washed with THF. The filtrate was concentrated under vacuum to obtain ammonia borane (283.9 g, 92%) at ~98% chemical purity, as was determined by both ^{11}B NMR spectroscopy (Figure 1(b)) (64 MHz, δ -22.1 ppm (q)) and hydride analysis. Most of the solvent THF was recovered and re-used.

Conclusions

In conclusion, we have developed a practical, large-scale synthesis of ammonia borane from sodium borohydride and ammonium sulfate in ammoniated, reagent-grade THF at ambient temperature and pressure. The presence of ammonia is critical for the reaction to proceed well. All of the operations are carried out in air, obviating the need for an inert atmosphere for the reaction. We believe that this protocol will reduce the cost of commercial AB (first feed) and augment the interest and utility of ammonia borane for hydrogen storage applications. Mechanistic studies on the influence of ammonia on the "metathesis" are in progress.

Notes and references

Herbert C. Brown Center for Borane Research, Purdue University, 560 Oval Drive, West Lafayette, IN 47907-2084, USA. E-mail: chandran@purdue.edu

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8. It became impractical to condense several litres of ammonia to carry out the synthesis of AB on the scale we needed.

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11. In reference 6, Autrey and co-workers mention that Shore and Parry prepared AB (ref. 3) "*from NH$_4$Cl and LiBH$_4$ in diethyl ether when a trace of NH$_3$ was present, eqn (3)*". However, the equation 3 in ref. 6 describes "(*THF with trace NH$_3$*)". This appears to be an error since Shore-Parry's report (ref. 3b), suggests the contrary (see ref. 12):

12. This was also observed by Shore and Parry in ref. 3b. They have stated: "*As a preliminary experiment, the reaction between sodium borohydride and ammonium chloride was studied in diethyl ether. Even when small amounts of ammonia were used to accelerate the gas evolution, the production of hydrogen was negligible.*"

13. Caution: Adequate safety precautions should be taken while carrying out these experiments. Due to the toxic and corrosive nature of ammonia and the liberation of large quantities of highly flammable

hydrogen, the reactions described in Tables 1 and 2 (and the 10 mole-scale reaction) were carried out in a well-ventilated hood with the reaction vessel outlet directly leading into the hood exhaust.