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A Short Chronological Review on the Syntheses of Amine-Boranes

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ABSTRACT

Since their discovery by Burg and Schlesinger in 1937, amine-boranes have enjoyed a rich preparative history and have experienced reinvigorated interest as valuable compounds. These borane complexes have been implemented in a variety of applications, spanning from reagents in organic syntheses to hydrogen storage materials. The importance of amine-boranes derives especially from their reductive abilities. Given the utility of amine-boranes and their current resurgence, a mini review on their general properties and notable preparations is both timely and potentially of interest to organic and materials chemists alike.

1. Introduction

Formally, amine-boranes can be described as complexes of borane, which acts as a Lewis acid, and an amine, which acts as a Lewis base. In this complex, the nitrogen atom's lone pair of electrons forms a coordinate covalent, also known as a dative, bond via donation into the vacant borane 2*p* orbital (Figure 1). [1] Such borane adducts can typically be formed with any Lewis base (molecules containing nitrogen, oxygen, phosphorous, or sulfur, wherein the hetero-atom possesses an available pair of non-bonding electrons). Common, simplistic examples of these classical adducts include ammonia-borane (NH_3-BH_3, AB), borane-tetrahydrofuran (BH_3-THF, BTHF), phosphine-borane (PH_3-BH_3, PB), borane-dimethylsulfide [BH_3-$S(CH_3)_2$, BDMS, DMSB], etc.

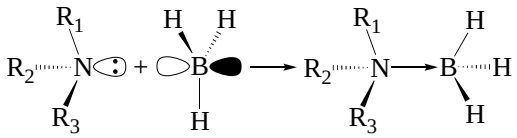

Figure 1. sp3$\boldsymbol{\sigma}$-p$\boldsymbol{\sigma}$ dative bond formation in an amine-borane

The discovery of a boron-nitrogen dative bond is attributable to Gay-Lussac in 1809 [2], and in 1937, Burg and Schlesinger were credited with the first report of an amine-borane, trimethylamine-borane (Figure 2). [3] With regards to Gay-Lussac, Burg, and Schlesinger, their initial discoveries have ushered more than three-quarters of a century (and beyond) of research into amine-boranes and their derivatives, with diverse applications ranging from reagents in organic syntheses [4] to hydrogen storage materials [5] to pharmacologically active compounds. [6]

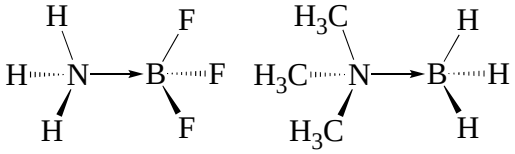

Figure 2. Ammonia-trifluoroborane (left) & trimethylamine-borane (right)

The first historical application of amine-boranes is taken to be as reducing agents, as noted in Hutchins et al.'s seminal 1984 review. [7] A full treatment of the numerous applications of amine-boranes and their derivatives, as well as their relatives like phosphine- (or phosphane-) and sulfide-boranes, is not within the scope of this introduction, though such literature serves as the basis for several fine investigations [6c, 8] and reviews (Figure 3 [9]). [1, 2b, 7, 10].

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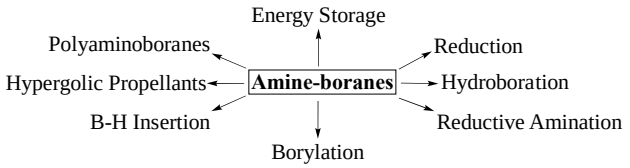


Figure 3. Amine-borane applications (Adapted from Kulkarni & Ramachandran, 2017)

Amine-boranes are perhaps most commonly recognized as valuable reagents due to the hydridic nature of the hydrogen atoms on the borane functionality; it is this hydridicity that enables the diverse and unique chemistry of amine-boranes (To illustrate this principle, some older representations of amine-boranes, historically called amine-"borines" or "-borazanes," denote positive and negative charges on the N- and B-atoms, respectively, while maintaining the overall neutrality of the complex) (Figure 4). [2b, 10d, 11] It is evident that AB is the structurally simplest of the amine-boranes, regarding the substitution on the N-atom.

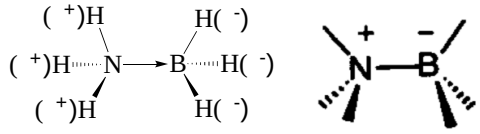


Figure 4. General hydridicity of ammonia-borane (left) & historical representation, intentionally antiquated [10d] (right)

By extension, the generally broad classifications of amine-boranes include: ammonia-borane (AB), primary (1°), secondary (2°), tertiary (3°), and heteroaryl (HA) amine-boranes, wherein the N-atom is involved in the aromaticity of the ring; these classifications describe the amount of non-hydrogen substitution on the N-atom. Within the 2° and 3° classifications, there exists the subset of heterocyclic (HC) amine-boranes, e.g., aziridine-borane, wherein the N-atom is part of the closed ring. Though not as prominent, there are also amine-bisboranes (Bis), [12] with hydrazine-bisborane ($H_3BNH_2NH_2BH_3$) and ethylenediamine-bisborane [$H_3BNH_2(CH_2)_2NH_2BH_3$] as the most recognized examples; there appears to be scant reporting of amine-tris-, tetrakis-, or pentakis-boranes, especially no higher than five -BH_3 groups. [13] Interestingly, a recent (2019) patent describes the preparation of a trisborane complex [*N*,*N*-bis[2-(dicyclohexylphosphino)ethylamine-trisborane], wherein two of the three -BH_3 groups are coordinated to P-atoms and the third -BH_3 group is coordinated to an N-atom, representing a hybrid (Hyb) amine/phosphine-borane. [14] Moreover, there exists a subset within each of the aforementioned categories, barring AB, that includes functionalized (Func) amine-boranes, for instance methan*ol*amine-borane, 2-diethylaminoethane*thiol*-borane, or *allyl*amine-borane. In some instances, these accompanying functional groups are sensitive to boranation, i.e., installment of the -BH_3 group, so care must be taken when choosing a preparative method, as will later be discussed.

In terms of the hydridicity of an amine-borane, this particular property is dependent upon both the N-atom's and the B-atom's substituent(s), though in the case of non-substitution on the B-atom (BH_3), hydride-donating tunability lies with the N-atom. More generally, the overall stability of an amine-borane is contingent on the substitution(s) of the N- and B-atoms. As an extreme example, aniline-borane is stable at -30 °C, the minimum temperature required for its preparation, but can begin to dehydrocouple as ambient temperatures are approached, assuming standard pressure. [2b, 10d, 15] The most notorious factor influencing amine-borane stability is the steric bulk of the group(s) on both the B- and N-atoms. The steric bulk phenomenon has been quantitatively demonstrated by assessing the molar enthalpies of formation (ΔH_f) between certain amines and BTHF; the reported ΔH_f trends are: 1) *n*$BuNH_2$-BH_3 > *n*Bu_2NH-BH_3 > *n*Bu_3N-BH_3 and 2) Et_2NH-BH_3 > *n*Pr_2NH-BH_3 > *n*Bu_2NH-BH_3. [2b, 16] Understandably, the resultant instability from increasingly bulky groups on the B- and/or N-atoms is due to poor orbital overlap (Figure 1). There have also been suggestions that increased alkyl bulk on the N-atom entails reduced Lewis basicity by increasing the bond angle around the N-atom, thereby reducing the *p* character of the interacting lone-pair and increasing its *s* character. [2b, 17] As a general rule of thumb, Hutchins et al. posit that a stable adduct can be formed so long as the pK_a of the amine is greater than 5.0 – 5.5. [7] It is also noted that those amines whose pK_a values lie within that range can form the dative bond with borane but that this N-B bond is weaker compared to those amines with pK_a values greater than the specified range.

Invariably, some of the same principles governing the stability of an amine-borane adduct also apply to the hydride-donating capability of the amine-borane; it is understood that the amine-borane adduct must itself be stable in order to react. Most prominently, when describing amine-boranes simply bearing the -BH_3 moiety, the identity of the amine governs reductive capabilities of the hydrides. For example, it has been shown that increasing alkyl substitution on the amine decreases reducing ability, illustrated by the trend AB > RNH_2-BH_3 > R_2NH-BH_3 > R_3N-BH_3. [2b, 7] Regarding the sister compounds, heteroaryl- and *N*-arylamine-boranes, the trend is that those amines with lower pK_a values are better reducing agents. In an application-related example, several different amine-boranes were tested in their reductive abilities towards a gold salt, $AuPPh_3Cl$, for the preparation of nanoparticles, and their capacities to reduce the salt were: AB > *t*-butylamine-borane ≈ triethylamine-borane > morpholine-borane, illustrating the general effect of the N-atom's substituents on hydridicity. [10b, 18]

Another interesting facet of hydride-donating

governability is the report that acidic, aqueous/mixed aqueous solvents can enhance the reducing ability of some amine-boranes; this has been demonstrated using morpholine-borane and several of its derivatives and relatives. [2b, 10h, 19] In a specific example, without acidification, *N*,*N*,*N*-trimethylamine-borane is unable to reduce cyclohexanone to the corresponding alcohol within 38 hours reaction time. With acidification, the ketone-alcohol transformation is affected within 8 minutes with 80% conversion. It has also been noted that solvent selection and increased temperatures, up to a certain extent (~70 < *T* < 100 °C), can improve amine-borane hydridicity.[7] Finally, the addition of a Lewis acid catalyst, such as $AlCl_3$ or BF_3, markedly improves the reductive effect of certain amine-boranes due to a complexing action of the Lewis acid with the carbonyl oxygen, which in turn facilitates the intermolecular hydride transfer from the amine-borane to the δ^+ carbon. [7, 20]

Within the framework of organic chemistry, amine-boranes are most prominently viewed as reducing agents; Hutchins et al. regard amine-boranes as essential "in the arsenal of reductive weapons available to chemists." [7] Though not definitive, it is within reason to suggest that of the available reducing agents, including amine-boranes, sodium borohydride ($NaBH_4$), also known as sodium tetrahydridoborate, is the most widely used and commonly recognized. [21] In fact, it has been boldly asserted that "every beginning organic text mentions the use of sodium borohydride as a reducing agent." [22] Moreover, *Ullmann's Encyclopedia of Industrial Chemistry* indicates that thousands of metric tons of $NaBH_4$ are annually manufactured and utilized worldwide, representing a multimillion dollar business; such usage warrants the recognition of $NaBH_4$ as "by far the most important commercially available complex hydride." [21b, 23] Other popular, often-employed reducing agents include: lithium aluminum hydride (LAH), [24] lithium borohydride (LBH), [25] lithium triethylborohydride [Superhydride®, LiTEBH], [26] sodium cyanoborohydride ($NaBH_3CN$), [27] lithium aminoborohydrides (LABs), [28] diisobutylaluminum hydride (DIBAL, DIBAL-H), [29] sodium-bis(2-methoxyethoxy)aluminum hydride (SMEAH, Red-Al®), [30] and triethylsilane (TES). [31] A computational study ranks AB, a somewhat representative amine-borane, as roughly in between TES, a weak reducing agent, and BH_4^-, an intermediate reducing agent, in terms of reducing strength, as measured by ΔG values. [21c]

Given such an abundance of reducing agents, one might be prompted to consider how amine-boranes are set apart from their counterparts. With reference to the previous discussion, reducing strength is certainly the most obvious distinction that can be made between amine-boranes and other reducing agents. However, tunability of amine-borane reducing strength is made possible by 1) manipulating the N-atom's substituent(s), 2) acidifying the solution, 3) varying the solvent, 4) adding a Lewis acid catalyst, and/or 5) adjusting the reaction temperature. It is worthwhile however to note that Brown and coworkers experimented with the tunability of sodium borohydride's (SBH) reducing strength by changing the cation and substituting the H atom(s) with alkyl or alkoxy groups. [32]

Though Heiden and Latham cite AB as a representative amine-borane in their study on "[e]stablishing hydride donor abilities," [21c] it is difficult to make a generalization about the hydridicity of amine-boranes due to the vastness of this class of compounds. Aside from customizable reducing abilities, amine-boranes are oftentimes far more soluble than their fellow hydride donors in common solvents, both aprotic and protic; some of these solvents include: benzene, dichloromethane, ether, hexane, methanol, tetrahydrofuran, and toluene. Notably, amine-boranes are mostly unreactive towards water and other protic solvents. [2b, 7, 10h] Finally, amine-boranes offer tantalizing advantages, especially over certain reducing agents like LAH, LBH, and Superhydride® as well as boranating agents like diborane (B_2H_6, DB), BTHF, and BDMS, in terms of air- and moisture-sensitivity, pyrophoricity, and toxicity. [2b, 33]

The current discussion would be remiss if one of the more exotic applications of amine-boranes was not discussed prior to their synthetic history. By complexing the -BH_3 moiety with an asymmetric amine [$H_{(3-n)}R_nN$, such that n = {2, 3} and $R_1 \neq R_2 \neq R_3$], it is possible to impart stereogenicity to the resultant amine-borane and perform an enantioselective reduction (Figure 1). [10d, 34] Similarly, chiral molecules possessing an amine functional group can be boranated and converted to chiral reducing agents. [7, 35] Between those two categories of chiral amine-borane reducing agents, it could be argued that the most infamous example is the Corey-Itsuno, or Corey-Bakshi-Shibata (CBS), reduction. The reaction development was first begun by Itsuno and coworkers in 1981 by reducing prochiral aromatic ketones with chiral alkoxy-amine-borane complexes. [36] Itsuno et al.'s work was extended by Corey, Bakshi, and Shibata in 1987, whereby Corey et al. demonstrated excellent enantioselectivity for the reduction of ketones using chiral oxazaborolidines (Figure 5). [37]

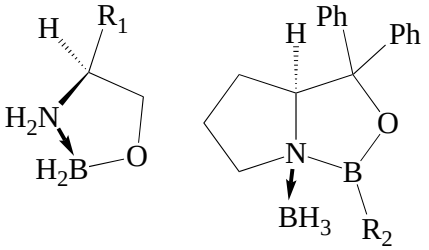
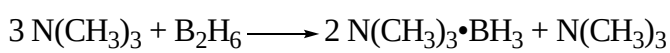


Figure 5. Itsuno's alkoxy-amine-borane (left) & Corey's oxazaborolidine-borane (right)

2. Chronological Syntheses of Amine-Boranes

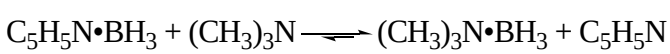
Having provided a cursory overview of amine-boranes and their properties, a chronological history of their most notable preparations can be presented. The emphasis of this timeline is to denote the first report of a particular synthetic style; once these syntheses are initially reported, there are seemingly innumerable accounts wherein most of the methods are employed and occasionally developed further. For clarification, the aim of this chronology is to establish a history of synthetic methods for amine-boranes, of which ammonia-borane is both a prime and unique example. Though some of the following synthetic methods are applicable to the synthesis of AB, not all of the methods can accommodate this parent amine-borane. Likewise, there are synthetic methods for attaining AB that are not amenable to other amine-boranes. As such, the current discussion will not emphasize those preparative methods that are exclusive to AB; there are several reviews that seek to address the vast preparative methods for AB alone. [10j, 33b, 38]

As mentioned earlier, the first report of an amine-borane, trimethylamine-"borine," was contributed by Burg and Schlesinger in 1937 (Scheme 1). [3] Brown later described the diborane-based process for preparing "borine trialkyl amines" in 1958. [39]



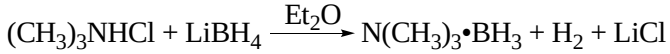
Scheme 1. Synthesis of trimethylamine-borane via diborane & free amine

In 1942, Brown, Schlesinger, and Cardon used the diborane protocol to develop a transamination method for synthesizing amine-boranes, wherein the free amine displaces the amine that is already complexed with borane (Scheme 2). [40] The transamination method was later expounded upon by Baldwin and Washburn in 1961, [41] as well as several others, including the Ramachandran group. [42]



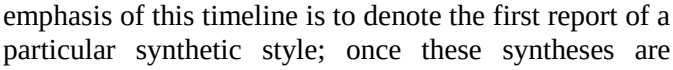
Scheme 2. Synthesis of trimethylamine-borane via transamination

More than a decade passed before another novel synthetic procedure for amine-boranes was presented, when Schaeffer and Anderson prepared trimethylamine-borane via LBH in 1949 (Scheme 3). [43]



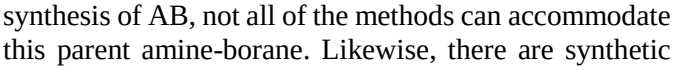
Scheme 3. Synthesis of trimethylamine-borane via LBH & amine•hydrochloride

In 1952, Banus, Gibb, Jr., and Bragdon posited a thermal-decomposition method for making amine-boranes (Scheme 4). [44] The pyrolysis method was further explored by Safronov, Jalisatgi, and Hawthorne in their 2019 patent investigating the decomposition of organoammonium tetrahydroborates. [45]



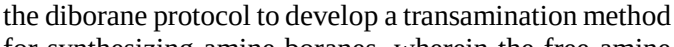
Scheme 4. Synthesis of trimethylamine-borine via tetramethylammonium borohydride

In 1953, Schechter presented a unique synthesis of amine-boranes via electrolysis between an anode and cathode of an ionic borohydride in a non-aqueous solvent like an amine (Scheme 5). [46]



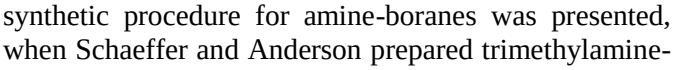
Scheme 5. Synthesis of dimethylamine-borane via electrolysis with Hg cathode and Pt anode

In a similar fashion to Schaeffer and Anderson's LBH preparative method, Taylor, Grant, and Sands synthesized pyridine-borane using SBH with the amine as the solvent in 1955 (Scheme 6). [47] It is likely that previous authors did not report a synthesis of amine-boranes via SBH due to difficulties associated with SBH's preparation, though a suitable preparation had in fact been known for some time. [48] However, due to World War II national security concerns, Schlesinger, Brown, and Finholt were unable to publish their findings. [21b, 21e, 32b, 49] The chemical and patent literature is rife with adjustments and alleged improvements to this particular process. [50]



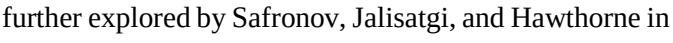
Scheme 6. Synthesis of pyridine-borane via SBH & amine•hydrochloride

Shortly after Taylor, Grant, and Sands's synthesis of pyridine-borane, several patents and publications from both academia and the chemical industry began describing the preparation of amine-boranes. First among these descriptions was from Köster in February 1957, wherein he developed a route to amine-boranes using high pressure hydrogenolysis of trialkylboranes (Scheme 7). [51]



Scheme 7. Synthesis of triethylamine-borane via TEB & free amine

Soon after Köster's work, "Preparation of Amine-Borines" was proposed by Jenkner in March 1957, wherein he prepared various amine-boranes with an emphasis on the addition of boron trichloride to the reaction mixture (Scheme 8); [52] other ensuing patents have extended the scope of Jenkner's work. [53]



Scheme 8. Synthesis of trimethylamine-borine via BCl_3/NaH & free amine

Concluding 1957 as a popular year for amine-borane related patents, Bragdon described a three-step, amine-carbamate-based preparation in August 1957 (Scheme 9). [54]

$$CO_2 + 2\,C_3H_7NH_2 \longrightarrow C_3H_7NHCOOC_3H_7NH_3 \quad (1)$$

$$NaBH_4 + C_3H_7NHCOOC_3H_7NH_3 \longrightarrow C_3H_7NHCOONa + C_3H_7NH_3BH_4 \quad (2)$$

$$C_3H_7NH_3BH_4 \longrightarrow C_3H_7NH_2BH_3 + H_2 \quad (3)$$

Scheme 9. Synthesis of isopropylamine-borane via SBH & an amine-carbamate

Following Jenkner's patent, as a corporate entity, Farbenfabriken Bayer Aktiengesellschaft formulated a British patent for an amine-borane synthetic process in May 1959, wherein the amine-borane is obtained from a tertiary amine salt, an aqueous solution of metal borohydride, and an inert solvent (Scheme 10). [33b, 55] However, Haberland and Stroh filed an identical U.S. patent earlier in 1958 for the same process. [56] Notably, many other patents have followed suit with "similar yet different" acid-mediated proposals. [57]

$$(CH_3CH_2)_3N + KBH_4 + B(OH)_3 + H_2O \longrightarrow (CH_3CH_2)_3N{\bullet}BH_3 + KB(OH)_4 + H_2$$

Scheme 10. Synthesis of triethylamine-borazane via KBH/boric acid & free amine

Later that same year in July 1959, Lang and Schubert patented an amine-borane synthesis using a metal borohydride and a boron trihalide or boron trihalide etherate (Scheme 11). [58] In 1964, Snover extended Lang and Schubert's work through his patent regarding *in-situ* preparation of diborane, subsequent reaction of diborane with a free amine, and isolation of the resultant amine-borane by crystallization from water. [59]

$$4\,(CH_3)_3N + 4\,BF_3{\bullet}O(C_2H_5)_2 + 3\,NaBH_4 \longrightarrow 4\,(CH_3)_3N{\bullet}BH_3 + 4\,(C_2H_5)O + 3\,NaBF_4$$

Scheme 11. Synthesis of trimethylamine-borane via boron trifluoride-diethyletherate & SBH

Following Lang and Schubert's work, Ashby in August 1959 defined a synthetic process for amine-boranes characterized by reacting a fully-esterified aryl ester of an oxyacid of boron with a metal borohydride (Scheme 12). [60]

$$C_{18}H_{15}BO_3 + NaBH_4 + C_6H_5N(CH_3)_2 \xrightarrow{\text{cat. } AlCl_3} C_6H_5N(CH_3)_2{\bullet}BH_3 + NaB(OC_6H_5)_4$$

Scheme 12. Synthesis of dimethyl aniline borane via phenyl borate/SBH & free amine

In February 1960, arguably the most commonly-used method for obtaining amine-boranes was established by Kelly and Edwards, wherein BTHF was used for boranation (Scheme 13). [61] There seems to be agreement that this is the first reported use of BTHF as a boranating agent for amines; [33b] this assertion also agrees with the timeline of chemical history since THF was not commercially available until 1956, [62] so applications involving BTHF as a -BH_3 carrier would understandably follow shortly thereafter.

$$(CH_2NH_2)_2 + 2\,C_4H_8O{:}BH_3 \longrightarrow (CH_2NH_2BH_3)_2 + 2\,C_4H_8O$$

Scheme 13. Synthesis of ethane 1,2-diamineborane via BTHF

After Kelly and Edwards' notable procedure, Marshall prepared amine-boranes via a dialkoxyborane and the free amine in March 1960 (Scheme 14). [63]

$$3\,BH(OCH_3)_2 + C_5H_5N \xrightarrow{B(OCH_3)_3} C_5H_5N{\bullet}BH_3 + B(OCH_3)_3$$

Scheme 14. Synthesis of pyridine-borane via dimethoxyborane & free amine

In 1962, Ashby and Foster proposed "A New and Convenient Route to the Amine-Boranes" (Scheme 15). [64] Their protocol uses a borate ester with an amine solvent to obtain the amine-borane.

$$B(OC_6H_5)_3 + Al + 3/2\,H_2 \xrightarrow{N(CH_2CH_3)_3} N(CH_2CH_3)_3{\bullet}BH_3 + Al(OC_6H_5)_3$$

Scheme 15. Synthesis of triethylamine-borane via borate ester & free amine as solvent

Following Ashby and Foster's synthesis, Matsumara and Tokura in 1968 published a "superior" preparation using liquid SO_2, with the superiority purportedly owing to the weakly acidic nature of SO_2 relative to other previously used acids. [65] However, the authors fail to fully characterize the reaction, referring to the products as the desired amine-borane and an unidentified "inorganic product," presumed to be sodium sulfoxylate (Scheme 16).

$$(CH_3CH_2)_3N + NaBH_4 \xrightarrow{\text{liq. } SO_2} (CH_3CH_2)_3N{\bullet}BH_3 + \text{inorganic product}$$

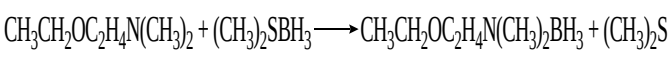
Scheme 16. Synthesis of triethylamine-borane via liquid SO_2/SBH & free amine

Later that decade in 1969, Nainan and Ryschkewitsch put forth an amine-borane synthetic procedure involving iodine for the generation of diborane from SBH (Scheme 17). [66]

$$2\,NaBH_4 + 2\,(CH_3)_2NH + I_2 \longrightarrow 2\,NaI + 2\,(CH_3)_2NH{\bullet}BH_3 + H_2$$

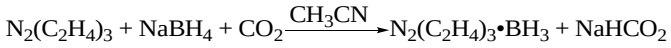
Scheme 17. Synthesis of dimethylamine-borane via SBH/iodine & free amine

Rivalling BTHF as another popular agent for boranation of amines, BDMS appears to have first been used in a similar manner by Burke and Hough in 1976 as part of their patent, "Water Soluble Tertiary Amine Boranes (Scheme 18)." [33b, 67]



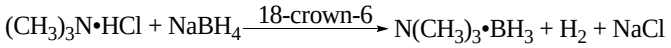
Scheme 18. Synthesis of 2-ethoxy-*N*,*N*-dimethylethan-1-amine-borane via BDMS & free amine

In 1984, a Czech patent was prepared by Plesek, Stibr, Drdakova, and Jelinek that describes a method similar to Matsumara and Tokura's method, wherein CO_2 acts as a Lewis acid for the amine-borane formation (Scheme 19). [68] In 1991, Arduengo developed a method similar to the Czech patent, though Arduengo sought to avoid the water-washing step. [33b, 69] Later authors (Cao et al., 2012) suggest that the inorganic product is Na_2CO_3 as opposed to $NaHCO_2$, and that $H_{2(g)}$ is in fact a product of the reaction. [70]



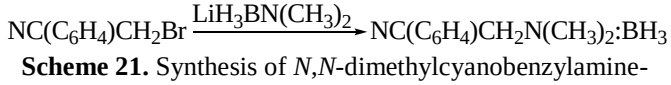
Scheme 19. Synthesis of 1,4-diazabicyclo[2.2.2]octane-monoborane via SBH/CO_2

As a unique example, Kampel and Warshawsky in 1994 published an 18-crown-6-mediated synthesis of various amine-boranes in ether (Scheme 20). [71]



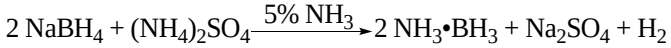
Scheme 20. Synthesis of trimethylamine-borane via 18-crown-6 & amine•hydrochloride

Following Kampel and Warshawsky's work, in 1999, Collins, Lanz, Goralski, and Singaram formulated a lithium *N*,*N*-dialkylaminoborohydride-mediated route towards amine-boranes (Scheme 21). [72]

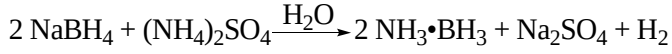


Scheme 21. Synthesis of *N*,*N*-dimethylcyanobenzylamine-borane via lithium aminoborohydride

There are also several examples of amine-borane synthetic procedures developed in the Brown Center for Borane Research. The first of these described by Ramachandran and Gagare in 2007 focused exclusively on high-purity (>98%) AB synthesis (Scheme 22) by fine-tuning a metathesis procedure developed by Geanangel in 1977. [38, 73] The concentration of the reaction medium was critical in obtaining high-purity AB. This method was further modified by the same group for a large-scale preparation of AB involving ammonia as an additive. [74] Ramachandran and Kulkarni then described that the role of ammonia is that of a reagent (Scheme 22). [75] Water can also be used as a promoting additive, as described by them in 2017 (Scheme 23). [76]

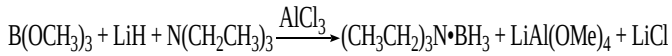


Scheme 22. Ammonia-promoted synthesis of ammonia borane



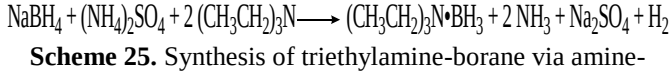
Scheme 23. Water-promoted synthesis of ammonia-borane

In 2012, Ramachandran, Raju, and Gagare proposed a one-pot preparation of AB and several trialkylamine-boranes from trimethyl borate, LiH, and $AlCl_3$ in the presence of the desired amine (Scheme 24). [77]



Scheme 24. Synthesis of triethylamine-borane via $B(OMe)_3$/LiH/$AlCl_3$ and free amine

In 2015, the salt metathesis method was expanded to include other amine-boranes aside from AB (Scheme 25). [78]



Scheme 25. Synthesis of triethylamine-borane via amine-ammonium salt equilibration

Lastly, in 2016, a bicarbonate-mediated process was optimized and developed that accommodates amines of varying degrees as well as functionalized amines (Scheme 1.24). [76]

Scheme 26. Synthesis of 1-propanamine-borane via SBH/$NaHCO_3$ & free amine

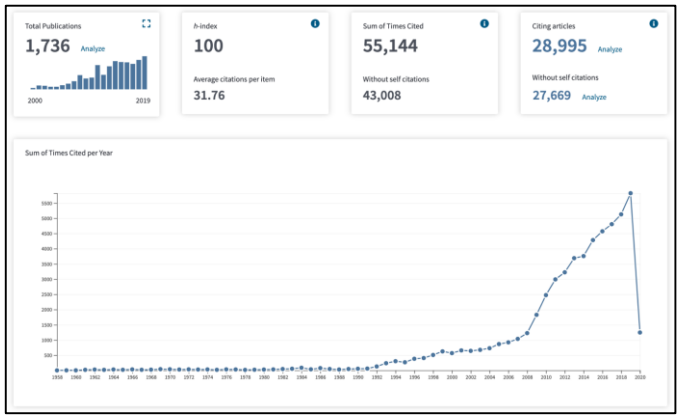


Figure 6. Web of Science™ citation report with "amine-boranes" as the Topic from 1937-2020 (per 19-May-2020)

3. Conclusion

Simply by looking at the numerous synthetic strategies, it is evident that amine-boranes have maintained their relevance since their discovery. However, a quick Web of Science™ search using the "Topic" "amine-boranes" reveals an exponentially growing interest in these salient compounds (Figure 6). In light of the renewed attention received by amine-boranes and their plentiful applications, it is imperative that new methods are

optimized and developed to allow access to as many forms of these compounds as possible.

Acknowledgements

Nil.

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