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CO₂ reduction with protons and electrons at a boron-based reaction center†

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Borohydrides are widely used reducing agents in chemical synthesis and have emerging energy applications as hydrogen storage materials and reagents for the reduction of CO₂. Unfortunately, the high energy cost associated with the multistep preparation of borohydrides starting from alkali metals precludes large scale implementation of these latter uses. One potential solution to this issue is the direct synthesis of borohydrides from the protonation of reduced boron compounds. We herein report reactions of the redox series [Au(B₂P₂)]ⁿ (*n* = +1, 0, −1) (B₂P₂, 9,10-bis(2-(diisopropylphosphino)phenyl)-9,10-dihydroboranthrene) and their conversion into corresponding mono- and diborohydride complexes. Crucially, the monoborohydride can be accessed *via* protonation of [Au(B₂P₂)][−], a masked borane dianion equivalent accessible at relatively mild potentials (−2.05 V vs. Fc/Fc⁺). This species reduces CO₂ to produce the corresponding formate complex. Cleavage of the formate complex can be achieved by reduction (*ca.* −1.7 V vs. Fc/Fc⁺) or by the addition of electrophiles including H⁺. Additionally, direct reaction of [Au(B₂P₂)][−] with CO₂ results in reductive disproportionation to release CO and generate a carbonate complex. Together, these reactions constitute a synthetic cycle for CO₂ reduction at a boron-based reaction center that proceeds through a B–H unit generated *via* protonation of a reduced borane with weak organic acids.

Introduction

Since their discovery by Schlesinger and Brown in the 1940s,¹ borohydrides have become ubiquitous reducing agents in the synthesis of fine and commodity chemicals.² More recently, borohydrides have attracted interest in energy storage applications,³ both as a dense and readily handled source of H₂ and in the reduction of CO₂ to fuels such as formic acid and methanol.⁴ The first report of the reaction of NaBH₄ with CO₂ dates back to 1955 when Wartik and Pearson described the solution (dimethyl ether) and solid-state reactions with mass-balance and hydrolytic analysis of the products.⁵ In 1967, the reaction of NaBH₄ with CO₂ in aqueous conditions was shown to produce sodium formate.⁶ The intrinsic role of the borohydride ion in CO₂ reduction was later investigated by Mizuta in 2014 who showed that, in the presence of a catalytic amount of NaBH₄, BH₃·THF effectively reduces CO₂ to trimethylboroxine.⁷ A year later, Cummins reported the direct reaction of NaBH₄ with CO₂ yields the triformatoborohydride that could be hydrolyzed to yield formic acid.⁸ Additional studies over the last decade have found that in the presence of a suitable catalyst,

pinacol borane (HBpin) and catechol borane (HBcat) can reduce CO₂ to a range of products⁹ including carbon monoxide¹⁰ and formaldehyde,¹¹ formic acid,¹² and methanol equivalents.¹³

Despite their broad utility, one drawback to these reagents is the substantial energy required for their production. For example, millions of kg of NaBH₄ are produced each year by the NaH reduction of B(OMe)₃ in the Brown–Schlesinger process.¹⁴



NaH is prepared from the reaction of metallic Na with H₂ gas,¹⁴ and the reduction of NaCl to metallic Na in the Downs process. The process requires high temperature (>600 °C) and operating potentials of 8 V or more for practical reaction rates.¹⁵ As a result, the stoichiometric reduction of CO₂ with NaBH₄, or similarly produced B–H species,¹⁶ entails a significant energy cost.

One potential solution to this issue would involve the direct construction of B–H bonds from the protonation of reduced boron compounds accessed at potentials tolerable to common solvents. Such a process would be analogous to the generation of transition metal hydrides *via* the reduction and protonation of a transition metal complex (Fig. 1). Despite the difficulty in accessing doubly reduced boranes,¹⁷ there has been recent progress in the protonation of low valent boron compounds to generate B–H bonds (Fig. 2). In 2006, Nozaki *et al.* reported the isolation of the boryllithium compound LiB(2,6-ⁱPrC₆H₄)(NCH₂)₂,

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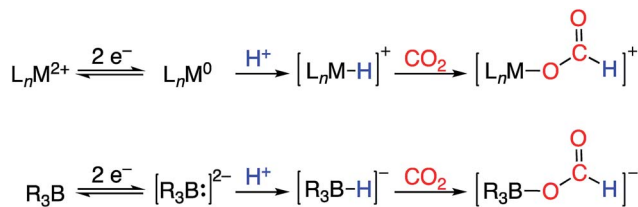


Fig. 1 Redox-coupled hydride formation at a transition metal complex (top) and borane (bottom) as a strategy for CO₂ electro-reduction to formate.

which reacts as a boryl anion equivalent, and showed that it could be protonated with H₂O to give the corresponding hydroborane.¹⁸ Bertrand *et al.* have prepared the carbene-stabilized borylene (CAAC)₂BH (CAAC = cyclic (alkyl)(amino)carbene) that could be protonated with trifluoromethanesulfonic acid (TfOH) to yield the corresponding boronium salt.¹⁹ A related bis(oxazol-2-ylidene)-phenylborylene system reported by Kinjo also produced a B–H moiety *via* protonation with TfOH.²⁰ Furthermore, Wagner synthesized a diborylmethane dianion and a doubly boron-doped dibenzo[*g,p*]chrysene dianion that could be protonated to yield the corresponding hydride bridged B–H–B species.²¹ Additionally, Szymczak *et al.* reported a conceptually relevant series of Mn/Cr-borazine complexes that could be reduced and then protonated to yield a bridging metalborohydride.²² The reactivities (in particular, towards hydride transfer) of these B–H bonds formed *via* protonation have not been reported.

We recently reported the synthesis of the diphosphine tethered diboraanthracene ligand B₂P₂ (9,10-bis(2-

(diisopropylphosphino)phenyl)-9,10-dihydroboranthrene) and a series of its gold complexes in three states of charge. The anionic complex, [Au(B₂P₂)]⁻[K(18-c-6)] (1), which features an unprecedented borohydride moiety, could be accessed at remarkably mild potentials (−2.05 V vs. Fc/Fc⁺, MeCN)²³ owing to the formation of a strong 3-centered, 2-electron bond between Au and the two B atoms.²⁴ Considering that 1 can be thought of as a masked borane dianion, we wondered if protonation of this complex could provide direct access to a hydridic B–H unit (Fig. 2). We herein report the synthesis and characterization of this borohydride complex, Au(B₂P₂)H (2), which can be generated *via* direct hydride reduction of Au(B₂P₂)Cl (3), FLP-type dihydrogen activation, H-atom addition to the boron-centered radical complex Au(B₂P₂)• (4) or, most notably, by protonation of 1 with mild organic acids. Borohydride 2 is sufficiently reactive to reduce CO₂ to formate, and cleavage of the resulting B–OCHO bond can be achieved either by addition of an electrophile (including H⁺) or by one electron reduction. These results collectively represent a synthetic cycle for CO₂ reduction to formate with protons and electrons, with the key finding being the generation of a hydridic borohydride unit *via* protonation of a reduced borane at modest potentials. This reaction sequence, along with Wagner's recent reports of CO₂ hydrogenation²⁵ and the reductive disproportionation of CO₂ (ref. 26) catalyzed by DBA derivatives, illustrates the promise of redox-active boranes in the reduction of CO₂, an area dominated by transition metal chemistry.²⁷ Furthermore, given the recent application of boron-doped graphene to CO₂ electro-reduction,²⁸ these molecules offer well-defined molecular models²⁹ of fundamental chemical processes that may underlie small molecule reactivity at doped graphitic carbon surfaces.

Results and discussion

Our initial synthetic approaches to a B–H containing derivative of Au(B₂P₂) began with direct hydride for halide substitution (Scheme 1). Addition of 1 equiv. K[*sec*-Bu₃BH] to 3 gave borohydride 2 in 89% yield. This complex could also be prepared in good yield by exposing 3 to an excess of Et₃SiH. Additionally, 2 could be synthesized *via* frustrated Lewis pair (FLP) H₂ activation in the presence of DBU (DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene): exposure of a THF solution of equimolar 3 and DBU to 1 atm H₂ resulted in the immediate formation of 2 as judged by ¹H, ¹¹B, and ³¹P NMR spectroscopies. This reaction is presumably mediated by the pseudo-three-coordinate boron and is consistent with a relatively weak Au–B interaction in 3. Single-crystal X-ray diffraction (XRD) studies of 2 show it to be a zwitterion in the solid state with an intact B–H bond on the DBA face opposite the Au center, analogous to the previously reported structure of zwitterion 3 (Fig. 3). The H atom was located in the electron difference map and is bound to a quasi-tetrahedral B atom (∑∠C–B–C = 340.5°). On the opposite side of the DBA linker, the Au ion is bound by both P donors in a roughly linear fashion (∠P–Au–P = 156.8°) with a single Au–B interaction (*d*_{AuB} = 2.644(1) Å) to one nearly-planar B atom (∑∠C–B–C = 359.8°). The ¹H NMR spectrum of 2 features a signal at 5.09 ppm for a B–H proton resonance with the

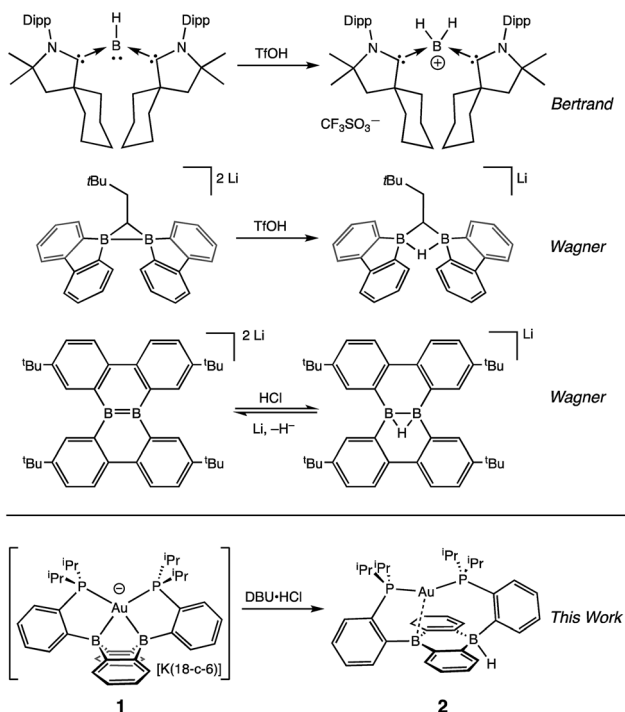
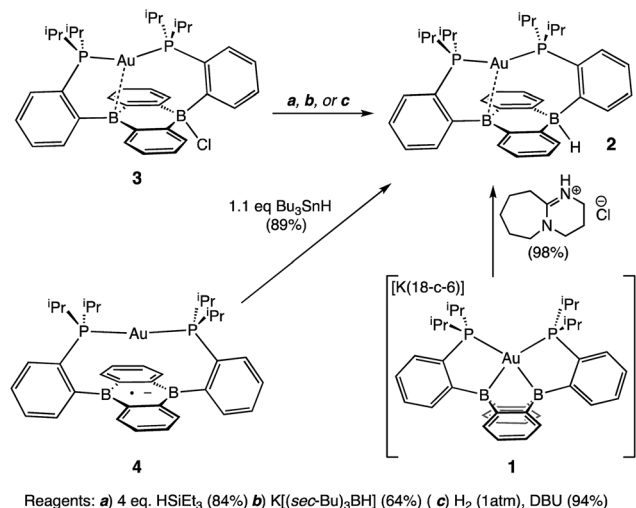


Fig. 2 Protonation of reduced boron compounds to give tetra-coordinate B–H moieties.



Scheme 1 Synthesis of Au(B₂P₂)H from H⁻, H⁺, and H⁺.

expected four-line pattern for coupling to a single ¹¹B atom ($J_{\text{BH}} = 80$ Hz). The ¹¹B NMR shows a corresponding doublet at -10.01 ppm ($J_{\text{BH}} = 80$ Hz) while the ³¹P NMR spectrum features two doublets at 58.4 and 55.9 ppm ($J_{\text{PP}} = 255.0$ Hz), consistent with inequivalent phosphine ligands on the NMR timescale. Given the precedent for H-atom transfer reactivity at boron,³⁰ we also targeted the synthesis of **2** from the neutral radical species **4** via H-atom addition. Reaction of Au(B₂P₂) with one equivalent of Bu₃SnH produces **2** and Bu₆Sn₂ over 12 hours via apparent H-atom transfer as judged by NMR of reaction mixtures.

To probe the synthesis of **2** via protonation of **1**, we exposed **1** to a series of organic acids. Addition of one equivalent of solid [Ph₂NH₂][Cl] or [2,6-Me₂pyH][Cl] to CD₃CN solutions of **1** resulted in immediate effervescence and formation of dark purple reaction mixtures which were revealed by NMR analysis to contain a mixture of H₂, **3**, and **4**. Fortunately, addition of one equivalent of DBU·HCl to a solution of **1** in CD₃CN gave rise to a pale-yellow solution exhibiting ¹H, ¹¹B, and ³¹P NMR resonances that matched authentic samples of **2** (Fig. S5–S7†) with no H₂ observed. Furthermore, **2** is stable to treatment with excess DBU·HCl.

With borohydride **2** in hand, we examined its reactivity with CO₂. Exposure of a C₆D₆ solution of **2** to 1 atm of CO₂ resulted in

quantitative formation of the corresponding formate complex Au(B₂P₂)(O₂CH) (**5**) within seconds (Scheme 2). The solid-state structure of **5** confirms the insertion of CO₂ into the B–H bond, with the resulting formate ion bound through a single O to one boron atom (Fig. 3). The zwitterionic structure of **5** is analogous to **2** and **3**, with a tetrahedral boron center bound to the formate oxygen ($\sum \angle \text{C–B–C} = 339.1^\circ$) and an intermediate length contact between Au and the non-formate bound B atom ($d_{\text{AuB}} = 2.632$ Å). The ¹H NMR spectrum of **5** in CDCl₃ is consistent with C_{2v} symmetry in solution, with a lone singlet in the ³¹P NMR spectrum at 56.1 ppm and ¹¹B{¹H} NMR displaying a broad singlet at 26.9 ppm. Similar to **3**, the observed C_{2v} symmetry in solution along with a ¹¹B chemical shift between that of bona fide three- and four-coordinate B centers in DBA containing molecules^{17hf} implies rapid exchange of the formate ion between each boron site of the DBA ring, a phenomenon also observed in **3**.²² The ¹³C{¹H} NMR spectrum of **5** contains a resonance at 168.2 ppm corresponding to the formate carbon atom, and FTIR spectroscopy revealed a strong band at 1672 cm⁻¹ for the formate C=O stretch.

Next, we assessed the ability of electrophiles such as TMSCl and HCl to effect B–O bond scission. Treatment of **5** with excess TMSCl resulted in the immediate formation of **3** as judged by ¹H and ³¹P NMR along with new resonances for

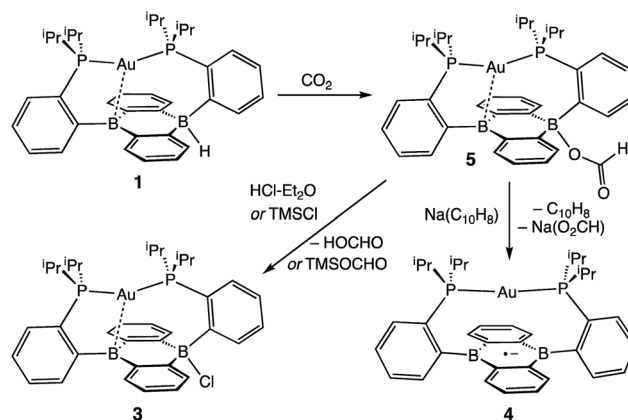
Scheme 2 CO₂ reduction to formate by Au(B₂P₂)H.

Fig. 3 Thermal ellipsoid plots (50%) of Au(B₂P₂)H (**2**, left) and Au(B₂P₂)(O₂CH) (**5**, right). Unlabeled ellipsoids correspond to carbon. Solvent molecules and most hydrogen atoms have been omitted for clarity.



Fig. 4 Cyclic voltammogram of Au(B₂P₂)(O₂CH) performed in 0.1 M [tBu₄N][PF₆] in CH₃CN at a scan rate of 100 mV s⁻¹.



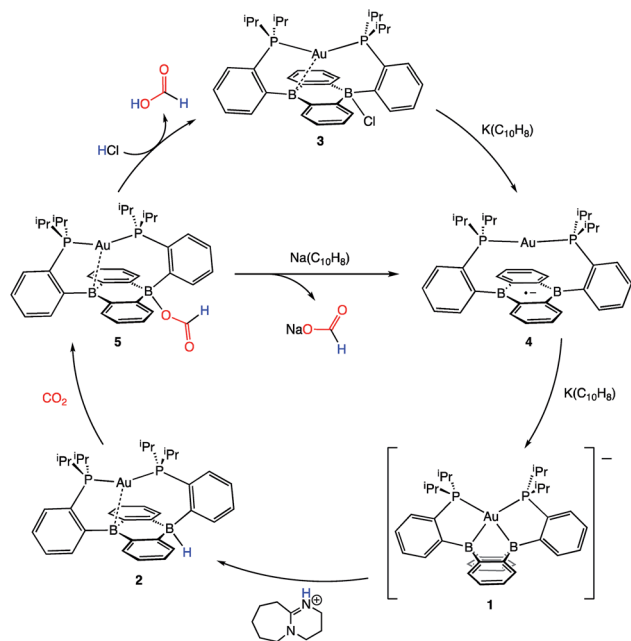


Fig. 5 A closed synthetic cycle for the reduction of CO₂ to formic acid with protons and electrons mediated by a redox active, metal-stabilized diboraanthracene platform.

trimethylsilylformate (Fig. S13[†]), accomplishing the net hydrosilylation of CO₂.³¹ While silyl electrophiles have strong precedent to mediate E–O bond cleavage in main group systems,³² we wondered if a suitable acid would be able to protonate the B–OCHO bond to yield formic acid. To this end, addition of [Ph₂NH₂][Cl] or DBU·HCl to CDCl₃ solutions of 5 saw no observable reaction over the course of days at room temperature. However, addition of one equivalent of HCl·Et₂O to 5 resulted in the immediate formation of the chloride complex 3 by ¹H and ³¹P NMR spectroscopy with resonances for HCO₂H observed in the ¹H NMR spectrum.

Following successful electrophilic B–O bond cleavage in 5 to yield 3, the reductive cleavage of the B–OCHO unit was explored. Cyclic voltammetry (CV) performed on 5 revealed a quasireversible process at $E_{1/2} = -1.74$ V vs. Fc/Fc⁺ which gave rise to an

oxidative daughter wave at ca. -1.5 V (Fig. 4). This daughter wave occurs at roughly the same potential as the oxidation of [Au(B₂P₂)]^{0/+1}, consistent with the hypothesis that one electron reduction of 5 forms [5][−] which then undergoes formate dissociation on the CV timescale to afford neutral 4. To unambiguously confirm the liberation of formate ion, 5 was treated with 1 equivalent of Na(C₁₀H₈) in THF. A turbid, dark-purple solution immediately formed, indicating formation of 4. The precipitated solids were collected by filtration and dissolved in D₂O with ¹H NMR analysis revealing formation of NaCO₂H (Fig. S12[†]). To our knowledge, this is the only example of reductive cleavage of a B–OCHO bond to yield formate. This process is presumably driven by the accessible one-electron reduction chemistry of 5 (-1.74 V vs. Fc/Fc⁺) enabled by the DBA core and speaks to the utility of frontier orbital modulation by incorporation of boron into polycyclic aromatic hydrocarbon frameworks.³³ Collectively, these results outline a synthetic cycle for CO₂ reduction with protons and electrons mediated exclusively at boron (Fig. 5).

In addition to the monoborohydride chemistry described above, we were able to generate a diborohydride species *via* formal sequential hydride addition to 3. Two equivalents of K[*sec*-Bu₃BH] reacted with 3 in Et₂O to give the anionic diborohydride complex [Au(B₂P₂)H₂][K(Et₂O)] (6) (Scheme 3). Single-crystal XRD reveals 6 to be a dimer in the solid state, (Fig. 6) with two [Au(B₂P₂)H₂][−] units bridged by two [K(Et₂O)]⁺ cations *via* contacts between the B–H and K atoms. The [Au(B₂P₂)H₂][−] component features a linear P–Au–P moiety (\angle P–Au–P = 161.9°) that sits above the DBA core with no appreciable interaction between Au and B ($d_{\text{AuB}} > 3.25$ Å). The H atoms bound to both B atoms were located on the electron difference map and both B centers exhibit a pseudo-tetrahedral geometry ($\sum \angle$ C–B–C = 337.5°). ¹H and ¹¹B NMR spectra feature a 4-line pattern and doublet, respectively, for the B–H moieties in 6, analogous to the monoborohydride 2 (Fig. S14[†]). Compound 6 is structurally related to the diborohydride species resulting from H₂ activation by reduced DBA compounds reported by Wagner.³⁴



Scheme 3 Synthesis of Diborohydride 6 and its reactivity with CO₂.



Fig. 6 Thermal ellipsoid plots (50%) of the dimer of [Au(B₂P₂)H₂][K(Et₂O)] (6, left) and [Au(B₂P₂)(O₂CH)₂][K(18-c-6)] (7, right). Unlabeled ellipsoids correspond to carbon. Solvent molecules, a disordered crown ether component in 6, and most hydrogen atoms have been omitted for clarity.





Fig. 7 Thermal ellipsoid plots (50%) of the anion $[\text{Au}(\text{B}_2\text{P}_2)(\text{CO}_3)][\text{K}(18\text{-c-}6)]$ (**8**, left) and $\text{Au}(\text{B}_2\text{P}_2)(\text{OSiPr}_3)$ (**9**, right). Unlabeled ellipsoids correspond to carbon. Solvent molecules, disordered components, and hydrogen atoms have been omitted for clarity.

Diborohydride **6** is also reactive towards CO_2 (1 atm), cleanly generating the corresponding diformate complex, which was isolated as its 18-crown-6 adduct, $[\text{Au}(\text{B}_2\text{P}_2)(\text{O}_2\text{CH}_2)_2][\text{K}(18\text{-c-}6)]$ (**7**). Single-crystal XRD confirmed the insertion of CO_2 into both B–H bonds, with B atoms puckered out of planarity to accommodate each OCHO unit. Additionally, the formate moieties in **7** were identified by ^1H NMR (8.34 ppm), $^{13}\text{C}\{^1\text{H}\}$ NMR (168.2 ppm) and FTIR spectroscopy ($\text{C}=\text{O}$, 1672 cm^{-1}).

Having probed the $[\text{Au}(\text{B}_2\text{P}_2)]$ system for CO_2 reduction chemistry from its mono- and dihydrides, we additionally explored the direct reaction of CO_2 with **1**. Wagner *et al.* recently reported that 9,10-dithio-9,10-diborataanthracene reacts with CO_2 to yield CO_3 and CO *via* reductive disproportionation.²⁵ Reaction of **1** with 1 atm of CO_2 in C_6D_6 resulted in the immediate formation of a colorless solution with no detectable precipitate. A single crystal suitable for XRD studies was obtained from CO_2 saturated reaction mixtures and revealed the product to be the carbonate adduct, $[\text{Au}(\text{B}_2\text{P}_2)\text{CO}_3][\text{K}(18\text{-c-}6)]$ (**8**, Fig. 7) (Scheme 4). The asymmetric unit of **8** contains two crystallographically distinct molecules which are chemically equivalent in gross terms but exhibit minor differences in their geometries, most notably in their B–O distances, which range

from $1.550(6)\text{ \AA}$ to $1.578(8)\text{ \AA}$. This spread of B–O distances is consistent with a soft $[\text{CO}_3]^{2-}$ binding potential, in agreement with Wagner's results.²⁵ Solution NMR spectroscopy of **8** is consistent with C_{2v} symmetry and the $[\text{CO}_3]^{2-}$ unit was identified by $^{13}\text{C}\{^1\text{H}\}$ NMR (168.0 ppm) and FTIR (1592 cm^{-1}) spectroscopies with $^{13}\text{CO}_2$ experiments confirming these assignments (see ESI†).

In order to probe the mechanism of the formation of **8** from **1** and CO_2 , we explored the reaction by NMR spectroscopy at low temperature. Recent reports on reduced boron-containing heterocycles,²¹ offer extensive precedent for the cycloaddition of CO_2 across the boron atoms, and we sought to probe whether a similar CO_2 adduct, $[\text{Au}(\text{B}_2\text{P}_2)\text{CO}_2]^-$ (**1-CO₂**), might be an intermediate in the formation of **8**. Addition of a single equivalent of CO_2 to a frozen solution of the anion **1** in d_8 -toluene followed by insertion into a precooled ($-50\text{ }^\circ\text{C}$) NMR spectrometer and subsequent variable temperature NMR monitoring resulted in a 1 : 1 mixture of starting material **1** and the carbonate adduct **8**. When the same experiment was carried out with $^{13}\text{CO}_2$ enhanced intensity was observed corresponding to the $\text{Au}(\text{B}_2\text{P}_2)^{13}\text{CO}_3$ resonance at 168.2 ppm along with free ^{13}CO at 184.5 ppm. These results are consistent with endergonic binding of CO_2 to the DBA core followed by rapid reaction with a second equivalent of CO_2 to release CO and form **8**, analogous to the mechanism established by Wagner in a related system.²⁵ As we were unable to observe the putative CO_2 adduct $[\text{Au}(\text{B}_2\text{P}_2)\text{CO}_2]^-$, we attempted to trap it by other chemical means during the reaction of **1** with CO_2 . Solutions of **1** are stable in the presence of triisopropylsilylchloride (TIPSCl); however, addition of 1 atm CO_2 to a thawing C_6D_6 solution of **1** and TIPSCl resulted in the immediate formation of a pale-yellow solution. Single-crystal XRD studies revealed the product to be the zwitterion $\text{Au}(\text{B}_2\text{P}_2)(\text{OSi}^i\text{Pr}_3)$ (**9**), which contains a triisopropylsilyloxy anion bound to one B atom (Fig. 7). The ^{31}P NMR spectrum contains a set of doublets at 56.0 ($J_{\text{P-P}} = 240\text{ Hz}$) and 52.5 ($J_{\text{P-P}} = 240\text{ Hz}$) ppm while the ^{11}B NMR spectrum featured a broad resonance at 51.5 and a sharper singlet at 2.99 ppm. Two crystallographically distinct molecules of **9** are present in the asymmetric unit although their geometries are essentially identical (Fig. S44†). The formation of **9** occurs with CO loss as judged by $^{13}\text{CO}_2$ labeling experiments. Exposure of **9** to additional CO_2 (1 atm) did not lead to any further reaction, ruling out additional reaction of the $-\text{OTIPS}$ moiety with CO_2 as has been previously observed for metal-siloxide units.³⁵

Conclusions

In conclusion, we have synthesized a reactive borohydride complex, **2**, *via* formal hydride addition, dihydrogen activation, radical H-atom addition, and, most crucially, reduction/protonation. The borohydride unit rapidly inserts CO_2 to afford the formate complex **5**. Both CV and synthetic studies confirm that **5** can be reduced at $E_{1/2} = -1.79\text{ V vs. Fe/Fe}^+$ and undergo formate loss to give the neutral radical **4** and formate *via* reductive B–O cleavage. The cleavage of the B–O bond in **5** can also be achieved *via* addition of electrophiles including TMSCl or $\text{HCl}\cdot\text{Et}_2\text{O}$, to give **3** and TMSOCHO or formic acid,



Scheme 4 Reduction of CO_2 to CO by $[\text{Au}(\text{B}_2\text{P}_2)]^-$.



respectively. Additionally, direct reaction of the anion **1** with 1 atm of CO₂ results in the extrusion of CO and the formation of carbonate complex **8** via the reductive disproportionation of CO₂. Collectively, these reactions outline a strategy for the reduction of CO₂ with protons and electrons via reactive borohydride species generated at redox-active, conjugated boranes, and efforts to extend this chemistry to electrocatalytic systems are underway.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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