Measurement of the T+T Neutron Spectrum Using the National Ignition Facility

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Neutron time-of-flight spectra from inertial confinement fusion experiments with tritium-filled targets have been measured at the National Ignition Facility. These spectra represent a significant improvement in energy resolution and statistics over previous measurements, and afford the first definitive observation of a peak resulting from sequential decay through the ground state of $^5$He at low reaction energies $E_{c.m.} \leq 100$ keV. To describe the spectrum, we have developed an $R$-matrix model that accounts for interferences from fermion symmetry and intermediate states, and show these effects to be non-negligible. We also find the spectrum can be described by sequential decay through $\ell = 1$ states in $^5$He, which differs from previous interpretations.

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In addition to earlier accelerator work \[7,10,11,14\], fusion experiments based on muon catalysis \[4,5\] and inertial confinement \[6\] have been conducted. Although the precise details of detectors differed among experiments, most have deduced the neutron spectrum from either proton or deuteron recoils \[4–6,10,11\]. It is interesting to note that only three groups have reported their experimental energy resolution (full width at half maximum): 0.5 \[14\], 1.3 \[6\], and 2.8 MeV \[11\]. The work presented in this Letter has combined the inertial confinement approach with time-of-flight technique to perform measurements resolved to 280 keV \[22\]—a factor of \(\approx 2\) improvement over any previous experiment.

The first reported measurement of the neutron spectrum \((E_{\text{c.m.}} = 110 \text{ keV})\) \[10\] was interpreted as a statistical distribution, accompanied by a much smaller \((\approx 10\%)\) \(^{5}\)He ground-state contribution. Wong et al. \[14\] later determined at slightly higher energies \((250 \text{ keV})\) that 70% of decays proceeded through correlated dineutron emission, with the remainder split between the ground \((20\%)\) and first-excited \((10\%)\) states of \(^{5}\)He. As stipulated in their paper the branching ratios were directly tied to an assumption of a strong dineutron channel. The predominance of that channel is contrary to the findings of Poutissou et al. \[7\] \((20 \text{ keV})\), who stated that any \(n-n\) correlations were masked by those from \(n-\alpha\), and Matsuzaki et al. \[5\] \((\approx 0 \text{ keV})\), who emphasized the importance of \(n-\alpha\) interactions. Yet the conclusions of both groups were strongly model dependent as no definitive signature of \(n-\alpha\) interactions was visible in their data, such as the peak at 8.7 MeV in the spectra of Refs. \[10,14\] from sequential decays through the ground state of \(^{5}\)He. The significance of these interactions at low reaction energies was further brought into question by a recent Letter \[6\] that reported no observable \(n-\alpha\) effects at \(E_{\text{c.m.}} = 23 \text{ keV}\). Casey et al. \[6\] pointed out the diminishing strength of the \(^{5}\)He ground-state peak with reaction energy, from Wong et al. to Allen et al. \[10\] to Poutissou et al., who also reported no appreciable contribution from this channel. In addition, the correlated dineutron distribution of Refs. \[13,14\] was found to describe the measurements of Casey et al. Utilizing a new experimental capability, we report, in this Letter, the first direct observation of the peak from the \(^{5}\)He ground-state channel at low energies. Further, with the \(R\)-matrix model, we find the main features in these new measurements can be described by sequential decay through \(\ell = 1\) states in \(^{5}\)He.

The energy distribution of particles emitted by reactions in unbound states can be described with \(R\)-matrix methods, as given by Barker \[21\]. But when a reaction leads to a final state containing identical particles, the standard formalism must be adapted to treat an amplitude with exchange symmetry. For the low energy \(T(t,2n)\alpha\) reaction, coupling tritons in an \(s\) wave to form a \(0^+\) state, the amplitude can be generalized as

\[
\mathcal{M}_{p_1 p_2}^{J^G} = \sum_{m_1 m_2 m} \frac{(-1)^{J+m}}{\sqrt{2J+1}} \left( \ell m \ell \frac{1}{2} \nu \right) Y_{m_1} Y_{m_2} \left( p_1 \right) Y_{c_1 m_2} \left( p_2 \right) e^{-i(\phi_1 + \phi_2)} \frac{p_1 p_2}{p_1 p_2 \sum_{\Delta J \Delta \lambda} \sum_{J} B_{J} Y_{m_1}' \left( \rho_{23} \right) \times 1 - (B_J - S_{23} + iP_{23}) R_{J},
\]

(1)

The numerical subscripts in Eq. (1) reflect the decay process: emission of neutron 1 and the subsequent disintegration of \(^{5}\)He to neutron 2 and \(\alpha\) particle 3. For a given \(J^G\) in \(^{5}\)He and orientations \(\nu\) of emitted neutrons, summations are performed over possible angular momentum quantum numbers. Clebsch-Gordan coefficients along with spherical harmonics \(Y_{m_1}, Y_{m_2}\), which depend on projections of momenta \(p\) in the three-body \(p_1\) and recoil center-of-mass \(\rho_{23}\) systems, describe the angular correlation between neutrons. Only the ground \(3/2^-\) and first-excited \(1/2^-\) states of \(^{5}\)He are directly accessible from reaction energies relevant here, and for both cases \(\ell = 1\) neutrons are ejected in each stage of the breakup. Energy levels \(E_{J},\) reduced-width amplitudes \(\gamma_{J}\), boundary values \(B_{J}\), and feeding factors \(A_{J}\) are the \(R\)-matrix parameters contained above, and all except the \(A_{J}\) factors can be constrained with high precision \(n-\alpha\) scattering data \[23\]. The remaining terms are calculable for a given channel radius and partial wave: the hard sphere phase shift \(\Phi\) and the penetration \(P\) and shift \(S\) factors.

Exchanging neutron indices in Eq. (1) yields a second expression, which is necessary to construct the antisymmetry amplitude. The energy distribution is obtained by summing the amplitude over \(J\), squaring the magnitude, then summing over \(\nu_1\) and \(\nu_2\), and multiplying by the three-body phase-space factor \[24\]. Interferences from symmetry and intermediate states originate from cross terms in the squared amplitude. Lastly, to describe kine-

matically incomplete measurements, such as the spectra considered here, an integration is performed over angles of the unobserved neutron. Figure 1 presents spectra that result from the procedure outlined above. The spectrum calculated for the \(1/2^-\) partial wave (middle panel) illustrates the importance of antisymmetry, which leads to a \(\approx 30\%\) contribution.

Inertial confinement experiments were conducted at the National Ignition Facility. Here, temporally shaped laser beams were used to generate a soft x-ray field that ablatively imploded a spherical plastic capsule filled with 99.99% tritium gas \((0.1\%\) deuterium). Using time-of-flight detectors, an ion temperature of \(k_B T = 3.3(3) \text{ keV}\) [or an effective energy for the \(T(t,2n)\alpha\) reaction of \(E_{\text{c.m.}} = 16(1) \text{ keV}\)] within the burn volume was extracted from thermal broadening of nearly monoenergetic 14 MeV neutrons produced by the \(T(d,n)\alpha\) reaction. A total neutron yield in excess of \(10^{13}\) was produced over the \(\approx 200 \text{ ps}\)
The relative flat baseline several decades induced background from residual deuterium in the capsu-
tering of the neutron spectrum from intervening material 
ground created during implosions. Attenuation and scat-
covered each line of sight to suppress the photon back-

1.3 cm thick attenuator (95% W, 3% Ni, and 2% Fe) 
and the second was designed to clean up after the first. A 
tor defined a 8.3 cm diameter opening on the detector face 
was doubly collimated with 1 m of steel: the first collima-
chamber center along separate lines of sight [25]. Each line 
expected distribution from thermal broadening [27]. 
Careful attention has also been given to describing light 
decay time of the scintillator over observed neutron ener-
gies. Consistency checks of the scintillator response have 
measured the IRFs. Further refinements have been made to account for neutron transport in the scintillator. Constructed IRFs have been validated over many measurements of the $T(d, n)\alpha$ peak, in which good fits to data ($\chi^2 = 1$) were obtained with the expected distribution from thermal broadening [27]. Careful attention has also been given to describing light production in the scintillator over observed neutron energies. Consistency checks of the scintillator response have been performed in situ with activation foils, which agree with the scintillators to 8%.

The $R$-matrix spectrum was fitted simultaneously to data from both detectors. This method combines neutron statistics and averages over systematic differences between measurements. The fitting algorithm first thermally broadens a trial spectrum then adjusts for attenuation or scattering and scintillation response. Next, for each detector, the

duration of thermonuclear reactions, affording excellent statistics and timing. Measurements have also been performed with a capsule containing a deuterium-to-tritium ratio of 3:1. These data serve to establish the neutron-induced background from residual deuterium in the capsules, and show a relatively flat baseline several decades below the preceding $T(d, n)\alpha$ peak (see Fig. 2, bottom panel).

Neutron spectra were recorded by two 10 cm by 5 cm xylene scintillators, positioned over 20 m from the target chamber center along separate lines of sight [25]. Each line was doubly collimated with 1 m of steel: the first collima-
tor defined a 8.3 cm diameter opening on the detector face and the second was designed to clean up after the first. A 
3.3 cm thick attenuator (95% W, 3% Ni, and 2% Fe) 
covered each line of sight to suppress the photon back-
ground created during implosions. Attenuation and scat-
tering of the neutron spectrum from intervening material 
has been taken into account with MCNP [26] simulations, and corrections were $\lesssim 10\%$ above 2 MeV.

Implosions are singular events which generate tremen-
dous neutron fluxes, therefore, the standard methods of pulse counting are not applicable. Detectors were operated in current mode and their signals were digitized with 1 GHz oscilloscopes. Interpreting current mode data requires knowledge of the impulse response functions (IRFs) from detectors. As the light decay time of the scintillator is rather insensitive to particle type, short pulses (100 ps) of x rays have been used to measure the IRFs. Further refinements have been made to account for neutron transport in the scintillator. Constructed IRFs have been validated over many measurements of the $T(d, n)\alpha$ peak, in which good fits to data ($\chi^2 = 1$) were obtained with the expected distribution from thermal broadening [27]. Careful attention has also been given to describing light production in the scintillator over observed neutron energies. Consistency checks of the scintillator response have been performed in situ with activation foils, which agree with the scintillators to 8%.

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FIG. 1 (color online). $R$-matrix spectra resulting from the fitted feeding factors are shown above. Decays through partial waves of the ground and first-excited states of $^3$He are shown in the top and middle panels, respectively. Each partial wave contains an interference term from antisymmetrization, which is proportional to the overlap between primary and secondary distributions. For the $J = 1/2^-$ partial wave, the interference term makes a $\approx 30\%$ contribution. The bottom panel displays the coherent sum of both partial waves. An interference created within the neutron angular correlation manifests itself in the spectrum. The feeding factors determine the sign of this interference.

FIG. 2 (color online). Experimental corrections applied to the modeled spectrum, as discussed in the text, are displayed in successive order (top panel). The combined fit is plotted over energy-binned data from the 22 m detector (bottom panel), in the region of interest and over the full range of neutron energies. Statistical errors are approximately the size of the data points. Transitions through the ground state of $^3$He produce a peak at $\approx 8.7$ MeV; the broad distribution peaked around 6 MeV can largely be described by the first-excited state in $^3$He. For reference, the short-dashed (cyan) curve shows the effect of not including antisymmetry. The background from deuterium contamina-
tion, which is illustrated better in the inset, has a minimal effect in the region of interest.
algorithm transforms the modified spectrum from energy into time of flight and convolves with the IRFs. The top panel of Fig. 2 illustrates these experimental corrections. A χ² minimization of the resulting spectrum to data determines free parameters with the MINUIT2 package [28]. Four feeding factors A_{1A} were allowed to vary in the fit; all remaining parameters were fixed to values reported by Stammbach and Walter [23].

Data corresponding to neutron energies ≲ 1 MeV were excluded from the analysis presented in Fig. 2 because of limited detector sensitivity. Digitizer noise from oscilloscopes represented the main source of statistical uncertainty in the data. Fluctuations due to neutron events were much smaller, as ≈ 10⁶ neutrons interacted with the scintillator to produce the signal in the region of interest. Systematic uncertainties have been investigated for ion temperature, attenuation or scattering, region of interest, and scintillator response. These uncertainties become more important for data below 4.5 MeV.

Separate analyses were undertaken for each systematic error at its 1σ deviation, and the sum of these individual errors (16%) was added in quadrature with uncertainties determined from the fitting routine (1%) to give a total error of 16%. The best fit results in a χ² = 1440 for 660 data points and 4 free parameters (χ²/v = 2.2), and comparable values of χ²/v result for each detector. This fit determines branching ratios between the 3/2⁻ and 1/2⁻ states of 29 ± 16% and 71 ± 16%, respectively. The error in the ratio is anticorrelated to maintain unity. Note that the ratio is largely insensitive to the interference between partial waves, as can be seen in the bottom panel of Fig. 1. While differences between the fitted curve and data appear in several locations, the model describes the main features in the spectrum quite well, particularly in the region of the spectrum that is least susceptible to systematic errors ≳ 4.5 MeV.

New spectra from inertial confinement fusion experiments with enriched tritium targets have been measured at the National Ignition Facility. These measurements provide conclusive evidence for n-α interactions in the T + T neutron spectrum produced by thermonuclear environments, through the first direct observation of a neutron peak from transitions via the ground state of ⁵He. A description of the data was obtained with an R-matrix model that accounts for the coherence between intermediate states and fermion symmetry, which was shown in this Letter to be non-negligible. Fits of the model to the spectrum show a large contribution from the 1/2⁻ partial wave in ³He, which differs from the dominant role found for either correlated dineutron emission [6] or statistical decay [10]. Future work will investigate the possible role of dineutron and/or sequential s-wave emission within the framework of the new R-matrix approach.

Although a reasonable description of the data was obtained with the R-matrix model, we acknowledge that the present analysis has limitations as it represents a two-body approximation to what is strictly a three-body problem. Also, the interpretation of the neutron singles spectrum can be subject to ambiguities that only kinematically complete measurements distinguish. We hope these new data encourage further work in theory and experiment, and improve evaluations of fusion experiments.

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