White Paper for *Frontiers of Plasma Science Panel*

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Title:	**Plasma nuclear science for exploring nuclear physics relevant to stellar nucleosynthesis**
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1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Plasma nuclear science for exploring nuclear physics relevant to stellar nucleosynthesis

Thermonuclear reaction rates and nuclear processes have been explored traditionally by means of conventional accelerator experiments, which are difficult to execute at conditions relevant to Stellar Nucleosynthesis (SN) and Big-Bang Nucleosynthesis (BBN). Even when measurements are possible using accelerators at relevant energies, thermonuclear reaction rates in stars and BBN are inherently different from those in accelerator experiments. The fusing nuclei are surrounded by bound electrons in accelerator experiments, whereas electrons occupy mainly continuum states in a stellar environment and in HED plasmas. Developing a High-Energy-Density (HED) platform for measurements of this type allows us to push the frontiers of laboratory nuclear astrophysics into a new realm.

Here, we describe recent preliminary accomplishments and future directions for using HED plasmas for studies of T+T, ^{3}He+^{3}He and T+^{3}He reactions, which are relevant to either SN or BBN. Future work will include using HED plasmas with varying conditions at OMEGA and the NIF, with current/upgraded/new nuclear diagnostics [1-4] and new models and theory [5-6], to understand details of the underlying physics of light-ion reactions by simultaneously measuring yields and spectra of several reaction products.

Lessons learned from these early studies of T+T, ^{3}He+^{3}He and T+^{3}He reactions will be used in studies of other reactions, including p+D$\rightarrow$^{3}He+γ. The goals are to explore thermonuclear reaction rates and relevant basic nuclear physics in stellar-like plasma environments, compare results to traditional accelerator experiments, and push the frontier into regimes not reachable through existing platforms.

<u>1. The T+T reaction</u>: To extend previous studies of the T+T$\rightarrow\alpha$+n+n reaction [7-8], a mirror reaction to the ^{3}He+^{3}He$\rightarrow\alpha$+p+p solar fusion reaction, novel measurements of the T+T neutron spectrum have been conducted at OMEGA at Gamow peak energies in the range of 18–55 keV. These reactions proceed through different intermediate states (final state interactions) to the 3-body final state, and the shapes of the resulting broad energy spectra are modified based on the relative strength of the different final state interactions. Preliminary results from this effort are shown in Fig. 1. The neutron spectra clearly display a ^{5}He ground state-resonance at 8.7 MeV in addition to the characteristic three-body continuum from 0 – 9.4 MeV. The ^{5}He ground state is an example of a short-lived, intermediate state which will subsequently decay to an alpha particle and a neutron. Most notable is the difference in relative strength of the n+^{5}He resonance between the 18 and 55 keV data, which is in contradiction to current theoretical modeling. A possible explanation for this variation is that the T+T reaction can go through the l=1 wave (in addition to l=0) and more easily overcome the angular momentum barrier of the l=1 channel, which seems to favor the ground state of ^{5}He at higher Gamow peak energies. Refined theoretical modeling and further measurements will address this conjecture.

No accurate measurements of the T+T neutron spectrum below 2 MeV currently exist [5]. In addition, while a first attempt to measure the T+T alpha spectrum has been conducted, this measurement was compromised by D+T alphas originating from deuterium contamination in the T_2 fuel. On the basis of this result (with 1% deuterium contamination level in the T_2 gas), it is evident that the deuterium contamination level in the T_2 gas must be reduced to a level below 0.1% for a clean measurement of the T+T alpha spectrum. We plan to use HED plasmas for the first time to simultaneously measure complete spectra of neutrons and alphas from the T+T reaction. Having information about the T+T alpha spectrum and the low-energy part of the T+T neutron spectrum will be essential to understanding the final-state interactions. In particular, the shape of the high-energy portion of the T+T alpha spectrum is crucial for identifying the role of the n-n final-state interactions. Upgraded and new neutron and charged-particle spectrometry techniques [3-4] will be used for these measurements.

<u>2. The ^{3}He+^{3}He reaction</u>: A proof-of-principle study of the ^{3}He+^{3}He$\rightarrow\alpha$+p+p solar fusion reaction at a Gamow peak energy of ~165 keV has been conducted using HED plasmas at OMEGA, and the result from that measurement is shown in Fig. 2. This reaction constitutes the final and dominant energy-producing step of the proton-proton I chain, responsible for ~86% of the ^{4}He produced in the sun.

Analogous to the T+T reaction, the ^{3}He+^{3}He reaction is also expected to proceed through a number of possible intermediate states of varying strength, which modify the shape of the final spectrum. The spectrum shown in Fig. 2, measured with compact Wedge-Range-Filter proton spectrometers [1], displays a three-body continuum and a p+^{5}Li resonance at 9.1 MeV. As the alpha spectrum and proton spectrum below 4 MeV could not be measured in this experiment, we plan to implement a new type of compact spectrometer to measure complete spectra of both the alphas and protons from the ^{3}He+^{3}He reactions [9]. That capability will allow detailed probing of final-state interactions between the alpha and two protons by measuring complete spectra of these particles. In particular, the shape of the alpha spectrum at the high-energy end is crucial for identifying the role of the p-p final state interaction in a six-nucleon system. This information will be used to benchmark nuclear theory. Detailed measurements of the full spectral shape will also enable more accurate interpretation of accelerator-measured ^{3}He+^{3}He reaction rates.

Measuring the ^{3}He+^{3}He reaction at lower Gamow-peak energy is very challenging on OMEGA, where plasmas with lower Gamow peak energy do not produce enough yield for a high-statistics measurement. To experimentally probe the ^{3}He+^{3}He reaction at Gamow peak energies down to ~50 keV, we plan to take this effort to NIF, where the larger plasmas and higher laser energy on capsule enable these measurements. In parallel to the experimental effort, new theoretical models are also being developed and benchmarked by the experiments. The purpose of this theoretical effort is to accurately describe the ^{3}He+^{3}He reaction and reaction-product spectra at Gamow peak energies from ~165 keV down to solar conditions (the ^{3}He+^{3}He Gamov peak energy is 22 keV in our Sun).

3. The T+^{3}He reaction: Using HED plasmas at OMEGA, a first set of preliminary T+^{3}He data has been obtained at a Gamow peak energy of ~80 keV (Fig. 3). In addition to the 3-body final state T+^{3}He→α+p+n (analogous to T+T and ^{3}He+^{3}He), two other possible branches for this reaction are T+^{3}He→α+d and T+^{3}He→^{6}Li+γ. The motivation for studying this reaction is, first, the lack of high-quality data for the n+p and deuteron branches at low reactant energies [10]. Second, a significantly larger γ-producing branch than expected could explain the anomalously high concentrations of ^{6}Li in primordial material in low-metallicity halo stars [11-12].

The first preliminary results, which will be used to begin addressing these questions, are shown in Figs. 3a and 3b. Like the T+T and ^{3}He+^{3}He spectra, the T+^{3}He proton spectrum shown in Fig. 3a clearly shows the three-body continuum and the p+^{5}He resonance at ~9.3 MeV. A large discrepancy between measured and R-matrix modeled spectra is observed, indicating that more refined modeling needs to be developed. Additionally, the deuteron branch has been measured (but not shown here), which together with the proton branches will further constrain the physics of final-state interaction between the reaction products. In an extension of this experiment, the T+^{3}He proton spectrum and ratio of the deuteron and proton branches will be probed at various Gamow peak energies, including lower Gamow-peak energies only accessible on NIF, which will increase our understanding of the underlying physics of this reaction at various HED plasma conditions.

In Fig. 3b, the measured S-factor for the T(^{3}He,γ)^{6}Li reaction is shown and contrasted to higher-energy data taken by Blatt *et al*. [13]. The preliminary OMEGA data, obtained in collaboration with LANL, shows that the T(^{3}He,γ)^{6}Li S-factor is nearly as low as expected from extrapolations of the Blatt data [14] and seems to rule out a larger γ-producing reaction branch as an explanation for the anomalously high concentrations of ^{6}Li observed in primordial material [11-12]. As this is a radiative-capture reaction, it is surprising that the S-factor decreases significantly with decreasing reactant energy. This was the main reason why Boyd and Madsen erroneously ruled out the Blatt data and assumed a constant high value for the S-factor at low reactant energies in their BBN modeling. An R-matrix calculation by Gerry Hale appears to better capture the measurements; the low-energy calculated behavior may be due to an interference effect of direct capture. New data at lower Gamow-peak energy will address this question. The error bars will be reduced by removing the DT-γ background in the T^{3}He-γ data. This will be accomplished by using tritium gas with a much lower deuterium contamination level. Lower Gamow-peak energies will be achieved in measurements at the NIF.

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Figures

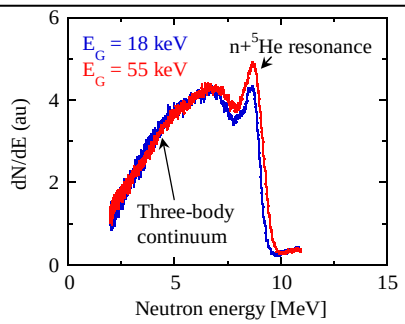

FIG. 1. Measured neutron spectra from T+T reactions in a HED plasma characterized by Gamow peak energy of 18 keV (blue) and 55 keV (red). The spectra indicate that the shape varies with Gamow peak energy, which is in contradiction with current understanding. Additional experiments and refined theoretical modeling will address this issue. (Note: the OMEGA data are preliminary and have not yet been corrected for the spectrometer response function.)

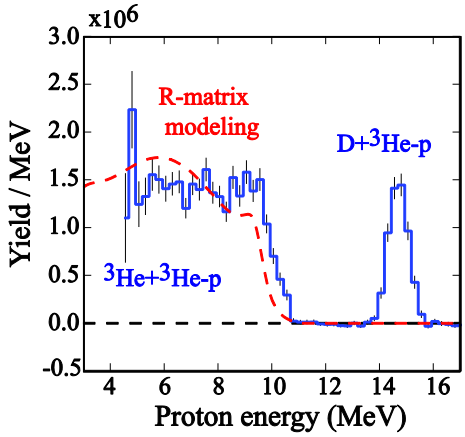

FIG. 2. The first ^{3}He+^{3}He proton spectrum ever obtained using High-Energy-Density (HED) plasmas. This proton spectrum was measured with WRF proton spectrometers on OMEGA at a Gamow-peak energy E_G~165 keV. For comparison, an R-matrix modeled spectrum is also shown. Clearly, the theoretical spectrum does not describe the measured data well. The underlying reason for this will be addressed in future work, which will involve studies of this reaction along with the analogue T+T and T+^{3}He reactions at as-of-yet unexplored lower Gamow-peak energies to probe the physics of final-state interactions and how they vary with Gamow-peak energy. A small D+^{3}He proton signal (at ~14.7 MeV) from deuterium contamination in the ^{3}He fuel is also observed in these data.

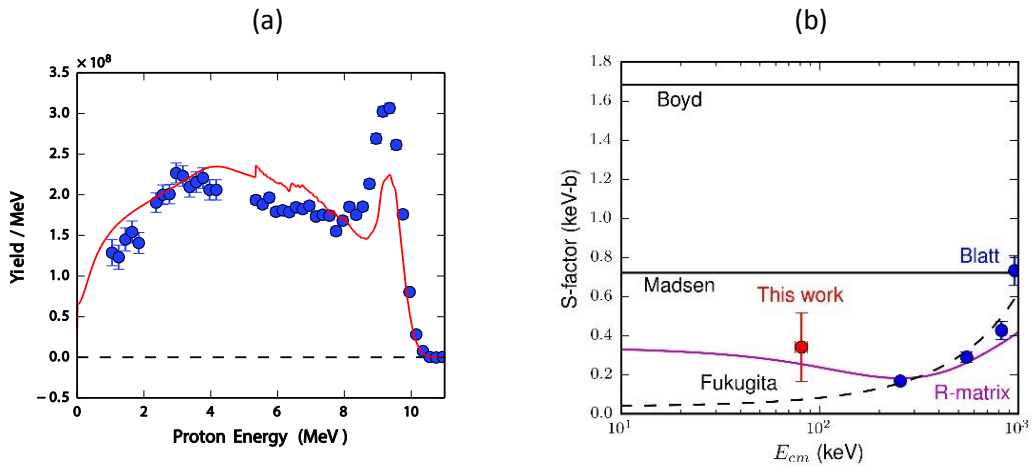

FIG. 3. (a) The first measured T+^{3}He proton spectrum ever obtained using HED plasmas. A large discrepancy between measured (blue points) and R-matrix modeled (red line) spectrum indicates that the theoretical modeling needs to be refined. (b) Measured S-factor for the T(^{3}He,γ)^{6}Li reaction (red data point), which is contrasted to higher-energy data taken by Blatt *et al*. [13]. Boyd [11] and Madsen [12] expected a flat S-factor for this radiative capture reaction, but our OMEGA data show that was incorrect. The R-matrix calculation by Gerry Hale appears to better capture the measurements; the low-energy calculated behavior may be due to an interference effect of direct capture. New data with reduced error bars and at lower energy will address this question. Our data also show that this reaction cannot explain observations of anomalously high concentrations of ^{6}Li in primordial material.