Multiple metal-bound oligomers from Ir-catalysed dehydropolymerisation of $\text{H}_3\text{B} \cdot \text{NH}_3$ as probed by experiment and computation†

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Multiple metal-bound oligomers in the dehydropolymerisation of $\text{H}_3\text{B} \cdot \text{NH}_3$ have been observed by electrospray-ionisation mass spectrometry and NMR spectroscopy using the catalytic metal fragment $\left[\text{Ir(PCy}_3)_2(\text{H})_2\right]^{-}$. A computational study suggests that stericity dictates whether multiple dehydrogenation/\(\text{B} \cdot \text{N}\) coupling of amine-boranes $\text{H}_3\text{B} \cdot \text{NRR}'\text{H}$ ($R, R' = \text{Me}$ or $\text{H}$) is observed, and also demonstrates the experimentally observed requirement for additional amine-borane to promote dehydrocoupling.

Introduction

The dehydropolymerisation of amine-boranes $\text{H}_3\text{B} \cdot \text{NRH}_2$ ($R = \text{H}, \text{Me}$) is a promising methodology for the synthesis of new $\text{B} \cdot \text{N}$ materials, for example polymeric materials that are isoelectronic with graphitic carbon.1–3 Precursors to $\text{B} \cdot \text{N}$ materials such as white graphene.4 Catalysis of these processes by a transition metal fragment offers potential for control of kinetics and final product distributions, and various systems have been shown to promote dehydropolymerisation.4–12 Non-metal catalysed processes have also been discussed.13,14

The mechanism of catalytic dehydropolymerisation of $\text{H}_3\text{B} \cdot \text{NH}_3$ or $\text{H}_3\text{B} \cdot \text{NMeH}_2$ has been suggested to be based upon dehydrogenation followed by a second metal-mediated coordination polymerisation step.5,6,10,12,15,16 In particular, there is growing evidence to suggest that transient amino-borane ($e.g. \text{H}_2\text{B} \cdot \text{NH}_2$ or $\text{H}_2\text{B} \cdot \text{NMeH}$), that arises from dehydrogenation of the precursor amino-borane, remains associated with the metal.17 If liberated these unsaturated fragments form the corresponding borazine or oligomerisation (Scheme 1), or can be trapped by hydroboration of exogenous cyclohexene – assuming such reactions are faster than polymerisation ($i.e. \text{B} \cdot \text{N}$ bond formation leading to a growing polymer chain). In addition bulky primary amine-boranes, $\text{H}_3\text{B} \cdot \text{N-BuH}_2$,18 or secondary amine-boranes, e.g. $\text{H}_3\text{B} \cdot \text{NMe}_2\text{H}$,19,20 give simple amino-borane products rather than extensive oligomerisation. Adding to the complexity, different metal/ligand combinations likely lead to subtly different mechanisms.6,10,12

Direct mechanistic insight into the dehydropolymerisation process through the observation of intermediates has been sparse. Recently we reported the isolation of the product of the first oligomerisation event in such a process by reaction of $\left[\text{Ir(PCy}_3)_2(\text{H})_2\right]^{-} \text{NMeH}_2\text{BH}_2\text{NMeH}_2\text{BH}_2\text{NMeH}_2$ to form $\left[\text{Ir(PCy}_3)_2(\text{H})_2\right]^{-}\text{NMeH}_2\text{BH}_2\text{NMeH}_2\text{BH}_2\text{NMeH}_2\text{BH}_2\text{NMeH}_2\text{BH}_2\text{NMeH}_2$ (Scheme 2).21 This reaction is slow and does not produce higher oligomers, and a tentative mechanism was suggested to account for this selectivity. With bulkier $\text{H}_3\text{B} \cdot \text{NMe}_2\text{H}$ only dehydrogenation to form the bound amino-borane ($i.e. 4\text{a}*$) is observed.19

We now report that with $\text{H}_3\text{B} \cdot \text{NH}_3$ dehydropolymerisation can also be promoted by 1 and that, in contrast to $\text{H}_3\text{B} \cdot \text{NMeH}_2$, higher oligomeric products bound to the metal centre (6a–e; Scheme 2) can be observed by electrospray ionisation mass spectrometry (ESI-MS) and NMR spectroscopy. ESI-MS provides the ideal analytical platform to study these processes as it allows for the convenient analysis of mixtures of products under inert conditions.22–24 Computational studies10,19,24,27 offer a mechanistic rationale for oligomerisation that explains both the difference in the degree of oligomerisation with increasing steric bulk between the amine-boranes $\text{H}_3\text{B} \cdot \text{NH}_3$, $\text{H}_3\text{B} \cdot \text{NMeH}_2$, $\text{H}_3\text{B} \cdot \text{NMe}_2\text{H}$ and that 5b, (Scheme 2) is observed by ESI-MS.
and H$_3$B-NMe$_2$H and the previously noted requirement for additional amine-borane to promote this process.$^{21}$

**Results and discussion**

Addition of one equivalent of H$_3$B-NH$_3$ to 1$^{19}$ in C$_6$H$_5$F solvent results in the immediate formation of the sigma amine-borane complex [Ir(PCy$_3$)$_2$(H)$_2$(N$^-$H$_3$-BH$_2$)]$^{+}$[BarF$_4$]$^{-}$ 6a in quantitative yield by NMR spectroscopy. There is no onward dehydrogenation after 4 hours under these conditions, but addition of further H$_3$B-NH$_3$ (10 equivalents total) results in the formation of higher oligomers, [Ir(PCy$_3$)$_2$(H)$_2$(N$^-$H$_3$-NH$_3$)]$^{+}$[BarF$_4$]$^{-}$ n = 1–4. This requirement for additional amine-borane to promote dehydrogenation has been noted before in these systems, although its role has only been speculated upon.$^{21}$ Fig. 1 shows the ESI-MS spectra of the reaction of 1 with the amine-boranes H$_3$B-NMe$_2$H$_x$-H$_{1-x}$ (x = 0–3) demonstrating the increasing degrees of dehydrogenation and oligomerisation with decreasing steric bulk of the amine-borane. Under these conditions H$_3$B-NMe$_2$H undergoes dehydrogenation with no subsequent B–N coupling (4a$^*$),$^{19}$ while H$_3$B-NMeH$_2$ gives the product of one dehydrocoupling event (5b).$^{21}$ By contrast for H$_3$B-NH$_3$ metal-bound oligomers arising from up to four of these dehydrocoupling events are observed by ESI-MS (6b–e), which all show excellent fits with calculated isotopomer patterns, with 6d/e (n = 4, 5; Scheme 2) observed as [M–H$^+$]$^+$ cations. In the $^1$H$^{11}$B NMR spectrum of this mixture three distinct pairs of Ir····H–B and Ir–H environments are observed in an approximate 1 : 10 : 10 ratio (see ESI†), which are assigned to 6a, 6b and 6c respectively (vide infra), consistent with the major species observed by ESI-MS (6a–c). The $^{11}$B$^{1}$H NMR spectrum of this mixture shows broad, potentially overlapping, signals in the Ir–H–B and [BH$_3$] regions, and the $^{31}$P$^{1}$H NMR spectrum shows two tightly-coupled AB doublets in approximately equal ratio, the third species (i.e. 6a) being too low in intensity to be observed. The identity of these complexes has been confirmed by the independent synthesis of 6b and 6c from the preformed borazanes H$_3$B-NH$_3$BH$_2$-NH$_3$,$^{28}$ and H$_3$B-(NH$_3$BH$_2$)$_2$-NH$_3$,$^{29}$ respectively. Scheme 3 shows the solid-state structure (as the [BarF$_4$]$^-$ salts$^{30}$ from [Ir(PCy$_3$)$_2$(H)$_2$(N$^-$H$_3$-NH$_3$)]$^{+}$[BarF$_4$]$^{-}$, 2) of 6c, alongside that of 6a, which confirm formation, being closely related to analogous complexes 3a, 4a, 5a and 5b.$^{19,21}$ Over time (24 h) these mixtures of products degrade to give bimetallic products identified by ESI-MS as [[Ir(PCy$_3$)$_2$(H)$_2$][Ir$_2$(NH$_3$BH$_2$)$_2$]]$^{+}$ 7a–d (n = 0 to 3 respectively), presumably in which the anionic amino-boranes [H$_3$B(NH$_3$BH$_2$)$_2$]$^-$ bridge between two cationic metal fragments. Recrystallisation of this mixture afforded small amounts of the borohydride complex$^{11}$ [[Ir(PCy$_3$)$_3$(H)$_2$][Ir$_2$(NH$_3$-H$_3$-BH$_2$)]$^{+}$[BarF$_4$]$^{-}$ 7a (see ESI† for a solid-state structure). We were unable to definitely characterise the other byproducts of this decomposition.

Borazine was also observed during the oligomerisation of H$_3$B-NH$_3$ ($\sim$10%) by $^{11}$B NMR spectroscopy relative to [BarF$_4$]$^-$, which might suggest free amino-borane is formed as a transient intermediate during the reaction.$^{15,18}$ Addition of excess cyclohexene to the reaction did not result in the observation of any hydroboration product, Cy$_3$B=NH$_3$, a trapping reaction that

![Scheme 2](image-url)
has previously been suggested to be indicative of free amino-
borane in dehydrocoupling reactions.\textsuperscript{15} As recently noted, however, this process relies on hydroboration being kinetically competitive with oligomerisation, which might not necessarily be the case.\textsuperscript{16}

Although these data are consistent with a growing oligo-
meric chain at the \{Ir(PCy\textsubscript{3})\textsubscript{2}(H)\textsubscript{2}\}\textsuperscript{+} fragment, similar to those observed by ESI-MS for olefin polymerisation,\textsuperscript{32,33} these observations cannot discount a scenario where metal-catalysed dehydrogenation forms the free amino-borane, H\textsubscript{3}B=NH\textsubscript{3}, which then polymerises off-metal,\textsuperscript{13} with the most soluble short-
chain oligomers then coordinating to the metal fragment. However, as computation suggests (\textit{vide infra}) that the first dehydrogenation has a significantly higher barrier than subsequent oligomerisation we propose that this scenario is less likely. To probe further the oligomerisation process, three sequential additions of 1.1 equivalents of H\textsubscript{3}B-NH\textsubscript{3} to 1 gave progressively longer oligomer chains (\textit{i.e.} 6a–6c) as measured by ESI-MS (see ESI†), although this mixture was biased towards 6a and 6b, suggesting that the sigma-bound oligomeric units, \textit{e.g.} 6b or 6c, are only weakly bound with the metal centre and can be displaced by excess H\textsubscript{3}B-NH\textsubscript{3}. Confirming this, addition of two equivalents of H\textsubscript{3}B-NH\textsubscript{3} to 6c immediately results in a mixture of 6a–c and free H\textsubscript{3}B-(NH\textsubscript{2}BH\textsubscript{2})\textsubscript{2}-NH\textsubscript{3}, with 6c the major observed product. After 4 hours this has developed into a mixture of 6a–e with 6b and 6c the major products. Addition of 2 equivalents of H\textsubscript{3}B-NH\textsubscript{3} to 6d results in the formation of 6b and relatively smaller amounts of 6c–6e (by ESI-MS), the latter presumably derived from further dehydrocoupling events from 6b with H\textsubscript{3}B-NH\textsubscript{3} (Scheme 4). Overall this suggests a mechanism in which the formed sigma-bound oligomer can be displaced by other amine-boranes, \textit{i.e.} reversible chain transfer can occur. At the end of the reaction (24 h) a white solid is recovered that shows an IR spectrum essentially identical to polyaminoborane.\textsuperscript{34} Use of 5 equivalents each of H\textsubscript{3}B-NH\textsubscript{3} and H\textsubscript{3}B-NMe\textsubscript{2}H\textsubscript{2} gave a mixture of metal-bound co-oligomers \{Ir(PCy\textsubscript{3})\textsubscript{2}(H)[H(H\textsubscript{2}BNH\textsubscript{2}H\textsubscript{2})\textsubscript{2}(H\textsubscript{2}BNMe\textsubscript{2}H\textsubscript{2})H]\\textsuperscript{+} (x = 0, 1, y = 1, 2; x = 1, y = 0; x = 2, y = 1).

Density functional theory (DFT) calculations\textsuperscript{35} have been used to study the mechanism of the dehydrocoupling of H\textsubscript{3}B-NH\textsubscript{3} at 6a with particular focus on (i) the requirement for additional H\textsubscript{3}B-NH\textsubscript{3} to induce dehydrogenation, (ii) the mechanism of the B–N coupling step and (iii) the varying affinities of the different amine-boranes toward oligomerisation. These calculations employed PMe\textsubscript{3} ligands, with [Ir(PMe\textsubscript{3})\textsubscript{2}(H)\textsubscript{2}(\eta\textsuperscript{1}-H\textsubscript{3}B-NMe\textsubscript{2}H\textsubscript{3})\textsubscript{2}]\textsuperscript{+} (denoted 6a\textsuperscript{+}, x = 0, 5a\textsuperscript{+}, x = 1 and 4a\textsuperscript{+}, x = 2) the model initial reactants, and use a BP86-D3(C\textsubscript{6}H\textsubscript{6}F) protocol. We report free energies derived from gas-phase BP86-optimisations, corrected for dispersion and solvation effects. Each key step in the dehydrocoupling process (B–H/N–H bond activation and B–N bond coupling) presented more than one possible transition state and the most accessible of these are presented here, with alternative structures given in the ESI.†

We have previously modelled the dehydrogenation of H\textsubscript{3}B-NMe\textsubscript{2}H in [Ir(PMe\textsubscript{3})\textsubscript{2}(H)\textsubscript{2}(\eta\textsuperscript{1}-H\textsubscript{3}B-NMe\textsubscript{2}H\textsubscript{3})\textsubscript{2}]\textsuperscript{3+} (4a\textsuperscript{3+}) to form the corresponding amino-borane adduct (\textit{i.e.} 4a\textsuperscript{4+}, a model of 4a\textsuperscript{+} in Scheme 2) and defined a mechanism based on sequential B–H activation, H\textsubscript{2} loss and rate-limiting N–H activation.\textsuperscript{19} Applying this mechanism to H\textsubscript{3}B-NH\textsubscript{3} dehydrogenation in 6a\textsuperscript{+} reveals a barrier of 33.8 kcal mol\textsuperscript{–1} in which the N–H activation step is again rate-limiting (see Fig. S1–3, ESI†). With an added H\textsubscript{3}B-NH\textsubscript{3} molecule a related mechanism can be characterised but with a significantly reduced barrier of 26.7 kcal mol\textsuperscript{–1} (Fig. 2). In this process the second H\textsubscript{3}B-NH\textsubscript{3} molecule first adds to 6a\textsuperscript{+} to give [Ir(PMe\textsubscript{3})\textsubscript{2}(H)\textsubscript{2}(\eta\textsuperscript{1}-H\textsubscript{3}B-NH\textsubscript{3})\textsubscript{2}]\textsuperscript{3+}, 16a\textsuperscript{3+}, with a binding energy of 5.0 kcal mol\textsuperscript{–1}. This stabilisation is in part due to a BH(δ–)–H(δ+) dihydrogen interaction between the two H\textsubscript{3}B-NH\textsubscript{3} ligands.\textsuperscript{36,37} B–H activation in 16a\textsuperscript{3+} entails a

![Scheme 3](image1)

**Scheme 3** Synthesis of 6a, 6b and 6c. Solid-state structures (50% displacement ellipsoids) of 6a and 6c. Selected hydrogen atoms are shown and the [BAR\textsubscript{Cl}\textsubscript{4}]\textsuperscript{–} anions are omitted for clarity. See ESI† for full details.

![Scheme 4](image2)

**Scheme 4** Addition of 2 equivalents of H\textsubscript{3}B-(NH\textsubscript{2}BH\textsubscript{2})-NH\textsubscript{3} to 6a results in the formation of higher oligomers.

![Fig. 2](image3)

**Fig. 2** Computed free energy reaction profile (kcal mol\textsuperscript{–1}, BP86-
D3(C\textsubscript{6}H\textsubscript{6}F)) for dehydrogenation of H\textsubscript{3}B-NH\textsubscript{3} in 6a\textsuperscript{+} in the presence of added H\textsubscript{3}B-NH\textsubscript{3}.
characterised that involved the direct reaction of two H$_2$B

$\quad +26.7 \text{kcal mol}^{-1}$

from which rate-limiting N

H$_{13}$

being facilitated by the addition of amine-borane to

˚

1.42

the amino-borane ligand in

pathways are given in the ESI (see Fig. S12

†

tent with the lack of any bound amino-borane intermediates

I$_6^a$

give [Ir(PMe$_3$)$_2$(BH$_2$NH$_3$)(H)(H$_2$)(H$_2$)][I$_6^a$]$_2$ ($G = +15.9$ kcal mol$^{-1}$). H$_2$ loss then leads to

I$_6^a$$_3$ ($G = +10.7$ kcal mol$^{-1}$)

from which rate-limiting N–H activation occurs via

I$_6^a$$_{NH1}$ ($G = +26.7$ kcal mol$^{-1}$) to give

I$_6^a$$_4$ in which both an amine- and an amino-borane are bound to the metal centre.

The computed geometry of

I$_6^a$$_{NH1}$

is shown in Fig. 3a and shows transfer of H$^1$ from the BH$_2$NH$_3$ ligand to Ir (N$^1$–H$^1$ = 1.42 Å; Ir–H$^1$ = 1.74 Å) while a dihydrogen bonding interaction is maintained with the spectator H$_2$BH$_2$NH$_3$ ligand (H$^{24}$–H

˚

1.80 Å). This feature stabilises both

I$_6^a$$_{NH1}$

and its precursor

I$_6^a$$_3$ and so contributes to a reduction in the overall barrier to dehydrogenation of 7.1 kcal mol$^{-1}$ compared to the reaction direct from

I$_6^a$

without added amine-borane. An alternative transition state, 

I$_6^a$$_{NH1}$(Alt 1), in which the second H$_2$B

NH$_3$ ligand adopts an $\eta^2$(B,H) bonding mode (similar to the amino-borane ligand in

I$_6^a$$_{NH2}$, see Fig. 3b and below) is comparable in energy ($G = +26.9$ kcal mol$^{-1}$, see Fig. S6(b)†).

Both forms of

I$_6^a$$_{NH1}$

are consistent with dehydrogenation being facilitated by the addition of amine-borane to

I$_6^a$$. Similar reductions in barriers to dehydrogenation have very recently been reported for H$_2$B-NMe$_3$H dehydrogenation using [Rh(chelating phosphine)]$^+$ fragments. 38

For the subsequent B–N coupling step a total seven different pathways have been characterised. Four of these stem from intermediate

I$_6^a$$_4$

and entail B–H activation in the H$_2$B-NH$_3$ ligand to produce a Lewis acidic [H$_2$BNH$_3$] moiety that then couples with H$_2$B=NH$_2$. In most cases these processes occur in one step. Two further pathways have been characterised for the direct reaction of free H$_2$B=NH$_2$ with either

I$_6^a$

or its B–H activated form. All of these pathways, however, have computed barriers in excess of 28 kcal mol$^{-1}$, and as this is higher than the barrier to dehydrogenation these pathways would be inconsistent with the lack of any bound amino-borane intermediates being observed experimentally. Full details of these alternative pathways are given in the ESI (see Fig. S12†).

A significantly more accessible B–N coupling route was characterised that involved the direct reaction of two H$_2$B=NH$_2$

units. This process therefore requires the prior dehydrogenation of a second H$_2$B-NH$_3$ molecule and a pathway for this, analogous to that shown in Fig. 2, has been defined starting from

I$_6^a$$_4$

and forming [Ir(PMe$_3$)$_2$(H)$_2$(N$^2$H$_2$B=NH$_2$)]$^+$ ($I_6^a$$_2$) and free H$_2$B=NH$_2$ (see also Fig. S7–9†).

I$_6^a$$_2$ is closely related to that calculated for the product of dehydrogenation of H$_2$B-NMe$_3$H by the same fragment. 39 The key N–H activation transition state in this process, 

I$_6^a$$_{NH2}$ (Fig. 3b), has a free energy of +24.2 kcal mol$^{-1}$ and features a spectator $\eta^3$(B,H)-H$_2$B=NH$_2$ ligand that stabilises the metal centre. Oligomerisation then proceeds through the reaction of

I$_6^a$$_2$

with H$_2$B=NH$_2$ and the associated reaction profile (Fig. 4) shows B–N coupling via

I$_6^a$$_{NH5}$ at only +17.9 kcal mol$^{-1}$. The structure of this transition state (Fig. 5) shows that the Ir-bound amino-borane has rearranged to an $\eta^3$-(B,H) mode that exposes the pendant [NH$_3$] moiety to attack by the second, incoming amino-borane (N$^1$–B$^2$ = 2.37 Å). As this occurs a hydride transfers from Ir onto N$^2$ (Ir–H$^{24}$ = 1.63 Å; H$^{24}$–N$^2$ = 1.64 Å) to generate an $\eta^2$(B,H)-H$_2$B-NH$_2$BH$_2$-NH$_2$ ligand in the resultant intermediate

I$_6^a$$_8$ ($G = +1.6$ kcal mol$^{-1}$). Addition of H$_2$ (I$_6^a$$_9$, $G = +7.3$ kcal mol$^{-1}$) and facile B–H reductive coupling gives the final model product, [Ir(PMe$_3$)$_2$(H)$_2$(N$^2$H$_2$B-NH$_2$BH$_2$-NH$_2$)]$^+$, $6b'$ ($G = -10.9$ kcal mol$^{-1}$). 40 This coupling process is similar to that suggested by...
Schneider and co-workers in bifunctional Ru(H)2(PMe₃)(PNP) catalysis [PNP = HN(CH₂CH₂PH₅⁺Bu₃)₂], in which an N–H activated H₃B·NH₃ group undergoes B–N coupling with H₂B=NH₂ during dehydropolymerisation. ¹⁰

Reaction profiles analogous to those in Fig. 2 and 4 were also computed for the dehydrocoupling of H₃B·NMe₃H₂ at 5a’ and H₂B·NMe₂H at 4a’. Similar dehydrogenation barriers are found in each case (5a’/H₂B·NMe₃H₂: 25.2 kcal mol⁻¹; 4a’/H₂B·NMe₂H: 26.2 kcal mol⁻¹) and in the absence of a second amine-borane molecule these barriers increase to above 33 kcal mol⁻¹, reiterating the promotional effect of added amine-borane on this process. In contrast the B–N coupling transition states are more substrate-dependent and increase significantly in energy with the size of the amine-borane (6a’/H₂B·NMe₂H: 19.7 kcal mol⁻¹; 5a’/H₂B·NMe₃H₂: 19.9 kcal mol⁻¹; 4a’/H₂B·NMe₂H: 26.5 kcal mol⁻¹). This trend is consistent with oligomerisation being accessible for both H₂B·NH₃ and H₂B·NMe₃H₂, but this step becoming significantly more difficult for the larger H₂B·NMe₃H₂. Indeed oligomerisation is not seen experimentally for 4a’/H₂B·NMe₂H under the conditions used here.⁴¹

An analogous mechanism based on dehydrocoupling of H₃B·NH₃ and H₂B·NH₂BH₂·NH₃ can account for the formation of the H₂B·(NH₂BH₂·NH₃)₂ trimer seen in 6c (modelled by 6c’). The key energetics are similar to those computed in the pathway for the formation of 6b’: dehydrogenation of H₂B·NH₃ (in the presence of H₂B·NH₂BH₂·NH₃) has an overall barrier of 26.3 kcal mol⁻¹, then dehydrogenation of H₂B·NH₂BH₂·NH₃ (now in the presence of H₂N=BH₂) has a barrier of 24.3 kcal mol⁻¹. The order of dehydrogenation is important, however, as the alternative initial dehydrogenation of H₂B·NH₂BH₂·NH₃ (in the presence of H₂B·NH₃) has a higher barrier of 28.1 kcal mol⁻¹ (see Fig. S15†). The subsequent B–N coupling transition state is again more accessible than dehydrogenation, TS₆b”’(B₃N₆) (Fig. 6a) having a computed energy of 21.2 kcal mol⁻¹. In this case there are two possible B–N coupling outcomes, depending on whether H₂B=NH₃ (as in TS₆b”’(B₃N₆)) or H₂B=NHBBH₂·NH₃ (TS₆b”’(B₃N₆), Fig. 6b) is bound to Ir in the transition state. The former case leads to a straight chain oligomer product, and is 2.3 kcal mol⁻¹ more stable than the alternative that gives a branched chain product. The barrier for this second oligomerisation step is close to that for the B–N coupling of H₂B·NMe₃H₂ (19.9 kcal mol⁻¹), highlighting the similar behaviour of these two mono-substituted amine-boranes. This in turn suggests that subsequent chain growth with further H₂B·NH₃ may proceed via transition states related to TS₆b”’(B₃N₆) in which the growing oligomer chain extends away from the metal centre with minimal additional steric impact. By the same token, H₂B·NMe₃H₃ trimerisation is more difficult with the equivalent transition state, TS₅b”’(B₃N₆), equating to a higher barrier of +24.8 kcal mol⁻¹ (Fig. 6c). This trend towards higher oligomerisation barriers as the size of the amine-borane increases is consistent with the experimental observations (i.e. 5a giving 5b alone whereas 6a can undergo multiple oligomerisation steps to give 6b–e).

A potential side reaction within this mechanistic picture involves the cyclisation of two aminoboranate fragments, either directly at the metal (e.g. via reaction of H₂B=NH₃ with [Ir(PMe₃)₃(H₂)₂(η²-H₂B=NH₃)₃], 16a’) or via an off-metal process involving two free aminoboranates. In fact for H₂B·NH₃ both these processes are computed to be competitive with B–N coupling via TS₆a”’(B₃N₆), dimerisation at 16a’, having a transition state energy of +15.4 kcal mol⁻¹ while the off-metal process has a barrier of 16.2 kcal mol⁻¹ (see Fig. S16†). Some dimerisation (and trimerisation) may therefore be anticipated, and indeed evidence of this is seen in the small amount of borazine that is observed as minor products in the oligomerisation processes.

Overall the proposed dehydrogenation/oligomerisation mechanism captures the key trends observed experimentally by ESI-MS and NMR spectroscopy. In particular the promotional effect of added amine-borane on dehydrogenation for all three H₂B·NMe₃H₃₊ₓ (x = 0–2) species and the decreasing propensity toward oligomerisation as the size of the amine-borane increases are reproduced. However, some issues do remain: (i) the absolute barriers computed for the dehydrogenation are ca. 26 kcal mol⁻¹ and so are rather high for a (albeit slow) room temperature process; (ii) once dehydrogenation has occurred, the competing H₂B=NH₂ dimerisation processes are computed to be slightly more favourable than oligomerisation. One reason for these discrepancies may be the use of a model system in the present study, where PMe₃ is used in place of PCy₃ ligands. However, an additional factor may be that both the key N–H activation (e.g. TS₆a”’(NH₁)) and B–N coupling (e.g. TS₆a”’(B₃N₆))
transition states exhibit a vacant site that offers the potential for further stabilisation. Indeed a third H3B-NH3 molecule was found to promote both of these steps (see Scheme 5 and Fig. 7). Starting from 16a\textsuperscript{1,AB} dehydrogenation proceeds with a reduced overall barrier of 22.4 kcal mol\textsuperscript{-1} to give 16a\textsuperscript{1,AB} at −4.9 kcal mol\textsuperscript{-1} and from here B–N coupling has a barrier of only 9.4 kcal mol\textsuperscript{-1}. Moreover, B–N coupling (and the completion of the oligomerisation process) are now kinetically preferred over dimer formation. Therefore several substrate molecules may cooperate to promote the oligomerisation process. Alternatively a solvent molecule may interact with the unsaturated metal centre and so promote the oligomerisation step, although we have not attempted to explicitly model this here.

**Conclusions**

In summary, we report the observation and characterisation of multiple metal-bound oligomers in the dehydrocoupling of H3B-NH3. This contrasts with only a single oligomerisation event being observed for H3B-NMeH\textsubscript{2} and none for H3B-NMeH. Interrogation of the likely mechanism using computational methods reveals that initial dehydrogenation of H3B-NH3 is a higher energy process than both the subsequent dehydrogenation of a second amine-borane and metal-promoted B–N bond formation to form an oligomeric borazane bound to the metal centre. Steric factors play an important role in determining the barrier to B–N coupling which increases with x in the H3B-NMe\textsubscript{x}H\textsubscript{1−x} series (x = 0–2). These studies also suggest a role for additional amine- or amino-borane in promoting dehydrocoupling processes through the formation of adduct species and complementary N–H···H–B interactions, an observation we noted from experimental studies both here and previously\textsuperscript{31} and recently from computational studies on related systems.\textsuperscript{31}

An overall mechanism that captures these observations is shown in Scheme 6. For H3B-NH3 initial dehydrogenation of the amine-borane (step 1) has the highest barrier (+26.7 kcal mol\textsuperscript{-1}), with the subsequent dehydrogenation of a second amine-borane (step 2) proceeding through a slightly lower energy transition state at +24.2 kcal mol\textsuperscript{-1}. The transition state for the B–N coupling of the resultant amino-boranes (step 3) is then most accessible of all (+17.9 kcal mol\textsuperscript{-1}). The rather high barrier to dehydrogenation (step 1) means that these systems turnover rather slowly, especially compared to others that rapidly promote dehydropolymerisation.\textsuperscript{4–12} However, the corollary is that intermediates such as 6a–e can be observed, allowing for direct mechanistic insight. For subsequent oligomerisations (e.g. to form 6c, R = BH\textsubscript{2}NH\textsubscript{3} Scheme 6) the key transition state energies retain the same pattern, thus promoting formation of a growing oligomeric chain at the metal centre. When the amine-borane is changed to H3B-NMe\textsubscript{H} the same computed pattern still holds for the initial oligomerisation, but the second B–N coupling transition state (+24.8 kcal mol\textsuperscript{-1}) does becomes very close in energy to those for the two dehydrogenation steps (+25.4 kcal mol\textsuperscript{-1} and +24.0 kcal mol\textsuperscript{-1}). Clearly B–N coupling is disfavoured by the greater bulk and experimentally only 5b is observed to be formed. For H3B-NMe\textsubscript{H} no B–N bond formation to give a linear diborazane is observed under these experimental conditions, with 4a\textsuperscript{t} formed only.

B–N coupling is also calculated to be competitive with amino-borane cyclisation, consistent with the observation of a small amount of borazine. However, coupling must be faster than reaction of exogenous cyclohexene with amino-borane as no hydroborated product is observed under these conditions. Our mechanism therefore has some similarities to those recently proposed for the catalytic dehydropolymerisation of H3B-NH3 using a bifunctional Ru-based catalyst\textsuperscript{8} and of H3B-NMeH\textsubscript{2} using Ir(BuPOCOP\textsubscript{Bu})H\textsubscript{2}.\textsuperscript{6,12} Although the intimate mechanistic details of these two systems likely differ, both propose dehydrogenation to form an amino-borane, that then must undergo fast metal-mediated B–N coupling, as neither system promotes hydroboration when exogenous cyclohexene is added.
Amine-borane dehydrocoupling presents a high degree of mechanistic complexity that is additionally highly catalyst specific. Although the precise mechanism outlined here might be rather system specific, the observations and suggested pathways presented might help guide future work on developing and understanding this challenging transformation. Ultimately the goal is the design of improved catalysts for this important process that have the potential to produce B-N materials “to order”.

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Notes and references

2 A. Staubitz, A. P. M. Robertson, M. E. Sloan and I. Manners, Chem. Rev., 2010, 110, 4023–4078.
34 ESI-MS has been used to analyse the metal-free product of dehydropolymerisation. See, for example, mass spectra reported in ref. 4, 6 and 12.
35 Calculations were run with the Gaussian suite of programs and employed the BP86 functional. Rh and P centres described with the Stuttgart RECPs and associated basis set with added d-orbital polarisation on P (ζ = 0.387) and 6-31G** basis sets for all other atoms. Free energies are reported in the text, based the gas-phase values, incorporating corrections for dispersion effects using...
Grimme’s D3 parameter set (i.e. BP86-D3) and solvent (C₆H₅F, PCM approach). See ESI† for references and full details.


40 Experimentally, addition of sequential equivalents of H₃B-NMe₂H to 1 under a sparge of Ar to remove H₂ resulted in a reduced yield of 5b with significant amounts of unidentified decomposition products formed.

41 When H₃B-NMe₂H is added to the amino-borane complex 4a* significant (~35%) quantities of the corresponding linear diborazane are observed, suggesting that under these conditions of a high local concentration of H₂B=NMe₂ the B-N bond forming reaction is kinetically competent. See ref. 19. This experimental observation is consistent with the essentially similar barriers to dehydrogenation and B-N coupling calculated here for the secondary amine-borane. At lower concentrations of amine-borane used in this study dimerisation to form [H₂B=NMe₂]₂ dominates and the diborazane is not observed.
