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Measurements of the $T(t, 2n)^4$He Neutron Spectrum at Low Reactant Energies from Inertial Confinement Implosions


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Measurements of the neutron spectrum from the $T(t, 2n)^4$He ($tt$) reaction have been conducted using inertial confinement fusion implosions at the OMEGA laser facility. In these experiments, deuterium-tritium (DT) gas-filled capsules were imploded to study the $tt$ reaction in thermonuclear plasmas at low reactant center-of-mass (c.m.) energies. In contrast to accelerator experiments at higher c.m. energies (above 100 keV), these results indicate a negligible $n + ^5$He reaction channel at a c.m. energy of 23 keV.

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In inertial confinement fusion (ICF) experiments at the University of Rochester’s OMEGA laser system [1] and Lawrence Livermore National Laboratory’s National Ignition Facility (NIF) [2], spherical capsules are irradiated with lasers to compress and heat the interior fuel to high enough temperatures and densities for fusion reactions to occur. These thermal plasma environments more closely resemble the burning core in a star (e.g., thermonuclear reactant-energy distributions and electron screening environment [3]) than the conditions in accelerator experiments discussed in this Letter show a negligible $n + ^5$He reaction channel. The neutron spectrum is also important to ICF. In particular, the $tt$ spectrum overlaps with part of the down-scattered neutron (DSn) spectrum, which is often used to diagnose areal density ($\rho_R$), an essential metric of implosion performance [9,10].

As the $tt$ reaction produces three particles in the final state, the $tt$ neutron spectrum is challenging to calculate theoretically. The neutron spectrum can be approximated using a sequential decay model [12]. This includes the $n + n + ^4$He phase space (distorted by the $n-n$ final-state interaction), along with the ground-state $n + ^5$He(GS) and
the excited-state \( n + ^3\text{He}(\text{ES}) \) channels, which are summarized by
\[
T + T \rightarrow 2n + ^4\text{He}, \quad Q = 11.3 \text{ MeV},
\]
\[
T + T \rightarrow n + ^3\text{He}(\text{GS}), \quad Q = 10.4 \text{ MeV},
\]
\[
T + T \rightarrow n + ^3\text{He}(\text{ES}), \quad Q = 9.2 \text{ MeV}.
\]

In the \( n + n + ^4\text{He} \) exit channel [Eq. (1)], two neutrons are emitted over an energy range of 0–9.4 MeV. If the neutrons and \(^4\text{He} \) nuclei do not have a strong interaction and contributions from the initial-state wave functions are ignored, the neutron spectrum takes the form of an elliptical spectrum [13]. However, this spectrum may be modified by the \( n-n \) interaction, skewing the neutron spectrum towards lower energies [14] as calculated by Lacina et al. [15] and shown in Fig. 1(a). The \( n + ^3\text{He}(\text{GS}) \) channel modifies the neutron spectrum through the formation of the short-lived \(^3\text{He} \) nucleus in the ground-state, resulting in a neutron with a peak energy of 8.7 MeV [Eq. (2)]. Similarly, the excited-state channel \( n + ^3\text{He}(\text{ES}) \) modifies the neutron spectrum through the formation of an excited \(^3\text{He}(\text{ES}) \) nucleus (whose energy level is 1.27 MeV above the ground state), resulting in a broader neutron energy distribution with a peak at about 7.7 MeV [16]. The \( n + ^3\text{He} \) spectral shapes, shown in Fig. 1(a), were calculated using \(^3\text{He}(\text{GS}) \) and \(^3\text{He}(\text{ES}) \) data from Tilley et al. [17]. Estimates of the relative strengths of these reaction channels have traditionally been determined from accelerator experimental data (above 100 keV) [7,11,12].

One such experiment was performed by Wong et al. [12], who measured the \( tt \) neutron spectrum at a c.m. energy of 250 keV [see Fig. 1(b)]. They determined that all three contributions were observed in the ratios of 70% \( n + n + ^4\text{He} \) (using the Lacina [15] calculated spectrum), 20% \( n + ^3\text{He}(\text{GS}) \), and 10% \( n + ^3\text{He}(\text{ES}) \), and additionally concluded that the \( n + ^3\text{He}(\text{GS}) \) neutron peak is isotropic in the c.m. system within their accuracy of ~10%. In another experiment at a c.m. energy of 110 keV, Allen et al. [11] measured a \( n + ^3\text{He}(\text{GS}) \) ratio to \( n + n + ^4\text{He} \) of about 5%, indicating that the branching ratio is smaller at 110 keV than observed at 250 keV. In a third experiment by Larose-Poutissou et al. [18], the \( tt \) alpha spectrum was measured in coincidence with one of the two emitted neutrons at a c.m. energy of 20 keV (separated by 176° to emphasize the \( n-n \) interaction), and they suggested that the \( n + ^3\text{He}(\text{GS}) \) channel is unimportant [19].

The apparent reactant-energy dependence of these channel strengths underscores the importance of measuring the \( tt \) neutron spectrum directly under thermonuclear conditions. To make quantitative the comparison between thermonuclear ICF implosion data and accelerator data, it is necessary to convert the observed implosion ion temperature \((T_i)\) into the reactant c.m. energy. The peak (also called Gamow peak energy) of the reactant-energy distribution can be expressed as \( E_{cm} = (bT_i/2)^{3/2} \), which has a FWHM \( \sim (16 \ln E_{cm}/T_i/3)^{1/2} \). Here, the Gamow penetration factor \((b)\) is \( b = \sqrt{2}\pi e^2Z_1Z_2/h \). For \( tt, \) \( b = 38.5 \text{ keV}^{1/2} \), and for \( ^3\text{He}^3\text{He}, \) \( b = 154 \text{ keV}^{1/2} \) \((T_i\) and \( E_{cm} \) are expressed in keV) [5]. For temperatures readily achievable in an OMEGA ICF implosion (2–15 keV), the c.m. energies for the \( tt \) reaction are in the range 10–45 keV.

The experiments presented herein were conducted with the 60 beam, 30 kJ OMEGA laser system [1]. The neutron spectrum, including the \( tt \) neutron component, was measured with the Magnetic Recoil Spectrometer (MRS) [10,20–22]. This was accomplished by converting neutrons, incident on a 164 \( \mu \text{m} \) thick CD\(_2\) foil positioned close to the implosion, into elastically scattered recoil deuterons. The forward scattered recoil deuterons were selected, momentum analyzed, and focused by a magnetic spectrometer onto an array of CR-39 nuclear track detectors [23]. The CR-39 array recorded the deuteron spectrum, which was then used to determine the neutron spectrum.

Figure 2(a) shows MRS data summed over the nominally identical [24] OMEGA shots 55641–55647. In this series, six [25], 865 \( \mu \text{m} \) diameter, 9.5 \( \mu \text{m} \) thick deuterated
plastic capsules filled with 12 atm of DT fuel \( f_T/f_D = 0.63 \) [26], where \( f_T \) and \( f_D \) are the tritium and deuterium fuel fractions, respectively) were each imploded with 23 kJ of energy, delivered in 1 ns-square laser pulses resulting in a total neutron yield of \( 2.6 \times 10^{14} \). A burn averaged ion temperature of 8.0 ± 0.5 keV was determined from the neutron time-of-flight \((n\text{TOF})\) diagnostic suite [27].

The MRS measured recoil deuteron spectrum is shown in Fig. 2(a), where the black points represent the primary \( dt \) and DSn data, and the gray (red) points represent mostly the \( tt \) data (some DSn signal exists in this region as well, as indicated by the DSn fit). The primary 14 MeV \( dt \) peak is evident in Fig. 2(a) at a deuteron energy of \( \sim 11.6 \) MeV; the energy shift is a result of kinematics and energy loss in the \( \text{CD}_2 \) foil. The DSn spectrum is visible and isolated from other spectral components in the deuteron-energy range 8–10 MeV. The black line in Fig. 2(a) represents the best fit to the primary \( dt \) and DSn components shown by the black data points.

In the fitting process, the neutron spectrum [Fig. 2(b)] is folded with the MRS-response function to create a modeled recoil deuteron spectrum [10, 28]. The magnitude of the DSn spectrum is used as a fit parameter to the measured data, while the shape of the DSn spectrum is defined by the fuel and shell mixture and the differential cross section for \( n-d, n-t, \) and \( n-C \) scattering [28]. To ensure that the fitted DSn level is sound, the inferred total \( \rho R \) (fuel and shell) from the DSn spectrum [29] is compared to well-established charged particle measurements [23]. The DSn inferred \( \rho R \) of \( 35 \pm 5 \) mg/cm\(^2\) is in agreement with the complementary charged particle inferred \( \rho R \) of \( 40 \pm 6 \) mg/cm\(^2\) [30–32]. The \( tt \) neutron component, which dominates the spectrum at deuteron energies below 8 MeV, is determined directly from the data and therefore absent from the modeled neutron spectrum in Fig. 2(b).

The \( tt \) neutron spectrum is obtained by subtracting the best-fit contribution from DSn and then converting the recoil deuteron energy to neutron energy through the MRS-response function [28]. This procedure was repeated for six different implosion series, using capsules with \( \text{SiO}_2 \), \( \text{CD} \), and CH shells (summarized in Table I), providing a range of \( T_i \) between 3.5–8 keV (average of 5.8 keV).

Figure 3 shows the \( tt \) neutron spectrum that was obtained by taking the average of the spectra measured from each implosion series. This was done to improve the statistical accuracy and to reduce possible systematic error introduced by the DSn subtractions [33, 34]. Also shown in Fig. 3 are modeled neutron spectra, convolved with the MRS resolution, for the \( n+n+\text{He} \) reaction channel.

![Figure 2](image-url)

**FIG. 2** (color online). (a) MRS measured recoil deuteron spectrum summed over OMEGA shots 55641-55647 (points). The deuteron peak at \( \sim 11.6 \) MeV is due to the primary 14 MeV \( dt \) neutrons, and the width of this peak is mainly due to the MRS resolution. The DSn component is observed in the deuteron-energy range of 8–10 MeV. A best fit to the \( dt \) and DSn components (black data points) is shown by the solid black line. The remaining \( tt \) neutron signal [gray (red) data points] rises above the DSn background (DSn Bkg) below 8 MeV. (b) Modeled neutron spectrum that gives the best fit to the measured \( dt \) and DSn components for the black points discussed in (a).

<table>
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<tr>
<th>Integrated OMEGA shots</th>
<th>Target ([\text{gas(atm)}])shell(\Delta R)([\mu \text{m}])</th>
<th>(Y_{\text{D}\text{Ta}}) (units of (10^{13}))</th>
<th>(T_i) (keV)</th>
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<td>55983-55989</td>
<td>DT(17)CH([20])</td>
<td>3.8</td>
<td>3.5</td>
</tr>
<tr>
<td>58157-58159, 58161-58162</td>
<td>DT(15)CH([15])</td>
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<td>5.1</td>
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<tr>
<td>55074-55083</td>
<td>DT(18)CH([16])</td>
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<td>5.3</td>
</tr>
<tr>
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<td>DT(19)CH([14])</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td>58163, 58208</td>
<td>DT(10)SiO(_2)([3.8])</td>
<td>13.2</td>
<td>7.4</td>
</tr>
<tr>
<td>55641-55647</td>
<td>DT(12)CD([9.5])</td>
<td>25.5</td>
<td>8.0</td>
</tr>
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</table>

*TABLE I.* Shot numbers, target specifications (gas pressure, shell type and thickness), and observed DT yield \((Y_{\text{D}\text{Ta}})\) and \(T_i\) for each series used in this study. Each capsule was filled with DT gas with an average tritium-to-deuterium ratio of \( f_T/f_D = 0.62 \) that varied by \(<3\%\) between each series [26].
used a simplified sequential decay model, the negligibly obtained at 110 and 250 keV \cite{11,12}. Even though we have are consistent with the general trend in the accelerator data (model calculations [39] that treat the three-cluster that include the full six-body dynamics and simpler cluster advance to ICF applications. Specifically, hydrodynamic action channel shown in Fig. 4(a) is of immediate rele-

FIG. 3 (color online). The $tt$ neutron spectrum averaged over all implosion series spectra. The solid line represents the modeled $n + n + ^4He$ channel, while the dashed and dotted lines represent 5\% and 20\% contributions of the $n + ^5He(GS)$ channel, respectively. All three models were convolved with the MRS resolution for direct comparison to the measured data (the neutron energy resolution is 0.55 MeV). As indicated by the spectrum, no $n + ^5He(GS)$ reaction channel is observed.

(solid line), along with 5\% (dashed line), and 20\% (dotted line) strengths of the $n + ^5He(GS)$ channel. The measured data show that the $n + ^5He(GS)$ channel is insignificant \cite{35} to a statistical uncertainty of $\sim 2\%$, based on a $\chi^2$ sensitivity analysis \cite{28}.

Using the results shown in Fig. 3, the relative intensity of $n + ^5He(GS)$ to the total $tt$ reaction yield is compared to accelerator experiments at higher c.m. energies in Fig. 4(a) \cite{36}. The energy used in this comparison is the Gamow peak energy of the reactant distribution that produced the spectrum in Fig. 3 ($E_{\text{cm}} = 23$ keV with a FWHM $\sim 22$ keV), as shown and compared to the accelerator measurements in Fig. 4(b). The 23 keV data in Fig. 4(a) are consistent with the general trend in the accelerator data obtained at 110 and 250 keV \cite{11,12}. Even though we have used a simplified sequential decay model, the negligibly small $n + ^5He(GS)$ channel apparent in Fig. 3, along with the suggested trend of Fig. 4(a), implies that $n + ^5He(GS)$ is suppressed at these low reactant c.m. energies. Motivated by this result, \textit{ab initio} calculations \cite{37,38} that include the full six-body dynamics and simpler cluster model calculations \cite{39} that treat the three-cluster ($n + n + ^4He$) dynamics are currently being developed for the $tt$ neutron spectrum at these c.m. energies \cite{40}.

The observed relative strength of the $n + ^5He(GS)$ reaction channel shown in Fig. 4(a) is of immediate relevance to ICF applications. Specifically, hydrodynamic simulations of ICF implosions using LASNEX \cite{41} indicate that the $tt$ reaction contributes significantly to the total neutron spectrum in tritium-rich THD implosions at the NIF \cite{42}. By default, LASNEX simulates the $tt$ neutron emission using the channel strengths obtained by Wong \textit{et al.} \cite{12} at 250 keV c.m. energy \cite{43}. However, Fig. 4(a) indicates that the $n + ^5He(GS)$ contribution to the $tt$ neutron emission is negligible in ICF-relevant conditions. It is also interesting to note that related calculations of the $^3He^3He$ reaction \cite{7} determine the relative strengths of $^3He^3He$ reaction channels ($p + p + ^4He$ and $p + ^5Li$) from the $tt$ spectrum measured by Wong \cite{12} (because $tt$ and $^3He^3He$ are mirror reactions). Therefore, the results of Fig. 4(a) pose the question as to whether a similar relationship exists for $^3He^3He$, resulting in a suppression of the $p + ^5Li$ channel at the solar Gamow peak energy ($E_{\text{cm}} = 21$ keV \cite{44}). To that end, experiments have begun to directly measure the $^3He^3He$ proton spectrum in OMEGA implosions \cite{45}.

To improve upon the measurements of the $tt$ neutron spectrum at OMEGA, implosions of pure $T_2$ gas filled capsules \cite{46} will greatly reduce the $dt$ yield and thereby the DSN background. This will eliminate the principle source of background in these measurements and reduce the uncertainty in the measured $tt$ neutron spectrum. In addition, a low-energy neutron spectrometer \cite{47} is being designed for measurements of the $tt$ neutron spectrum in the range of 0.1–5 MeV.

In summary, the $tt$ neutron spectrum has been measured at low reactant c.m. energies in thermonuclear plasmas using a variety of ICF capsule implosions at OMEGA. The results show that, in contrast to accelerator data at higher c.m. energies (above 100 keV), the $n + ^5He$ channel is not observed in these experiments. This result is of immediate relevance in the interpretation of the ICF neutron spectrum at the NIF. It also raises questions about the channel strengths for the $^3He^3He$ reaction, which is the dominant energy-producing step in the solar proton-proton chain.
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[14] A strong n-n interaction should produce a distribution favored at ~Q/3 or ~4 MeV because the two neutrons emitted together, like an unbound dineutron, would kinematically share 2/3 Q (instead of 5/6 Q as in the uninteracting case).
[16] This neutron has a broad emission spectrum due to the very short lifetime of 5He(ES).
[19] While they suggested that the n + 5He(GS) channel is unimportant in their data, they indicated that the n + 5He(ES) channel may be important, a result that is counterintuitive.
[24] Six implosions were integrated to obtain better statistics because the neutron detection efficiency is relatively low. Nominal identical shell thickness, diameter, fill pressure, and laser profiles within an implosion series result in very similar Ts and nuclear yield. In this series, the shot-to-shot Ts varied by 3% and the DT yield varied by 39%.
[25] OMEGA shot 55645 was not a target shot and produced no yield.
[26] W. Shmayda (private communication).
[29] The Dn spectrum is linearly proportional to the imploded capsule areal density.
[30] Areal density asymmetries of 20% are commonly encountered for these types of capsule implosions.
[33] Systematic errors could be induced by uncertainty in the neutron scattering cross sections. However, the impact of this is greatly reduced because each series type has a different Dn intensity (areal densities ranging from 13–71 mg/cm2) and is dominated by different scattering cross sections (SiO2, CD, and CH shells). Furthermore, the standard deviation of the mean at each point in the average spectrum is typically the same order or smaller than the statistical uncertainty, indicating that the spectra from each series are in agreement with one another.
[35] As the n + 5He(GS) channel was not observed, the n + 5He(ES) channel was ignored.
[36] Both of the accelerator experiments shown were performed at 90° relative to the incoming beam, whereas this work is integrated over all angles. However, Wong et al. showed the n + 5He(GS) neutron emission is isotropic at 250 keV and therefore we believe it is reasonable to assume that it remains isotropic at lower reactant energies.
[40] I. J. Thompson and S. Quaglioni (private communication).
[43] G. Zimmerman (private communication).
[47] M. Gatu Johnson (to be published).