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Nuclear Reaction Rates in Laser-Driven Non-Equilibrium Plasmas

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Recent advancements in laser-based particle acceleration technologies have opened new possibilities for conducting nuclear reaction studies at tabletop scales. Among various laser-based nuclear reaction experiments, this research focuses on the pitcher-catcher configuration utilizing laser-driven ion beams.

Typically, nuclear reaction rates in equilibrium plasmas, such as astrophysical environments, are calculated using Maxwell-Boltzmann distributions. However, laser-driven ion beams generated through the Target Normal Sheath Acceleration (TNSA) mechanism [1,2] inherently produce non-equilibrium ion distributions. As a result, equilibrium-based models are insufficient, requiring a framework that accounts for non-equilibrium ion distributions.

In this study, we first conduct detailed numerical calculations focusing on the p + ^{11}B fusion reaction, widely investigated in pitcher-catcher experiments. By numerically modeling the proton beam's non-equilibrium distribution, we determine the reaction rates as functions of the relevant laser parameters, identifying optimal conditions under which the fusion reactivity reaches a theoretical maximum of $\langle\sigma v\rangle = 8.12 \times 10^{-16}\,\mathrm{cm}^3/\mathrm{s}$ [3]. These findings establish a fundamental upper limit for achievable fusion reactivity in laser-driven p + ^{11}B experiments, even under optimized experimental conditions.

Second, we present an analytical formulation of nuclear reaction rates derived from the self-similar solution of the TNSA mechanism [1], offering explicit results for non-resonant nuclear reactions. This analytical approach redefines the traditional Gamow energy window, extending its applicability to non-equilibrium, laser-driven plasmas. The outcomes of this framework not only provide valuable guidance for designing future laser-driven nuclear fusion experiments but also enhance our understanding of astrophysical nuclear processes.

[1] Mora, P. 2003, PhRvL, 90, 185002

[2] Fuchs, J., Antici, P., d'Humières, E., et al. 2006, NatPh, 2, 48

[3] Hwang, E., Cheoun, M.-K., & Jang, D. 2025, arXiv:2504.07124

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