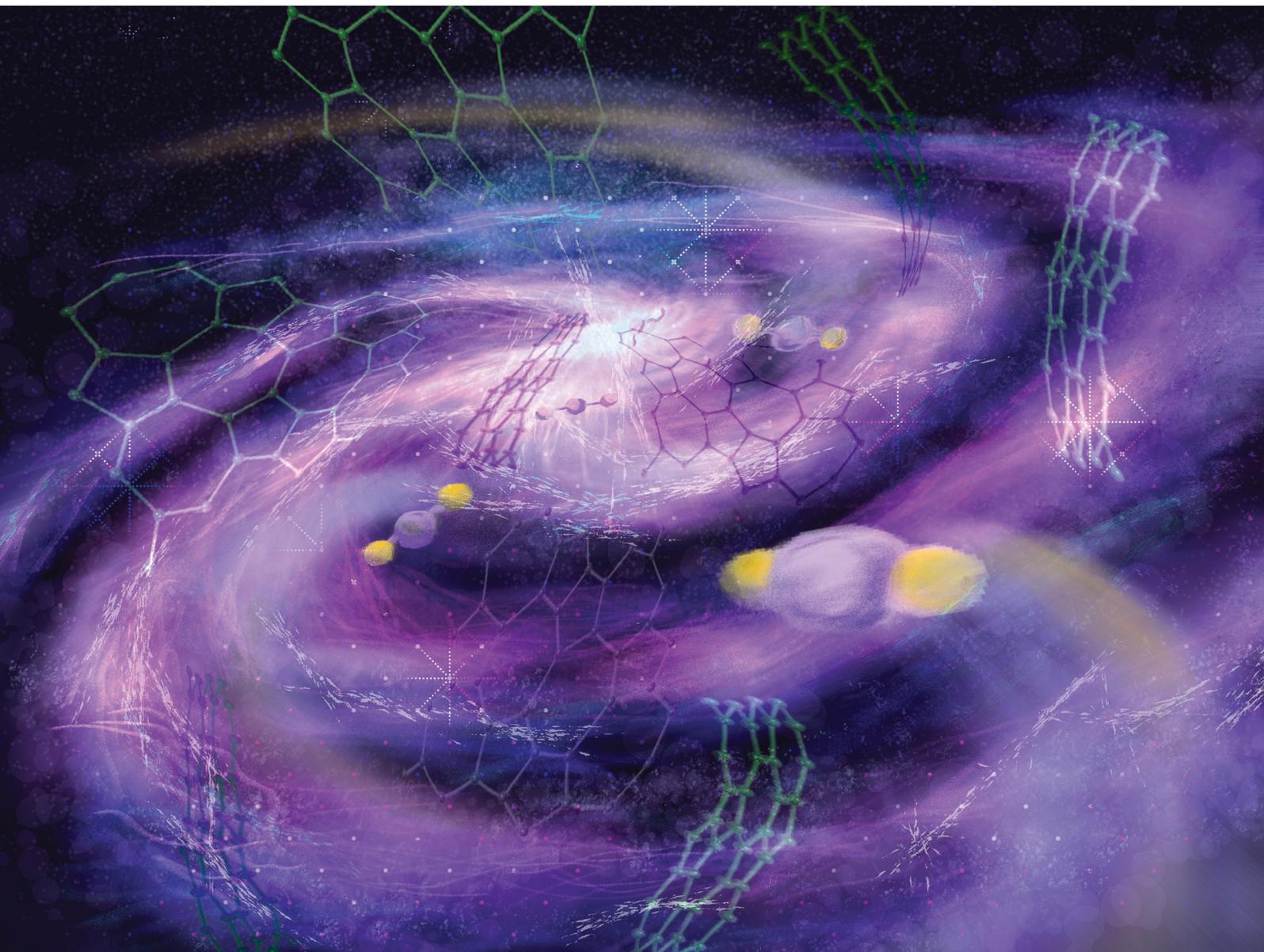


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Probing layered  $Y(TM)B_4$  ( $TM = Cr, Mo$  and  $W$ ) borides as  
efficient hydrogen evolution reaction electrocatalysts


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## Probing layered Y(TM)B<sub>4</sub> (TM = Cr, Mo and W) borides as efficient hydrogen evolution reaction electrocatalysts

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**In this study, three layered ternary metal borides were analyzed: YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. YWB<sub>4</sub> demonstrated the highest catalytic activity, surpassing the Pt/C catalyst by 185 mV overpotential at an industrially relevant current density of 1000 mA cm<sup>-2</sup>. Furthermore, stability testing revealed that YWB<sub>4</sub> retained 95% of its initial activity after 25 hours of continuous operation (5000 cycles) at 1000 mA cm<sup>-2</sup>, underscoring its potential as a robust and sustainable HER catalyst for hydrogen production.**

Due to growing public concern over limited fossil fuel reserves, environmental issues, and climate change, there has been a significant rise in interest towards sustainable and renewable energy sources.<sup>1</sup> Hydrogen has stood out as a highly promising solution to the global energy crisis in recent years due to its high energy density, zero-carbon emission, and eco-friendly nature, and consequently, it is viewed as a viable alternative to fossil fuels.<sup>2–5</sup> The industrial generation of hydrogen from fossil fuels, which releases CO<sub>2</sub> alongside H<sub>2</sub>, is inconsistent with the principles of sustainable development in today's society and economy.<sup>6</sup> Water splitting powered by renewable resources is regarded as one of the most promising technologies.<sup>7,8</sup> Electrochemical and photoelectrochemical processes are the two leading methods for water splitting.<sup>9</sup> Practically, electrocatalysis is preferred over photocatalysis due to its superior efficiency.<sup>10</sup> Recently, water electrolysis has attracted significant interest as a method for hydrogen production. This process involves using electrical energy to split water into hydrogen (*via* the hydrogen evolution reaction, HER) and oxygen (*via* the oxygen evolution reaction, OER), making it a promising approach for generating hydrogen using renewable energy sources.<sup>11–13</sup> Electrocatalysts are crucial for efficiently producing hydrogen and minimizing the overpotential in water electrolysis. Platinum group metals are

recognized as the most efficient electrocatalysts for the HER, offering low overpotentials.<sup>14</sup> Due to their high cost and limited availability, their applications remain restricted.<sup>15</sup> Consequently, developing highly efficient, low-cost HER electrocatalysts to replace Pt-based materials is crucial for large-scale hydrogen production.

Bulk metal borides have recently attracted attention for their remarkable properties, such as superhardness,<sup>16</sup> thermoelectric behavior,<sup>17</sup> magnetic characteristics<sup>18,19</sup> and potential solid-state fuels.<sup>20</sup> In recent years, compounds derived from earth-abundant transition metals have gained significant research attention because of their affordability and widespread availability.<sup>21,22</sup> Some transition-metal-derived materials found to be more active and stable for the HER are transition metal alloys (TMAs),<sup>13</sup> dichalcogenides (TMDs),<sup>23</sup> nitrides (TMNs)<sup>24</sup> and carbides (TMCs).<sup>25</sup> In recent times, transition metal borides like Mo-B (in both bulk and nanoscale forms),<sup>26–30</sup> MoAlB (bulk),<sup>31</sup> Co-B (amorphous),<sup>32,33</sup> Ni-B (amorphous and nanoscale),<sup>34</sup> Co-Ni-B (amorphous),<sup>35</sup> and FeB<sub>2</sub> (nanoscale)<sup>9</sup> have emerged as promising HER electrocatalysts. This is attributed to their abundance, cost-effectiveness, and excellent HER performance and stability in acidic and alkaline environments. Metal borides, compared to metal carbides, sulphides, and phosphides, exhibit better HER activity (Table S3). Although these materials are superior at low current densities, they underperform at high current densities (Table S3).

In recent years, molybdenum-based materials like molybdenum disulfide,<sup>36</sup> molybdenum carbide,<sup>37</sup> and molybdenum phosphides<sup>38</sup> have been widely studied as cost-effective alternative electrocatalysts for the hydrogen evolution reaction (HER). Although molybdenum and tungsten share similar chemical and physical properties, tungsten-based materials have been significantly less explored than molybdenum. For instance, tungsten disulfide,<sup>39</sup> carbides,<sup>40</sup> and phosphides<sup>41</sup> demonstrate comparable or even superior HER activity relative to their molybdenum analogues. Nevertheless, tungsten-based borides have not yet been explored. Chromium belongs to the

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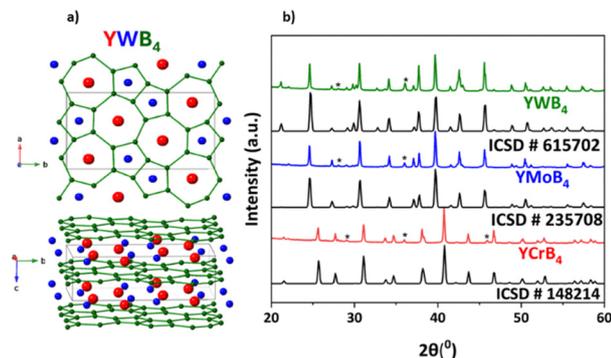


Fig. 1 (a) Crystal structure of YWB<sub>4</sub>, (b) powder X-ray diffraction patterns for YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. Reference patterns: ICSD 148214,<sup>45</sup> 235708,<sup>46</sup> and 615702,<sup>43</sup> respectively. (\*) – peaks for YB<sub>4</sub>.

same group in the periodic table as molybdenum and tungsten, and therefore shares specific chemical characteristics, including the ability to form similar compounds with boron.<sup>42</sup>

In this study, the successful synthesis of YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> analogues was presented; among these, YWB<sub>4</sub> exhibits excellent HER activity and high current density performance. These materials were prepared *via* arc-melting, following the method detailed in the SI. Briefly, high-purity yttrium, chromium, molybdenum, tungsten, and boron powders were weighed in the Y : M : B = 1 : 1 : 4.25 stoichiometric ratios (totaling 0.75 g), compacted into pellets, and then arc-melted under an argon atmosphere. Optimizing arc-melting parameters, particularly the applied current, was determined to be a critical step for the successful synthesis of the desired phases (SI). The synthesized materials were characterized using powder X-ray diffraction (PXRD) (Fig. 1). Fig. 1a depicts the crystal structures of YWB<sub>4</sub> (*Pbam*, ICSD 615702).<sup>43</sup> This crystal structure is similar to AlB<sub>2</sub>, with both being layered with alternating layers of boron and metal. However, in AlB<sub>2</sub> the boron atoms are arranged in sheets of hexagons, while in YWB<sub>4</sub> the boron atoms are arranged in 7- (accommodating Y) and 5-membered rings (accommodating Cr, Mo, and W metals). This is due to the difference in radii of Y (180 pm) and other transition metals (Cr – 140 pm, Mo – 145 pm, and W – 135 pm).<sup>44</sup> The bond lengths of the three crystal structures are listed in Table S1, and they follow the trend of the atomic radii for the three metals (increasing from Cr to Mo and decreasing for W). The bond length correlates with the activity seen for the Cr, Mo and W cases, suggesting that an optimal bond length can be achieved through solid-solution formation that would further enhance the performance. Fig. 1b presents the powder X-ray diffraction patterns for all three compounds. Each target phase was successfully formed with more than 95% weight purity, although a minor impurity phase (YB<sub>4</sub>) was also detected. Pure YB<sub>4</sub> showed essentially no catalytic activity (Fig. S2) and as such does not contribute to the activity of the main phase.

The electrochemical hydrogen evolution reaction (HER) activity of the ternary borides YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> has been investigated for the first time. Electrochemical measurements were conducted in a conventional three-electrode setup using

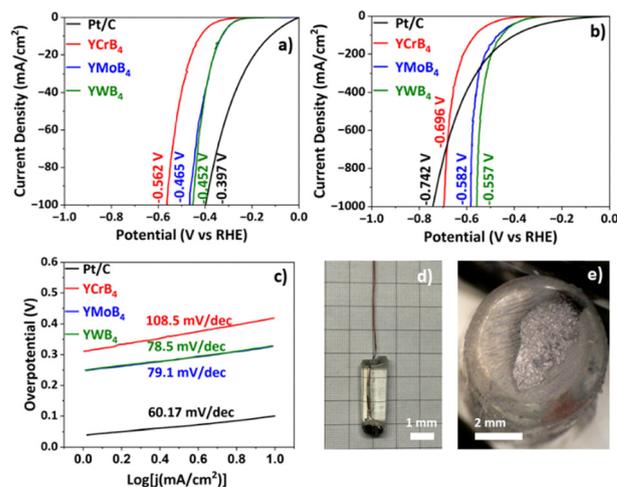


Fig. 2 (a) Polarization curves of 20% Pt/C, YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> measured in 0.5 M H<sub>2</sub>SO<sub>4</sub>. (b) Polarization curves showing high current density behaviours of 20% Pt/C, YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. (c) The corresponding Tafel plots of 20% Pt/C, YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. (IR-drop was compensated.) (d) Working electrode assembly after polishing on sandpaper. (e) Electrode surface of YWB<sub>4</sub>.

0.5 M H<sub>2</sub>SO<sub>4</sub> as the electrolyte, with a scan rate of 5 mV s<sup>-1</sup> and an IR compensation applied (Fig. 2). The working electrodes consisted of polished arc-melted ingots mounted in epoxy and attached to copper wire (details in the SI). As shown in the polarization curves in Fig. 2a, YWB<sub>4</sub> exhibited the lowest overpotential of 452 mV to reach a current density of 100 mA cm<sup>-2</sup>, outperforming both YCrB<sub>4</sub> and YMoB<sub>4</sub>. This establishes YWB<sub>4</sub> as a highly efficient HER catalyst, with its overpotential being 110 mV lower than that of YCrB<sub>4</sub> (562 mV) at 100 mA cm<sup>-2</sup>. Under high current densities of 1000 mA cm<sup>-2</sup>, the overpotential difference increases to 139 mV compared to YCrB<sub>4</sub> (Fig. 2b). Notably, when the current density exceeds the industrial benchmark of 300 mA cm<sup>-2</sup>,<sup>47</sup> it not only further increases the overpotential difference between YWB<sub>4</sub> and YCrB<sub>4</sub> (Fig. 2b), but also provides a superior performance of about 25% over the self-tested Pt/C. A comparison of the samples studied in this paper with other reported metal borides is presented in Table S3. The mechanism of the catalytic process and the nature of the active sites are currently under investigation through a computational collaboration.

The Tafel plot is commonly used to show the catalytic mechanism of the hydrogen evolution reaction (HER). In general, three fundamental steps can serve as the rate-determining step (RDS): the Volmer step (electrochemical hydrogen ion adsorption, Tafel slope  $\approx$  120 mV dec<sup>-1</sup>), the Heyrovsky step (electrochemical desorption,  $\approx$  40 mV dec<sup>-1</sup>), and the Tafel step (chemical desorption,  $\approx$  30 mV dec<sup>-1</sup>). The experimentally determined Tafel slopes for YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> are 108.5 mV dec<sup>-1</sup>, 79.1 mV dec<sup>-1</sup>, and 78.5 mV dec<sup>-1</sup>, respectively (Fig. 2c). These values fall within a range of 78.5–108.5 mV dec<sup>-1</sup>, which does not correspond precisely to any of the ideal theoretical slopes. This indicates the complexity of the HER mechanism on these bulk catalysts and makes it



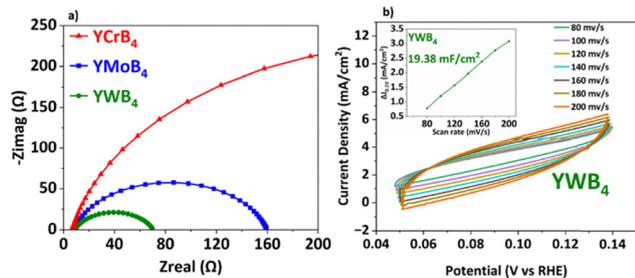


Fig. 3 (a) Electrochemical impedance spectroscopy (EIS) Nyquist plots of YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. (b) Cyclic voltammetry curve of YWB<sub>4</sub>. (Inset showing the difference in the current density of  $\Delta J (J_a - J_c)$  at 0.1 V vs. RHE plotted against the scan rate is fitted to a linear regression to estimate  $C_{dl}$ .)

challenging to identify the RDS from Tafel analysis alone. Nonetheless, YWB<sub>4</sub> displays the smallest Tafel slope, indicating a more rapid and efficient HER process compared to the other boride samples. Fig. 2d and Fig. 2e represent the working electrode assembly after polishing on sandpaper and the electrode surface of YWB<sub>4</sub>, respectively.

As shown in Fig. 3a, the solution resistance ( $R_s$ ) that was used for IR-drop compensation was nearly identical for all samples, attributed to the consistent electrode preparation method. The Nyquist plots for each sample were fitted using an equivalent circuit model incorporating a constant phase element (CPE). The excellent HER performance of YWB<sub>4</sub> can be linked to its high electrochemically active surface area (ECSA). The ECSA of YWB<sub>4</sub> is shown in Fig. 3b and estimated by determining its double-layer capacitance ( $C_{dl}$ ) using cyclic voltammetry (CV) at scan rates ranging from 80 to 200  $\text{mV s}^{-1}$  in the non-faradaic region (0.05–0.15 V vs. RHE).<sup>42</sup> YWB<sub>4</sub> exhibited a  $C_{dl}$  value of 19.38  $\text{mF cm}^{-2}$ , which exceeds several previously reported values,<sup>28,42,48</sup> further highlighting its superior catalytic activity.

X-ray photoelectron spectroscopy (XPS) data were collected to investigate the surface composition of YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> before and after electrocatalysis (Fig. S4–S12). The starting surfaces indicate typical metal boride features, with a thin oxide/hydroxide formation upon exposure to air. Metallic features are clearly derived from the asymmetry of the boride core levels. After electrocatalysis, a thicker oxide/hydroxide layer of similar composition as the initial surface is measured. The SEM–EDS characterization (Fig. S13–S15) and XPS data (Table S1) confirm the uniform distribution of Y, transition metals (Cr, Mo, W), and B in YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub>. The obtained atomic ratios closely match the desired stoichiometric ratios, confirming homogeneous mixing and successful formation of the desired borides.

Catalyst stability and durability are essential factors for real-world applications, particularly in acidic media. To evaluate these characteristics, comprehensive tests were conducted on the Y(TM)B<sub>4</sub> electrodes. Long-term stability was assessed *via* cyclic voltammetry over 2500 ( $\approx 12.5$  hours) to 5000 cycles ( $\approx 25$  hours) for YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> at a high current density of 1000  $\text{mA cm}^{-2}$ . As illustrated in Fig. 4a, the post-test polarization curve showed only a slight deviation for all the

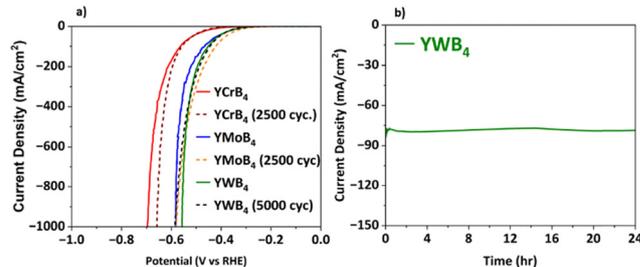


Fig. 4 (a) Polarization curve of YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> before and after 2500, 2500, and 5000 cycles, respectively. (b) Chronoamperometry curve of YWB<sub>4</sub> for 24 h.

electrodes, with the YWB<sub>4</sub> electrode retaining a high percentage (95%) of its initial catalytic activity. Durability was further examined for YWB<sub>4</sub> through a continuous electrolysis experiment (chronoamperometry) at a constant current density of approximately 80  $\text{mA cm}^{-2}$  for 24 hours. As shown in Fig. 4b, the current density remained nearly unchanged, indicating excellent durability. These findings demonstrate that YWB<sub>4</sub> exhibits outstanding stability and durability under extended, industrial scale operating conditions, making it a strong candidate for sustainable hydrogen production in harsh environments.

In conclusion, the ternary metal borides YCrB<sub>4</sub>, YMoB<sub>4</sub>, and YWB<sub>4</sub> were successfully synthesized *via* arc melting, characterized, and evaluated for their hydrogen evolution reaction (HER) performance in a highly acidic environment for the first time. Among them, YWB<sub>4</sub> demonstrated the highest HER activity, outperforming both its counterparts and even surpassing the performance of the commercial Pt/C catalyst at elevated current densities. Additionally, YWB<sub>4</sub> exhibited remarkable long-term stability and durability, with negligible loss in HER activity after 5000 cycles and 25 hours of continuous operation in an acidic electrolyte. These findings highlight the significant potential of boride-based materials as promising HER electrocatalysts for future sustainable hydrogen production.

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## Conflicts of interest

There are no conflicts to declare.



## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: details of synthesis and characterization of the metal borides. See DOI: <https://doi.org/10.1039/d5cc06558e>.

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