A \textsuperscript{d\textsuperscript{10}} Ag(\textit{i}) amine–borane $\sigma$-complex and comparison with a $d^8$ Rh(\textit{i}) analogue: structures on the $\eta^1$ to $\eta^2:\eta^2$ continuum$^\ddagger$

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H$_3$B·NMe$_3$ $\sigma$-complexes of $d^8$ [L$_1$]Rh[BAr$_4$$_\text{d}$] and $d^{10}$ [L$_1$]Ag[BAr$_4$$_\text{d}$] (where L$_1$ = 2,6-bis-[1-(2,6-diisopropylphenylimino)ethyl]pyridine) have been prepared and structurally characterised. Analysis of the molecular and electronic structures reveal important but subtle differences in the nature of the bonding in these $\sigma$-complexes, which differ only by the identity of the metal centre and the d-electron count. With Rh the amine–borane binds in an $\eta^2:\eta^2$ fashion, whereas at Ag the unsymmetrical (Ag···H$_3$B·NMe$_3$) unit suggests a structure lying between the $\eta^2:\eta^2$ and $\eta^4$ extremes.

Fig. 1 (i) H–B activation; (ii) examples of $\sigma$-amine–borane complexes, (iii) complexes reported in this work. [BAr$_4$$_\text{d}$]$^-$ anions are not shown.

Introduction

Transition metal $\sigma$-complexes, in which an E–H bond (e.g., E = H, B, C, Si) binds with a metal centre through a 3-centre 2-electron interaction, are of fundamental interest due to their central role in E–H activation.$^1$ For example, amine–borane $\sigma$-complexes,$^2$ exemplified by [M]···H$_3$B·NRH$_2$ (Fig. 1), are key intermediates in the catalytic dehydropolymerisation of amine–boranes that leads to the formation of B–N polymeric materials,$^3$–$^5$ B–B coupling$^6$ or hydroboration reactions.$^7$

H$_3$B·NMe$_3$ is often used as a model substrate for such processes as it provides insight into the initial binding step of the amine–borane, there being no protic N–H available for onward reaction. Transition metal $\sigma$-complexes of H$_3$B·NMe$_3$ have been reported across the transition metal series,$^5$ e.g., for group 6 (A),$^2$ 7, 8 (ref. 9) and 9 (B, C).$^6$,$^10$ Both $\eta^1$ and $\eta^2$:$\eta^2$ binding modes of H$_3$B·NMe$_3$ have been observed, depending on the steric and electronic demands of the metal, Fig. 1(ii), and the principal bonding interaction can be described by $\sigma$-donation from the B–H bond into an empty metal d orbital.$^2$ Recently the isolation of the first H$_3$B·NMe$_3$ $\sigma$-complex of a group 11 metal was reported, the $d^{10}$ Cu(\textit{i}) complex D, with a $\eta^2$:$\eta^2$-bound H$_3$B·NMe$_3$. Analysis of the bonding showed that the bent \{CuL$_2$\} fragment presents a LUMO largely of 4s character that receives electron density from the B–H bonds, while back bonding was negligible.$^{11,12}$ This is a relatively rare example a coinage metal$^{11,12}$ that shows close interactions with E–H bonds.

We report here a straightforward route to a H$_3$B·NMe$_3$ $\sigma$-complex of the coinage metal Ag(\textit{i}), complex 1Fig. 1(iii), that is supported by the pincer ligand 2,6-bis-[1-(2,6-diisopropylphenylimino)ethyl]pyridine, L$_1$. Such highly tuneable ligands have been used, for example, with Fe and Co centres in olefin polymerisation catalysis.$^{18,19}$ They also support the generation

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$^\ddagger$Electronic supplementary information (ESI) available: Synthesis, characterisation data, structures of 3, 7 and 8, computational details. CCDC 1895514–1895519. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c9dt00971j
of latent low coordinate Ag(I) complexes, e.g. (L)AgOTf (OTf = triflate), that coordinate arenes,20,21 while (L)RhCl have been used as precursors for nanoparticle dehalogenation catalysts22 (L = 2,6-bis-[1-(2,6-R-phenylimino)ethyl]pyridine). The synthesis of a directly analogous σ-complex of Rh(I), 2, is also reported here. This offers a rare opportunity to directly compare the structures, bonding and NMR spectroscopic reporters for mono-cationic d⁸ and d¹⁰ σ-complexes in systems where only the identity of the metal is changed.

Results and discussion

An appropriate operationally unsaturated precursor for the synthesis of a H₃B·NMe₃ adduct of Ag(I) is the arene-bridged dimeric complex [(L₁)Ag][BArF₆]₂, 4 (Scheme 1), which comes from addition of Na[BArF₆] to (L₁)AgOTf, 3, itself prepared by addition of Ag[OTf] to free L₁. The synthesis and structure of monomeric complex 3 is detailed in the ESI.†

In the solid-state complex 4 is a solvent-free, weakly associated dimer, which approaches coordinative saturation through η⁷ interactions with the aryl groups on a neighbouring ligand. There is no crystallographically imposed symmetry. The Ag···arene distances suggest a weak interaction [Ag···C 2.439(6)–2.623(6) Å]. They are comparable, but generally longer, than distances found in a Ag(η⁷-N)-heterocyclic carbene arene-bridged dimer [2.444(4), 2.348(4) Å],2,3 or [(L)Ag(η²-toluene)][OTf] [2.464(7) Å].20 The appearance of a very simple ¹H NMR spectrum for 4 as signalled by a single ¹Pr environment even at 183 K (CD₂Cl₂), suggests these weak silver–arene interactions are not retained in solution, or at the very least the molecule is highly fluxional, as the solid-state structure (even allowing for time-averaged C₂ symmetry) would be expected to show 4 different ¹Pr groups. DOSY (Diffusion-Ordered Spectroscopy) experiments determined the diffusion coefficients for complexes 3 and 4 in CD₂Cl₂ to be very similar (1.166 ± 0.014 × 10⁻⁹ m² s⁻¹ for 3 and 1.126 ± 0.013 × 10⁻⁹ m² s⁻¹ for 4), suggesting 4 is a monomer in solution, likely a CD₂Cl₂ adduct similar to that observed for a Ag(η⁷-N)-heterocyclic carbene complex reported by Rivard and co-workers.23

Consistent with this latent coordinative unsaturation, addition of one equivalent (per Ag) of H₃B·NMe₃ to 4 gave the air- and light-stable, bright yellow σ-complex [(L₁)Ag(H₃B·NMe₃)][BArF₆], 1, isolated in 98% yield. Similarly, addition of one equivalent of Na[BArF₆] to [(L₁)RhCl] 5 to (L₁)RhCl 5- in CH₂Cl₂ affords the known latent-coordinatively unsaturated 6,26 which also likely exists as an adduct in CH₂Cl₂ solution,27 that forms a σ-complex [(L₁)Rh(H₃B·NMe₃)][BArF₆] 2 with H₃B·NMe₃, which can be isolated as a dark green solid (79% yield).

The molecular structures of 1 and 2 were determined by single crystal X-ray diffraction (Scheme 1). For both, the high quality of the data allowed for the BH₃ hydrogens to be located

Scheme 1 Synthesis of complexes 1–6. (i) AgOTf, CH₂Cl₂; (ii) Na[BArF₆], CH₂Cl₂; (iii) H₃B·NMe₃, CH₂Cl₂; (iv) [Rh(C₂H₄)₂Cl]₂, toluene. R = 3,5-Pr₂C₆H₃. Selected bond lengths [Å] and angles [°] 1: Ag₁–H₁A, 2.22(3); Ag₁–H₁B, 2.01(3); Ag₁–N₁ 2.377(13); Ag₁–N₂ 2.430(13); Ag₁–C₁ 2.458(13); N₄–B₁ 1.609(3); N₁–Ag₁–B₁ 171.33(8); N₃–Ag₁–N₂ 134.14(5). 2: Rh₁–H₁A, 1.97(4); Rh₁–H₁B, 1.93(4); Rh₁–N₁ 1.91(2); Rh₁–N₂ 2.06(2); Rh₁–N₃ 2.02(2); Rh₁–B₁ 2.30(6); N₁–B₁ 1.58(8); N–Rh₁–B₁ 169.12(15); N₁–Rh₁–N₁ 156.76(9); ellipsoids at the 30% probability level. 4: Ag₁–C₄₅, 2.52(5); Ag₁–C₄₄, 2.57(7); Ag₂–C₁₂, 2.439(6); Ag₂–C₁₃, 2.623(6) Å. Hydrogen atoms, other than those at boron, and [BArF₆]⁻, are omitted for clarity. Inset shows key structural metrics for the σ-interactions.
and freely refined. The different electron configurations of the d\(^{9}\) Rh(i) and d\(^{10}\) Ag(i) centres lead to subtle differences in the coordination geometry about each metal centre. In both cases a \( \kappa^2\)-binding of L1 is observed, albeit with considerably longer Ag–N distances [2.3737(13)–2.4306(13) Å] than Rh–N [1.910(2)–2.061(2) Å], even taking into account the small difference in covalent radii (Rh, 1.42; Ag, 1.45 Å). This may simply reflect a bound Rh-complex. Interestingly, the local coordination 16.8° confirms the greater steric pressure in the more strongly slightly larger for complex 2 this is measured as [97(2)°]. The bonding in MeCN adducts (Scheme 2), \([(\text{L1})\text{Ag(NCMe)}][\text{BAR}^4]\), 7, and \([(\text{L1})\text{Rh(NCMe)}][\text{BAR}^4]\), 8, by addition of 100 equivalents or one equivalent of MeCN respectively to the corresponding M\(^{+}\) complexes of Rh(I) that show \( \eta^2\eta^2 \) binding, e.g. C [2.199(3) Å], it is shorter than found for \( \eta^1 \) binding, e.g. B [2.759(6) Å]. This lengthening may be due to the steric effects with flanking \( \{\text{iPr}_2\text{C}_6\text{H}_3\}\) groups. To measure such differences, in a self-consistent manner, we have prepared and structurally characterised (ESI†) the corresponding MeCN adducts (Scheme 2), \([(\text{L1})\text{Ag(NCMe)}][\text{BAR}^4]\), 7, and \([(\text{L1})\text{Rh(NCMe)}][\text{BAR}^4]\), 8, by addition of 100 equivalents or one equivalent of MeCN respectively to the corresponding amine–borane complexes.\(^{29}\) The linear nitrile offers a minimal steric profile and thus baselines the metal–ligand geometry, and in particular the angle formed between the two planes that the aryl rings define (\( \beta \)), Scheme 1 inset. Coordination of the amine–borane results in the aryl groups moving apart, and this is measured as \( \Delta \beta \) between the two structures. That this is slightly larger for complex 2 compared with 1 [19.2° versus 16.8°] confirms the greater steric pressure in the more strongly bound Rh-complex. Interestingly, the local coordination environment around Rh, with the \( \sigma \)-amine–borane \( \{\text{H}_2\text{B}\} \) motif sitting orthogonal to the ligand plane is reminiscent of the bonding mode calculated for the closely related, but much less stable, \( \sigma \)-methane complex \([\text{Rh}([\text{PONOP})(\text{H}_2\text{CH}_2)]][\text{BAR}^4]\) \([\text{PONOP} = \kappa^2\text{2,6-(Bu}_2\text{PO)(C}_6\text{H}_3\text{N}_2]^\text{+}\)] although in this case an \( \eta^2 \)-structure is slightly favoured over the symmetric \( \eta^2 \) motif.

These subtle structural differences are carried over into the solution NMR data. For 1 the BH\(_3\) group is observed as a singlet at \( \delta \) 1.82 in the 298 K \( ^1\text{H} \{^{11}\text{B}\} \) NMR spectrum (CD\(_2\)Cl\(_2\)), shifted slightly downfield compared to the free ligand [\( \delta \) 1.64] (Scheme 3). At 183 K this separates into a broad doublet due to coupling to \( ^{107/109}\text{Ag} \) [\( \delta \) (AgH) = 41 Hz], confirmed by measurement at two different spectrometer frequencies, alongside a temperature-induced chemical shift. This signal did not resolve into terminal and coordinated B–H resonances, suggesting a low energy exchange, even at 183 K. The loss of coupling at higher temperature suggests an exchange process that involves rapid and reversible H\(_3\)B·NMe\(_3\) decoordination. In the \( ^{11}\text{B} \) NMR spectrum the amine–borane is observed as a broad quartet at \( \delta \) −16.3, shifted upfield compared to free H\(_3\)B·NMe\(_3\) in CD\(_2\)Cl\(_2\) [\( \delta \) −8.3, \( \Delta \delta \) −8]. The NMR data for complex 2 are subtly different. The BH\(_3\) group is observed as a doublet at \( \delta \) −1.37 [\( \delta \) (RhH) = 15.1 Hz] in the 298 K \( ^1\text{H} \{^{11}\text{B}\} \) NMR spectrum. This coupling constant does not change upon lowering the temperature to 183 K, indicative of both fast exchange and a process that retains the borane bound with the metal centre. We propose a hemilabile \( \eta^3\eta^2\eta^1\eta^1 \) fluxional process, as has been calculated\(^{31}\) in related systems. The \( ^{11}\text{B} \) NMR signal for complex 2 shows a broad singlet at \( \delta \) −4.2, now shifted downfield compared to free H\(_3\)B·NMe\(_3\), \( \Delta \delta \) +4.1.

DFT calculations\(^{32}\) have been employed to assess the different M⋯H\(_3\)B·NMe\(_3\) interactions in 1* and 2*, the cations of 1 and 2 respectively. Optimised geometries (Scheme 4) reproduce the more symmetric structure of 2* compared to the Ag⋯H\(_3\)B·NMe\(_3\) moiety in 1*. The calculations also highlight subtle changes in the B–H bond distances, in particular a shortening of the B1–H1A and B1–H1B bonds in 2* (both 1.276 Å) relative to the shorter distance computed for the non-interacting B1–H1C bond (1.203 Å). In 1* the B–H distances
follow the trend $\text{B1–H1B} \,(1.263 \text{ Å}) > \text{B1–H1A} \,(1.239 \text{ Å}) > \text{B1–H1C} \,(1.210 \text{ Å})$ suggesting that B1–H1B and B1–H1A both interact with the Ag centre, albeit to a different extent. $^{11}\text{B}$ chemical shifts of $\delta$=−22.0 and $\delta$=−1.6 were computed for $1^+$ and $2^+$ respectively, and compare with $\delta$=11.7 calculated for free H$_3$B·NMe$_3$ ($\Delta\delta$=10.3 and +10.1 respectively). Thus the experimental trend is reproduced, although the shifts relative to H$_3$B·NMe$_3$ are over-estimated in the calculations.

The fully optimised structures provided generally good agreement with the experimentally-determined metrics, but do over-estimate the M···B1 and M···N distances. One of us$^{33}$ and others$^{34}$ have shown that geometries computed for isolated molecular species can deviate significantly from experimental structures derived from X-ray crystallography, especially where weak intramolecular interactions are at play in defining the observed geometry. Therefore, electronic structure analyses were based on geometries in which the heavy atoms were fixed in the positions determined experimentally with only the H atom positions being optimised. These structures (data in plain text, Scheme 4) show the same geometric trends for the B···H and M···H distances as the fully optimised structures, although the Ag···H$_3$B·NMe$_3$ unit is somewhat more symmetrical than before. These structures were then analysed with Quantum Theory of Atoms in Molecules (QTAIM)$^{35}$, Natural Bond Orbital (NBO)$^{36}$ and Non-Covalent Interaction Plots (NCIPlots)$^{37}$.

Details of the QTAIM molecular graphs for $1^+$ and $2^+$ are shown in Scheme 5. The asymmetry of $1^+$ is highlighted by the appearance of the single Ag1···H1B bond path. Accordingly, the B1···H1B Bond Critical Point (BCP) shows a reduced electron density, $\rho(r)$, indicative of donation to the Ag centre. However, $\rho(r)$ for the B1···H1A BCP is also lower than that for B1···H1C and this, along with the rather flat electron density topology between Ag1 and H1A, suggests a weak interaction may be present. For $2^+$ the symmetrical Rh···H$_3$B·NMe$_3$ interaction is reflected in two similar bond paths, Rh1···H1B and Rh1···H1A, which encircle a Ring Critical Point (RCP). $\rho(r)$ values for the associated BCPs are similar to the Ag1···H1B BCP in $1^+$, although the higher values of $\rho(r)$ associated with the Rh system suggest a stronger M···H$_3$B·NMe$_3$ interaction in that case.

NBO calculations on $1^+$ highlight the Ag 5s orbital as the key acceptor in the Ag···H$_3$B·NMe$_3$ interaction, with donation from both σ-orbitals associated with B1···H1A and B1···H1B (Scheme 6). Quantifying these through the 2nd order perturbation analysis confirms the latter donates more strongly ($\Delta E(2)=19.3 \text{ kcal mol}^{-1}$) but that donation from B1···H1A is also significant ($\Delta E(2)=10.5 \text{ kcal mol}^{-1}$). For $2^+$ the d$^8$ electron count means a second low-lying acceptor becomes available in the form of the Rh1···N1 σ* orbital, whereas the equivalent orbital for the d$^{10}$ Ag$^+$ complex is filled. Donation into the Rh1···N1 σ* orbital now dominates in $2^+$ and occurs to a similar extent (ca. 27 kcal mol$^{-1}$) from both B1···H1A and B1···H1B. These interactions are reinforced by weaker donation into the predominantly Rh 5s acceptor orbital (ca. 9 kcal mol$^{-1}$). The total donation is therefore approximately twice that computed for the Ag ← H1B···B1 interaction. In neither cation is there evidence for any significant M → H$_3$B·NMe$_3$ back donation, as noted previously.$^5$

Scheme 4  Selected computed distances (Å) and $^{11}\text{B}$ chemical shifts for the cations of $1$ and $2$. Distances in italics are from full optimisations; those in plain text from partial optimisations with heavy atom positions fixed from the experimental data.

Scheme 5  Details from the QTAIM molecular graphs for $1^+$ (top) and $2^+$ (bottom), focussing on the M···H$_3$B·NMe$_3$ regions. Contours are plotted in the M···H1B–H1A plane with selected atoms, bond paths and critical points lying above or below this plane being cloaked for clarity. Values of $\rho(r)$, the electron densities at selected BCPs (green circles) and RCPs (pink circles) are shown in Å$^{-3}$. Full molecular graphs and Laplacian contour plots are available in the ESI.$^+$

Scheme 6  Key donor–acceptor interactions (illustrated for the B1···H1A bond) and 2nd order interaction energies (kcal mol$^{-1}$) derived from NBO analyses of $1^+$ and $2^+$. For $1^+$ the acceptor orbital is 97.7% 5s character; for $2^+$ it is 81.6% 5s and 18.4% 5d.
**Conclusions**

By selecting a ligand framework, \( \mathbf{L_1} \), that supports latent low coordinate complexes of Rh and Ag, the structures of, and bonding in, \( \text{d}^8 \) and \( \text{d}^{10} \) \( \sigma \)-amine borane complexes can be directly compared empirically and using computational methods. The \( \text{d}^8\)-Rh(\text{i}) metal centre, which has access to an additional \( \text{d} \)-based unoccupied orbital compared with Ag(\text{i}), binds \( \text{H}_3\text{B} \cdot \text{NMe}_3 \) more strongly, as evidenced by: (i) a more definitive \( \eta^2: \eta^2 \) \( \text{M} \cdots \text{B} \) coordination motif, (ii) a significantly shorter \( \text{M} \cdots \text{B} \) distance, (iii) a non-dissociative process for \( \text{H}_3\text{B} \cdot \text{NMe}_3 \) fluxionality, (iv) stronger \( \text{M} \cdots \text{H}_2\text{B} \) interactions as measured by QTAIM and NBO analysis and (v) NCIPlots that highlight the more symmetric and stronger \( \sigma \)-bonding in the Rh-analogue. The coherence of all of these experimental and computational observations underscores the importance of deploying multiple analytical methodologies when studying this important class of complex.

**Conflicts of interest**

There are no conflicts to declare.

**Acknowledgements**

EPSRC EP/M024210/1 and SCG Chemicals Co. Ltd. Dr Nicholas Rees for DOSY experiments.

**Notes and references**

Addition of only 1 equivalent of MeCN to 1 causes broadening, but no significant chemical shift change, of the H$_2$B-NMe$_3$ signal that suggests a rapid ligand exchange is occurring, that favours the amine–borane adduct.


DFT calculations were performed with Gaussian 09 with optimisations using the BP86 functional with SDD basis sets and pseudopotentials on Rh and Ag and 6-31G** basis sets on all other atoms. $^{11}$B chemical shifts were computed with the B3LYP functional with 6-311+g** basis sets on C, N, B and H atoms and included a correction of dichloromethane solvation (PCM approach). See ESI† for full details and references.


