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

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Measurements of the neutron spectrum from the $T(t, 2n)^4He$ (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 $n + {}^5He$ 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, providing unique opportunities to explore new areas of low-energy plasma-nuclear science [4] and stellar nucleosynthesis [5]. One reaction of interest to both these areas is $T(t, 2n)^4He$ (or tt). The tt reaction is relevant to stellar nucleosynthesis because it is the mirror reaction to the stellar ${}^3He({}^3He, 2p)^4He$ (or ${}^3He{}^3He$) reaction [6], which is the dominant energy-producing step in the solar proton-proton chain [5]. Studying the tt reaction provides information about the ${}^3He{}^3He$ reaction, as mirror reactions have similar nuclear behavior (after correcting for the difference in the Coulomb potential and isospin) [5–7]. One probe of this nuclear behavior is the shape of the emitted particle spectrum, which is sensitive to the final-state interactions among the emitted particles. The tt neutron spectrum is a broad continuum of energies due to the three-body kinematics that govern two neutrons and a ${}^4He$ ion. The n-n and n-${}^4He$ final-state interactions [8] modify the spectrum from an otherwise nearly elliptical energy spectrum. Therefore, measuring the tt neutron spectrum provides information that can be used to constrain models of the final-state interactions. A quantitative understanding of the tt 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 (ρR), an essential metric of implosion performance [9,10].

In this Letter, we present measurements of the neutron spectrum from the tt reaction that were carried out by using a variety of deuterium-tritium (DT) gas-filled capsule implosions at the OMEGA laser [1]. Using the implosion and diagnostic capabilities on OMEGA, the tt reaction was measured at a reactant center-of-mass (c.m.) energy of 23 keV. The tt neutron spectrum is found to differ significantly from the spectra determined from accelerator experiments conducted at c.m. energies above 100 keV [11,12]. More specifically, the "low-c.m.-energy" ICF experiments discussed in this Letter show a negligible $n + {}^5He$ reaction channel.

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 $n + n + {}^4He$ phase space (distorted by the n-n final-state interaction), along with the ground-state $n + {}^5He(GS)$ and the excited-state $n + {}^5\mathrm{He(ES)}$ channels, which are summarized by

$$\mathrm{T} + \mathrm{T} \rightarrow 2n + {}^4_2\mathrm{He}, \qquad Q = 11.3\ \mathrm{MeV}, \tag{1}$$

$$\mathrm{T} + \mathrm{T} \rightarrow n + {}^5_2\mathrm{He(GS)}, \qquad Q = 10.4\ \mathrm{MeV}, \tag{2}$$

$$\mathrm{T} + \mathrm{T} \rightarrow n + {}^5_2\mathrm{He(ES)}, \qquad Q = 9.2\ \mathrm{MeV}. \tag{3}$$

In the $n + n + {}^4\mathrm{He}$ exit channel [Eq. (1)], two neutrons are emitted over an energy range of 0–9.4 MeV. If the neutrons and ^{4}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 $n + {}^5\mathrm{He(GS)}$ channel modifies the neutron spectrum through the formation of the short-lived ^{5}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 $n + {}^5\mathrm{He(ES)}$ modifies the neutron spectrum through the formation of an excited ^{5}He(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 $n + {}^5\mathrm{He}$ spectral shapes, shown in Fig. 1(a), were calculated using ^{5}He(GS) and ^{5}He(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].

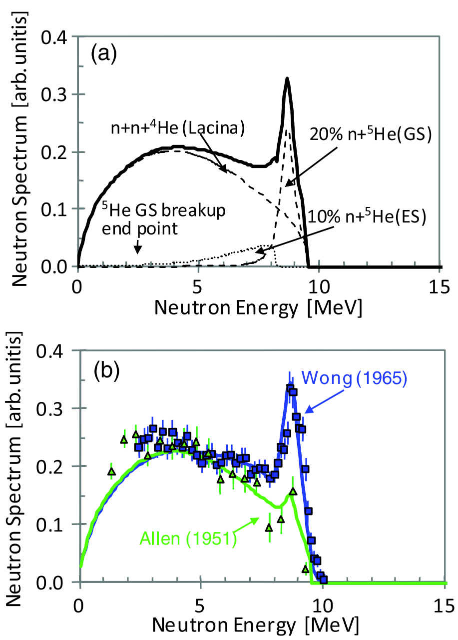

FIG. 1 (color online). (a) Model neutron spectrum for the *tt* reaction, including contributions from the $n + n + {}^4\mathrm{He}$, $n + {}^5\mathrm{He(GS)}$, and $n + {}^5\mathrm{He(ES)}$ channels. This simple analysis neglects interference in the final state and does not include the ^{5}He-breakup neutrons as they are below the detection limit for the data discussed in this Letter (contributions from ^{5}He are shown *a posteriori* to be negligible). (b) Measured *tt* neutron spectrum from Allen *et al.* [11] (green triangles) and Wong *et al.* [12] (blue squares) at c.m. reactant energies of 110 and 250 keV, respectively. The best fits to the two data sets are also shown (solid lines) using the model described above.

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% $n + n + {}^4\mathrm{He}$ (using the Lacina [15] calculated spectrum), 20% $n + {}^5\mathrm{He(GS)}$, and 10% $n + {}^5\mathrm{He(ES)}$, and additionally concluded that the $n + {}^5\mathrm{He(GS)}$ 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 $n + {}^5\mathrm{He(GS)}$ ratio to $n + n + {}^4\mathrm{He}$ 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 $n + {}^5\mathrm{He(GS)}$ 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 $E_{\mathrm{c.m.}} = (bT_i/2)^{2/3}$, which has a FWHM $\sim(16 \ln 2 E_{\mathrm{c.m.}} T_i/3)^{1/2}$. Here, the Gamow penetration factor (b) is $b = \sqrt{2m_r}\pi e^2 Z_1 Z_2/\hbar$. For *tt*, $b = 38.5\ \mathrm{keV}^{1/2}$, and for ^{3}He^{3}He, $b = 154\ \mathrm{keV}^{1/2}$ (T_i and $E_{\mathrm{c.m.}}$ 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 μm 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 μm diameter, 9.5 μm thick deuterated

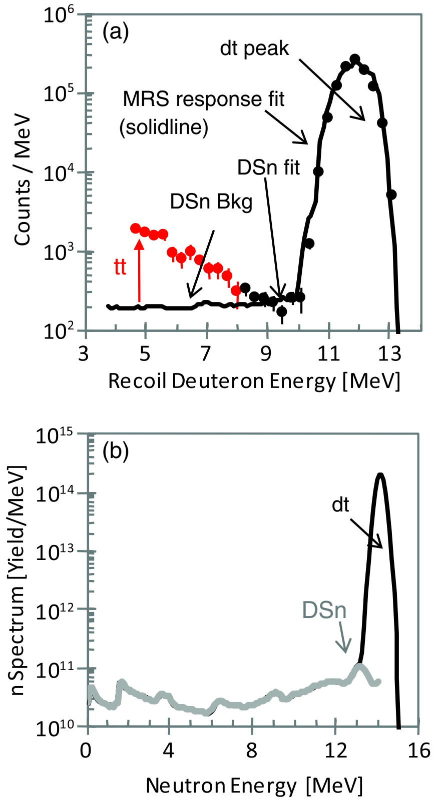

FIG. 2 (color online). (a) MRS measured recoil deuteron spectrum summed over OMEGA shots 55641-55647 (points). The deuteron peak at ~11.6 MeV is due to the primary 14 MeV *dt* neutrons, and the width of this peak is mainly due to the MRS resolution. The DS*n* component is observed in the deuteron-energy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

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 2.6×10^{14}. A burn averaged ion temperature of 8.0 ± 0.5 keV was determined from the neutron time-of-flight (*n*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 DS*n* data, and the gray (red) points represent mostly the *tt* data (some DS*n* signal exists in this region as well, as indicated by the DS*n* fit). The primary 14 MeV *dt* peak is evident in Fig. 2(a) at a deuteron energy of ~11.6 MeV; the energy shift is a result of kinematics and energy loss in the CD_2 foil. The DS*n* 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 DS*n* 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 DS*n* spectrum is used as a fit parameter to the measured data, while the shape of the DS*n* 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 DS*n* level is sound, the inferred total ρR (fuel and shell) from the DS*n* spectrum [29] is compared to well-established charged particle measurements [23]. The DS*n* inferred ρR of 35 ± 5 mg/cm^2 is in agreement with the complementary charged particle inferred ρR of 40 ± 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 DS*n* 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 SiO_2, 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 DS*n* subtractions [33,34]. Also shown in Fig. 3 are modeled neutron spectra, convolved with the MRS resolution, for the $n + n + {}^4$He reaction channel

TABLE I. Shot numbers, target specifications (gas pressure, shell type and thickness), and observed DT yield (Y_{DTn}) 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].

Integrated OMEGA shots	Target [gas(atm)shellΔR[μm]]	Y_{DTn} (units of 10^{13})	T_i (keV)
55983-55989	DT(17)CH[20]	3.8	3.5
58157-58159, 58161-58162	DT(15)CH[15]	7.4	5.1
55074-55083	DT(18)CH[16]	15.8	5.3
58165, 58209-58210	DT(19)CH[14]	5.0	5.6
58163, 58208	DT(10)SiO_2[3.8]	13.2	7.4
55641-55647	DT(12)CD[9.5]	25.5	8.0

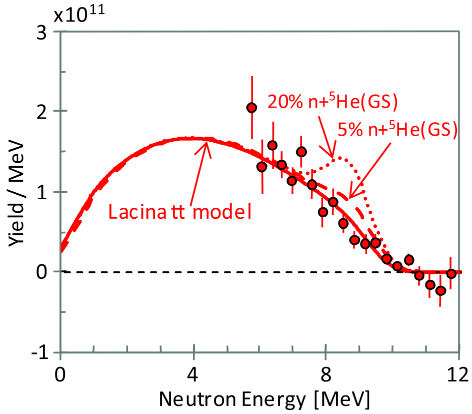

FIG. 3 (color online). The *tt* neutron spectrum averaged over all implosion series spectra. The solid line represents the modeled $n + n + {}^4$He channel, while the dashed and dotted lines represent 5% and 20% contributions of the $n + {}^5$He(GS) channel, respectively. All three models were convolved 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 $n + {}^5$He(GS) reaction channel is observed.

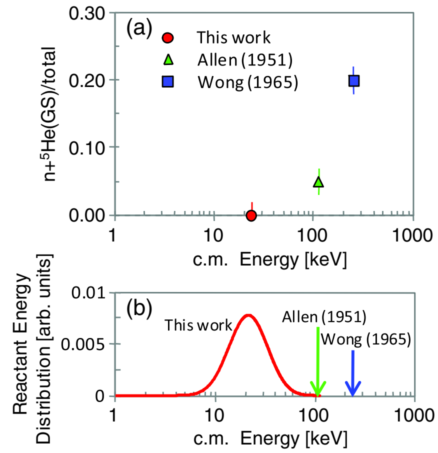

FIG. 4 (color online). (a) Ratio of the $n + {}^5$He(GS) to the total *tt* reaction yield as a function of c.m. energy. The red circular data point was determined from the neutron spectrum shown in Fig. 3. This measurement is compared to accelerator experiments shown in Fig. 1(b). (b) Calculated reactant-energy distribution [gray (red) curve] for the thermonuclear ICF measurement shown in (a). The c.m. energies for the accelerator experiments are indicated by vertical arrows since their widths are negligible on this scale.

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

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

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

To improve upon the measurements of the *tt* neutron spectrum at OMEGA, implosions of pure T_2 gas filled capsules [46] will greatly reduce the *dt* yield and thereby the DS*n* 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 [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 $n + {}^5$He 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 ^{3}He^{3}He reaction, which is the dominant energy-producing step in the solar proton-proton chain.

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