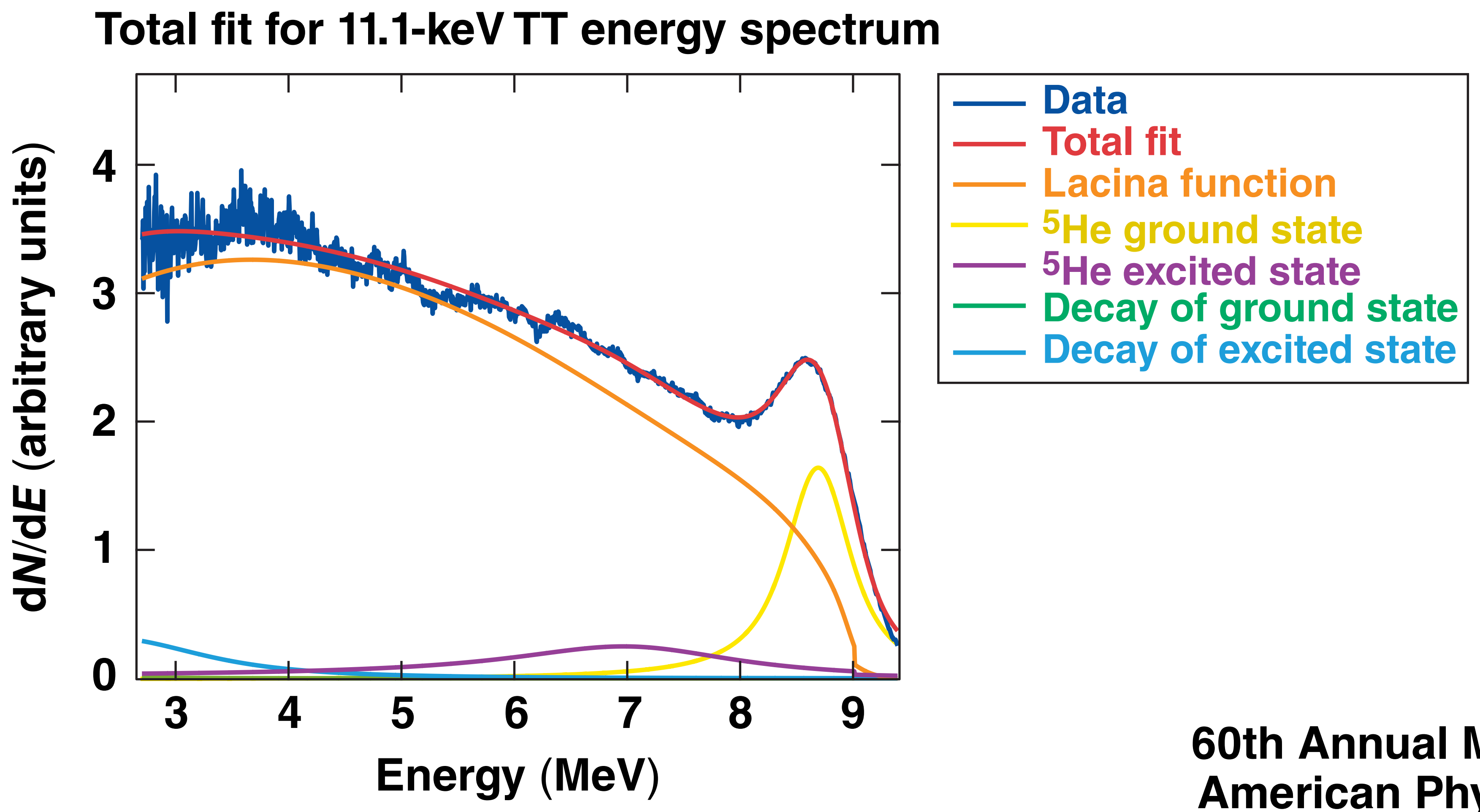
# Wave-Function Amplitude Analysis of the $^5$He Resonance in the TT Neutron Spectrum





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Summary

# 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

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# Collaborators

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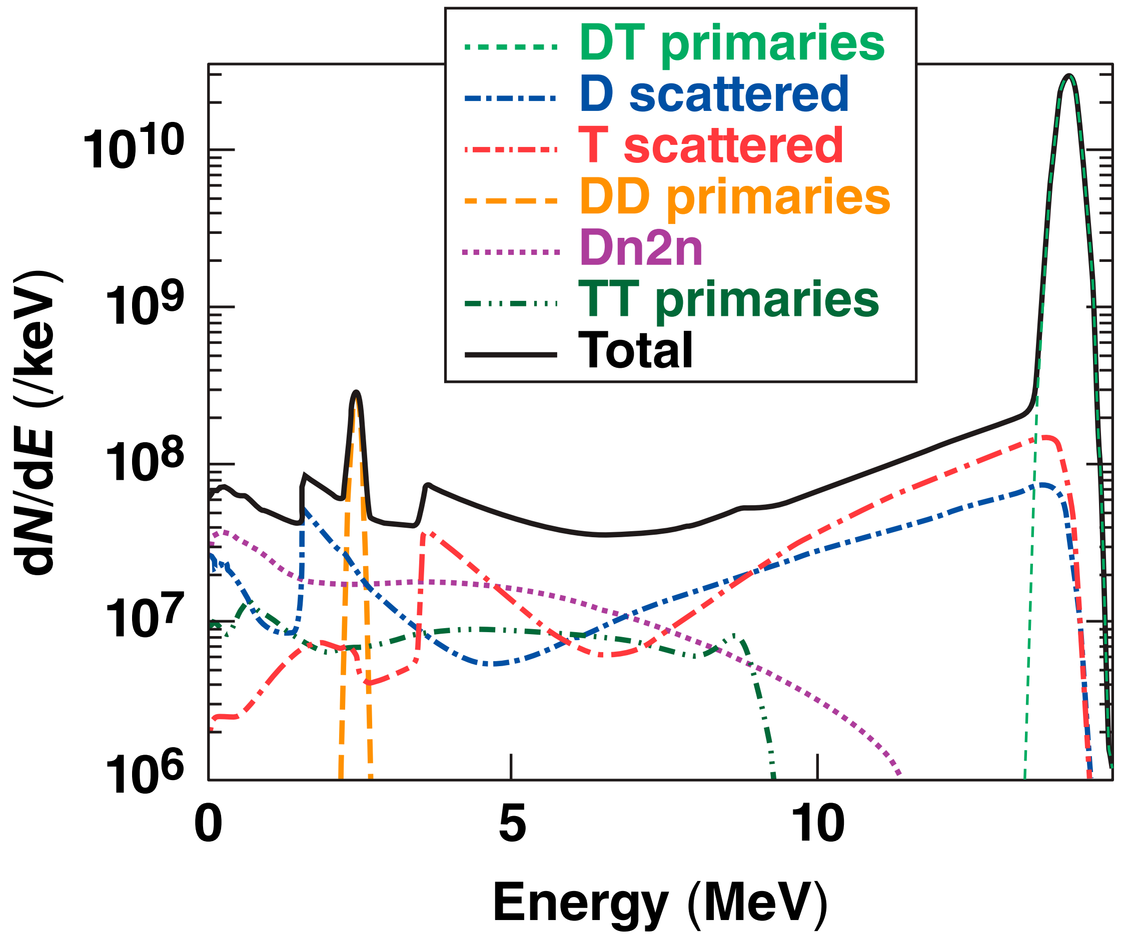
# The neutron spectrum from TT fusion is an important component of all DT ICF experiments

- **Other components include nD and nT single scatters, multiple scatters, deuterium breakup, and TT neutron spectrum**




TC13279a

LLE Review Quarterly Report 150, 104 (2017).

# The TT neutron spectrum includes four main contributions

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

$^5He \rightarrow {}^4He + n$

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

$^5He^* \rightarrow {}^4He + n$

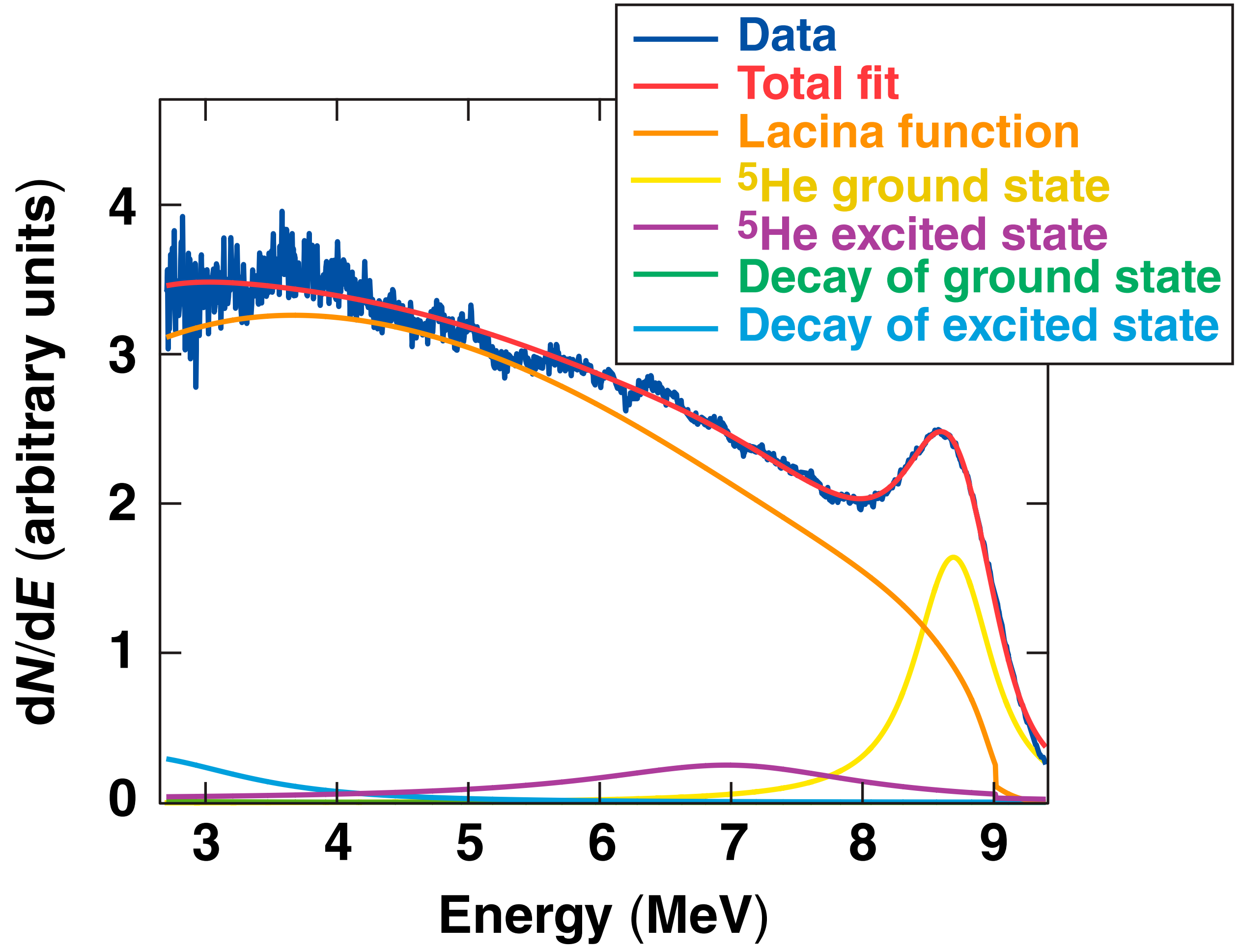
3) $T + T \rightarrow {}^4He + (2n)$

$(2n) \rightarrow n + n$

4) $T + T \rightarrow {}^4He + n + n$

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

**Total fit for 11.1-keV TT energy spectrum**




*C. R. Brune *et al.*, Phys. Rev. C 92, 014003 (2015); M. Gatu Johnson *et al.*, Phys. Rev. Lett. 121, 042501 (2018).

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# 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

$$\mathrm{BW}(E, E_0, \Gamma) = \frac{k}{\left(E^2 - E_0^2\right)^2 + E_0^2\Gamma^2} \text{ with } k = \frac{2\sqrt{2}\, E_0 \Gamma \gamma}{\pi \sqrt{E_0^2 + \gamma}} \text{ and } \gamma = E_0 \sqrt{E_0^2 + \Gamma^2}$$

- Gaussian represents thermal broadening and can be described by

$$\mathrm{G}(E, E_0, \sigma) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-(E - E_0)^2 / 2\sigma^2} \text{ with } \sigma = \sqrt{\frac{2TE_0 m_n}{m_n + m_{^5\mathrm{He}}}}$$

- Convolution is applied using

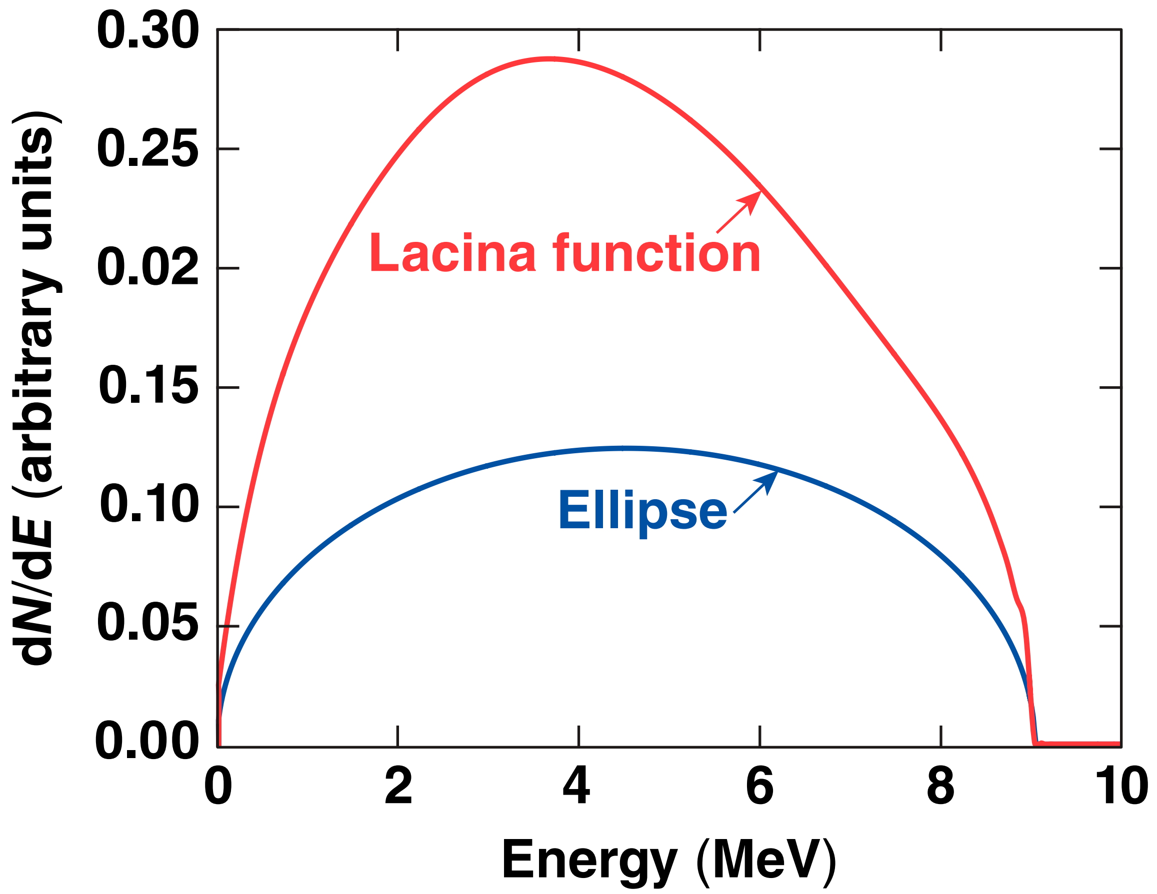
$$(\mathrm{BW} * \mathrm{G})(x) = I \int_0^{\infty} \mathrm{G}(x - E', 0, \sigma)\, \mathrm{BW}(E', E_0, \Gamma)\, \mathrm{d}E'$$

# The most accurate representation of the T + T → $^4$He + 2n neutron spectrum comes from Lacina's work

- The general three-body spectrum for $s = 0$ can be described as an ellipse

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$$

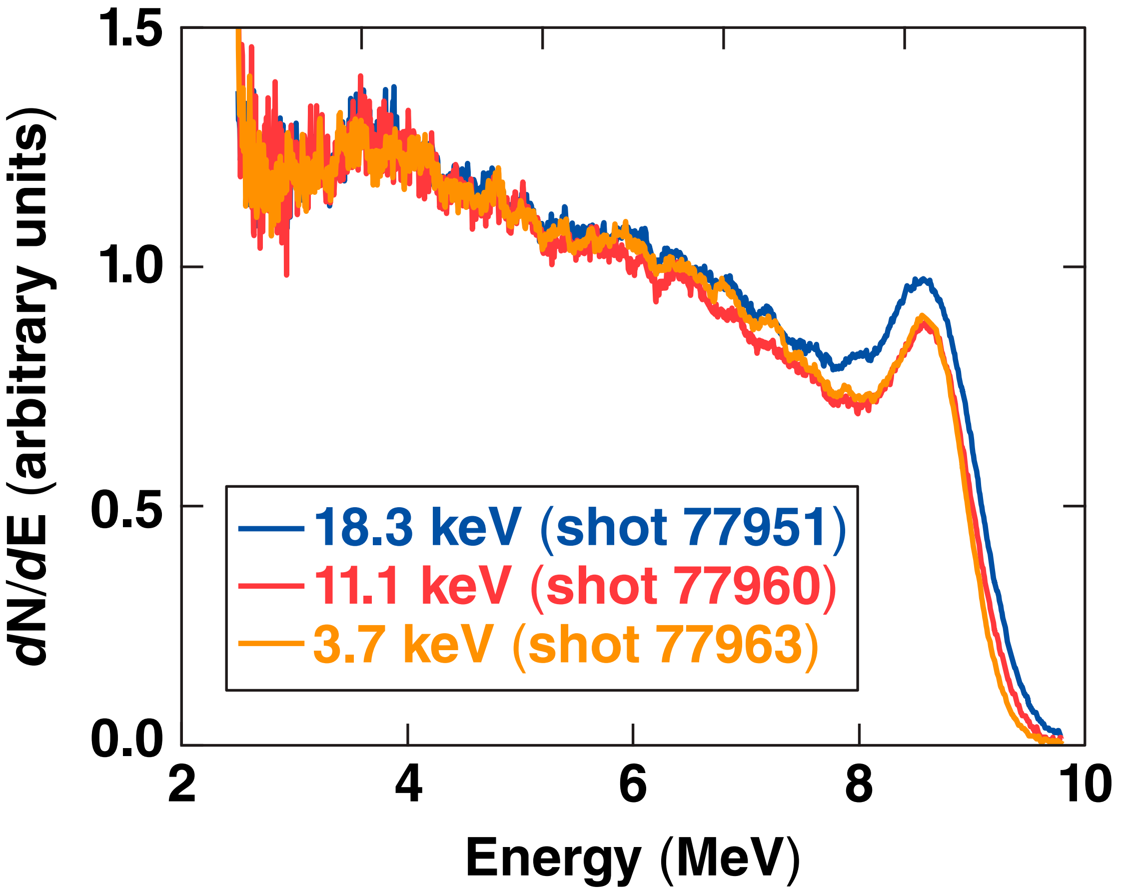
- Lacina's work* describes the ellipse-shaped spectrum with a modification for the dineutron state (interference term in the wave function)




*B. Lacina, J. Ingley, and D. W. Dorn, Lawrence Livermore National Laboratory, Livermore, CA, Report UCRL-7769 (1965).

# 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)
- $V(t) = \left[ 50\Omega * \frac{k_2}{k_1} * \mathrm{NLO}(E) * \frac{\mathrm{d}N}{\mathrm{d}E}\frac{\mathrm{d}E}{\mathrm{d}t} \right] \otimes \mathrm{IRF}$
  - NLO includes nonlinear light output, beamline attenuation, and neutron energy deposition
- Data shown are "d*N*/d*E*" $\sim V * (\mathrm{d}t/\mathrm{d}E) / \mathrm{NLO}$, normalized to the 5-MeV point




CM: center of mass
nTOF: neutron time of flight
IRF:instrument response function

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# Forward fit was used to determine neutron parameters for the $^5$He states

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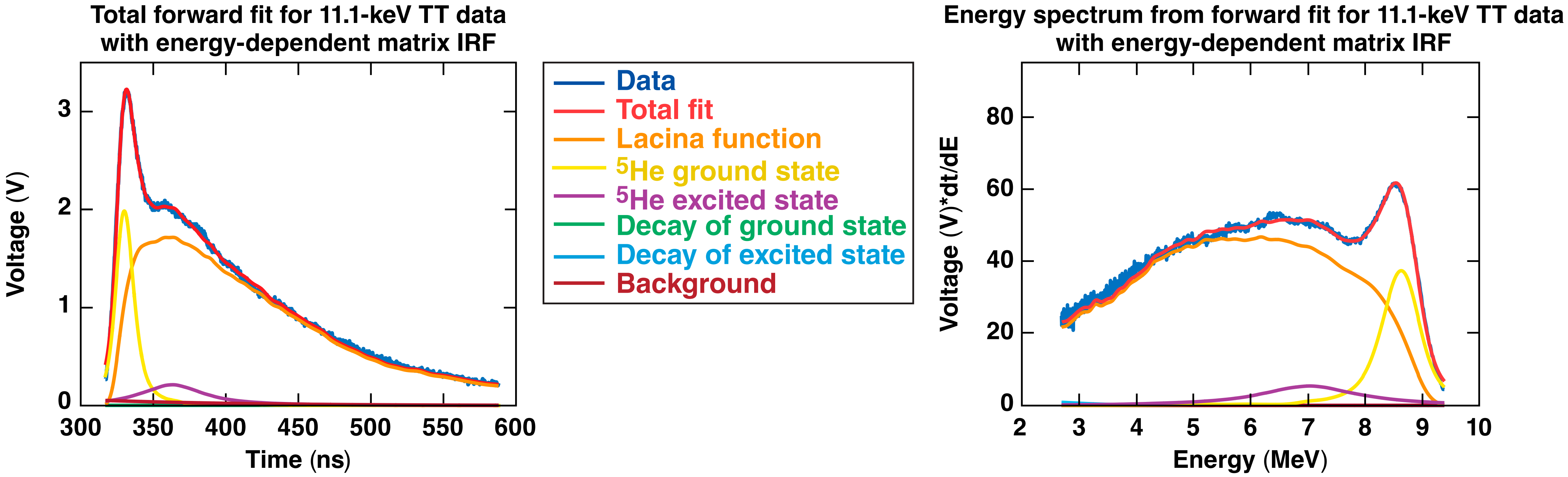
- A series of fits to "d*N*/d*E*" (without IRF) was used to determine start parameters and boundaries for the forward fit
- $V(t) = \left(\mathrm{NLO}(E) * \frac{dN}{dE}\frac{dE}{dt}\right) \otimes \mathrm{IRF}$
  - d*N*/d*E* includes $^5$He ground state, $^5$He excited state, decay of $^5$He states, 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

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

- 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**

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

| | |
|---|---|
| Ground-state mass (amu) | $5.01221 \pm (1 \times 10^{-6})$ |
| Ground-state width (MeV) | 0.50354±0.00728 |
| Ground-state half-life (s) | $(906 \times 10^{-24}) \pm (11 \times 10^{-24})$ |

**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.**


* G. Audi *et al.*, Nucl. Phys. A 729, 3 (2003).
** C. Wong, J. D. Anderson, and J. W. McClure, Nucl. Phys. 71, 106 (1965).

# 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

| $^5$He excited-state energy (MeV above ground state) | $^5$He excited-state width | Source |
|---|---|---|
| 2.0 | 2.4 | This work (with Lacina function) |
| 2.0 | 2.4 | Wong, Anderson, and McClure[1] |
| 2.6 | 4.0 | Fessenden and Maxson[2] |
| 3.8 | 3.1 | Arena *et al.*[3] |
| 3.2 | ? | Sayre *et al.*[4] |
| 1.3 | 3.2 | Tilley *et al.*[5] |

- 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 → $^5$He + $\gamma$.**

[1] C. Wong, J. D. Anderson, and J. W. McClure, Nucl. Phys. 71, 106 (1965).
[2] P. Fessenden and D. R. Maxson, Phys. Rev. 133, B71 (1964).
[3] N. Arena *et al.*, J. Phys. Soc. Jpn. 60, 100 (1991).
[4] D. B. Sayre *et al.*, Phys. Rev. Lett. 111, 052501 (2013).
[5] D. R. Tilley *et al.*, "Energy Levels of Light Nuclei A = 5," http://www.tunl.duke.edu/nucldata/ourpubs/05_2002.pdf (28 September 2017) (unpublished).

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

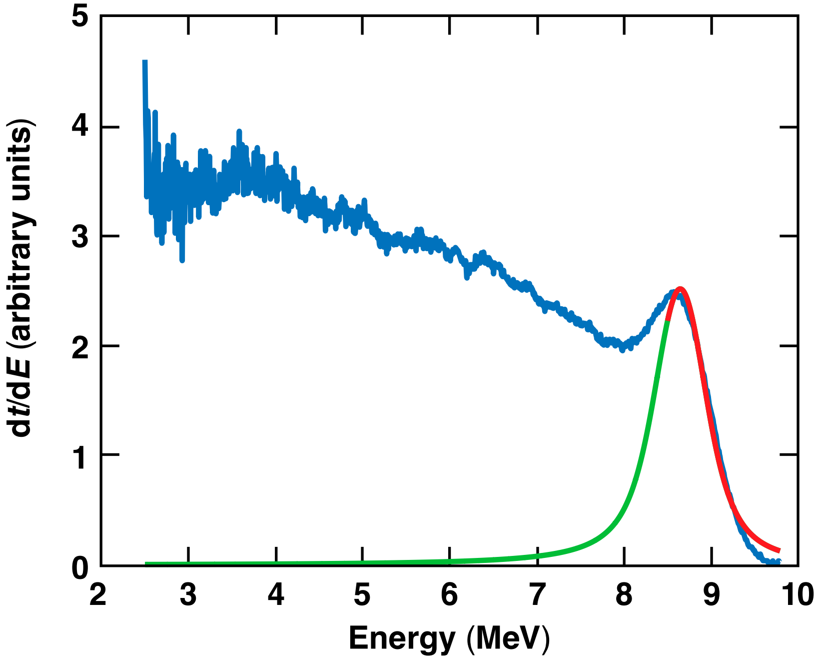
- Three sets of data at different ion temperatures are available from OMEGA implosions
- A series of three fits was conducted as a function of energy to determine likely parameters for the components of the spectrum
  - results from these fits were used to constrain a forward fit to the original time 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

E28060

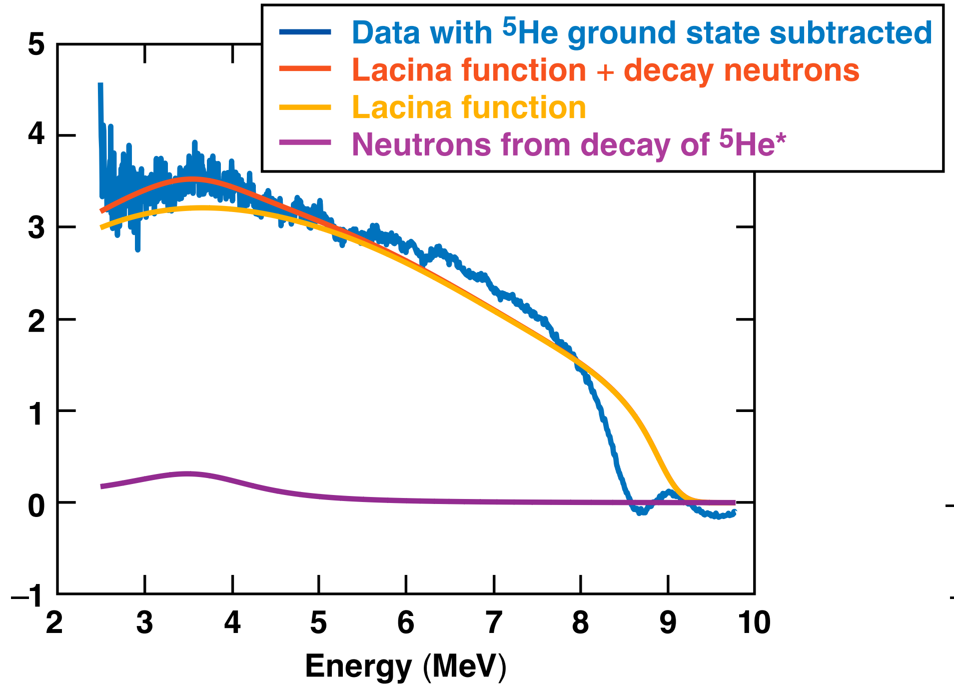
# A series of three least-squares fits was performed to determine likely parameters

- 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

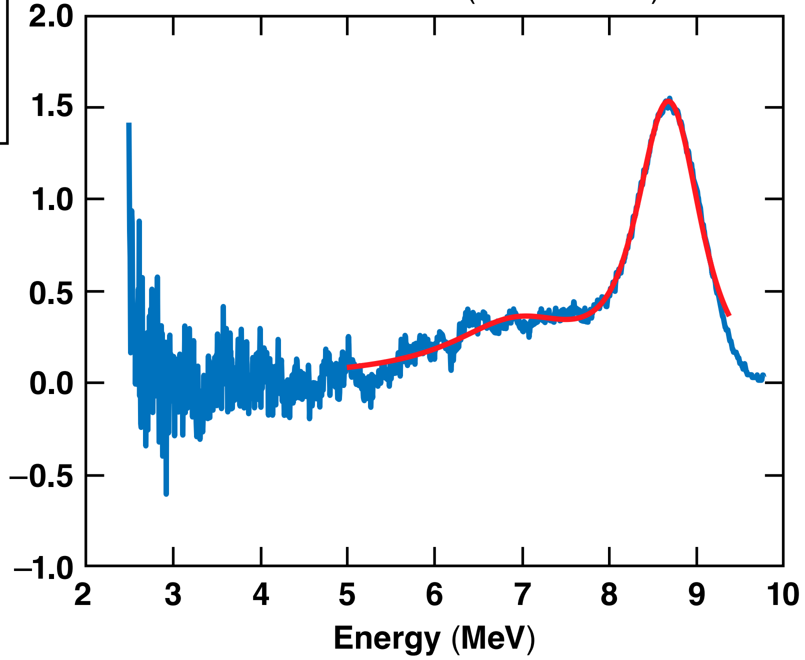
TT data for $kT = 11.1$ keV (fit for 8.5+ MeV)




Fit for Lacina function + decay neutrons (11.1 keV)



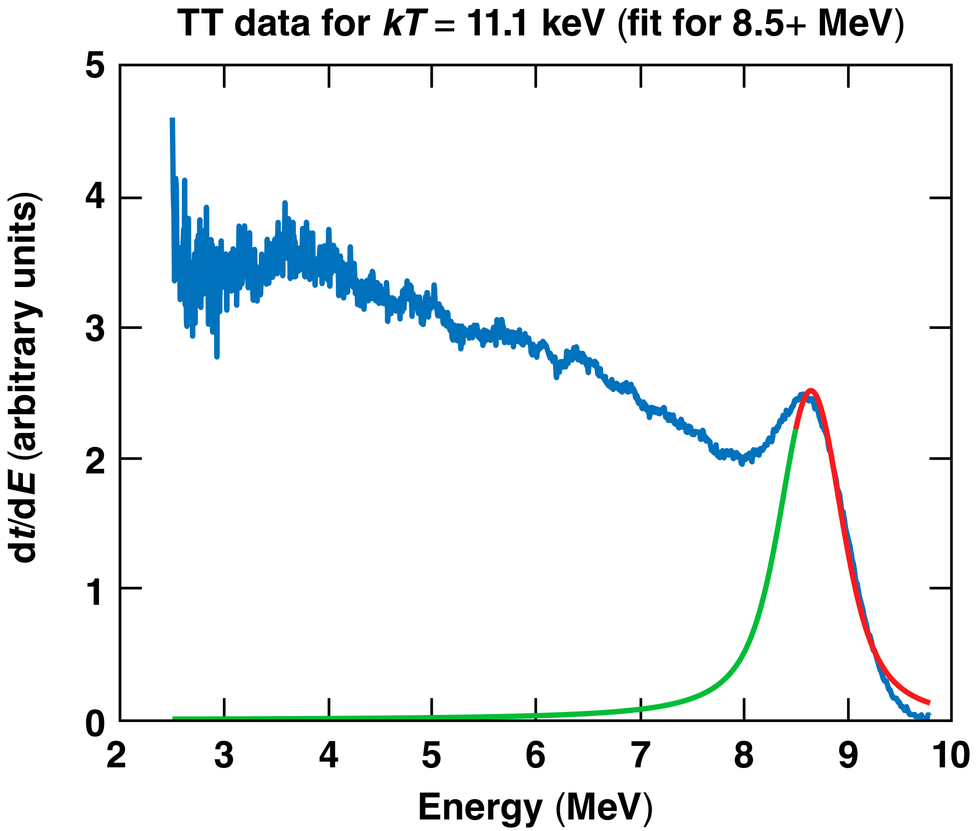

Ground and excited state fits to ellipse subtracted data ($T = 11.1$ keV)




E28069

# 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

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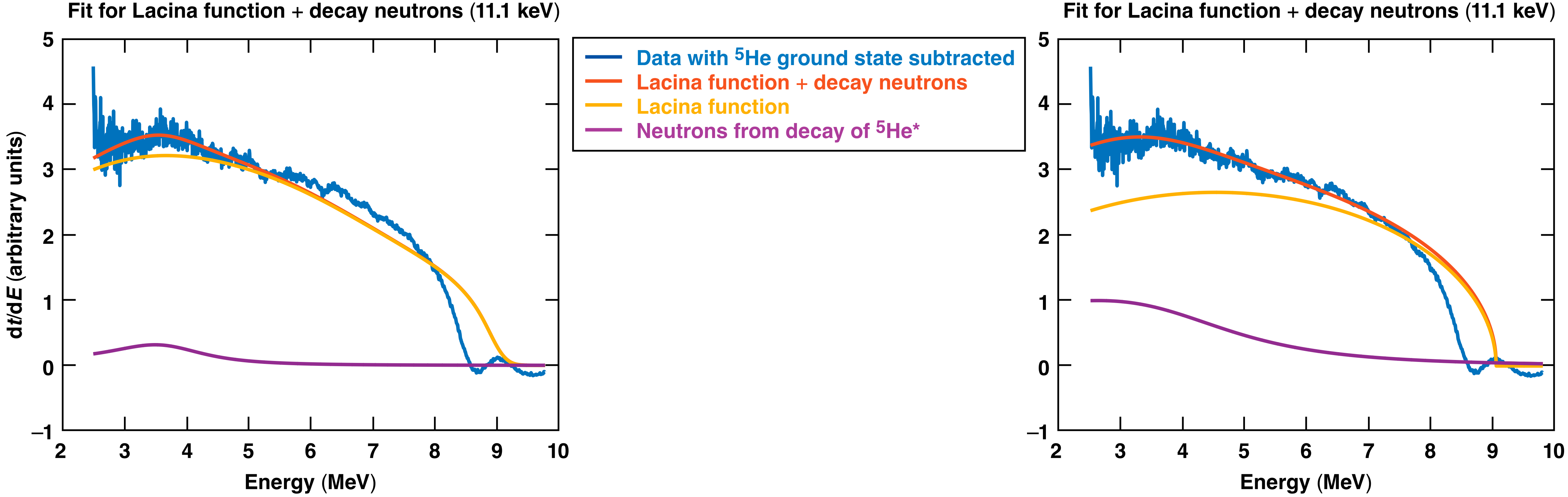
# A series of four least-squares fits was performed to determine likely parameters

- Step 2: Subtract $^5$He ground-state function and fit remaining data with $E < 5$ MeV
- Subtraction isolates region containing T + T→$^4$He + 2n and first excited state of $^5$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 $^5$He ground state
- Simultaneous fit to all data—each has same parameters except for intensity

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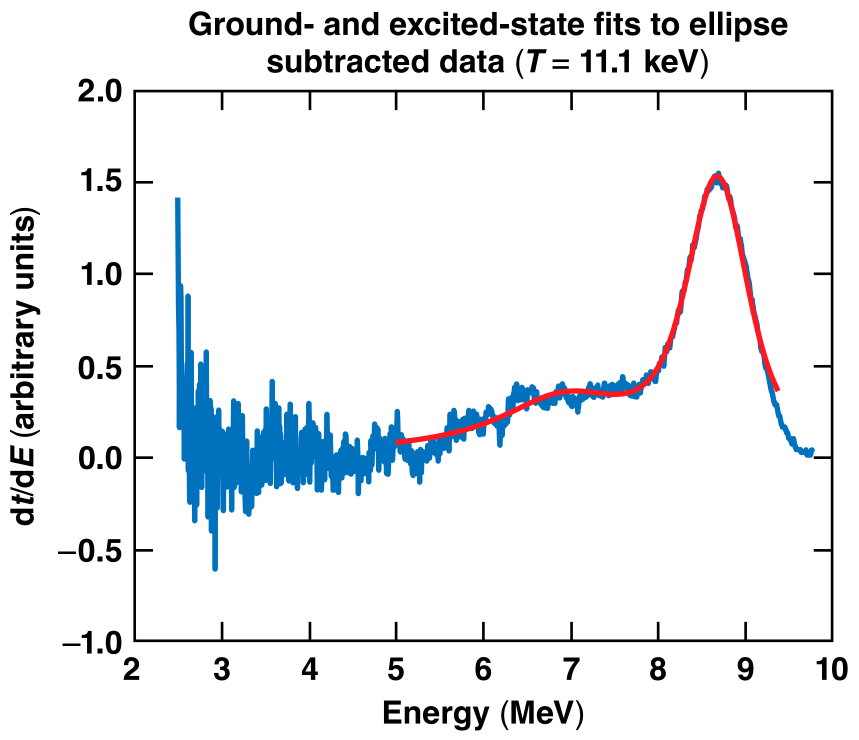
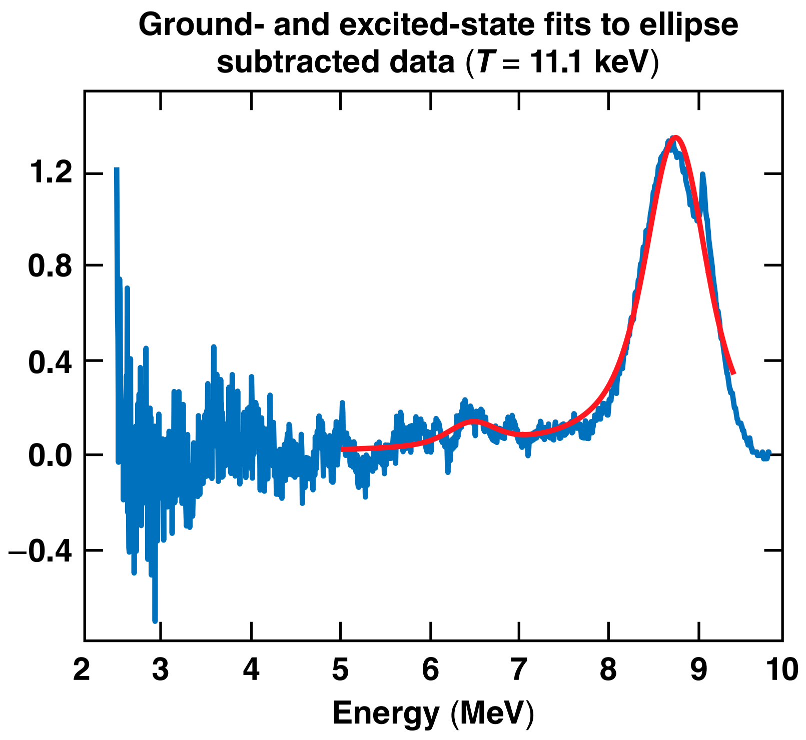
# A series of four least-squares fits was performed to determine likely parameters

- Step 3: Subtract previous fit function from original data and fit remaining data with *E* > 5 MeV to sum of two convolutions
- Subtraction here isolates data containing the ground state and first excited state of $^5$He
- Simultaneous fit to all data—fit functions for each data set share parameters with the exception of intensity

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# 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 ~150% of accepted value

**Final neutron parameters**

| | 18.3 keV | 11.1 keV | 3.7 keV |
|---|---|---|---|
| Lacina I | 3.9492 ± 0.0350 | 11.2621 ± 0.0516 | 2.0518 ± 0.0275 |
| Ground state $E_0$ (MeV) | 8.6997 ± 0.0011 | 8.6997 ± 0.0011 | 8.6997 ± 0.0011 |
| Ground state $\Gamma$ (MeV) | 0.4184 ± 0.0060 | 0.4184 ± 0.0060 | 0.4184 ± 0.0060 |
| Ground state I | 0.6970 ± 0.0074 | 1.5655 ± 0.0140 | 0.2443 ± 0.0040 |
| Excited state $E_0$ (MeV) | 7.0260 ± 0.0191 | 7.0260 ± 0.0191 | 7.0260 ± 0.0191 |
| Excited state $\Gamma$ (MeV) | 1.9855 ± 0.1370 | 1.9855 ± 0.1370 | 1.9855 ± 0.1370 |
| Excited state I | 0.4301 ± 0.0420 | 0.8090 ± 0.0730 | 0.1773 ± 0.0255 |
| $R^2$ | 0.9983 | 0.9982 | 0.9957 |
| Reduced $\chi^2$ | 1.0100 | 1.0084 | 1.0322 |

**$^5$He parameters**

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


* G. Audi *et al.*, Nucl. Phys. A 729, 3 (2003).
** C. Wong, J. D. Anderson, and J. W. McClure, Nucl. Phys. 71, 106 (1965).

# 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 ~150% of accepted value

**Final neutron parameters**

| | 18.3 keV | 11.1 keV | 3.7 keV |
|---|---|---|---|
| Ellipse I | 3.3357 ± 0.0206 | 8.8917 ± 0.0525 | 1.6964 ± 0.0168 |
| Ground state $E_0$ (MeV) | 8.7169 ± 0.0015 | 8.7169 ± 0.0015 | 8.7169 ± 0.0015 |
| Ground state $\Gamma$ (MeV) | 0.3647 ± 0.0047 | 0.3647 ± 0.0047 | 0.3647 ± 0.0047 |
| Ground state I | 0.6210 ± 0.0046 | 1.3797 ± 0.0091 | 0.2096 ± 0.0034 |
| Excited state $E_0$ (MeV) | 3.0333 ± 0.2065 | 3.0333 ± 0.2065 | 3.0333 ± 0.2065 |
| Excited state $\Gamma$ (MeV) | 1.9855 ± 0.6999 | 1.9855 ± 0.6999 | 1.9855 ± 0.6999 |
| Excited state I | 0.9791 ± 0.1134 | 4.1094 ± 0.3270 | 0.4520 ± 0.0898 |
| $R^2$ | 0.9985 | 0.9980 | 0.9957 |
| Reduced $\chi^2$ | 1.0094 | 1.0084 | 1.0084 |

**$^5$He parameters**

| | |
|---|---|
| *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**


* G. Audi *et al.*, Nucl. Phys. A 729, 3 (2003).
** C. Wong, J. D. Anderson, and J. W. McClure, Nucl. Phys. 71, 106 (1965).