Laser-driven non-thermal aneutronic Proton-Boron fusion reactions in solid-density plasma

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Deuterium-tritium (D-T) fusion has been the primary focus of nuclear fusion energy research due to its relatively low ignition temperature of approximately 10 keV. However, its practical application will face environmental concerns, including tritium leakage, neutron-induced material embrittlement, and the scarcity of tritium resources. Here, we have developed a reliable diagnostic scheme for investigating the potential of high-intensity laser-driven proton-boron (^{11}B (p, α) 2α or p-^{11}B) fusion as an alternative to D-T fusion [1]. By leveraging advanced laser systems and innovative target geometries, this research provides insights into laser-driven proton acceleration, proton transport, and nuclear reaction dynamics through precise diagnostics and computational modeling for advancing the understanding of p-^{11}B fusion reactions and for fast ignition inertial confinement fusion [2].

The p-^{11}B reaction is aneutronic, making it a safer and more viable option for energy production. The thermal fusion approach of p-^{11}B reaction requires an ignition temperature of 240 – 320 keV due to its lower reactivity and more substantial bremsstrahlung losses [3]. A non-thermal approach offers an alternative for p-^{11}B-based fusion energy, and several groups reported significant increases in the detected number of α particles beyond simple theoretical predictions with the non-thermal approach. Proposed mechanisms for these enhancements include plasma screening [4] and α-particle-driven avalanche reaction [5].

Previous p-^{11}B fusion studies relied heavily on α particle detection using a track detector. However, energetic hydrogen, boron, and other ions emanating from laser-produced plasma and environmental α emitters easily contaminate these detector signals. Additionally, the produced α particles may be stopped within the fuel itself. Therefore, precise measurement of the in-target proton energy distribution is essential to understand the p-^{11}B fusion reaction comprehensively.

The present study developed an activation-based diagnostics scheme that utilizes radioactive byproducts, specifically ^{11}B (p, n) ^{11}C and ^{10}B (p, α) ^{7}Be reactions. This method determines proton energy distribution inside the target by using different dependences of the cross-section of these reactions on proton energy. This method involves one-dimensional transport calculations considering cold, solid-density decaborane ($H_{14}B_{10}$) with a density of 0.94 g/cm³ as the target material. The model assumes straight-line proton paths without accounting for straggling and uses cold-stopping power obtained from SRIM simulations for interactions between proton and target. Production probabilities of ^{11}C and ^{7}Be were calculated for different monoenergetic protons. The incident proton energy distribution was assumed to follow a Boltzmann distribution with a single slope temperature, which is consistent with previous experimental observations. The segment and slope temperature of the Boltzmann distribution were found to agree with the measured quantities of ^{11}C and ^{7}Be. Finally, the number of p-^{11}B fusion reactions was estimated using the reaction cross-sections and the inferred proton energy distribution.

The experiment utilized decaborane ($H_{14}B_{10}$) composed of boron with a natural isotopic ratio. The p-^{11}B fuel exploded following kJ-class LFEX laser shots, releasing debris that contained radioactive isotopes. The p-^{11}B fuel was located at the center of the debris capture. The debris capture is a high-purity aluminum tube having holes for laser and plasma x-ray diagnostics with a 3.84π steradian coverage, assuming a debris collection probability of 0.96 (= 3.84/4.0). This assumption may lead to a slight underestimation of the actual number of p-^{11}B reactions. Figure 1 presents γ-ray spectroscopy of the captured debris, revealing two distinct γ -ray peaks at 477.6 keV and 511 keV. Figure 2 shows decay curves of γ-ray peaks with their half-lifetimes corresponding to those of ^{7}Be (53.2 days) and ^{11}C (20.4 minutes). The radioactivities of ^{7}Be and ^{11}C were calculated from the detected γ-ray counts, considering the spatial distribution of the radioactive isotopes within the debris collector and the detection efficiency. The radioisotope distribution was measured using an imaging plate covering the debris collector. The detection efficiency was modeled using the GEANT4 Monte Carlo simulation code, which accounted for variations in efficiency based on the isotope locations.

This study introduces an innovative hollow spherical-shell fuel geometry in addition to the traditional in-target and pitcher-catcher configuration. In the hollow shell design, protons and boron nuclei, accelerated from the inner surface of the shell, collide at the center of the shell and then create a high-temperature and high-density plasma core, thereby increasing the probability of fusion reactions. The experimental results showed that the p-^{11}B reactions in the hollow spherical geometry were more frequent than in-target or pitcher-catcher setups.

Furthermore, decaborane and borophane were chosen as target materials for their high boron content. The compression characteristics of these materials under laser-driven shock waves were also observed with X-ray free electron laser SACLA, revealing structural features attributed to their inherent non-uniformities behind the shock wave. This analysis is critical for understanding their implosion dynamics and optimizing their use in future fusion systems.

Deformable mirrors are being installed in the LFEX laser system to increase the laser's focusing intensity to 1×10^{20} W/cm^2, which is expected to improve the p-^{11}B reaction efficiency further. Using the enhanced LFEX laser, we will also investigate the performance of advanced proton acceleration mechanisms, such as hole boring or radiation pressure acceleration [6], which enabled more efficient and moderate proton acceleration, increasing reaction rates in the coming experiment.

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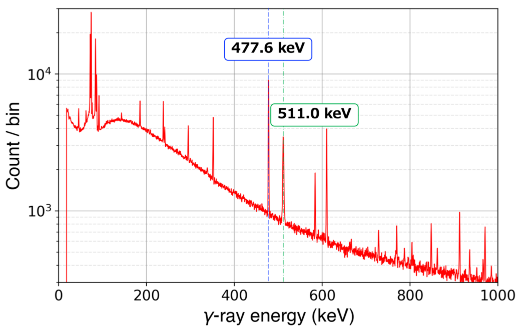

Figure 1 γ-Ray spectrum emitted from the debris collector after a laser shot. Two distinct peaks at 477.6 keV and 511 keV correspond to ^{7}Be and ^{11}C nuclei.

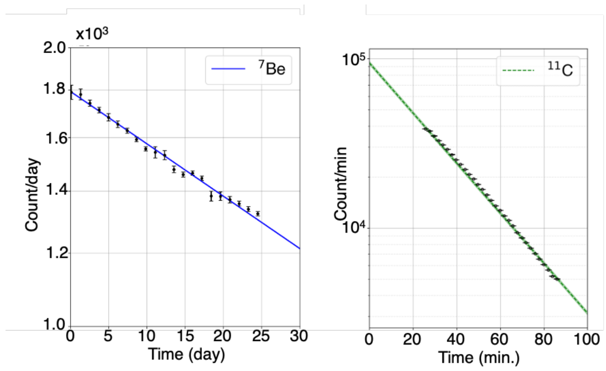

Figure 2 Decay curve of 477.6 keV and 511 keV γ-rays. The measured half-lifetimes are consistent with the half-lifetimes of ^{7}Be (53.2 days) and ^{11}C (20.4 min.).