First experimental evidence of a variant neutron spectrum from the T(T,2n)α reaction at center-of-mass energies in the range of 16-50 keV


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First experimental evidence of a variant neutron spectrum from the T(T,2n)α reaction at center-of-mass energies in the range of 16-50 keV

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Full calculations of six-nucleon reactions with a three-body final state have been elusive and a long-standing issue. We present neutron spectra from the T(t,2n)α (TT) reaction measured in inertial confinement fusion experiments at the OMEGA laser facility at ion temperatures from 4 to 18 keV, corresponding to center-of-mass energies (E_c.m.) from 16 to 50 keV. A clear difference in the shape of the TT-neutron spectrum is observed between the two E_c.m., with the 4He ground state resonant peak at 8.6 MeV being significantly stronger at the higher than at the lower energy. The data provides the first conclusive evidence of a variant TT-neutron spectrum in this E_c.m. range. In contrast to earlier available data, this indicates a reaction mechanism that must involve resonances and/or higher angular momenta than L=0. This finding provides an important experimental constraint on theoretical efforts that explore this and complementary six-nucleon systems, such as the solar 3He(3He,2p)α reaction.

The six-nucleon reaction between two tritons T(t,2n)α (TT) has proven challenging to determine theoretically because it produces three particles in the final state [1-4]. Accurate experimental data are required to guide the theoretical efforts. Available cross section data for this reaction [5-10], although relatively inaccurate, are consistent with a flat S-factor below center-of-mass energy E_c.m.=500 keV. Measurements by Wong et al. [11] as a function of angle also indicate an isotropic cross section at E_c.m.=160 keV. Combined, these two observations suggest that an s-wave reaction channel (L=0) dominates in this E_c.m. range and that any resonance contributions arise from very broad states. This interpretation, which is also consistent with theoretical studies using a microscopic model [12] and R-matrix methods [13], would mean that the shape of the reaction product energy spectra would be independent of E_c.m. In contrast, Casey et al. [14] explored the idea based on the limited previous TT-neutron spectral data [11,14-18] that the shape may possibly depend on E_c.m. However, due to widely varying systematics between the different measurements in combination with large uncertainties, such a dependence has not been demonstrated.

In this letter, we report on accurate new measurements of the TT reaction at E_c.m. in the range 16-50 keV at the OMEGA laser [19], which provide the first conclusive demonstration of an E_c.m. dependence in the TT-neutron spectrum. This result indicates a reaction mechanism that, unexpectedly, must involve resonances and/or higher angular momenta than L=0. These findings may also have implications for the 3He(3He,2p)α (3He3He) mirror reaction, which plays an important role in the solar proton-proton (pp) chains [20]. The S-factor for this reaction is inferred based on accelerator measurements of the 3He3He reaction rate [20-24]. In particular, measurements at solar-fusion-relevant energies were obtained at the LUNA underground accelerator facility [20,22-23], where the setup allows for measurement of 3He3He-protons with energies above 2.75 MeV. The analysis and interpretation of the LUNA data rely on an extrapolation to energies below 2.75 MeV assuming an elliptical proton spectrum for determination of the total 3He3He reaction rate [23]. As our findings suggest that the 3He3He proton spectral shape likely varies with E_c.m., the use of an elliptical spectrum in the analysis of the LUNA 3He3He data may not be adequate. As an example, if the R-matrix spectral shape calculated by Brune et al. [25] was used instead for this extrapolation, the inferred 3He3He reaction rate would be 8% higher than reported. With a total estimated uncertainty of 4% for the 3He3He S-factor [20], such an adjustment would have an impact on the pπl/(pπl+pπII) branching ratio and hence on solar neutrino physics, motivating the need for a deeper understanding of the shape of the 3He3He proton spectrum.

The experiment reported herein was explicitly designed to generate a range of ion temperatures (T_ion) (hence E_c.m.) to accurately study the TT-neutron spectrum at different E_c.m., while maintaining identical measurement conditions. Glass capsules (1 mm outer diameter, 3 μm shell thickness) were filled with 3.2 or 8.2 atm of T2 gas with 0.36% and 0.15% deuterium impurity by atom, respectively, and irradiated with the 60 OMEGA laser beams directly incident on the capsule. T_ion (inferred from the broadening of measured DT neutron spectra [26]) was tuned by varying the laser pulse shape and beam focus together with the gas-fill pressure [27]. A neutron-averaged T_ion=18.3±0.5 keV was obtained by irradiating a low-pressure target with a square pulse with 0.6 ns duration delivering 16 kJ of energy with the laser beams focused to the center of the capsule. A 2.0-ns ramped laser pulse delivering 24 kJ energy onto the high-pressure capsule with defocused beams provided a T_ion of 3.7±0.5 keV. An intermediate-temperature case was obtained by imploding a high-pressure capsule with the 0.6 ns square pulse delivering 16 kJ of energy with all the beams focused to the center of the capsule (T_ion=11.1±0.5 keV). The duration of burn was about 0.2 ns for all implosions. Resulting implosion parameters are summarized in Table I. Calculated burn-averaged E_c.m. distributions for the three implosions are shown in FIG. 1. The reactions occur over a range of E_c.m. because of the thermal ion-velocity distributions in these ICF experiments [28]. Additionally, T_ion is not uniform throughout an ICF implosion; this was considered in the calculation of the distributions in FIG. 1 by using radial temperature and density
profiles from 1D radiation-hydrodynamics simulations with the code HYADES [29], constrained to match measured T\textsubscript{ion} (see Ref. 27 for details). These calculations also show that the DT and TT burn-averaged T\textsubscript{ion} are expected to be virtually the same for these implosions. Average E\textsubscript{c.m.} of 16 keV, 36 keV and 50 keV are inferred for the implosions with T\textsubscript{ion}=3.7 keV, 11.1 keV and 18.3 keV, respectively.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Pulse shape</th>
<th>Laser energy (kJ)</th>
<th>Capsule diameter (µm)</th>
<th>Shell thickness (µm)</th>
<th>T\textsubscript{2} fill pressure (atm)</th>
<th>TT-n yield (×10\textsuperscript{12})</th>
<th>DT E\textsubscript{c.m.} (keV)</th>
<th>E\textsubscript{c.m.} (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77951</td>
<td>0.6ns square</td>
<td>16.1</td>
<td>1004</td>
<td>2.9</td>
<td>3.3</td>
<td>0.49±0.05</td>
<td>18.3±0.5</td>
<td>50</td>
</tr>
<tr>
<td>77960</td>
<td>0.6ns square</td>
<td>16.1</td>
<td>1004</td>
<td>2.9</td>
<td>8.2</td>
<td>1.27±0.14</td>
<td>11.1±0.5</td>
<td>36</td>
</tr>
<tr>
<td>77963</td>
<td>2ns ramp</td>
<td>24.1</td>
<td>1009</td>
<td>3.0</td>
<td>8.2</td>
<td>0.24±0.03</td>
<td>3.7±0.5</td>
<td>16</td>
</tr>
</tbody>
</table>

![FIG. 1. Calculated center-of-mass energy distributions for the implosions with T\textsubscript{ion}=3.7 keV (solid black), T\textsubscript{ion}=11.1 keV (dashed blue) and T\textsubscript{ion}=18.3 keV (dash-dot red).](image)

![FIG. 2. nTOF-measured signal traces for shots 77951 (dash-dot red, T\textsubscript{ion}=18.3 keV) and 77963 (solid black, T\textsubscript{ion}=3.7 keV). The time axis has been corrected for capsule burn time (0.8 ns for 77951 and 1.7 ns for 77963). The corresponding neutron energy scale is indicated at the top. The traces are normalized to match in the time interval 361-371 ns (0.8 ns for 77951 and 1.45 ns for 77963). The ratio for shot 77960 with intermediate E\textsubscript{c.m.}=36 keV (not shown in FIG. 2) falls between the two at 0.50, indicating a gradual change in the spectrum with varying E\textsubscript{c.m.}](image)
(using both Verbinski and Craun & Smith light yield curves) with the phenomenological R-matrix model described in Ref. 25, with six feeding factors as free parameters. Thermal Doppler broadening of the spectra is considered in the analysis. As the statistical uncertainty in the measured spectra is dominated by oscilloscope digitization noise, it is challenging to assign realistic error bars to the 402 individual data points. This was handled in the analysis by assigning data-point errors that give reduced $\chi^2$ for a $3^{rd}$ degree polynomial fit to a slow-varying region of the spectrum (370-520 ns). As an example, the resulting R-matrix fit to the PMT-A spectrum for shot 77951 using the Verbinski light-yield curve is shown in FIG. 3. With statistical error bars as described above, a $\chi^2_{\text{red}}$=2.0 is determined for this fit [36]. Also shown in FIG. 3 are the individual R-matrix components comprising the fit, including a component to account for net interference between all partial waves (see Ref. 25 for details).

The R-matrix feeding factors resulting from the fits to the PMT-D spectra using the Craun & Smith light-yield curve are summarized in Table II, together with the statistical uncertainty in each case (a full summary of all inferred feeding factors and $\chi^2_{\text{red}}$ from each fit can be found in the supplemental material [37]). The underlying assumption of the R-matrix analysis is that the TT reaction proceeds through the s-wave ($L=0, J=0^+$) only. Two levels ($\lambda$, in Table II) are considered for each partial wave in the $\alpha+n$ system, and one partial wave / level is assumed for the dineutron system (nn). Each level has a feeding factor $A_{\lambda\lambda}$, determined by the fit to data, and its sign determines the interferences between individual waves and channels. The $3/2^-$ partial wave describes the peak seen at 340 ns ($E_{\text{c.m.}}$=8.6 MeV), which can be distinguished well from the broad continuum that follows. The feeding factor for the $3/2^-$, $\lambda=1$ state increases in strength over the investigated $E_{\text{c.m.}}$, in unison with the high-energy peak in the spectrum. (The $3/2^-$, $\lambda=2$ state, which also contributes to the $3/2^-$ component in FIG. 3, lies mainly in the continuum.)

The fully reduced TT-neutron spectra for shots 77951 and 77963, with nTOF instrument response and thermal Doppler broadening removed, are contrasted in FIG. 4. These final spectra represent the average of the spectra obtained using the Craun & Smith and Verbinski light-yield curves and PMT-A and PMT-D data in the analysis. The linewidth represents the total systematic uncertainty defined as the difference between the average and each extreme. The $^3$He gs peak is clearly more pronounced for the spectrum measured at $E_{\text{c.m.}}$=50 keV than for the $E_{\text{c.m.}}$=16 keV case. Note that the peak at 2 MeV is also associated with the $^3$He gs; this enhancement in the spectrum corresponds to the subsequent decay of $^3$He into a neutron and an alpha particle.

![Graph showing signal vs. oscilloscope time for different channels](image)

![Graph showing neutron energy vs. intensity](image)

### Table II. Feeding factors inferred from R-matrix fits to shots 77951 ($T_{\text{ion}}$=18.3 keV, $E_{\text{c.m.}}$=50 keV), 77060 ($T_{\text{ion}}$=11.1 keV, $E_{\text{c.m.}}$=36 keV) and 77963 ($T_{\text{ion}}$=3.7 keV, $E_{\text{c.m.}}$=16 keV).

<table>
<thead>
<tr>
<th>Ch</th>
<th>$\lambda$</th>
<th>$A_{\lambda\lambda}$ 77951</th>
<th>$A_{\lambda\lambda}$ 77960</th>
<th>$A_{\lambda\lambda}$ 77963</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2-</td>
<td>1</td>
<td>-24.4±1.1 Stat</td>
<td>-27.7±1.6 Stat</td>
<td>-18.6±1.6 Stat</td>
</tr>
<tr>
<td>1/2-</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/2-</td>
<td>1</td>
<td>-16.8±0.1 Stat</td>
<td>-17.5±0.2 Stat</td>
<td>-18.2±0.1 Stat</td>
</tr>
<tr>
<td>1/2-</td>
<td>2</td>
<td>-218±5 Stat</td>
<td>-128±8 Stat</td>
<td>-292±7 Stat</td>
</tr>
<tr>
<td>3/2</td>
<td>1</td>
<td>9.8±0.03 Stat</td>
<td>9.08±0.04 Stat</td>
<td>8.85±0.03 Stat</td>
</tr>
<tr>
<td>3/2</td>
<td>2</td>
<td>223±3 Stat</td>
<td>242±4.1 Stat</td>
<td>240±3 Stat</td>
</tr>
<tr>
<td>nn</td>
<td>1</td>
<td>13.8±0.2 Stat</td>
<td>15.1±0.2 Stat</td>
<td>14.7±0.2 Stat</td>
</tr>
</tbody>
</table>
The underlying physics behind the observed $E_{c.m.}$ dependence is not clear. As stated in the introduction, previous data for this reaction are consistent with only s-waves involving very broad states, in which case the spectral shape would be independent of energy. The observed $E_{c.m.}$ dependence indicates a more complicated reaction mechanism that must involve resonances and/or higher angular momenta than $L=0$. Theoretical calculations by Thomson and Tang using a resonating group model [38] and more recently by Arai et al. using a microscopic cluster model [39] suggest the presence of a $0^-$ resonance of $^4\text{He}$ around 0.5 MeV above the TT threshold and with a large width ($\sim 4$ MeV). Ab-initio calculations of the $^4\text{He}+n$ continuum carried out using a soft NN interaction that accurately describes nucleon-nucleon data also suggest the presence of $0^-$ resonances near the TT threshold [4]. The present experiment may be probing the low-energy tail of this resonance, and the way it decays. If this is the case, the observed spectra will have s-wave and p-wave channel contributions, and it is not unreasonable to think that the p-wave case, the observed spectra will have s-wave and p-wave channel energy tail of this resonance, and the way it decays. If this is the case, the observed spectra will have s-wave and p-wave channel contributions, and it is not unreasonable to think that the p-wave contributions may increase with higher $E_{c.m.}$, as we approach the $0^-$ resonance. The possible ways of forming an $n+^4\text{He} \; 0^-$ state are:

1. $n(1/2^+)+^4\text{He}(1/2^+)$, with $S=1$, $L=1$
2. $n(1/2^+)+^4\text{He}(1/2^+)$, with $S=0$, $L=0$
3. $n(1/2^+)+^4\text{He}(3/2^+)$, with $S=2$, $L=2$

The first two channels are Pauli suppressed, because the s-shell is complete. Hence, channel (iii) will be dominant. This channel requires a relative angular momentum $L=2$ between the neutron and the $^4\text{He}$. Given the large Q-value of the TT reaction, there is most likely enough energy in the system to allow $L=2$ for $^4\text{He}+n$. As we have seen, the $^4\text{He}$ 3/2+ state gives rise to the peak at the high energy edge of the TT-neutron spectrum. This suggests that if the p-wave contribution increases with energy, then the relative intensity of the $^4\text{He}$ 3/2+ peak is also expected to increase, as observed.

An alternative explanation is that there could be a $0^+$, T=1 excited state in $^4\text{He}$ above the ground state, in the vicinity of the TT-reaction threshold, with a total width sufficiently narrow to cause the observed change in spectral shape over 30 keV in excitation energy. It is notoriously hard to detect a $0^+$ resonance in scattering, because most s-wave phase shifts look like hard-sphere phases, and the presence of a resonance modifies that behavior only slightly. A fit to the limited sets of data that exist for $^4\text{He}$+$n$ (TT differential elastic scattering cross sections and Tt(2n)x cross sections) gives (in addition to the ground-state level) a broad $0^+$ resonance at an excitation energy of 13.65 MeV and a negative parity resonance at 14.38 MeV.

The data set reported herein demonstrates an energy dependence in the TT-neutron spectral shape in the range of $E_{c.m.}=16-50$ keV, but does not conclusively distinguish between different theoretical hypotheses for explaining this observation. This means that it is impossible to predict how the spectral shape will evolve with further varying $E_{c.m.}$ on the basis of currently available information. Such predictions would require full ab-initio calculations including all possible resonances, which are not currently available. If, e.g., $0^-$ is responsible for the observed 3/2- peak enhancement with $E_{c.m.}$, then we may expect this peak to remain low towards lower energy and increase in importance towards higher energy until the energy is above the resonance, at which point it may again start to decrease (unless other resonances come into play at this higher energy). Note also that if the energy dependence observed in the TT-neutron spectrum is due to $0^-$ or $0^+$ resonances as suggested here, then equivalent energy dependencies are expected also for the $^4\text{He}^3\text{He}$ reaction, although shifted in energy due to the Coulomb barrier. This observation should motivate further theoretical investigations of the few-body physics governing these 6-nucleon systems, and provide guidance for ongoing ab-initio efforts [2-4].

In conclusion, using the OMEGA laser to implode T$_2$-gas-filled thin-glass-shell capsules, the TT-neutron spectrum has been studied at $E_{c.m.}$ of 16, 36 and 50 keV. For the first time, the resulting data conclusively demonstrate an energy dependence in the spectral shape over this $E_{c.m.}$ range. This observation indicates a more complicated reaction mechanism than the s-wave only previously assumed for this reaction. In particular, the relative strength of the peak associated with the 3/2+ $^4\text{He}$ ground state is found to increase with increasing $E_{c.m.}$, possibly indicating the impact of a $0^-$ p-wave resonance. An equivalent energy dependence for the mirror $^4\text{He}^3\text{He}$ reaction could impact analysis of accelerator measurements used as basis for evaluation of the $^3\text{He}^4\text{He}$ S-factor at solar-fusion energies.

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References

31. In ICF, the time-scale for burn is short enough where the implosion time can be used as the start signal, and only a single detector is required for the nTOF measurement (the burn duration for these implosions is ~100 ps). Neglecting the impulse response of the detector, E=0.5m×d2/t2, where m is the neutron mass, d detector distance, and t flight time.
32. Photek Ltd., St. Leonards-on-Sea, East Sussex TN38 9NS, United Kingdom.
35. Given the challenges in assigning statistical error bars, the χ2red value should not be considered as a strict statistical metric for quality of fit. Inspection of FIG. 3 demonstrates the quality of the fit with χ2red=2.0.
36. See Supplemental material [...url...] for feeding factor results for each fit performed.