Wave-Function Amplitude Analysis of the $^5$He Resonance in the TT Neutron Spectrum

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Total fit for 11.1-keV TT energy spectrum

- Data
- Total fit
- Lacina function
- $^5$He ground state
- $^5$He excited state
- Decay of ground state
- Decay of excited state

Energy (MeV)

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The properties of $^5$He are analyzed using the TT neutron spectrum

- Three sets of data at different ion temperatures are available from OMEGA implosions.
- A series of three fits was conducted as a function of energy to determine likely parameters for the components of the spectrum.
  - Results from these fits were used to constrain a forward fit to the original time series.
- $^5$He ground-state mass agrees with literature; width is $\sim 1.5 \times$ accepted value.
- $^5$He excited state was found to be about 2 MeV above the ground state with a width of 2.4 MeV.
Collaborators

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The neutron spectrum from TT fusion is an important component of all DT ICF experiments.

- Other components include nD and nT single scatters, multiple scatters, deuterium breakup, and TT neutron spectrum.
The TT neutron spectrum includes four main contributions

1) \( T + T \rightarrow ^{5}\text{He} \text{ (ground state)} + n \)
\( ^{5}\text{He} \rightarrow ^{4}\text{He} + n \)

2) \( T + T \rightarrow ^{5}\text{He}^* \text{ (first excited state)} + n \)
\( ^{5}\text{He}^* \rightarrow ^{4}\text{He} + n \)

3) \( T + T \rightarrow ^{4}\text{He} + (2n) \)
\( (2n) \rightarrow n + n \)

4) \( T + T \rightarrow ^{4}\text{He} + n + n \)

R-matrix analysis* can be used for two-body problems, but not three-body problems

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* C. R. Brune et al., Phys. Rev. C 92, 014003 (2015);
Each reaction branch can be modeled through a convolution with a Gaussian temperature profile

- $^5$He states can be described by a Breit–Wigner (BW) distribution, which represents a nuclear resonance

$$\text{BW}(E, E_0, \Gamma) = \frac{k}{(E^2 - E_0^2)^2 + E_0^2 \Gamma^2}$$

with $k = \frac{2 \sqrt{2} E_0 \Gamma \gamma}{\pi \sqrt{E_0^2 + \gamma}}$ and $\gamma = E_0 \sqrt{E_0^2 + \Gamma^2}$

- Gaussian represents thermal broadening and can be described by

$$G(E, E_0, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(E - E_0\right)^2/2\sigma^2}$$

with $\sigma = \sqrt{\frac{2TE_0 m_n}{m_n + m_{^5\text{He}}}}$

- Convolution is applied using

$$\langle \text{BW} \ast G \rangle(x) = \int_0^\infty G(x - E', 0, \sigma) \text{BW}(E', E_0, \Gamma) dE'$$
The most accurate representation of the $T + T \to ^4\text{He} + 2n$ neutron spectrum comes from Lacina’s work.

- The general three-body spectrum for $s = 0$ can be described as an ellipse:
  $\frac{(x - h)^2}{a^2} + \frac{(y - k)^2}{b^2} = 1$

- Lacina’s work* describes the ellipse-shaped spectrum with a modification for the dineutron state (interference term in the wave function).

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Neutron data were collected at OMEGA at ion temperatures of 18.3 keV, 11.1 keV, and 3.7 keV

- These temperatures correspond to CM energies 50 keV, 36 keV, and 16 keV
- All shots were exploding pushers filled with tritium (+ some small amount of deuterium contamination)
- Detection with 13.4-m nTOF detector (xylene scintillator)
- \( V(t) = \left( \frac{50 \Omega}{k_2} \right) \frac{k_2}{k_1} \cdot \text{NLO}(E) \cdot \frac{\text{d}N}{\text{d}E} \frac{\text{d}E}{\text{d}t} \otimes \text{IRF} \)
  - NLO includes nonlinear light output, beamline attenuation, and neutron energy deposition
- Data shown are “\( \frac{\text{d}N}{\text{d}E} \)” \( \sim V(\text{d}t/\text{d}E)/\text{NLO} \), normalized to the 5-MeV point

CM: center of mass
nTOF: neutron time of flight
IRF: instrument response function
Forward fit was used to determine neutron parameters for the $^5$He states

- A series of fits to $dN/dE$ (without IRF) was used to determine start parameters and boundaries for the forward fit.

- \[ V(t) = \text{NLO}(E) \times \frac{dN}{dE} \text{d}t \] \( \otimes \) IRF
  - $dN/dE$ includes $^5$He ground state, $^5$He excited state, decay of $^5$He states, Lacina function, and a small DT background component.

- Ground-state mean energy around 8.7 MeV, width of 0.4 MeV.

- First excited-state mean energy around 7 MeV, width of 2 MeV.
Kinematic equations must be used to convert from neutron parameters to $^5$He parameters

- Accepted values for ground state are mass $= 5.01222 \pm 0.00005$ amu$^*$ and half-life $= 616 \times 10^{-24} \pm 150 \times 10^{-24}$ s$^**$

$^5$He ground-state parameters from forward fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-state mass (amu)</td>
<td>$5.01221 \pm (1 \times 10^{-6})$</td>
</tr>
<tr>
<td>Ground-state width (MeV)</td>
<td>$0.50354 \pm 0.00728$</td>
</tr>
<tr>
<td>Ground-state half-life (s)</td>
<td>$(906 \times 10^{-24}) \pm (11 \times 10^{-24})$</td>
</tr>
</tbody>
</table>

The $^5$He ground state agrees well with the accepted value, but lifetime/width differs from the accepted value by a factor of 1.5.

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Mass and width of the $^5$He first excited state are not well known

- There is little agreement on the energy and width of the first excited state

<table>
<thead>
<tr>
<th>$^5$He excited-state energy (MeV above ground state)</th>
<th>$^5$He excited-state width</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>2.4</td>
<td>This work (with Lacina function)</td>
</tr>
<tr>
<td>2.0</td>
<td>2.4</td>
<td>Wong, Anderson, and McClure$^1$</td>
</tr>
<tr>
<td>2.6</td>
<td>4.0</td>
<td>Fessenden and Maxson$^2$</td>
</tr>
<tr>
<td>3.8</td>
<td>3.1</td>
<td>Arena et al.$^3$</td>
</tr>
<tr>
<td>3.2</td>
<td>?</td>
<td>Sayre et al.$^4$</td>
</tr>
<tr>
<td>1.3</td>
<td>3.2</td>
<td>Tilley et al.$^5$</td>
</tr>
</tbody>
</table>

- Results from fit using Lacina function agrees with Wong’s values$^1$

Future plans for a gamma spectrometer should enable direct measurement of $^5$He levels using $D + T \to ^5$He + $\gamma$.

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The properties of $^5$He are analyzed using the TT neutron spectrum

- Three sets of data at different ion temperatures are available from OMEGA implosions
- A series of three fits was conducted as a function of energy to determine likely parameters for the components of the spectrum
  - results from these fits were used to constrain a forward fit to the original time series
- $^5$He ground-state mass agrees with literature; width is ~1.5× accepted value
- $^5$He excited state was found to be about 2 MeV above the ground state with a width of 2.4 MeV
A series of three least-squares fits was performed to determine likely parameters

- Step 1: Fit for ground state using data $E > 8.5$ MeV
- Step 2: Subtract $^5$He ground-state function and fit remaining data with $E < 5$ MeV
  - three-body shape (Lacina or ellipse) + Breit–Wigner
- Step 3: Subtract previous fit function from original data and fit remaining data with $E > 5$ MeV to sum of two Breit–Wigner distributions
A series of four least-squares fits was performed to determine likely parameters

- Step 1: Fit for ground state using data $E > 8.5$ MeV
- Fit function is convolution of Gaussian and Breit–Wigner
- Simultaneous fit for all three data sets
  - each data set will have same $E_0$ and $\Gamma$ but different intensities

![Graph showing the fit for $kT = 11.1$ keV (fit for 8.5+ MeV)]
A series of four least-squares fits was performed to determine likely parameters

- Step 2: Subtract $^5\text{He}$ ground-state function and fit remaining data with $E < 5$ MeV
- Subtraction isolates region containing $T + T \rightarrow ^4\text{He} + 2n$ and first excited state of $^5\text{He}$
- Fit function is either an ellipse or the Lacina function convolved with Gaussian
  - An additional Breit–Wigner is included to model possible neutrons from the decay of the $^5\text{He}$ ground state
- Simultaneous fit to all data—each has same parameters except for intensity
A series of four least-squares fits was performed to determine likely parameters

- Step 3: Subtract previous fit function from original data and fit remaining data with \( E > 5 \text{ MeV} \) to sum of two convolutions
- Subtraction here isolates data containing the ground state and first excited state of \(^5\text{He}\)
- Simultaneous fit to all data—fit functions for each data set share parameters with the exception of intensity
Kinematic equations must be used to convert from neutron parameters to $^5$He parameters

- $^5$He ground state agrees well with accepted value, but lifetime is $\sim$150% of accepted value

### Final neutron parameters

<table>
<thead>
<tr>
<th>E0 (MeV)</th>
<th>18.3 keV</th>
<th>11.1 keV</th>
<th>3.7 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lacina I</td>
<td>$3.9492 \pm 0.0350$</td>
<td>$11.2621 \pm 0.0516$</td>
<td>$2.0518 \pm 0.0275$</td>
</tr>
<tr>
<td>Ground state $E_0$ (MeV)</td>
<td>$8.6997 \pm 0.0011$</td>
<td>$8.6997 \pm 0.0011$</td>
<td>$8.6997 \pm 0.0011$</td>
</tr>
<tr>
<td>Ground state $\Gamma$ (MeV)</td>
<td>$0.4184 \pm 0.0060$</td>
<td>$0.4184 \pm 0.0060$</td>
<td>$0.4184 \pm 0.0060$</td>
</tr>
<tr>
<td>Ground state $I$</td>
<td>$0.6970 \pm 0.0074$</td>
<td>$1.5655 \pm 0.0140$</td>
<td>$0.2443 \pm 0.0040$</td>
</tr>
<tr>
<td>Excited state $E_0$ (MeV)</td>
<td>$7.0260 \pm 0.0191$</td>
<td>$7.0260 \pm 0.0191$</td>
<td>$7.0260 \pm 0.0191$</td>
</tr>
<tr>
<td>Excited state $\Gamma$ (MeV)</td>
<td>$1.9855 \pm 0.1370$</td>
<td>$1.9855 \pm 0.1370$</td>
<td>$1.9855 \pm 0.1370$</td>
</tr>
<tr>
<td>Excited state $I$</td>
<td>$0.4301 \pm 0.0420$</td>
<td>$0.8090 \pm 0.0730$</td>
<td>$0.1773 \pm 0.0255$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9983</td>
<td>0.9982</td>
<td>0.9987</td>
</tr>
<tr>
<td>Reduced $\chi^2$</td>
<td>1.0100</td>
<td>1.0084</td>
<td>1.0322</td>
</tr>
</tbody>
</table>

### $^5$He parameters

- *Ground state mass (amu)*: $5.01221 \pm 1e-06$
- Ground state width (MeV): $0.50354 \pm 0.00728$
- *Ground state half-life (s)*: $906e-24 \pm 11e-24$
- Excited state mass (amu): $5.01437 \pm 0.00002$
- Excited state width (MeV): $2.38851 \pm 0.16475$
- Excited state half-life (s): $191e-24 \pm 11e-24$

*Accepted values for ground state are mass = $5.01222 \pm 0.00005$ amu and half-life = $616 \times 10^{-24} \pm 150 \times 10^{-24}$ s*

Kinematic equations must be used to convert from neutron parameters to $^5$He parameters

- $^5$He ground state agrees well with accepted value, but lifetime is $\sim 150\%$ of accepted value

<table>
<thead>
<tr>
<th>Final neutron parameters</th>
<th>5$^5$He parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.3 keV</td>
<td>Ellipse I</td>
</tr>
<tr>
<td>11.1 keV</td>
<td>Ground state E$_0$ (MeV) 8.7169 ± 0.0015</td>
</tr>
<tr>
<td>3.7 keV</td>
<td>Ground state $\Gamma$ (MeV) 0.3647 ± 0.0047</td>
</tr>
<tr>
<td>Ellipse I</td>
<td>Ground state I 0.6210 ± 0.0046</td>
</tr>
<tr>
<td></td>
<td>Excited state E$_0$ (MeV) 3.0333 ± 0.0206</td>
</tr>
<tr>
<td></td>
<td>Excited state $\Gamma$ (MeV) 1.9855 ± 0.6999</td>
</tr>
<tr>
<td></td>
<td>Excited state I 0.9791 ± 0.1134</td>
</tr>
<tr>
<td></td>
<td>Reduced $\chi^2$ 0.9985</td>
</tr>
</tbody>
</table>

*Ground state mass (amu) 5.01218 ± 2e-06

Ground state width (MeV) 0.43890 ± 0.00560

*Ground state half-life (s) 1040e-24 ± 11e-24

Excited state mass (amu) 5.01952 ± 0.00027

Excited state width (MeV) 6.36457 ± 0.84114

Excited state half-life (s) 72e-24 ± 8e-24

*Accepted values for ground state are mass = 5.01222±0.00005 amu* and half-life = $616 \times 10^{-24} \pm 150 \times 10^{-24}$ s**