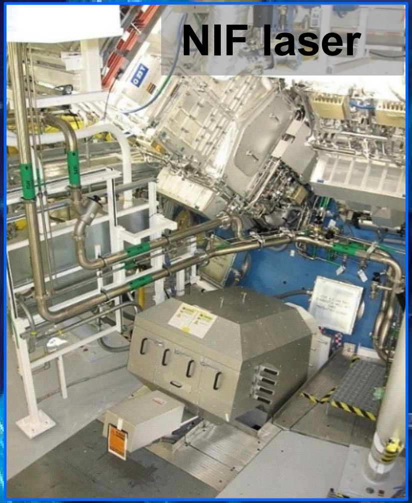
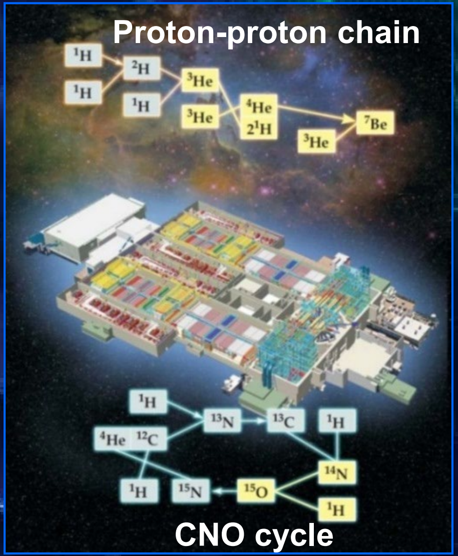
Using high energy density plasmas for nuclear experiments relevant to nuclear astrophysics



Proton spectrometers

Proton-proton chain



CNO cycle

Maria Gatu Johnson
Massachusetts Institute of Technology

HEDS seminar
Aug 10, 2023

Collaborators

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Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a nascent field with much potential

- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions
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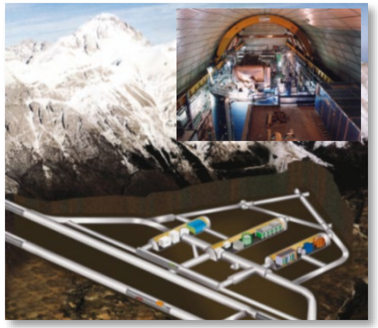
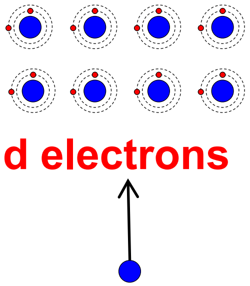
In contrast to accelerators normally used for nuclear physics experiments, lasers create conditions similar to stellar cores

Accelerator experiments



Cold Target

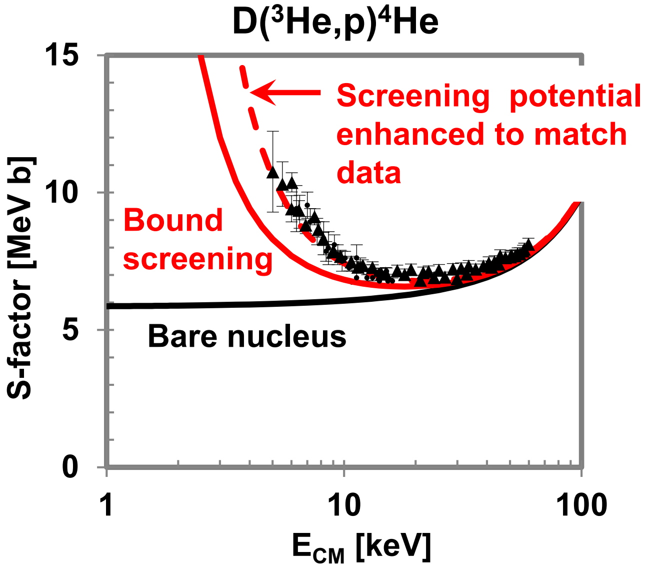


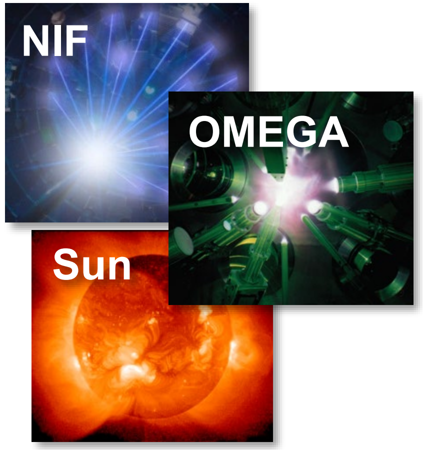
Ions

Bound electrons

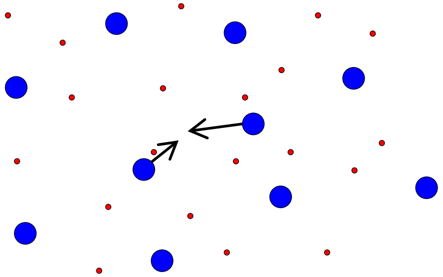
Monoenergetic ion

Bound electron screening





Dense and hot plasma



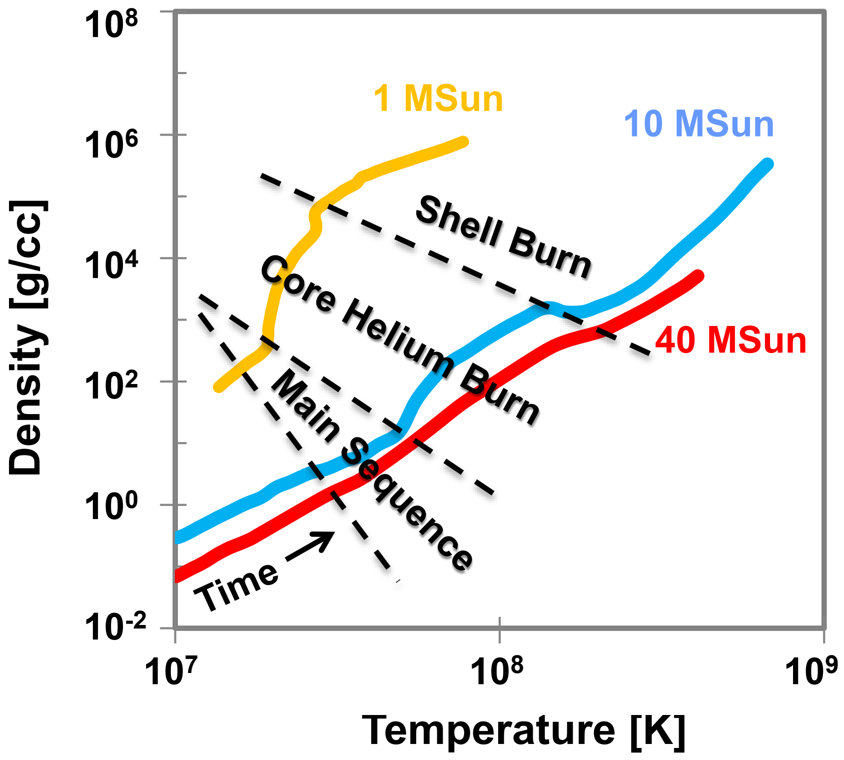
Thermal ions

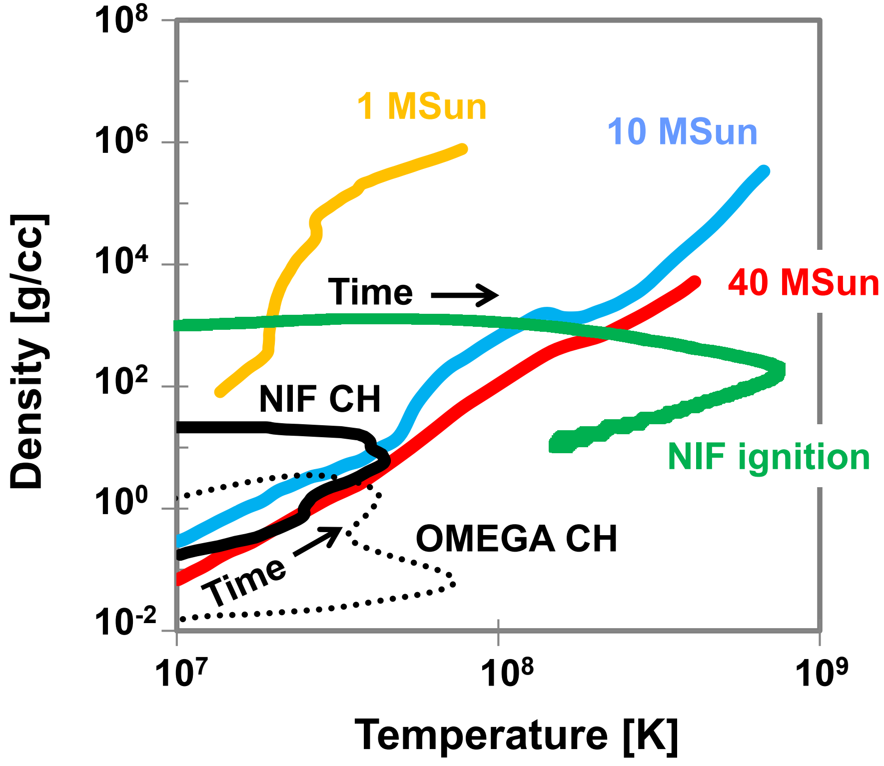
Thermal electrons

Debye screening

M. Aliotta *et al*, NP A (2001).
U. Schröder *et al*, NIM B (1989).
H. J. Assenbaum *et al*, ZP (1987).

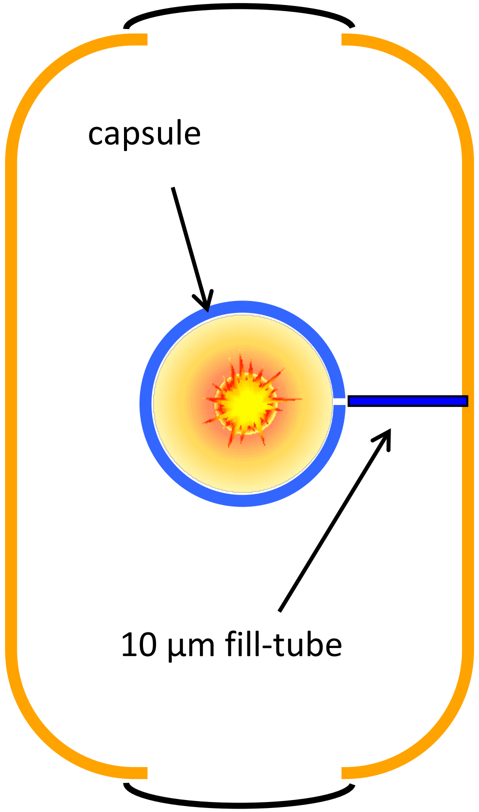
Capsule implosions at the OMEGA and NIF lasers create HED-plasma conditions that are similar to the interior of a star





Stellar evolution simulations by Dave Dearborn (LLNL).
NIF simulations Harry Robey and Bob Tipton (LLNL).
OMEGA simulation P. B. Radha (UR).

Neutron fluxes achieved at the NIF are higher than anywhere else on earth by several orders of magnitude



Example:
4e17 neutrons/implosion[1]
Burn duration <100 ps
→ 4e27 n/s

Burn region size ~100µm
→ $\sim 10^{30}$ n/s/cm^2 in capsule

Hohlraum radius ~3mm
→ $\sim 10^{27}$ n/s/cm^2 on hohlraum wall

Such fluences are directly relevant for s- and/or r-process studies[2,3]

---

[1] H. Abu-Shawareb et al., Phys. Rev. Lett. 129, 071001 (2022); A. Zylstra et al., Nature 601, 542 (2022).
[2] S. LePape et al., Phys. Rev. Lett. 120, 245003 (2018)
[3] C. Cerjan et al., J. Phys. G: Nucl. Part. Phys. 45, 033003 (2018)

At the NIF in particular, all these conditions come together in one experiment

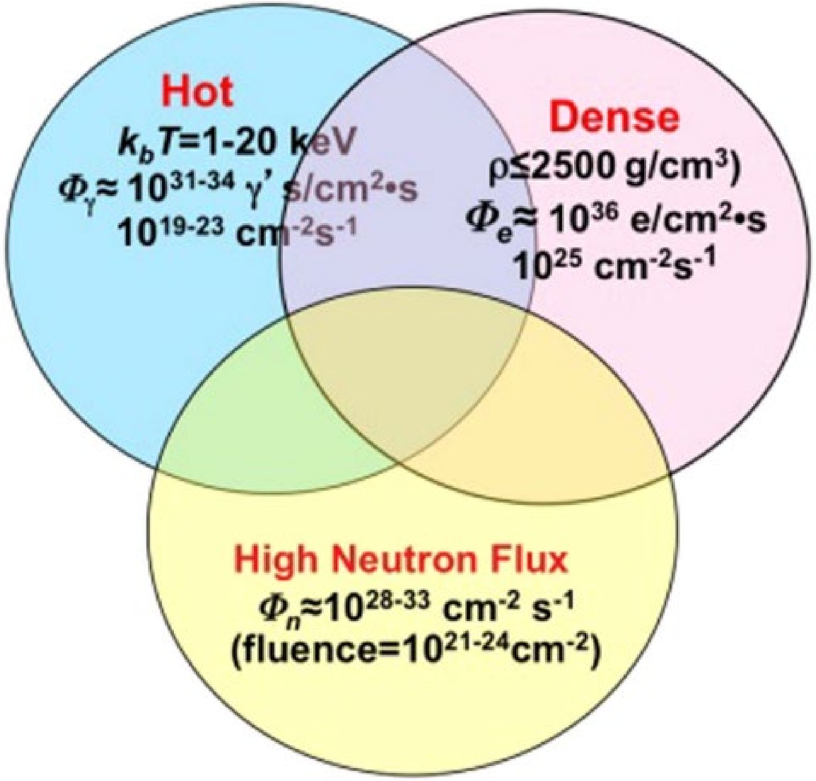
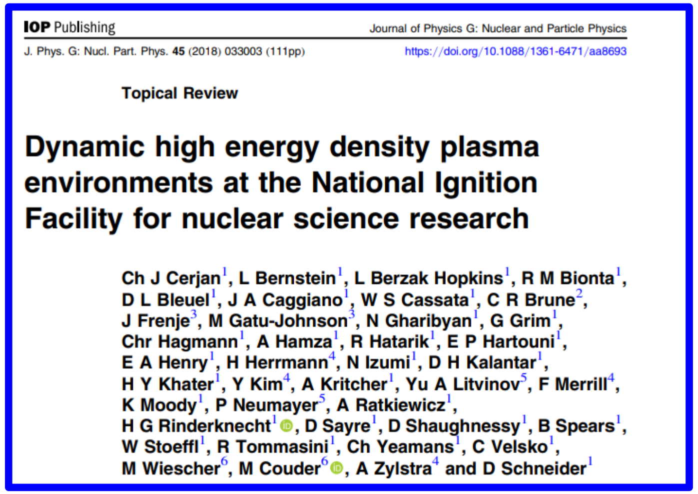


Illustration from *Cerjan et al.,*
J. Phys. G: Nucl. Part. Phys. 45 (2018):



IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **45** (2018) 033003 (111pp) — https://doi.org/10.1088/1361-6471/aa8693

Topical Review

Dynamic high energy density plasma environments at the National Ignition Facility for nuclear science research

Ch J Cerjan[1], L Bernstein[1], L Berzak Hopkins[1], R M Bionta[1],
D L Bleuel[1], J A Caggiano[1], W S Cassata[1], C R Brune[2],
J Frenje[3], M Gatu-Johnson[3], N Gharibyan[1], G Grim[1],
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H Y Khater[1], Y Kim[4], A Kritcher[1], Yu A Litvinov[5], F Merrill[4],
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W Stoeffl[1], R Tommasini[1], Ch Yeamans[1], C Velsko[1],
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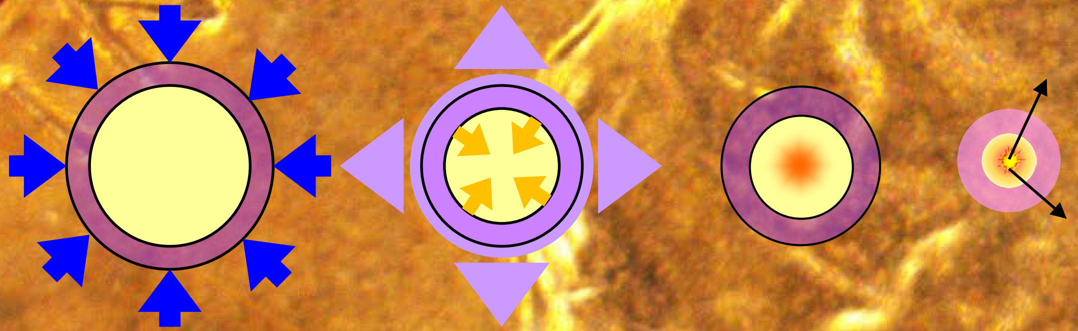
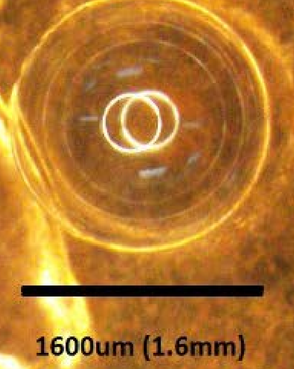
Existing and future nuclear diagnostics at the laser facilities enable exploitation of these plasmas for study of reactions relevant to stellar and big bang nucleosynthesis

Stellar-like conditions are reached by imploding capsules containing the relevant fuels

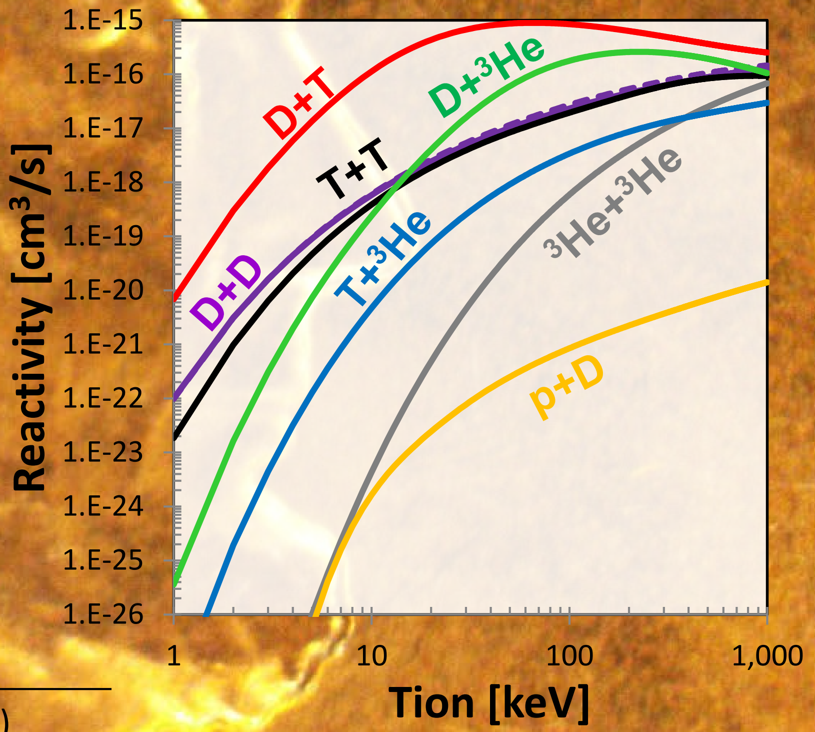




Basic platform requirements:

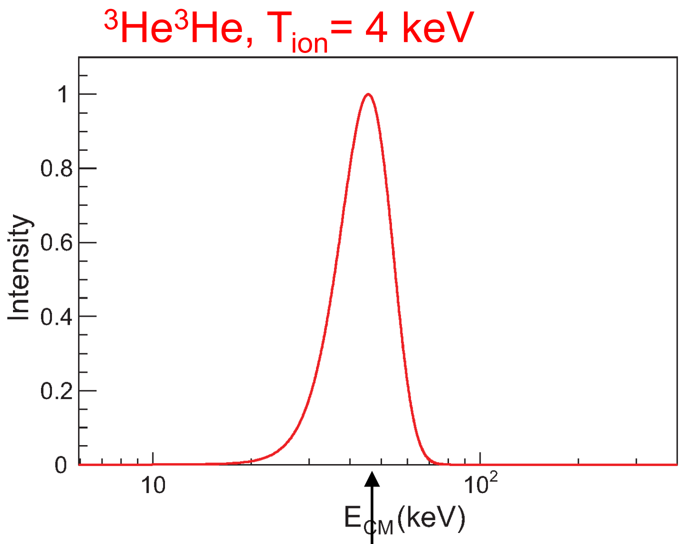
- Low areal density (for charged particles)
- High enough yield to allow probing

Achievable plasma conditions determine astrophysical relevance



Gatu Johnson et al., Phys. Plasmas 24, 041407 (2017)

Gamow-peak energies are directly related to HED-plasma ion temperatures and S-factors are directly related to cross sections



Gamow peak energy
E_G=45 keV

Gamow factor

Gamow-peak energy (average c-m energy): $$E_G = \left(\frac{F_G}{4T_{ion}}\right)^{\frac{1}{3}} T_{ion}$$

S-factor: $$S(E_G) = \sigma(E_G) \times E_G e^{\sqrt{F_G/E_G}}$$

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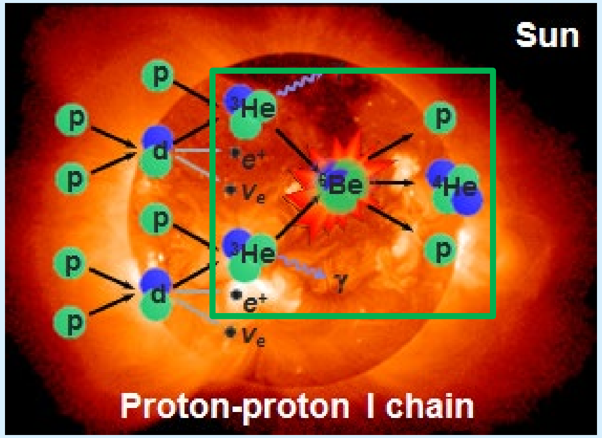
Initial experiments have focused on probing the complementary ^{3}He+^{3}He, T+^{3}He and T+T reactions

^{3}He+^{3}He

$^3He+^3He \rightarrow \alpha + p + p$ is responsible for nearly half the energy generation in our sun:



- The ^{3}He^{3}He S-factor determines the pp-I/(pp-II + pp-III) branching ratio and is important for neutrino oscillation physics[1)]

T+^{3}He

T+^{3}He can proceed through several different branches:

$T+^3He \rightarrow \alpha + p + n$
$T+^3He \rightarrow \alpha + d$
$T+^3He \rightarrow {}^6Li + \gamma$

- An anomalously high S-factor for the gamma branch has been hypothesized to explain ^{6}Li abundance in primordial material **– this was ruled out (Zylstra et al., PRL 117, 035002 (2016))**

T+T

$T+T \rightarrow \alpha + n + n$ is a mirror reaction to ^{3}He^{3}He

- Basic nuclear physics governing few-body reactions with 3 particles in final state not well understood

- Also important for ICF (contributes to the neutron spectrum)

The unique ensemble of T+T, T+^{3}He and ^{3}He+^{3}He spectra provides insight into final-state interactions in six-nucleon systems

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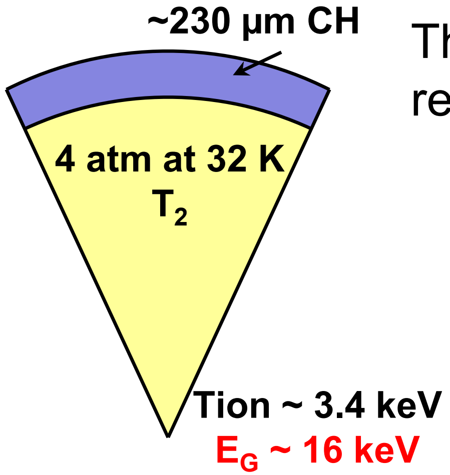
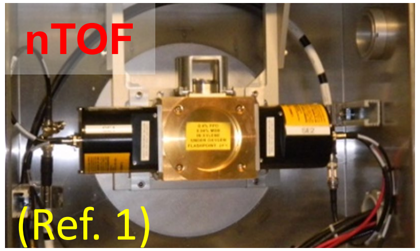
[1)] Adelberger et al., Rev. Mod. Phys 83, 2011

A NIF measurement of the T+T neutron spectrum at E_G = 16 keV provided new insights about the T+T reaction …



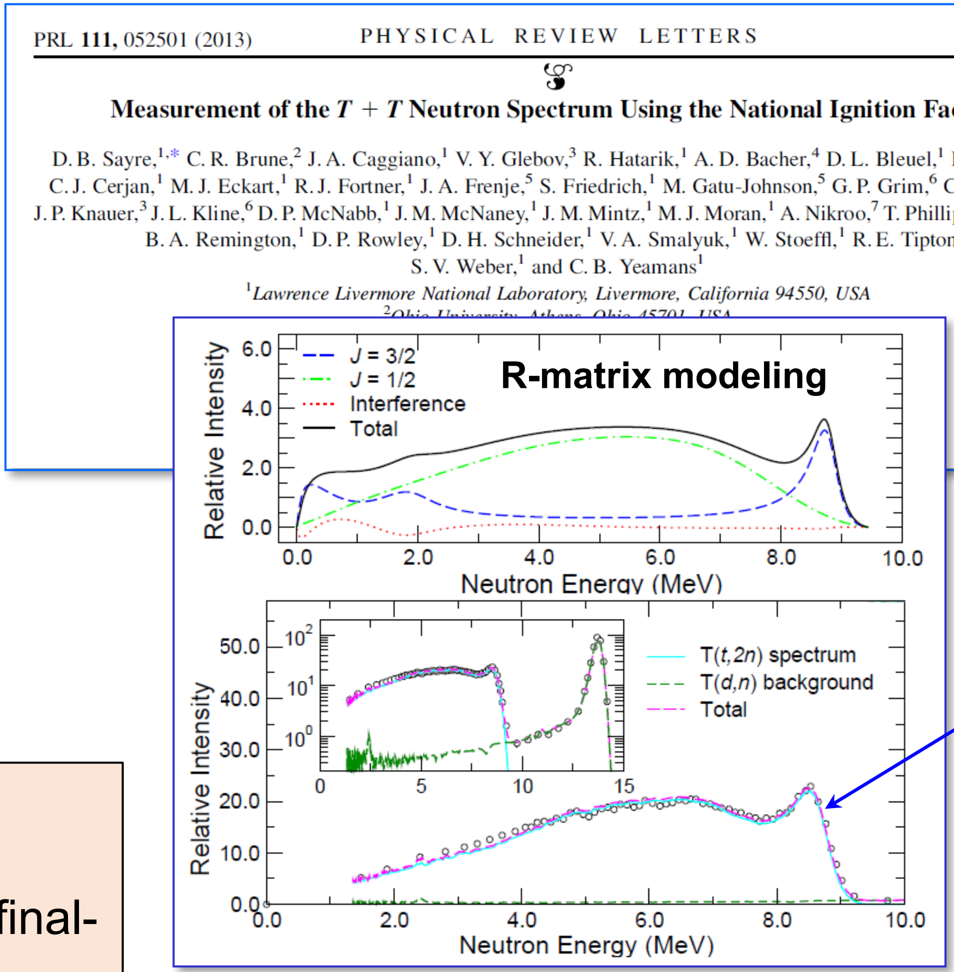


The basic physics governing this 6-nucleon reaction are not well understood:

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

$$\begin{bmatrix} {}^5He + n \\ {}^5He^* + n \\ (nn) \end{bmatrix}$$

- Conclusive evidence of n-α interactions at E_G = 16 keV
- R-matrix modeling indicates that interference between final-state particles matters



PRL **111,** 052501 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

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

D. B. Sayre,[1,*] C. R. Brune,[2] J. A. Caggiano,[1] V. Y. Glebov,[3] R. Hatarik,[1] A. D. Bacher,[4] D. L. Bleuel,[1] D. T. Casey,[1] C. J. Cerjan,[1] M. J. Eckart,[1] R. J. Fortner,[1] J. A. Frenje,[5] S. Friedrich,[1] M. Gatu-Johnson,[5] G. P. Grim,[6] C. Hagmann,[1] J. P. Knauer,[3] J. L. Kline,[6] D. P. McNabb,[1] J. M. McNaney,[1] J. M. Mintz,[1] M. J. Moran,[1] A. Nikroo,[7] T. Phillips,[1] J. E. Pino,[1] B. A. Remington,[1] D. P. Rowley,[1] D. H. Schneider,[1] V. A. Smalyuk,[1] W. Stoeffl,[1] R. E. Tipton,[1] S. V. Weber,[1] and C. B. Yeamans[1]

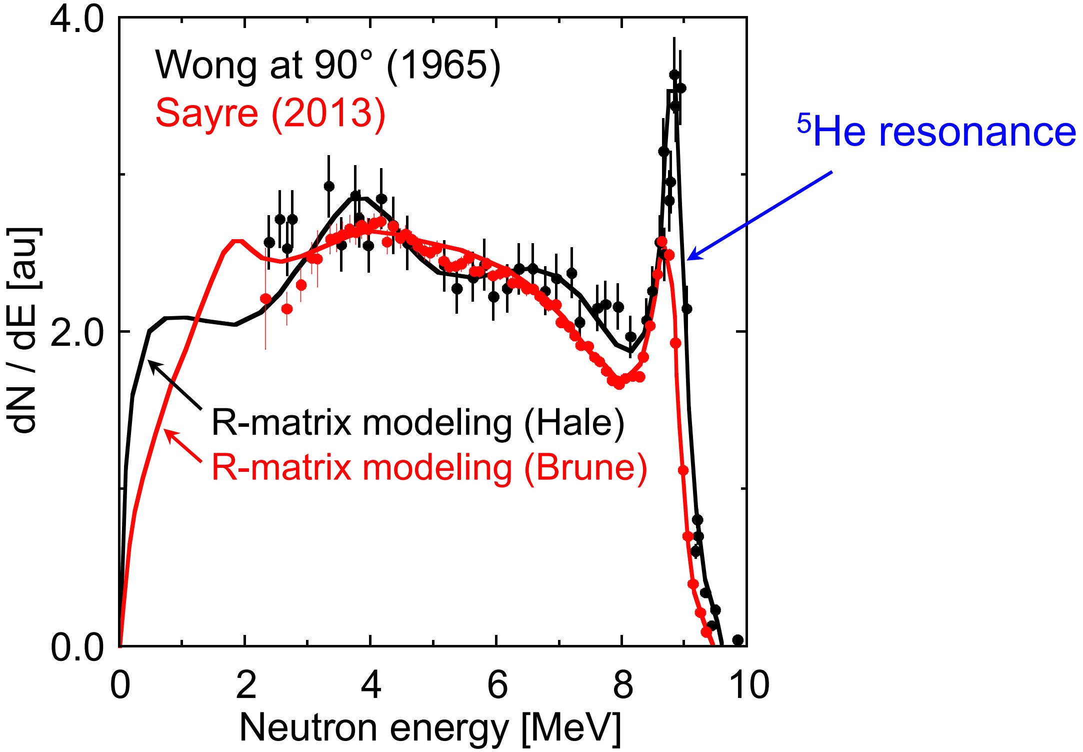
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

^{5}He resonance

---

[1] Neutron time-of-flight spectrometer, Clancy et al., SPIE proceedings (2014)

…but left some questions unanswered: The NIF result at E_G = 16 keV is different from Wong's result[2] at E_{CM} = 160 keV

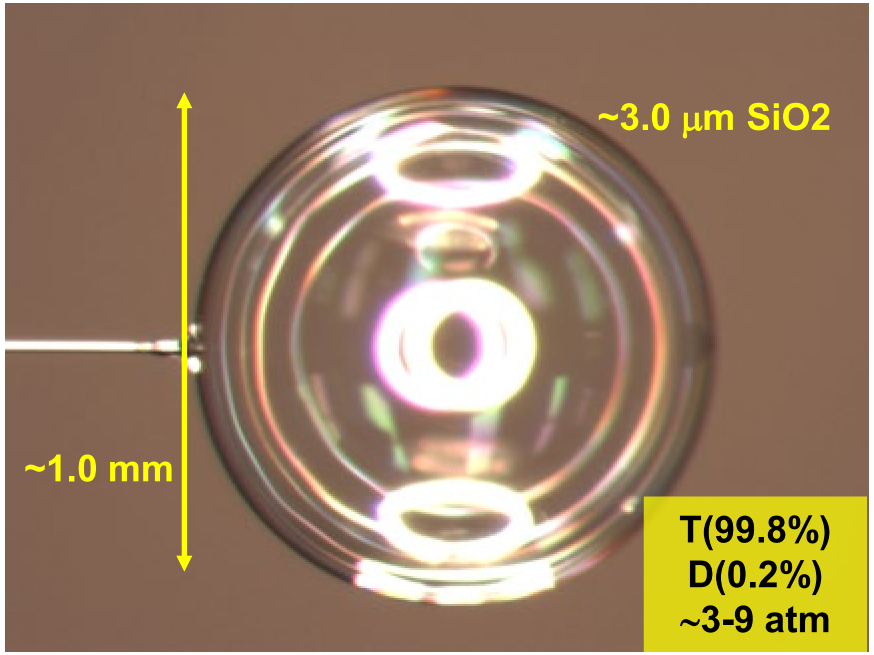


The Sayre and Wong spectra may indicate that the reaction mechanism is changing with E_G (ref 3), or the difference might be explained by an angular-distribution effect

---

[1] Sayre et al, PRL (2013).
[2] Wong et al, NP (1965).
[3] Bacher et al, FewBody Meeting (2015)

To address these questions, an OMEGA experiment was designed to probe the T+T spectrum over a range of Gamow-peak energies from 16 to 50 keV



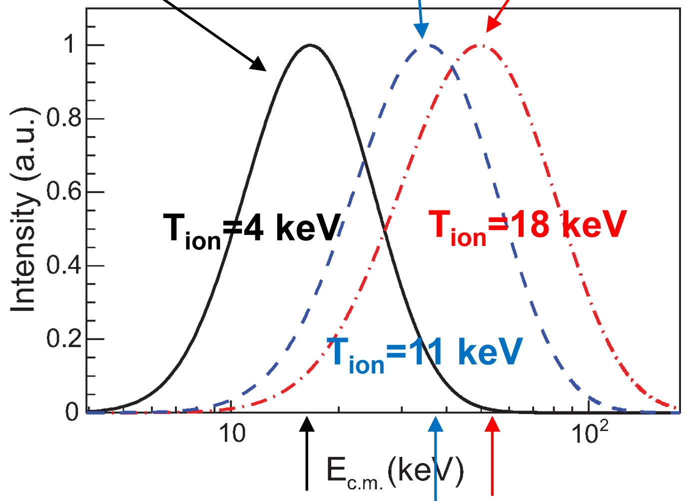
T(99.8%)
D(0.2%)
~3-9 atm

TT experiment team at LLE, July 2015

9 atm fill
0.6 ns square laser pulse
All beams to TCC

9 atm fill
2 ns ramped laser pulse
defocused beams

3 atm fill
0.6 ns square laser pulse
All beams to TCC



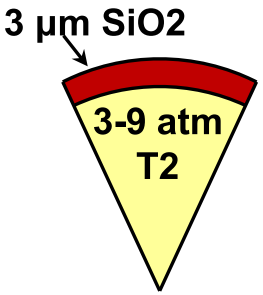
E_G=16 keV

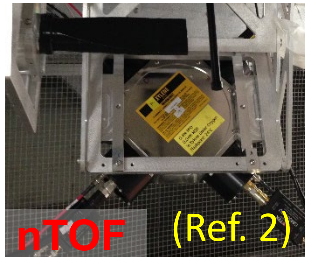
E_G=36 keV

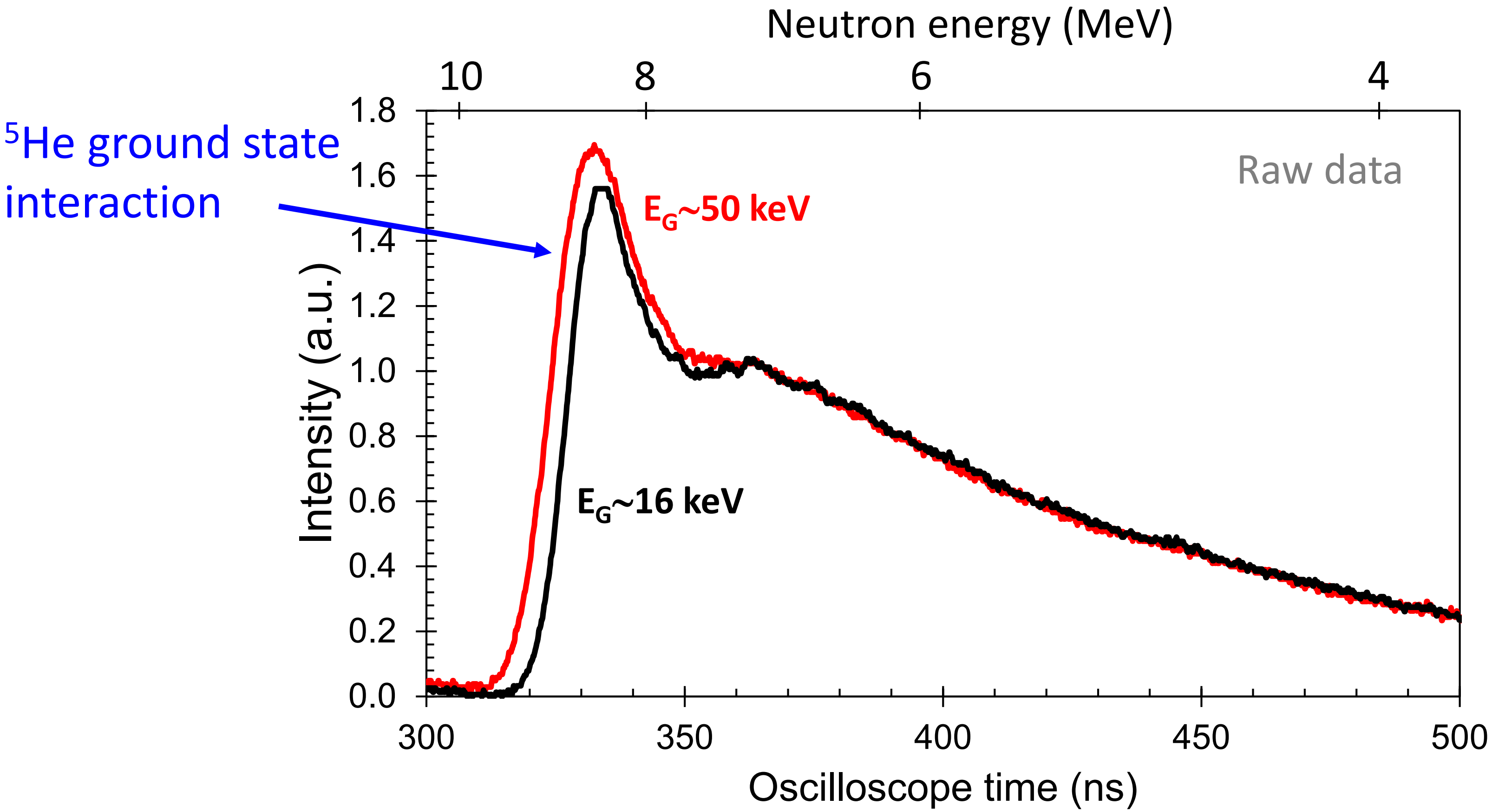
E_G=50 keV

Gatu Johnson et al., Phys. Plasmas 24, 041407 (2017)

The data set clearly indicates a difference in spectral shape as a function of Gamow peak energy[1)]







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[1] Gatu Johnson et al., PRL (2018)

[2] Neutron time-of-flight spectrometer, Forrest et al., RSI (2012, 2016)

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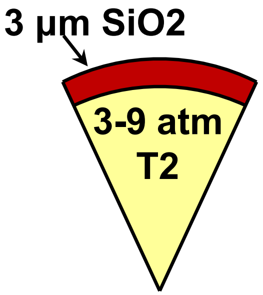

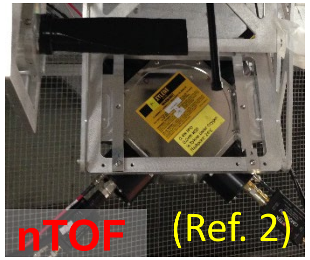

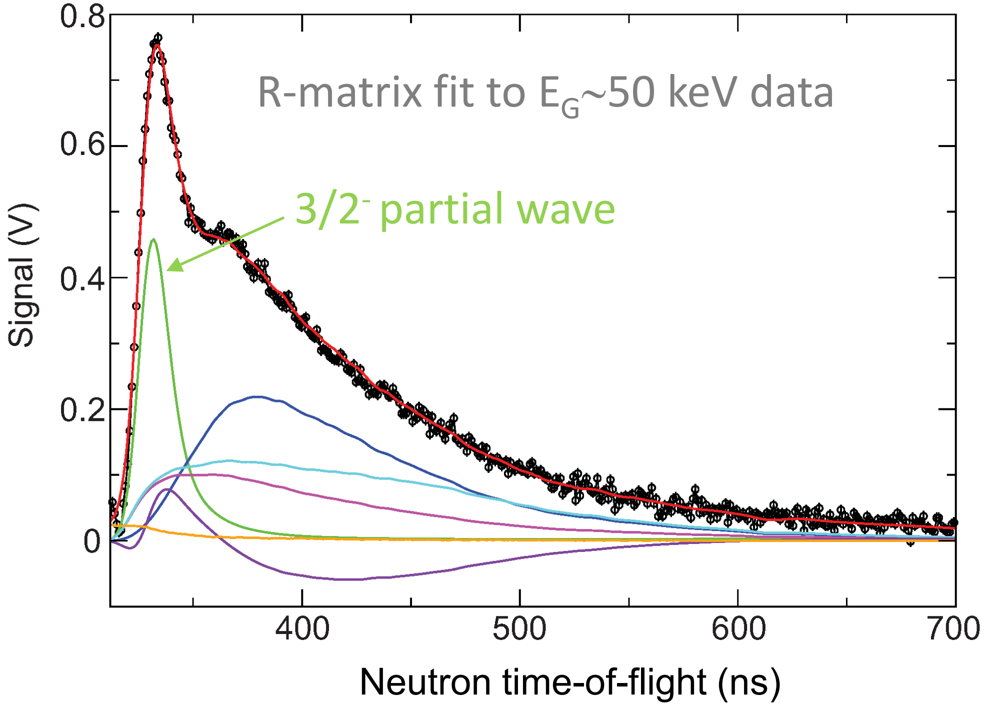

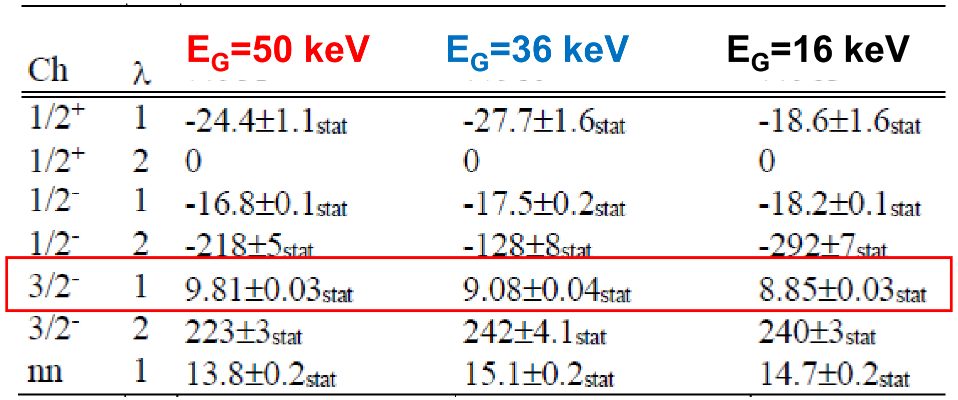

Ch	λ	E_G=50 keV	E_G=36 keV	E_G=16 keV
1/2$^+$	1	-24.4±1.1$_{stat}$	-27.7±1.6$_{stat}$	-18.6±1.6$_{stat}$
1/2$^+$	2	0	0	0
1/2$^-$	1	-16.8±0.1$_{stat}$	-17.5±0.2$_{stat}$	-18.2±0.1$_{stat}$
1/2$^-$	2	-218±5$_{stat}$	-128±8$_{stat}$	-292±7$_{stat}$
3/2$^-$	1	9.81±0.03$_{stat}$	9.08±0.04$_{stat}$	8.85±0.03$_{stat}$
3/2$^-$	2	223±3$_{stat}$	242±4.1$_{stat}$	240±3$_{stat}$
nn	1	13.8±0.2$_{stat}$	15.1±0.2$_{stat}$	14.7±0.2$_{stat}$

^{5}He ground state peak strength increases as a function of energy

---

[1] Gatu Johnson et al., PRL (2018)

[2] Neutron time-of-flight spectrometer, Forrest et al., RSI (2012, 2016)

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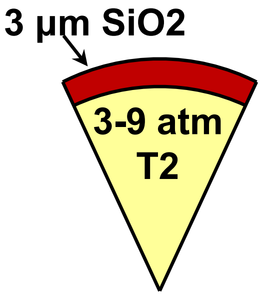

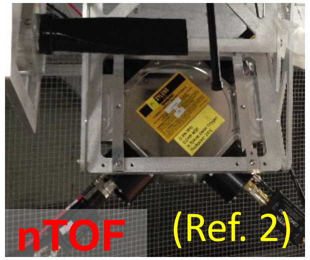

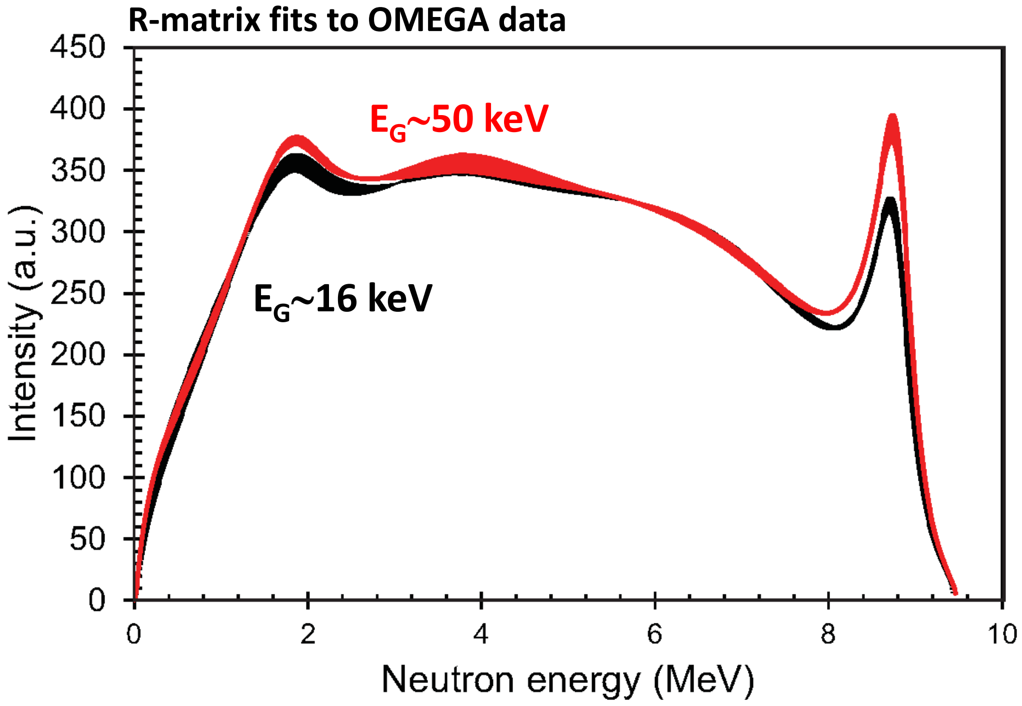

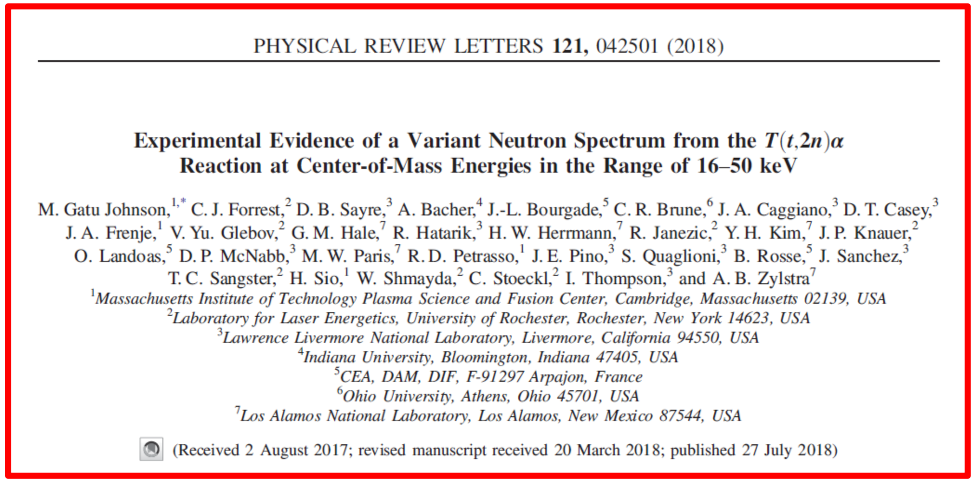

PHYSICAL REVIEW LETTERS **121,** 042501 (2018)

Experimental Evidence of a Variant Neutron Spectrum from the $T(t,2n)\alpha$ Reaction at Center-of-Mass Energies in the Range of 16–50 keV

M. Gatu Johnson,[1,*] C. J. Forrest,[2] D. B. Sayre,[3] A. Bacher,[4] J.-L. Bourgade,[5] C. R. Brune,[6] J. A. Caggiano,[3] D. T. Casey,[3] J. A. Frenje,[1] V. Yu. Glebov,[2] G. M. Hale,[7] R. Hatarik,[3] H. W. Herrmann,[7] R. Janezic,[2] Y. H. Kim,[7] J. P. Knauer,[2] O. Landoas,[5] D. P. McNabb,[3] M. W. Paris,[7] R. D. Petrasso,[1] J. E. Pino,[3] S. Quaglioni,[3] B. Rosse,[5] J. Sanchez,[3] T. C. Sangster,[2] H. Sio,[1] W. Shmayda,[2] C. Stoeckl,[2] I. Thompson,[3] and A. B. Zylstra[7]

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[7] *Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*

(Received 2 August 2017; revised manuscript received 20 March 2018; published 27 July 2018)

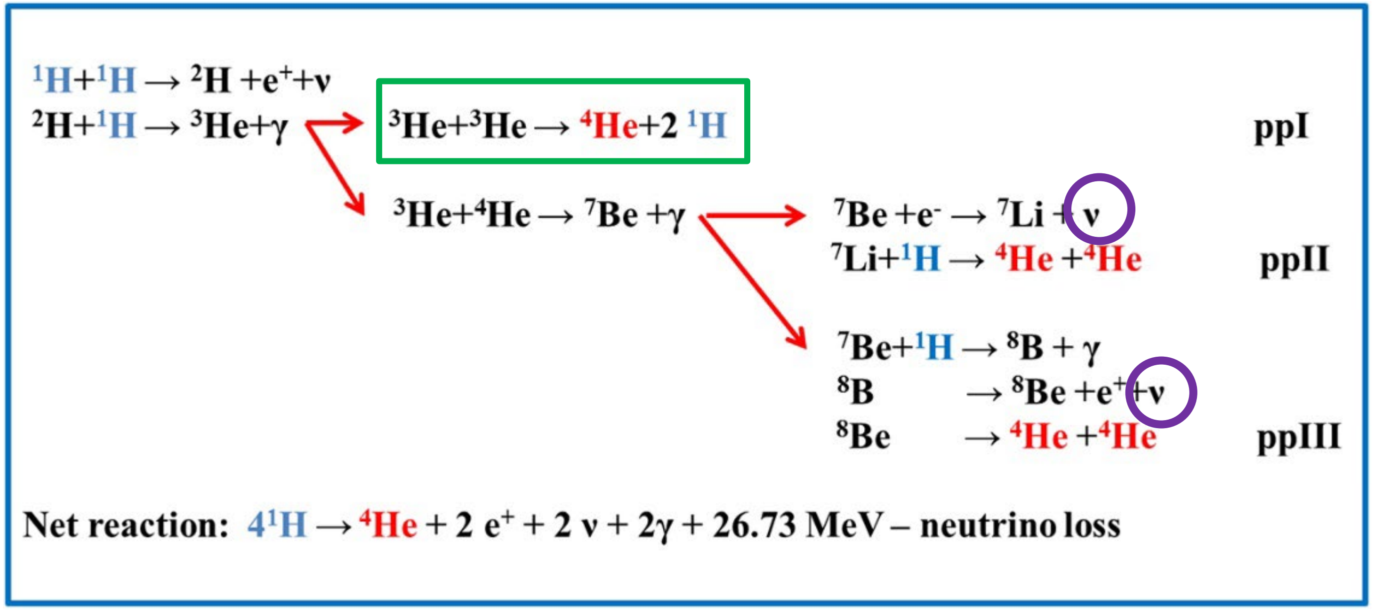
- R-matrix analysis assumes contributions from 0+ state (s-wave) only; p-wave may also contribute
- If this is the explanation, then it is likely that an energy dependence will exist also for the mirror $^3He+^3He$ reaction

---

[1] Gatu Johnson et al., PRL (2018)

[2] Neutron time-of-flight spectrometer, Forrest et al., RSI (2012, 2016)

The S-factor for the ^{3}He^{3}He reaction impacts the ppI/(ppII+ppIII) branching ratio, and provides an important constraint on neutrino physics[1)]



${}^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu$

${}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$ **ppI**

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu$

${}^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$ **ppII**

${}^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu$

${}^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$ **ppIII**

Net reaction: $4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\,\nu + 2\gamma + 26.73$ **MeV – neutrino loss**

Uncertainty in the ^{3}He^{3}He S-factor directly impacts uncertainty in calculated neutrino fluxes from solar models

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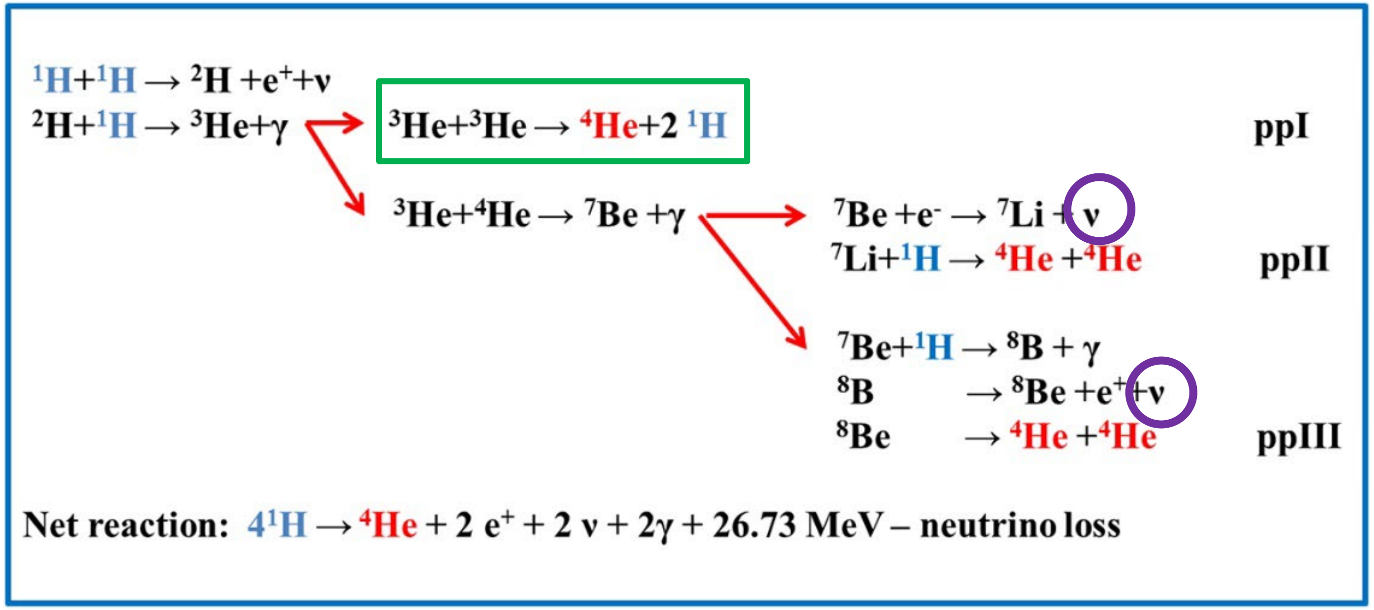
[1)] Vinyoles, Ap. J 2017

[2)] Brune, Solar Fusion III workshop, 2022

The S-factor for the ^{3}He^{3}He reaction impacts the ppI/(ppII+ppIII) branching ratio, and provides an important constraint on neutrino physics1)



$^{1}\mathrm{H}+{}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu$

$^{2}\mathrm{H}+{}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$

$^{3}\mathrm{He}+{}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$ ppI

$^{3}\mathrm{He}+{}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

$^{7}\mathrm{Be}+e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu$

$^{7}\mathrm{Li}+{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$ ppII

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Net reaction: $4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\,\nu + 2\gamma + 26.73$ MeV – neutrino loss

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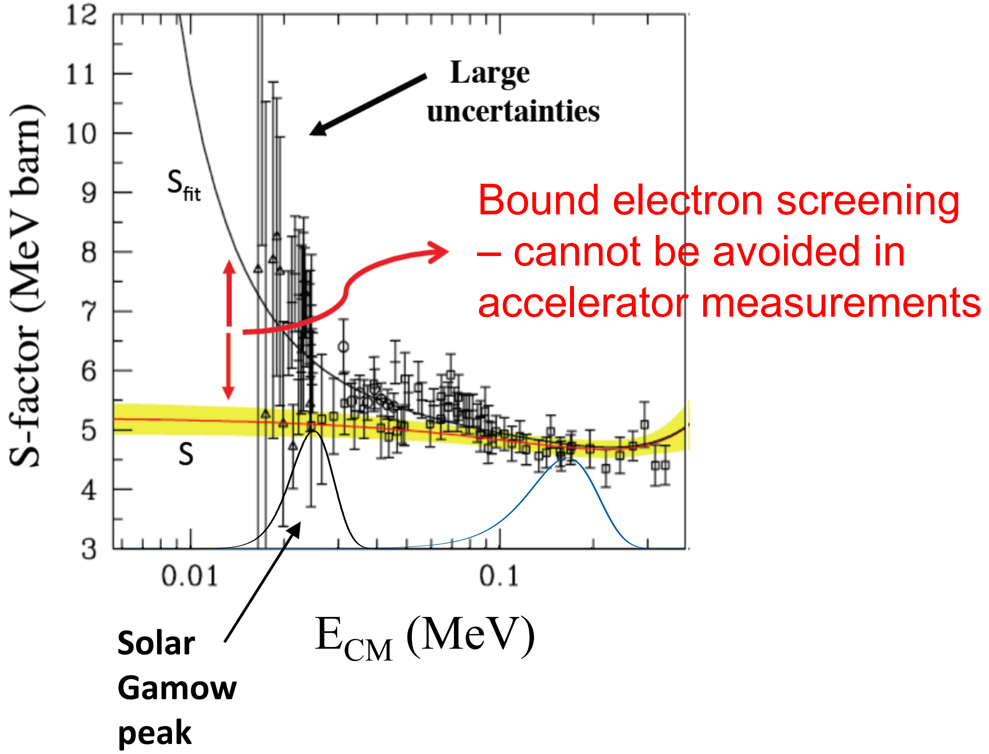
Adelberger et al., Rev. Mod. Phys 83, 2011



Accelerator S-factor measurements assume a spectral shape for the ^{3}He+^{3}He proton spectrum which is most likely inaccurate2)

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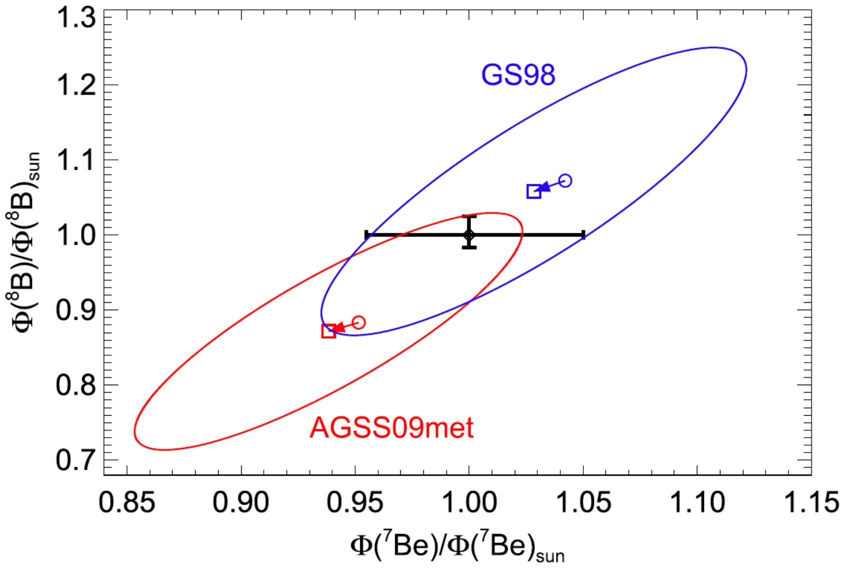
1)Vinyoles, Ap. J 2017

2)Brune, Solar Fusion III workshop, 2022

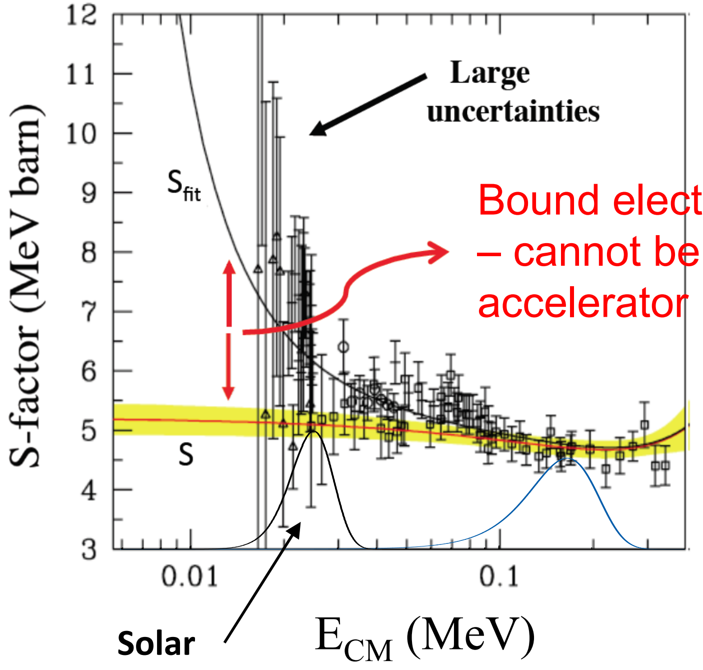
The S-factor for the ^{3}He^{3}He reaction impacts the ppI/(ppII+ppIII) branching ratio, and provides an important constraint on neutrino physics$^{1)}$

Vinyoles, Ap. J 2017



Current assumed ±5.2% uncertainty on solar ^{3}He^{3}He S-factor has a 2.3% impact on the calculated solar neutrino flux

Adelberger et al., Rev. Mod. Phys 83, 2011



Bound electron screening – cannot be avoided in accelerator measurements

Solar Gamow peak

Accelerator S-factor measurements assume a spectral shape for the ^{3}He+^{3}He proton spectrum which is most likely inaccurate$^{2)}$

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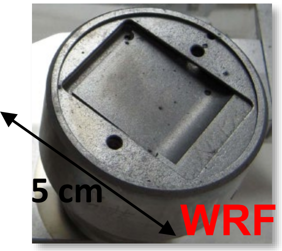
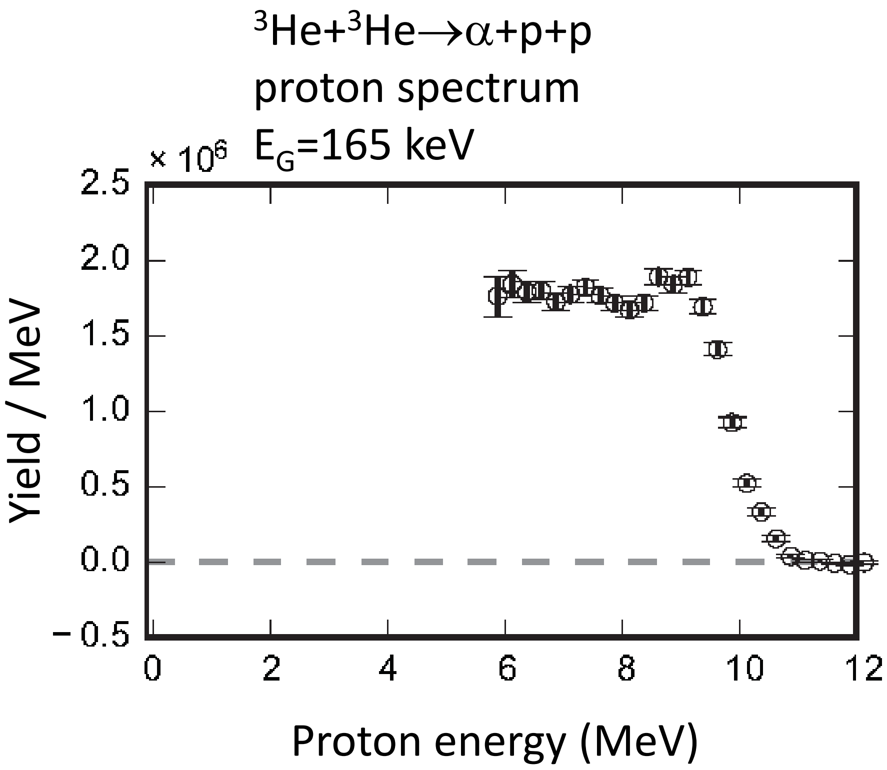
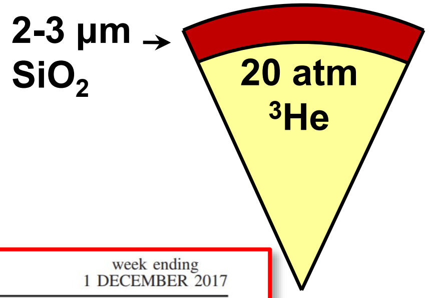
1)Vinyoles, Ap. J 2017

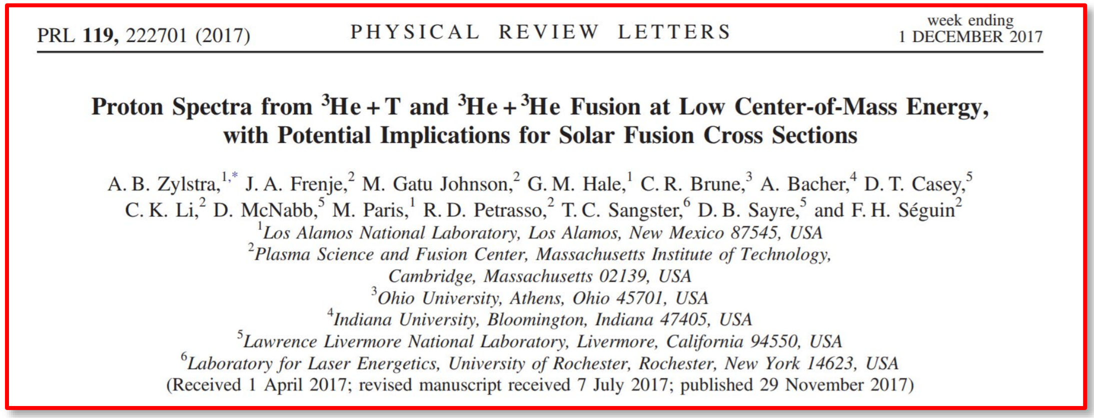
2)Brune, Solar Fusion III workshop, 2022

Initial measurements of the $^3He+^3He$ proton spectrum have been made at OMEGA at E_G=165 keV




$^3He+^3He \rightarrow \alpha+p+p$
proton spectrum
E_G=165 keV




PRL **119,** 222701 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Proton Spectra from ^3He+T and $^3He+^3He$ Fusion at Low Center-of-Mass Energy, with Potential Implications for Solar Fusion Cross Sections

A. B. Zylstra,[1,*] J. A. Frenje,[2] M. Gatu Johnson,[2] G. M. Hale,[1] C. R. Brune,[3] A. Bacher,[4] D. T. Casey,[5] C. K. Li,[2] D. McNabb,[5] M. Paris,[1] R. D. Petrasso,[2] T. C. Sangster,[6] D. B. Sayre,[5] and F. H. Séguin[2]
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[2]*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Ohio University, Athens, Ohio 45701, USA*
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[5]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[6]*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*
(Received 1 April 2017; revised manuscript received 7 July 2017; published 29 November 2017)

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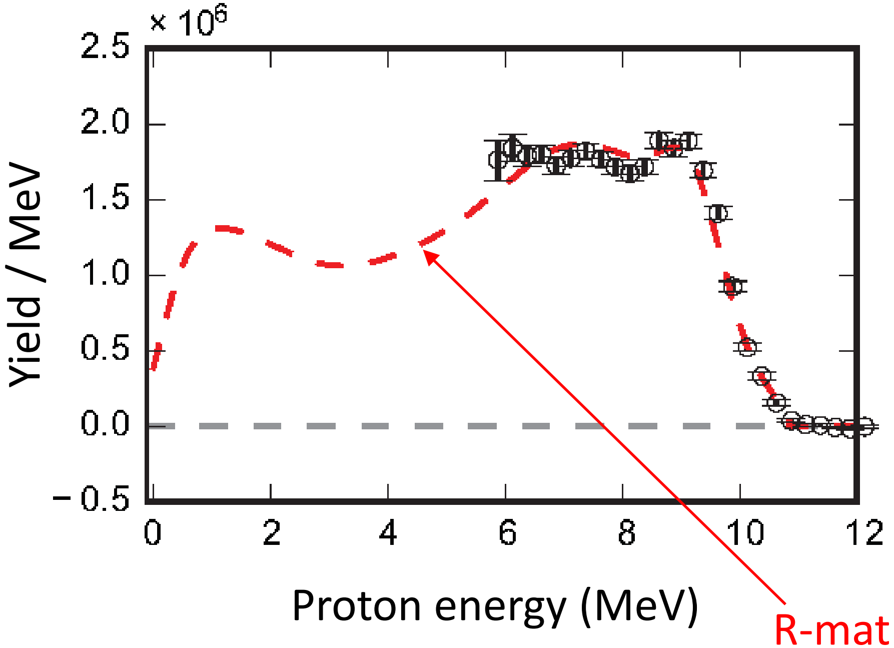
[1] Zylstra et al., PRL (2017)
[2] Wedge-Range Filter proton spectrometer, Séguin et al., RSI (2003)
[3] Magnetic Recoil Spectrometer, Frenje et al., RSI (2008)
[4] Charged Particle Spectrometer, Hicks, MIT PhD thesis (1999)

These initial ^{3}He+^{3}He OMEGA measurements indicate differences compared to T+T results

$^3He+^3He \rightarrow \alpha+p+p$

E_G=165 keV



R-matrix analysis with feeding factors based on Wong T+T data

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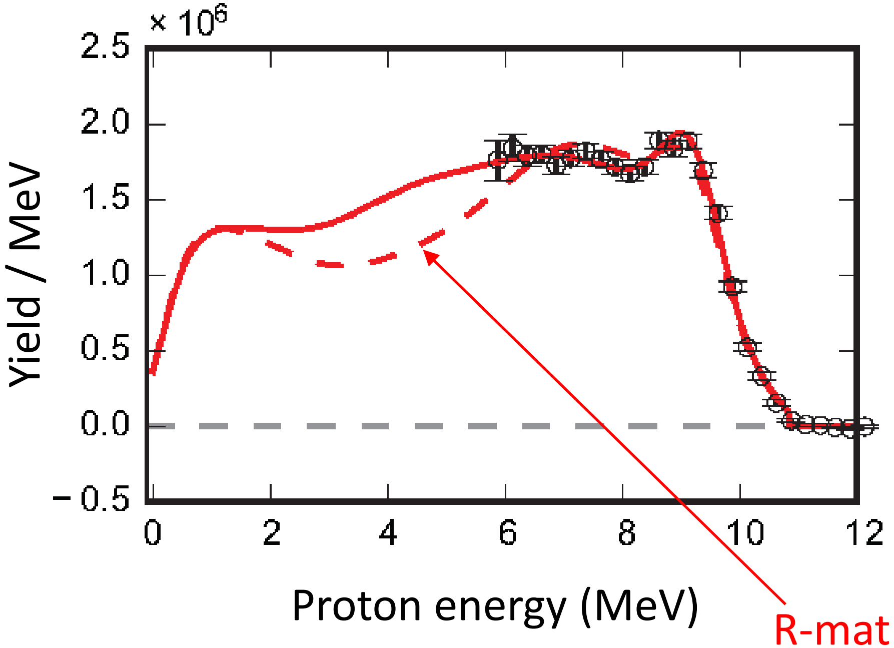

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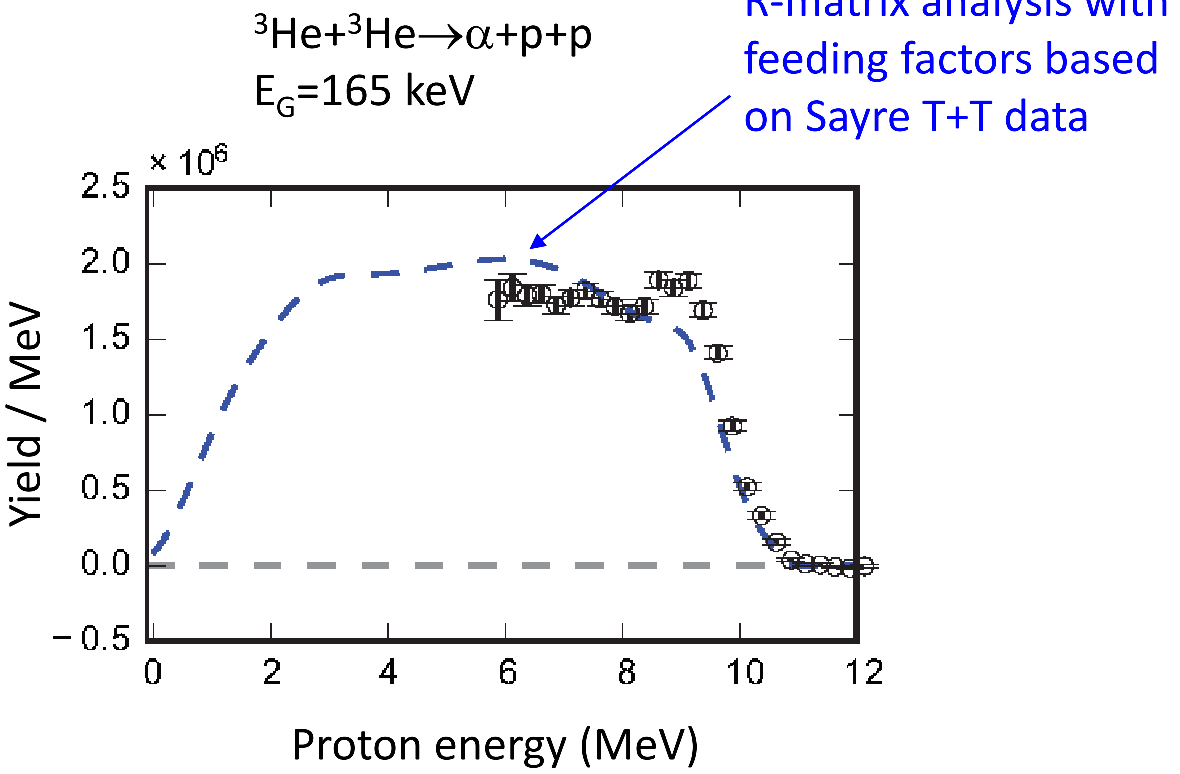
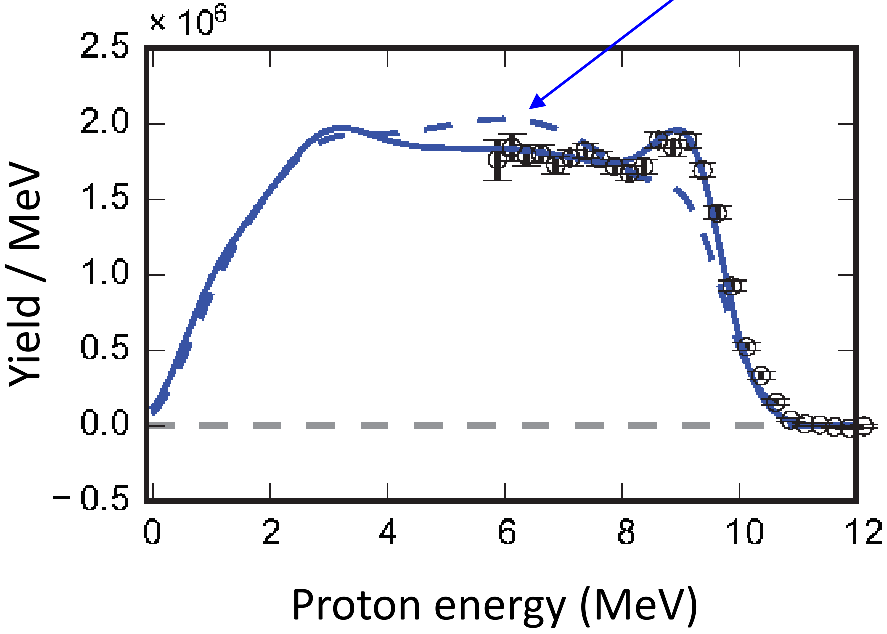


R-matrix analysis with feeding factors based on Sayre T+T data

These initial ^{3}He+^{3}He OMEGA measurements indicate differences compared to T+T results

^{3}He+^{3}He→α+p+p
E_G=165 keV

R-matrix analysis with feeding factors based on Sayre T+T data



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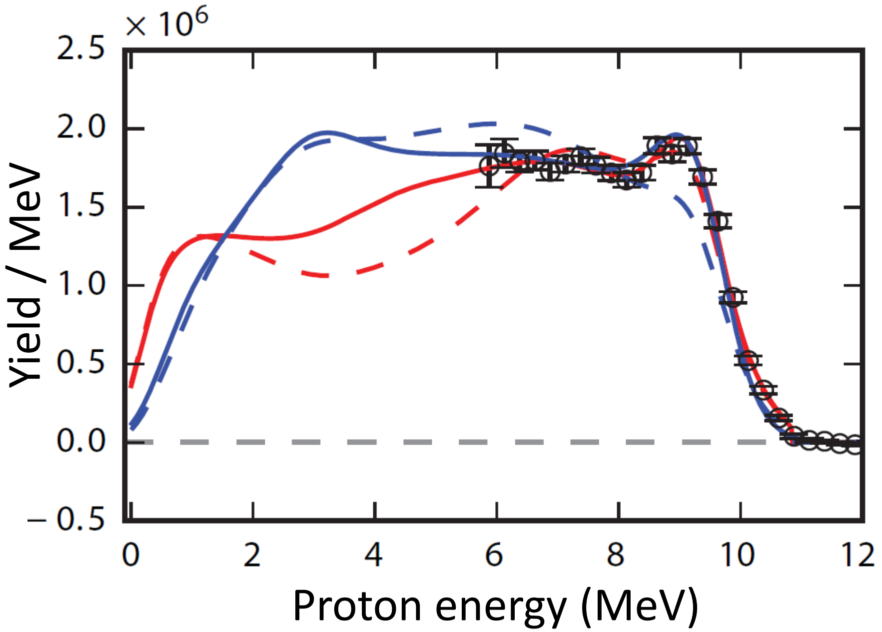


There are also differences between the two R-matrix models

These results illustrate the poor understanding of few-body reactions.

- Are the differences due to an E_G dependence?
- If so, what would this imply for the ^{3}He^{3}He cross section?
    - S-factor inferred from accelerator data can vary 8% depending on spectral model used

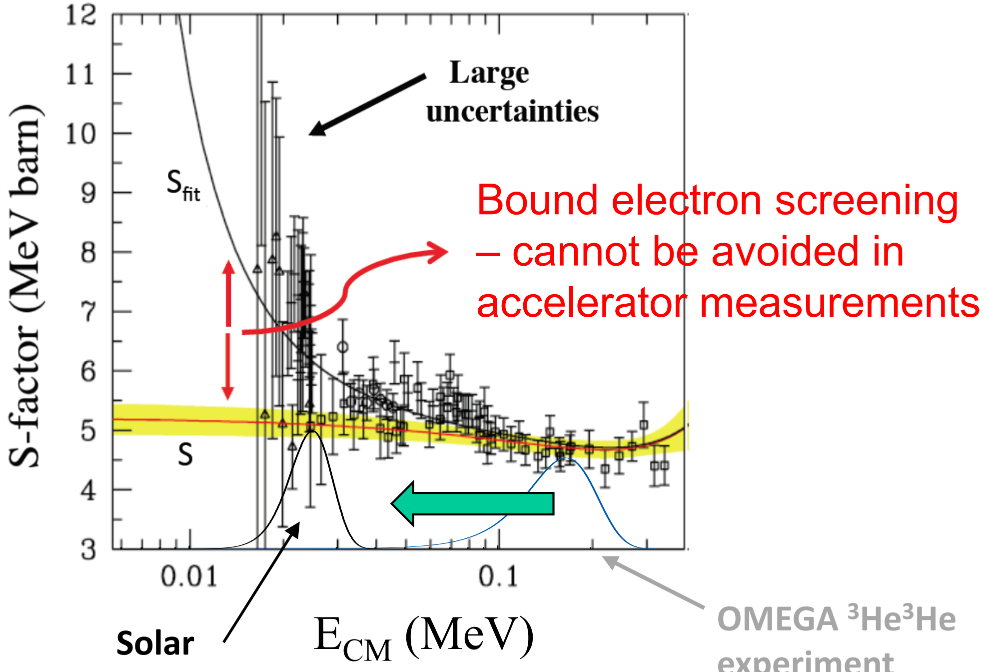
Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a nascent field with much potential

- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions
- Recent experiments have provided the first exciting results on the solar ^{3}He+^{3}He, BBN-relevant T+^{3}He and complementary T+T reactions
- Ongoing efforts focus on probing the solar $^3\mathrm{He}^3\mathrm{He}\rightarrow\alpha+p+p$ reaction at more stellar-relevant conditions (OMEGA E_G=165 keV, solar E_G=21 keV) and at lower proton energy
- Future work includes developing the platform for CNO-relevant measurements (e.g., the p+^{15}N-α/γ branching ratio) and for studying neutron capture on s-process branch-point nuclei

Next steps in the ^{3}He+^{3}He effort are to push to more solar-relevant energies, and to measure the proton spectrum at lower energy

A DS experiment leverages NIF to push towards solar-relevant Gamow-peak energies:

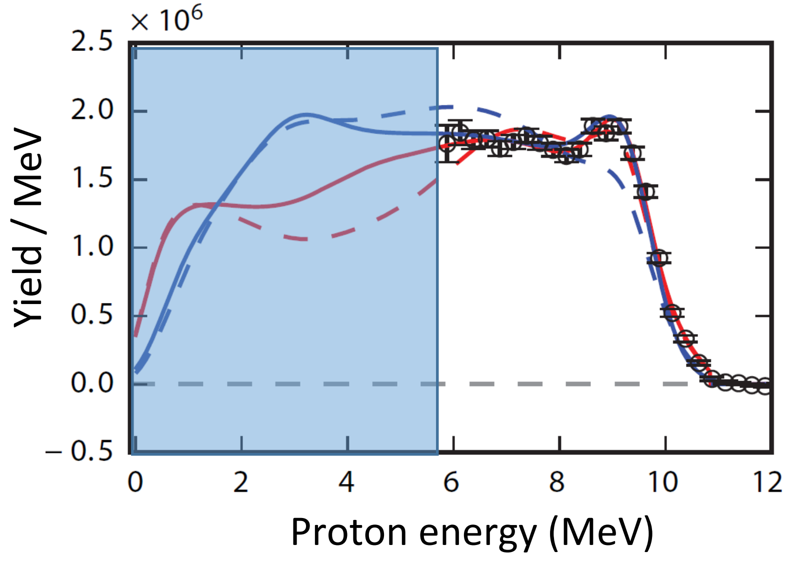
Adelberger et al., Rev. Mod. Phys 83, 2011



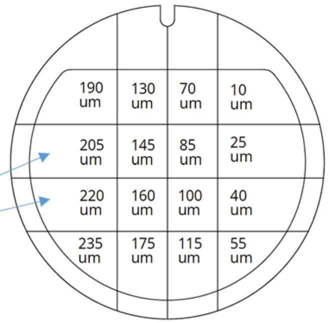
Solar Gamow peak

OMEGA ^{3}He^{3}He experiment (E_G=165 keV)

An OMEGA experiment leverages new detector technology to push to lower proton energy:

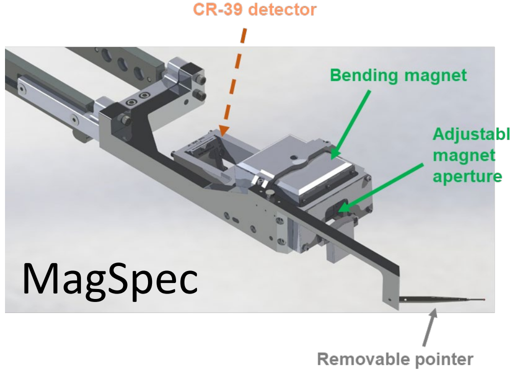


New optimized Step Range Filter (SRF) design:*

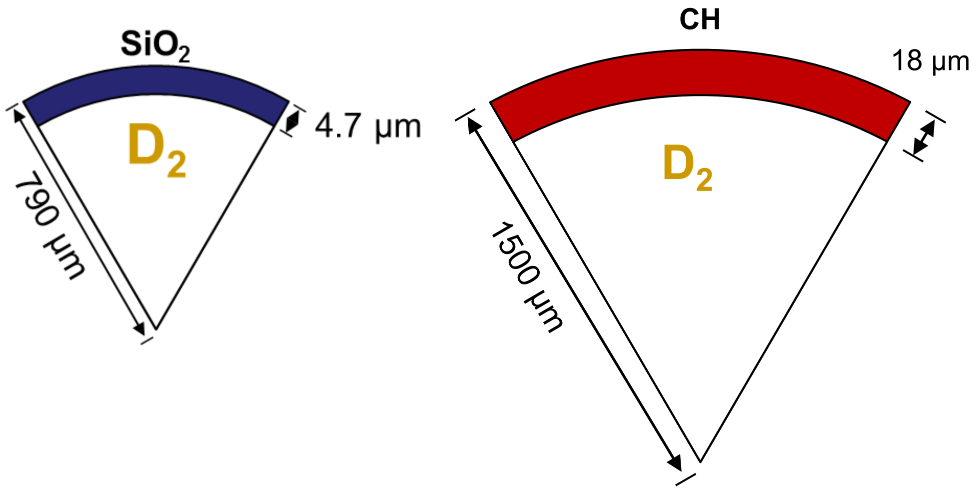


190 um	130 um	70 um	10 um
205 um	145 um	85 um	25 um
220 um	160 um	100 um	40 um
235 um	175 um	115 um	55 um

Tantalum steps fielded in front of CR39



The NIF experiments leverage the higher laser energy available at NIF to drive larger capsules, producing enough yield at lower T_{ion}/E_{cm}



$Y \sim n_1 \times n_2 \times <\sigma v(T_{ion})> \times V \times t$

Gatu Johnson et al., Phys. Plasmas (2018)

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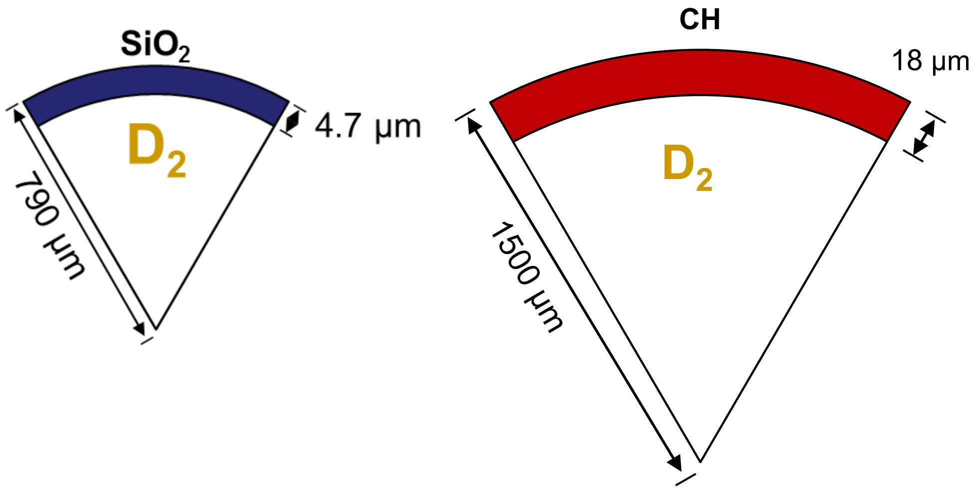
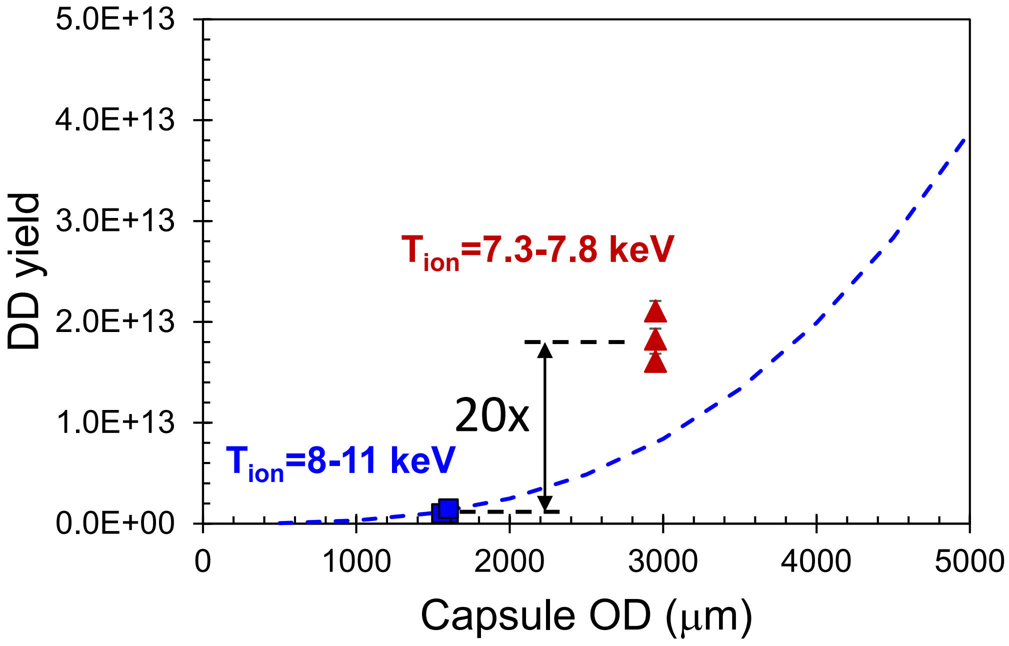


$Y \sim n_1 \times n_2 \times \langle\sigma v(T_{ion})\rangle \times V \times t$



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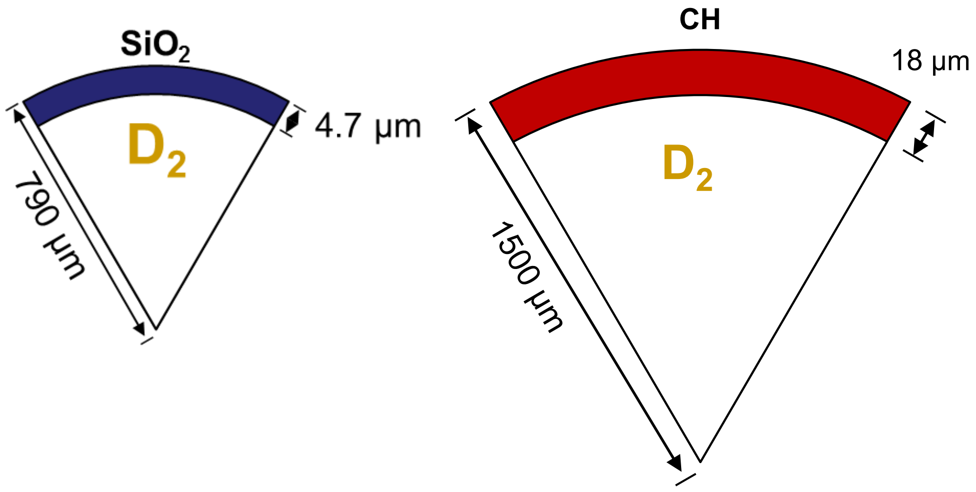

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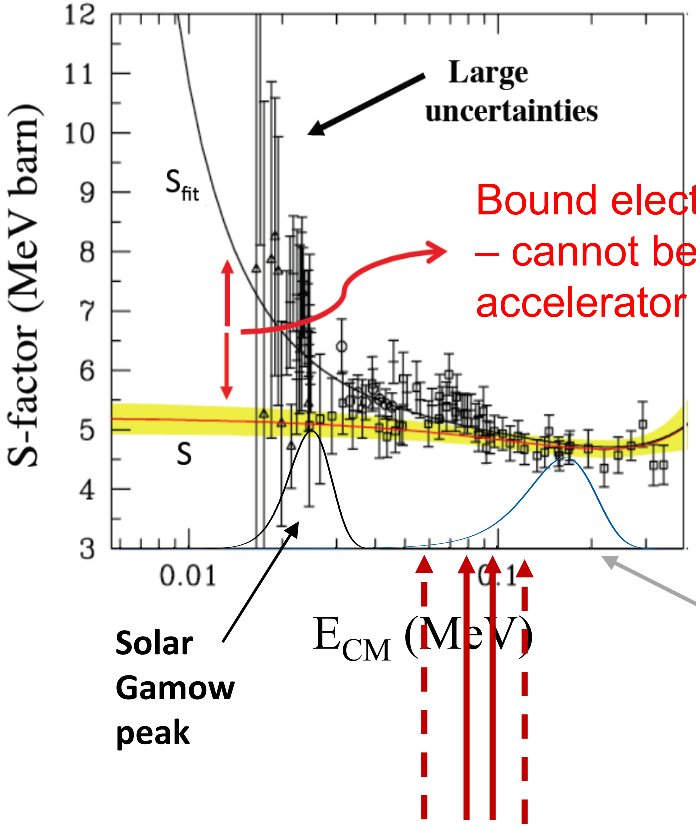


Large uncertainties

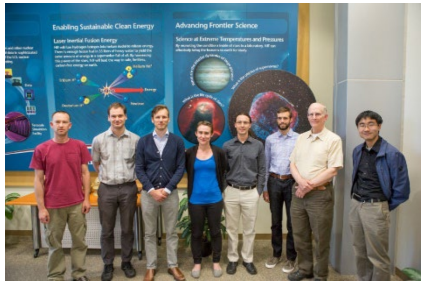
Bound electron screening – cannot be avoided in accelerator measurements

Solar Gamow peak

OMEGA ^{3}He^{3}He experiment (E_G=165 keV)

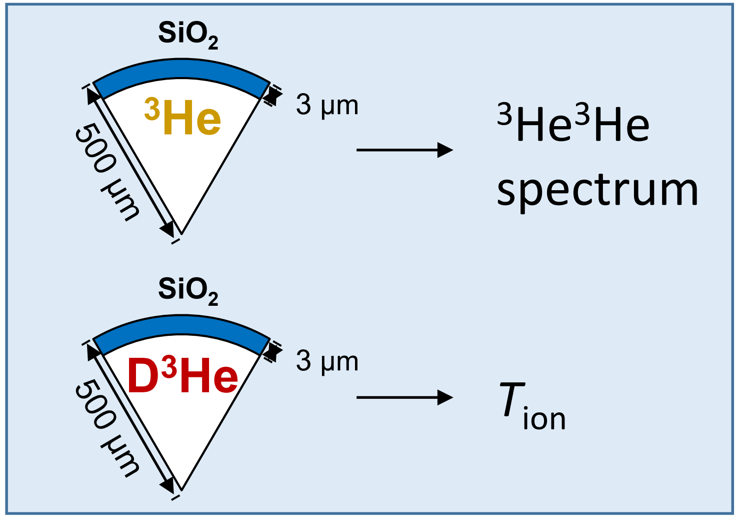
NIF measurements

Experiments relied on WRF as the primary diagnostic



Gatu Johnson et al., Phys. Plasmas (2018)

The more recent OMEGA experiments were specifically intended to obtain proton data at lower energy using new detectors



TIM	Diag (3He/D3He)
TIM1	Framing camera
TIM2	Trident: **WRFx2, SRF**
TIM3	**MagSpec**
TIM4	**WRF**
TIM5	**SRF**/PXTD
TIM6	**SRF**/Clear LOS

Implosion platform optimized for high yield and minimal spectral distortion[1)]

Shot #	Fill type	6-11 MeV yield*	D^{3}He yield*	DD yield**	DD T_{ion} (keV)
101917	^{3}He	2.0e7	-	-	
101918	^{3}He	2.2e7	-	-	
101919	^{3}He	1.0e8	-	-	
101921	^{3}He	7.4e7	-	-	
101922	D^{3}He	-	2.4e10	~1e9	
101923	D^{3}He	-	2.7e10	~1e9	16.5±0.5

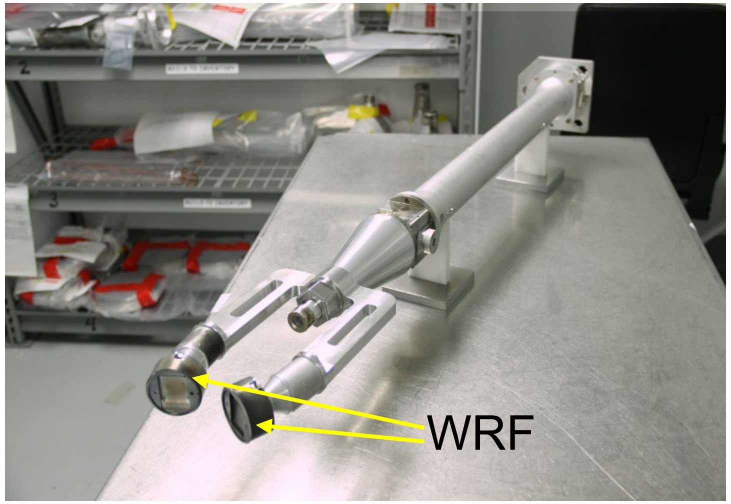
*Based on average of TIM2 POS4 and POS12 WRF data, fielded 26cm from TCC
**Yield lower than predicted → larger uncertainty, and T_{ion} measurement only worked on 101923

[1)] Gatu Johnson et al., Phys. Plasmas (2017)

Three high-efficiency proton spectrometers are being leveraged to measure the ^{3}He+^{3}He proton energy spectrum

Wedge-range-filters (WRF)

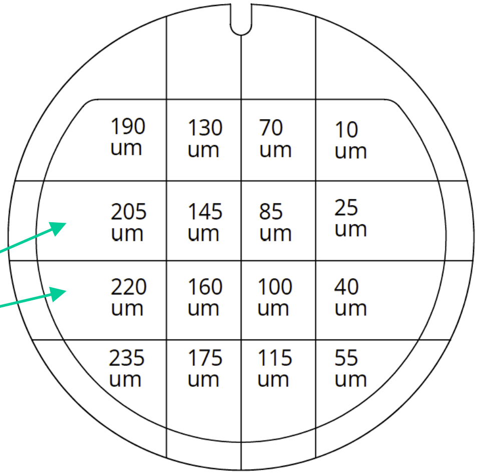
Low-energy cut-off: ~5 MeV



Step-range-filters (SRF)

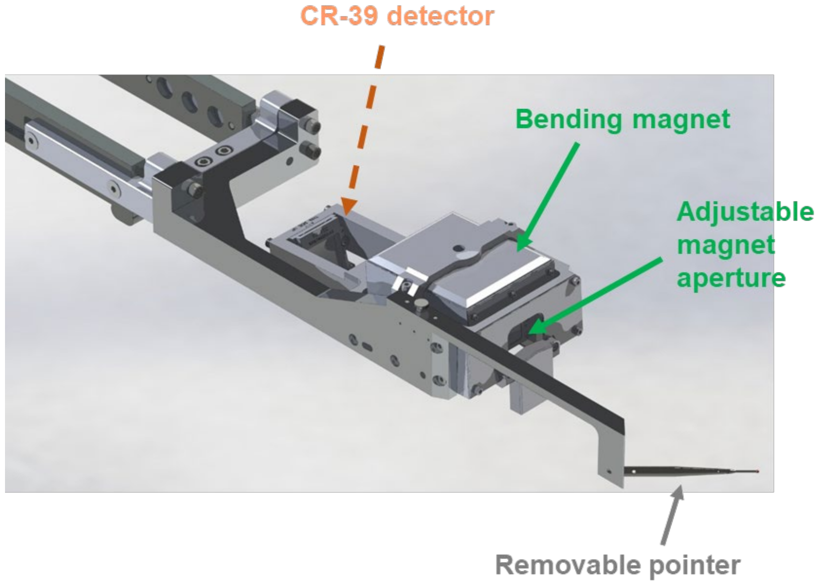
New optimized Step Range Filter (SRF) design:*

Tantalum steps fielded in front of CR39



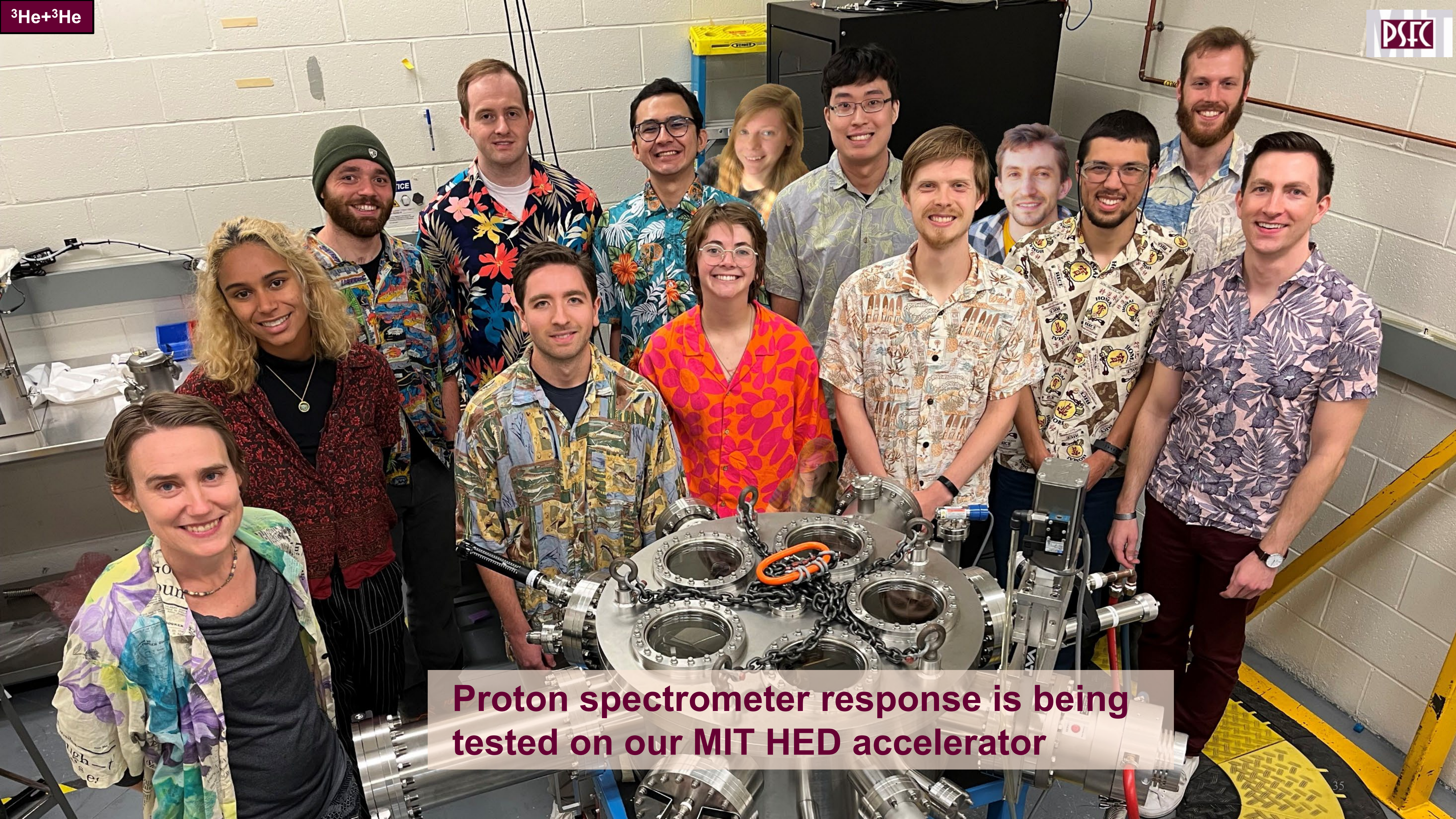
190 um	130 um	70 um	10 um
205 um	145 um	85 um	25 um
220 um	160 um	100 um	40 um
235 um	175 um	115 um	55 um

Magnetic Spectrometer (MagSpec)



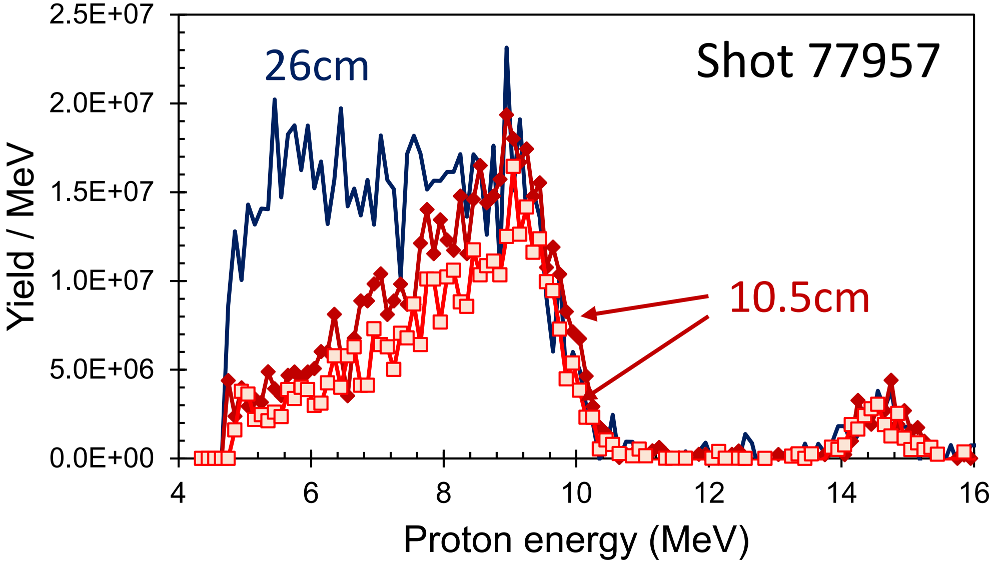
WRF analysis for NIF shots:
Brandon Lahmann and Justin Kunimune

^{3}He+^{3}He



Proton spectrometer response is being tested on our MIT HED accelerator

WRF spectrometers have been used as a workhorse for many years, but recent data raise questions about impact of x-rays on response



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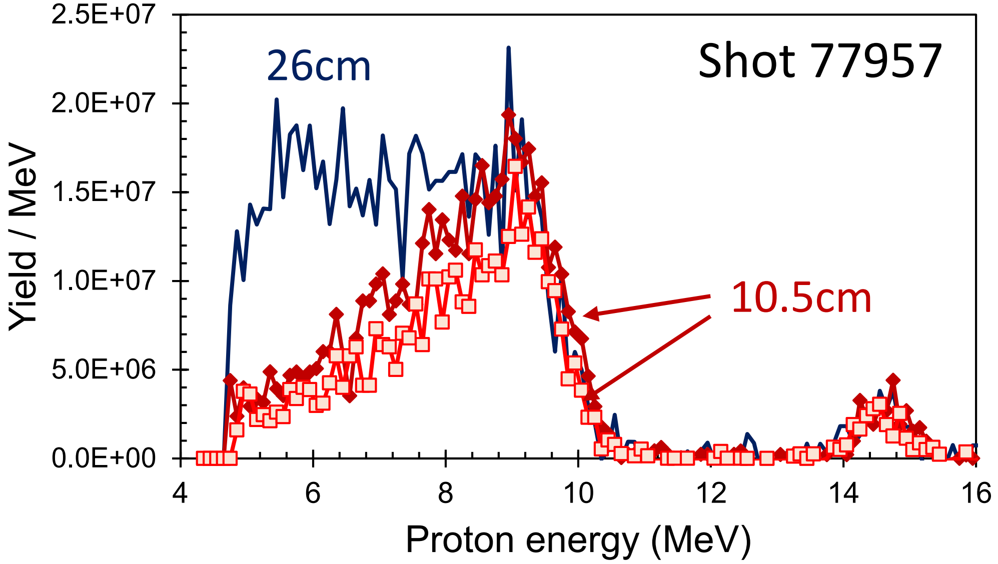
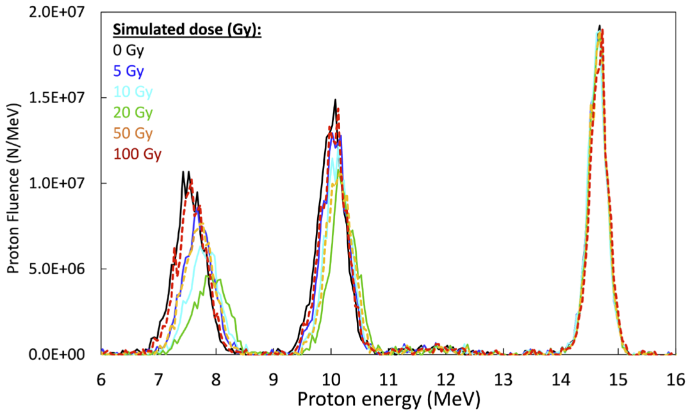


Rinderknecht et al., RSI 86, 123511 (2015):



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^{3}He+^{3}He

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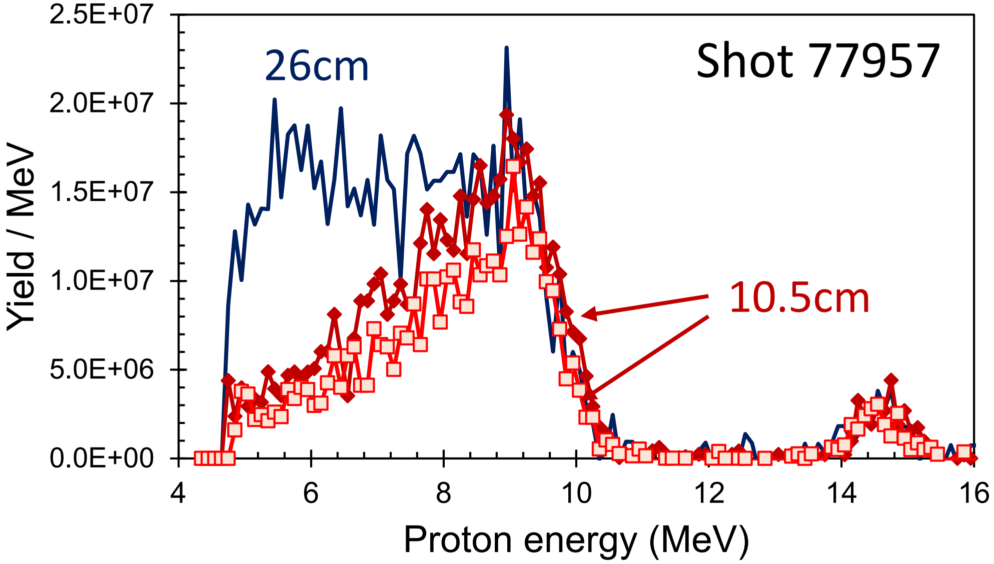

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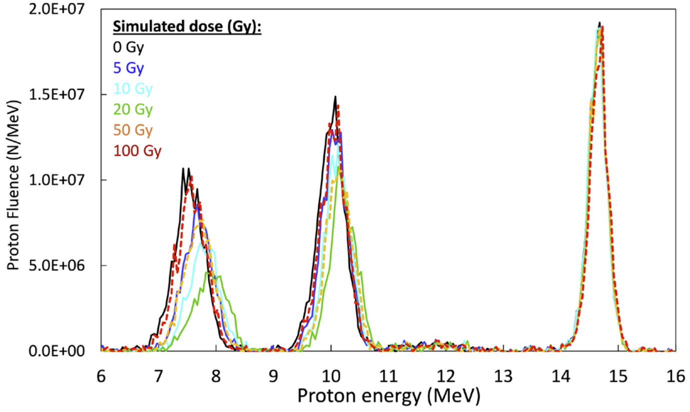
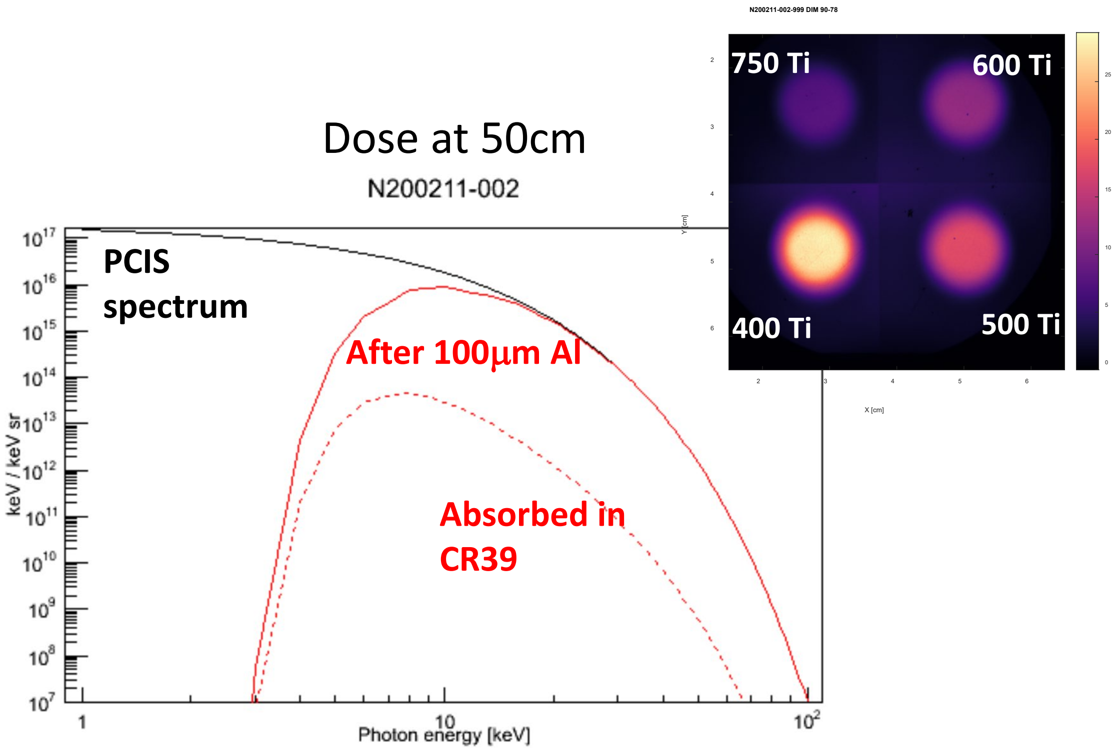


X-ray dose and energy spectrum inferred from x-ray penumbral imaging (PCIS) data obtained on NIF shots:



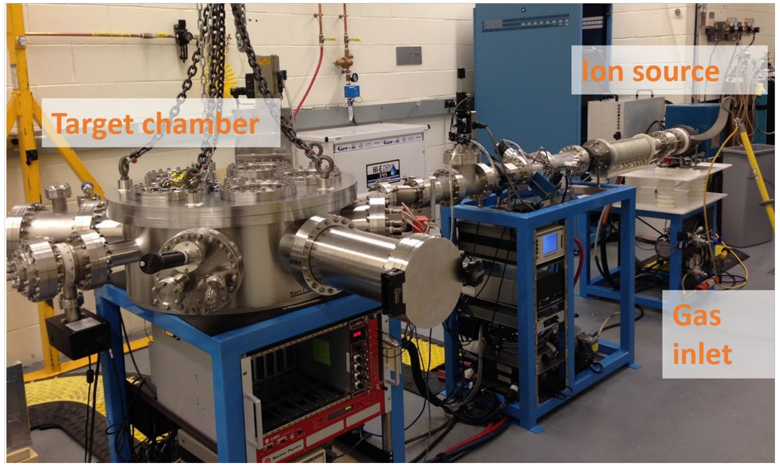
Total dose 11.0 Gy
(Total dose at 10cm: 275 Gy)

WRF analysis for NIF shots:
Brandon Lahmann and Justin Kunimune

Question about x-ray impact on WRF response is being addressed in the MIT accelerator lab

MIT x-ray source

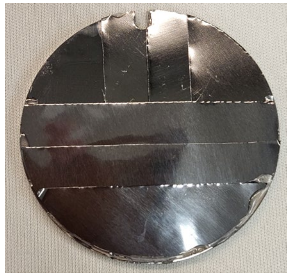
MIT Linear Electrostatic Ion Accelerator (LEIA)



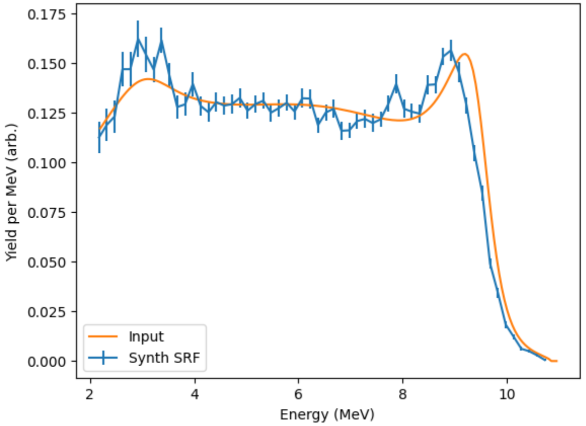
- Use x-ray source to expose assembly to x-rays
- Use accelerator to add protons at three different energies

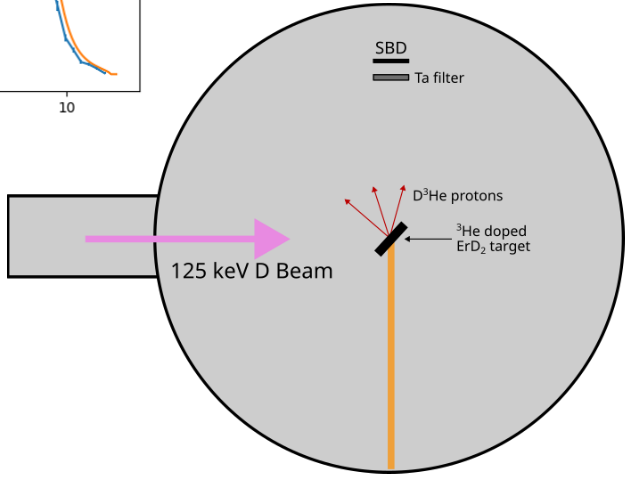
- **Critical to know x-ray dose**
  - **Skylar is working on this using a ^{241}Am source, image plates, and a new image plate scanner**

An SRF design optimized for ^{3}He+^{3}He proton measurements was developed for the OMEGA campaign; its response is being characterized



- A 16-step filter design is used for maximal energy coverage
- A Monte Carlo simulation toolkit was developed to simulate SRF response
- Results are being compared to accelerator exposures for validation





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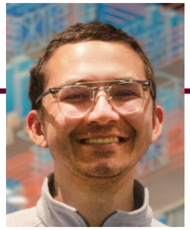
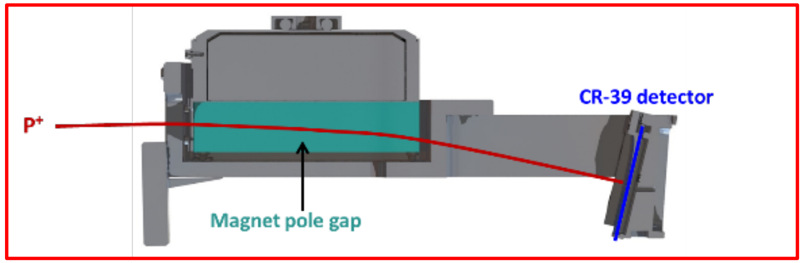
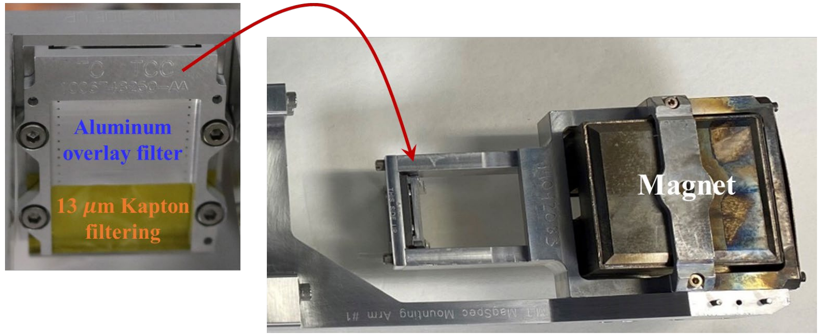
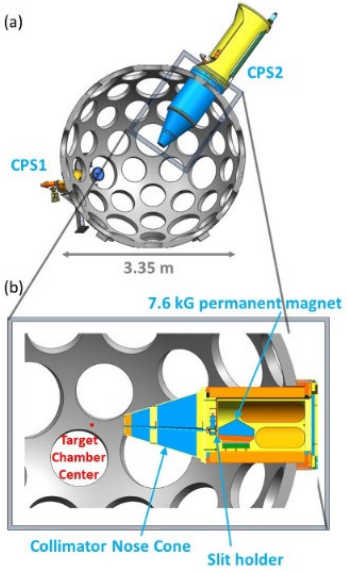
*T.M. Johnson et al., in preparation for Rev. Sci. Instrum. (2023)

The new MagSpec* detector is now available for use at both OMEGA and the NIF, with in-situ calibration efforts ongoing at OMEGA

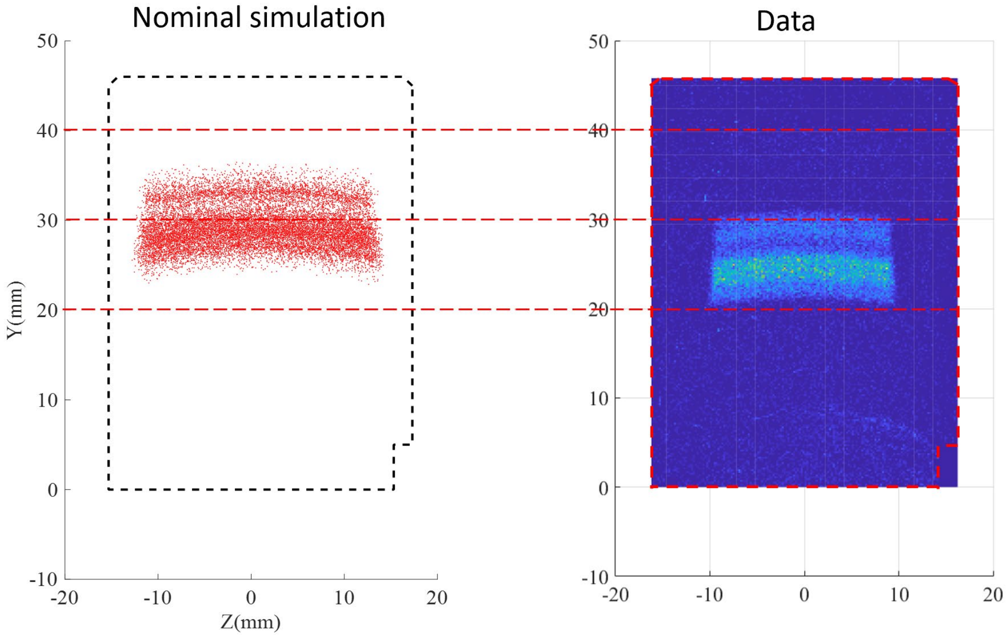








Adrian et al., Rev. Sci. Instrum. (2022)



MagSpec was first fielded on the 2020 NIF DS campaign, but due to a design problem the D^{3}He protons interfere with the ^{3}He^{3}He spectrum for that initial implementation

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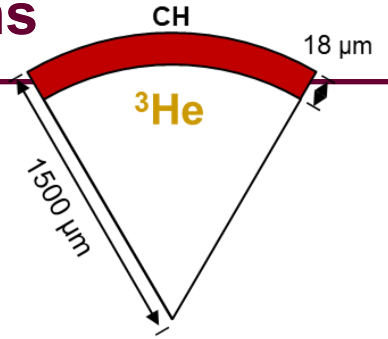
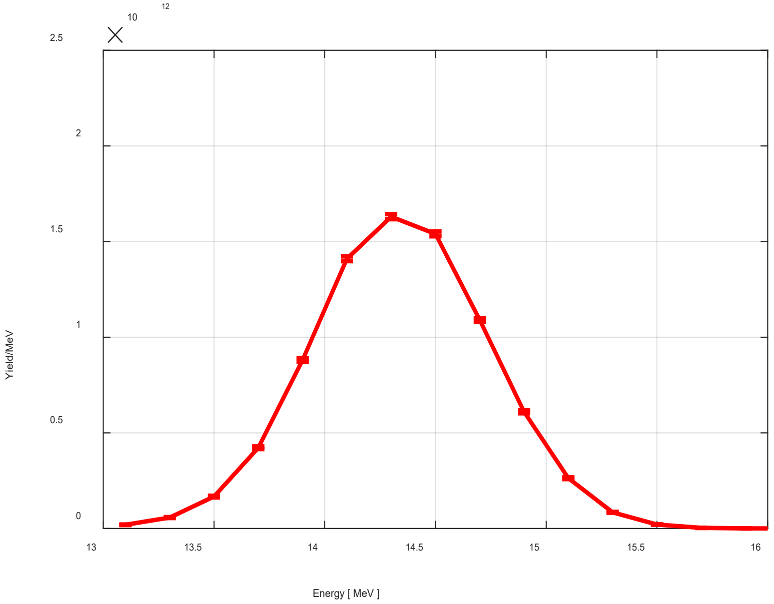
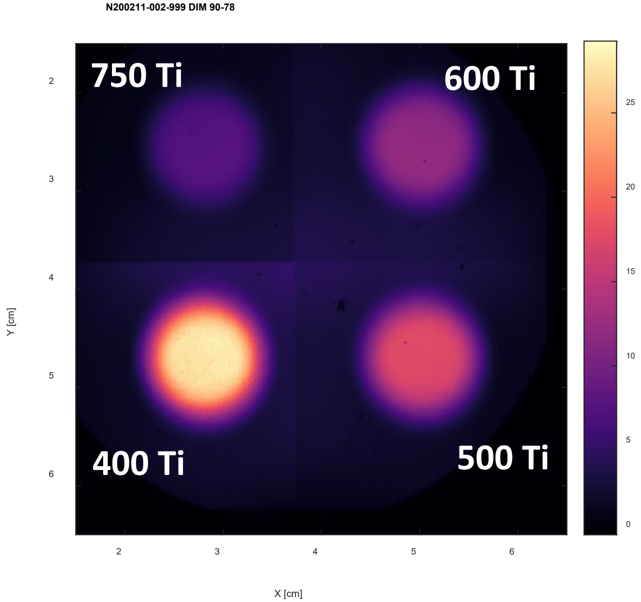
*J. Pearcy et al., to be submitted to Rev. Sci. Instrum. (2023)

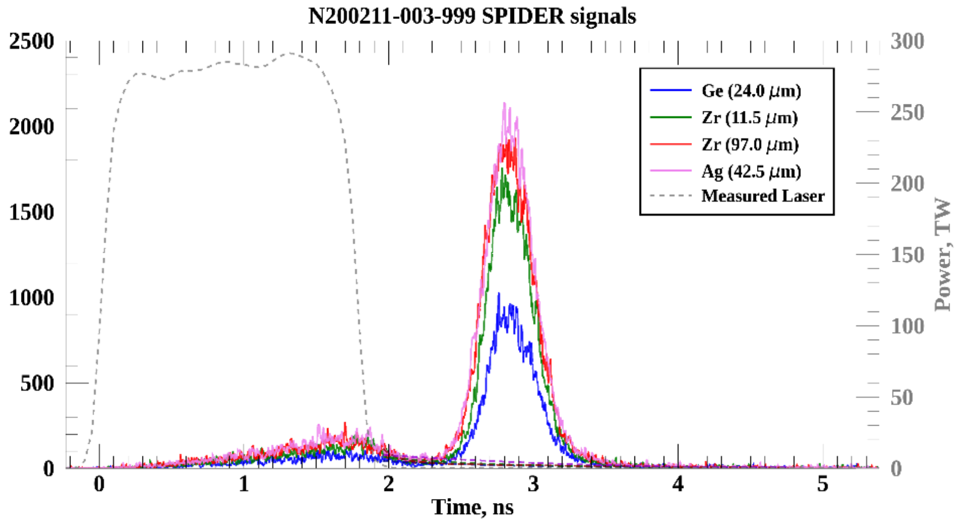
Measured proton spectra, differentially filtered x-ray penumbral imaging, and x-ray burn history are being used[1] to constrain NIF implosion conditions



Average WRF Measurements for N200211-003 (19% D content)







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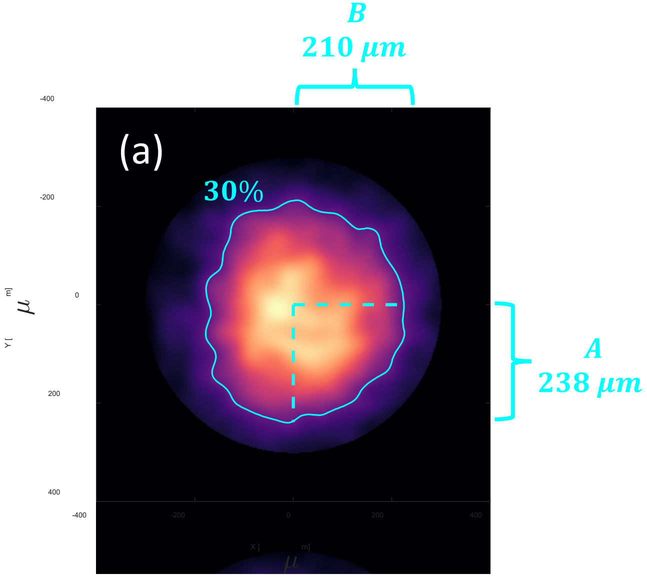
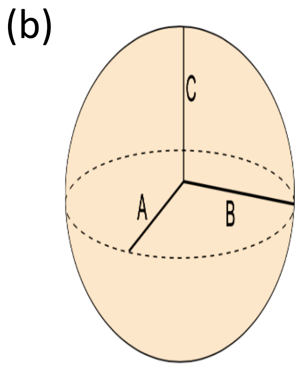
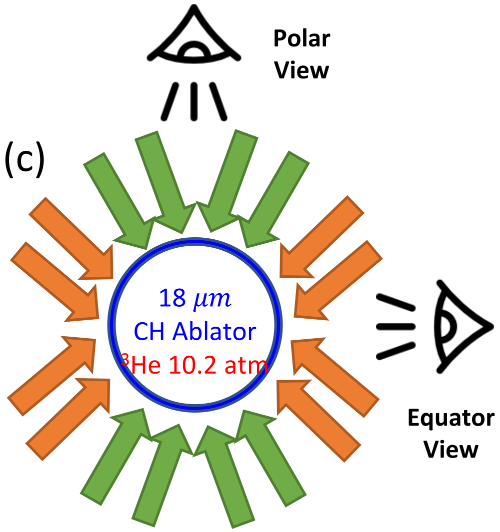
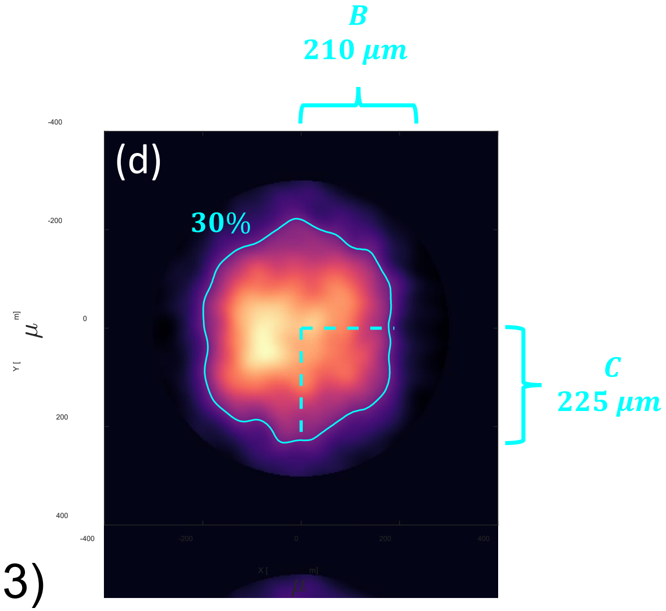
[1] P.J. Adrian, PhD thesis, MIT (2023)

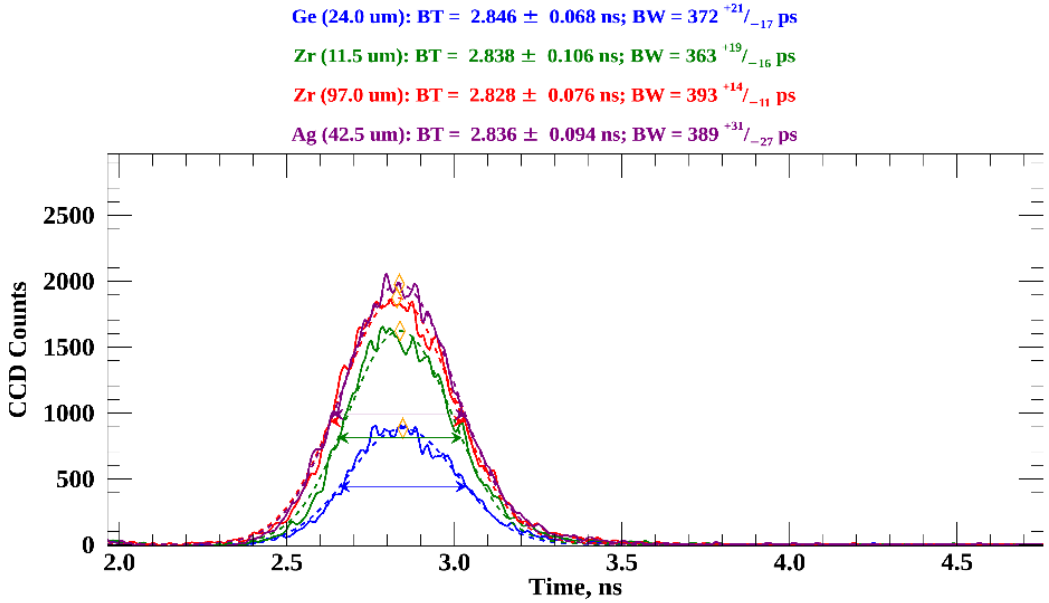
The penumbral x-ray images are used to constrain the hot-spot volume (V_{hs}), and the SPIDER burn history data gives the burn duration (τ)











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[1] P.J. Adrian, PhD thesis, MIT (2023)

Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a nascent field with much potential

- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions

- Recent experiments have provided the first exciting results on the solar ^{3}He+^{3}He, BBN-relevant T+^{3}He and complementary T+T reactions

- Ongoing efforts focus on probing the solar ^{3}He^{3}He$\rightarrow\alpha$+p+p reaction at more stellar-relevant conditions (OMEGA E_G=165 keV, solar E_G=21 keV) and at lower proton energy

- Future work includes developing the platform for CNO-relevant measurements (e.g., the p+^{15}N-α/γ branching ratio) and for studying neutron capture on s-process branch-point nuclei

Future

There is a rich set of opportunities to study nuclear reactions using HED plasmas at OMEGA and the NIF

Charged-particle induced reactions:

- **T(t,2n)^{4}He** (analogue to ^{3}He(^{3}He,2p)^{4}He) [1]
- **T(^{3}He,np)^{4}He, T(^{3}He,d) ^{4}He, T(^{3}He,γ)^{6}Li** (BBN) [2]
- **^{3}He(^{3}He,2p)^{4}He** (pp-I) [3]
- **D(p,γ)^{3}He** (Brown dwarfs, protostars) [4]
- **T(d,γ)^{5}He** [5]
- **^{4}He(D,γ)^{6}Li** (BBN)
- **^{4}He(T,γ)^{7}Li** (BBN)
- **^{4}He(^{3}He,γ)^{7}Be** (Solar)
- **^{6}Li(p,α)^{3}He** (BBN)
- **^{7}Li(p,α)^{4}He** (BBN)
- **^{7}Be(p,γ)^{8}B** (Solar)
- **^{7}Be(α,γ)^{11}C** (BBN)
- **^{11}B(p,α)^{8}Be** (Basic nuclear)
- **^{15}N(p,α)^{12}C/ ^{15}N(p,γ)^{16}O** (CNO)
- **^{10}B(p,α)^{7}Be** [8]
- **^{12}C(p,γ)^{13}N** [8]
- **^{14}N(p,γ)^{15}O** [8]

Proposed for NIF

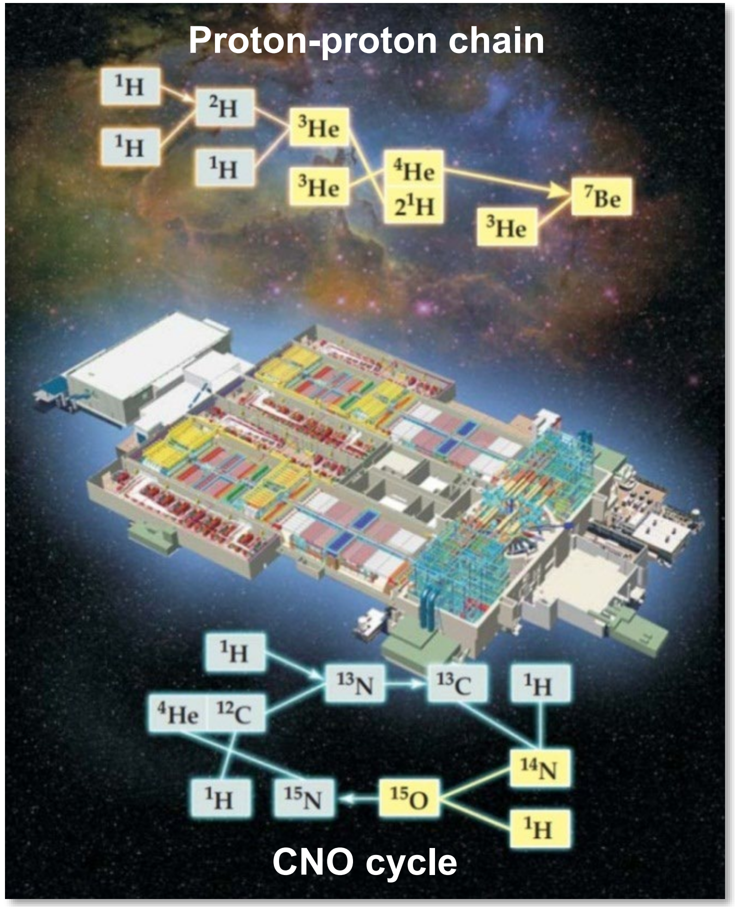
Published
Ongoing
Proposed
Near future?

Neutron-induced reactions:

- **n-d and n-T** at 14 MeV [6]
- **D(n,2n)** at 14 MeV [7]
- **T(n,2n)** at 14 MeV
- Various (n,γ) processes
- **Li(n,2n), Be(n,2n)**, other (n,2n) processes

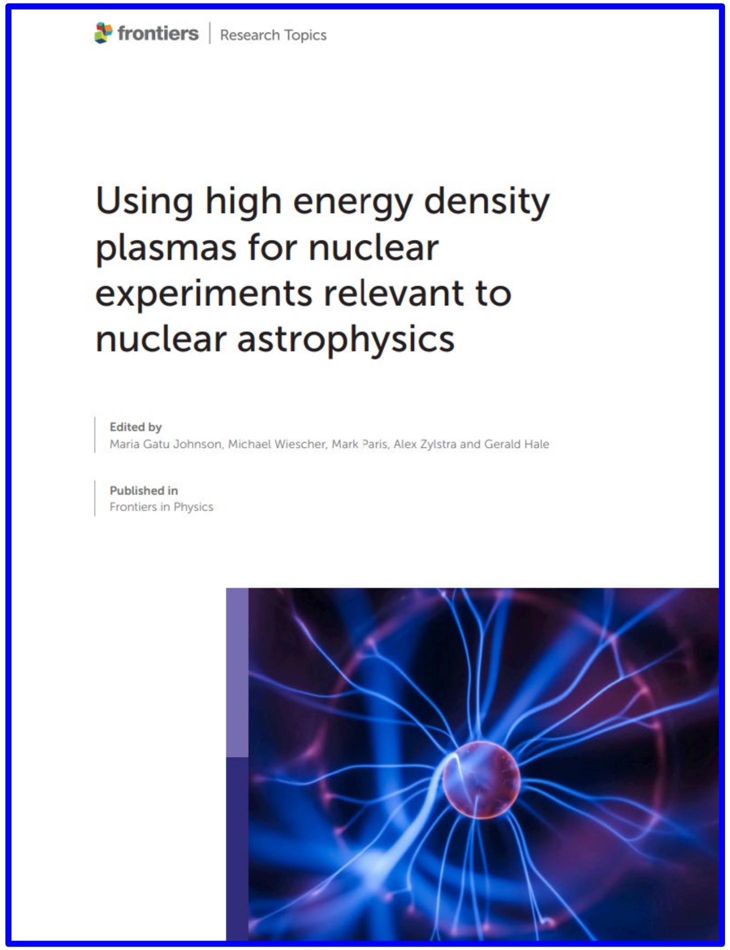
Plasma effects:

- **Screening**
- **NEET/NEEC**
- **s-process relevant reactions**
- **r-process relevant reactions**



1: Casey et al., PRL 2012; Sayre et al., PRL 2013; Gatu Johnson et al., PRL 2018
2-4: Zylstra et al., PRL 2016; Zylstra et al., PRL 2017
5: Kim et al., PoP and PRC (2012)
6: Frenje et al., PRL 2011
7: Forrest et al., NIM A 2018
8: Wiescher et al., Front. Phys 2022

A recent *Frontiers in Physics* “Research Topic” collects articles on ongoing work at this new frontier

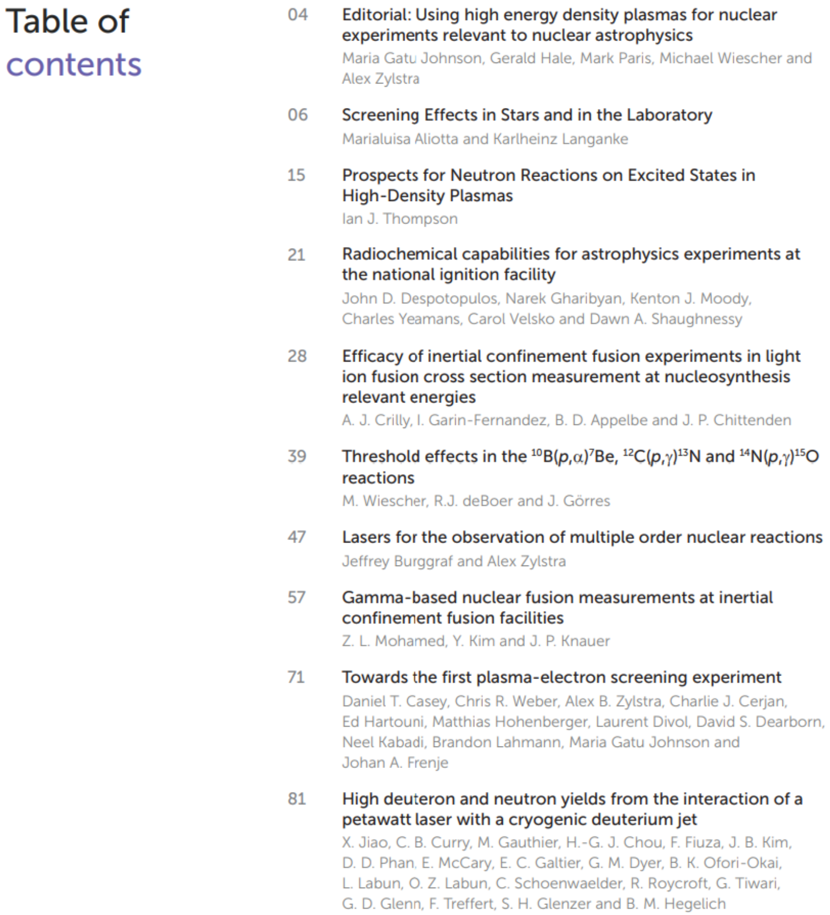


frontiers | Research Topics

Using high energy density plasmas for nuclear experiments relevant to nuclear astrophysics

Edited by
Maria Gatu Johnson, Michael Wiescher, Mark Paris, Alex Zylstra and Gerald Hale

Published in
Frontiers in Physics



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