First measurement of the $T(\text{^3He,}\gamma)^{6}\text{Li}$ reaction using high-energy-density plasmas


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First measurement of the $T(^3\text{He},\gamma)^6\text{Li}$ reaction using high-energy-density plasmas

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Nuclear reactions during the big bang created light nuclei from protons and neutrons, in a process called Big-Bang Nucleosynthesis (BBN). These reactions occurred in a ‘network’, producing elements up to Li and Be. High levels of $^6\text{Li}$ observed in low-metallicity stars1 present a problem for BBN theory, which cannot explain the observations. Here we use an inertially-confined high-energy-density laboratory plasma to measure the rate for the reaction $T(^3\text{He},\gamma)^6\text{Li}$, a candidate for anomalously-high $^6\text{Li}$ production during BBN2; we find that the rate is too low to explain the observed levels of $^6\text{Li}$ in low-metallicity stars. Further, we find that current BBN models use rates either too high or too low at low energies. This improved knowledge of the $T(^3\text{He},\gamma)^6\text{Li}$ reaction rate will strengthen future BBN modeling using an adjusted rate, but cannot explain high levels of observed $^6\text{Li}$. This is the first use of laboratory plasmas to address an open problem in nuclear astrophysics; as these plasmas have similar conditions to stellar cores and the universe during the big bang; we anticipate that similar experiments using this technique will enhance our understanding of big-bang and stellar nucleosynthesis in the future.

While most light nuclei abundances in primordial material are explained well by the BBN theory3–5, observations of high levels of $^6\text{Li}$ in low-metallicity stars1,6 disagree with BBN-modeled levels of $^6\text{Li}$ by three orders of magnitude.

During BBN several nuclear reactions could produce excess $^6\text{Li}$, such as $^4\text{He}(\text{D},\gamma)^7\text{Li}$ and $^3\text{He}(\gamma)^6\text{Li}$. Recent work has ruled out the first reaction7, while the latter has been hypothesized as a solution to this problem2 if the rate is much higher than expected.

The nuclear physics of this hypothesis is contentious8 yet still an open question5. This is primarily due to the lack of high-quality data for this reaction, with previous experiments being conducted primarily at high energies and with large inconsistencies between the reported datasets9. Only one dataset exists at low energy ($E_{cm} \leq 1$ MeV), which is in the range where BBN reactions occurred; the fidelity of this data has also been questioned in the literature2,5. This strongly motivates additional experiments to determine if this reaction could explain the observed levels of $^6\text{Li}$ in low-metallicity stars via BBN production.

In this Letter, we report on novel measurements of the $T(^3\text{He},\gamma)^6\text{Li}$ reaction using high-energy-density plasmas (HEDP), which were generated by using the OMEGA laser facility10 to implode gas-filled thin-glass ‘exploding pusher’11 capsules as shown in Fig. 1. In these experiments, the laser delivered 17KJ of energy in a 600ps duration square pulse, illuminating the outer surface of a glass microballoon 960 $\mu$m in diameter and 2.5 $\mu$m thick, filled with a 30:70 atomic mixture of T and $^3\text{He}$ gas at 20 atm.

![Diagram](image-url) FIG. 1. Left: Experimental schematic, right: capsule pie diagram. The 60 OMEGA laser beams illuminate the outer surface of a small spherical glass shell, which is filled with $T_2$ and $^3\text{He}$ gas. The shell is 960 $\mu$m in diameter and 2.5 $\mu$m thick, filled with a 30:70 atomic mixture of T and $^3\text{He}$ gas at 20 atm.
density plasma in which nuclear reactions occurred\textsuperscript{11,12}. In these implosions, ion temperatures reached \( \sim 20 \text{ keV} \) (2.3 \( \times \) \( 10^8 \) K) while ion number densities were \( \sim 4 \times 10^{22} \text{ cm}^{-3} \), and fusion burn occurred over \( \sim 100 \text{ ps} \).

The \( T(\text{He},\gamma)^9\text{Li} \) reaction produces an energetic \( \gamma \) ray at 15.8 MeV, which was measured with a Gas Cherenkov Detector (GCD)\textsuperscript{13}. In this instrument, the incident \( \gamma \) rays Compton scatter electrons into a gas-filled pressure cell, where the electrons exceed the local speed of light, producing Cherenkov light that is detected with a photomultiplier tube\textsuperscript{13,14}. The number of detected Cherenkov photons depends on the system response, energy of the initial \( \gamma \) ray, and total number of \( \gamma \) rays produced in the implosion; for more details on the detector response and analysis, see the Supplemental Information.

The raw Cherenkov detector data are shown in Fig. 2. Each curve corresponds to a single implosion on the left, which are averaged by fuel type on the right. The peak signal corresponds to the peak \( \gamma \) production, with each curve shifted so peak burn occurs at \( t = 0 \). The signal width corresponds to a combination of the instrument temporal response and the burn duration of the implosion. Signal later in time at \( \sim 0.5 \text{ ns} \) is a photomultiplier tube ring, which is excluded in the analysis. The data from the \( T^3\text{He} \)-filled implosions are shown by the blue curves. There are three main sources of background for this measurement.

The primary source of background is due to a \( \sim 1.5\% \) deuterium (D) impurity in the \( T_2 \) gas used for these experiments, resulting in D+T reactions that generate \( \gamma \) rays at 16.75 MeV with a branching ratio of \( \sim 4 \times 10^{-5} \) (fraction of total DT reactions)\textsuperscript{14}. Since the D+T cross section is much higher than the T+\( ^3\text{He} \) cross section, this is the dominant source of background. \( T_2 \)-filled implosions with the D contamination were used to measure the background level, shown as red curves in Fig. 2. On the \( T_2 \) shots, the total Cherenkov signal and DT neutron yield were measured, the latter with standard time-of-flight diagnostics\textsuperscript{15}, giving the Cherenkov signal produced per DT neutron. Since the \( \gamma/n \) ratio is constant, this factor is used with the measured DT neutron yield to calculate the Cherenkov signal due to DT reactions in the \( T^3\text{He} \) implosions. The second source of background was measured in an implosion with only \( ^3\text{He} \) gas, shown in Fig. 2 by the green curve, where Cherenkov signal is generated from either a plasma process or \( ^3\text{He}+^3\text{He} \) reactions\textsuperscript{14}. A third source of background is \( D^4\text{He} \) reactions, producing \( \gamma \) rays with a branching ratio of \( \sim 1.2 \times 10^{-4} \). The contribution from \( D^4\text{He} \) fusion is subtracted using measured \( D^3\text{He} \) proton yields.

The \( T^3\text{He} \) \( \gamma \) contribution is determined by subtracting the three background sources from the total signal. Detailed analysis is discussed in the Supplemental Information. From this measurement, the average \( T^3\text{He} \) \( \gamma \)-ray yield is \( Y_{\gamma} = (7.0 \pm 1.0_{\text{stat}} \pm 2.8_{\text{sys}}) \times 10^5 \) per shot. The quantity of interest in these experiments is the astrophysical S-factor (\( S \)) for the \( T(\text{He},\gamma)^9\text{Li} \) reaction, which is related to the cross section (\( \sigma \)) as

\[
\sigma = S(E_{cm}) \frac{e^{-\sqrt{E_G/E_{cm}}}}{E_{cm}},
\]

where \( E_{cm} \) is the center-of-mass energy for the fusion reaction and \( E_G \) is the Gamow energy, which is a constant. In this form, the S-factor is only weakly dependent on \( E_{cm} \). To determine the S-factor from the \( \gamma \) yield in this experiment, a better-known \( T^3\text{He} \) reaction branch can be used as a reference:

\[ T + ^3\text{He} \rightarrow ^4\text{He} (4.8 \text{ MeV}) + d (9.5 \text{ MeV}). \]

The absolute yield of the 9.5 MeV deuterons was mea-
measured to be $Y_d = (1.17 \pm 0.01) \times 10^9$ per shot with six independent detectors using two different techniques: direct CR-39 track detection$^{16}$ and dipole magnetic spectroscopy$^{17,18}$. The total S-factor for the $T(^3\text{He},\gamma)^6\text{Li}$ branch is thus

$$S_\gamma = S_d \times \frac{Y_\gamma}{Y_d} = 0.34 \pm 0.15 \text{ keV-b.} \quad (3)$$

where the deuteron branch S-factor ($S_d$) was taken from ENDF$^{19}$, and the error bar is a quadrature sum of the statistical and systematic uncertainties. For astrophysical work, the quantity of interest is the cross section for production of $^6\text{Li}$, and thus includes capture to the ground state and second excited state (which decays via $\gamma$ emission to the ground state) but not the first or higher excited states. The astrophysical S-factor ($S_{\gamma,a}$) is smaller by a factor of $0.58\times$ (see Supplemental Information), giving

$$S_{\gamma,a} = 0.20 \pm 0.09 \text{ keV-b,} \quad (4)$$

In these experiments, the reactant $E_{cm}$ was determined from proton spectroscopy$^{20}$ of the reaction:

$$\text{D} + ^3\text{He} \rightarrow ^4\text{He} + p \ (14.7 \text{ MeV}). \quad (5)$$

From the line width of the $^3\text{He}$-proton spectrum, a thermal Maxwellian temperature of $19 \pm 1$ keV was determined$^{21}$. Radiation-hydrodynamic simulations show that the $^3\text{He}$ and $^3\text{He}$ reactions have burn-averaged temperatures well within 1 keV due to the similar reactivity energy dependence, suggesting a similar $T_i$ for the $^3\text{He}$ reaction. To account for the reactivity on simulation, we increase the uncertainty to $T_i = 19 \pm 2$ keV for the $^3\text{He}$ reaction, which corresponds to $E_{cm} = 81 \pm 6$ keV. In thermal plasmas, this average center-of-mass energy is sometimes referred to as the Gamow peak energy.

The astrophysical S-factor determined in this work is shown in Fig. 3, and contrasted to higher-energy data obtained in previous experimental work by Blatt$^9$. Values used in BBN reaction theories$^{2,5,8}$ are also shown for comparison. Finally, a R-matrix calculation, fit to the higher-energy accelerator data, is shown in the magenta curve. Our data shows good agreement with the R-matrix calculation. Given the energy dependence in the R-matrix calculation, our data are consistent with the Blatt measurement. The S-factor used by Boyd$^5$ is a significant overestimate of the reaction rate at $E_{cm} \leq 1$ MeV; Madsen’s value$^2$, based on the 1 MeV Blatt data, is also an overestimate at low energy. Finally, a direct polynomial extrapolation of the Blatt data by Fukugita$^8$ is found to underestimate the S-factor by 20%.

The $^3\text{He}(T,\gamma)^6\text{Li}$ S-factor predictions come from an R-matrix analysis of reactions in the $^6\text{Li}$ system. The analysis includes the two-body arrangement channels $d+^4\text{He}$, $t+^3\text{He}$, $\gamma+^6\text{Li}$, and $p+^5\text{He}$ as an approximation to the breakup channel $n+p+\alpha$. The analysis contains more than 3000 data points for different reactions among the channels listed above. The only data fitted for the $^3\text{He}(T,\gamma)^6\text{Li}$ reaction, however, are those from the 90-degree excitation-function measurement of Blatt et al.$^9$, which included the transitions $\gamma_0,\gamma_1,\gamma_2,\gamma_4$ to the ground state, and the first, second, and fourth excited states of $^6\text{Li}$, respectively. These data show no evidence of resonance structure at low energies.

The rise in the calculated S-factor at low energies appears to come from a resonance with $J^p = 1^+$ at an excitation energy of 16.19 MeV in $^6\text{Li}$, or at a center-of-mass energy almost 400 keV above the $t+^3\text{He}$ threshold. The width of this resonance is 1.62 MeV, most of it coming from the $d+^4\text{He}$ and $p+^5\text{He}$ channels. However, there is enough $S_1$ width in the $t+^3\text{He}$ channel and $M1$ width in the $\gamma+^6\text{Li}$ channel to give the observed low-energy structure in the $^3\text{He}(T,\gamma)^6\text{Li}$ S-factor. The resonance corresponds to a complex pole of the $S$ matrix located on the unphysical sheet closest to the physical sheet above all the channel thresholds, with a strength factor of 0.79, as described in Ref. 22. This interpretation and level assignments are preliminary, as the experimental evidence for it is unclear in the data used for the R-matrix analysis. Further, the data in this work cannot strongly constrain the low-energy behavior of the S-factor.

Based on these results, we conclude that the reaction $T(^3\text{He},\gamma)^6\text{Li}$ cannot produce sufficient $^6\text{Li}$ to explain the observed levels of $^6\text{Li}$ in primordial material. We find that the reaction rates used in astrophysical calculations tend to either under- or over-estimate the true rate based on the previous uncertainty in the low-energy behavior of this reaction. While the levels of $^6\text{Li}$ detected in some stars is debated$^{23}$, the excess has been confirmed for a few low-metallicity stars$^{1,24}$. This work, and a recent study...
of the D(α,γ)⁶Li reaction⁷, suggest that a big-bang nuclear physics solution to the ⁶Li problem is unlikely, lending weight to alternative theories such as in-situ stellar production⁵ or non-Standard-Model physics⁶–⁸. This result is also significant in that it represents the first use of HEDP to address an open problem in nuclear astrophysics. In a broader context, this effort is part of a program where HEDP are used to probe basic nuclear science⁹–³². As HEDP better mimic conditions in stellar interiors and the universe during BBN, a rich set of nuclear astrophysics research can be uniquely conducted at the OMEGA¹⁰ and National Ignition Facility (NIF)³³ lasers.


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II. AUTHOR CONTRIBUTIONS


III. COMPETING FINANCIAL INTERESTS

We declare that the authors have no competing interests as defined by Nature Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this article.