Progress of Proton-Boron Research for Fusion Energy in China

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Proton-11boron (p-11B) fusion offers a promising clean energy pathway, leveraging abundant, eco-friendly aneutronic fuel and offering direct electricity generation via alpha particles. However, it faces many challenges: extreme heating requirements, plasma performance demands, uncertainties in reaction cross-sections, and complexities tied to nonthermalized plasma physics (e.g., Rider's models [1]). Practical hurdles include boosting reaction rates, achieving sustained fusion in magnetic confinement systems, and refining diagnostic tools for reactor control. Despite these barriers, p-11B fusion garners major attention for its potential to deliver safe, near-limitless energy with minimal environmental impact. This overview is structured around three areas of this research: underlying physics of p-11B fusion reaction, enhancement of fusion rate, and study of p-11B reaction in magnetic devices.

The uncertainties in measurements and the role of unthermalized plasma conditions in p-11B fusion define the first area. The cross-section measurement techniques through the past 20 years have improved substantially beyond those of the 1960s and 1970s [2] with higher accuracy and covering broader solid angles. The results are shown in Fig. 1, indicating that the earlier measurements are verified. Rider's analysis [1] considered non-Maxwellian electron velocity distributions with very low electron-to-ion temperature ratios. However, by extending Rider's model to ion and electron temperatures to hundred's keV and accounting for the contribution of fusion alpha heating [3], we find a net energy gain window as shown in Fig. 2. The recirculating power loss fraction can drop to zero as T_e is raised beyond 130 keV. A minimum required energy confinement zone for Q-fusion > 10 is found when T_e/T_i is maintained around 0.5. Lower ratios would lead to higher recirculating power loss and lower Q-fusion.

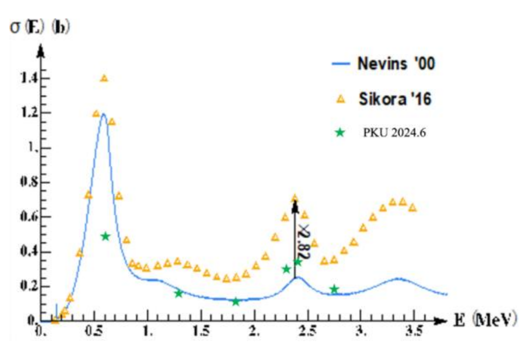

Fig. 1, p11B Cross-section data of new measurements and previous measurements.

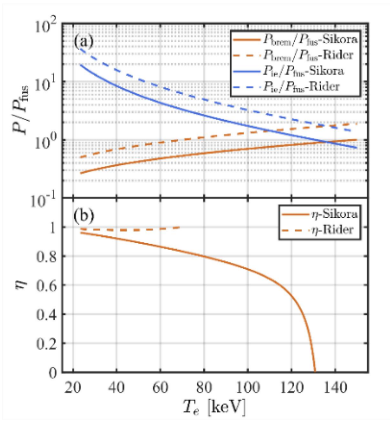

Fig. 2, (a) The ratio P/P_{fus} as a function of electron temperature. (b) the required recycled efficiency of the recirculating power as a function of electron temperature.

Secondly, enhancing the reaction rate is crucial for the success of p-11B fusion energy. Significant enhancements have been observed in accelerator and laser-based experiments, and theoretical efforts are underway to extend these findings to magnetic fusion conditions. In low energy proton-beam (120 - 260 keV) experiments, we found that the alpha-particle yield increased by ~30% when a proton beam impinges on a mixed-hydrogen-boron target, compared to a pure boron target (see, Fig. 3 [4]). When picosecond laser induced high-intensity energetic proton beams impinge on boron-bearing foam targets, we observed up to 10^{10}/sr alpha particles per laser shot [5]. A 2-3 orders of magnitude enhancement of proton beam intensity and a 4-5 orders enhancement of the alpha-particle yield are observed (see, Fig. 4). This nonlinear enhancement is under investigation and is currently attributed to the presence of strong electric fields enhancing non-thermal-to-thermal fusion reactions.

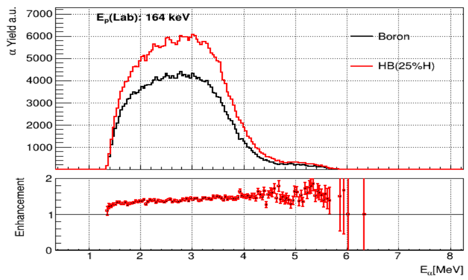

Fig. 3, A typical α spectrum at E_{lab} = 164 keV, comparing the boron (black) and HB (red) targets.

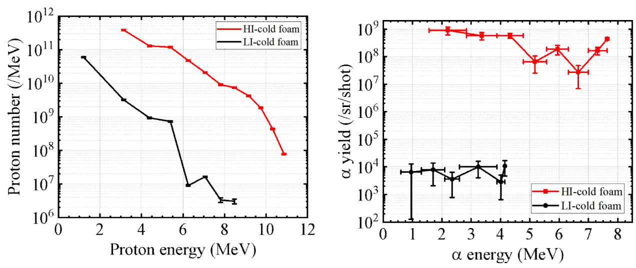

Fig. 4, The measured energy spectra of (a) proton beams and (b) alpha-particle beams from plasma and foam targets with protons in high intensity and low intensity.

Thirdly, achieving p11B reaction in magnetic fusion devices is a top priority. Systematic assessments for p11B reaction in magnetic fusion devices (EXL-50U [6] and EHL-2 [7]) have been conducted. In EHL-2, with 200keV 1MW NBI, 1.5×10^{15} and 5×10^{14} alpha particles per second are expected for thermal-thermal reactions and beam-thermal fusion respectively (see, Fig.5 [8]). In the case of EXL-50U, the ICRH-NBI synergy may drive superthermal-thermal p-^{11}B reactions and produces approximately 1.2×10^{9} alpha particles per second when 40-keV 500kW NBI and 50kW ICRH are applied (see, Fig.6). Feasibility of p-11B detection through lost-alpha-particle and Gamma-ray diagnostics are also carried out.

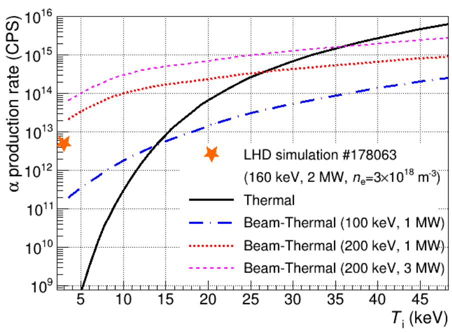

Fig. 5, Comparison of reactivities between thermal-thermal and beam-thermal reactions in EHL-2.

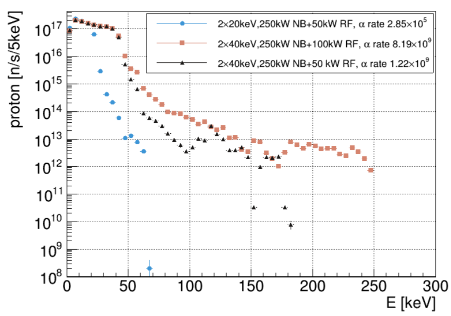

Fig. 6, Comparison of alpha production rate for NBI+ICRF scheme with different power combinations.

This progress and the challenges encountered in aneutronic p-11B fusion research will be presented.

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