

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/120145/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Jayaraman, Arumugam, Powell-Davies, Henry and Fontaine, Frédéric-Georges 2019. Revisiting the reduction of indoles by hydroboranes: A combined experimental and computational study. *Tetrahedron* 75 (14) , pp. 2118-2127. 10.1016/j.tet.2019.02.048

Publishers page: <http://dx.doi.org/10.1016/j.tet.2019.02.048>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

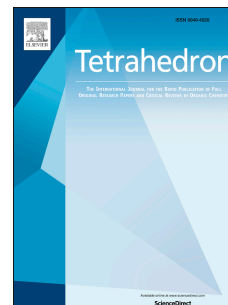
This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Accepted Manuscript

Revisiting the reduction of indoles by hydroboranes: A combined experimental and computational study

Arumugam Jayaraman, Henry Powell-Davies, Frédéric-Georges Fontaine



PII: S0040-4020(19)30208-X

DOI: <https://doi.org/10.1016/j.tet.2019.02.048>

Reference: TET 30171

To appear in: *Tetrahedron*

Received Date: 14 December 2018

Revised Date: 14 February 2019

Accepted Date: 22 February 2019

Please cite this article as: Jayaraman A, Powell-Davies H, Fontaine Frédéric-Georges, Revisiting the reduction of indoles by hydroboranes: A combined experimental and computational study, *Tetrahedron* (2019), doi: <https://doi.org/10.1016/j.tet.2019.02.048>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Revisiting the Reduction of Indoles by Hydroboranes: A Combined Experimental and Computational Study

Arumugam Jayaraman,[†] Henry Powell-Davies^δ and Frédéric-Georges Fontaine*^{†‡}

[†] Département de Chimie, Université Laval, 1045 Avenue de la Médecine, Québec City, Québec G1V 0A6, Canada

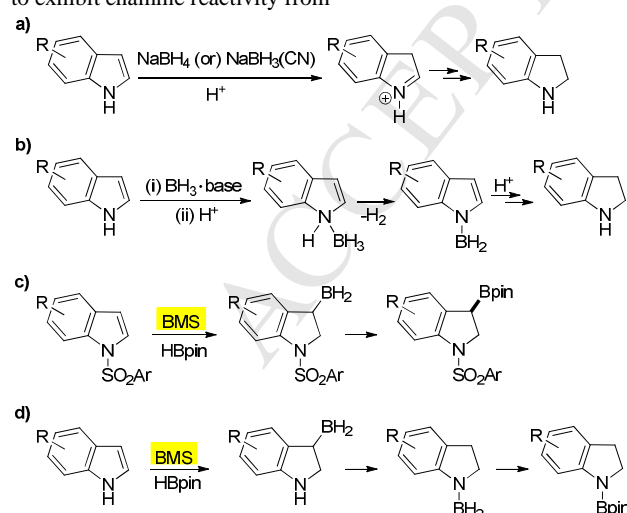
^δ School of Chemistry, Cardiff University, Cardiff, Cymru/Wales, UK

[‡] Canada Research Chair in Green Catalysis and Metal-Free Processes

ABSTRACT: A combined experimental and density functional computational study was used to probe the mechanism for the reduction of indoles using simple borane $\text{BH}_3\cdot\text{DMS}$ (DMS = dimethyl sulfide). Experimental and computational studies all steer to the formation of the reduced species 1- BH_2 -indolines as the resting state for this reaction, as opposed to the historically presumed formation of the unreduced 1- BH_2 -indoles, before the addition of a proton source to form the final product indolines. Furthermore, it was observed that molecular H_2 was generated and consumed in the reaction. Computations put forward hydroboration followed by protodeborylation as the very reasonable mechanistic route for the formation of experimentally observed major intermediate 1- BH_2 indolines. For the H_2 consumption in the reaction, computations suggest the frustrated Lewis pair-type heterolytic splitting of H_2 by a bis(3-indolyl)borane intermediate.

INTRODUCTION

The reduction of *N*-H indoles to indolines has been an ubiquitous reaction within the organic chemistry community and can be done using either transition metal catalysis¹ or simple stoichiometric reduction using hydroboranes.² For the latter, borohydrides such as NaBH_4 , $\text{NaBH}_3(\text{CN})$ or boranes, mostly on the form $\text{BH}_3\cdot\text{Lewis base}$, were employed along with a proton source. Reduction of indoles using borohydrides in the presence of a proton source was commonly presumed to proceed via an indolenium ion, by protonation of an indole substrate, followed by the addition of a hydride, leading to the desired indoline (Scheme 1a).^{2a-c} The same reaction using boranes, either B_2H_6 or BH_3 base, was postulated to proceed via the 1- BH_2 -indole intermediate, formed through dehydrogenative coupling of an initial B-N complex ($\text{BH}_3\cdot\text{indole}$) (Scheme 1b).^{2e} This intermediate subsequently abstracts a proton and a hydride in sequence to form the final indoline. While the latter mechanism for the reduction of indoles using boranes seems reasonable, indoles were generally regarded to exhibit enamine reactivity from

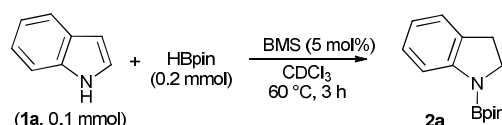


Scheme 1. Previously established mechanistic pathways (a-c) for reaction of protected and unprotected indoles with hydroboranes, and this current work (d) of a proposed reaction pathway for the reduction of indoles using hydroboranes. BMS = trihydridoborane dimethylsulfide complex.

the heterocyclic chemistry perspective.³ Hydroboration of enamines using boranes, leading to vicinal aminoboranes, at ambient and low temperature is well documented.⁴ Our recent exploration of the reactivity of ambiphilic aminoboranes and simple hydroboranes toward *N*-protected indoles⁵ revealed that hydroboration of indoles takes place when an electron withdrawing group (EWG) is present at the *N*-position, leading to formation of air and moisture-sensitive 3-boryl indoline intermediates (Scheme 1c). These unstable intermediates were trapped using HBpin, which led to stable 3-Bpin indolines. Recent studies on the reactivity of boranes without any hydride substituent toward *N*-protected indoles and enamines also showed compelling evidences for a strong interaction between boranes and the C3 of indoles and enamines.⁶ With this fresh understanding on the reactivity of protected indoles with a variety of boranes and the availability of new trapping techniques and modern instrumentations, we report herein our exploration of the reactivity of unprotected indoles with catalytic and stoichiometric amount of simple hydroboranes (Scheme 1d), and the various mechanistic possibilities for this deep-rooted reduction reaction.

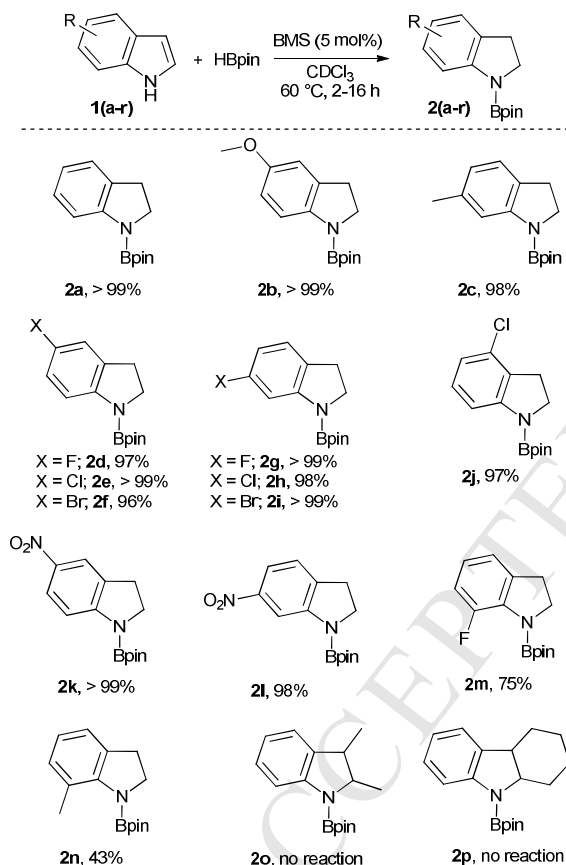
RESULTS AND DISCUSSION

Catalytic reactions. In analogy to our previous report on the BH_3 -catalyzed borylative dearomatization of 1-arylsulfonyl indoles,⁷ we looked at the effect of a catalytic quantity of borane dimethyl sulfide complex (BMS, 5 mol%) in presence of the unprotected parent indole and 2 equiv of pinacolborane (HBpin). When the reaction was carried out under strict water-free conditions either at room temperature (RT) for 16 h or at 60 °C for 3 h, 1-Bpin indoline (**2a**) was observed along with ~1 equiv of unreacted HBpin (Scheme 2). This result is surprising since the expected 1,3-diboryl indoline, which should form by the tandem BH_3 -catalyzed hydroboration of the alkene part of the pyrrole ring and dehydrogenative N-B coupling, was not observed.



Scheme 2. Reduction of indole using HBpin in the presence of catalytic BMS. BMS = trihydridoborane dimethylsulfide complex.

The reduction of the aromatic C(2)-C(3) moiety to two chemically inequivalent methylene units in product **2a** was apparent from NMR spectroscopy, where the ^1H NMR spectrum showed two triplets at δ 3.06 and 3.78 and the ^{13}C (APT) spectrum unambiguously showed two negative phase signals at δ 29.6 and 47.1. ^{11}B NMR spectroscopy and mass spectrometry also confirm the identity of **2a**. Other unprotected indoles that bear synthetically useful functionalities on the benzene ring, as shown in Scheme 3, provided similar results. Substrates such as 7-fluoro indole (**1m**) and 7-methyl indole (**1n**), however, led only to a moderate conversion, and no catalytic reaction was observed with 2,3-dimethyl indole (**1o**) and 1,2,3,4-tetrahydrocarbazole (**1p**).⁸ While most of the 1-Bpin indoline products were formed quantitatively, their purification by means of crystallization or column chromatography was not possible because of their facile hydrolysis, leading to the formation of indoline derivatives. Formation of 1-Bpin indoline derivatives is also viable through dehydrogenative coupling between unprotected indolines and HBpin in the presence of catalytic amount of BMS.⁹ Albeit, the use of indoles to form such products can be ideal in the perception of atom economy, as this synthetic route accumulates no by-product.



Scheme 3. Reduction of various indoles using HBpin and catalytic BMS, with conversions obtained from ^1H NMR (referenced from corresponding unreacted indole derivative) spectroscopy.

Stoichiometric reactions. To gain some mechanistic insight into how this catalytic reaction occurs, indole was treated with different molar ratios of BMS at different temperatures and reaction time in J. Young NMR tubes. The reaction conditions and results of these reactions are displayed in Table 1. With 1 equiv of BMS, the indole substrate disappeared completely after one hour at RT. Nevertheless, the reaction was incomplete as the ^1H and ^{11}B NMR spectroscopy reveal that a substantial amount of unreacted BMS was present in addition to the indoline- BH_3 complex (**3a**), molec-

ular H_2 , 1- BH_2 indoline (presumably in its dimeric form **4a**), and diindolyl borane **5a** (entry 1).

Table 1. Outcomes of the reaction of indole with few different equivalents of BMS at different temperature.

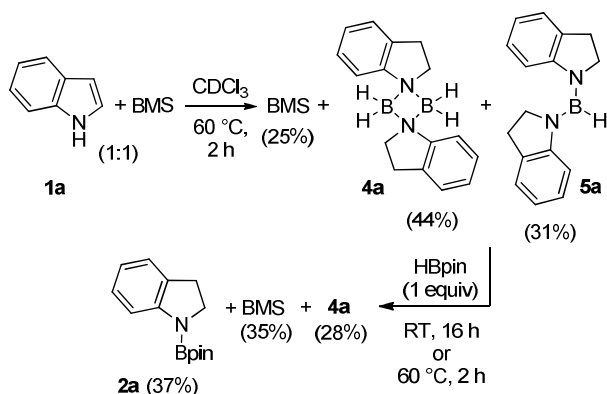
entry	1a:BMS	x (°C)	y (h)	BMS (%) ^a	3a (%) ^a	4a (%) ^a	5a (%) ^a
1 ^c	1:1	RT	1	45	8,5	12 ^b	28
2	1:1	60	2	25	0	44 ^b	31
3	1:2	60	2	19	0	76 ^b	5
4	1:0.5	60	2	0	0	6 ^b	94

^a The percentage is based on ^{11}B NMR integration. ^b The percentage mentioned is for the amount of boron atoms and is based on monomeric species (**4a'**) instead of the dimeric species **4a**, which would be half. ^c Based on the ^1H NMR integration, some amount of H_2 is present in solution.

Heating the same solution to $60\text{ }^\circ\text{C}$ for 2 h resulted in a decrease of the proportion of BMS, complete disappearance of the indoline- BH_3 complex (**3a**) and molecular H_2 , and appearance of species **4a** in major proportion and species **5a** in a significant proportion (entry 2).¹⁰ With 2 equivalents of BMS at $60\text{ }^\circ\text{C}$ after 2 h, species **4a** was observed as the major species (entry 3). On the other hand, under the same reaction conditions but with 0.5 equivalent of BMS, the formation of species **5a** was observed in majority (entry 4). Since indoline- BH_3 complex (**3a**) is only observed at room temperature, it becomes obvious that it is an intermediate that transforms to the more stable 1- BH_2 indoline (**4a**). Furthermore, comparison of the last two reactions (entries 3 and 4) with entry 2 suggests that disproportionation can take place where species **4a** can form **5a** with a concomitant release of BMS. The extent of the disproportionation depends on the stoichiometry of BMS used in the reaction. This relation is important when looking at the catalytic transformations in Scheme 3 since a 20:1 ratio of indole to BMS should favor the presence of analogues of **5a** rather than species **4a**. In all cases, we did not observe any evidence of the presence of species 1- BH_2 -indole, although we cannot definitely confirm that it cannot exist in undetectable concentrations.

Next, in an attempt to understand the generation of 1-Bpin indoline (**2a**), a stoichiometric amount of HBpin was added to the mixture of 1- BH_2 indoline (**4a**) and diaminoborane (**5a**) arising from the 1:1 reaction between indole and BMS. This reaction resulted in complete disappearance of the diaminoborane species **5a** and appearance of product **2a** at RT after 16 h (Scheme 4). Surprisingly, only a small portion of major species **4a** was consumed, even at elevated temperature ($60\text{ }^\circ\text{C}$). Interestingly, it suggests that higher yields of **2** are expected under catalytic conditions where a deficiency of BMS will be present relative to the parent indoles.

Revisiting the mechanism of indole reduction using BH_3 solvates. Reduction of unprotected indoles to indolines using a stoichiometric amount of $\text{BH}_3\cdot\text{THF}$ and the mechanistic details of this reaction have been studied half a century ago by Schmidt et al.^{2g} In their study, formation of the species 1- BH_2 indole was postulated as the resting state (Scheme 1b). Furthermore, it was reported that the establishment of this resting state accompanies a stoichiometric amount of H_2 liberation. Lastly, to obtain the final indoline product a prerequisite for a



Scheme 4. Reaction sequence for the transformation of indole to 1-Bpin indoline using stoichiometric BMS and HBpin.

stoichiometric amount of a proton source, such as methanol, which involves in protonation of the 1-BH₂ indole intermediates, was mentioned. While their mechanistic proposal seems logical, our experimental observations as mentioned in the previous section for the reaction between indole and BMS evidently diverges from their mechanistic proposal. Some of our experimental inferences include formation of the reduced species 1-BH₂ indoline (**4a**) without addition of any external proton source and generation of minor amount of H₂ in the reaction.

Due to the disparity between the previous and current experimental outcomes from the reaction of indole with simple hydroboranes, a further mechanistic scrutiny for this reaction is warranted. For this purpose, DFT computations at the ω B97XD/6-31g(d,p) level of theory were performed and are discussed in the following sections.

Computed dehydrogenative coupling route vs hydroboration route. Computations were first aimed at comprehending if the dehydrogenative N-borylation of indoles occurs first, as proposed by Schmidt and coworkers.^{2g} In line with their proposal, the formation of 1-boryl indole intermediate (**I2**) and H₂ from indole and BMS is thermodynamically favorable ($\Delta G = -14.6$ kcal/mol; Figure 1, red and green lines). However, in contrast to their hypothesis, the formation of initial N-B complex (**I1**) from indole and BMS is less favored as this step is endergonic by 9.1 kcal/mol. Moreover, formation of the postulated species 1-BH₂ indole (**I2**) and H₂ from reactants via a direct dehydrogenative coupling transition state (**TS(1-2)**, green line), as proposed by Bertrand *et al.* for the dehydrocoupling of primary and secondary amines with HBpin,¹¹ is kinetically inept as the ΔG^\ddagger is 30.7 kcal/mol. This barrier is too high to support the experimental reactivity at RT or 60 °C. Alternatively, the BH₃-assisted dehydrocoupling transition state (**TS(1-2)'**, red line), as evidenced previously by Shore *et al.* for the dehydrogenative coupling of amine-boranes,¹² is kinetically favorable compared to the previous route, as the transition state holds a barrier of 26.3 kcal/mol. Nevertheless, both processes are significantly higher in energy compared to the hydroboration of indole, which has a transition state (TS) barrier of 19.6 kcal/mol. As expected, the *syn* addition of H and BH₂ groups at C2 and C3 position, respectively, is kinetically more favored over the addition of boron at the C2 position ($\Delta G^\ddagger = 23.0$ kcal/mol).

Pathways for the formation of 1-BH₂ indoline (4a**) from 3-BH₂ indoline intermediate (**I4**).** As the hydroboration route seems favored, we explored next the possible pathways to generate 1-BH₂ indoline intermediate (**4a**) from the 3-BH₂ indoline

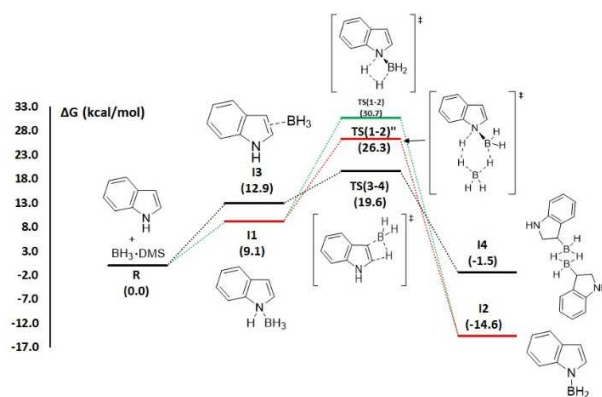
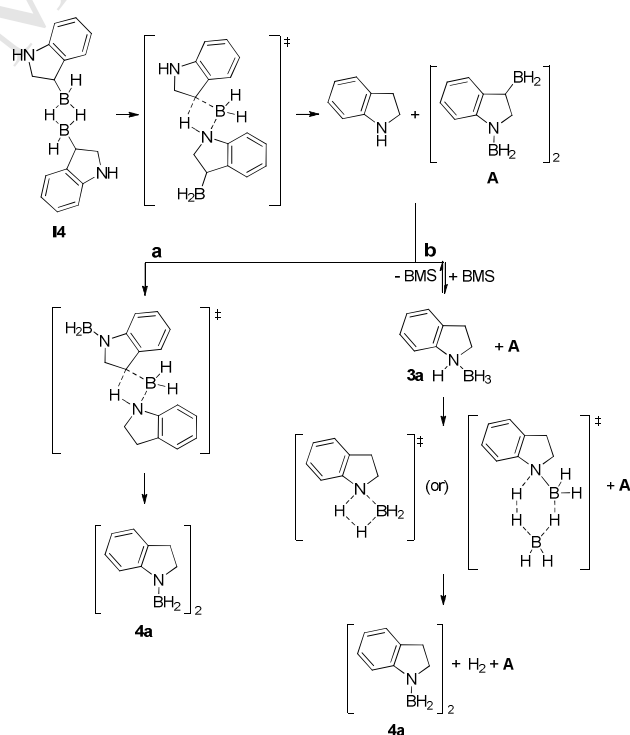


Figure 1. Computed dehydrogenative coupling routes (green and red lines) for formation of 1-BH₂ indole, and the hydroboration route (black line) to furnish 3-BH₂ indoline intermediate.

intermediate (**I4**). For this purpose, it was first considered for species **I4** to undergo a bimolecular protodeborylation process, leading to formation of indoline and 1,3-di-BH₂ indoline (**A**; Scheme 5, first step). As we have initially observed the species indoline-BH₃ complex (**3a**) from the stoichiometric reaction conducted at RT (see Table 1, entry 1), we next supposed that Lewis basic indoline can coordinate with the unreacted BMS to form **3a**. From this species, two pathways were conceived for the formation of the observed 1-BH₂ indoline (**4a**). In the first pathway, species **3a** reverses back to give indoline, which in turn reacts with 1,3-di-BH₂ indoline (**A**) through a protodeborylation transition state to afford only species **4a** (Scheme 5, pathway a). In the second pathway, the indoline-BH₃ complex **3a** undergoes either direct or BH₃-assisted dehydrogenative coupling to furnish **2a** along with equimolar amount of H₂ (Scheme 5, pathway b).



Scheme 5. Conceived pathways for the formation of 1-BH₂ indoline (**4a**) from 3-BH₂ indoline intermediate (**I4**). Pathway a involves protodeborylation, and pathway b entails BH₃ complexation followed by dehydrocoupling.

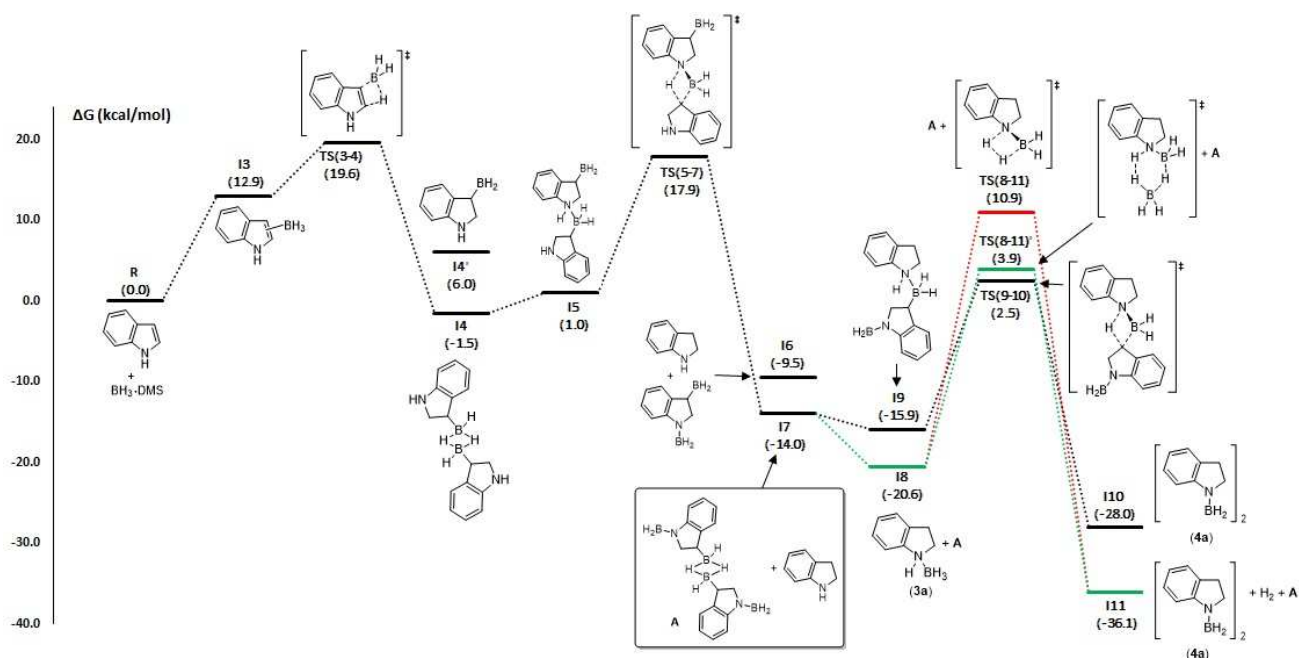


Figure 2. Computed different mechanistic pathways for the formation of resting state **4a** using the hydroborated intermediate **I4**.

From the analysis of the computed free energy profile for these two pathways (Figure 2), the pathway a (black line) that involves protodeborylation is slightly favored over pathway b (red and green lines) that encompasses the dehydrogenative coupling processes. For pathway a, the protodeborylation step from indole-BH₃ complex (**3a**) was rate limiting ($\Delta G^\ddagger = 23.1$ kcal/mol, step **I8** to **TS(9-10)**). For pathway b, the BH₃-assisted dehydrocoupling step from species **3a** was rate limiting ($\Delta G^\ddagger = 24.5$ kcal/mol, step **I8** to **TS(8-11)**). Since the rate limiting barriers of both pathways are only 1.4 kcal/mol apart from each other, the BH₃-assisted dehydrocoupling route of pathway b should be considered as kinetically competitive to pathway a. This phenomenon clarifies how a minor amount of H₂ was generated from the reaction of indole with BMS. The facile hydroboration of indole by BMS, and the succeeding deborylation processes of the formed 3-BH₂ indoline intermediate to furnish the observed 1-BH₂ indoline species (**4a**) clearly demonstrates that no external proton source is needed for the reduction of indole. The N-H functionality of indoline or 3-BH₂ indoline serves as an internal proton source. Experiments carried out using 1-D indole also support this view, as the deuterium atom was transferred exclusively to the C3 of 1-BH₂ indoline product (see Figure S7 in the Supplementary Material).

Pathways for formation of 1-BH₂ indoline (4a**) via the 3H-indole-BH₃ complex (**6a**).** As another possible pathway for the formation of 1-BH₂ indoline (**4a**) from indole and BMS, a tautomeric switch of indole from its 1H form to 3H form, followed by coordination of it to BH₃ of BMS, and subsequent rearrangements to the desired **4a** was considered (Scheme 6). Indoles are generally known to exist in two tautomeric forms, 1H and 3H.¹³ The equilibrium is dependent on the nature of the substituents on indoles and the pH of the solution. For example, 2-alkoxy indoles were reported to predominantly exist



Scheme 6. A pathway conceived for the formation of 1-BH₂ indoline (**4a**) from indole and BMS via 3H-indole-BH₃ complex (**6a**).

in their 3H tautomeric form.¹⁴ The spontaneous 1H-to-3H tautomeric switch was also observed for certain indoles under aqueous conditions.¹⁵ To ascertain the extent by which this tautomerism contributes to the formation of the observed species **4a** from the reaction between indole and BMS, the spontaneous equilibrium between the two tautomeric forms of selected indoles were computed. From the results listed in Table 2, only 2-methoxy indole was shown to spontaneously exist in its 3H form (entry 1). For other derivatives, the equilibrium lies far towards their 1H form, although with different endergonic energetics (entries 2-10). Therefore, presumably none of the indoles we examined experimentally may undergo a spontaneous switch to their 3H tautomer.

Table 2. Computed free energy difference (in kcal/mol) between selected 1H-indoles and their 3H-indole tautomers.

entry	substrate	ΔG (kcal/mol)
1	2-methoxy-1H-indole	-1.6
2	1H-indole	8.6
3	5-methoxy-1H-indole	6.1
4	5-fluoro-1H-indole	8.4
5	5-chloro-1H-indole	8.9
6	5-nitro-1H-indole	10.1
7	6-fluoro-1H-indole	8.7
8	6-chloro-1H-indole	9.1
9	6-nitro-1H-indole	10.7
10	4-chloro-1H-indole	8.6

Whereas several 1H-indoles may not undergo spontaneous tautomerization, Resconi and coworkers have demonstrated that in the presence of a strong Lewis acidic borane, B(C₆F₅)₃, various indoles can be converted to 3H-indole-B(C₆F₅)₃ complexes.¹⁶ The computed thermodynamics for the formation of the 3H-indole-B(C₆F₅)₃ complex from 1H-indole and B(C₆F₅)₃ shows that this

step is exergonic by 10.3 kcal/mol. The analogous calculations using boranes, BMS and $\text{BH}_3\cdot\text{THF}$, and 1*H*-indole disclosed that the formation of 3*H*-indole- BH_3 complex (**6a**) is exergonic as well ($\Delta G = -2.7$ and -3.7 kcal/mol, respectively). These results have driven us to continue exploring the mechanistic pathways for the rearrangement of species **6a** to 1- BH_2 indoline (**4a**).

The step going from **6a** to **4a** was exergonic with a ΔG of -25.3 kcal/mol (Figure 3; step **I13** to **I14**). However, the barrier for this step through a direct 1,3-hydride shift from boron to C2 was found higher ($\Delta G^\ddagger = 28.5$ kcal/mol; red line). Interestingly, the BH_3 -assisted transition state lowered the barrier down to 19.6 kcal/mol (black line). Despite the fact that the 1,3-hydride shift step from stage **I13** to **I14** to form the ultimate 1- BH_2 indoline (**4a**) seems feasible both thermodynamically and kinetically, the formation of the 3*H*-indole- BH_3 complex (**6a**) from 1*H*-indole and BMS appears to be less possible. This step through an initial B-N adduct (**I12**) formation followed by the DMS-assisted 1,3-proton shift from nitrogen to C3 appears kinetically inaccessible as it expresses a barrier of 34.8 kcal/mol (the first two mechanistic steps of Figure 3). Hence, if an alternative lower energy pathway exists to reach 3*H*-indole- BH_3 complex (**6a**) from 1*H*-indole and BMS, then this whole mechanistic pathway should be considered as a competing route to the first proposed hydroboration/self protodeborylation route, but none was found in our hands.

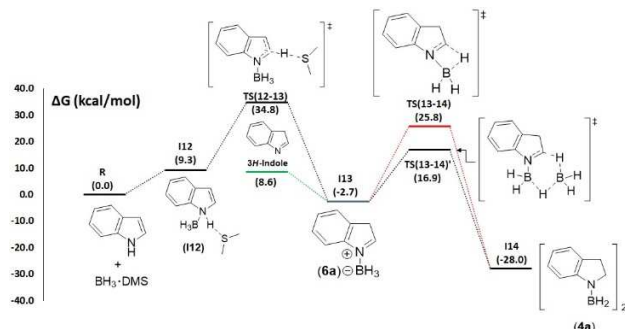
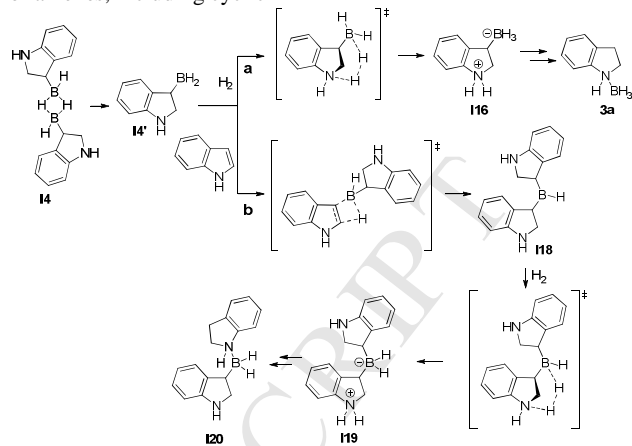


Figure 3. Computed mechanistic pathways for rearrangement of 3*H*-indole- BH_3 complex (**6a**) to 1- BH_2 indoline (**4a**).

Pathways for consumption of H_2 . One important experimental feature of the stoichiometric transformation was the consumption of initially evolved minor dihydrogen towards generation of **4a** and **5a**. For the investigation of mechanistic pathways for H_2 consumption, two pathways were considered (Scheme 7). In the first pathway (pathway a), the monomeric form (**I4'**) of 3- BH_2 indoline intermediate (**I4**) was viewed as an intramolecular vicinal frustrated Lewis pair (FLP), where the Lewis acid is the borane and the Lewis base is the nitrogen of indoline. Frustrated Lewis pairs,¹⁷ both intra- and intermolecular varieties, are widely known to activate the H-H bond of molecular hydrogen.¹⁸ Repo demonstrated that a similar BH_2 containing aminoborane can reversibly activate dihydrogen.^{18c} As a result, the species **I4'** was anticipated to cleave molecular H_2 and afford a zwitterion intermediate (**I16**), which may subsequently transform to the indoline- BH_3 complex (**3a**) through a self protodeborylation process. In the second path-

way (pathway b), the 3- BH_2 indoline intermediate (**I4**) initially hydroborates another indole substrate and forms the secondary borane (**I18**). This thought came from the fact that several examples of di-hydroboration by treating $\text{BH}_3\cdot\text{base}$ with over 2 equiv of alkenes, including cyclic



Scheme 7. Pathways for the consumption of generated H_2 in the reduction reaction. Pathway a involves H_2 cleavage by 3- BH_2 indoline (**I4'**), and pathway b involves H_2 cleavage by the dialkylborane **I20**.

olefins, and 1-arylsulfonyl indoles have been previously reported.¹⁹ In the next step of pathway b, the secondary borane **I18** cleaves H_2 in a similar fashion as that of **I4'** and forms the zwitterion **I19**, which may further transform to the indoline-3- BH_2 indoline complex (**I20**) by a self protodeborylation process. For pathway a, the computed structure of the monomeric 3- BH_2 indoline intermediate (**I4'**) is displayed in Figure 4a. The structure of this species indeed exhibits an important property of intramolecular frustrated Lewis pairs, which is the right orientation of the Lewis acid center to the non-bonding orbital of the Lewis basic center. The distance between the two Lewis centers of this species was found to be 3.073 Å, which is optimal for enabling H-H activation.²⁰ For comparison, its closed form (**I4'**-closed), with a strong B-N interaction ($R_{\text{B-N}} = 1.761$ Å), was optimized (Figure 4b), and found that this species is 10.3 kcal/mol higher in energy than its open form. Our computational attempts to enable H-H activation by species **I4'**-open form disclosed that there are two thermodynamically less favorable steps involved in this process (Figure 5, red line): (i) formation of the σ -complex **I15**, and (ii) formation of

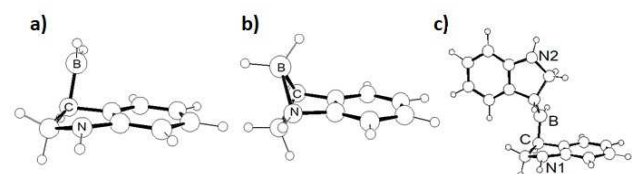


Figure 4. DFT optimized structures of: (a) **I4'**-open, (b) **I4'**-closed, and (c) double hydroborated borane **I18**. Selected distances (Å) and angles ($^\circ$) for: **I4'**-open, B-N = 3.073, B-C-N = 100.96; **I4'**-closed, B-N = 1.761, B-C-N = 53.89; **I18**, B-N1 = 3.186, B-C-N1 = 105.66.

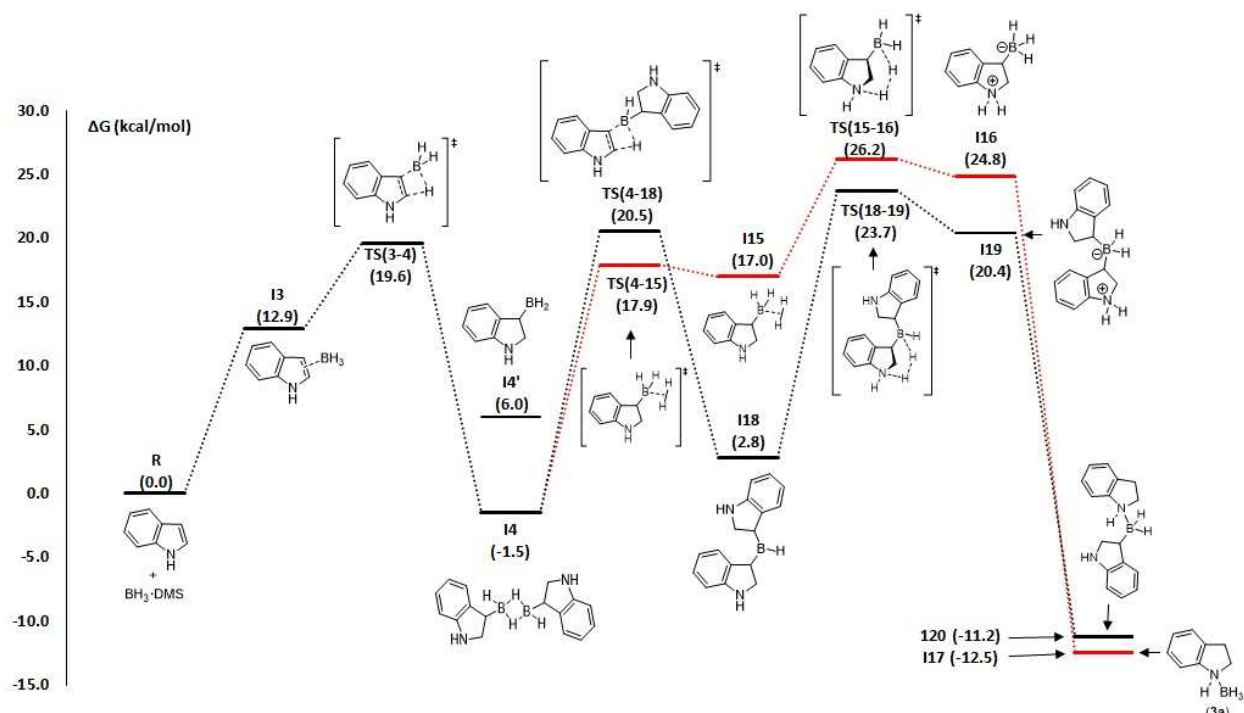
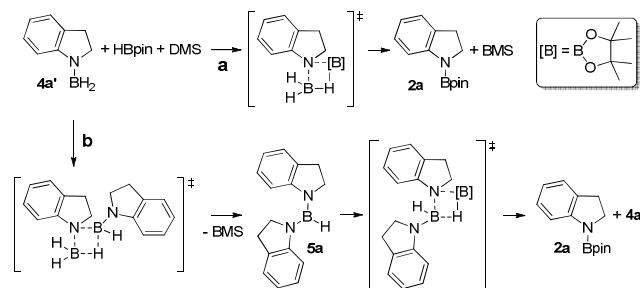


Figure 5. Computed mechanistic pathways for the consumption of generated H_2 by the intermediates of hydroboration of indoles by BMS.

zwitterion **I16** through splitting of H_2 , with an overall TS barrier of 27.7 kcal/mol. Thus, foreseeing intermediate **I4'** as an FLP to split H_2 is less promising. Alternatively, in the second pathway (pathway b), the diindolyl borane intermediate **I18** lies relatively in a favored position at the free energy scale (2.8 kcal/mole), which is only slightly endergonic ($\Delta G = 4.3$ kcal/mol) from the 3- BH_2 indoline intermediate (**I4**). The hydroboration energy barrier for this step to establish species **I18** is also achievable ($\Delta G^\ddagger = 22.0$ kcal/mol) under RT or 60 °C. The optimized structure of species **I18** and its selected structural parameters are shown in Figure 4c. As shown in this structure, this species displays the required orthogonal geometry around the Lewis centers to act as an intramolecular FLP for H_2 splitting. Like that of the 3- BH_2 indoline species **I4'**, the H_2 splitting process using species **I18** is endergonic ($\Delta G = 21.9$ kcal/mol) with respect to the 3- BH_2 indoline intermediate (**I4**) with a barrier of 25.2 kcal/mol. Yet, in comparison of this step to that of **I4'** (pathway a) the H_2 splitting route enabled by species **I18** should be highly considered, especially at 60 °C. Therefore, for the consumption of H_2 in the reaction we postulate the heterolytic splitting of H_2 by **I18**, leading to a zwitterion **I19**, which might undergo the self-bimolecular protodeborylation reaction as shown in pathway b of Scheme 7.

Pathways for the formation of 1-Bpin indoline (2a) from 1- BH_2 indoline (4a). As mentioned above in Scheme 4, the stoichiometric reaction among indole, BMS and HBpin proceeds through intermediates 1- BH_2 indoline (**4a**) and diaminoborane (**5a**) to afford the product 1-Bpin indoline (**2a**). Noteworthy of this stoichiometric reaction is that the intermediate **4a** was only partially consumed while the intermediate **5a** is completely consumed for the formation of product **2a**. To understand the formation of **2a** from species **4a** and HBpin, computations were performed. First, the DFT results suppose that species 1- BH_2 -indoline (**4a'**) is in equilibrium with dimer **4a** that has two dative N-B interactions, forming a four-membered B-N-B-N cycle. The dimeric species **4a** was found to be exergonic by 1.3 kcal/mol, and a barrier of 9.4 kcal/mol is required for the dissociation of **4a** to occur. From **4a'**

two pathways are possible to form 1-Bpin-indoline (**2a**). First, metathesis can occur directly between HBpin and **4a'** (Scheme 8, pathway a). Second, species **4a'** can first disproportionate to observed diaminoborane species **5a**, which will then react with HBpin (Scheme 8, pathway b). Computationally, for the whole first pathway (pathway a) a high barrier was found for the initial metathesis step ($\Delta G^\ddagger = 17.2$ kcal/mol) (Figure 6, red line). This energy barrier is easily attainable at RT or 60 °C. Albeit the reason for the observation of some unreacted species **4a** and HBpin in the stoichiometric reaction is due to the fact that species **4a** and HBpin may exist in equilibrium with 1-Bpin indoline and BMS. This can be inferred from the computed pathway where the starting stage **I21** and the product stage **I8** were found to be nearly equal in energy. For the second pathway (pathway b), computations show that disproportionation is much facile (Figure 6, black line). The high barrier in this pathway was for the metathesis step between diaminoborane (**5a**) and HBpin. Between these two pathways for the transformation of species 1- BH_2 indoline (**4a**) to 1-Bpin indoline (**2a**), pathway b which involves disproportionation followed by metathesis is highly favored.



Scheme 8. Pathways perceived for the transformation of 1- BH_2 indoline to 1-Bpin indoline. Pathway a involves a direct metathesis step, and pathway b entails disproportionation and metathesis steps.

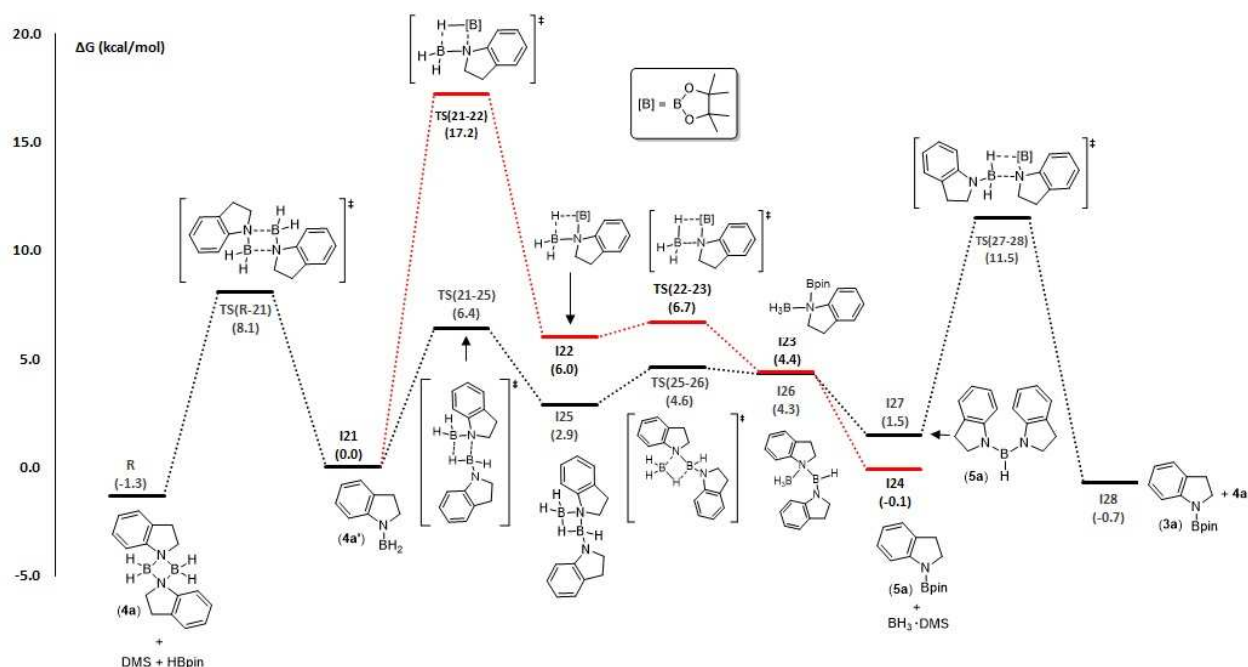


Figure 6. Mechanistic pathways for conversion of 1-BH₂ indoline (**4a**) to 1-Bpin indoline (**2a**) using HBpin and its disproportionation to diamino-borane and BMS.

Overall, based on the experimental and computational insights, the plausible catalytic cycles for the formation of 1-Bpin indolines from indoles, HBpin and the catalyst BMS are presented in Figure 7. Between the two catalytic cycles proposed, cycle B is more favored.

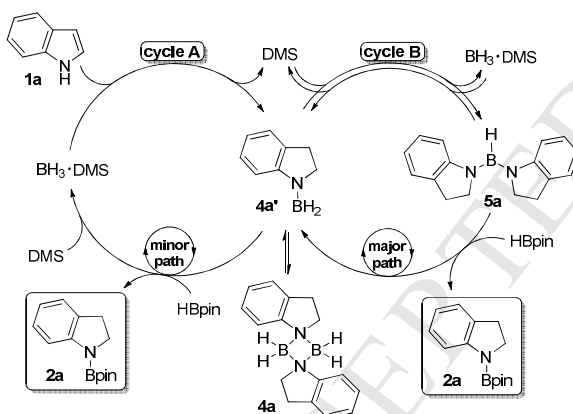


Figure 7. Plausible catalytic cycles for the transformation of 1-BH₂ indoline to 1-Bpin indoline.

Conclusions

According to our experiments on the reaction of indoles with simple hydroboranes of the form BH₃-base, in either stoichiometric or catalytic quantity, the major resting state arose was 1-boryl indoline in an atom economical manner. In addition, only a minor proportion of H₂ was generated through a relatively less competitive side reaction. These insights overturn the earlier mechanistic proposal of generation of stoichiometric amount of H₂ along with the formation of the resting state intermediate 1-boryl indole. Through DFT computations we recognized that indoles likely undergo concerted hydroboration with simple hydroboranes, in a similar fashion to that of the alkenes, alkynes, enamines and enol ethers as previously reported. This step was ensued by double self protodeborylation of the formed hydroborated intermediates, 3-BH₂ indolines, to furnish the experimentally observed resting species 1-BH₂ indolines. A minor proportion

of H₂ generated through a competing side reaction was observed to

be consumed in the reaction. For its consumption, computations suggest the FLP-type heterolytic splitting of H₂ by a dihydroborated borane intermediate. Other computational mechanistic possibilities pursued based on the recent experimental observations from the reaction of unprotected and protected indoles with tertiary boranes can be ruled out for the formation of 1-BH₂ indolines from indoles and simple hydroboranes.

Experimental section

General comments. All procedures were carried out in a glovebox under a nitrogen atmosphere. All unprotected indoles were used as received from commercial suppliers. Dichloromethane, chloroform and CDCl₃ were purified by vacuum-distillation from P₂O₅. C₆D₆ was purified by vacuum distillation from Na/benzophenone. Pinacolborane (HBpin) was freshly prepared from BMS and pinacol in dichloromethane by following a literature procedure.²¹ The prepared HBpin contains residual dichloromethane. The NMR spectra were recorded either on Agilent Technologies NMR spectrometer at 500.00 MHz (¹H), 125.757 MHz (¹³C), 160.46 MHz (¹¹B) and 470.385 MHz (¹⁹F) or on Varian Inova NMR AS400 spectrometer, at 400.0 MHz (¹H), 100.580 MHz (¹³C) and 376.29 MHz (¹⁹F) in CDCl₃ or C₆D₆. Mass Spectrometry analyses were carried out on an Agilent 6210 LC Time of Flight Mass Spectrometer, by means of electrospray ionization (ESI) method.

Catalytic reactions. All catalytic reactions for the formation of 1-Bpin indolines were carried out using either J. Young NMR tubes or sealable 20 mL microwave vials. Indoles in a 0.1 to 0.5 millimole scale was first dissolved in chloroform or CDCl₃ (0.5 – 2 mL), then HBpin (1.0 – 1.3 equiv) and catalytic quantity of BMS (5 mol%) were introduced. This was followed by the tube was quickly sealed. The reaction mixture was subsequently heated at 60 °C for 2 – 3 h. Afterwards, solvent and other volatiles were evaporated in vacuo at RT for 2 h. Our attempts to crystallize the obtained products as residue in the form of either oil or powder led to decomposition under inert atmosphere and hydrolyzes if kept outside in a sealed flask. As a result, isolated yields were not

possible and the obtained products as residue were characterized as soon as they were prepared. For characterization, the residue was dissolved in CDCl₃ for NMR spectroscopy. For mass spectrometry, a fraction (20 μL) of the CDCl₃ solution was taken and diluted with dichloromethane (1 mL).

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2a). Reaction time: 3 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.29 – 7.27 (m, 1H), 7.13 – 7.06 (m, 2H), 6.77 (td, *J* = 7.4, 1.1 Hz, 1H), 3.78 (t, *J* = 8.8 Hz, 2H), 3.06 (t, *J* = 8.8 Hz, 2H), 1.31 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 148.3, 131.4, 127.2, 124.4, 119.5, 112.6, 83.1, 47.0, 29.4, 24.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.8. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₂₀BNO₂ + H⁺: 245.1696; Found: 245.1646.

5-Methoxy-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2b). Reaction time: 3 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.15 (d, *J* = 8.6 Hz, 1H), 6.72 (d, *J* = 2.6 Hz, 1H), 6.63 (dd, *J* = 8.6, 2.7 Hz, 1H), 3.78 (t, *J* = 8.7 Hz, 2H), 3.75 (s, 3H), 3.02 (t, *J* = 8.7 Hz, 2H), 1.29 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 153.7, 142.1, 132.7, 112.6, 112.2, 111.0, 83.1, 55.9, 47.3, 29.9, 24.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.5. HRMS (ESI-TOF) *m/z*: Calcd for C₁₅H₂₂BNO₃ + H⁺: 276.1766; Found: 276.1750.

6-Methyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2c). Reaction time: 3 h. Conversion: 98%. ¹H NMR (500 MHz, CDCl₃): δ 7.09 (s, 1H), 6.98 (d, *J* = 7.5 Hz, 1H), 6.60 – 6.57 (m, 1H), 3.76 (t, *J* = 8.8 Hz, 2H), 3.00 (t, *J* = 8.7 Hz, 2H), 2.31 (s, 3H), 1.31 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 148.4, 137.0, 128.5, 124.0, 120.3, 113.3, 83.1, 47.3, 29.1, 24.7, 21.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.5. HRMS (ESI-TOF) *m/z*: Calcd for C₁₅H₂₂BNO₂ + H⁺: 260.1819; Found: 260.1811.

5-Fluoro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2d). Reaction time: 3 h. Conversion: 97%. ¹H NMR (500 MHz, CDCl₃): δ 7.15 (dd, *J* = 8.6, 4.7 Hz, 1H), 6.83 – 6.79 (m, 1H), 6.78 – 6.72 (m, 1H), 3.78 (t, *J* = 9.0 Hz, 2H), 3.03 (t, *J* = 9.2 Hz, 2H), 1.30 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 157.3 (d, *J* = 236.1 Hz), 144.3, 125.9, 113.1 (d, *J* = 22.9 Hz), 112.6 (d, *J* = 8.1 Hz), 111.6 (d, *J* = 23.8 Hz), 83.1, 47.4, 29.6, 24.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.5. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BFNO₂ + H⁺: 264.1568; Found: 264.1565.

5-Chloro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2e). Reaction time: 3 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.14 (dd, *J* = 8.4, 0.4 Hz, 1H), 7.05 – 6.95 (m, 2H), 3.75 (t, *J* = 9.2 Hz, 2H), 3.01 (t, *J* = 8.8 Hz, 2H), 1.28 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.7. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BClNO₂ + H⁺: 280.1273; Found: 280.1259.

5-Bromo-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2f). Reaction time: 3 h. Conversion: 96%. ¹H NMR (500 MHz, CDCl₃): δ 7.18 – 7.13 (m, 1H), 7.12 – 7.08 (m, 2H), 3.74 (t, *J* = 9.0 Hz, 2H), 3.01 (t, *J* = 8.8 Hz, 2H), 1.28 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.6. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BBrNO₂ + H⁺: 324.0768; Found: 324.0753.

6-Fluoro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2g). Reaction time: 3 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.03 – 6.91 (m, 2H), 6.41 (ddd, *J* = 9.3, 8.1, 2.4 Hz, 1H), 3.78 (d, *J* = 9.1 Hz, 2H), 2.98 (t, *J* = 8.8 Hz, 2H), 1.29 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.8. ¹⁹F NMR (470 MHz, CDCl₃): δ -114.9. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BFNO₂ + H⁺: 264.1568; Found: 264.1561.

6-Chloro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2h). Reaction time: 3 h. Conversion: 98%. ¹H NMR (500 MHz,

CDCl₃): δ 7.21 (s, 1H), 6.96 (d, *J* = 7.0 Hz, 1H), 6.69 (d, *J* = 7.8 Hz, 1H), 3.77 (t, *J* = 8.8 Hz, 2H), 2.99 (t, *J* = 8.8 Hz, 2H), 1.29 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.6. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BClNO₂ + H⁺: 280.1273; Found: 280.1257.

6-Bromo-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2i). Reaction time: 3 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.36 (d, *J* = 1.8 Hz, 1H), 6.92 (d, *J* = 7.8 Hz, 1H), 6.85 (dd, *J* = 7.8, 1.8 Hz, 1H), 3.76 (t, *J* = 8.8 Hz, 2H), 2.97 (t, *J* = 8.8 Hz, 2H), 1.29 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.6. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BBrNO₂ + H⁺: 324.0768; Found: 324.0752.

4-Chloro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2j). Reaction time: 3 h. Conversion: 97%. ¹H NMR (500 MHz, CDCl₃): δ 7.14 (dd, *J* = 8.0, 0.9 Hz, 1H), 7.00 (t, *J* = 8.0, 0.8 Hz, 1H), 6.73 (dd, *J* = 8.0, 0.9 Hz, 1H), 3.80 (t, *J* = 9.2 Hz, 2H), 3.09 (t, *J* = 8.9 Hz, 2H), 1.30 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 149.8, 130.4, 129.8, 128.7, 119.4, 110.7, 83.1, 46.7, 28.9, 24.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.2. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BClNO₂ + H⁺: 280.1273; Found: 280.1251.

5-Nitro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2k). Reaction time: 4 h. Conversion: > 99%. ¹H NMR (500 MHz, CDCl₃): δ 7.99 (d, *J* = 8.9 Hz, 1H), 7.93 (s, 1H), 7.24 (d, *J* = 9.2 Hz, 1H), 3.86 (t, *J* = 8.9 Hz, 2H), 3.10 (t, *J* = 8.9 Hz, 2H), 1.30 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 23.9. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BN₂O₄ + H⁺: 290.1438; Found: 290.1433.

6-Nitro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2l). Reaction time: 6 h. Conversion: 98%. ¹H NMR (500 MHz, CDCl₃): δ 7.97 (d, *J* = 2.2 Hz, 1H), 7.63 (dd, *J* = 8.1, 2.2 Hz, 1H), 7.14 (d, *J* = 8.1 Hz, 1H), 3.85 (t, *J* = 8.9 Hz, 2H), 3.11 (t, *J* = 8.6 Hz, 2H), 1.31 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 149.7, 148.3, 139.2, 124.1, 115.5, 107.2, 83.1, 47.6, 29.2, 24.7. ¹¹B NMR (160 MHz, CDCl₃): δ 23.9. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BN₂O₄ + H⁺: 290.1438; Found: 290.1426.

7-Fluoro-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2m). Reaction time: 16 h. Conversion: 75%. ¹H NMR (500 MHz, CDCl₃): δ 6.90 (dq, *J* = 7.2, 1.1 Hz, 1H), 6.84 (ddd, *J* = 11.0, 8.2, 1.3, 0.8 Hz, 1H), 6.74 (ddd, *J* = 8.2, 7.2, 4.3 Hz, 1H), 3.83 (t, *J* = 8.4 Hz, 2H), 3.01 (t, *J* = 8.4 Hz, 2H), 1.31 (s, 12H). ¹³C NMR (126 MHz, CDCl₃): δ 151.1, 149.1, 136.7, 136.7, 134.4, 134.3, 121.2, 121.1, 119.8, 119.8, 115.2, 115.0, 82.9, 49.7, 30.4, 24.6. ¹¹B NMR (160 MHz, CDCl₃): δ 23.5. ¹⁹F NMR (470 MHz): δ -124.6. HRMS (ESI-TOF) *m/z*: Calcd for C₁₄H₁₉BFNO₂ + H⁺: 264.1568; Found: 264.1559.

7-Methyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)indoline (2n). Reaction time: 16 h. Conversion: 43%. ¹H NMR (500 MHz, CDCl₃): δ 7.05 – 7.02 (m, 1H), 6.96 – 6.83 (m, 1H), 6.72 (m, 1H), 3.60 (t, *J* = 8.4 Hz, 2H), 3.10 (t, *J* = 8.4 Hz, 2H), 2.19 (s, 3H), 1.30 (s, 12H). ¹¹B NMR (160 MHz, CDCl₃): δ 21.2. HRMS (ESI-TOF) *m/z*: Calcd for C₁₅H₂₂BNO₂ + H⁺: 260.1819; Found: 260.1813.

Stoichiometric and sub-stoichiometric reactions. All stoichiometric and sub-stoichiometric reactions were carried out using J. Young NMR tubes in CDCl₃ at various temperatures and reaction hours. For monitoring the reaction between indole and BMS, indole (**1a**, 0.1 mmol, 11.7 mg) and BMS (0.1 mmol, 9.5 μL) dissolved in 0.5 mL CDCl₃ was employed at different temperatures. To understand the equilibrium between 1-BH₂ indoline (**4a**) and diamminoborane (**5a**) from the disproportionation reaction, the ratio between indole and BMS was varied by keeping indole at 0.1 mmol and varying BMS quantity from 0.2 to 0.05 mmol.

Computational details. Geometry optimizations and frequency calculations were performed at the hybrid DFT with dispersion-corrected functional ω B97XD,²² as implemented in the Gaussian 09 (revision C.01) software program.²³ The standard 6-31G(d,p) basis set was used. Transition state (TS) geometries were obtained using opt = (ts, noeigentest, calcf) algorithms.²⁴ Frequency calculations were performed on all optimized structures to verify the nature of the structures and to extract the thermochemistry information. From the frequency calculations we ensured that the TS structures had only one imaginary frequency and that the magnitudes of all frequencies were greater than the residual frequencies that are due to rotations and translations. Additionally, each TS was confirmed to be on the chosen reaction path by performing “plus-and-minus-displacement” minimization calculations where the TS structure was displaced ca. 0.05 Å or 5° on the imaginary frequency normal mode in both directions and subsequently the displaced geometries were optimized to the nearest minima.²⁵ The energies (ΔG) given are corrected for zero-point vibrational energies.

ASSOCIATED CONTENT

Supplementary Material. Computational details, energies and Cartesian coordinates, and NMR spectra of all new compounds from catalytic and stoichiometric reactions.

AUTHOR INFORMATION

Corresponding Author

*E-mail for F.-G.F.: frederic.fontaine@chm.ulaval.ca.

ORCID

Arumugam Jayaraman: 0000-0001-7116-4174

Henry Powell-Davies: 0000-0002-4665-5745

Frédéric-Georges Fontaine: 0000-0003-3385-0258

ACKNOWLEDGMENTS

We gratefully acknowledge National Sciences and Engineering Research Council of Canada (NSERC) and Centre de Catalyse et Chimie Verte (Quebec) for funding, and Compute Canada (CalculQuebec and Graham) for computational resources. F.-G.F. also thanks NSERC for the award of a Canada Research Chair.

REFERENCES AND NOTES

- (a) Fish, R. H.; Tan, J. L.; Thormodsen, A. D., *Organometallics*, **1985**, *4*, 1743-1747; (b) Rosales, M.; Navarro, J.; Sánchez, L.; González, A.; Alvarado, Y.; Rubio, R.; De La Cruz, C.; Rajmankina, T., *Transition Met. Chem.*, **1996**, *21*, 11-15; (c) Kuwano, R.; Sato, K.; Kurokawa, T.; Karube, D.; Ito, Y., *J. Am. Chem. Soc.*, **2000**, *122*, 7614-7615; (d) Bianchini, C.; Meli, A.; Vizza, F., *Eur. J. Inorg. Chem.*, **2000**, *2001*, 43-68; (e) Barbaro, P.; Bianchini, C.; Meli, A.; Moreno, M.; Vizza, F., *Organometallics*, **2002**, *21*, 1430-1437.
- (a) Gribble, G. W.; Lord, P. D.; Skotnicki, J.; Dietz, S. E.; Eaton, J. T.; Johnson, J., *J. Am. Chem. Soc.*, **1974**, *96*, 7812-7814; (b) W. Gribble, G., *Chem. Soc. Rev.*, **1998**, *27*, 395-404; (c) Maryanoff, B. E.; McComsey, D. F., *J. Org. Chem.*, **1978**, *43*, 2733-2735; (d) Biswas, K. M.; Dhara, R.; Roy, S.; Mallik, H., *Tetrahedron*, **1984**, *40*, 4351-4357; (e) Berger, J. G., *Synthesis*, **1974**, *1974*, 508-510; (f) Seyden-Penne, J., *Reductions by the Alumino- and Borohydride in Organic Synthesis*. 2 ed.; Wiley-VCH: New York, 1997; (g) Monti, S. A.; Schmidt III, R. R., *Tetrahedron*, **1971**, *27*, 3331-3339.
- Bandini, M., *Org. Biomol. Chem.*, **2013**, *11*, 5206-5212.
- Fisher, G. B.; Goralski, C. T.; Nicholson, L. W.; Hasha, D. L.; Zakett, D.; Singaram, B., *J. Org. Chem.*, **1995**, *60*, 2026-2034.
- (a) Legare, M. A.; Courtemanche, M. A.; Rochette, E.; Fontaine, F. G., *Science*, **2015**, *349*, 513-516; (b) Légaré-Lavergne, J.; Jayaraman, A.; Misal Castro, L. C.; Rochette, É.; Fontaine, F.-G., *J. Am. Chem. Soc.*, **2017**, *139*, 14714-14723; (c) Jayaraman, A.; Misal Castro, L. C.; Fontaine, F.-G., *Org. Process Res. Dev.*, **2018**, *22*, 1489-1499.
- (a) Focante, F.; Camurati, I.; Nanni, D.; Leardini, R.; Resconi, L., *Organometallics*, **2004**, *23*, 5135-5141; (b) Dureen, M. A.; Brown, C. C.; Stephan, D. W., *Organometallics*, **2010**, *29*, 6422-6432.
- (a) Jayaraman, A.; Misal Castro, L. C.; Desrosiers, V.; Fontaine, F.-G., *Chem. Sci.*, **2018**, *9*, 5057-5063; (b) Ang, N. W. J.; Buettner, C. S.; Docherty, S.; Bismuto, A.; Carney, J. R.; Docherty, J. H.; Cowley, M. J.; Thomas, S. P., *Synthesis*, **2018**, *50*, 803-808.
- In contrast, the stoichiometric reaction between these substrates and BMS led to a complete consumption of the substrate and formation of multiple unidentifiable species.
- The same also works without addition of catalytic amount of BMS, but requires an elevated temperature (80 °C) and a long reaction time (16h).
- The same products can also be obtained at room temperature but requires a long reaction time (~48 h).
- Romero, E. A.; Peltier, J. L.; Jazzar, R.; Bertrand, G., *Chem. Commun.*, **2016**, *52*, 10563-10565.
- Chen, X.; Zhao, J.-C.; Shore, S. G., *J. Am. Chem. Soc.*, **2010**, *132*, 10658-10659.
- Friedrichsen, W.; Traulsen, T.; Elguero, J.; Katritzky, A. R., *Tautomerism of Heterocycles: Five-Membered Rings with One Heteroatom*. In *Advances in Heterocyclic Chemistry*, Katritzky, A. R., Ed. Academic Press: 2000; Vol. 76, pp 85-156.
- Nakagawa, M.; Hino, T., *Tetrahedron*, **1970**, *26*, 4491-4503.
- Gut, I. G.; Wirz, J., *Angew. Chem. Int. Ed.*, **1994**, *33*, 1153-1156.
- Guidotti, S.; Camurati, I.; Focante, F.; Angellini, L.; Moscardi, G.; Resconi, L.; Leardini, R.; Nanni, D.; Mercandelli, P.; Sironi, A.; Beringhelli, T.; Maggioni, D., *J. Org. Chem.*, **2003**, *68*, 5445-5465.
- (a) Fontaine, F.-G.; Stephan, D. W., *Phil. Trans. Royal Soc. A*, **2017**, *375*; (b) Stephan, D. W., *Science*, **2016**, *354*, 6317; (c) Fontaine, F.-G.; Rochette, É., *Acc. Chem. Res.*, **2018**, *51*, 454-464; (d) Stephan, D. W.; Erker, G., *Angew. Chem. Int. Ed.*, **2015**, *54*, 6400-6441; (e) Stephan, D. W., *J. Am. Chem. Soc.*, **2015**, *137*, 10018-10032; (f) Stephan, D. W., *Acc. Chem. Res.*, **2015**, *48*, 306-316; (g) Erker, G.; Stephan, D. W., *Frustrated Lewis Pairs I and II*. Springer: New York, 2013.
- (a) Stephan, D. W.; Erker, G., *Angew. Chem. Int. Ed.*, **2009**, *49*, 46-76; (b) Rokob, T. A.; Hamza, A.; Stirling, A.; Soós, T.; Pápai, I., *Angew. Chem. Int. Ed.*, **2008**, *47*, 2435-2438; (c) Chase, P. A.; Stephan, D. W., *Angew. Chem. Int. Ed.*, **2008**, *47*, 7433-7437; (d) Chernichenko, K.; Nieger, M.; Leskelä, M.; Repo, T., *Dalton Trans.*, **2012**, *41*, 9029-9032; (e) Chernichenko, K.; Kótai, B.; Pápai, I.; Zhivonitko, V.; Nieger, M.; Leskelä, M.; Repo, T., *Angew. Chem. Int. Ed.*, **2014**, *54*, 1749-1753; (f) Courtemanche, M.-A.; Rochette, É.; Légaré, M.-A.; Bi, W.; Fontaine, F.-G., *Dalton Trans.*, **2016**, *45*, 6129-6135.
- (a) Brown, H. C.; Klender, G. J., *Inorg. Chem.*, **1962**, *1*, 204-214; (b) Jayaraman, A.; Desrosiers, V., Unpublished results. Université Laval: 2017.
- (a) Sumerin, V.; Chernichenko, K.; Schulz, F.; Leskelä, M.; Rieger, B.; Repo, T., Amine-Borane Mediated Metal-Free Hydrogen Activation and Catalytic Hydrogenation. In *Frustrated Lewis Pairs I: Uncovering and Understanding*, Erker, G.; Stephan, D. W., Eds. Springer Berlin Heidelberg: Berlin, Heidelberg, 2013; pp 111-155; (b) Schulz, F.; Sumerin, V.; Heikkinen, S.; Pedersen, B.; Wang, C.; Atsumi, M.; Leskelä, M.

- Repo, T.; Pyykkö, P.; Petry, W.; Rieger, B., *J. Am. Chem. Soc.*, **2011**, *133*, 20245-20257.
21. Macé, A.; Touchet, S.; Andres, P.; Cossío, F.; Dorcet, V.; Carreaux, F.; Carboni, B., *Angew. Chem. Int. Ed.*, **2016**, *55*, 1025-1029.
22. Chai, J.-D.; Head-Gordon, M., *Phys. Chem. Chem. Phys.*, **2008**, *10*, 6615-6620.
23. Frisch, M. J. T., G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Petersson, G. A.; Nakatsuji, H.; Li, X.; Caricato, M.; Marenich, A.; Bloino, J.; Janesko, B. G.; Gomperts, R.; Mennucci, B.; Hratchian, H. P.; Ortiz, J. V.; Izmaylov, A. F.; Sonnenberg, J. L.; Williams-Young, D.; Ding, F.; Lipparini, F.; Egidi, F.; Goings, J.; Peng, B.; Petrone, A.; Henderson, T.; Ranasinghe, D.; Zakrzewski, V. G.; Gao, J.; Rega, N.; Zheng, G.; Liang, W.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Throssell, K.; Montgomery, Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Keith, T.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Millam, J. M.; Klene, M.; Adamo, C.; Cammi, R.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Farkas, O.; Foresman, J. B.; and Fox, D. J. *Gaussian*, Gaussian Inc.: Wallingford CT, 2016.
24. (a) Baker, J., *J. Comp. Chem.*, **1986**, *7*, 385-395; (b) Peng, C.; Ayala, P. Y.; Schlegel, H. B.; Frisch, M. J., *J. Comp. Chem.*, **1996**, *17*, 49-56.
25. (a) Jayaraman, A.; East, A. L. L., *J. Org. Chem.*, **2012**, *77*, 351-356; (b) Jayaraman, A.; Berner, G. M.; Mihichuk, L. M.; East, A. L. L., *J. Mol. Catal. A: Chem.*, **2011**, *351*, 143-153; (c) East, A. L. L.; Berner, G. M.; Morcom, A. D.; Mihichuk, L., *J. Chem. Theory Comput.*, **2008**, *4*, 1274-1282.

TOC graphic:

