Enhanced hydrogen storage properties of a dual-cation (Li⁺, Mg²⁺) borohydride and its dehydrogenation mechanism‡

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In this paper, we present a new method to synthesize a dual-cation (Li⁺, Mg²⁺) borohydride. It is found that Li−Mg−B−H is formed by mechanical milling a mixture of LiBH₄ and MgCl₂ with a molar ratio of 3 : 1 in diethyl ether (Et₂O) and a subsequent heating process. The morphology and structure of the as-prepared Li−Mg−B−H compound are studied by SEM, XRD, FTIR and NMR measurements. Further experiments testify that Li−Mg−B−H can release approximately 12.3 wt% of hydrogen under 4 bar initial hydrogen pressure from room temperature to 500 °C and reach a maximum desorption rate of 13.80 wt% per h at 375 °C, which is 30 times faster than that of pristine LiBH₄. Thermal analysis indicates that the decomposition process of the new compound involves three steps: (1) Li−Mg−B−H first decomposes into LiBH₄ and MgH₂ and synchronously releases a number of H₂ molecules; (2) MgH₂ decomposes to Mg and H₂; (3) LiBH₄ reacts with Mg, generating H₂, MgB₂ and LiH. Moreover, Li−Mg−B−H is proved to be partially reversible, which can release 5.3 wt% hydrogen in the second dehydrogenation process. The strategy of altering the χₚ of metal ions in borohydrides may shed light on designing dual-cation borohydrides with better hydrogen storage performance.

Introduction

Hydrogen, which produces nearly zero pollutant emission from power generators, is regarded as one of the most promising cost-effective and renewable energy carriers during past decades. However, a safe hydrogen storage technology with a high energy density still challenges scientists worldwide. LiBH₄, which has high gravimetric and volumetric hydrogen densities (18.5 wt% and 121 kg·H₂ per m³), is regarded as one of the most promising hydrogen storage materials. Nevertheless, LiBH₄ is thermodynamically stable and kinetically sluggish in dehydrogenation. Besides, extremely rigorous temperature and pressure conditions are required for LiBH₄ to re-form, which severely limits its practical on-board automobile application.

In past decades, numerous attempts have been carried out to destabilize LiBH₄, including catalyst doping, reactive composite formation, nanocorralment and a combination of strategies. Recently, Orimo et al. found that the thermodynamic stability of ionic borohydrides can be correlated fairly well with the Pauling electronegativity χₚ of metal ions, M⁺; the higher χₚ of M⁺, the less stable M(BH₄)ₓ will be. This finding suggests that the thermodynamic stability of LiBH₄ can be tuned by using metal ions M⁺ with higher χₚ to partially substitute the Li cations to form a dual-cation borohydride LIM(BH₄)ₓ₋₁. Employment of this strategy has yielded several novel dual-cation borohydrides. Jiang et al. successfully synthesized a new Li−Ca−B−H complex borohydride with its first dehydrogenation step started at ca.70 °C, much lower than those of pristine LiBH₄ and Ca(BH₄)₂. Choudhury et al. prepared a new complex hydride LiMn(BH₄)₁ with a 3 : 1 ratio of precursor materials LiBH₄ and MnCl₂ via the solid-state mechano-chemical process. Thermogravimetric analysis (TGA) of LiMn(BH₄)₁ indicated that ca. 8.0 wt% hydrogen can be released between 135 °C and 155 °C in a single dehydrogenation step. Kim et al. found that ball milling LiBH₄ and ScCl₃ produced LiCl and a unique crystalline hydride, which has been unequivocally identified via multinuclear solid-state nuclear magnetic resonance (NMR) to be LiSc(BH₄)₄. Fang et al. claimed that they had synthesized a dual-cation borohydride directly from LiBH₄ and Mg(BH₄)₂ with molar ratio of 1 : 1. Rapid hydrogen release from the LiBH₄/Mg(BH₄)₂ sample was
initiated at around 240 °C, which is about 30 °C and 170 °C lower than that of LiBH₄ and Mg(BH₄)₂. However, Bardaji et al. investigated the physical mixture of xLiBH₄(1–x)Mg(BH₄)₂ with x = 0.10, 0.25, 0.33, 0.40, 0.50, 0.60, 0.66, 0.75, 0.80, 0.90, 1 and found it was only a physical mixture but not a dual-cation borohydrate. The eutectic composition was found to exist at 0.50 < x < 0.60 exhibiting a eutectic melting at 180 °C and the decomposition of the material begins right after the melting. At 270 °C the x = 0.50 composite release about 7.0 wt% of hydrogen. Therefore no confirmed synthesis of dual-cation LiMg(BH₄)₂ has been reported yet.

Inspired by the theory and experiments above, it seems that thermodynamic stability of LiBH₄ can be decreased by introducing metal ions with higher χp. Besides, the most feasible way to synthesize a dual-cation borohydrate is milling LiBH₄ with metal chloride. In this paper, we focus on the Li–Mg–B–H system, aiming to elucidate the possible formation of a dual-cation borohydrate via wet-milling LiBH₄ and MgCl₂ in Et₂O. The samples are carefully characterized and determined by the SEM, XRD, FTIR and NMR measurements, and their hydrogen storage properties have been investigated.

Experimental section

All sample operations were performed in an Ar-filled glovebox, which was equipped with a circulator purification system to maintain the H₂O and O₂ levels below 0.1 ppm. LiBH₄ (assay 95%, Alfa Aesar), NaBH₄ (96%, Sinopharm Chemical Reagent co., Ltd) and MgCl₂ (assay 98%, Sigma) were used as starting materials. Et₂O (C₄H₁₀, 99.5%, Hangzhou Chemical Reagent co., Ltd) was used as solvent. 2 g mixture of LiBH₄ and MgCl₂ in a molar ratio of 3 : 1 together with 60 mL of Et₂O was put into a milled liquid mixture containing borohydride system, aiming to elucidate the possible formation of a dual-cation borohydrate. In this paper, we focus on the Li–Mg–B–H system, aiming to elucidate the possible formation of a dual-cation borohydrate via wet-milling LiBH₄ and MgCl₂ in Et₂O. The samples are carefully characterized and determined by the SEM, XRD, FTIR and NMR measurements, and their hydrogen storage properties have been investigated.

Results and discussion

Morphology and elemental distribution of samples were identified by scanning electron microscopy (SEM, Hitachi SU-70) equipped with an energy dispersive X-ray spectroscopy (EDX, HORIBA-Max). X-ray diffraction analysis was conducted on an X’Pert Pro X-ray diffractometer (PANalytical, Netherlands) with Cu Kα radiation at 40 kV and 40 mA. A special container fully filled with high purity Ar was prepared to avoid air exposure during sample transferring and testing. Fourier transform infrared (FTIR) spectra were obtained with a Bruker Tensor 27 unit in transmission mode. Solid state magic angle spinning (MAS) NMR spectra were obtained using a Bruker Avance 300 MHz spectrometer with a wide bore 7.04 T magnet and employing a boron-free Bruker 7 mm CP/MAS probe. The spectral frequency was 75 MHz for the 11B nucleus and the NMR shifts are reported in parts per million (ppm) externally referenced to NaBH₄. The powder materials were packed into 7 mm ZrO₂ rotors in an argon-filled glovebox and were sealed with tight fitting Kel-F caps. The one-dimensional (1D) 11B MAS NMR spectra were acquired after a 1.7 µs single π/2 pulse (corresponding to radio field strength of 92.6 kHz). The spectra were recorded at a MAS spinning rate of 5 kHz. The recovery delay was set to 5 s. Spectra were acquired at 20 °C.

Morphology and structure of as-prepared samples

SEM images of as-prepared samples are presented in Fig. 1. LiBH₄ has a flocculent surface in Fig. 1a (×1.00k) and larger magnification picture (Fig. 1b) shows a smooth surface with small holes in it. Comparing Fig. 1c with 1e, the as-synthesized Mg(BH₄)₂ shows similar morphology with the as-prepared Li–Mg–B–H but with worse electroconductivity. Under enlarged magnification, as-prepared Li–Mg–B–H shows a smooth surface similar to that of LiBH₄, while a much rougher surface with small particles on it emerges in the as-synthesized Mg(BH₄)₂. In addition, as we can see from the EDX mapping data of Li–Mg–B–H in Fig. S1† the Mg and B elements are dispersed homogeneously in the Li–Mg–B–H matrix, further demonstrating the possibility of the formation of a new compound.

In order to determine the microstructures of as-prepared Li–Mg–B–H, XRD and FTIR examinations of LiBH₄, as-synthesized Mg(BH₄)₂ and as-prepared Li–Mg–B–H were recorded, presented in Fig. 2. The XRD pattern of as-synthesized Mg(BH₄)₂ in Fig. 2c shows diffraction peaks of both low temperature phase α-Mg(BH₄)₂ and high temperature phase β-Mg(BH₄)₂, indicating that the as-synthesized Mg(BH₄)₂ was a mixture of α-Mg(BH₄)₂ and β-Mg(BH₄)₂. The physical mixture of LiBH₄ and Mg(BH₄)₂ with a molar ratio of 1 : 1 (Fig. 2c) shows the total diffraction peaks of LiBH₄ and Mg(BH₄)₂. The appearance of LiCl in Fig. 2d and in the filter residue (Fig. S2†) demonstrates the reaction between LiBH₄ and MgCl₂ occurred during the wet-chemical ball milling process. Combining all the analyses of the diffraction patterns of relevant samples, peaks at 2θ = 16°, 18.1°, 19.1°, 25°, 27.3° in Fig. 2d should be assigned predominately to a new phase, this agrees well with Fang’s conclusion and these new phases may come from a new dual-cation borohydrate.
From the results of FTIR measurements, typical features of [BH₄]⁻ group can be readily observed in the spectra, i.e. the stretching and deformation of B–H bonds in the regions between 2200 and 2400 cm⁻¹ and 1100 and 1300 cm⁻¹, respectively. The B–H absorption band is split into three contributions at 2386 cm⁻¹, 2291 cm⁻¹, and 2223 cm⁻¹. The B–H bending vibration in LiBH₄ is at 1125 cm⁻¹ while that of Mg(BH₄)₂ is split into two contributions at 1125 cm⁻¹ and 1267 cm⁻¹. The presence of an absorption band around 1033 cm⁻¹ contributes to a Li–Mg–B–H sample. In order to further clarify the specificity of Li–Mg–B–H, NMR measurements were adopted to test the chemical shift of ¹¹B of LiBH₄, as-synthesized Mg(BH₄)₂, as-prepared Li–Mg–B–H, physical mixed LiBH₄–Mg(BH₄)₂, respectively. If the as-prepared Li–Mg–B–H is a physical mixture, the chemical shift peak of ¹¹B should be a combination of those of LiBH₄ and Mg(BH₄)₂. However, as the NMR results shown in Fig. 3, as-prepared Li–Mg–B–H exhibits different peaks. The peaks of LiBH₄, Mg(BH₄)₂ and physical mixed LiBH₄–Mg(BH₄)₂ appear at -40.30, -39.89, and -40.02 ppm, respectively. The peak of physical mixed sample is asymmetric (a shoulder at around -45 ppm) and the chemical shift is just between -40.30 and -39.89 ppm, which proves the nature of physical mixing. However, the chemical shift of ¹¹B in the primary new Li–Mg–B–H compound is -39.59 ppm, indicating a new chemical circumstance for B. Considering that the starting ingredient are 3LiBH₄–MgCl₂, the new compound is more likely to be LiMg(BH₄)₂.
measure out the exact composition of the new compound. Through the above discussion, the as-prepared Li–Mg–B–H is not just a physical mixture of LiBH₄ and Mg(BH₄)₂ but a new dual-cation borohydride.

**Hydrogen desorption performance**

The DSC-MS characteristics of as-prepared Li–Mg–B–H are shown in Fig. 4. DSC curve exhibits five endothermic peaks, which correspond to the structure transition (104.4 °C), melting (174.2 °C), and decomposition of as-prepared Li–Mg–B–H (260.9, 358.3, 391.6 °C), respectively. MS results demonstrate that the gas released is pure H₂ without B₂H₆, and MS desorption peak temperatures are in good agreement with DSC results. Kou et al. found that initial hydrogen pressure had a great impact on the dehydrogenation of 2LiBH₄→MgH₂ system. Under four bar initial hydrogen pressure, LiBH₄ reacts with Mg to yield MgB₂, which is essential for the reversibility of this system. Four bar initial hydrogen pressure was also adopted to explore its effect on the decomposition of Li–Mg–B–H. Fig. S3† presents the XRD patterns of the decomposed sample of Li–Mg–B–H at different initial hydrogen pressures. We can see from Fig. S3† that when hydrogen pressure raises to 4 bar a tip bumps up at around 42°, which is the main diffraction peak of MgB₂. This testifies that four bar initial hydrogen pressure can help to form MgB₂ during decomposition. Hence, variable temperature hydrogen desorption behavior of the as-prepared samples was conducted using a TPD apparatus under four bar initial hydrogen pressure.

Fig. 5 shows TPD curves of LiBH₄, as-synthesized Mg(BH₄)₂, and as-prepared Li–Mg–B–H. It was observed that the decomposition of the pristine LiBH₄ started sluggishly at 320 °C, resulting in a final release of 4.3 wt% hydrogen at 500 °C. As-synthesized Mg(BH₄)₂ first decomposed at 300 °C, quickly releasing a large amount of H₂ with the elevating temperature and finally reached a 11.7 wt% hydrogen release at 500 °C. Worth-noting, the operating temperature for hydrogen desorption of as-prepared Li–Mg–B–H was significantly reduced to 250 °C, 70 °C and 50 °C lower compared to that of pristine LiBH₄ and as-synthesized Mg(BH₄)₂, respectively. In total, 12.3 wt% hydrogen was released from the dual-cation borohydride, which is three times larger comparing to that of pristine LiBH₄ (4.3 wt%) and higher than that of as-synthesized Mg(BH₄)₂ (11.7 wt%). Furthermore, the new compound can release hydrogen at a rate of 13.80 wt% per h at 375 °C, just as fast as as-synthesized Mg(BH₄)₂, 30 times faster than pristine LiBH₄ (0.45 wt% per h). The findings indicate that the idea of using higher X_p of metal ions Mg²⁺ to partially substitute the Li cations to form a dual-cation borohydride Li–Mg–B–H truly improves both the dehydrogenation thermodynamics and kinetics of LiBH₄.

**Dehydrogenation reaction mechanism**

In order to fully understand the dehydrogenation process, the as-prepared Li–Mg–B–H was heated to different temperatures (295, 395, and 495 °C) according to the DSC-MS and TPD results and the decomposed products were collected and applied with XRD and FTIR measurements, displayed in Fig. 6. In the XRD
patterns, Fig. 6b shows that high-temperature phase of LiBH$_4$, MgH$_2$ and MgO (MgO comes from the air contamination of the sample during operation) formed after heated at 295 °C. From the FTIR profile in Fig. 6b, we can see that the peaks of the B–H bonding at 2291, 2223 and 1125 cm$^{-1}$, which confirm the presence of LiBH$_4$.$^8$ When heated up to 395 °C, metallic Mg and MgO are the only phases detected by XRD, whereas the diffraction peaks of MgH$_2$ are completely absent. The FTIR pattern shows that LiBH$_4$ still exists. So in this step, MgH$_2$ decomposes to Mg and H$_2$. As the dehydrogenation temperature further increases to 495 °C, the final products are Mg, MgO, MgB$_2$ and LiH. And the peaks of B–H bonds disappear in FTIR, indicating the complete decomposition of LiBH$_4$. To sum up, the main decomposition pathway of the new compound under four bar initial hydrogen pressure can be described as follows:

**Fig. 4** DSC and MS profiles of Li–Mg–B–H at a heating rate of 5 °C min$^{-1}$ from room temperature to 500 °C.

**Fig. 5** TPD profiles of LiBH$_4$, Mg(BH$_4$)$_2$ and Li–Mg–B–H at a heating rate of 2 °C min$^{-1}$ from room temperature to 500 °C under 4 bar initial hydrogen pressure.

**Fig. 6** XRD patterns and FTIR spectra of Li–Mg–B–H decomposed at different temperatures: (a) room temperature, (b) 295 °C, (c) 395 °C, and (d) 495 °C.
Hydrogen storage reversibility

Reversibility is one of the key features for hydrogen storage materials, especially for on-board applications. In order to study the reversibility of the new compound, we use temperature programmed absorption as well as isothermal rehydrogenation. Fig. 7a shows the temperature absorption curve from room temperature to 500 °C with a heating rate of 2 °C min⁻¹. The pressure is increasing linearly before the temperature is heated to 420 °C, while maintaining and even decreasing when the temperature is above 420 °C. This indicates that the
The dehydrogenated product of Li–Mg–B–H could be rehydrogenated at about 420 °C. From the isothermal rehydrogenation curve at 420 °C in Fig. 7b, the reduction in hydrogen pressure is related to the amount of absorbed hydrogen. XRD patterns (see in Fig. S4†) show that the rehydrogenated sample is composed of MgH2 and LiBH4. The dehydrogenation performance of the rehydrogenated sample was further carried out. The dehydrogenation curve is shown in Fig. 8, and it can be observed that the rehydrogenated products can release 5.3 wt% hydrogen, indicating that the new compound has certain reversibility. Nevertheless, this is a great improvement for the reversibility of Li–Mg–B–H comparing with a previous work,21 which can only be rehydrogenated to MgH2 and release about 2 wt% hydrogen. Owing to the complexity of Li–Mg–B–H, detailed experimental and theoretical studies are still required to better understand the cyclic de/rehydrogenation behaviors of the Li–Mg–B–H system.

Conclusion

In summary, a new dual-cation borohydride Li–Mg–B–H has been successfully synthesized by ball-milling 3LiBH4 + MgCl2 mixture in Et2O. Further investigations show that dehydrogenation performance of the new Li–Mg–B–H was affected by initial hydrogen pressure. Under four bar initial hydrogen pressure, the onset dehydrogenation temperature of Li–Mg–B–H (250 °C) is 70 °C and 50 °C lower compared to pristine LiBH4 and Mg(BH4)2, respectively. The Li–Mg–B–H can release 12.3 wt% hydrogen from room temperature to 500 °C according to the following three steps:

(Step 1)

\[ \text{Li–Mg–B–H} \rightarrow x\text{LiBH}_4 + \text{MgH}_2 + B + H_2 \quad (0 < x \leq 1) \]

(Step 2)

\[ \text{MgH}_2 \rightarrow \text{Mg} + \text{H}_2 \]

(Step 3)

\[ x\text{LiBH}_4 + \text{Mg} \rightarrow 0.5x\text{MgB}_2 + x\text{Li} + 1.5\text{H}_2 + (1 - 0.5x)\text{Mg} \]

In addition, partial reversibility of Li–Mg–B–H has been demonstrated and 5.3 wt% hydrogen can be released in the second cycle. According to the experimental results of this work, the strategy of altering the \( \chi_0 \) of metal ions in LiBH4 can truly improve the hydrogen storage properties of LiBH4 and it may provide general guidance and inspiration in dual-cation borohydrides hydrogen storage materials with advanced and controllable performances.

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