



# CHORUS

This is the accepted manuscript made available via CHORUS. The article has been published as:

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

D. T. Casey, J. A. Frenje, M. Gatu Johnson, M. J.-E. Manuel, N. Sinenian, A. B. Zylstra, F. H. Séguin, C. K. Li, R. D. Petrasso, V. Yu Glebov, P. B. Radha, D. D. Meyerhofer, T. C. Sangster, D. P. McNabb, P. A. Amendt, R. N. Boyd, S. P. Hatchett, S. Quaglioni, J. R. Rygg, I. J. Thompson, A. D. Bacher, H. W. Herrmann, and Y. H. Kim

Phys. Rev. Lett. **109**, 025003 — Published 10 July 2012

DOI: [10.1103/PhysRevLett.109.025003](https://doi.org/10.1103/PhysRevLett.109.025003)

# Measurements of the $T(t,2n)^4\text{He}$ neutron spectrum at low reactant energies from inertial confinement implosions

D. T. Casey, J. A. Frenje, M. Gatu Johnson, M. J.-E. Manuel, N. Sinenian, A. B. Zylstra, F. H. Séguin, C. K. Li, and R. D. Petrasso

*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

V. Yu Glebov, P. B. Radha, D. D. Meyerhofer,<sup>a)</sup> and T. C. Sangster  
*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623*

D. P. McNabb, P. A. Amendt, R. N. Boyd, S. P. Hatchett, S. Quaglioni, J. R. Rygg, and I. J. Thompson  
*Lawrence Livermore National Laboratory, Livermore, California 94550*

A. D. Bacher  
*Department of Physics, Indiana University, Bloomington, Indiana 47405*

H. W. Herrmann and Y. H. Kim  
*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

Measurements of the neutron spectrum from the  $T(t,2n)^4\text{He}$  (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 (CM) energies. In contrast to accelerator experiments at higher CM energies (above 100 keV), these results indicate a negligible  $n+^5\text{He}$  reaction channel at a CM energy of 23 keV.

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  $T(t,2n)^4\text{He}$  (or tt). The tt reaction is relevant to stellar nucleosynthesis because it is the mirror reaction to the stellar  $^3\text{He}(^3\text{He},2p)^4\text{He}$  (or  $^3\text{He}^3\text{He}$ ) reaction [6], which is the dominant energy-producing step in the solar proton-proton chain [5]. Studying the tt reaction provides information about the  $^3\text{He}^3\text{He}$  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  $^4\text{He}$  ion. The n-n and n- $^4\text{He}$  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 ( $\rho R$ ), 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 (CM) energy of 23 keV. The tt neutron spectrum is found to differ significantly from the spectra determined from accelerator experiments conducted at CM energies above 100 keV [11, 12]. More specifically, the "low-CM-energy" ICF experiments discussed in this letter show a negligible  $n+^5\text{He}$  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  $n+n+^4\text{He}$  phase space (distorted by the n-n final state interaction), along with the ground-state  $n+^5\text{He}$ (GS) and the excited-state  $n+^5\text{He}$ (ES) channels, which are summarized by,

$$\begin{aligned}
T + T &\rightarrow 2n + {}^4_2\text{He}, & Q=11.3 \text{ MeV}, & (1) \\
T + T &\rightarrow n + {}^5_2\text{He(GS)}, & Q=10.4 \text{ MeV}, & (2) \\
T + T &\rightarrow n + {}^5_2\text{He(ES)}, & Q=9.2 \text{ MeV}. & (3)
\end{aligned}$$

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.1a. The  $n+{}^5\text{He(GS)}$  channel modifies the neutron spectrum through the formation of the short-lived  ${}^5\text{He}$  nucleus in the ground-state, resulting in a neutron with a peak energy of 8.7 MeV (Eq. 2). Similarly, the excited-state channel  $n+{}^5\text{He(ES)}$  modifies the neutron spectrum through the formation of an excited  ${}^5\text{He(ES)}$  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  $n+{}^5\text{He}$  spectral shapes, shown in Fig.1a, were calculated using  ${}^5\text{He(GS)}$  and  ${}^5\text{He(ES)}$  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].

One such experiment was performed by Wong et al. [12], who measured the tt neutron spectrum at a CM energy of 250 keV (see Fig.1b). 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%  $n+{}^5\text{He(GS)}$ , and 10%  $n+{}^5\text{He(ES)}$ , and additionally concluded that the  $n+{}^5\text{He(GS)}$  neutron peak is isotropic in the CM system within their accuracy of  $\sim 10\%$ . In another experiment at a CM energy of 110 keV, Allen et al. [11] measured a  $n+{}^5\text{He(GS)}$  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 CM energy of 20 keV (separated by  $176^\circ$  to emphasize the n-n interaction), and they suggested that the  $n+{}^5\text{He(GS)}$  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 CM energy. The peak (also called Gamow peak energy) of the reactant energy distribution can be expressed as  $E_{cm} = (b T_i/2)^{2/3}$ , which has a full-width half maximum of  $\text{FWHM} \sim (16 \ln 2 E_{cm} T_i/3)^{1/2}$ . Here, the Gamow penetration factor ( $b$ ), is  $b = \sqrt{2m_r \pi e^2 Z_1 Z_2} / \hbar$ . For tt,  $b = 38.5 \text{ keV}^{1/2}$  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 CM energies for the tt reaction are in the range 10-45 keV.

Fig.1: a) Model neutron spectrum for the tt reaction, including contributions from the  $n+n+{}^4\text{He}$ ,  $n+{}^5\text{He(GS)}$ , and  $n+{}^5\text{He(ES)}$  channels. This simple analysis neglects interference in the final state and does not include the  ${}^5\text{He}$ -breakup neutrons as they are below the detection limit for the data discussed in this paper (contributions from  ${}^5\text{He}$  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 CM reactant energies of 110 keV and 250 keV, respectively. The best fits to the two data sets are also shown (solid lines) using the model described above.

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  $\text{CD}_2$  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.

Fig. 2a 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  $8.0 \pm 0.5 \text{ keV}$  was determined from the neutron time-of-flight (nTOF) diagnostic suite [27]. The MRS measured recoil deuteron spectrum is shown in Fig. 2a, where the black points represent the primary dt and DS<sub>n</sub> data, and the red points represent mostly the tt data (some DS<sub>n</sub> signal exists in this region as well, as indicated by the DS<sub>n</sub> fit). The primary 14 MeV dt peak is evident in Fig. 2a at a deuteron energy of  $\sim 11.6 \text{ MeV}$ ; the energy shift is a result of kinematics and energy loss in the  $\text{CD}_2$  foil. The DS<sub>n</sub> spectrum is visible and isolated from other spectral components in the deuteron-energy range 8-10 MeV. The black line in Fig. 2a represents the best fit to the primary dt and DS<sub>n</sub> components shown by the black data points.

Fig. 2: a) MRS measured recoil deuteron spectrum summed over OMEGA shots 55641-55647 (points). The deuteron peak at  $\sim 11.6 \text{ MeV}$  is due to the primary 14 MeV dt neutrons, and the width of this peak is mainly due to the MRS resolution. The DS<sub>n</sub> component is observed in the deuteron-energy range of 8-10 MeV. A best fit to the dt and DS<sub>n</sub> components (black data points) is shown by the solid black line. The remaining tt neutron signal (red data points) rises above the DS<sub>n</sub> background below 8 MeV. b) Modeled neutron spectrum that gives the best fit to the measured dt and DS<sub>n</sub> components for the black points discussed in part a.

In the fitting process, the neutron spectrum (Fig. 2b) is folded with the MRS-response function to create a modeled recoil deuteron spectrum [10, 28]. The magnitude of the DS<sub>n</sub> spectrum is used as a fit parameter to the measured data, while the shape of the DS<sub>n</sub> 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<sup>2</sup> is in agreement with the complimentary charged particle inferred  $\rho R$  of  $40 \pm 6$  mg/cm<sup>2</sup> [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. 2b.

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 SiO<sub>2</sub>, CD, and CH shells (summarized in Table 1), providing a range of  $T_i$  between 3.5 – 8 keV (average of 5.8 keV). Fig. 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  $n+n+^4\text{He}$  reaction channel (solid red), along with 5% (dashed red) and 20% (dotted red) strengths of the  $n+^5\text{He(GS)}$  channel. The measured data shows that the  $n+^5\text{He(GS)}$  channel is insignificant [35] to a statistical uncertainty of  $\sim 2\%$ , based on a  $\chi^2$  sensitivity analysis [28].

Table 1: Shot numbers, target specifications (gas pressure, shell type and thickness), and observed DT yield ( $Y_{\text{DTn}}$ ) 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)Shell $\Delta R[\mu\text{m}]$	$Y_{\text{DTn}}$ ( $\times 10^{13}$ )	$T_i$ (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 <sub>2</sub> [3.8]	13.2	7.4
55641-55647	DT(12)CD[9.5]	25.5	8.0

Fig. 3: The tt neutron spectrum averaged over all implosion series spectra. The solid line represents the modeled  $n+n+^4\text{He}$  channel, while the dashed and dotted lines represent 5% and 20% contributions of the  $n+^5\text{He(GS)}$  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  $n+^5\text{He(GS)}$  reaction channel is observed.

Using the results shown in Fig. 3, the relative intensity of  $n+^5\text{He(GS)}$  to the total tt reaction yield is compared to accelerator experiments at higher CM energies in Fig. 4a [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. 4b. The 23 keV data in Fig. 4a is consistent with the general trend in the accelerator data obtained at 110 keV and 250 keV [11, 12]. Even though we have used a simplified sequential decay model, the negligibly small

$n+^5\text{He(GS)}$  channel apparent in Fig. 3, along with the suggested trend of Fig. 4a, implies that  $n+^5\text{He(GS)}$  is suppressed at these low reactant CM 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 ( $n+n+^4\text{He}$ ) dynamics, are currently being developed for the tt neutron spectrum at these CM energies [40].

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

The observed relative strength of the  $n+^5\text{He(GS)}$  reaction channel shown in Fig. 4a 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 CM energy [43]. However, Fig. 4a indicates that the  $n+^5\text{He(GS)}$  contribution to the tt neutron emission is negligible in ICF-relevant conditions. It is also interesting to note that related calculations of the  $^3\text{He}^3\text{He}$  reaction [7] determine the relative strengths of  $^3\text{He}^3\text{He}$  reaction channels ( $p+p+^4\text{He}$  and  $p+^5\text{Li}$ ) from the tt spectrum measured by Wong [12] (because tt and  $^3\text{He}^3\text{He}$  are mirror reactions). Therefore, the results of Fig. 4a pose the question as to whether a similar relationship exists for  $^3\text{He}^3\text{He}$ , resulting in a suppression of the  $p+^5\text{Li}$  channel at the solar Gamow peak energy ( $E_{\text{CM}} = 21$  keV [44]). To that end, experiments have begun to directly measure the  $^3\text{He}^3\text{He}$  proton spectrum in OMEGA implosions [45].

To improve upon the measurements of the tt neutron spectrum at OMEGA, implosions of pure T<sub>2</sub>-gas filled capsules [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 (LENS) [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 CM energies in thermonuclear plasmas using a variety of ICF capsule implosions at OMEGA. The results show that, in contrast to accelerator data at higher CM energies (above 100 keV), the  $n+^5\text{He(GS)}$  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  $^3\text{He}^3\text{He}$  reaction, which is the dominant energy-producing step in the solar proton-proton chain.

The authors thank the OMEGA operations, engineering, and scientific staff who supported this work at every level. We also thank G. Hale for valuable discussions. This work

was supported in part by the U.S. DOE (DE-FG52-09NA29553), NLUF (NA0000877), FSC (Rochester Subaward PO No. 415023-G, UR Account No. 5-24431),

a) Also Department of Mechanical Engineering, and Physics and Astronomy, University of Rochester.

- [1] T. R. Boehly *et al.*, *Optics Communications* **133**, 495 (1997).
- [2] E. I. Moses, *Journal of Physics: Conference Series* **112**, 012003 (2008).
- [3] E. G. Adelberger *et al.*, *Reviews of Modern Physics* **83**, 195 (2011).
- [4] J. A. Frenje *et al.*, *Physical Review Letters* **107**, 122502 (2011).
- [5] R. N. Boyd, *An introduction to nuclear astrophysics* (University of Chicago Press, Chicago, 2007).
- [6] A. Csótó, and K. Langanke, *Nuclear Physics A* **646**, 387 (1999).
- [7] M. B. Chadwick *et al.*, *Nuclear Data Sheets* **107**, 2931 (2006).
- [8] R. J. Slobodrian, *Reports on Progress in Physics* **34**, 175 (1971).
- [9] T. C. Sangster *et al.*, *Physics of Plasmas* **17**, 056312 (2010).
- [10] J. A. Frenje *et al.*, *Physics of Plasmas* **17**, 056311 (2010).
- [11] K. W. Allen *et al.*, *Phys Rev* **82**, 262 (1951).
- [12] C. Wong, J. D. Anderson, and J. W. McClure, *Nuclear Physics* **71**, 106 (1965).
- [13] G. G. Ohlsen, *Nuclear Instruments and Methods* **37**, 240 (1965).
- [14] A strong n-n interaction should produce a distribution favored at  $\sim Q/3$  or  $\sim 4\text{MeV}$  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).
- [15] B. Lacina, J. Ingley, and D. W. Dorn, (LLNL, UCRL-7769, 1965).
- [16] This neutron has a broad emission spectrum due to the very short lifetime of  $^3\text{He}(\text{ES})$ .
- [17] D. R. Tilley *et al.*, *Nuclear Physics A* **708**, 3 (2002).
- [18] R. Larose-Poutissou, and H. Jeremie, *Nuclear Physics A* **218**, 559 (1974).
- [19] While they suggested that the  $n+^5\text{He}(\text{GS})$  channel is unimportant in their data, they indicated that the  $n+^5\text{He}(\text{ES})$  channel may be important, a result that is counter-intuitive.
- [20] J. A. Frenje *et al.*, *Review of Scientific Instruments* **79**, 10E502 (2008).
- [21] D. T. Casey *et al.*, *Review of Scientific Instruments* **82**, 073502 (2011).
- [22] D. T. Casey *et al.*, *Physical Review Letters* **108**, 075002 (2012).
- [23] F. H. Seguin *et al.*, *Review of Scientific Instruments* **74**, 975 (2003).
- [24] Six implosions were integrated to obtain better statistics because the neutron detection efficiency is relatively low. Nominally identical shell thickness, diameter, fill pressure, and laser profiles within an implosion series, result in very similar  $T_i$  and nuclear yield. In this series, the shot-to-shot  $T_i$  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.

LLNL (412160-001G), LLNL (B580243), and prepared in part by LLNL (under DE-AC52-07NA27344).

- [27] V. Y. Glebov *et al.*, *Review of Scientific Instruments* **75**, 3559 (2004).
- [28] D. T. Casey, (PhD. thesis, MIT, Cambridge, MA, 2012).
- [29] The DSn 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.
- [31] F. H. Séguin *et al.*, *Physics of Plasmas* **9**, 3558 (2002).
- [32] C. K. Li *et al.*, *Physics of Plasmas* **10**, 1919 (2003).
- [33] Systematic errors could be introduced by uncertainty in the neutron scattering cross-sections. However, the impact of this is greatly reduced as each series type has a different DSn intensity (areal densities ranging from  $13\text{-}71 \text{ mg/cm}^2$ ) and is dominated by different scattering cross-sections ( $\text{SiO}_2$ , 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.
- [34] J. R. Taylor, *An introduction to error analysis: the study of uncertainties in physical measurements* (University Science Books, 1997).
- [35] As the  $n+^5\text{He}(\text{GS})$  channel was not observed the  $n+^5\text{He}(\text{ES})$  channel was ignored.
- [36] Both of the accelerator experiments shown were performed at  $90^\circ$  relative to the incoming beam, whereas this work is integrated over all angles. However, Wong *et al.* showed the  $n+^5\text{He}(\text{GS})$  neutron emission is isotropic at 250 keV and therefore we believe it is reasonable to assume that it remains isotropic at lower reactant energies.
- [37] S. Quaglioni *et al.*, arXiv:1203.0268 (2012).
- [38] P. Navrátil, and S. Quaglioni, *Physical Review C* **83**, 044609 (2011).
- [39] B. V. Danilin *et al.*, *Nuclear Physics A* **632**, 383 (1998).
- [40] I. J. Thompson and S. Quaglioni, private communication.
- [41] G. B. Zimmerman and W. L. Kruer, *Comments Plasma Phys. Controlled Fusion* **2**, 51 (1975).
- [42] M. J. Edwards *et al.*, *Physics of Plasmas* **18**, 051003 (2011).
- [43] G. Zimmerman, private communication.
- [44] E. G. Adelberger *et al.*, *Reviews of Modern Physics* **70**, 1265 (1998).
- [45] J. Frenje, private communication.
- [46] Preliminary measurements using  $\text{T}_2$ -gas filled implosions were obtained by V. Yu Glebov *et al.* [Bull. of Am. Phys. Soc. 2006, APS.2006.DPP.GO2.11] using the nTOF diagnostic, but a lack of a well characterized detector response and neutron scattering precluded a quantitative assessment of the  $n+^5\text{He}$  contribution to the spectrum.
- [47] M. Gatu Johnson, to be published.

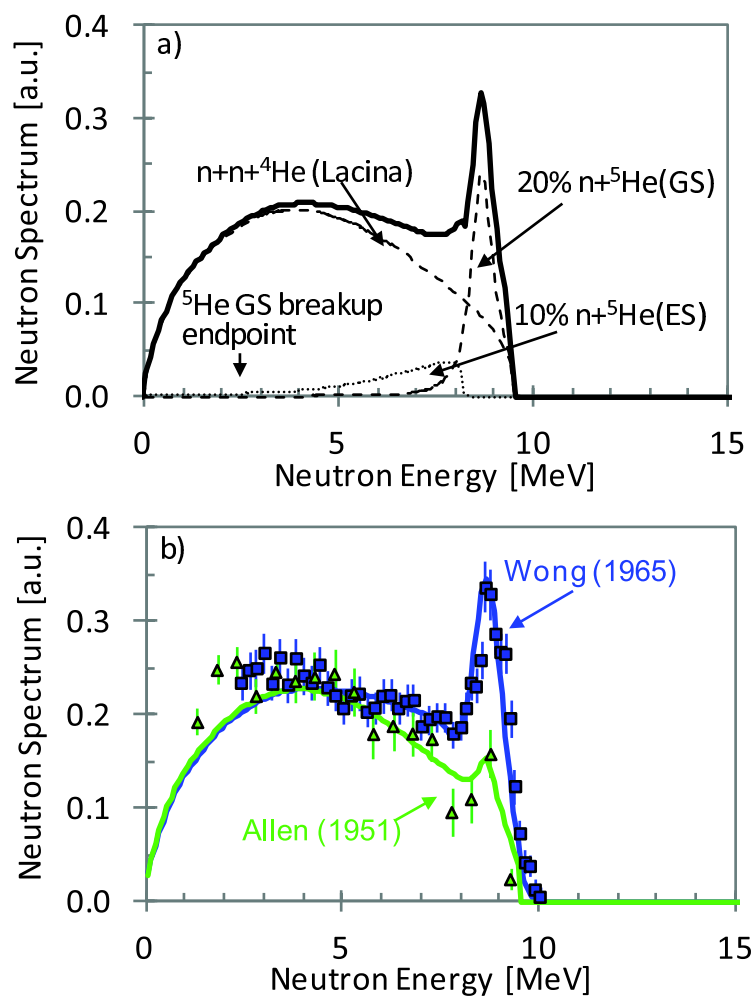


Figure 1 LQ13186 11MAY2012

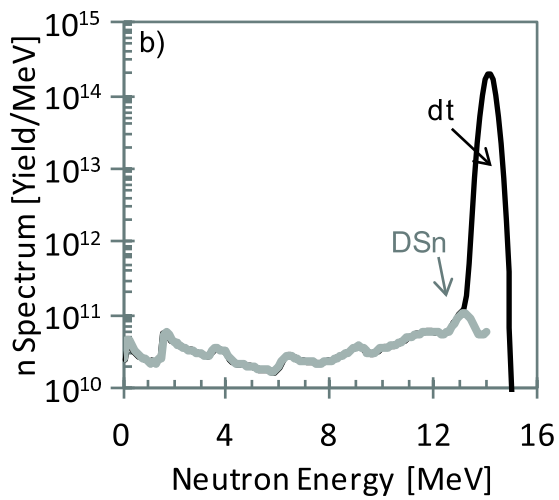
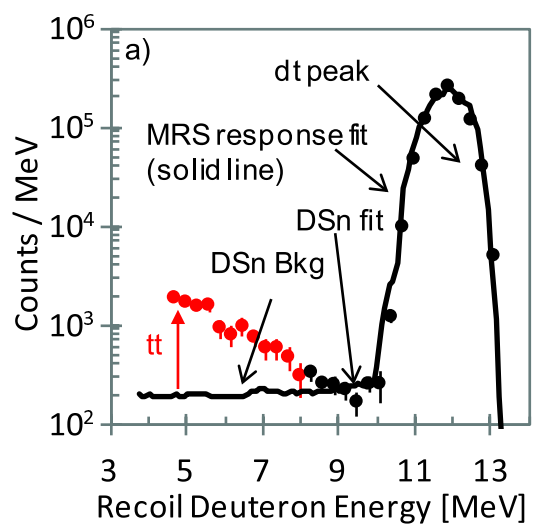


Figure 2

LQ13186

11MAY2012

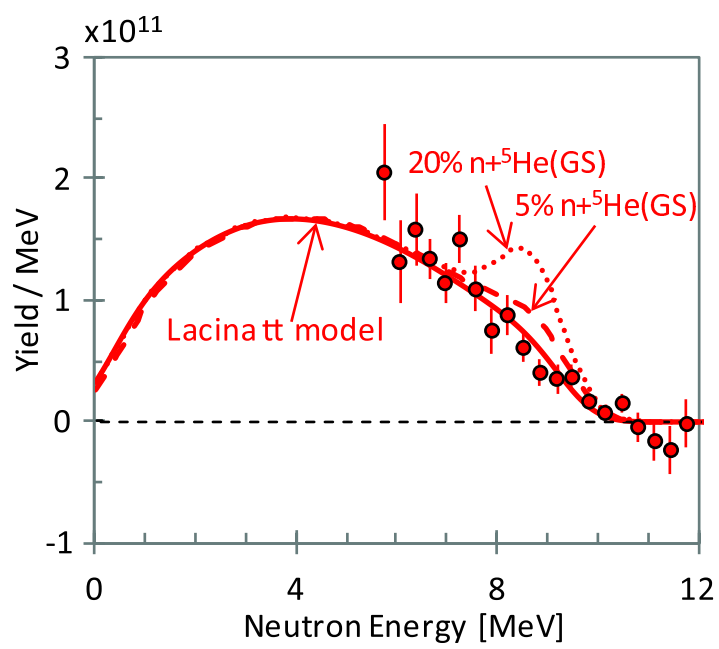


Figure 3 LQ13186 11MAY2012



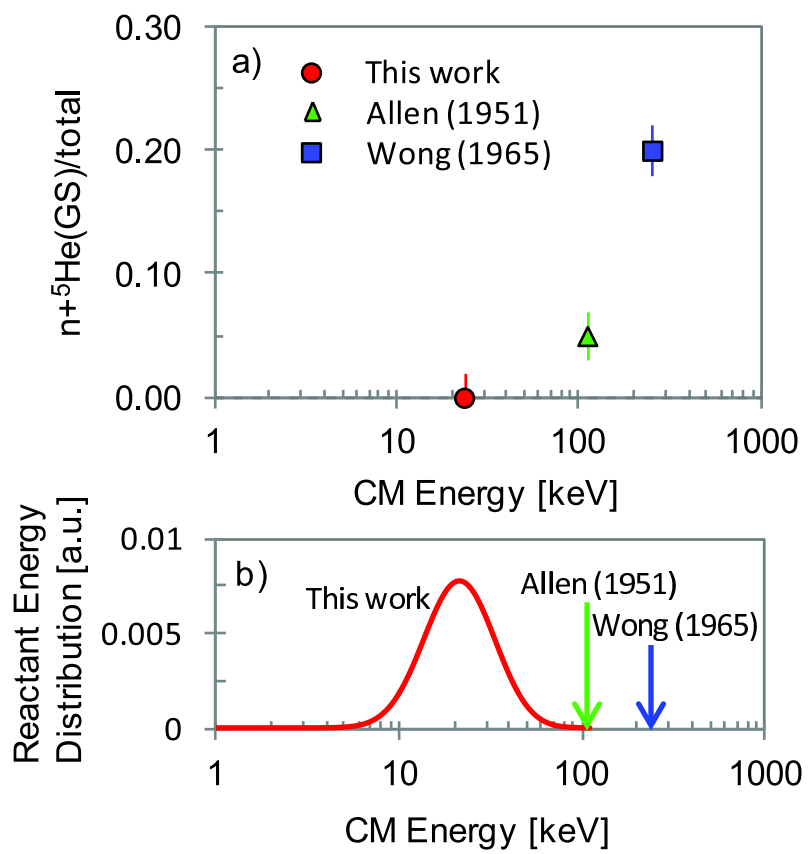


Figure 4