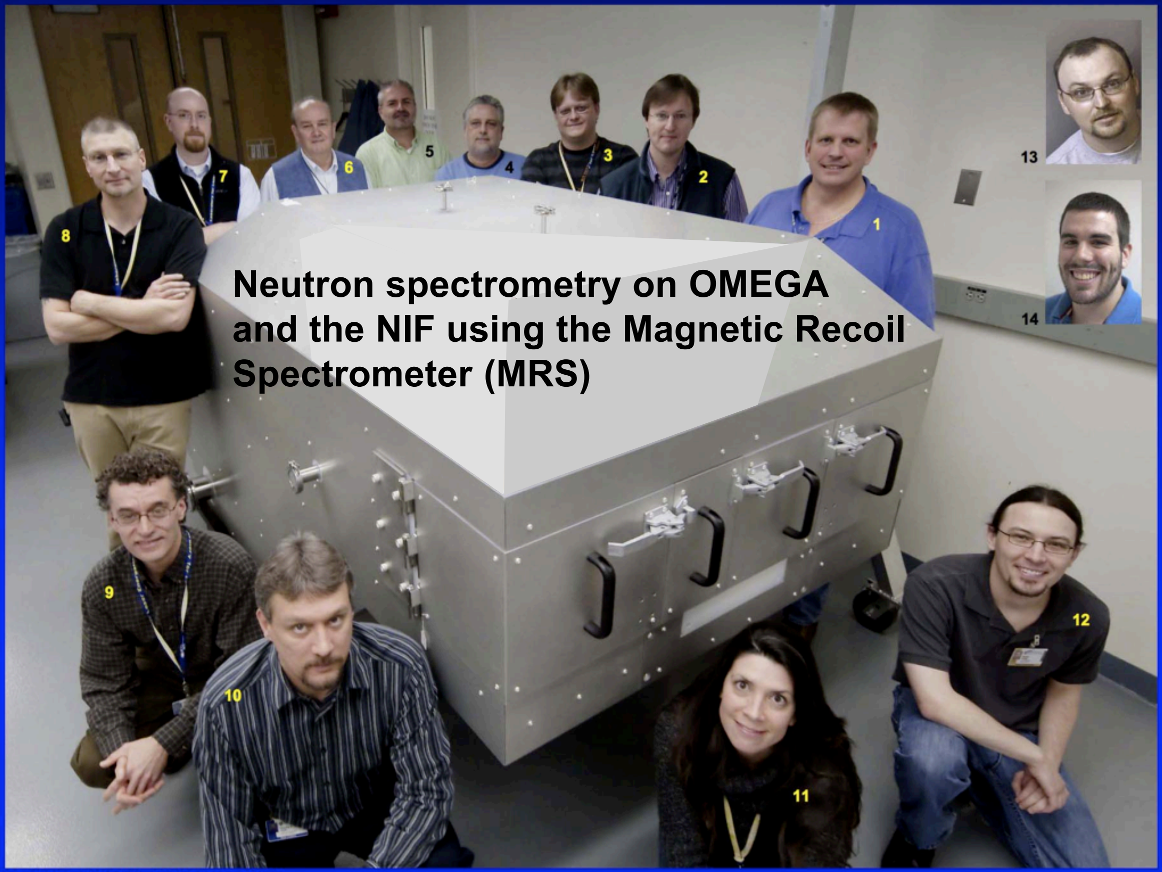
Neutron spectrometry on OMEGA and the NIF using the Magnetic Recoil Spectrometer (MRS)



by eugene kowaluk, 16 February 2010

1 Milt Shoup
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3 Jason Magoon
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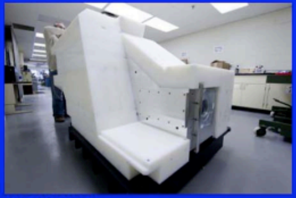
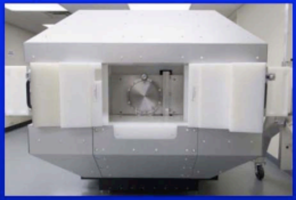
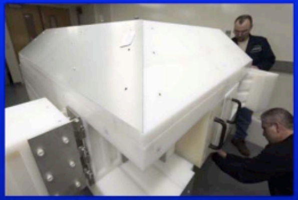
Milt Shoup, David Meyerhofer


Chad Abbott


C Abbott, J Magoon, M Romanofsky




John Szczepanski, Chad Abbott


T Lewis, M Romanofsky, C Abbott, J Szczepanski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Chad Abbott, Tom Lewis, Fred Rister


On the way to LLNL

Johan Frenje, OMEGA Laser User's Group
2nd Workshop, Rochester, NY, Apr 28 - 30, 2010

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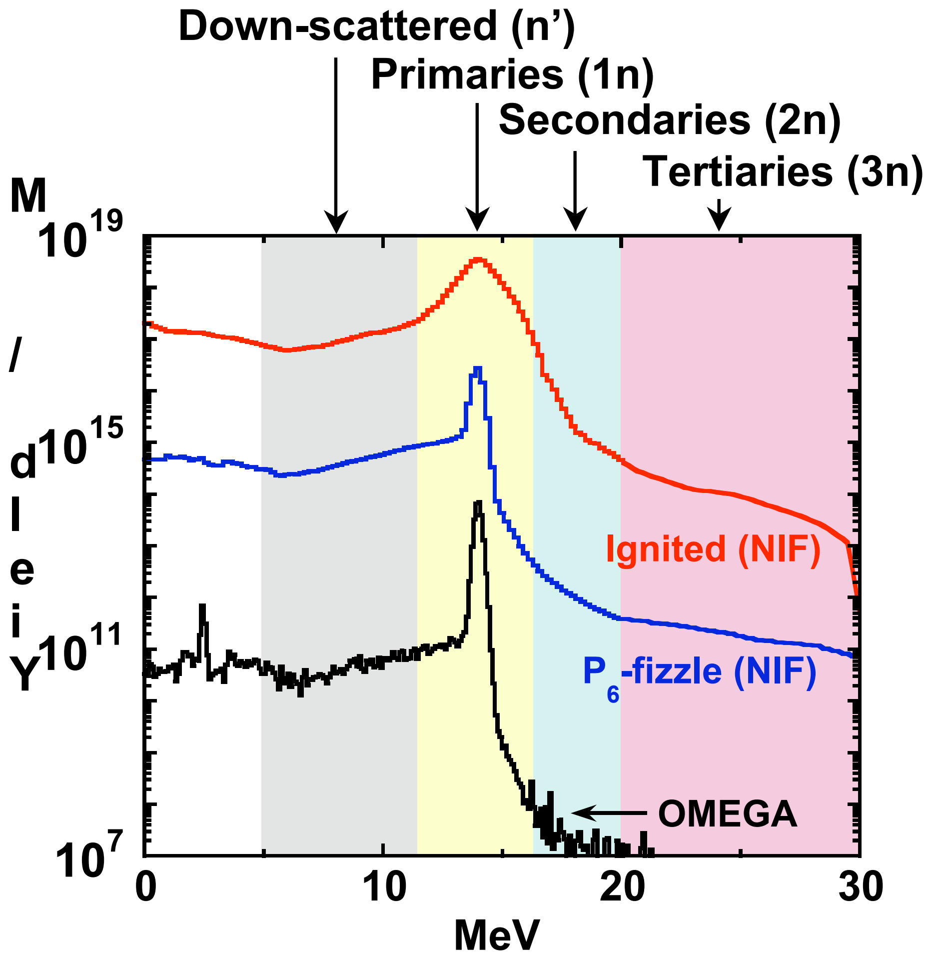
Summary

- **An MRS has been successfully implemented and successfully used on OMEGA for diagnosing high-ρR cryogenic DT implosions.**
- **OMEGA-MRS data and simulations indicate that the NIF MRS will accurately diagnose THD / DT implosions.**
- **Basic science experiments relevant to stellar nucleosynthesis and ICF are being conducted and planned at OMEGA and NIF, respectively.**

Outline

- **Motivation for the MRS**
- **The MRS principle**
- **The OMEGA MRS**
  - Systematic uncertainties
  - Experimental results
- **The NIF MRS**
  - *Ab initio* characterization of the MRS
  - Statistical uncertainties
  - Systematic uncertainties
- **Basic-science experiments relevant to stellar nucleosynthesis and ICF**

To provide information about several implosion parameters that will be integral for assessing failure modes



From down-scattered ($Y_{n'}$):

- ρR $\left(\frac{Y_{n'}}{Y_{1n}} \propto \rho R\right)$

From primaries (Y_{1n}):

- Y_{1n}
- T_i $\left(T_i \propto \Delta E_D^2\right)$
- *Alpha-particle physics*

From secondaries (Y_{2n}):

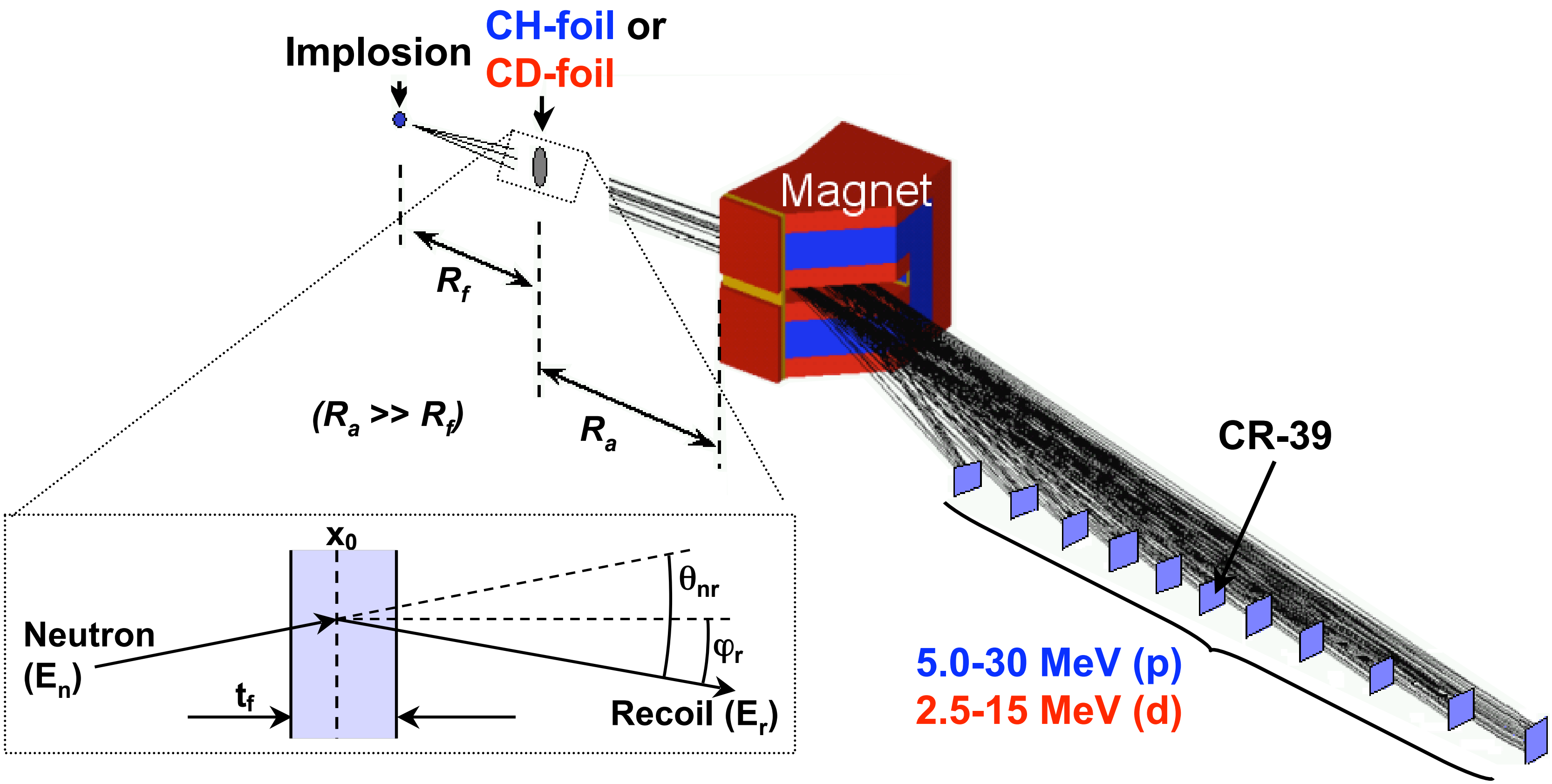
- T_e $\left(\frac{Y_{2n}}{Y_{1n}} \propto T_e^3\right)$
- *Alpha-particle physics***

From tertiaries (Y_{3n}):

- ρR $\left(\frac{Y_{3n}}{Y_{1n}} \propto \rho R\right)$

**J. Källne *et al.*, Phys. Rev. Letters 85, 1246 (2000).

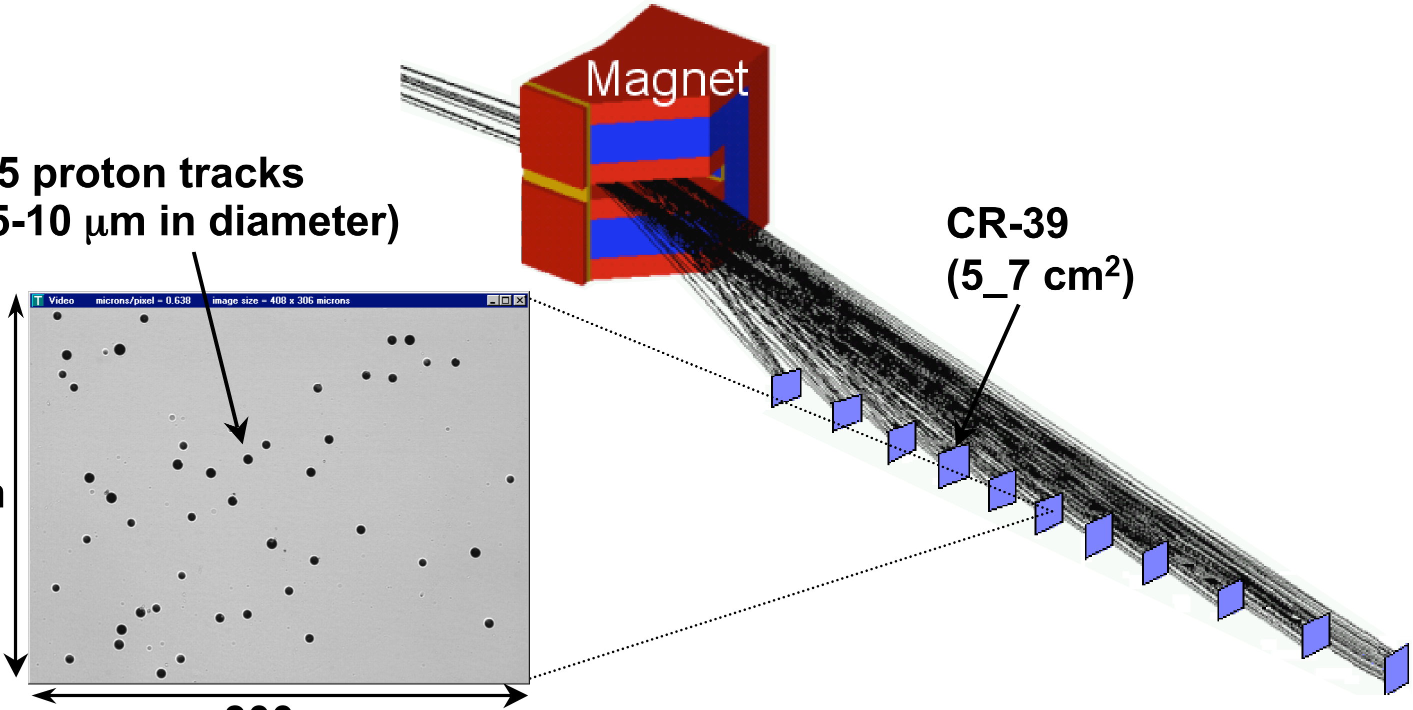
The neutron spectrum is measured by the MRS



$$E_r \approx \frac{4A}{(A+1)^2} E_n \mathrm{Cos}^2\theta_{nr} - \frac{1}{\mathrm{Cos}\varphi_r} \int_{x_o}^{t_f} \frac{dE(E_r)}{dx} dx$$

J.A. Frenje *et al.*, Rev. Sci. Instrum. 72, 854 (2001).

CR-39 detectors are used in the MRS for detection of forward scattered recoil particles (protons or deuterons)



45 proton tracks
(5-10 μm in diameter)

~ 200 μm

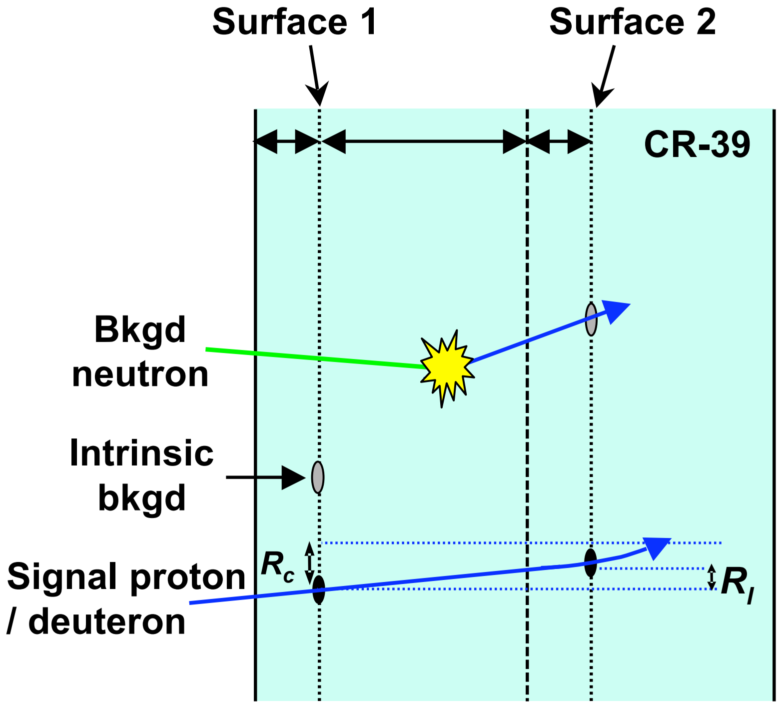
~ 300 μm

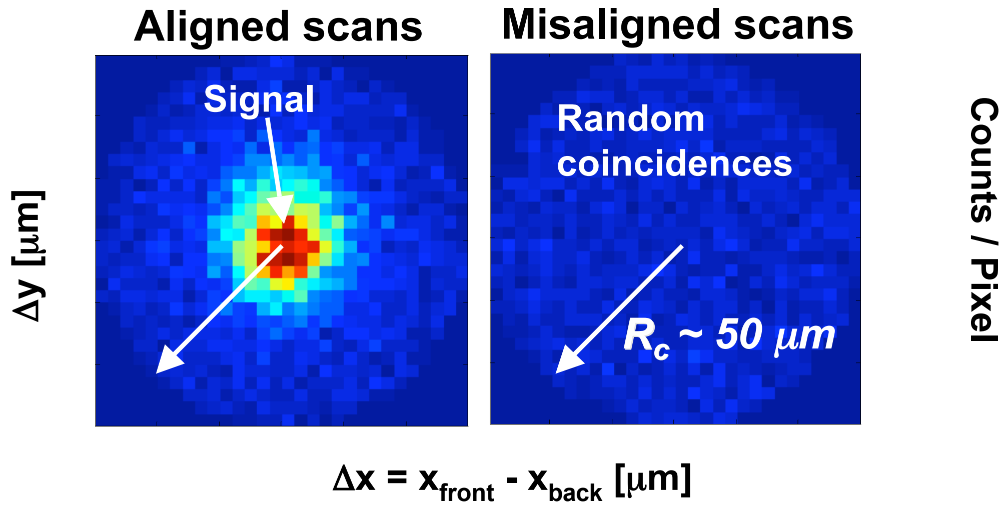
CR-39
(5_7 cm^2)

- **CR-39 detects the charged recoil particles with a 100% efficiency.**
- **CR-39 detects DT neutrons with an efficiency of 5_10^{-5}.****

** J.A. Frenje *et al.*, Rev. Sci. Instrum. 73, 2596 (2002).

The Coincidence Counting Technique (CCT) is applied to the MRS data for low-yield applications**





S/B is enhanced orders of magnitude when using the CCT

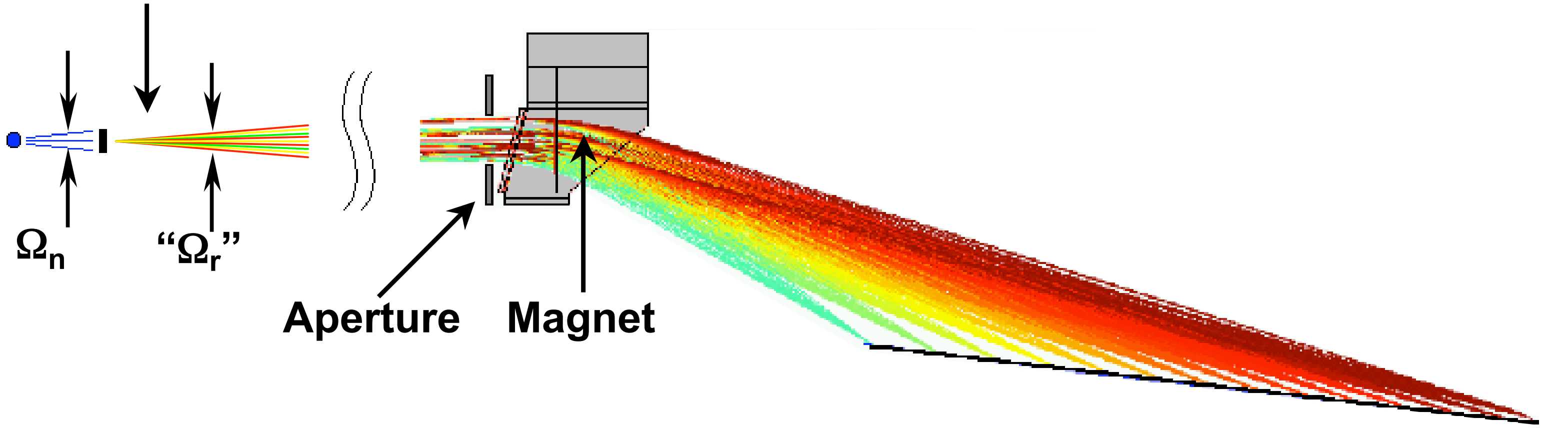
** Daniel Casey will talk about this in much more detail in the next presentation.

Detection efficiency – $\varepsilon_{MRS}(E_n)$

- Detection efficiency [$\varepsilon_{MRS}(E_n)$] can be expressed as

$$\varepsilon_{MRS}(E_n) = \frac{\Omega_n}{4\pi} n_i t_f \int^{"\Omega_r"} \frac{d\sigma(E_n)}{d\Omega_{lab}} d\Omega$$

n_i : number density
t_f : foil thickness



An absolute neutron spectrum is measured with high accuracy because Ω_n, n_i, t_f, $d\sigma/d\Omega_{lab}$ and Ω_r are well known

Energy resolution – $\Delta E_{MRS}(E_n)$

- Energy resolution [$\Delta E_{MRS}(E_n)$] can be expressed as

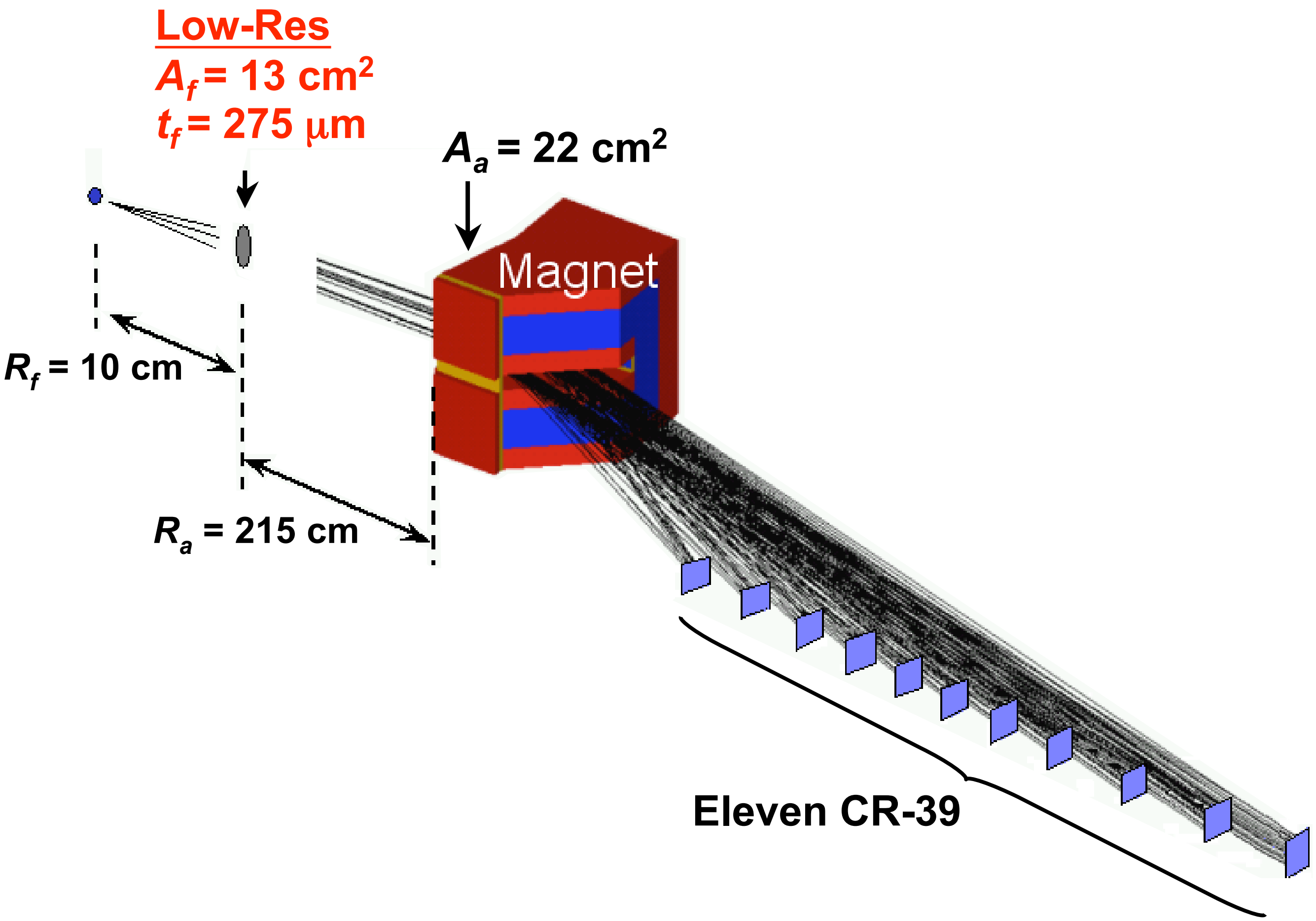
$$\Delta E_{MRS}(E_n) \approx \sqrt{\Delta E_f(E_n)^2 + \Delta E_k(E_n)^2 + \Delta E_m(E_n)^2}$$

$\Delta E_f(E_n)$ = Energy broadening in foil $\propto$ foil thickness (t_f)

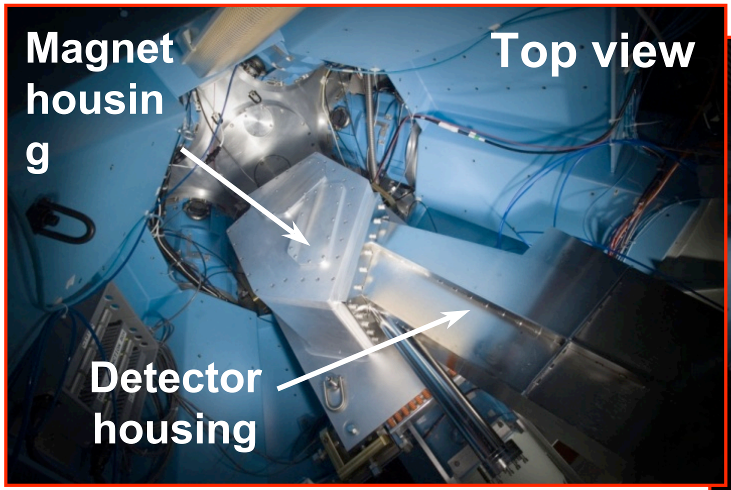
$\Delta E_k(E_n)$ = Kin. energy broadening $\propto$ foil size (A_f) and position (R_f)
aperture size (A_a) and position (R_a)

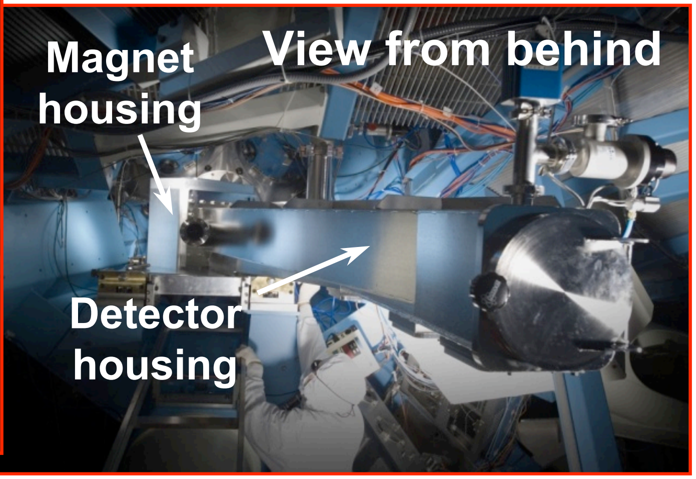
$\Delta E_m(E_n)$ = Ion opt. energy broadening $\propto$ magnet performance

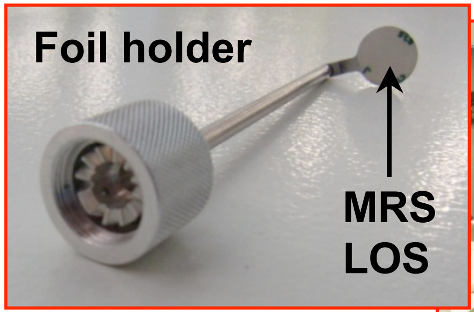
The OMEGA MRS

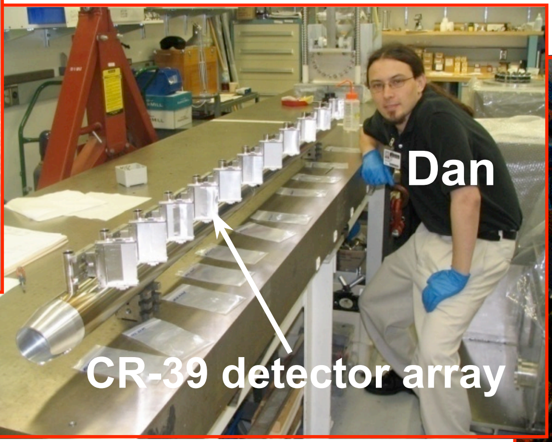


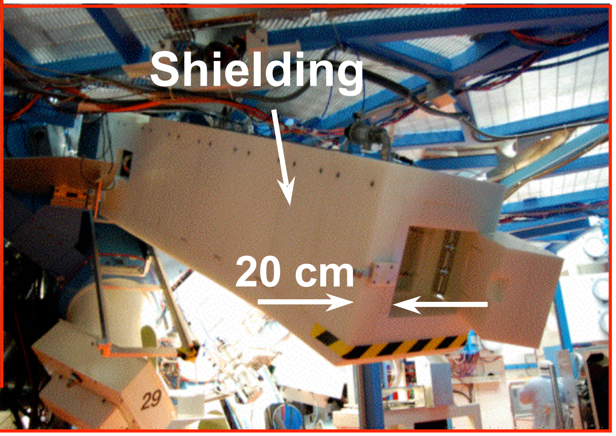
The OMEGA MRS was fully installed and commissioned in Spring 2008











J.A. Frenje *et al.*, Rev. Sci. Instrum. 79, 10E502 (2008)

The OMEGA MRS

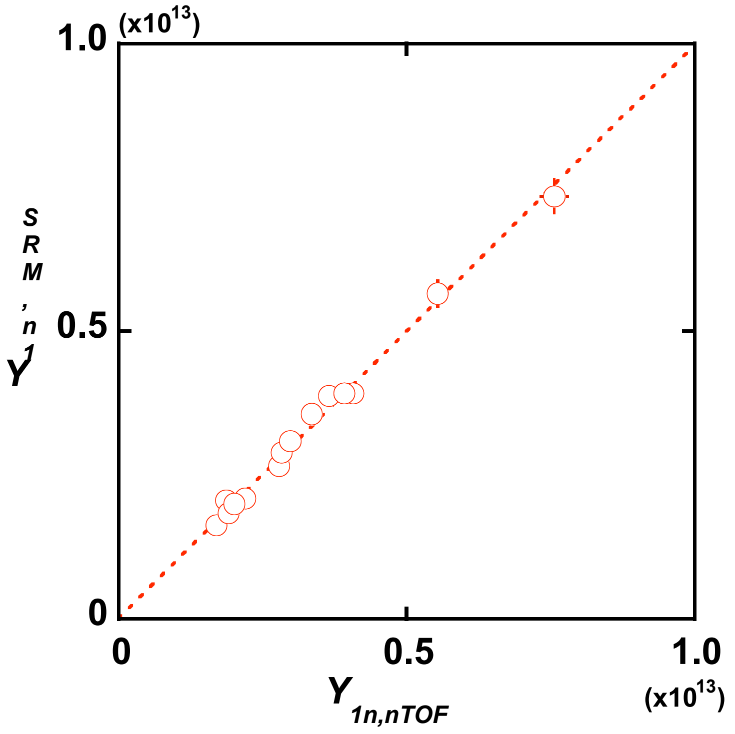
Systematic uncertainties for the different MRS parameters and their contribution to the total systematic uncertainty

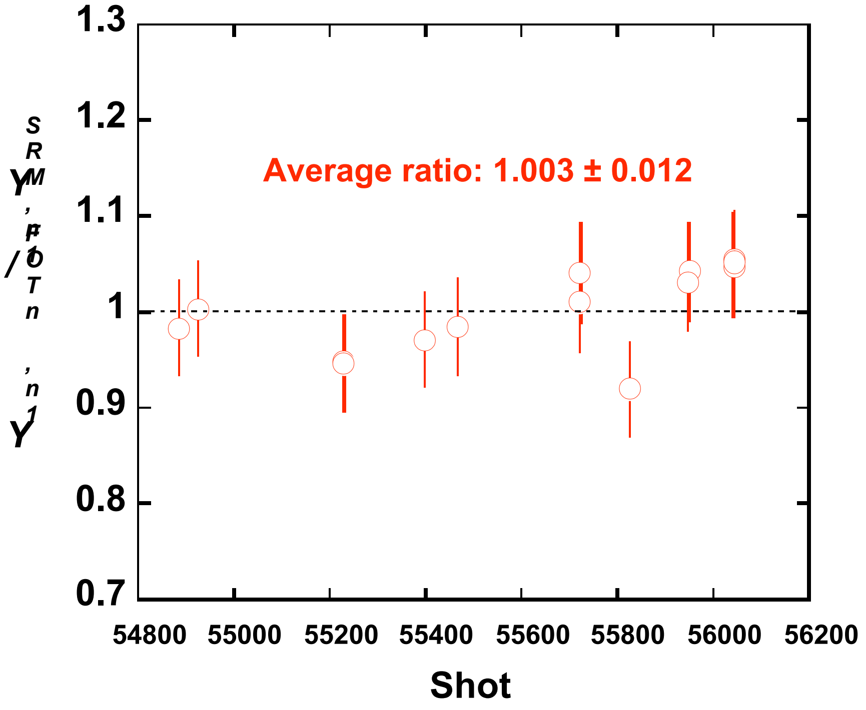
	Absolute	Low-Res [%]
Foil area uncertainty	±0.2 cm^2	±1.5
Foil distance uncertainty	±0.1 cm	±2.0
Number density uncertainty	±10^{21} cm^3	±1.3
Foil thickness uncertainty	±2.0 µm	±0.8
nd-cross section uncertainty (1n,0°)**	±12 mb/sr	±2.0
nd-cross section uncertainty (n',0°)**	±36 mb/sr	±3.5
Magnet aperture area uncertainty	±0.1 cm^2	±1.0
Magnet aperture distance uncertainty	±0.1 cm	±0.01
Total systematic uncertainty for *Y*		±3.7
Total systematic uncertainty for *dsf*		±4.0

$$\frac{\sigma_{Y_{1n}}}{Y_{1n}} \approx \sqrt{\left(\frac{\sigma_{A_f}}{A_f}\right)^2 + 4\left(\frac{\sigma_{R_f}}{R_f}\right)^2 + \left(\frac{\sigma_{n_i}}{n_i}\right)^2 + \left(\frac{\sigma_{t_f}}{t_f}\right)^2 + \left(\frac{\sigma_{\frac{d\sigma(p,0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(p,0^\circ)}{d\Omega_{lab}}}\right)^2 + \left(\frac{\sigma_{A_a}}{A_a}\right)^2 + 4\left(\frac{\sigma_{R_a}}{R_a}\right)^2}$$

$$\frac{\sigma_{dsf}}{dsf} \approx \sqrt{\left(\frac{\sigma_{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}\right)^2 + \left(\frac{\sigma_{\frac{d\sigma(n',0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(n',0^\circ)}{d\Omega_{lab}}}\right)^2}$$

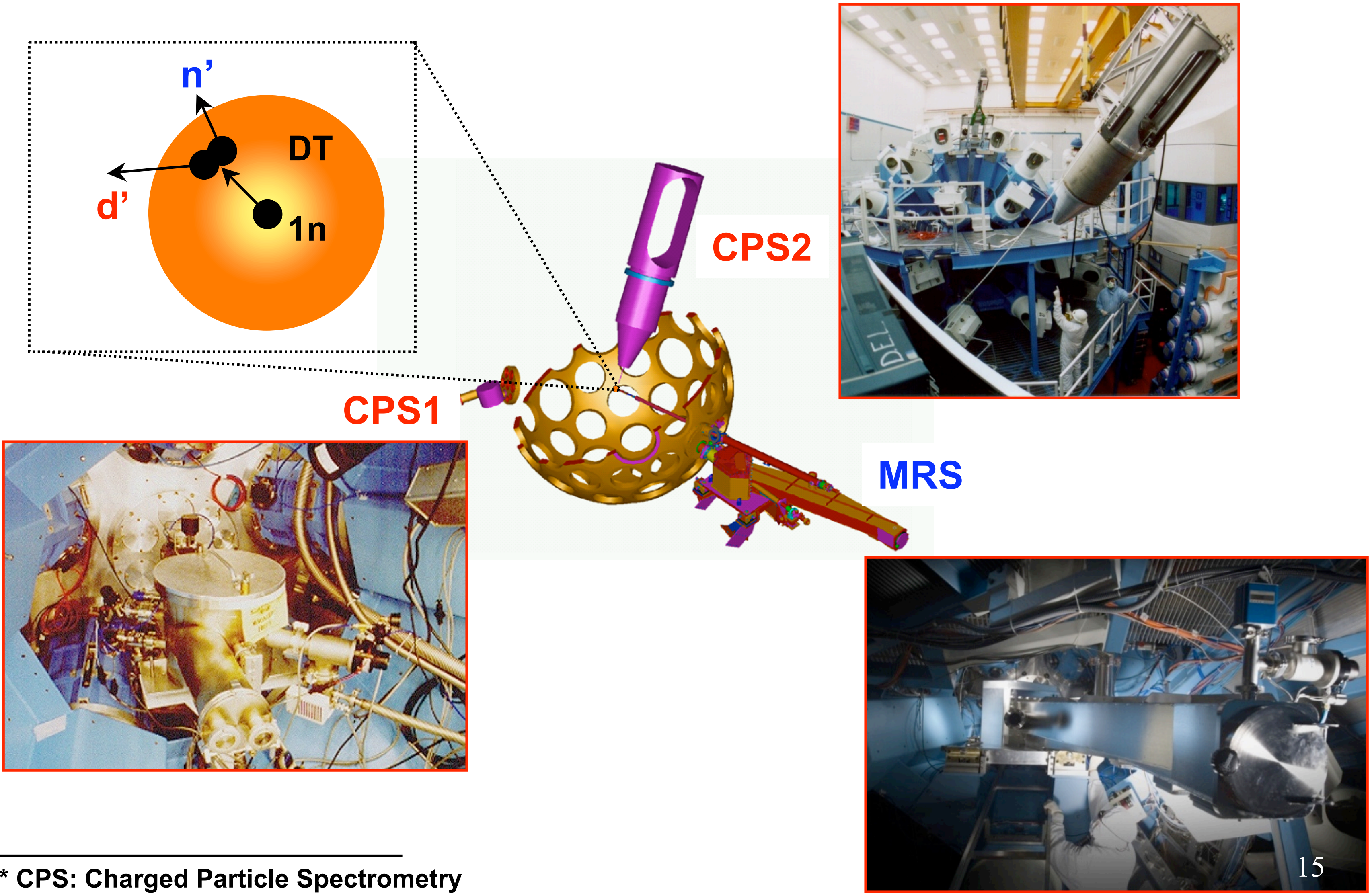
Y_{1n} determined from MRS (operated with a CD foil in Low-Res mode) is in good agreement with the nTOF data





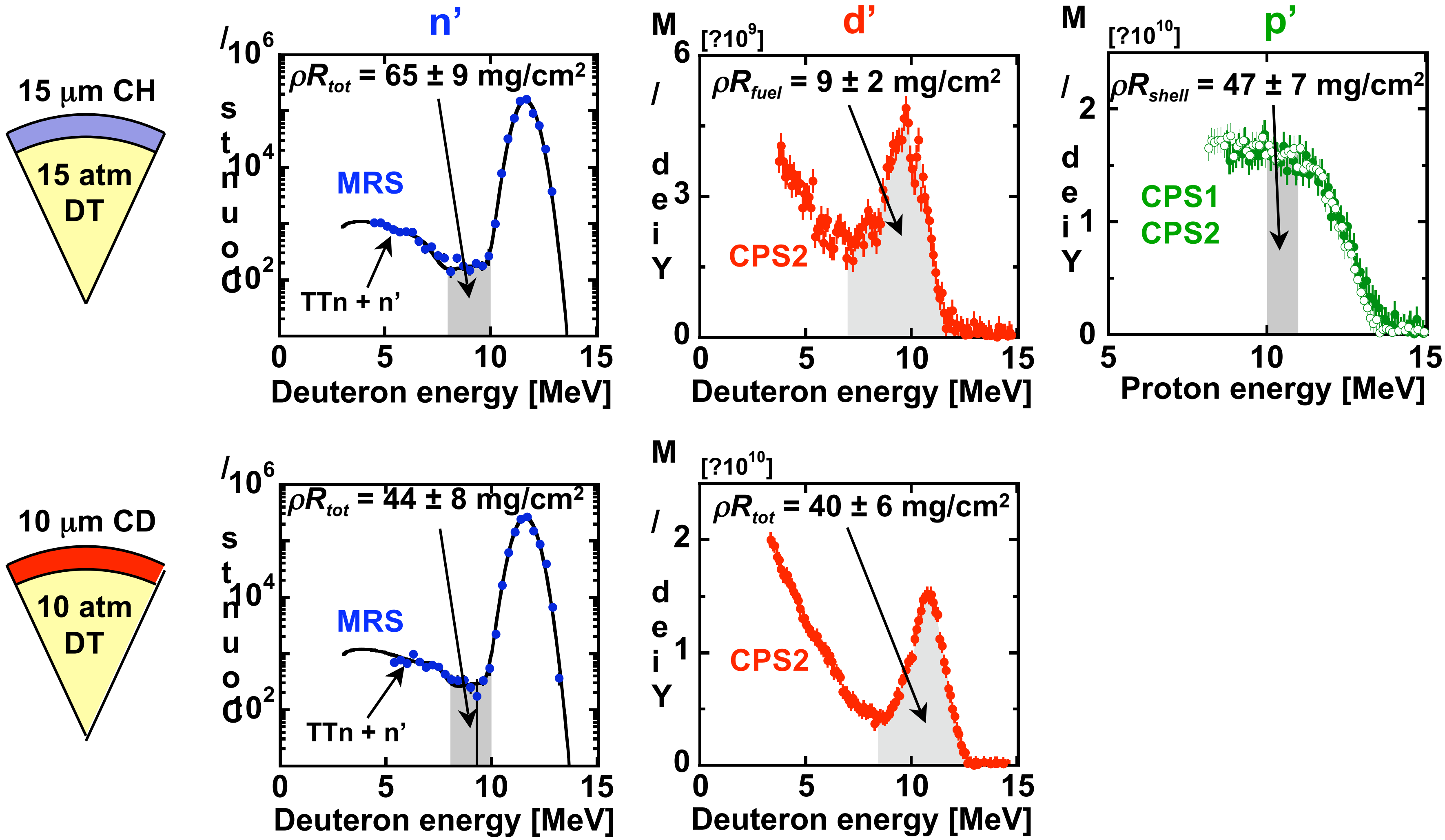
The error bars shown in the ratio plot are due to an assumed 3% nTOF uncertainty, and a statistical of ~1% and a systematic uncertainty of 4% for the MRS

ρR data obtained from well established CPS** techniques were used to authenticate the MRS-ρR data obtained at OMEGA



** CPS: Charged Particle Spectrometry
C.K. Li et al., Phys. Plasmas 8, 4902 (2001).

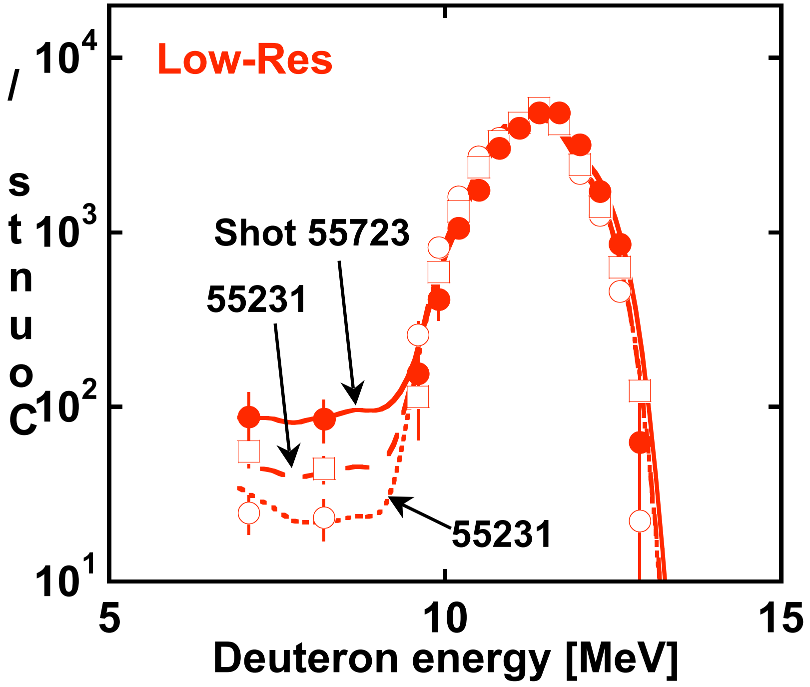
ρR values inferred from the CPS and MRS techniques are in good agreement for low-ρR plastic implosions



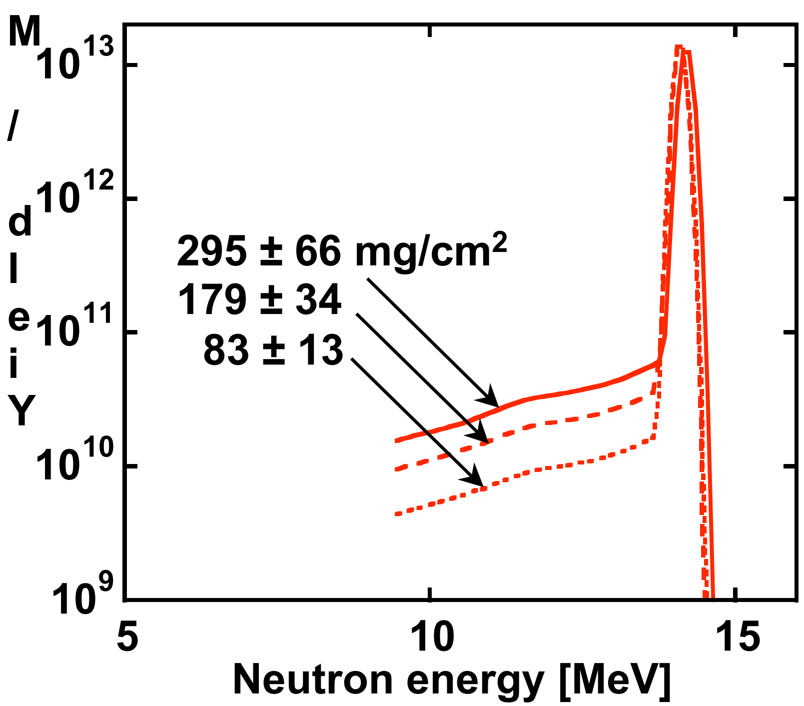
The OMEGA MRS

ρR in cryogenic DT implosions are now routinely diagnosed using the MRS measured n’ spectrum

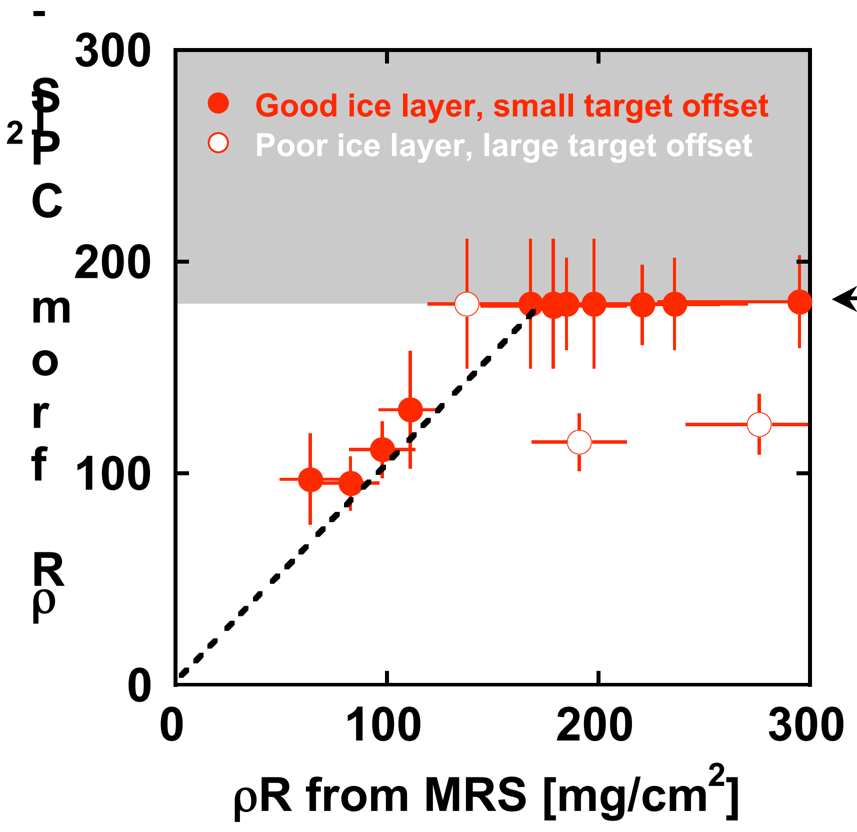
Measured MRS spectra



Modeled neutron spectra



ρR and *ρR* asymmetries in cryogenic DT implosions are diagnosed using CPS1, CPS2 and MRS



CPS technique saturated** (depends somewhat on the T_e and n_e in the high-density region)

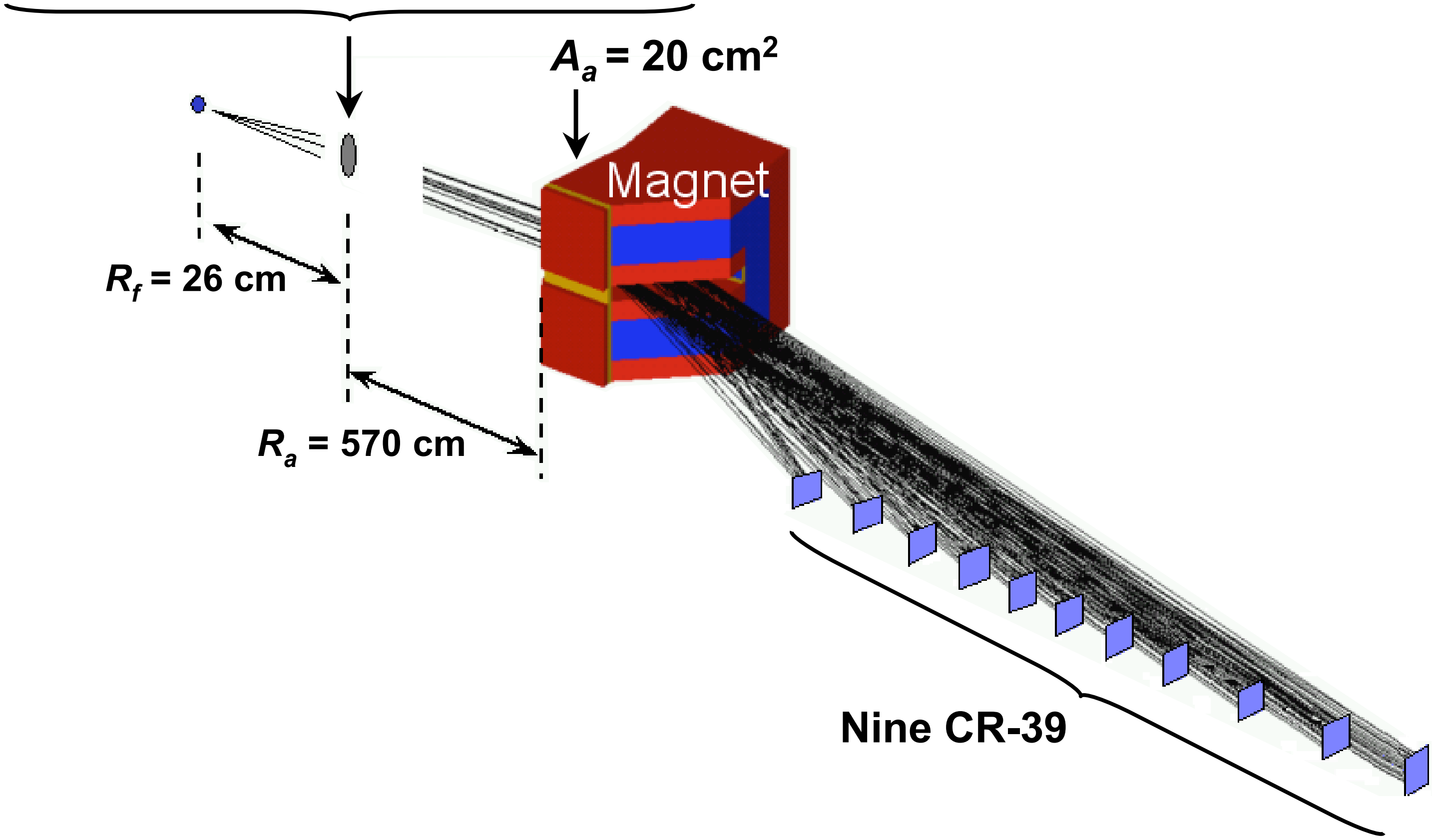
T.C. Sangster et al., accepted for publication in Phys. Plasmas (2010).
J.A. Frenje et al., accepted for publication in Phys. Plasmas (2010).
** J.A. Frenje et al., Phys. Plasmas 16, 042704 (2009).

The NIF MRS

High-Res
A_f = 13 cm^2
t_f = 50 μm

Med-Res
A_f = 13 cm^2
t_f = 125 μm

Low-Res
A_f = 13 cm^2
t_f = 275 μm



A_a = 20 cm^2

Magnet

R_f = 26 cm

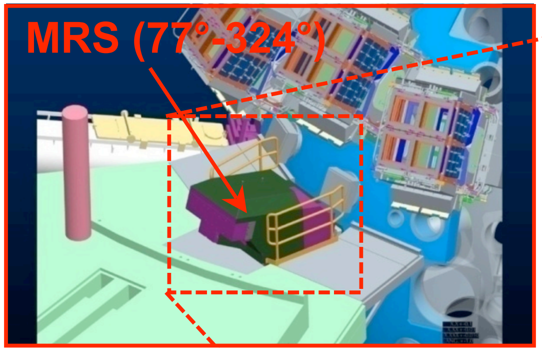
R_a = 570 cm

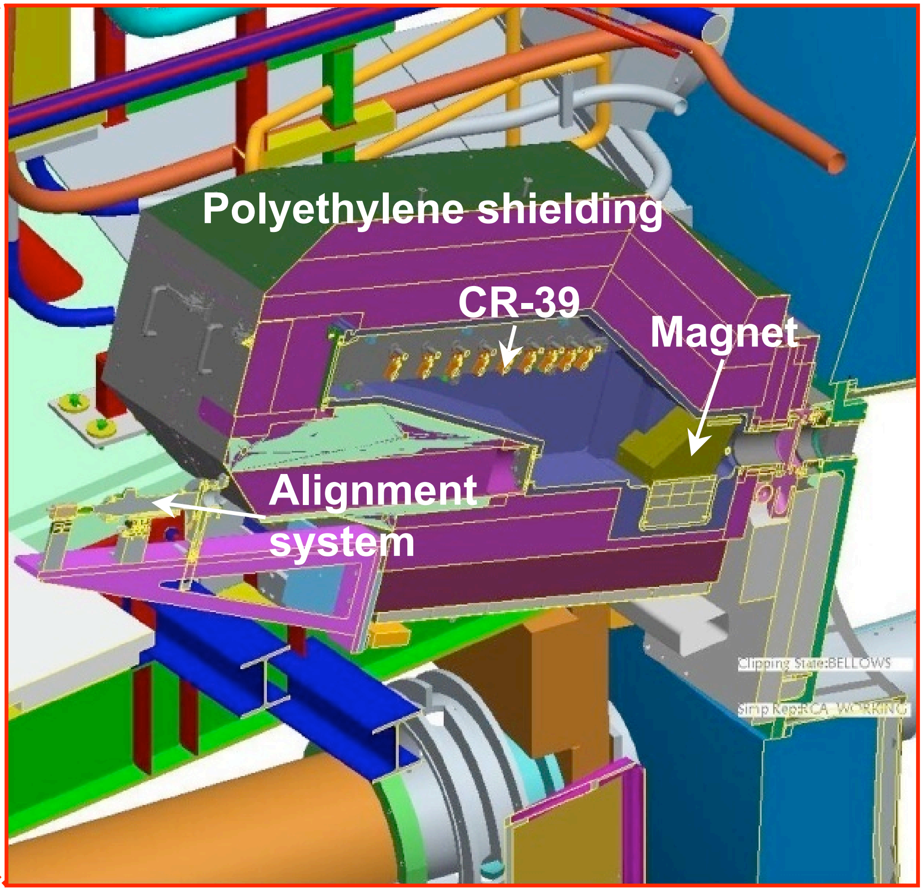
Nine CR-39

Different MRS configurations at the NIF will be used depending on application

	High-Res	Med-Res	Low-Res
Yield range	10^{15}-10^{19}	10^{14}-10^{18}	$<10^{14}$
Magnet distance to foil (R_a)	570	570	570
Magnet aperture area (A_a)	20	20	20
Foil distance to TCC (R_f)	26	26	26
Foil area (A_f)	13	13	13
CD-foil thickness (t_f)	50	125	275
CH-foil thickness (t_f)	100	250	500
ΔE_{MRS} (FWHM) at 14 MeV	480	820	1810
ε_{MRS} at 14 MeV**	2_10^{-11}	4_10^{-11}	8_10^{-11}

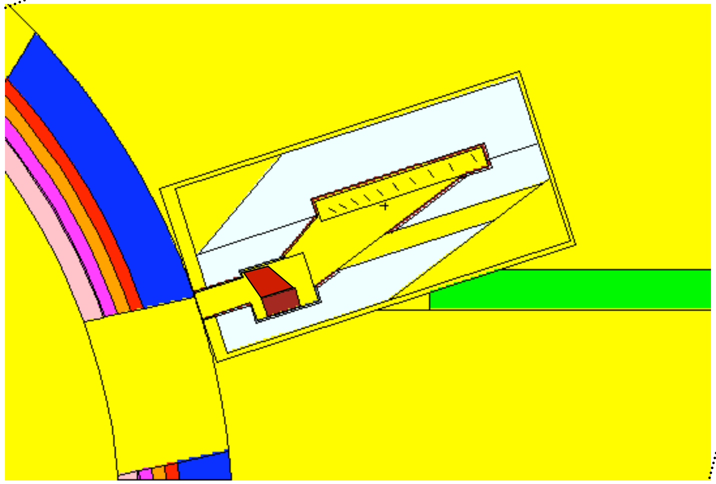
For maximum *S/B* and *S/N*, the NIF-MRS is fully enclosed by polyethylene shielding and positioned in the shadow of the NIF-target chamber

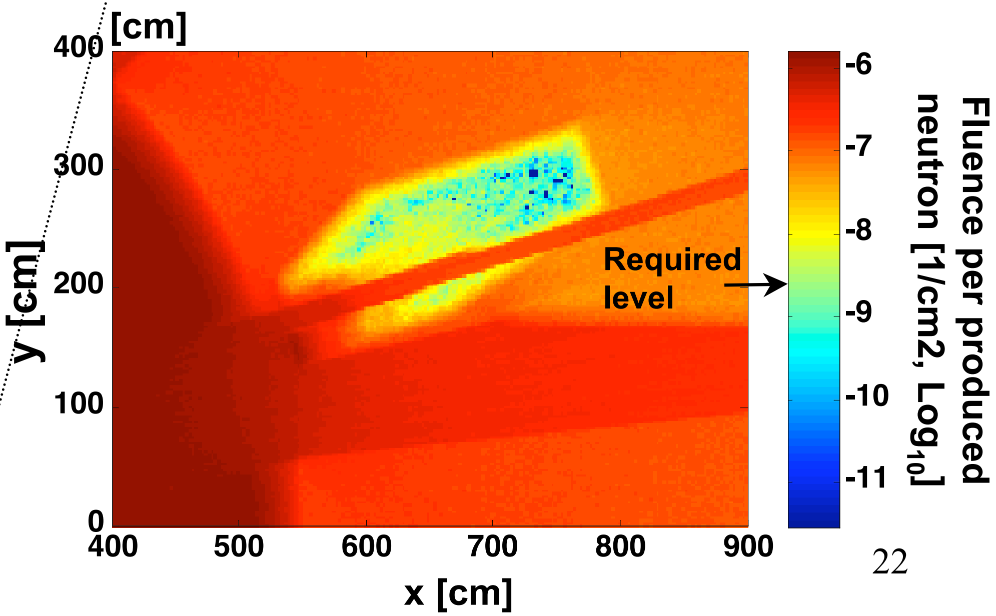




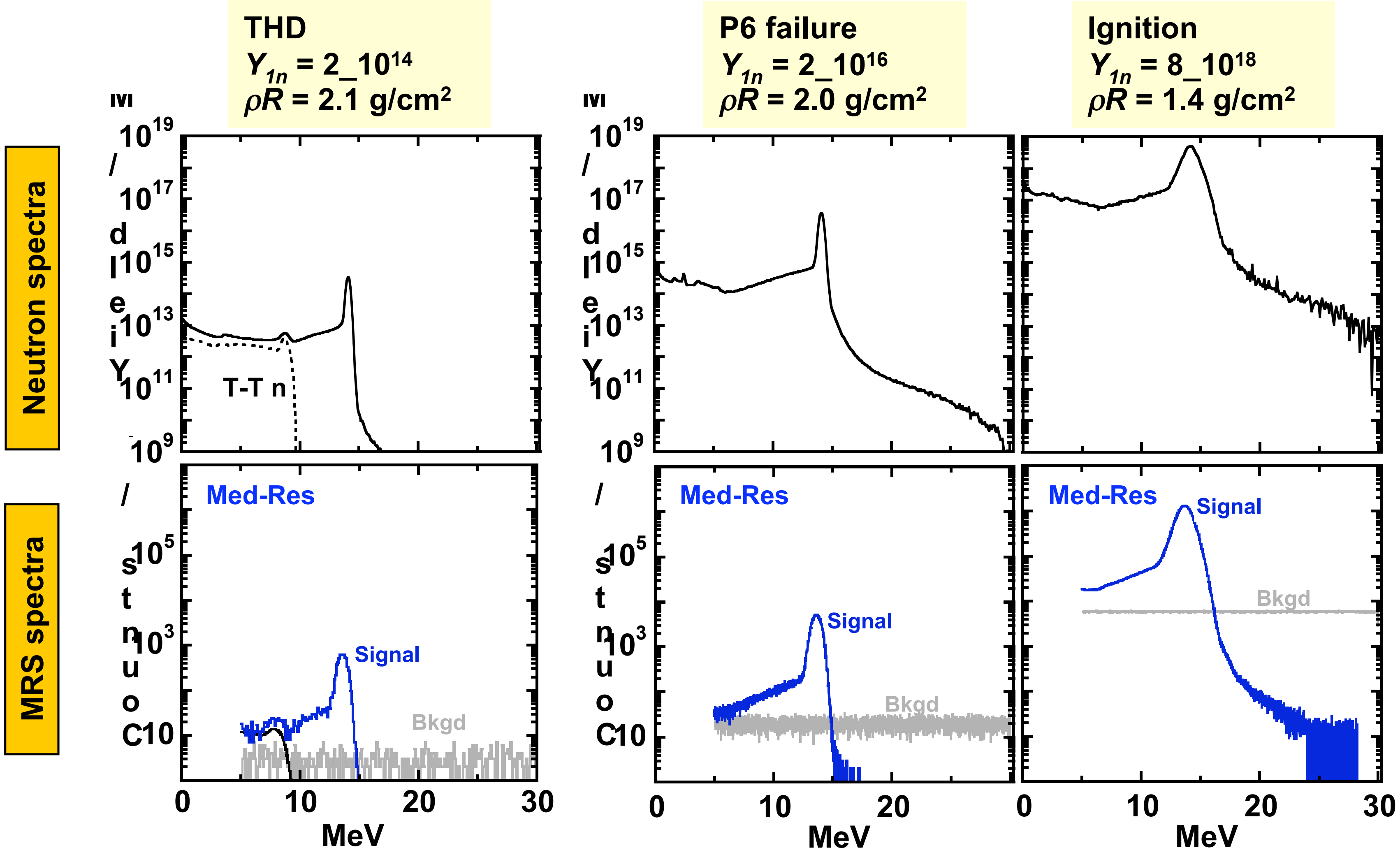
~6000 lbs of polyethylene shielding fully encloses the MRS to reduce the neutron fluence to the required level

MCNP model of
the MRS inside
the NIF target bay





OMEGA data and simulations indicate that the MRS will accurately diagnose THD and DT implosions at the NIF

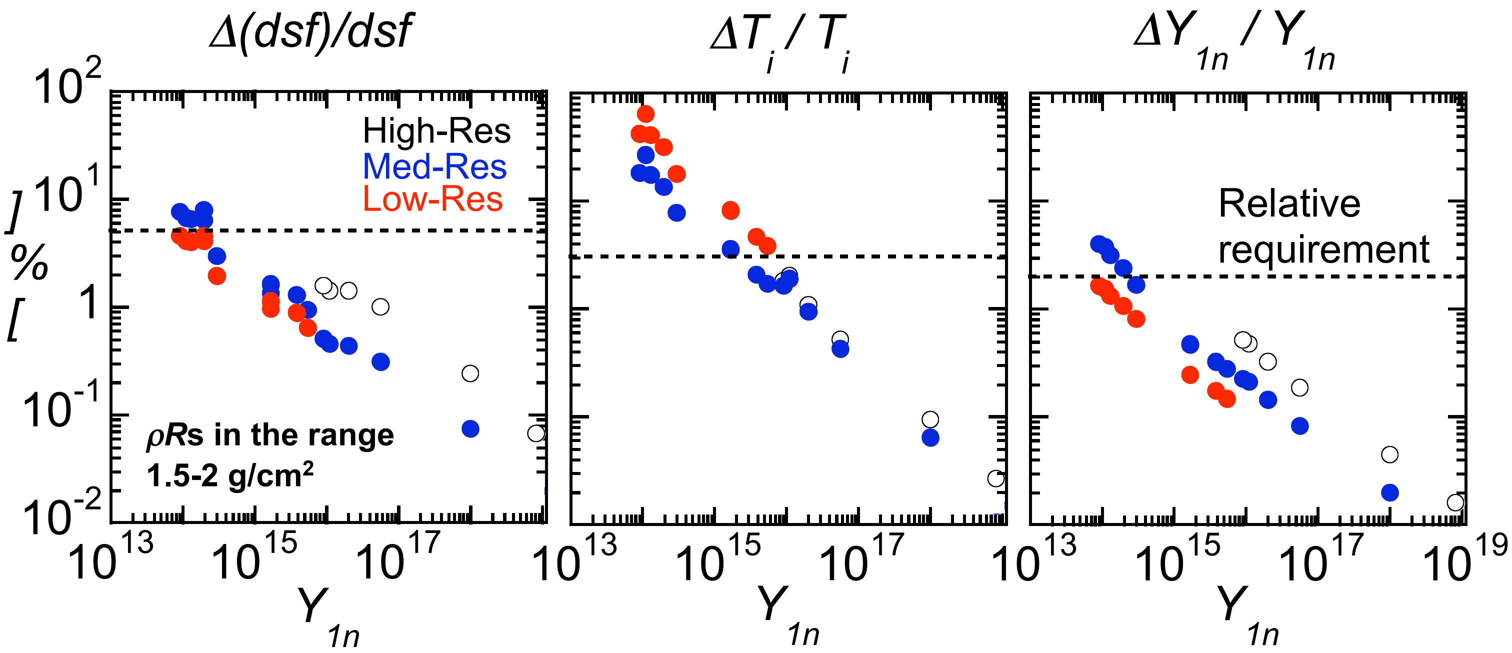


THD
$Y_{1n} = 2\_10^{14}$
$\rho R = 2.1\ \mathrm{g/cm^2}$

P6 failure
$Y_{1n} = 2\_10^{16}$
$\rho R = 2.0\ \mathrm{g/cm^2}$

Ignition
$Y_{1n} = 8\_10^{18}$
$\rho R = 1.4\ \mathrm{g/cm^2}$

Statistical uncertainty for the *dsf*, T_i and Y_{1n} as a function of neutron yield



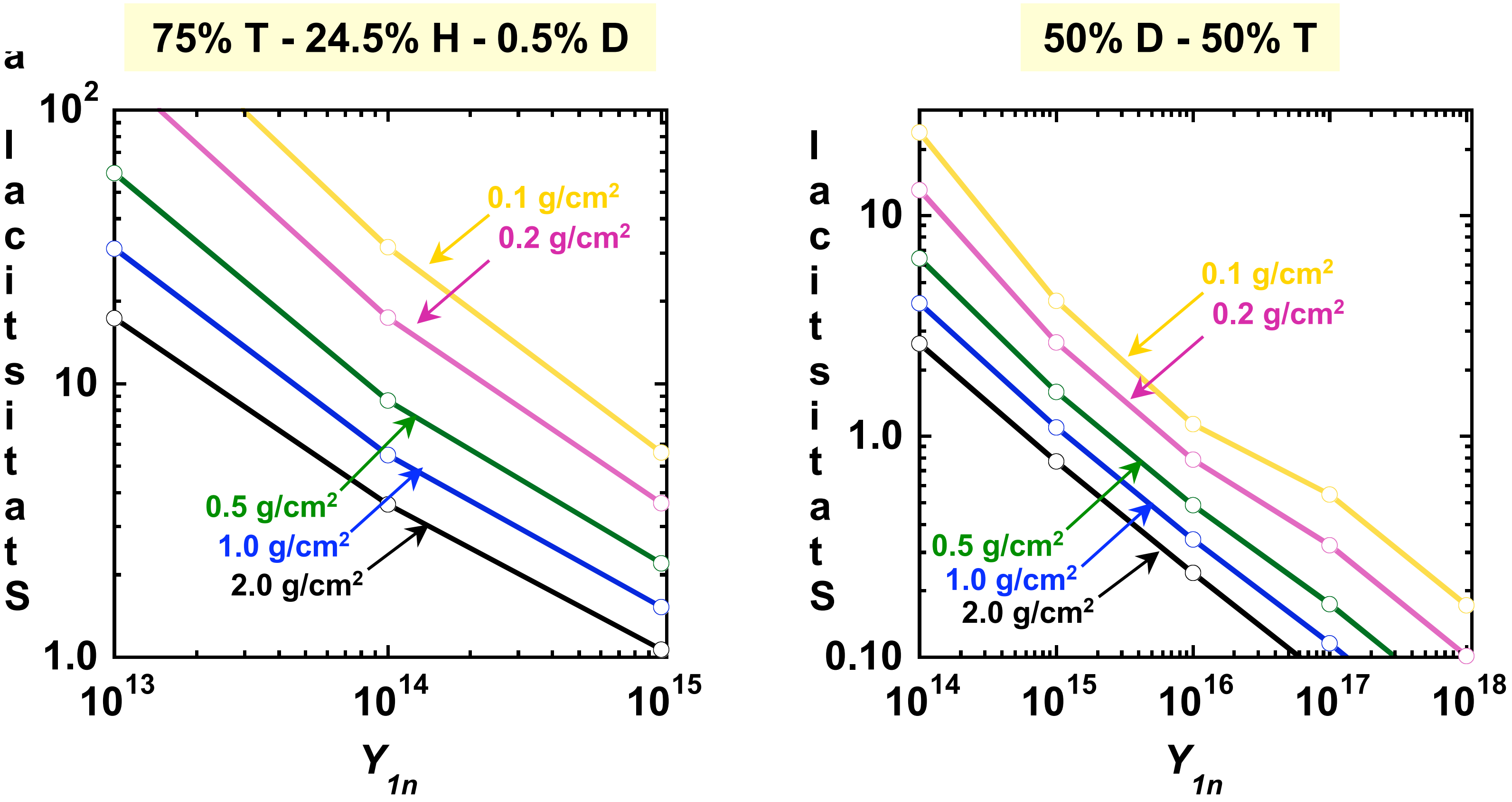
$$\frac{\Delta(dsf)}{dsf} = \frac{\sqrt{S_{n'}+2B}}{S_{n'}}$$

$$\frac{\Delta T_i}{T_i} = \left[1+\left(\frac{\Delta E_{MRS}}{\Delta E_D}\right)^2\right]\frac{1}{\sqrt{S_{1n}}}$$

$$\frac{\Delta Y_{1n}}{Y_{1n}} = \frac{1}{\sqrt{S_{1n}}}$$

$S_{n'}$: Down-scattered signal, which is to the 1st order proportional to ρR _ Y_{1n}
B: Background , which is proportional to Y_{1n}
ΔE_D: Doppler width
ΔE_{MRS}: MRS resolution at 14 MeV
S_{1n}: Primary signal

Statistical uncertainty for *dsf*** as a function of ρR and Y_{1n} for the MRS operated in Med-Res mode (THD and DT)



For DT an energy range of 5-12.5 MeV was used to determine the statistical uncertainty for *dsf* value.
For THD an energy range of 9.5-12.5 MeV was used to determine the statistical uncertainty for *dsf* value.

The NIF MRS

Systematic uncertainties for the different parameters and their contribution to the total systematic error for the MRS High-Res, Med-Res and Low-Res mode

	Absolute	High-Res [%]	Med-Res [%]	Low-Res [%]
Foil area uncertainty	±0.3 cm^2	±2.3	±2.3	±2.3
Foil distance uncertainty	±0.1 cm	±0.4	±0.4	±0.4
Number density uncertainty	$\pm 10^{21}$ cm^3	±1.3	±1.3	±1.3
Foil thickness uncertainty	±2.0 mm	±2.0	±0.8	±0.4
nd-cross section uncertainty (*1n*)	±12 mb/sr	±2.0	±2.0	±2.0
nd-cross section uncertainty (*n'*)	±36 mb/sr	±3.6	±3.6	±3.6
Response function uncertainty	±10 keV	±2.1	±1.1	±0.6
Magnet aperture area uncertainty	±0.2 cm^2	±1.0	±1.0	±1.0
Magnet aperture distance uncertainty	±0.1 cm	±0.02	±0.02	±0.02
Total systematic uncertainty for Y_n		±4.0	±3.6	±3.5
Total systematic uncertainty for *dsf*		±4.1	±4.1	±4.1
Total systematic uncertainty for T_i (@ 5 keV)		±2.9	±6.4	±13.4

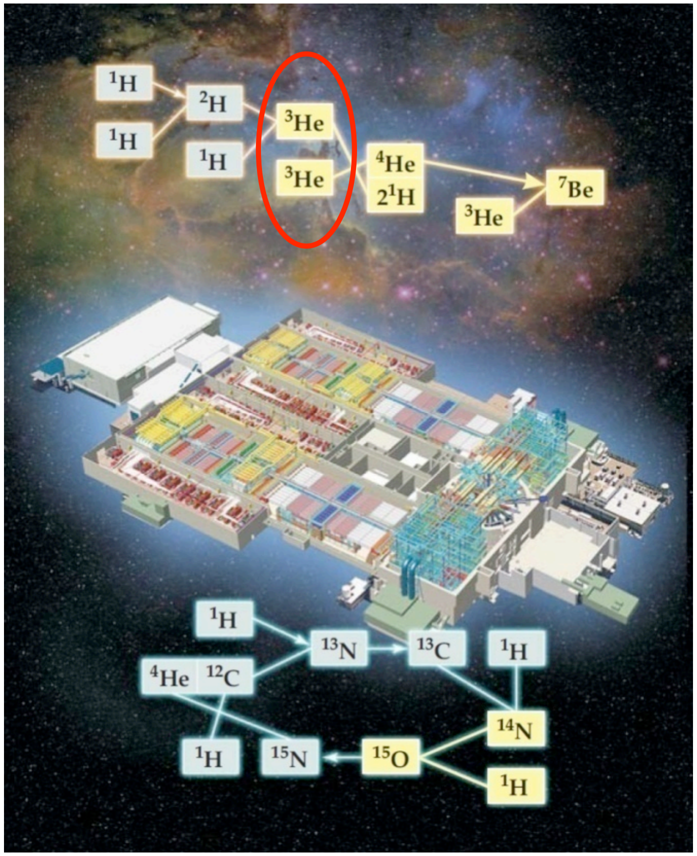
$$\frac{\sigma_{Y_{1n}}}{Y_{1n}} \approx \sqrt{\left(\frac{\sigma_{A_f}}{A_f}\right)^2 + 4\left(\frac{\sigma_{R_f}}{R_f}\right)^2 + \left(\frac{\sigma_{n_i}}{n_i}\right)^2 + \left(\frac{\sigma_{t_f}}{t_f}\right)^2 + \left(\frac{\sigma_{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}\right)^2 + \left(\frac{\sigma_{A_a}}{A_a}\right)^2 + 4\left(\frac{\sigma_{R_a}}{R_a}\right)^2}$$

$$\frac{\sigma_{dsf}}{dsf} \approx \sqrt{\left(\frac{\sigma_{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}\right)^2 + \left(\frac{\sigma_{\frac{d\sigma(n',0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(n',0^\circ)}{d\Omega_{lab}}}\right)^2}$$

$$\frac{\sigma_{T_i}}{T_i} \approx \frac{2}{\left(\frac{\Delta E_{meas}}{\Delta E_{MRS}}\right)^2 - 1} \frac{\sigma_{\Delta E_{MRS}}}{\Delta E_{MRS}}$$

Basic science

Basic science experiments relevant to stellar nucleosynthesis and ICF are being conducted / planned at OMEGA / NIF



1. **Measure the characteristics of the T(t,2n)^{4}He reaction** (an important mirror reaction to the ^{3}He(^{3}He,2p)^{4}He reaction that is part of the p-p chain in hydrogen burning stars).

2. **Measure ^{3}He(^{3}He,2p)^{4}He reaction** (this can be done by turning the MRS into a charged-particle spectrometer).

R.N. Boyd, L. Bernstein and C. Brune, Physics Today 62, August (2009).

Basic science

The 1st set of basic-science experiments, using the MRS, is focusing on studying the astrophysical S factor and reaction channels for the T(t,2n)^{4}He reaction

T(t,2n)^{4}He:

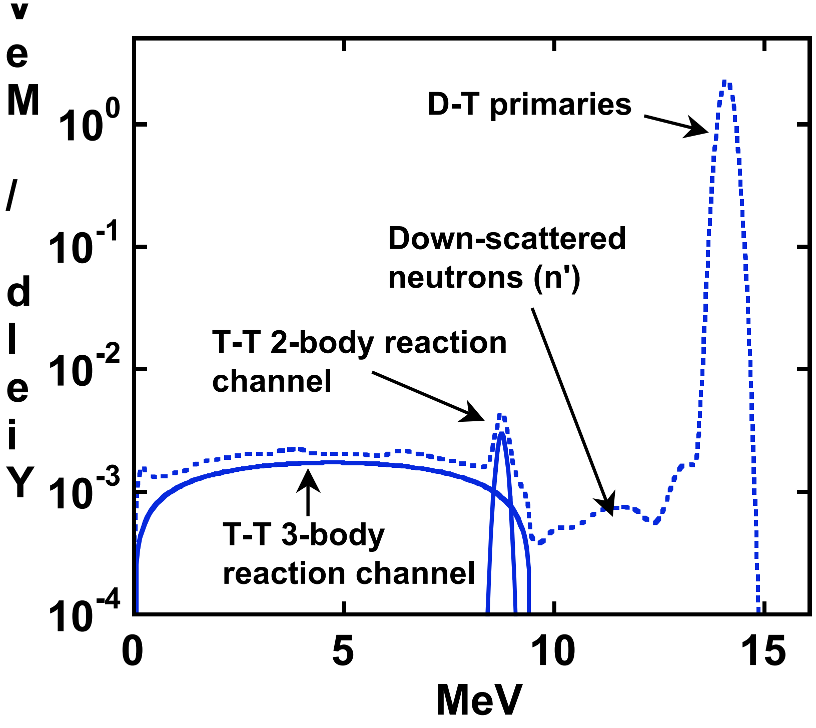
1. $T + T \rightarrow 2n + {}^4He$
2. $T + T \rightarrow {}^5He^* + n$ (8.8 MeV)

Branching ratio poorly known

Astrophysical S factor:

$$S_{TT}(\varepsilon) = \sigma_{TT} \cdot \varepsilon \cdot e^{\sqrt{\frac{b}{\varepsilon}}}$$

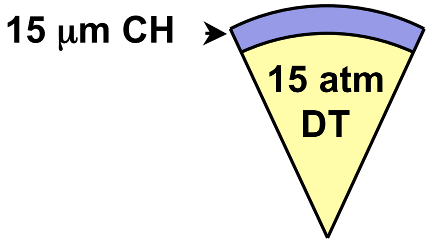
$$S_{TT} \sim \frac{Y_{TT}}{Y_{DT}} \cdot S_{DT}$$



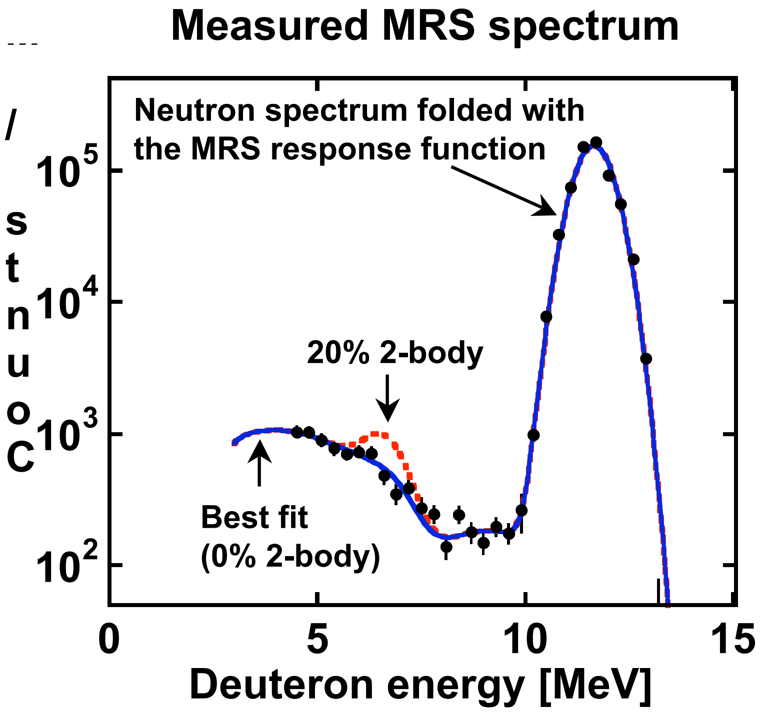
At the NIF, we can study the T(t,2n)^{4}He reaction at Gamow energies (E_G) of 10 - 40 keV

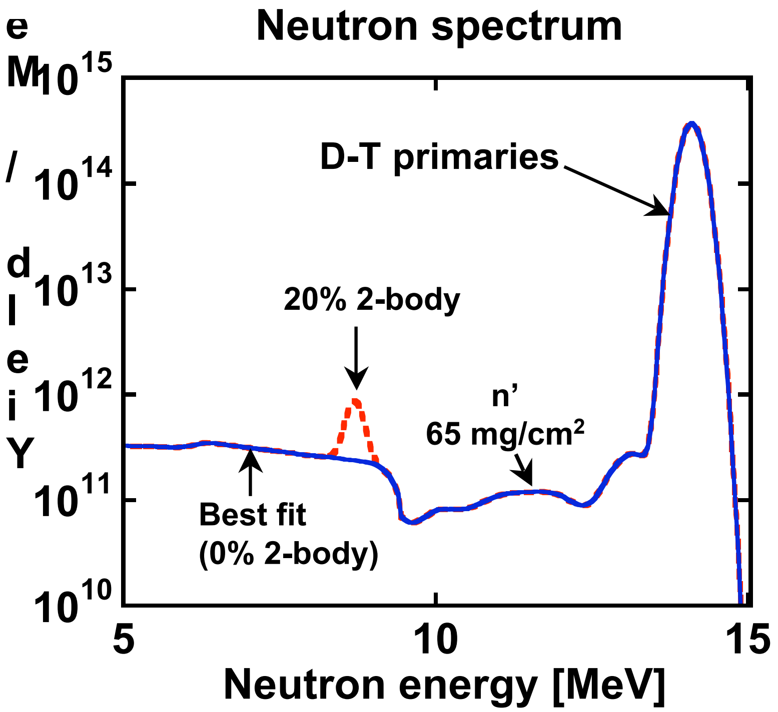
Basic science

Measurement of the T-T neutron spectrum at OMEGA suggests that the T-T reaction at 22 keV proceeds mainly through the direct three-body reaction channel –T(t,2n)^{4}He



23 kJ
1-ns square pulse
$Y_{1n} = 2\_10^{13}$
$\langle T_i \rangle_{1n}$ = 5.3 keV -> E_G = 22 keV


Measured MRS spectrum

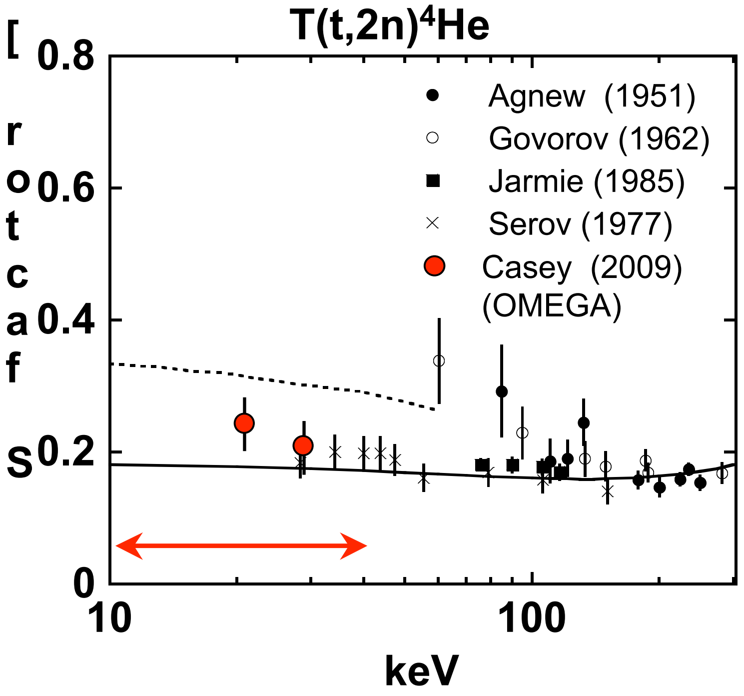

Neutron spectrum

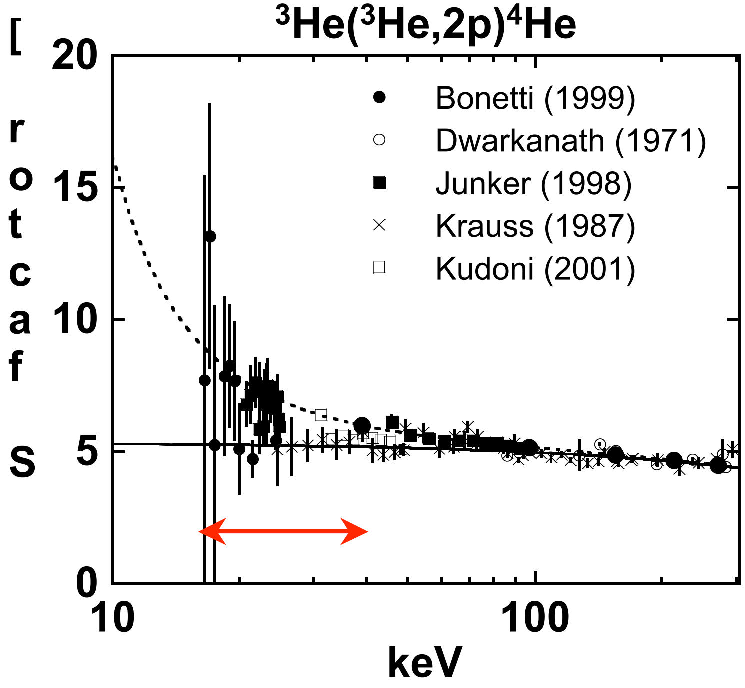
C. Wong et al., Nucl. Phys. 71(1965)106,
K. Allen et al., Phys. Rev. 82(1951)262,
V. Glebov et al., Bull. Am. Phys.Soc. (2008)

E_t = 500 keV -> T(t,n)^{5}He ~ 20%.
E_t = 220 keV -> T(t,n)^{5}He ~ 5%.
E_G~ 20 keV -> T(t,n)^{5}He ~ 0%.

Basic science

The astrophysical S factor for the T(t,2n)^{4}He has been measured for the first time using an ICF facility (the OMEGA laser)


T(t,2n)^{4}He


^{3}He(^{3}He,2p)^{4}He

In contrast to the accelerator-based experiments, electron screening does not have an impact on the measured S factor

Summary

- An MRS has been successfully implemented and successfully used on OMEGA for diagnosing high-ρR cryogenic DT implosions.
- OMEGA-MRS data and simulations indicate that the NIF MRS will accurately diagnose THD / DT implosions.
- Basic science experiments relevant to stellar nucleosynthesis and ICF are being conducted and planned at OMEGA and NIF, respectively.