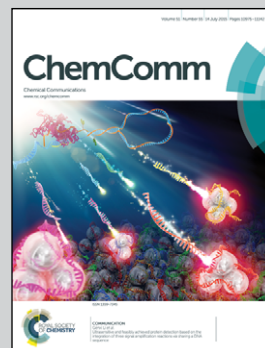


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A novel strategy for reversible hydrogen storage in  $\text{Ca}(\text{BH}_4)_2$

Reversible hydrogen storage is realized in  $\text{Ca}(\text{BH}_4)_2$ . The hydrogen release pathway can be controlled to proceed via  $\text{CaB}_2\text{H}_6$  to  $\text{CaB}_6$ , avoiding boron sinks that hinder reversibility at moderate conditions.

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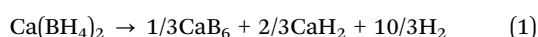
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## A novel strategy for reversible hydrogen storage in $\text{Ca}(\text{BH}_4)_2$ <sup>†</sup>

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**We report that decomposition pathway of  $\text{Ca}(\text{BH}_4)_2$  can be efficiently controlled by reaction temperature. That is, it decomposes into  $\text{CaB}_6$  at a lower temperature range of 320 to 350 °C, but into amorphous boron at 400 to 450 °C. We identified the formation of  $\text{CaB}_2\text{H}_6$  as the crucial intermediate step on the way to  $\text{CaB}_6$  that only forms at 320 to 350 °C.**

Hydrogen is considered an ideal synthetic energy carrier to replace the limited fossil fuels. Wide utilization of hydrogen as a fuel strongly relies on its safe and efficient storage and transport, particularly for mobile applications.<sup>1,2</sup> Light-weight metal borohydrides display high hydrogen densities and thereby offer hope to overcome the challenges associated with solid hydrogen storage.<sup>3</sup> In particular, some borohydrides display an enthalpy change in the decomposition reaction within the targeted window of 20–45 kJ mol<sup>−1</sup> H<sub>2</sub> for reversible on-board storage. For instance,  $\text{Ca}(\text{BH}_4)_2$  shows an enthalpy change of 36 ± 4 kJ mol<sup>−1</sup> H<sub>2</sub> in the decomposition reaction into  $\text{CaB}_6$  according to eqn (1).<sup>4–6</sup>



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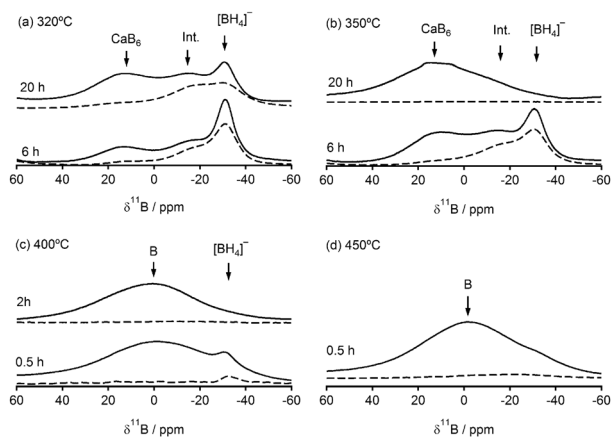
<sup>†</sup> Electronic supplementary information (ESI) available: Methods, H<sub>2</sub> desorption profiles of  $\text{Ca}(\text{BH}_4)_2$  in first two cycles, <sup>11</sup>B MAS NMR spectrum of rehydrogenated  $\text{Ca}(\text{BH}_4)_2$  (350 °C under 185 bar H<sub>2</sub>) after desorption at 450 °C, XRD of  $\text{Ca}(\text{BH}_4)_2$  after partial decomposition under vacuum at 320 to 400 °C, optimized Geometries and optimized cartesian coordinates of  $[\text{BH}_3\text{-OH}]^-$ , <sup>11</sup>B NMR spectra of hydrolysis products of  $\text{Ca}(\text{BH}_4)_2$ , NaBH<sub>4</sub>, LiBH<sub>4</sub> and  $\text{CaB}_6$  in aqueous solutions with different pH values, decay of  $[\text{BH}_3\text{-OH}]^-$  in alkaline solution, calculated IR of  $\text{CaB}_2\text{H}_6$  isomers compared to experimental IR observations, first principles cluster calculations. See DOI: 10.1039/c5cc03605d

One of the main obstacles for metal borohydrides to be utilized as hydrogen storage materials is their poor reversibility. It is generally believed that boron sinks (*i.e.*, amorphous B and/or  $[\text{B}_{12}\text{H}_{12}]^{2-}$  phases) form during the decomposition and hinder rehydrogenation. One strategy to avoid the formation of boron sinks is the addition of additives such as metals or metal hydrides to bind the boron in the form of a metal boride (*e.g.*, AlB<sub>2</sub> and MgB<sub>2</sub>) as the final product. For example, using Al or MgH<sub>2</sub> as an additive, the reversibility of LiBH<sub>4</sub> and NaBH<sub>4</sub> was dramatically improved.<sup>7–10</sup> However, this strategy does not work efficiently for other metal borohydrides such as  $\text{Ca}(\text{BH}_4)_2$ .<sup>5,11,12</sup> Also, the introduction of metal or metal hydrides will unavoidably lower the hydrogen capacity of the system, *e.g.*, from 18.4 wt% H for LiBH<sub>4</sub> to 11.4 wt% H for LiBH<sub>4</sub>–0.5Al.

A number of studies have been conducted aiming to alter the reaction pathway of  $\text{Ca}(\text{BH}_4)_2$ , including the methods of additive addition,<sup>13–16</sup> combination with other complex hydrides,<sup>17–19</sup> nano-confinement,<sup>20,21</sup> application of external H<sub>2</sub> pressure,<sup>22</sup> *etc.* However, all of these methods showed limited effect on avoiding the formation of boron sinks toward full reversibility of  $\text{Ca}(\text{BH}_4)_2$ . The full rehydrogenation to  $\text{Ca}(\text{BH}_4)_2$  has been considered impossible unless a very high H<sub>2</sub> pressure is applied, *i.e.* 400 to 700 bar H<sub>2</sub> at 400 to 440 °C.<sup>5,13,15,23–25</sup>

In present study, we identified the formation of  $\text{CaB}_2\text{H}_6$  as the crucial intermediate step on the way to  $\text{CaB}_6$ , which only forms below 370 °C. Thereby by controlling the decomposition temperature at 320 to 350 °C, the formation of boron sinks such as amorphous boron was efficiently avoided and  $\text{Ca}(\text{BH}_4)_2$  was decomposed in  $\text{CaB}_6$  and  $\text{CaH}_2$ , which facilitate the reversibly absorption of hydrogen under much mild conditions. This study provides new insights into the decomposition mechanism of  $\text{Ca}(\text{BH}_4)_2$  as well as instructions for further development of  $\text{Ca}(\text{BH}_4)_2$  as a hydrogen storage material.

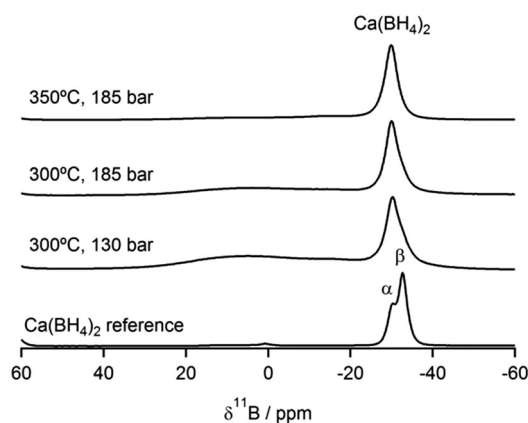
The decomposition of  $\text{Ca}(\text{BH}_4)_2$  was carried out at 320 to 450 °C under dynamic vacuum. The <sup>11</sup>B MAS NMR spectra of the solid residue after decomposition are shown in Fig. 1. After dehydrogenation at 320 °C for 6 to 20 h and 350 °C for 6 h, three resonances were observed, *i.e.*, undecomposed  $\text{Ca}(\text{BH}_4)_2$  at −31.0 ppm, an



**Fig. 1**  $^{11}\text{B}$  MAS NMR spectra of  $\text{Ca}(\text{BH}_4)_2$  after  $\text{H}_2$  desorption under vacuum at 320 °C to 450 °C (a–d). In (a) and (b), the resonance centered at –14 ppm indicates the formation of an intermediate (labelled Int.). Dashed lines represent the  $^{11}\text{B}$  CP-MAS NMR spectra.

intermediate centered at –14 ppm and newly formed  $\text{CaB}_6$  centered at 11 ppm.<sup>24</sup> In the sample dehydrogenated at 350 °C for 20 h, all B–H species disappeared where no B–H signal was detected in the  $^{11}\text{B}$ – $^1\text{H}$  CP-MAS NMR spectrum. Only the resonance assigned to  $\text{CaB}_6$  was observed, indicating the full decomposition of  $\text{Ca}(\text{BH}_4)_2$  into  $\text{CaB}_6$  and  $\text{CaH}_2$ . Also, approximately 9.3 wt% of released hydrogen was recorded during the dehydrogenation process at 350 °C for 20 h and in agreement with eqn (1). In contrast, in the samples decomposed at 400 and 450 °C, only broad resonances centered at 0 ppm, which is assigned to amorphous boron, were observed in the  $^{11}\text{B}$  MAS NMR spectra (Fig. 1c and d). These observations indicate an obvious temperature dependence of the decomposition pathway of  $\text{Ca}(\text{BH}_4)_2$ .

Due to the decomposition into  $\text{CaB}_6$  at 350 °C (20 h), the reversibility of  $\text{Ca}(\text{BH}_4)_2$  was achieved under relatively moderate conditions (300 to 350 °C, 130 to 185 bar  $\text{H}_2$ ). At 300 °C,  $\text{Ca}(\text{BH}_4)_2$  was partially recovered, as observed by  $^{11}\text{B}$  MAS NMR (Fig. 2). Above 90% of boron was transformed back to  $\text{Ca}(\text{BH}_4)_2$  at 350 °C and 185 bar  $\text{H}_2$ . The reversible hydrogen sorption was further confirmed by temperature-programmed-desorption measurements

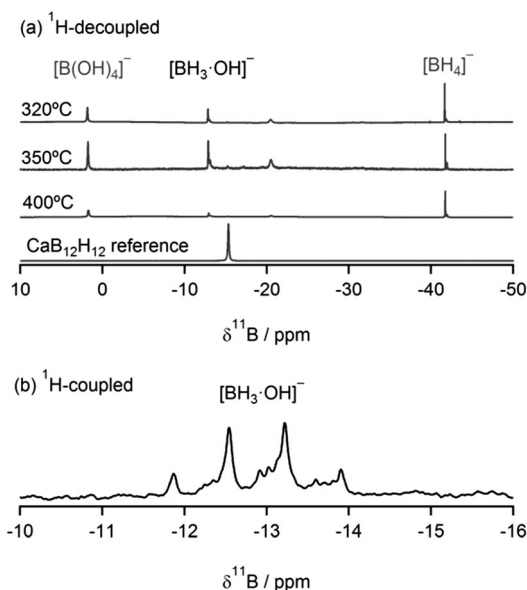


**Fig. 2**  $^{11}\text{B}$  MAS NMR spectra of the rehydrogenated  $\text{Ca}(\text{BH}_4)_2$  at 300 to 350 °C under 130 to 185 bar  $\text{H}_2$ , referred to the pure  $\text{Ca}(\text{BH}_4)_2$ . Before rehydrogenation,  $\text{Ca}(\text{BH}_4)_2$  was dehydrogenated at 350 °C for 20 h.

(Fig. S1, ESI<sup>†</sup>). In contrast, owing to the formation of amorphous boron as the major product at 450 °C (0.5 h), the reformation of  $\text{Ca}(\text{BH}_4)_2$  was very limited at 350 °C and 185 bar  $\text{H}_2$ , *i.e.*, approximately 33% of boron can be converted back to  $\text{Ca}(\text{BH}_4)_2$  (Fig. S2, ESI<sup>†</sup>). These results support the strategy of improving the reversibility by controlling the decomposition pathway.

Note that the intermediate was only observed at 320 and 350 °C (Fig. 1a and b), which shows a chemical shift at –14 ppm close to that of  $\text{CaB}_{12}\text{H}_{12}$  (–15.6 ppm). Thereby this intermediate was tentatively assigned to  $\text{CaB}_{12}\text{H}_{12}$  in the previous study.<sup>22,26</sup>  $\text{CaB}_{12}\text{H}_{12}$  was reported to be a highly stable compound. The self-decomposition of  $\text{CaB}_{12}\text{H}_{12}$  or the reaction between  $\text{CaB}_{12}\text{H}_{12}$  and  $\text{CaH}_2$  requires high temperature such as 600 °C.<sup>27</sup> Since  $\text{Ca}(\text{BH}_4)_2$  could be fully decomposed into  $\text{CaB}_6$  at 350 °C (Fig. 1b), the resonance at –14 ppm should be assigned to another intermediate such as  $\text{CaB}_2\text{H}_x$  ( $2 \leq x \leq 6$ ) which was proposed based on X-ray diffraction (XRD) results.<sup>28</sup> Accordingly,  $\text{CaB}_2\text{H}_x$  were observed by XRD in  $\text{Ca}(\text{BH}_4)_2$  after partial decomposition at 320 and 350 °C, which were not observed when the decomposition occurred at 400 °C (Fig. S3, ESI<sup>†</sup>).

To further identify the reaction intermediate for  $\text{Ca}(\text{BH}_4)_2$ , samples of  $\text{Ca}(\text{BH}_4)_2$  partially decomposed at 320 to 400 °C were dissolved in  $\text{D}_2\text{O}$  and measured by solution-state  $^{11}\text{B}$  NMR (Fig. 3). In all the samples investigated, no  $[\text{B}_{12}\text{H}_{12}]^{2-}$  species were observed. Instead, a new resonance at –13.0 ppm was observed when  $\text{Ca}(\text{BH}_4)_2$  decomposed 320 to 350 °C. It displayed a quartet splitting with a coupling constant  $J_{\text{B-H}}$  of 87 Hz (Fig. 3b), indicating the presence of  $[\text{BH}_3]$  units as  $[\text{BH}_3\cdot\text{OH}]^-$  in aqueous solution.<sup>31</sup> The structure of  $[\text{BH}_3\cdot\text{OH}]^-$  is shown in Fig. S4 (ESI<sup>†</sup>) and the chemical shift of  $[\text{BH}_3\cdot\text{OH}]^-$  was calculated to be –12.9 to –13.5 ppm (Table 1), in agreement with the experimental value.



**Fig. 3** (a)  $^{11}\text{B}$ ( $^1\text{H}$ ) NMR spectra recorded of  $\text{Ca}(\text{BH}_4)_2$  (dissolved in  $\text{D}_2\text{O}$ ) after decomposition under vacuum at 320 °C (6 h), 350 °C (6 h) and at 400 °C (0.5 h), respectively. A reference sample of  $\text{CaB}_{12}\text{H}_{12}$  shows its resonances at –15.3 ppm. (b)  $^1\text{H}$ -coupled  $^{11}\text{B}$  NMR spectra of the resonance at –13 ppm in (a), displaying a quartet splitting of  $[\text{BH}_3]$  unit ( $J_{\text{B-H}}$  of 87 Hz).



**Table 1** Absolute magnetic shielding values (ppm) and chemical shift (ppm) for different boron complexes calculated at B3LYP/6-311+G(2d,p) level of theory<sup>29,30</sup>

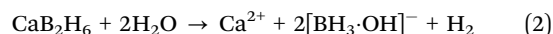
Molecule	Atom	Absolute shielding ( $\delta^{11}\text{B/ppm}$ )	Chemical shift ( $\delta^{11}\text{B/ppm}$ )	
			Referred to $\text{B}_2\text{H}_6$	Referred to $\text{B}(\text{OH})_3$
$\text{B}_2\text{H}_6$	B	83.6	—	—
$\text{B}(\text{OH})_3$	B	81.4	—	—
$\text{Ca}(\text{BH}_4)_2$	B1, B2	136.1	−34.5	−35.1 (−30.9 <sup>a</sup> )
$[\text{B}_2\text{H}_6]^{2-}$	B1, B2	138.5	−36.9	−37.5 (−31.4 <sup>b</sup> )
$[\text{BH}_3\cdot\text{OH}]^-$	B	114.5	−12.9	−13.5 (−13.0 <sup>a</sup> )
$\text{CaB}_2\text{H}_6$				
Isomer 1	B1, B2	105.0	−3.4	−4.0
Isomer 2	B1, B2	91.7 & 125.5	9.9 & −23.9	9.3 & −24.5

The chemical shift of  $\text{B}_2\text{H}_6$  is 18 ppm<sup>30</sup> and that of  $\text{B}(\text{OH})_3$  is 19.6 ppm (measured in this work). In brackets we show the experimental value in this work [a] and calculated value at “MP2/6-31G\* level in ref. 16 [b].

To verify whether the formation of  $[\text{BH}_3\cdot\text{OH}]^-$  results from the hydrolysis of undecomposed  $\text{Ca}(\text{BH}_4)_2$  in water or indicates the presence of a new intermediate, several control experiments were carried out. First, we investigated the hydrolysis of pure  $\text{Ca}(\text{BH}_4)_2$ . Since the presence of  $\text{CaH}_2$  in the decomposition products of  $\text{Ca}(\text{BH}_4)_2$  will produce alkaline solutions when it reacts with water, we dissolved pure  $\text{Ca}(\text{BH}_4)_2$  in aqueous solutions with pH values from 7 to 14. As shown in Fig. S5 (ESI<sup>†</sup>), no  $[\text{BH}_3\cdot\text{OH}]^-$  was observed in the aqueous solutions of  $\text{Ca}(\text{BH}_4)_2$ , regardless of pH values of the solution. This behavior differs from the alkaline metal borohydrides,  $\text{LiBH}_4$  and  $\text{NaBH}_4$ , which do produce  $[\text{BH}_3\cdot\text{OH}]^-$  when reacting with  $\text{D}_2\text{O}$  (Fig. S6, ESI<sup>†</sup>).

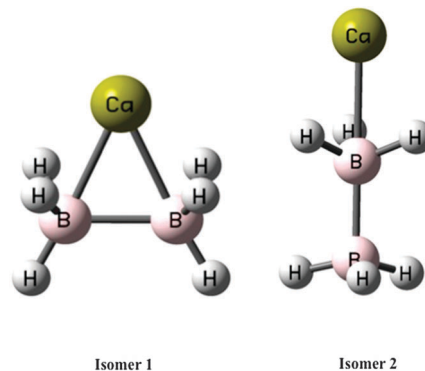
Furthermore, in the alkaline solution (pH = 14) of the partially decomposed  $\text{Ca}(\text{BH}_4)_2$  (350 °C, vacuum, 6 h), the  $[\text{BH}_3\cdot\text{OH}]^-$  species faded with time and converted to  $[\text{B}(\text{OH})_4]^-$  (Fig. S7, ESI<sup>†</sup>). In contrast, no obvious decay of  $[\text{BH}_4]^-$  was observed within 20 h. Also, the reaction of  $\text{CaB}_6$  with  $\text{D}_2\text{O}$  (pH = 7 to 14) at room temperature does not lead to any formation of  $[\text{BH}_3]$  species (Fig. S8, ESI<sup>†</sup>). Therefore, the  $[\text{BH}_3\cdot\text{OH}]^-$  species did not result from the hydrolysis of  $\text{Ca}(\text{BH}_4)_2$  or  $\text{CaB}_6$ , and must originate from an intermediate as observed by  $^{11}\text{B}$  MAS NMR (Fig. 1a and b) at the chemical shift of −14 ppm.

It is known that diborane splits into two  $[\text{BH}_3]$  units in organic solvents (*e.g.*, THF). The  $[\text{BH}_3\cdot\text{OH}]^-$  species observed in this study are very likely the evidence for the formation of a  $[\text{B}_2\text{H}_6]$  compound (*i.e.*,  $\text{CaB}_2\text{H}_6$ ), which analogously splits into two  $[\text{BH}_3]$  moieties in water. This process can be expressed by below equation:



The formation of  $\text{CaB}_2\text{H}_6$  as a reaction intermediate is supported by theoretical calculations. That is, within the compounds  $\text{CaB}_2\text{H}_x$  ( $2 \leq x \leq 6$ ), the formation of  $\text{CaB}_2\text{H}_6$  follows the lowest-energy decomposition pathway.<sup>32</sup>

In the previous study, the intermediate  $\text{CaB}_2\text{H}_x$  was assigned to the resonance at around −31 ppm in the solid-state  $^{11}\text{B}$  NMR spectra, the same chemical shift to  $\text{Ca}(\text{BH}_4)_2$ .<sup>16,26</sup> However, the first principles cluster calculations predicted that electrons redistribution occur when  $\text{Ca}(\text{BH}_4)_2$  converts to  $\text{CaB}_2\text{H}_6$  (Fig. S10, ESI<sup>†</sup>). In another



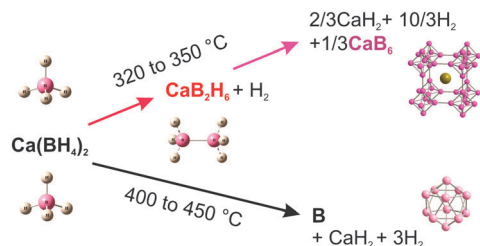
**Fig. 4** Two possible isomers of  $\text{CaB}_2\text{H}_6$  cluster.

word, the chemical environment of boron atoms will change and  $^{11}\text{B}$  chemical shift should be different between  $\text{Ca}(\text{BH}_4)_2$  and  $\text{CaB}_2\text{H}_6$ . The  $^{11}\text{B}$  chemical shift of  $\text{Ca}(\text{BH}_4)_2$  and  $\text{CaB}_2\text{H}_6$  were calculated (Table 1) based on the cluster structures. The calculated  $^{11}\text{B}$  chemical shift of  $\text{Ca}(\text{BH}_4)_2$  is −35.1 ppm referred to  $\text{B}(\text{OH})_3$ , which is close to the experimental values, *i.e.*, −30 and −33 ppm for  $\alpha$  and  $\beta$ - $\text{Ca}(\text{BH}_4)_2$ , respectively (Fig. 2).

The structure  $\text{CaB}_2\text{H}_6$  has been predicted to be monoclinic (space group,  $C2/c$ ),<sup>32</sup> which shows two arrangements of isomer (Fig. 4). Isomer 1 of  $\text{CaB}_2\text{H}_6$  contains one type of boron atom showing a  $^{11}\text{B}$  chemical shift at −4.0 ppm, and isomer 2 contains two types of boron atoms showing chemical shifts at 9.3 and −24.5 ppm, referred to  $\text{B}(\text{OH})_3$ . Either of the two arrangements will show a distinct downfield  $^{11}\text{B}$  resonance relative to  $\text{Ca}(\text{BH}_4)_2$ . Experimentally,  $^{11}\text{B}$  MAS NMR spectra in Fig. 1a and b show three resonances, whereby the two at −31 and 11 ppm were unambiguously attributed to  $\text{Ca}(\text{BH}_4)_2$  and  $\text{CaB}_6$ , respectively. The resonance at −14 ppm was reasonably assigned to  $\text{CaB}_2\text{H}_6$ . The broad feature of the  $^{11}\text{B}$  resonance of  $\text{CaB}_2\text{H}_6$  is owing to the co-existence of these three types of boron atoms.

Above all, we identified  $\text{CaB}_2\text{H}_6$  as the reaction intermediate and ruled out the formation of  $\text{CaB}_{12}\text{H}_{12}$  during the decomposition of  $\text{Ca}(\text{BH}_4)_2$  at 320 to 450 °C under vacuum. The appearance of  $\text{CaB}_2\text{H}_6$  is closely related to the formation of  $\text{CaB}_6$ , and thereby is considered as the crucial intermediate step on the way to  $\text{CaB}_6$ . Furthermore,  $\text{CaB}_2\text{H}_6$  only forms at 320 to 350 °C. This selective formation allows controlling decomposition of  $\text{Ca}(\text{BH}_4)_2$  by reaction temperature, as shown in Scheme 1. As a result, the decomposition of  $\text{Ca}(\text{BH}_4)_2$  at 320 to 350 °C circumvents the formation of boron sinks such as amorphous boron, facilitating the reversibly absorption of hydrogen under much mild conditions. The two distinct decomposition behavior at 320 to 350 °C and at 400 to 450 °C may be related to different physical states of  $\text{Ca}(\text{BH}_4)_2$  which was reported to melt above 370 °C.<sup>33</sup>

The  $[\text{B}_2\text{H}_6]^{2-}$  anion is isostructural to the  $\text{C}_2\text{H}_6$  ethane molecule,<sup>34</sup> which has been reported as a ligand in some organometallic compounds.<sup>35–37</sup> Other  $[\text{B}_2\text{H}_6]^{2-}$  containing compound such as  $\text{K}_2\text{B}_2\text{H}_6$  has been successfully synthesized in THF solution from the reaction of  $\text{K}_2\text{BH}_3$  and  $[\text{BH}_3]$  units.<sup>38</sup>  $\text{MgB}_2\text{H}_6$  has also been discussed,<sup>36,37</sup> while the DFT predictions did not support  $\text{MgB}_2\text{H}_6$  forming as an intermediate for the decomposition of  $\text{Mg}(\text{BH}_4)_2$ .<sup>39,40</sup> On the other hand, octahydroborate,  $[\text{B}_3\text{H}_8]^-$



Scheme 1 Temperature-dependent decomposition pathway of  $\text{Ca}(\text{BH}_4)_2$ .

containing compound, has been identified as the intermediate for  $\text{Mg}(\text{BH}_4)_2$  and  $\text{Y}(\text{BH}_4)_3$ .<sup>41,42</sup>

Why  $\text{CaB}_2\text{H}_6$  rather than  $\text{Ca}(\text{B}_3\text{H}_8)_2$  and  $\text{CaB}_{12}\text{H}_{12}$  forms as the intermediate for  $\text{Ca}(\text{BH}_4)_2$  were further investigated by out first principles cluster calculations. The geometries of the Ca salts including  $\text{Ca}(\text{BH}_4)_2$ ,  $\text{CaB}_2\text{H}_6$ ,  $\text{Ca}(\text{B}_3\text{H}_8)_2$  and  $\text{CaB}_{12}\text{H}_{12}$  are shown in Fig. S10 (ESI†). We found that among all Ca salts,  $\text{CaB}_2\text{H}_6$  is the most strongly bound salt followed by  $\text{Ca}(\text{BH}_4)_2$ ,  $\text{Ca}(\text{B}_3\text{H}_8)_2$  and  $\text{CaB}_{12}\text{H}_{12}$  (Table S2, ESI†). This suggests that during the decomposition of  $\text{Ca}(\text{BH}_4)_2$ , the most preferred intermediate phase is  $\text{CaB}_2\text{H}_6$  (Table S3, ESI†).

In summary, we reported a simple and efficient route to close the hydrogen sorption cycle for pure  $\text{Ca}(\text{BH}_4)_2$  under moderate conditions. Namely,  $\text{Ca}(\text{BH}_4)_2$  releases 9.5 wt% H at 320 to 350 °C via decomposition into  $\text{CaB}_2\text{H}_6$  and  $\text{CaH}_2$  without formation of boron sinks such as amorphous boron and  $\text{CaB}_{12}\text{H}_{12}$ , and rehydrogenation is achieved at the same temperatures and under 130 to 185 bar  $\text{H}_2$ . This affirms that  $\text{Ca}(\text{BH}_4)_2$  is still a promising candidate for reversible hydrogen storage. No additives or catalysts were used in the present study, leaving enough room for further improvement of the hydrogen sorption performance of  $\text{Ca}(\text{BH}_4)_2$  for practical applications.

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