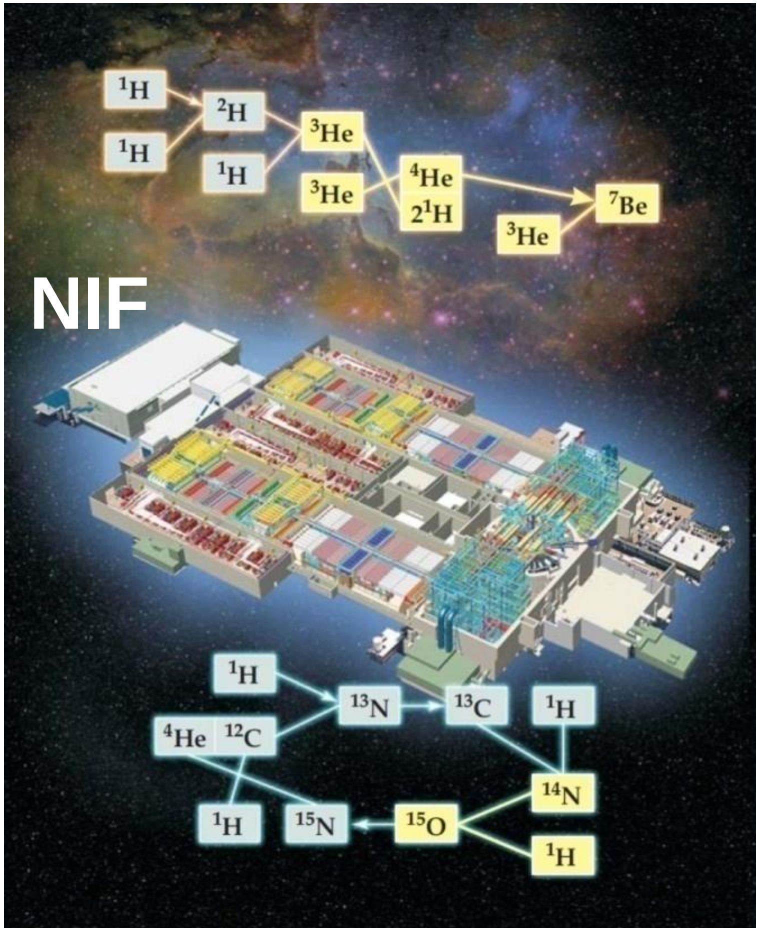
# First cross-section measurements of the $^{3}H(^{3}H,2n)\,^{4}He$ (or TT) nuclear reaction using an ICF facility (OMEGA)




**Motivation for this work:**

1. **To probe the underlying physics of the TT reaction at energies inaccessible by conventional accelerator techniques**
2. **To directly measure the TT cross-section in the absence of electron screening**
3. **TT is a mirror reaction to the $^{3}He(^{3}He,2p)^{4}He$ in the solar pp chain**
4. **Measure the TT neutron spectrum to help understand the ICF neutron spectrum**

**Image taken from: R.N. Boyd, Physics Today 62, August (2009).**

**Daniel Casey**

**2nd OMEGA Laser Users' Group Workshop**
Rochester, NY
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MIT Plasma Science & Fusion Center

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# Abstract

Accurate knowledge about thermonuclear reaction rates is important for understanding the generation of energy and synthesis of elements in stars. Several of these reactions are poorly known, resulting in significant discrepancies between observed and modeled abundances of some of the elements in the universe. To address this issue, we have conducted the first cross section and spectral measurements, using an ICF facility (the OMEGA laser), of the $T(t,2n)^4He$ reaction that is an important mirror reaction to the $^3He(^3He,2p)^4He$ reaction (which is part of the proton-proton chain in hydrogen burning stars). These direct measurements, which were conducted at energies inaccessible by conventional accelerator-based techniques, are not affected by electron screening. In contrast, the reaction cross section data obtained in accelerator experiments are enhanced significantly by electron screening (particularly at low energies). In addition, the spectral information obtained will allow the determination of the two-body to three-body branching ratio which according to theory should be different at these energies. In this poster, the first results from these experiments are presented.

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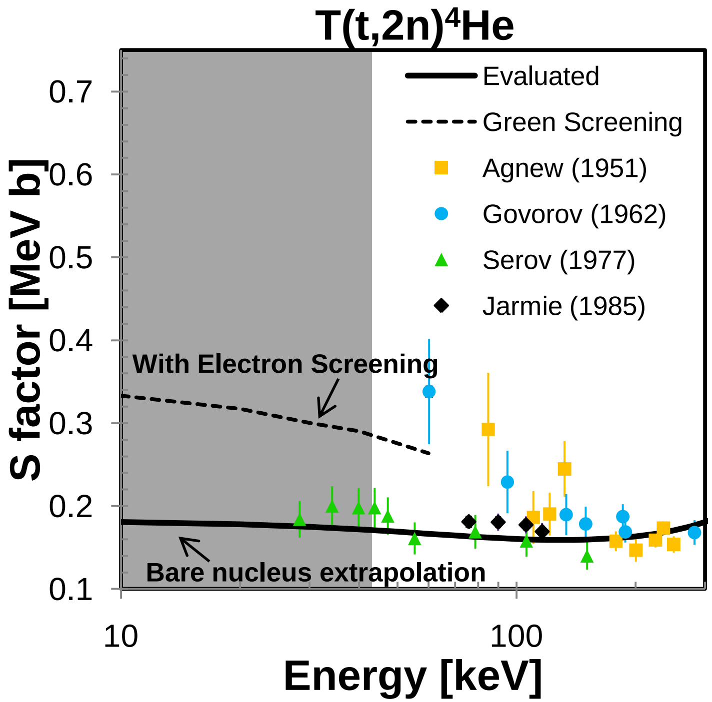
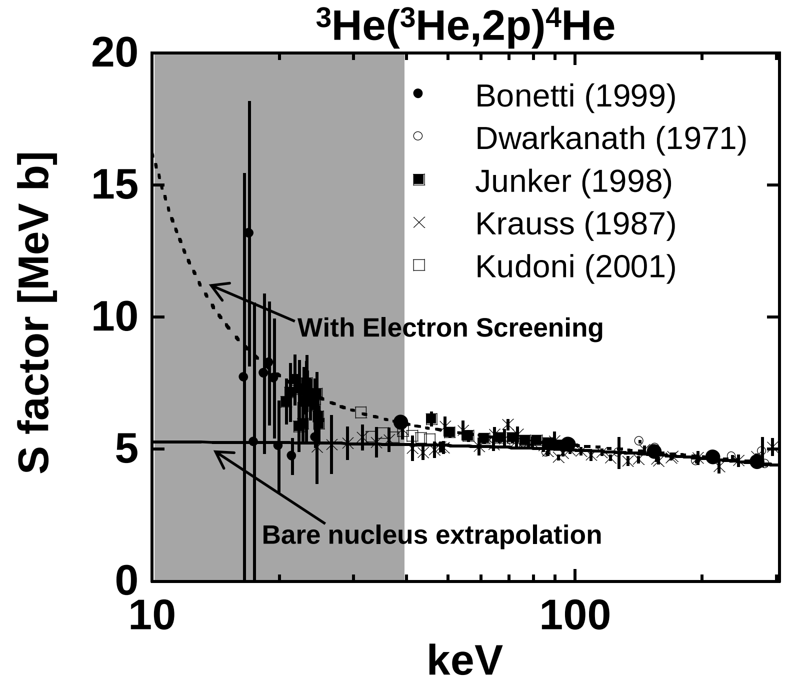
# ICF facilities offer the possibility to study the $^3He(^3He,2p)^4He$ and $T(t,2n)^4He$ reactions with unprecedented accuracy at solar energies

$S_{factor} \sim \sigma$ See slide 12 for more details

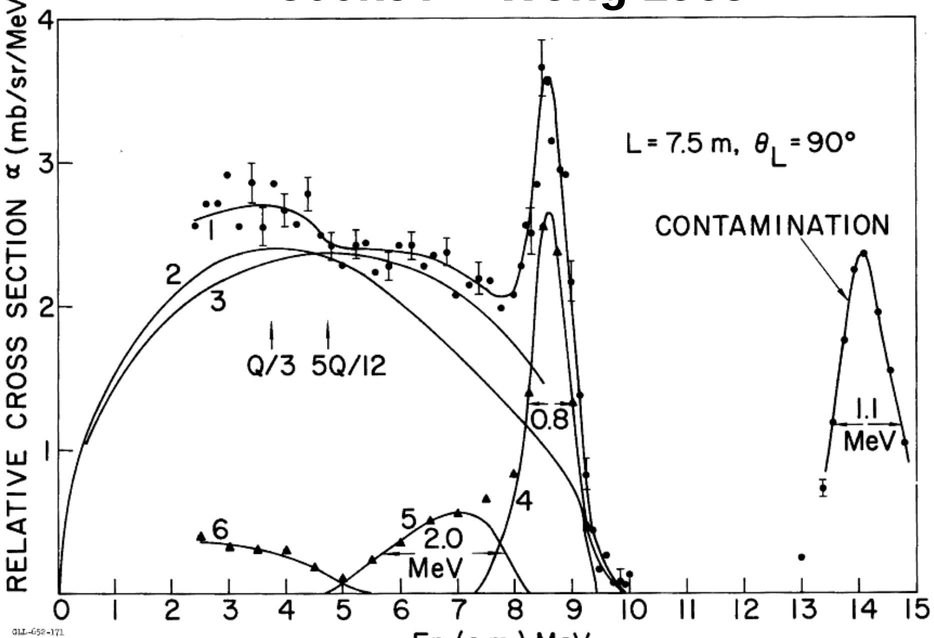


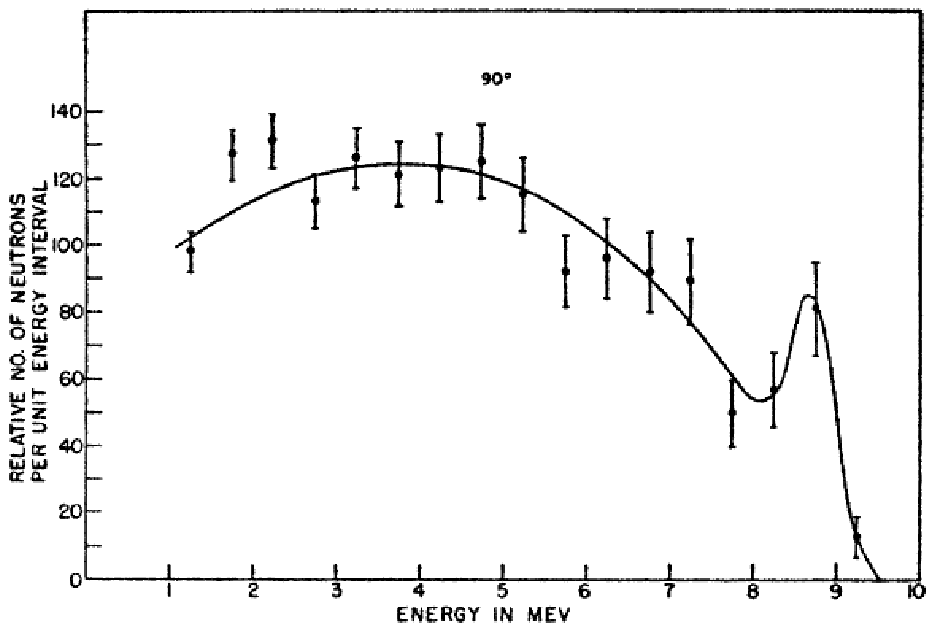

**At OMEGA and the NIF, electron screening is negligible**

# Measurements of the TT neutron spectral shape have not been performed at energies relevant to ICF and stellar nucleosynthesis

**500keV – Wong 1965**

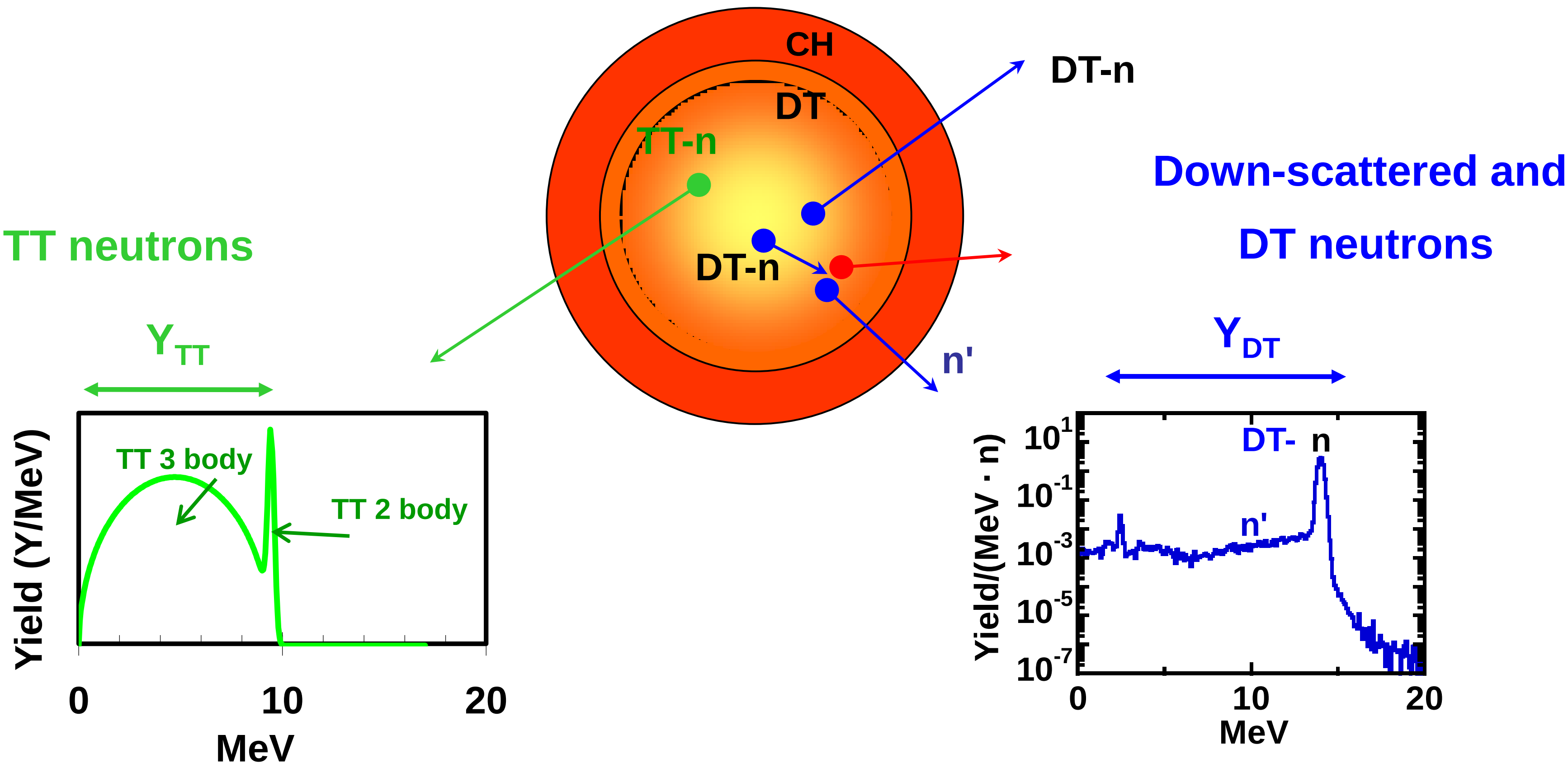



**220keV – Allen 1951**



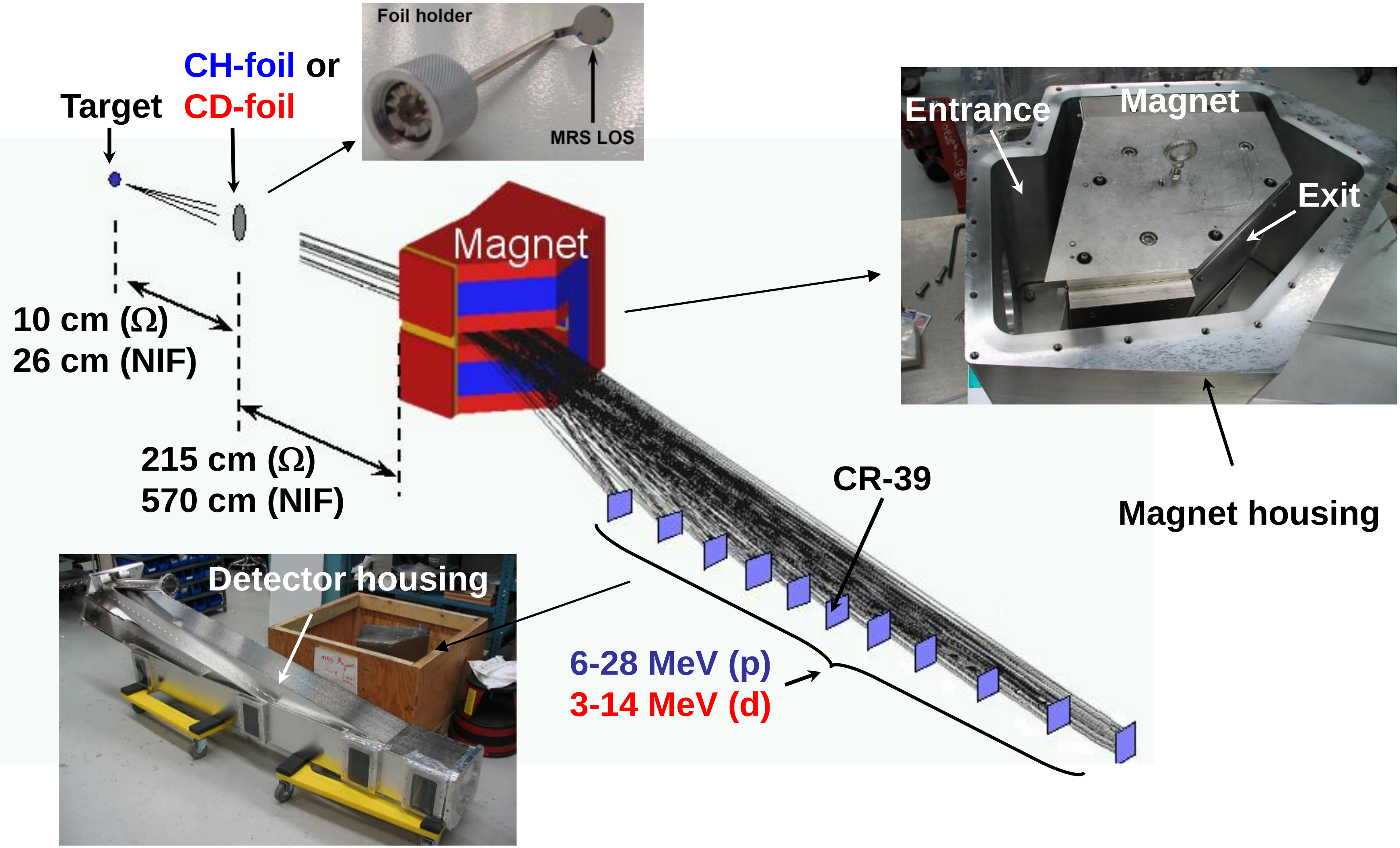

**According to theory the two-body to three-body branching ratio should be different than at energies relevant to ICF and stellar nucleosynthesis**

# The TT neutron spectrum lies on top of the down-scattered neutrons in the ICF neutron spectrum



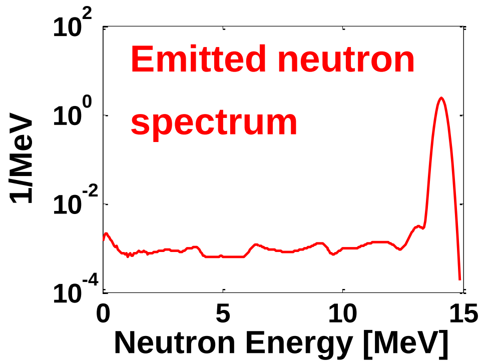

$Y_{n'} \propto \rho R \times Y_{DT}$

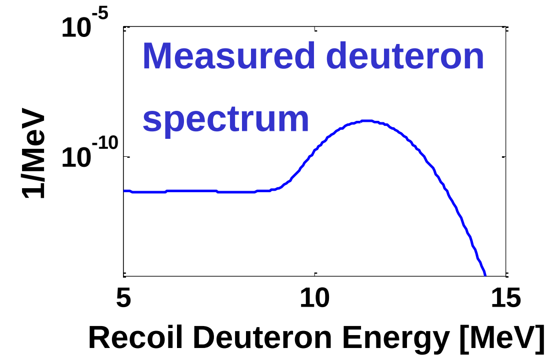
# The ICF neutron spectrum is measured by the Magnetic Recoil Spectrometer (MRS)



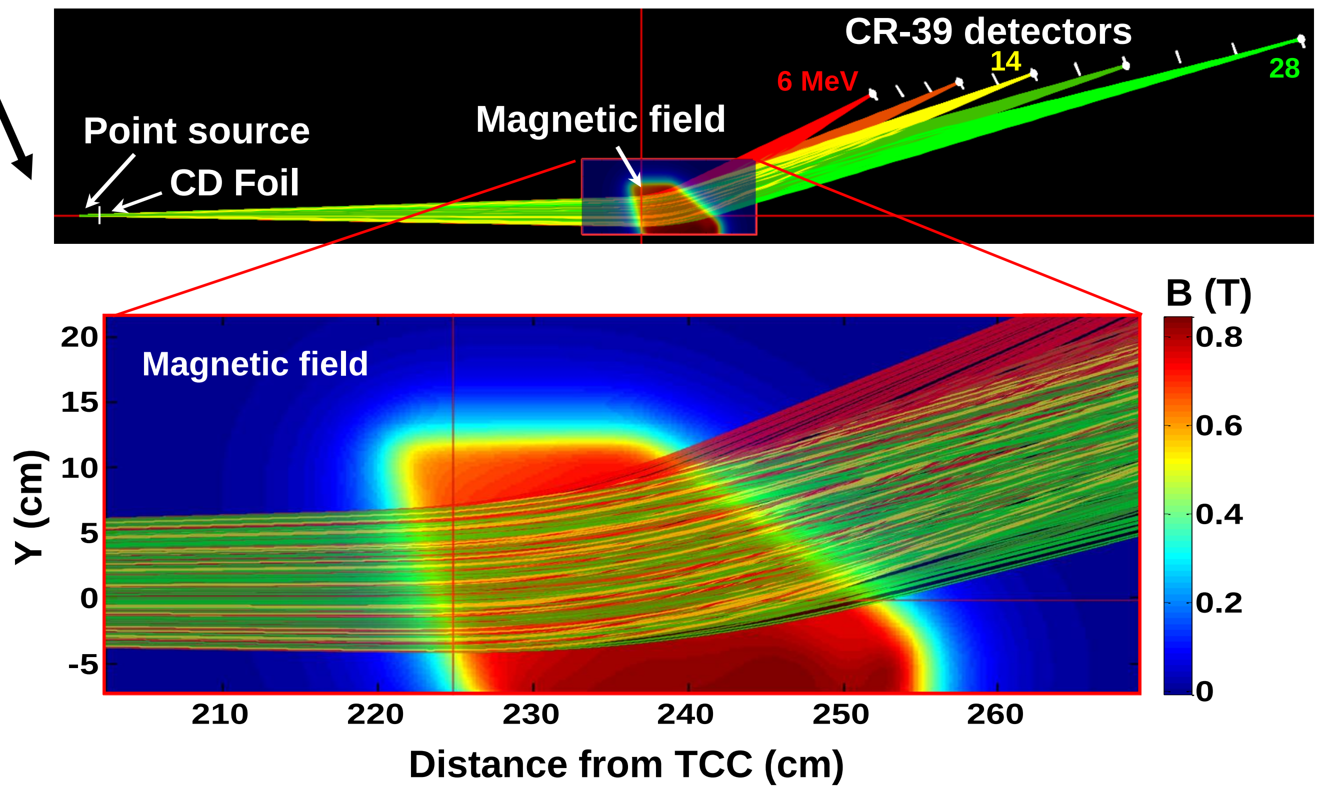

J. A. Frenje, Phys. Plasmas 17, 056311 (2010).

# The Monte Carlo code Geant4 is being used to model the full MRS detector response

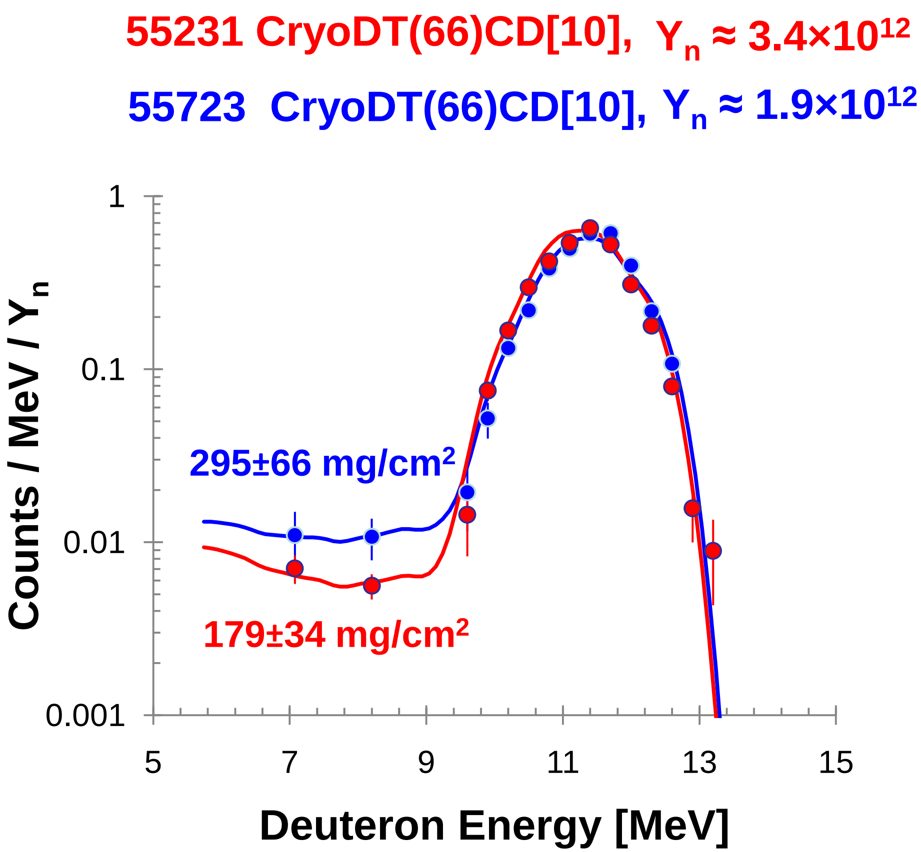


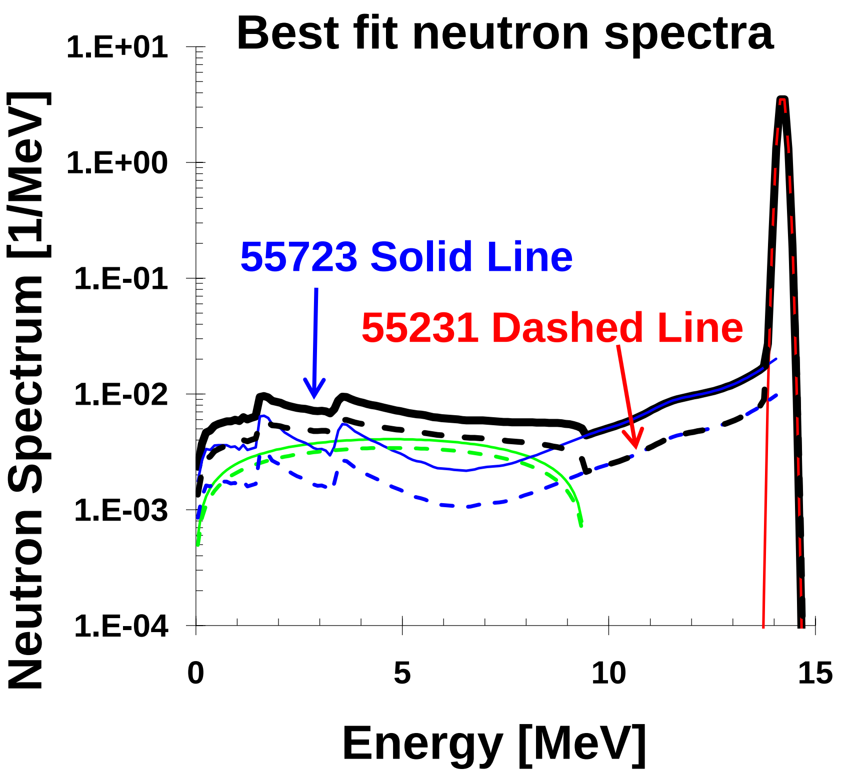




## MRS response function



# The MRS regularly diagnoses ρR in Cryogenic DT implosions at OMEGA including a recent implosion with ρR = 295 ± 66 mg/cm²




<u>Currently</u> no other ρR diagnostic operates (>180mg/cm²)

T. C. Sangster, - Phys. Plasmas 17, 056312 (2010).

V. Goncharov – Phys. Rev. Let. 104, 165001 (2010).

# At energies relevant to ICF the two-body to three-body branching ratio for the TT reaction is not well known

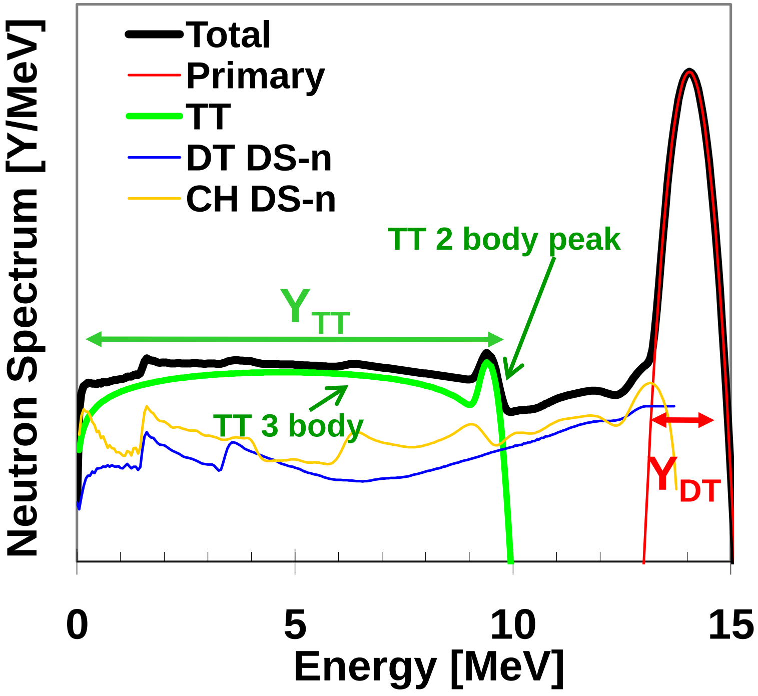
**Primary TT Neutrons**

**-Three-body**

**T + T → α + n + n (0-9.5 MeV)**

**-Two-body**

**T + T → *He$^5$ + n (8.7 MeV)**

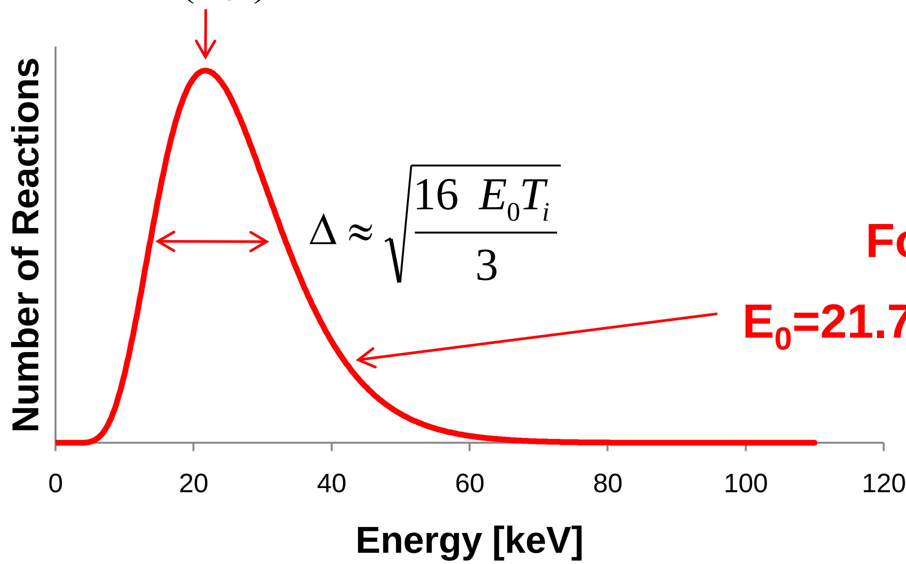


# The Gamow energy ($E_0$) is the most probable reaction energy for a thermal fusion plasma

$$E_0 = \left(\frac{\varepsilon_G}{4}\right)^{1/3} T_i^{2/3}$$

**Here $\varepsilon_G$ is the Gamow factor for Barrier penetration**

**$\varepsilon_G$ = 1.48 MeV for TT fusion**




$$\Delta \approx \sqrt{\frac{16\ E_0 T_i}{3}}$$

**For $T_i$ = 5.3keV,**

**$E_0$=21.7keV and $\Delta$=24.7keV**



S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion* (Oxford University Press, Oxford, 2004).

# The TT S-factor can be directly measured at the Gamow energy from the ratio of the TT and DT yields

$$\sigma_{TT}(\varepsilon) = \frac{S_{TT}(\varepsilon)}{\varepsilon} e^{-\sqrt{\varepsilon_G/\varepsilon}}$$

**Electron screening correction f ~ 1.008**

$$<\sigma v> \propto \left(A\,T^2\right)^{-1/3} f\; S\; e^{-3E_0/T}$$

**Gamow energy**

$$Y_{TT}/Y_{DT} \approx \frac{1}{2}\frac{n_T}{n_D}\frac{<\sigma v>_{TT}}{<\sigma v>_{DT}}$$

**Factor of ½ for reaction yield,**
**The three-body reaction releases two neutrons**

**is well known**

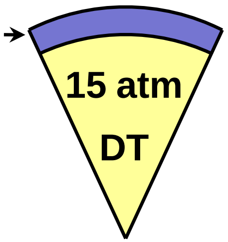
$$\Rightarrow \quad S_{TT} \propto \frac{\mathbf{Y_{TT}}}{\mathbf{Y_{DT}}} <\sigma v>_{DT}$$

**We can probe Gamow energies of ~8-40 keV at OMEGA**

*This assumes a non-resonant TT reaction and approximately equal DT and TT spatial and temporal burn profiles an assumption which has been validated with 1D Lilac simulations

**E. Adelberger, et al., "Solar Fusion Cross-Sections." Rev. Mod. Phys. 70, 1265 (1998).**

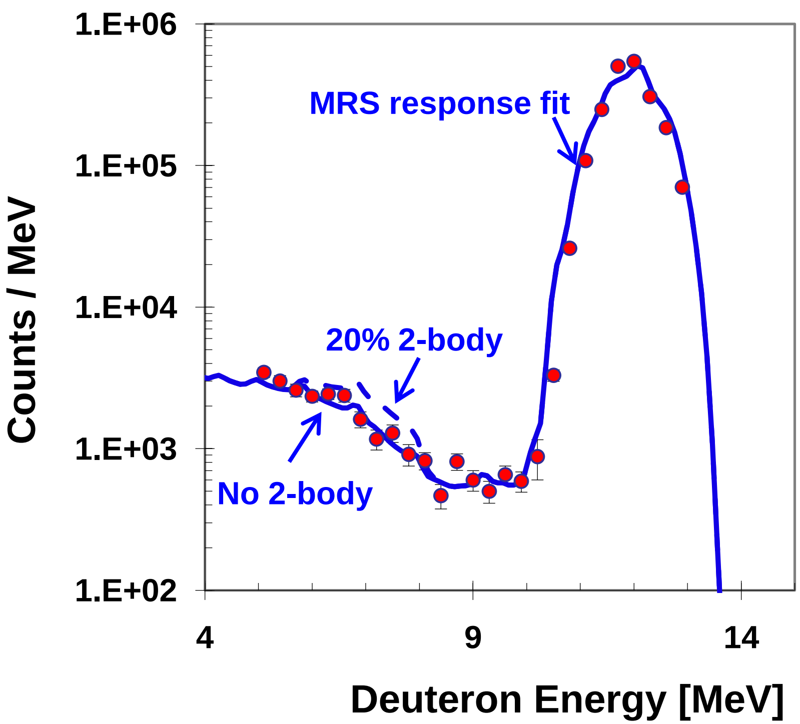
# The TT neutron spectrum was measured at ~5 keV and analysis indicates 2-body / 3 body ratio < 20%

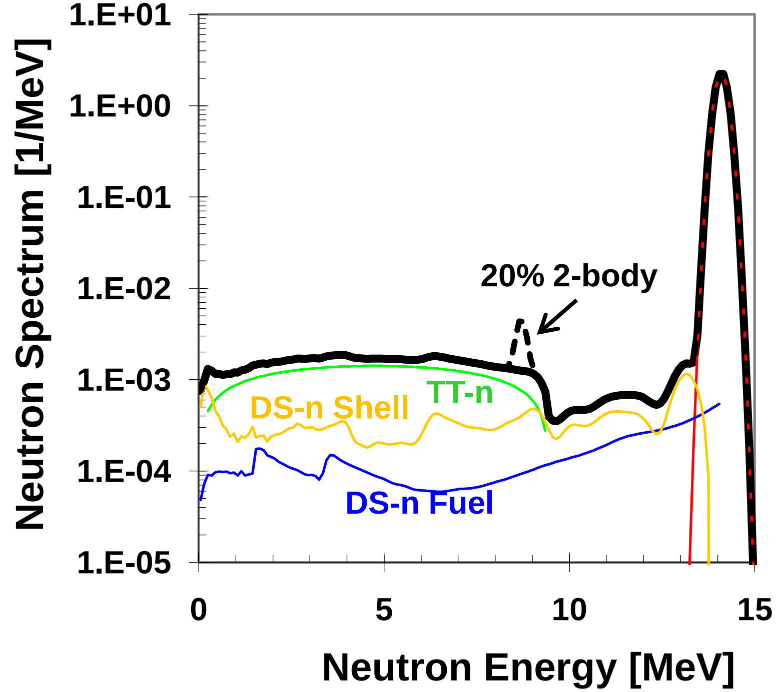



Integrated 9 shots $Y_n = 2\times10^{14}$

$<T_i>n = 5.3$ keV -> $E_0 = 22$ keV

$\rho R_{MRS} = 62\ mg/cm^2$




**Consistent with previous measurements by Glebov.**

**V. Yu. Glebov., "T–T Fusion Neutron Spectrum Measured in Inertial Confinement Fusion Experiment." Bul. American Physical Society (2006).**

Summary

# The MRS has been used to measure the TT reaction S-factor to energies lower than previously available

- Measurements using the MRS were used to study the TT fusion reaction through measured neutron spectra and to infer the astrophysical S-factor
- Neutron spectra measurements also show the 2-body/3-body branching ratio is < 20% at energies < 30 keV
- Future measurements at OMEGA and the NIF will be optimized to improve S-factor and branching ratio measurements and will be extended to other reactions such as $^{3}He(^{3}He,2p)^{4}He$ which is important for stellar nucleosynthesis

# Some Important References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