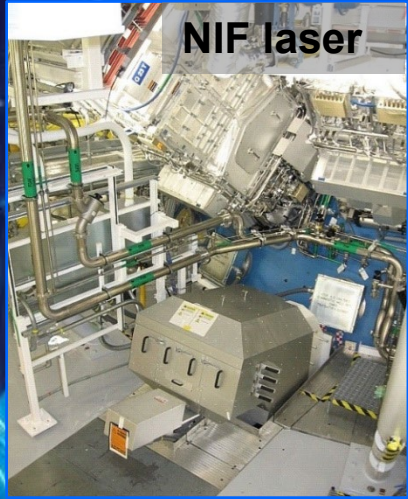
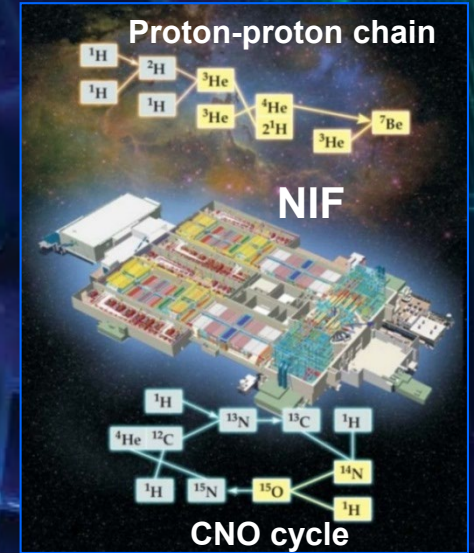
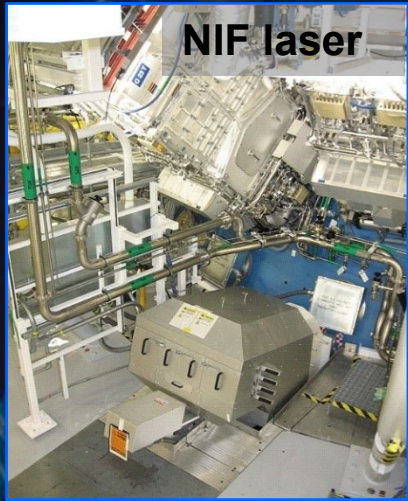
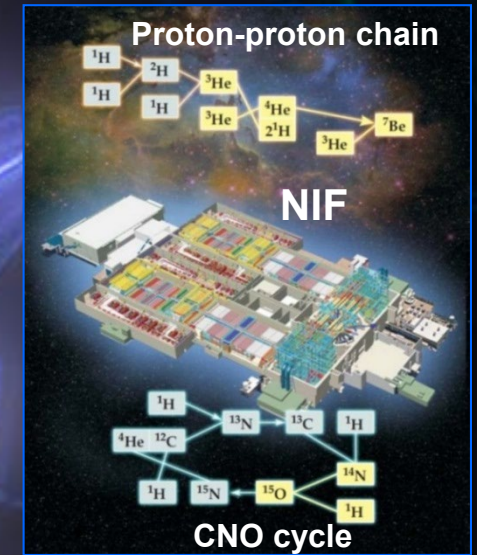


Using high energy density plasmas for nuclear experiments relevant to nuclear astrophysics



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



Collaborators

MIT

P. Adrian
S. Dannhoff
J. Frenje
T. Johnson
N. Kabadi
J. Kunimune
B. Lahmann
C. Li
C. Parker
J. Percy
R. Petrasso
F. Séguin
H. Sio
G.D. Sutcliffe

LLNL

A. Zylstra
D. Casey
M. Hohenberger
H. Whitley
J. Jeet
D. Sayre
J. Caggiano
C. Cerjan
L. Ellison
E. Hartouni
R. Hatarik
M. Hohensee
D. Holunga
S. Khan

LLNL cont'

L. Masse
D. McNabb
A. Nikroo
J. Pino
B. Remington
H. Robey
M. Rubery
J. Sanchez
P. Springer
I. Thompson
B. Tipton
S. Quaglioini

UR

C. Forrest
R.S. Craxton
E.M. Garcia
V. Glebov
R. Janezic
J. Knauer
P. McKenty
P.B. Radha
H. Rinderknecht
M. Rosenberg
T. Sangster
W. Seka
C. Stoeckl

LANL

G. Hale
H. Herrmann
Y. Kim
A. McEvoy
Z. Mohamed
M. Paris
M. Schmitt

Ohio Univ.
C.R. Brune

AWE
W. Garbett

Imperial College
B. Appelbe
A. Crilly
I. Garin-Fernandez

GA

M. Farrell
M. Hoppe
J. Kilkenny
M. Schoff

Indiana Univ.
A. Bacher

CEA
J.-L. Bourgade
O. Landoas

Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a promising new field with much still to learn

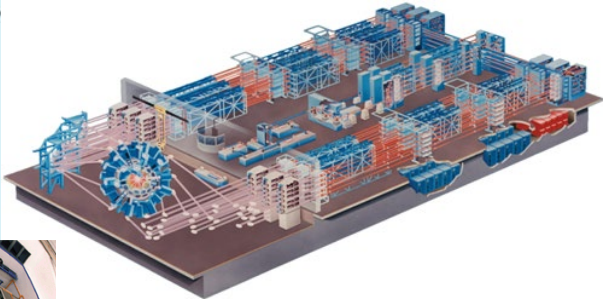
- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions:
 - ✓ Plasma environment
 - ✓ Hot and dense
 - ✓ High neutron flux achievable
- The NIF and OMEGA lasers are two primary facilities for executing experiments of this type
- Experiments are made possible by enabling nuclear diagnostics
- Initial results include spectral measurements for ${}^3\text{He}+{}^3\text{He}$ and the mirror $\text{T}+\text{T}$ reaction, and S-factor measurements for $\text{T}+{}^3\text{He}-\gamma$, $\text{p}+\text{D}$, $\text{p}+\text{T}$, and $\text{T}+\text{T}$
- Near-term work includes platform development for studying CNO-relevant reactions and electron screening effects; broad opportunities exist for additional efforts

High energy density conditions are generated at laser facilities such as the OMEGA and National Ignition Facility (NIF) lasers

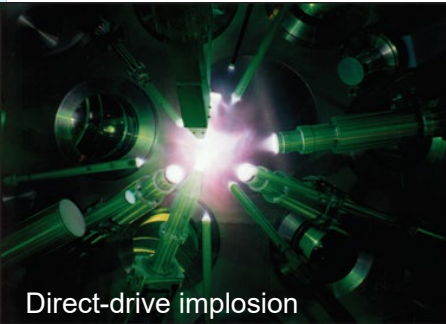


High energy density: extreme pressure (~1 Mbar - ~1000 Gbar)

High energy density conditions are generated at laser facilities such as the OMEGA and National Ignition Facility (NIF) lasers



60 laser beams
30 kJ energy



High energy density conditions are generated at laser facilities such as the OMEGA and National Ignition Facility (NIF) lasers

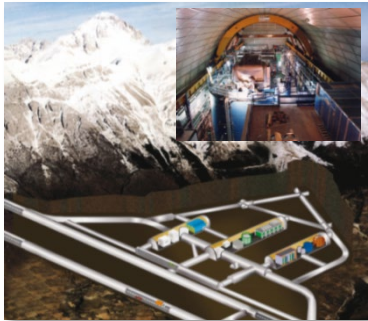
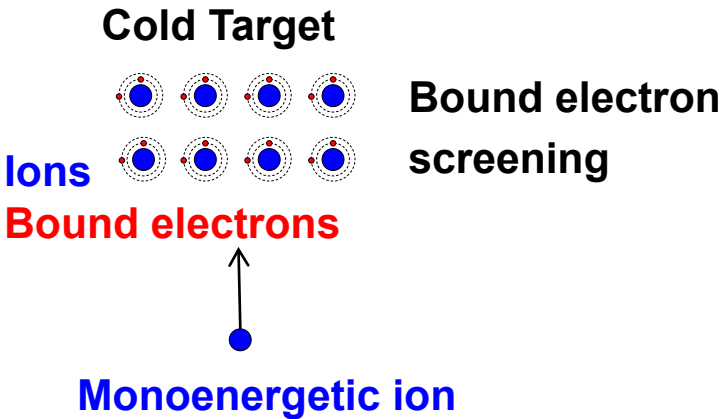
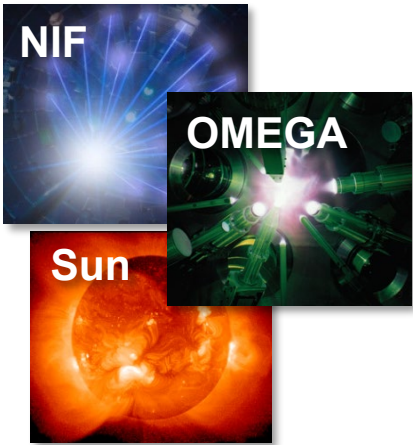
192 laser beams
1.9 MJ energy

60 laser beams
30 kJ energy

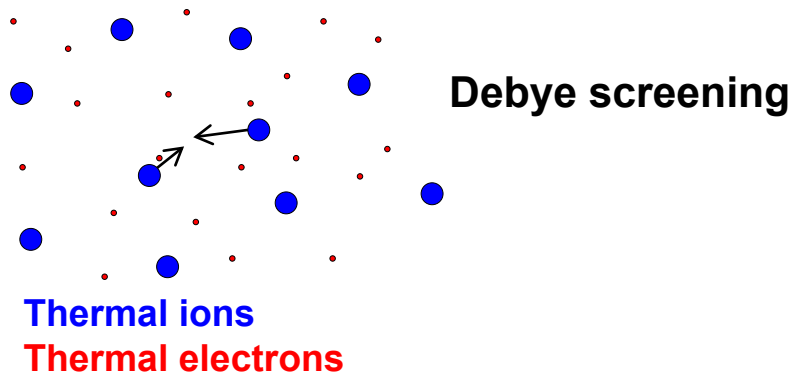
Direct-drive implosion

In contrast to accelerators normally used for nuclear physics experiments, lasers create conditions similar to stellar cores

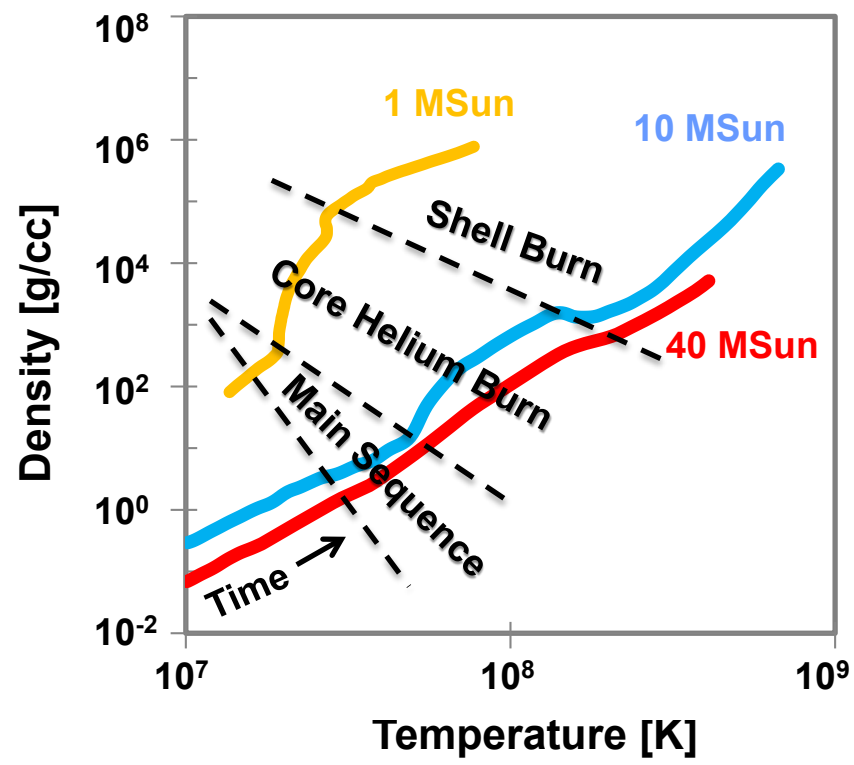
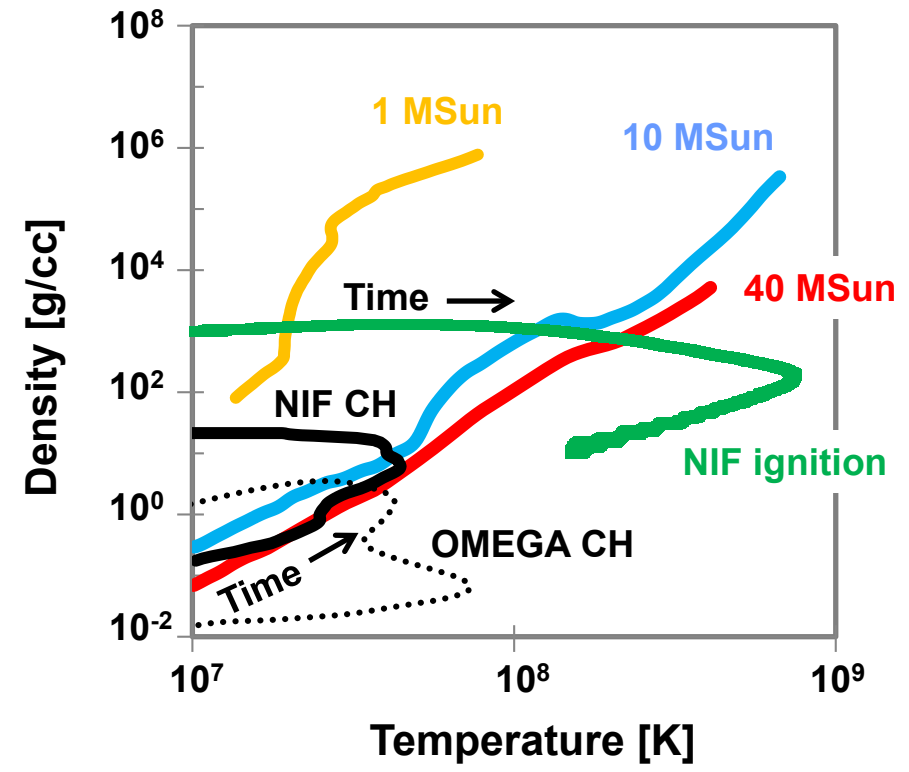
Accelerator experiments



Dense and hot plasma

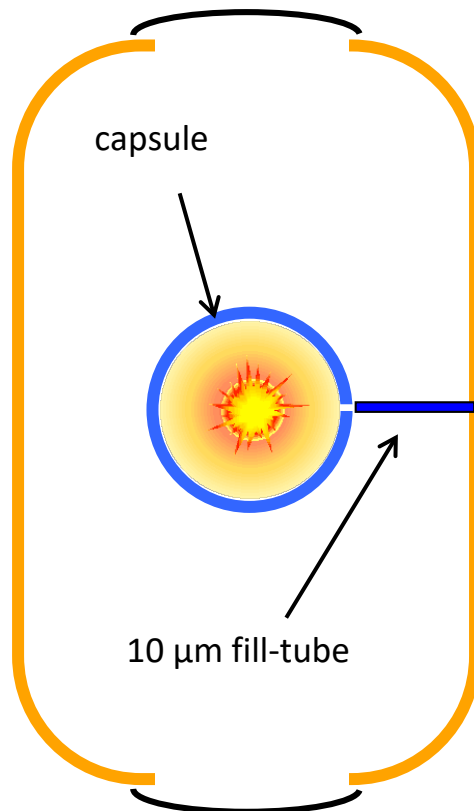


Capsule implosions at the OMEGA and NIF lasers create HED-plasma conditions that are similar to the interior of a star



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 National Ignition Facility (NIF) are higher than anywhere else on earth by several orders of magnitude



Example:

$4e17$ neutrons/implosion¹

Burn duration <100 ps

$\rightarrow 4e27$ n/s

Burn region size $\sim 100\mu\text{m}$

$\rightarrow \sim 10^{30}$ n/s/cm² in capsule

Hohlraum radius $\sim 3\text{mm}$

$\rightarrow \sim 10^{27}$ n/s/cm² on hohlraum wall

Such fluences are directly relevant for s- and/or r-process studies^{2,3}



¹H. Abu-Shawareb et al., Phys. Rev. Lett. 129, 071001 (2022); A. Zylstra et al., Nature 601, 542 (2022).

²S. LePape et al., Phys. Rev. Lett. 120, 245003 (2018)

³C. 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

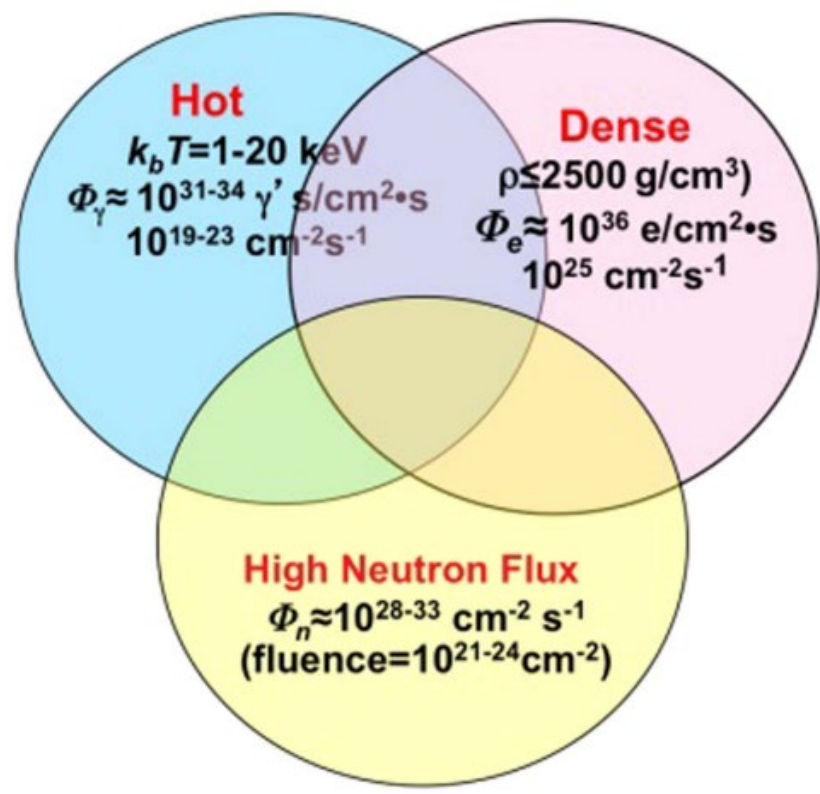


Illustration from Cerjan et al.,
J. Phys. G: Nucl. Part. Phys. 45 (2018):

IOP Publishing
Journal of Physics G: Nuclear and Particle Physics

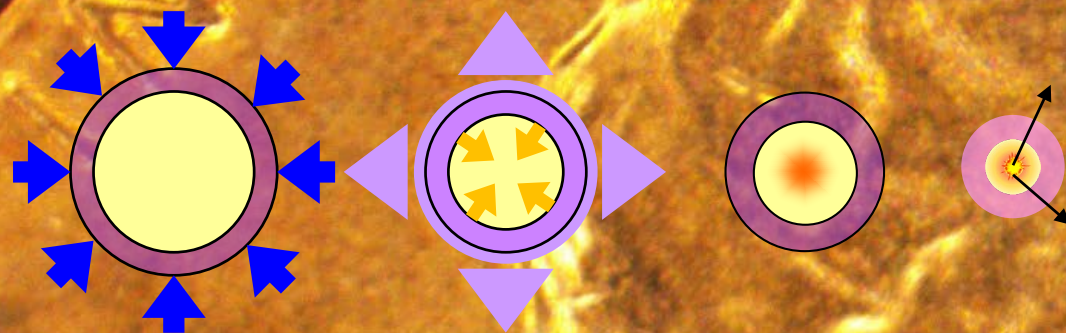
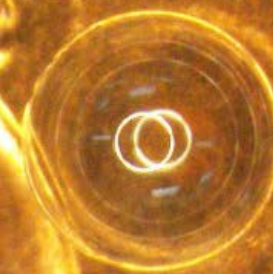
J. Phys. G: Nucl. Part. Phys. 45 (2018) 033003 (111pp)
<https://doi.org/10.1088/1361-6471/aa8693>

Topical Review

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

Ch J Cerjan¹, L Bernstein¹, L Berzak Hopkins¹, R M Bionta¹, D L Bleuel¹, J A Caggiano¹, W S Cassata¹, C R Brune², J Frenje³, M Gatu-Johnson¹, N Gharibyan¹, G Grim¹, Chr Hagmann¹, A Hamza¹, R Hatarik¹, E P Hartouni¹, E A Henry¹, H Herrmann⁴, N Izumi¹, D H Kalantar¹, H Y Khater¹, Y Kim⁴, A Kritcher¹, Yu A Litvinov⁵, F Merrill⁴, K Moody¹, P Neumayer⁵, A Ratkiewicz¹, H G Rinderknecht¹, D Sayre¹, D Shaughnessy¹, B Spears¹, W Stoeffl¹, R Tommasini¹, Ch Yeaman¹, C Velsko¹, M Wiescher⁶, M Couder⁶, A Zylstra⁴ and D Schneider¹

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

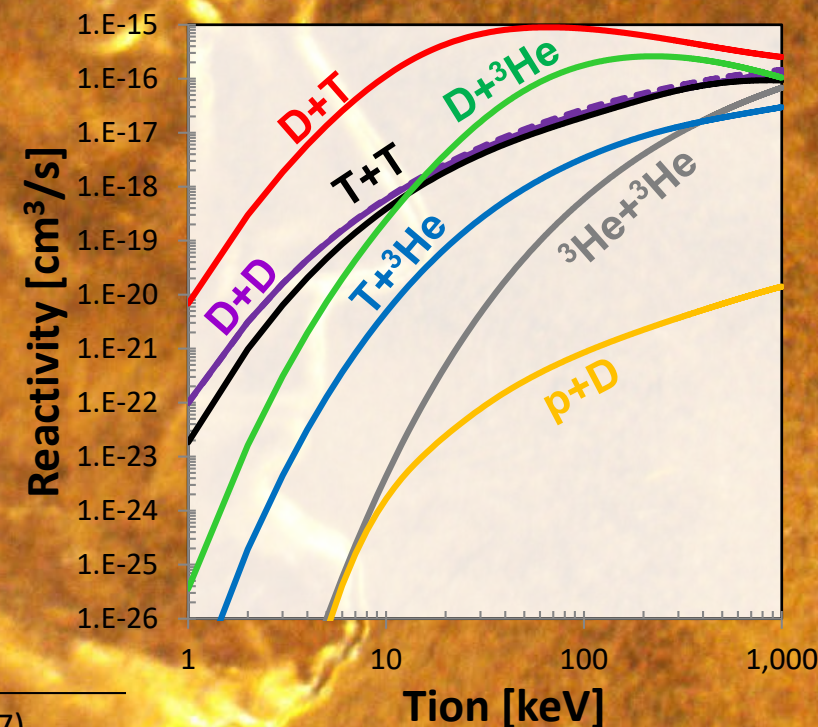


1600um (1.6mm)

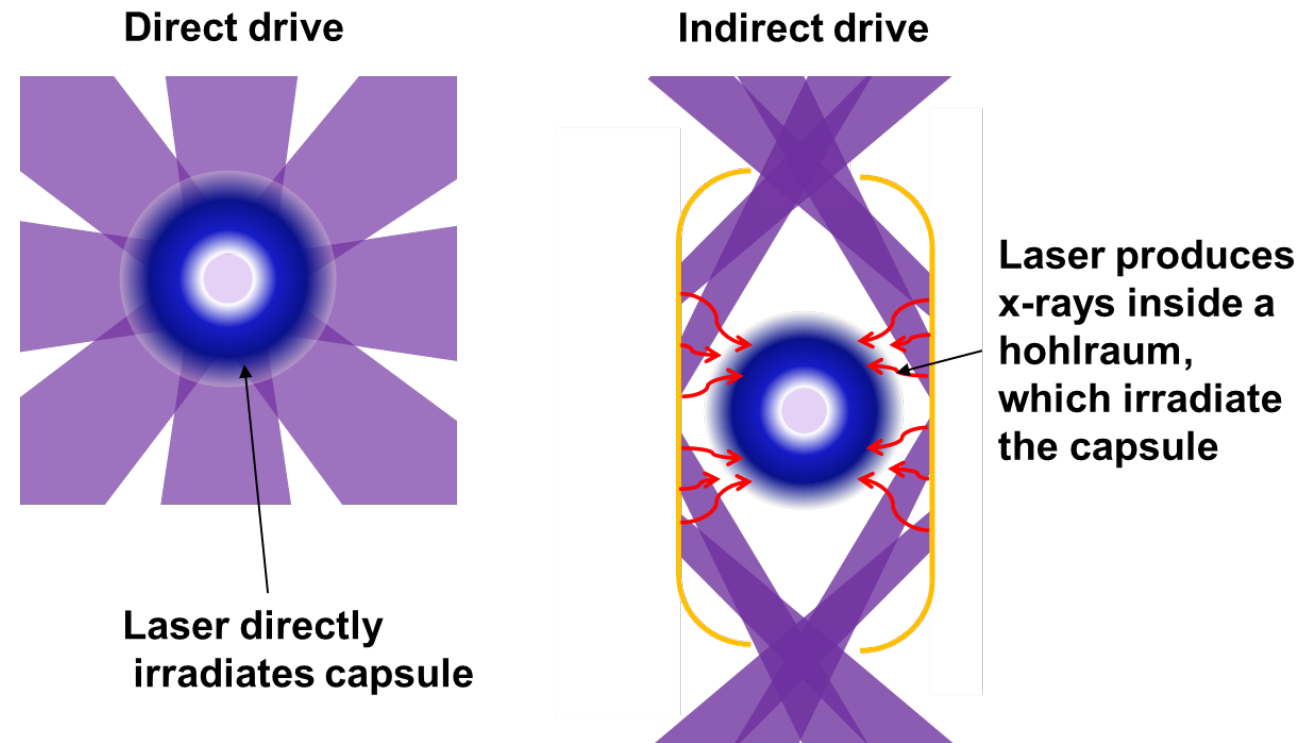
Basic platform requirements:

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

Achievable plasma conditions determine astrophysical relevance



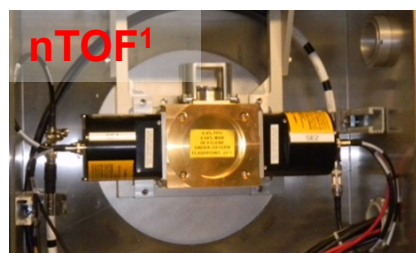
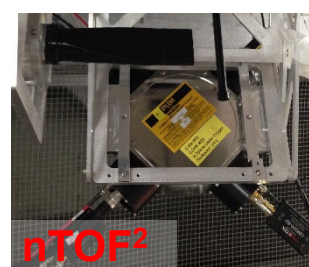
There are two main ways of executing the implosions



- Can achieve high temperature
- Can achieve high compression

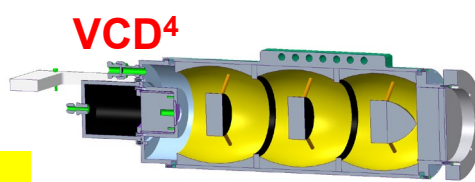
Existing and future nuclear diagnostics at the laser facilities enable exploitation of these plasmas for study of nuclear astrophysics-relevant reactions

Neutrons:



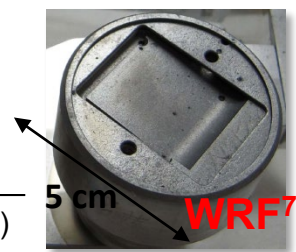
Need capability to measure low-energy neutrons!

Gamma:

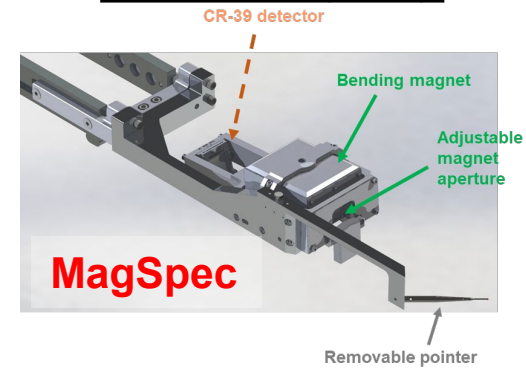
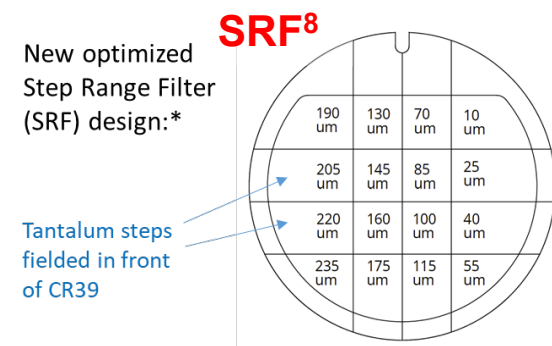


Need a gamma spectrometer!

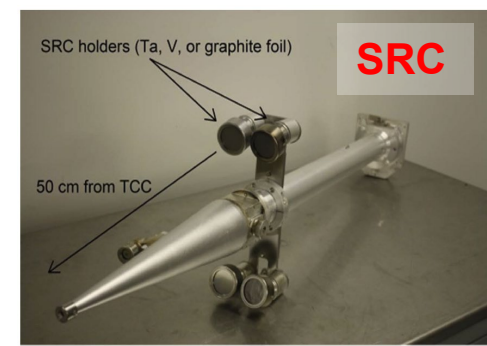
Low-Z ions:



Low-Z ions (new):



Radiochemistry:

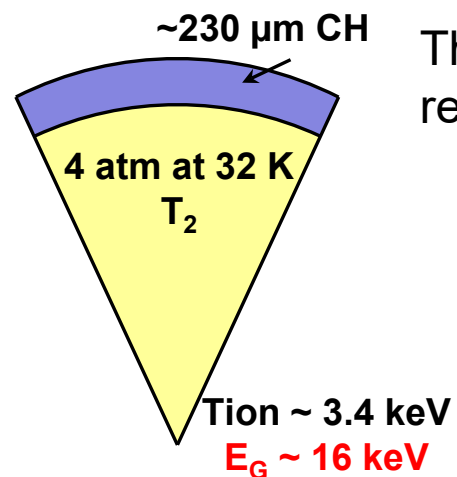


¹Neutron time-of-flight spectrometer, Clancy et al., SPIE proceedings (2014)
²Neutron time-of-flight spectrometer, Forrest et al., RSI (2012, 2016)
³Gas Cherenkov Detector, Mack et al., NIM A (2013).
⁴Vacuum Cherenkov Detector, Jeet et al, submitted to RSI (2022)
⁵Magnetic Recoil Spectrometer, Frenje et al., RSI (2008)
⁶Charged Particle Spectrometer, Hicks, MIT PhD thesis (1999)
⁷Wedge-Range Filter proton spectrometer, Séguin et al., RSI (2003)
⁸Step Range Filter, Johnson et al., submitted to RSI (2022)
⁹Radiochemistry for gaseous samples, Shaughnessy et al., RSI (2012)
¹⁰Solid Radiochemistry Collectors, Shaughnessy et al., RSI (2014)

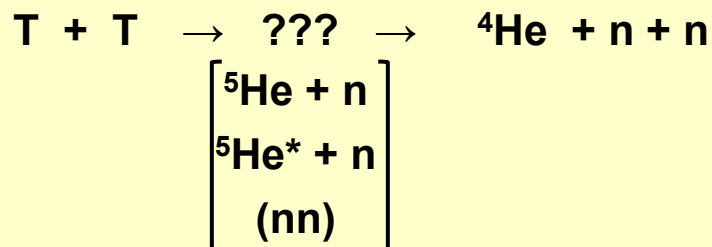
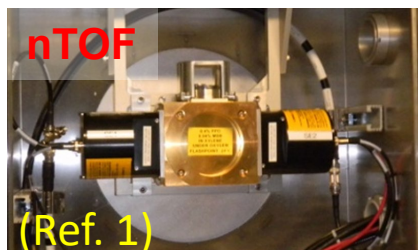
Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a promising new field with much still to learn

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- Initial results include spectral measurements for ${}^3\text{He}+{}^3\text{He}$ and the mirror T+T reaction, and S-factor measurements for $\text{T}+{}^3\text{He}-\gamma$, $\text{p}+\text{D}$, $\text{p}+\text{T}$, and $\text{T}+\text{T}$
- Near-term work includes platform development for studying CNO-relevant reactions and electron screening effects; broad opportunities exist for additional efforts

An initial NIF experiment measured the T+T neutron spectrum at $E_G = 16$ keV



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



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

PRL 111, 052501 (2013)

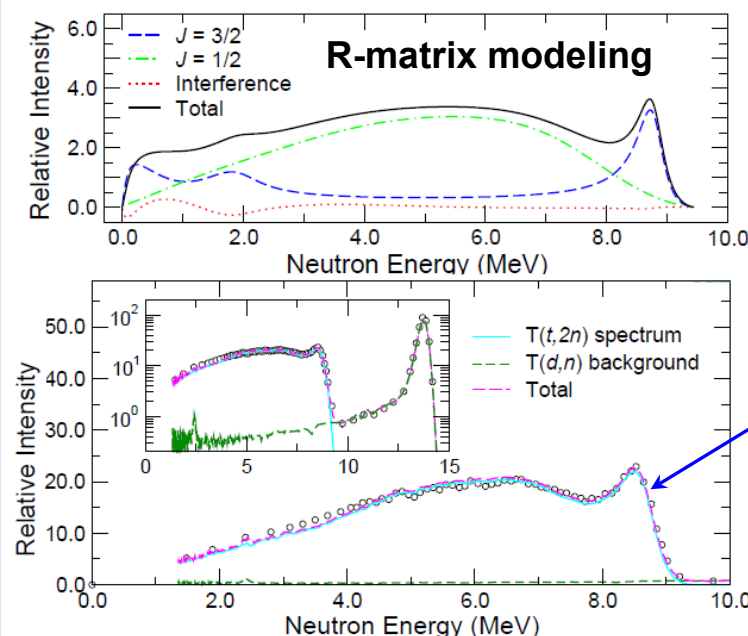
PHYSICAL REVIEW LETTERS

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. Yeamans¹

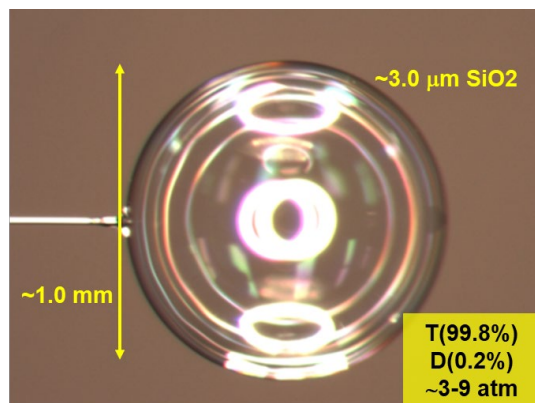
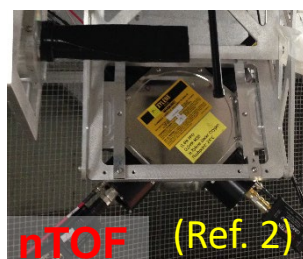
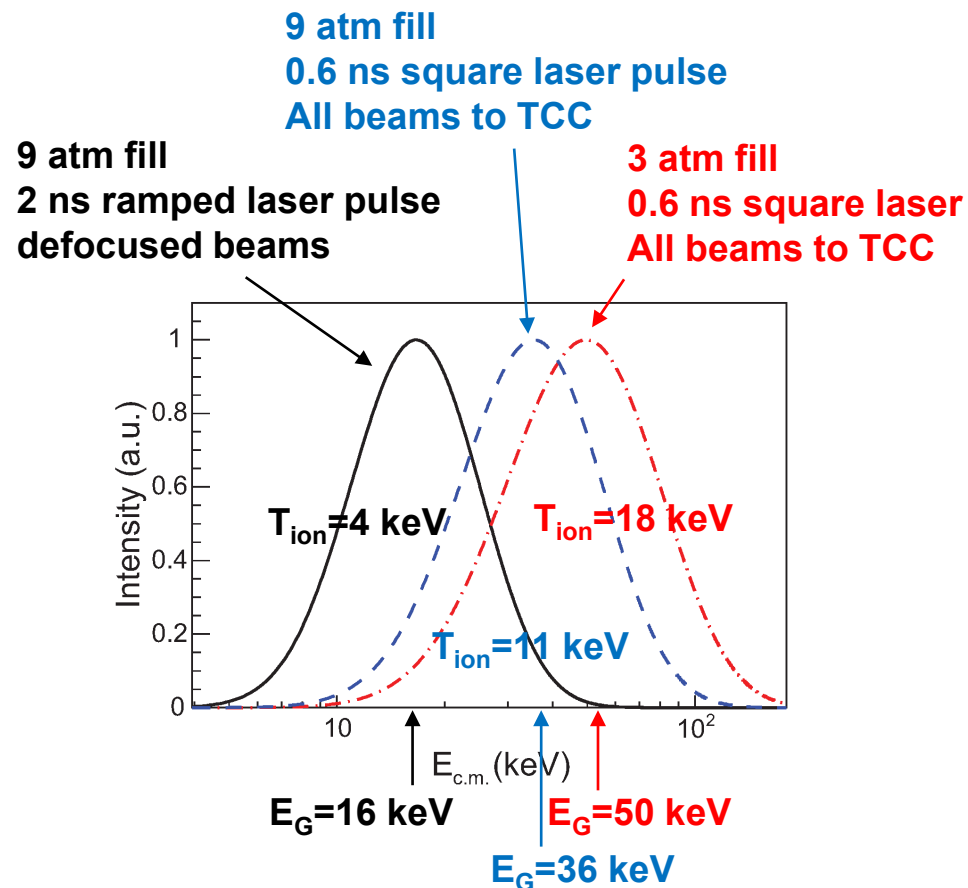
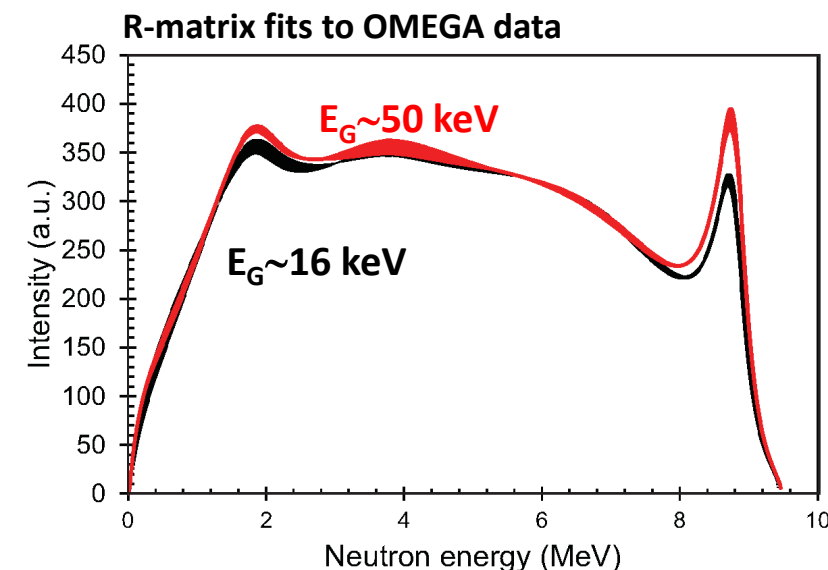
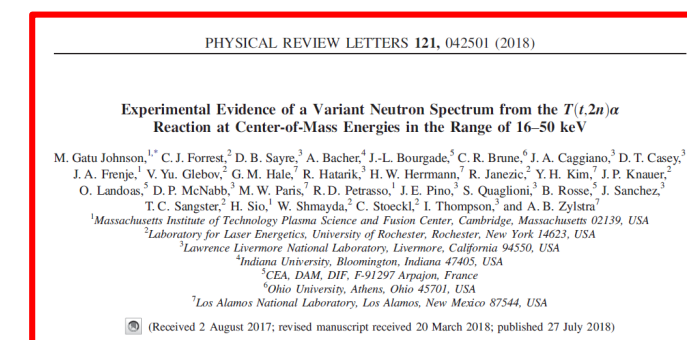
¹Lawrence Livermore National Laboratory, Livermore, California 94550, USA

²Ohio University, Athens, Ohio 45701, USA


⁵He
resonance

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

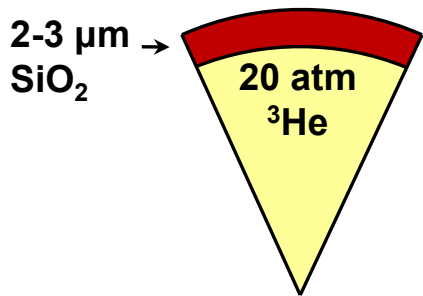
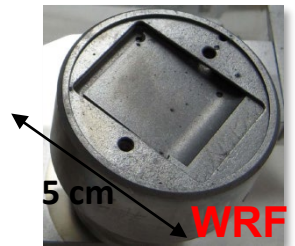
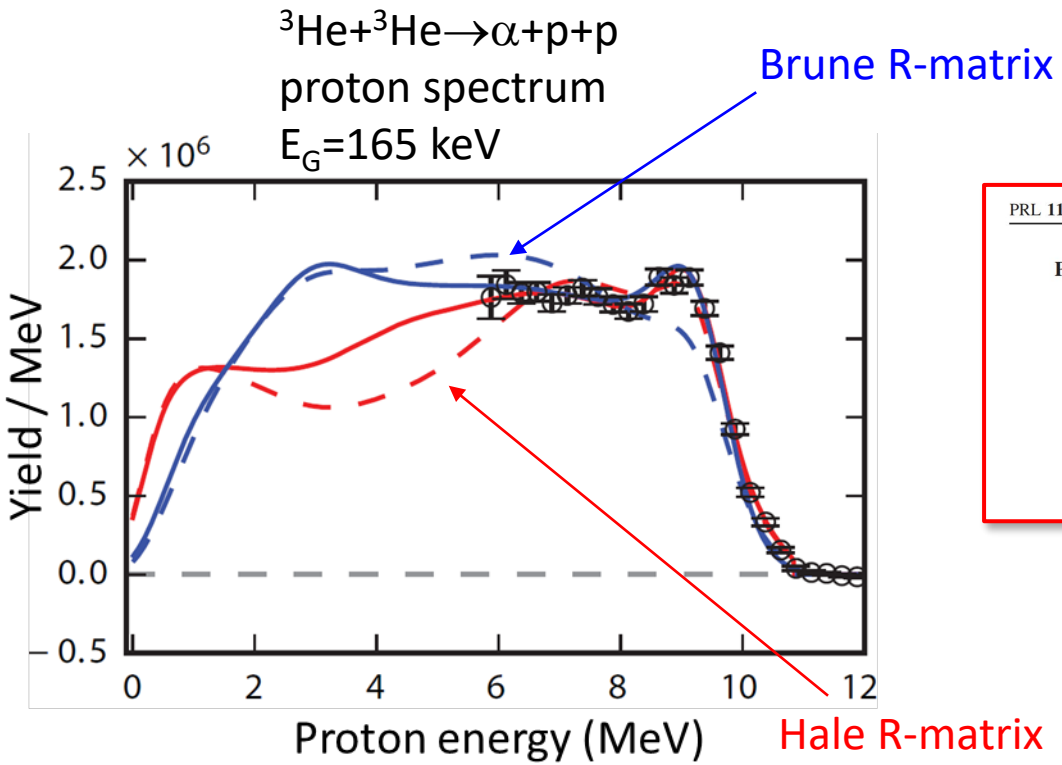
A subsequent study at OMEGA probed the T+T spectrum over a range¹⁾ of Gamow-peak energies from 16 to 50 keV, demonstrating changes over this range



¹Gatu Johnson et al., Phys. Plasmas 24, 041407 (2017)

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

Initial measurements of the ${}^3\text{He}+{}^3\text{He}$ proton spectrum were made at OMEGA



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

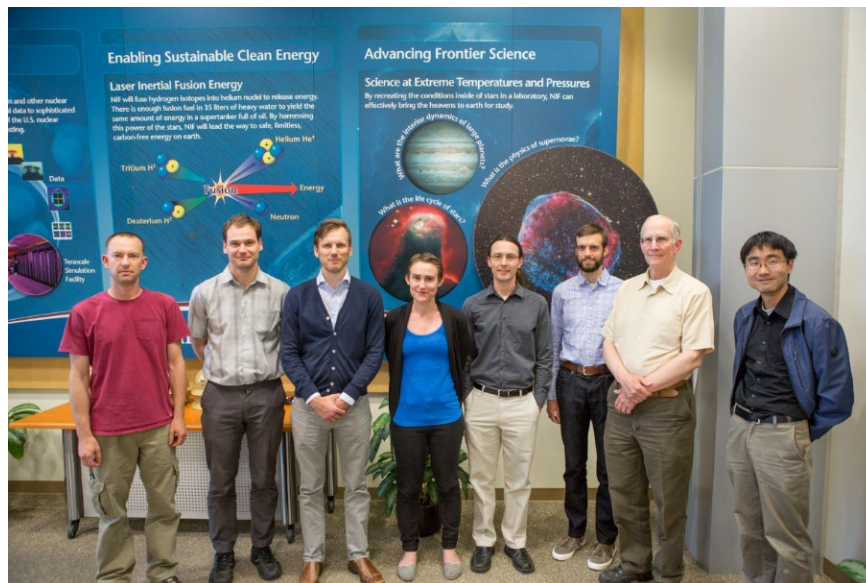
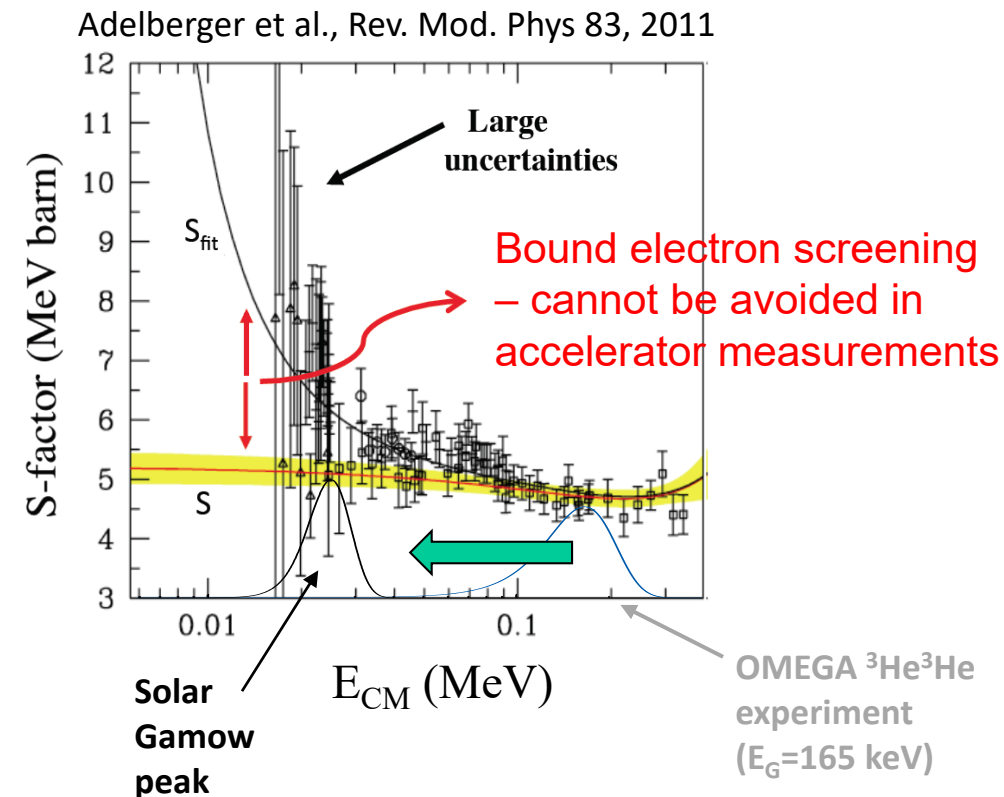
Proton Spectra from ${}^3\text{He} + \text{T}$ and ${}^3\text{He} + {}^3\text{He}$ Fusion at Low Center-of-Mass Energy, with Potential Implications for Solar Fusion Cross Sections

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. Séguin²

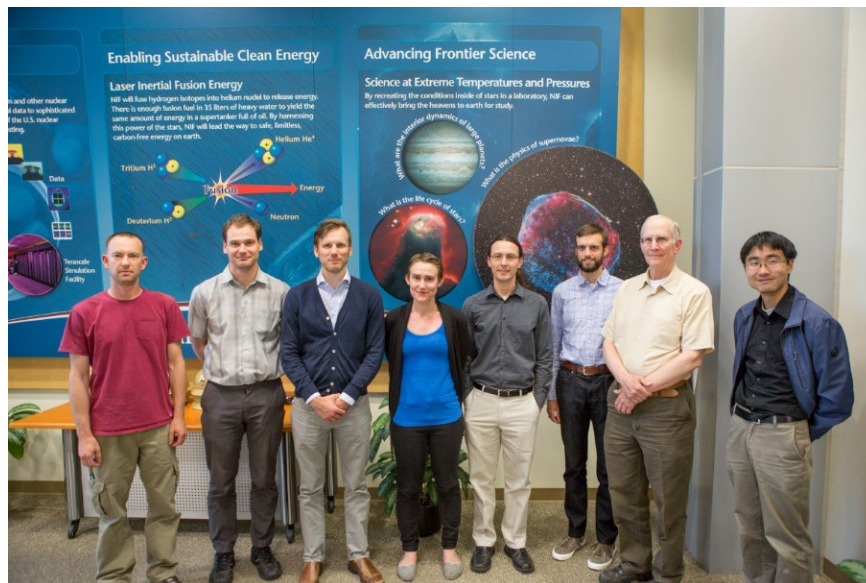
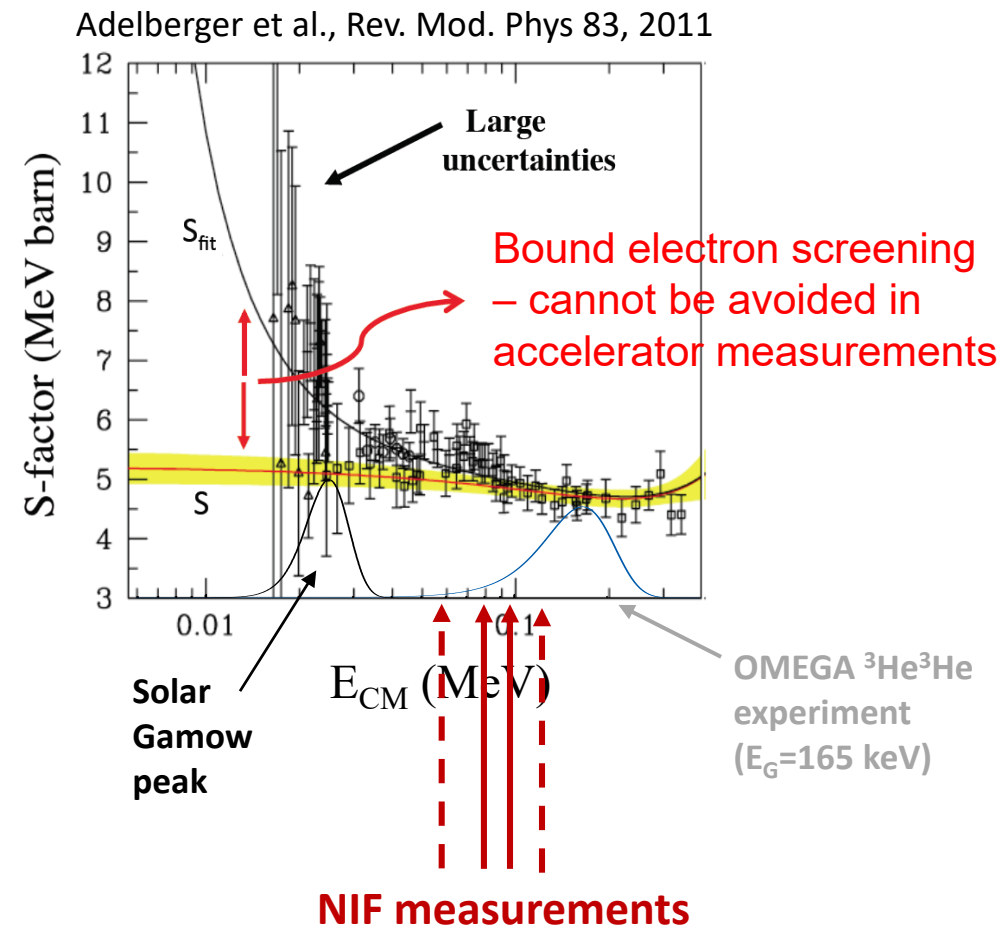
¹Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
²Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³Ohio University, Athens, Ohio 45701, USA
⁴Indiana University, Bloomington, Indiana 47405, USA
⁵Lawrence Livermore National Laboratory, Livermore, California 94550, USA
⁶Laboratory 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)

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

A NIF Discovery Science experiment leverages NIF to push the boundaries towards solar-relevant Gamow-peak energies

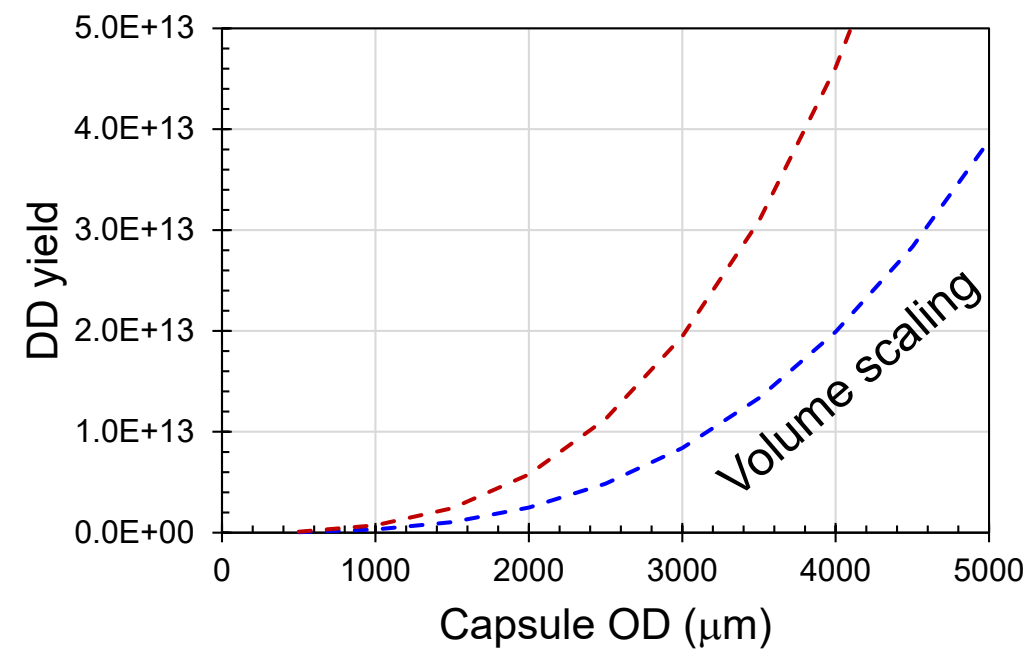


A NIF Discovery Science experiment leverages NIF to push the boundaries towards solar-relevant Gamow-peak energies



Higher yield at low(er) Gamow-peak energy is achieved by using larger capsules – NIF is required to drive these larger capsule implosions

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



Two Physics of Plasmas papers describe the efforts to optimize the NIF Direct Drive Exploding Pusher platform for these measurements

PHYSICS OF PLASMAS **24**, 041407 (2017)



Development of an inertial confinement fusion platform to study charged-particle-producing nuclear reactions relevant to nuclear astrophysics

M. Gatu Johnson,¹ A. B. Zylstra,² A. Bacher,³ C. R. Brune,⁴ D. T. Casey,⁵ C. Forrest,⁶ H. W. Herrmann,² M. Hohenberger,⁶ D. B. Sayre,⁵ R. M. Bionta,⁵ J.-L. Bourgade,⁷ J. A. Caggiano,⁵ C. Cerjan,⁵ R. S. Craxton,⁶ D. Dearborn,⁵ M. Farrell,⁸ J. A. Frenje,¹ E. M. Garcia,⁶ V. Yu. Glebov,⁶ G. Hale,² E. P. Hartouni,⁵ R. Hatarik,⁵ M. Hohensee,⁵ D. M. Holunga,⁵ M. Hoppe,⁸ R. Janezic,⁶ S. F. Khan,⁵ J. D. Kilkenny,⁸ Y. H. Kim,² J. P. Knauer,⁶ T. R. Kohut,⁵ B. Lahmann,¹ O. Landoas,⁷ C. K. Li,¹ F. J. Marshall,⁶ L. Masse,⁵ A. McEvoy,² P. McKenty,⁶ D. P. McNabb,⁵ A. Nikroo,⁵ T. G. Parham,⁵ M. Paris,² R. D. Petrasso,¹ J. Pino,⁵ P. B. Radha,⁶ B. Remington,⁵ H. G. Rinderknecht,⁵ H. Robey,⁵ M. J. Rosenberg,⁶ B. Rosse,⁷ M. Rubery,⁹ T. C. Sangster,⁶ J. Sanchez,⁵ M. Schmitt,² M. Schoff,⁸ F. H. Séguin,¹ W. Seka,⁶ H. Sio,¹ C. Stoeckl,⁶ and R. E. Tipton⁵

¹Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

²Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA

³Indiana University, Bloomington, Indiana 47405, USA

⁴Ohio University, Athens, Ohio 45701, USA

⁵Lawrence Livermore National Laboratory, Livermore, California 94550, USA

⁶Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

⁷CEA, DAM, DIF, F-91297 Arpajon, France

⁸General Atomics, San Diego, California 92186, USA

⁹Plasma Physics Department, AWE plc, Reading RG7 7PR, United Kingdom

(Received 14 October 2016; accepted 12 December 2016; published online 28 March 2017)

PHYSICS OF PLASMAS **25**, 056303 (2018)



Optimization of a high-yield, low-areal-density fusion product source at the National Ignition Facility with applications in nucleosynthesis experiments

M. Gatu Johnson,^{1,a)} D. T. Casey,² M. Hohenberger,² A. B. Zylstra,³ A. Bacher,⁴ C. R. Brune,⁵ R. M. Bionta,² R. S. Craxton,⁶ C. L. Ellison,² M. Farrell,⁷ J. A. Frenje,¹ W. Garbett,⁸ E. M. Garcia,⁶ G. P. Grim,² E. Hartouni,² R. Hatarik,² H. W. Herrmann,³ M. Hohensee,² D. M. Holunga,² M. Hoppe,⁷ M. Jackson,⁷ N. Kabadi,¹ S. F. Khan,² J. D. Kilkenny,⁷ T. R. Kohut,² B. Lahmann,¹ H. P. Le,² C. K. Li,¹ L. Masse,² P. W. McKenty,⁶ D. P. McNabb,² A. Nikroo,² T. G. Parham,² C. E. Parker,¹ R. D. Petrasso,¹ J. Pino,² B. Remington,² N. G. Rice,⁷ H. G. Rinderknecht,² M. J. Rosenberg,⁶ J. Sanchez,² D. B. Sayre,² M. E. Schoff,⁷ C. M. Shulldberg,⁷ F. H. Séguin,¹ H. Sio,¹ Z. B. Walters,² and H. D. Whitley²

¹Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, Massachusetts 02139, USA

²Lawrence Livermore National Laboratory, Livermore, California 94550, USA

³Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA

⁴Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

⁵Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

⁶Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

⁷General Atomics, San Diego, California 92186, USA

⁸AWE plc, Aldermaston, Reading RG7 4PR, United Kingdom

(Received 29 November 2017; accepted 2 February 2018; published online 9 March 2018)

Using this platform for S-factor measurements is challenging, as it requires accurate knowledge of D impurity and T_{ion}

The ${}^3\text{He}{}^3\text{He}$ reactivity is determined based on the ${}^3\text{He}{}^3\text{He}$ -to- $\text{D}{}^3\text{He}$ yield ratio:

$$\underbrace{\frac{Y_{3\text{He}3\text{He}-p}}{Y_{\text{D}3\text{He}-p}}}_{\text{Measure this}} \approx \frac{f_{3\text{He}}}{f_{\text{D}}} \frac{\langle \sigma v \rangle_{3\text{He}3\text{He}}}{\langle \sigma v \rangle_{\text{D}3\text{He}}}$$

The S-factor is then calculated from the reactivity*:

$$\langle \sigma v \rangle \approx \sqrt{\frac{2\tau}{m_r kT}} \frac{4}{3} S(E_0) \left(1 + \frac{5}{12\tau} \right) e^{-\tau}$$

*Casey et al., Nature Physics (2017)

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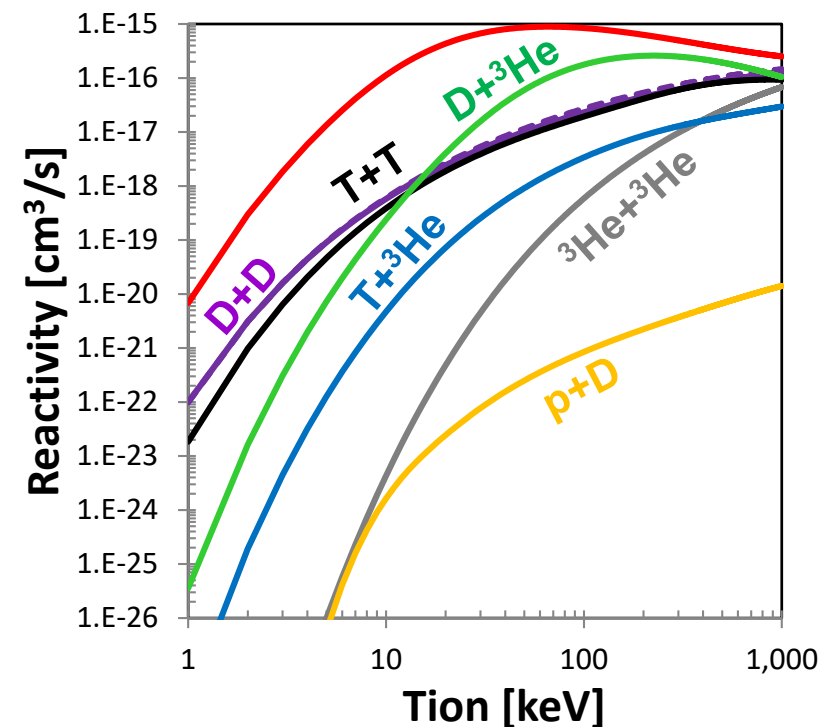
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Take this as known. Requires accurate knowledge of T_{ion} :

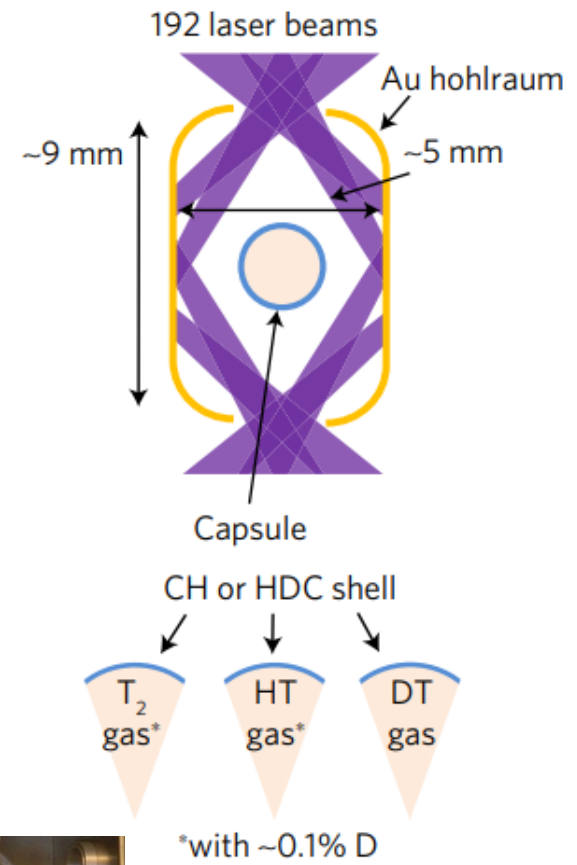
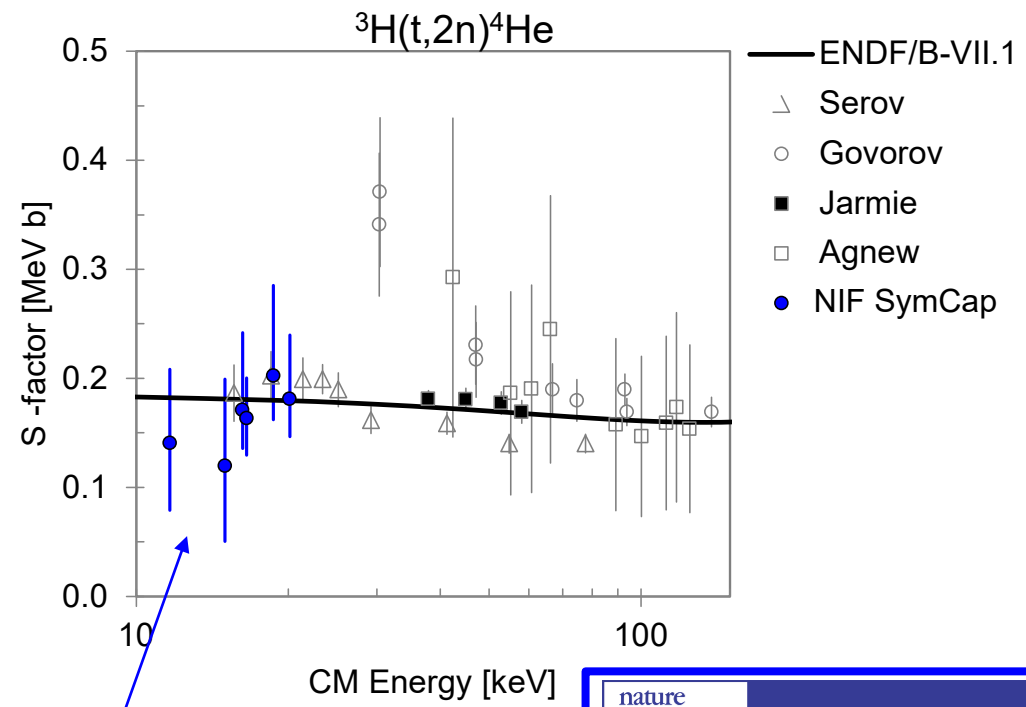
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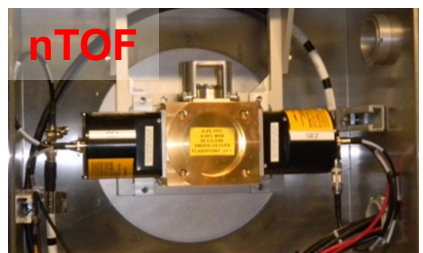


*Casey et al., Nature Physics (2017)

The ability to make S-factor measurements on this platform was demonstrated by measuring T+T relative to D+T on NIF



Casey et al., Nature Physics (2017)



ARTICLES

PUBLISHED ONLINE: 7 AUGUST 2017 | DOI: 10.1038/NPHYS4220

Thermonuclear reactions probed at stellar-core conditions with laser-based inertial-confinement fusion

D. T. Casey^{1*}, D. B. Sayre¹, C. R. Brune², V. A. Smalyuk¹, C. R. Weber¹, R. E. Tipton¹, J. E. Pino¹, G. P. Grim¹, B. A. Remington¹, D. Dearborn¹, L. R. Benedetti¹, J. A. Frenje³, M. Gatu-Johnson³, R. Hatarik¹, N. Izumi¹, J. M. McNaney¹, T. Ma¹, G. A. Kyrala⁴, S. MacLaren¹, J. Salmonson¹, S. F. Khan¹, A. Pak¹, L. Berzak Hopkins¹, S. LePape¹, B. K. Spears¹, N. B. Meezan¹, L. Divol¹, C. B. Yeamans¹, J. A. Caggiano¹, D. P. McNabb¹, D. M. Holunga¹, M. Chiarappa-Zucca¹, T. R. Kohut¹ and T. G. Parham¹

The S-factor for the T+³He-γ branch was measured relative to T+³He-d at OMEGA, ruling it out as a source for high ⁶Li levels in primordial material

PRL 117, 035002 (2016)PHYSICAL REVIEW LETTERSweek ending 15 JULY 2016

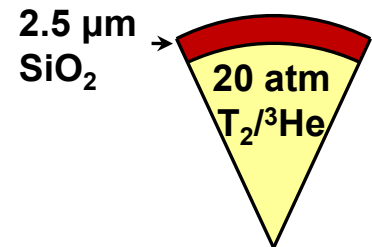
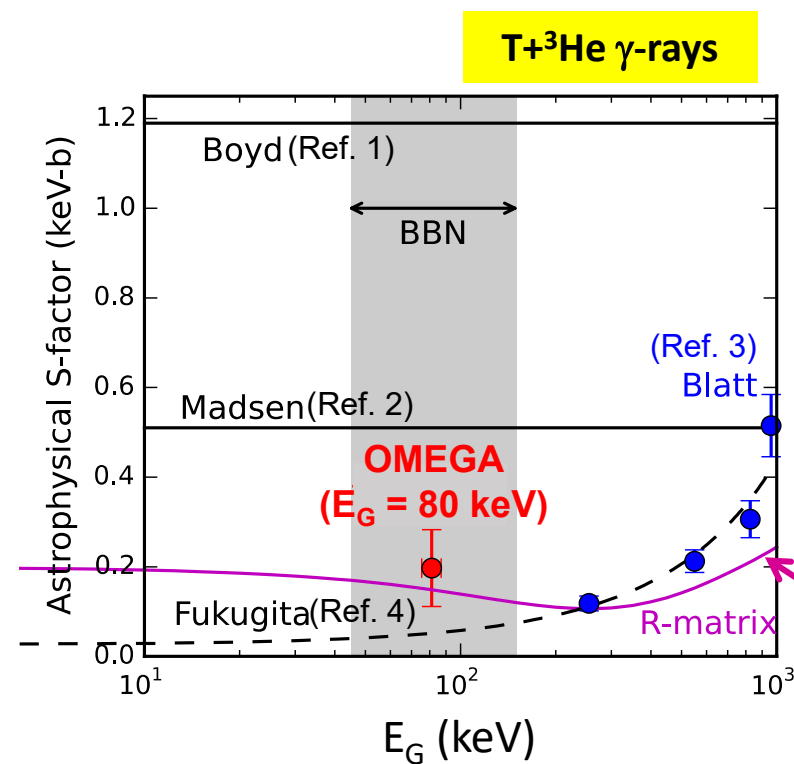


Using Inertial Fusion Implosions to Measure the T + ³He Fusion Cross Section at Nucleosynthesis-Relevant Energies

A. B. Zylstra,^{1,2,*} H. W. Herrmann,² M. Gatu Johnson,¹ Y. H. Kim,² J. A. Frenje,¹ G. Hale,² C. K. Li,¹ M. Rubery,³ M. Paris,² A. Bacher,⁴ C. R. Brune,⁵ C. Forrest,⁶ V. Yu. Glebov,⁶ R. Janezic,⁶ D. McNabb,⁷ A. Nikroo,⁸ J. Pino,⁷ T. C. Sangster,⁶ F. H. Séguin,¹ W. Seka,⁶ H. Sio,¹ C. Stoeckl,⁶ and R. D. Petrasso¹

¹Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
²Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
³Plasma Physics Department, AWE plc, Reading RG7 4PR, United Kingdom
⁴Indiana University, Bloomington, Indiana 47405, USA
⁵Ohio University, Athens, Ohio 45701, USA
⁶Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
⁷Lawrence Livermore National Laboratory, Livermore, California 94550, USA
⁸General Atomics, San Diego, California 92186, USA

(Received 13 April 2016; published 11 July 2016)

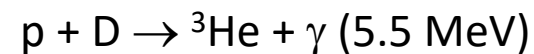
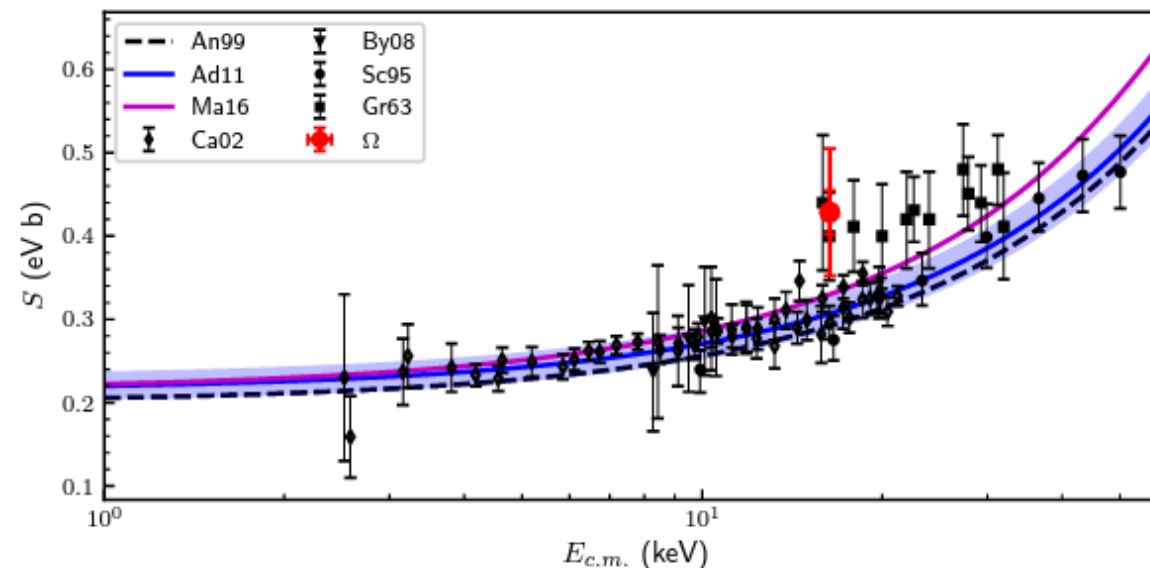
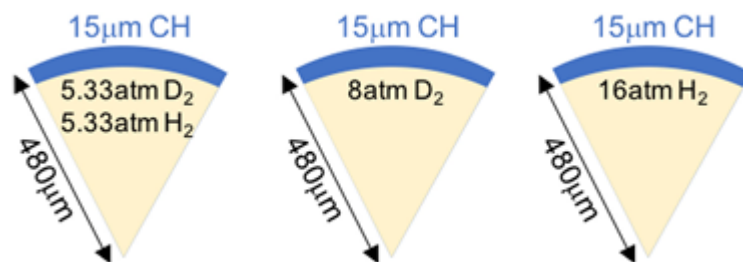


Calculation by Gerry Hale (LANL)

¹Blatt et al., Phys. Rev. (1968).
²Madsen et al., PRD (1990).
³Boyd et al., PRD (2010).
⁴Fukugita et al., PRD (1990).
⁵Mack et al., NIM A (2013).

The p+D S-factor was measured relative to the D+D S-factor in HED conditions, using plastic shell OMEGA implosions

New, higher pressure,
reduced threshold Gas
Cherenkov Detector



PHYSICAL REVIEW C **101**, 042802(R) (2020)

Rapid Communications

${}^2\text{H}(p, \gamma){}^3\text{He}$ cross section measurement using high-energy-density plasmas

A. B. Zylstra,^{1,*} H. W. Herrmann,² Y. H. Kim,² A. McEvoy,² J. A. Frenje,³ M. Gatu Johnson,³ R. D. Petrasso,³ V. Yu. Glebov,⁴ C. Forrest,⁴ J. Delettrez,⁴ S. Gales,⁵ and M. Rubery⁵

¹Lawrence Livermore National Laboratory, Livermore, California 94550, USA

²Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

³Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

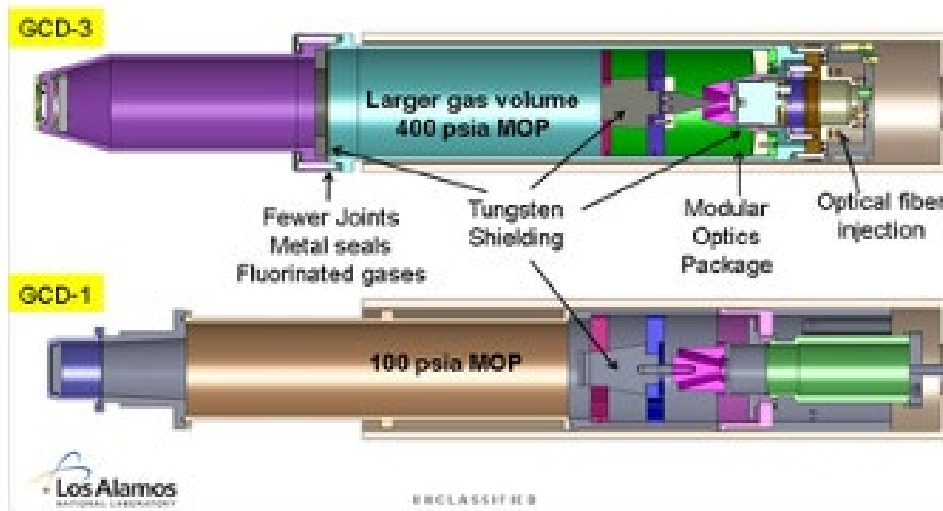
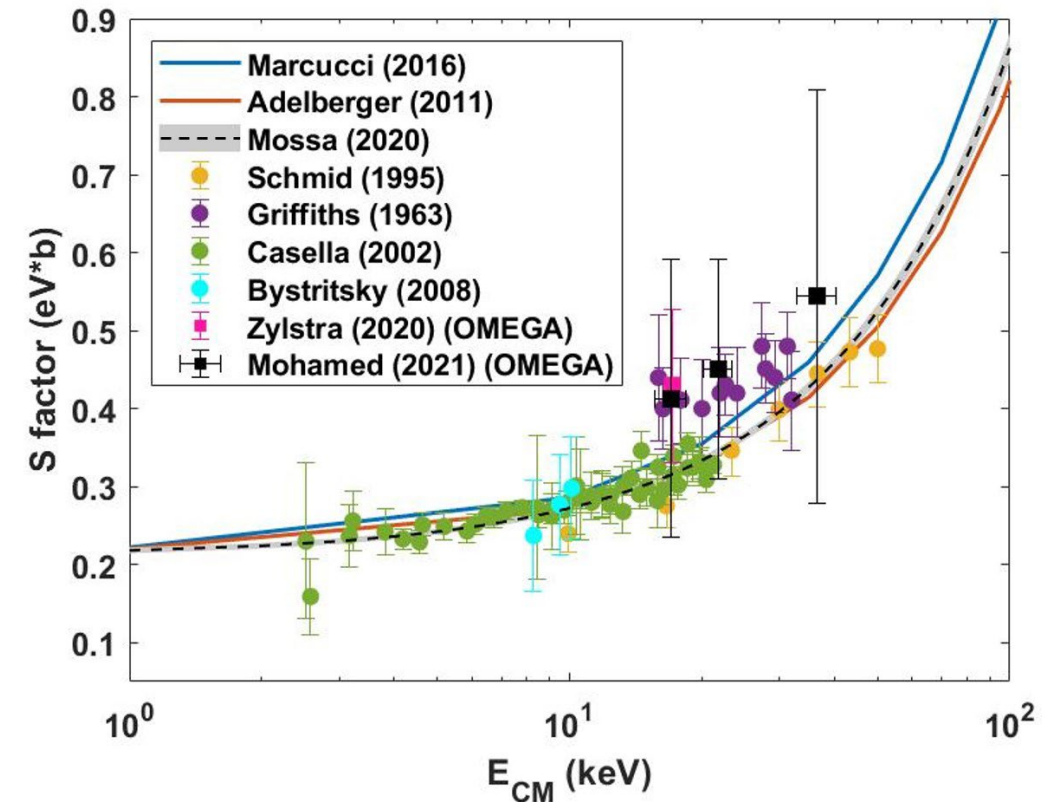
⁴Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

⁵Plasma Physics Department, AWE plc, Reading RG7 4PR, United Kingdom

(Received 22 September 2019; revised manuscript received 7 February 2020; accepted 6 April 2020; published 27 April 2020)

A second OMEGA experiment subsequently extended the p+D study to span a broader range of CM energies

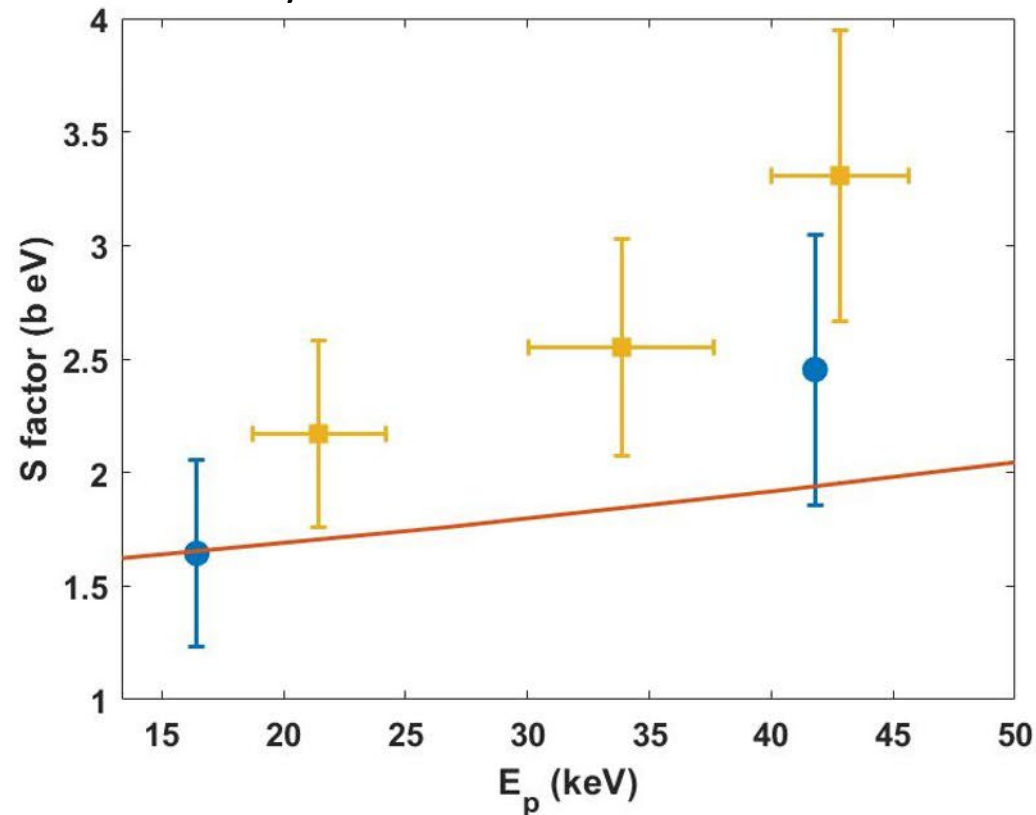
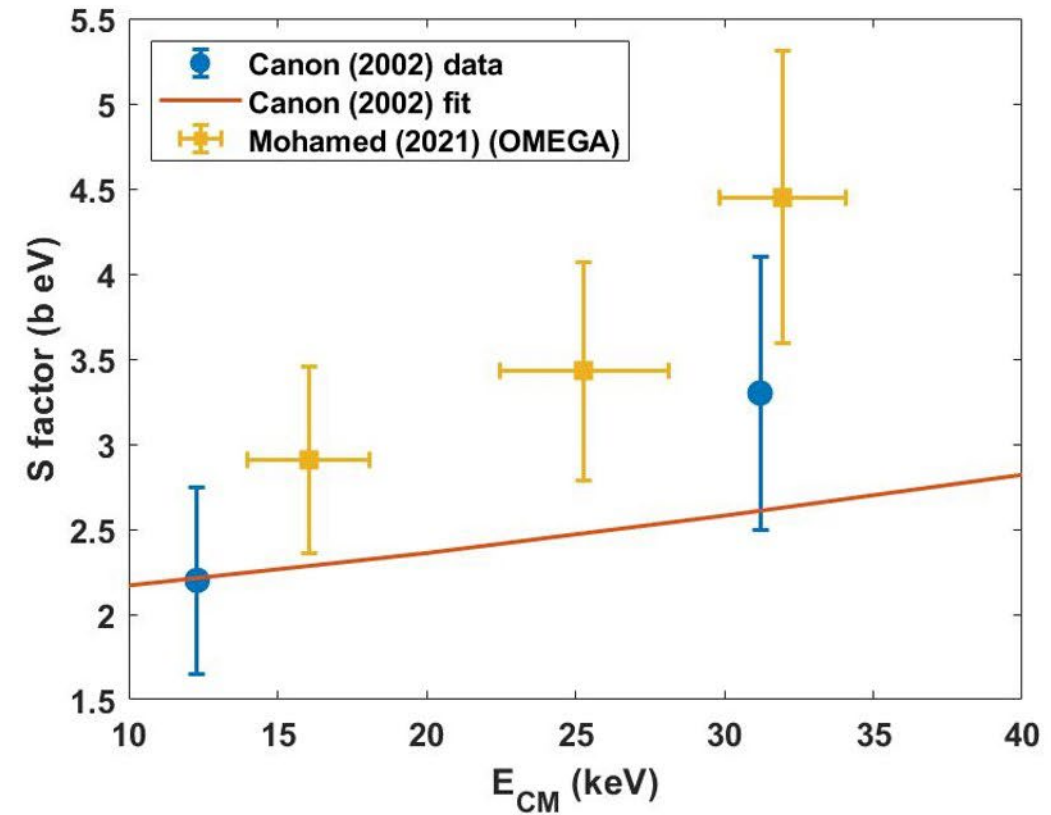
Work by Zaarah Mohamed



Z. Mohamed et al., Front. Phys. 10:944339. (2022); submitted to Phys. Rev. C (2022).

Implosions at OMEGA with the enabling GCD detectors also provided the first p+T S-factor measurements in an HED setting

Work by Zaarah Mohamed

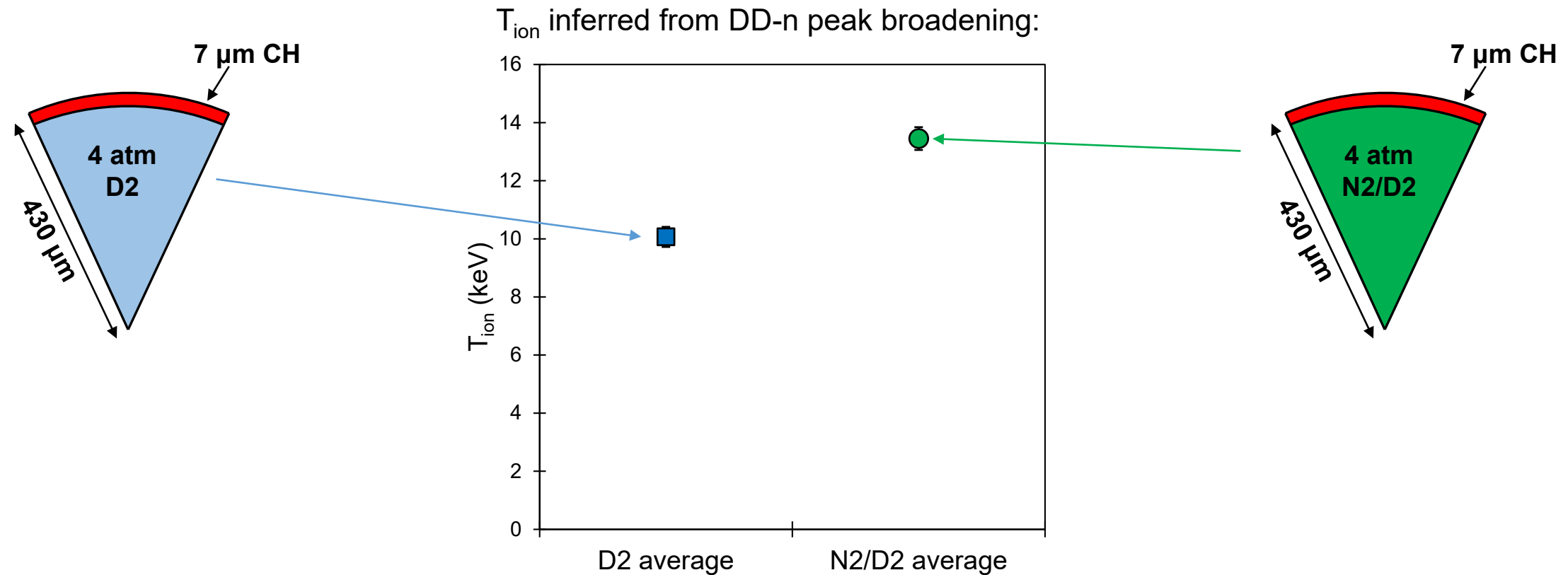


Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a promising new field with much still to learn

- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions:
 - ✓ Plasma environment
 - ✓ Hot and dense
 - ✓ High neutron flux achievable
- The NIF and OMEGA lasers are two primary facilities for executing experiments of this type
- Experiments are made possible by enabling nuclear diagnostics
- Initial results include spectral measurements for ${}^3\text{He}+{}^3\text{He}$ and the mirror $\text{T}+\text{T}$ reaction, and S-factor measurements for $\text{T}+{}^3\text{He}-\gamma$, $\text{p}+\text{D}$, $\text{p}+\text{T}$, and $\text{T}+\text{T}$
- Near-term work includes platform development for studying CNO-relevant reactions and electron screening effects; broad opportunities exist for additional efforts

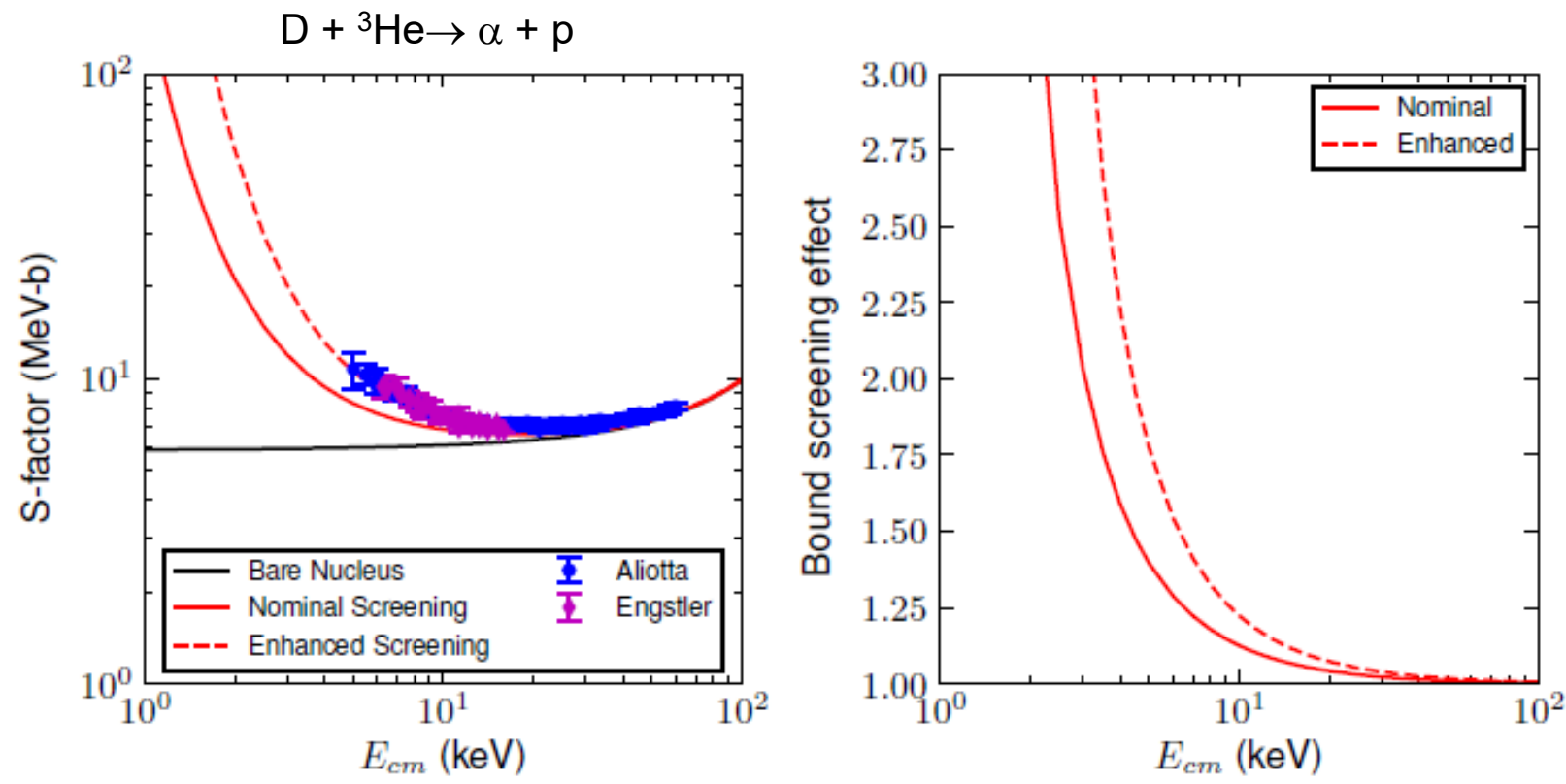
Early efforts have focused on low-Z ion reactions; platform development has started for studies of CNO-relevant mid-Z ion reactions

First test: Can high enough T_{ion} be maintained with mid-Z gas fill in the capsules?



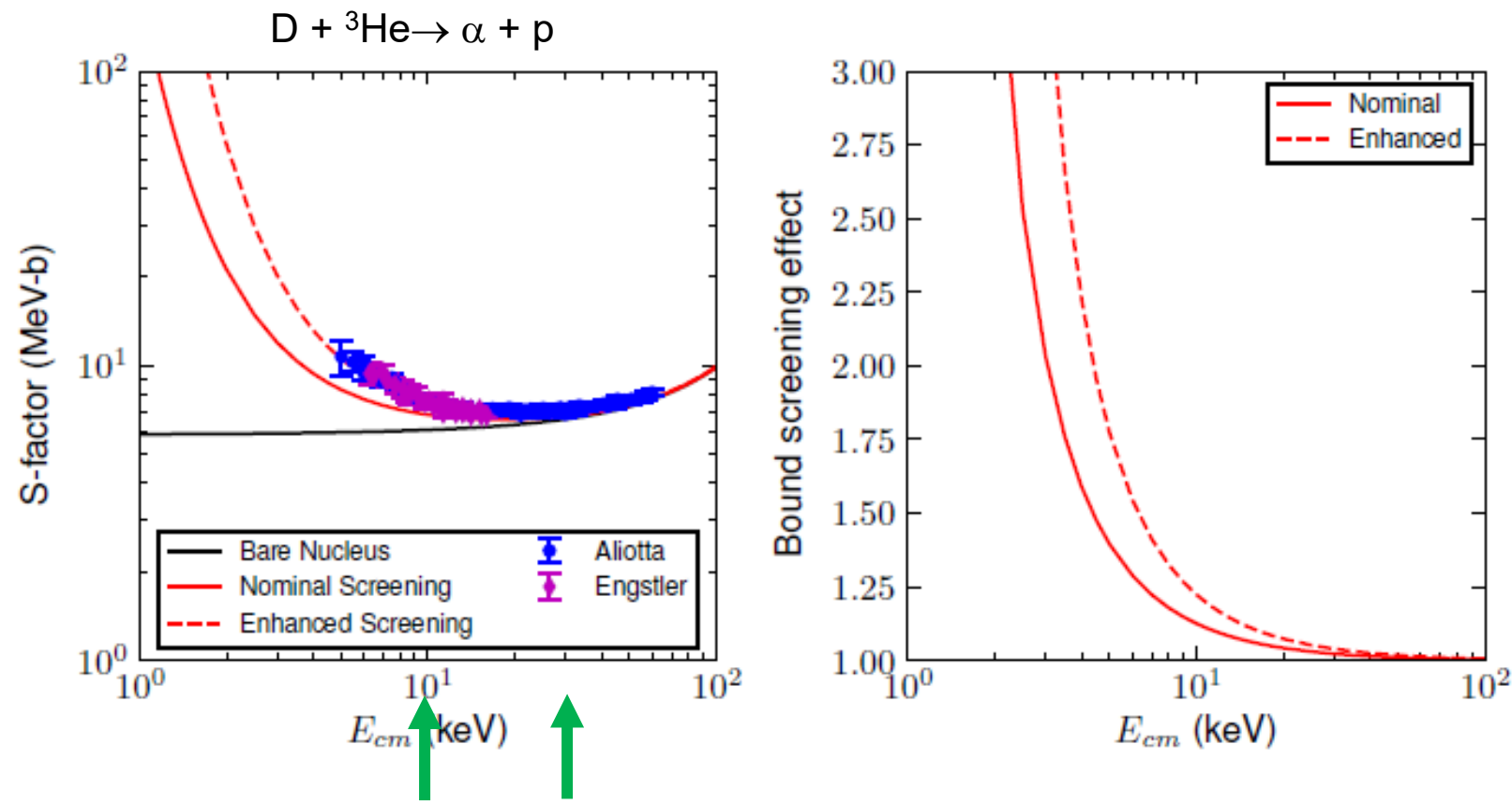
Gatu Johnson et al., “Impact of mid-Z gas fill on dynamics and performance of shock-driven implosions at the OMEGA laser”, submitted to Phys. Rev. E (2022).
Jeet et al., “Development of a platform for studying solar CNO reactions in an ICF plasma”, in preparation (2023)

An ongoing NIF experiment is addressing the impact of bound electron screening



M. Aliotta *et al*, NP A (2001).
 S. Engstler *et al.*, Phys. Lett. B (1988).

An ongoing NIF experiment is addressing the impact of bound electron screening



Working to probe
this range at NIF

M. Aliotta *et al*, NP A (2001).
S. Engstler *et al.*, Phys. Lett. B (1988).

The first step is to measure the bare nuclear cross section, but longer term, we want to measure plasma screening user higher density plasmas

- An experiment to probe plasma screening requires that the effect is larger than the experimental yield uncertainty

- Higher charge Z
 - Lower temperature kT
 - Higher density n
- } → larger screening effect:

- Lower $T_{\text{ion}} \rightarrow$ lower yield
- Higher density $\rightarrow$ charged particles won't escape

- Proposed path forward: Increase Z to get high screening in a feasible experiment
 - Design calculations under way to find the right regime
 - Effort to minimize experimental uncertainties in progress

Simplest plasma screening model¹⁾:

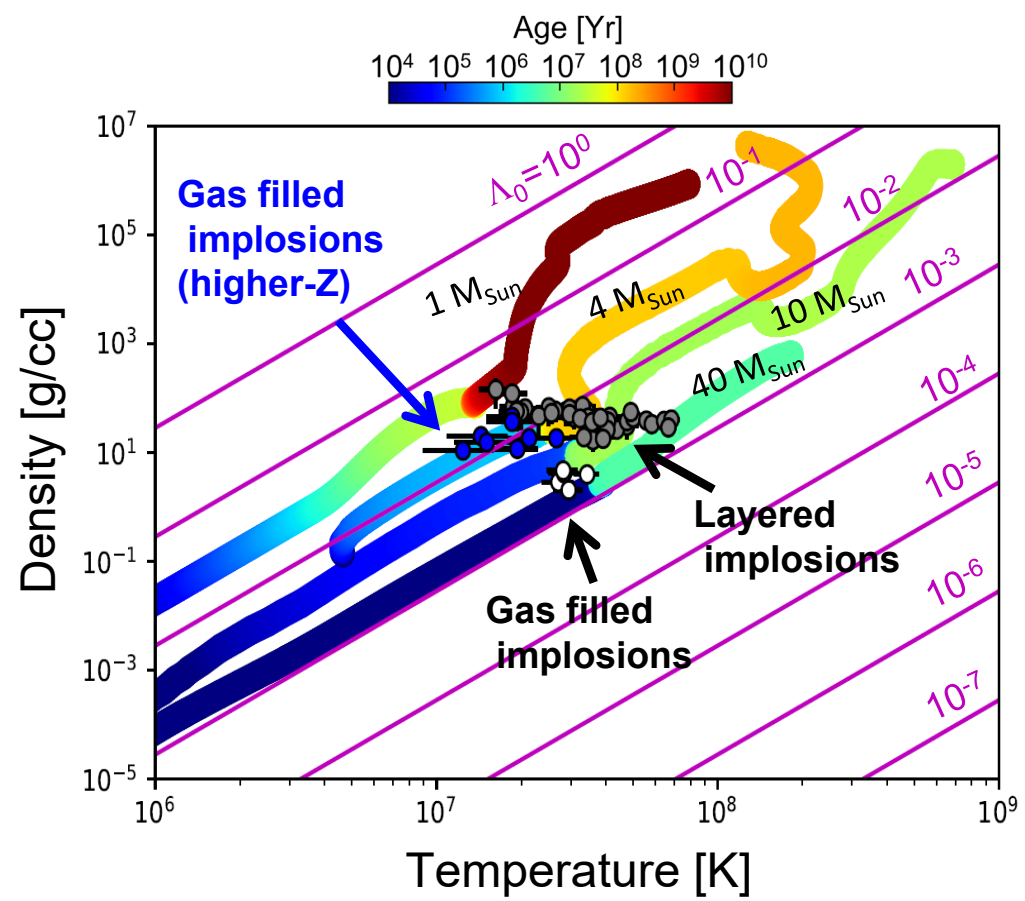
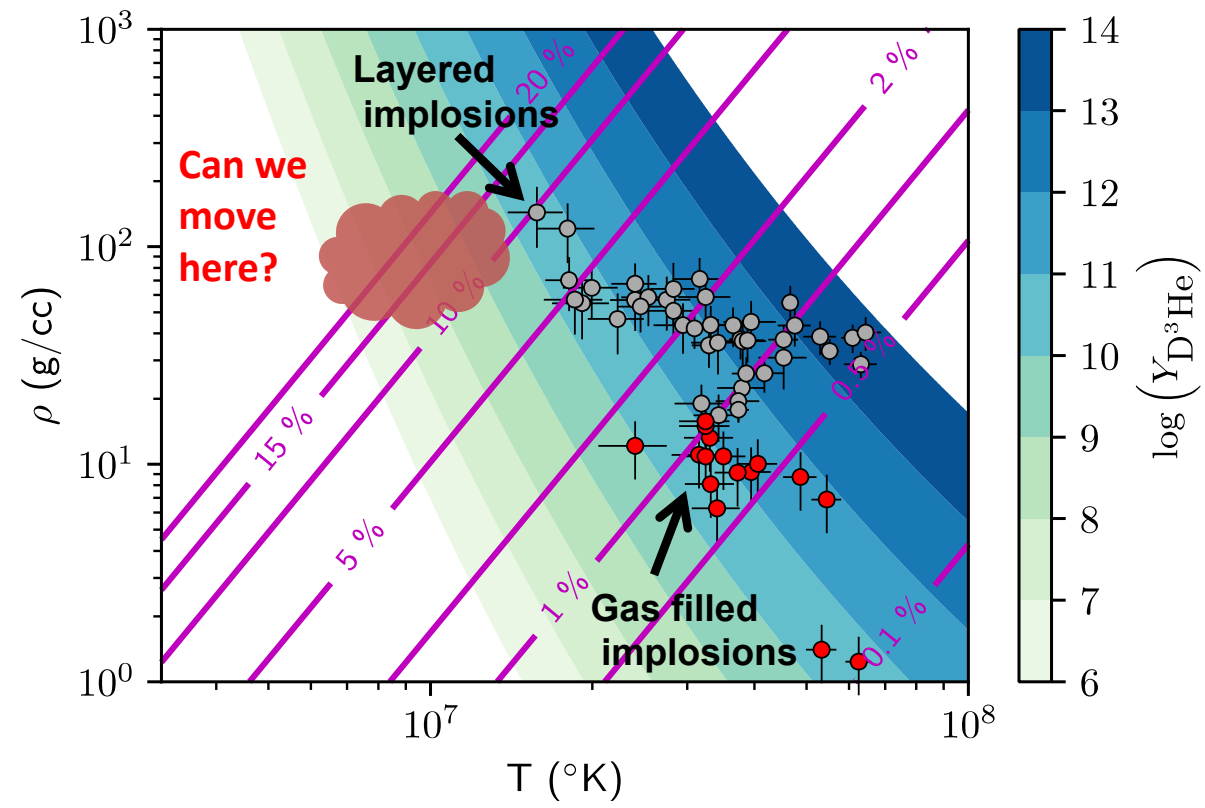
$$\frac{\sigma_{\text{screened}}}{\sigma} \approx e^{Z_1 Z_2 \tilde{z} \Lambda_0}$$

$$\Lambda_0 = (4\pi)^{1/2} e^3 n^{1/2} / (kT)^{3/2}$$

We are working on designing an experiment where plasma screening effects will be directly measureable

¹Salpeter, E. E., Aust. J. Phys. 7, 373. (1954)

Design calculations suggest that this might be achievable

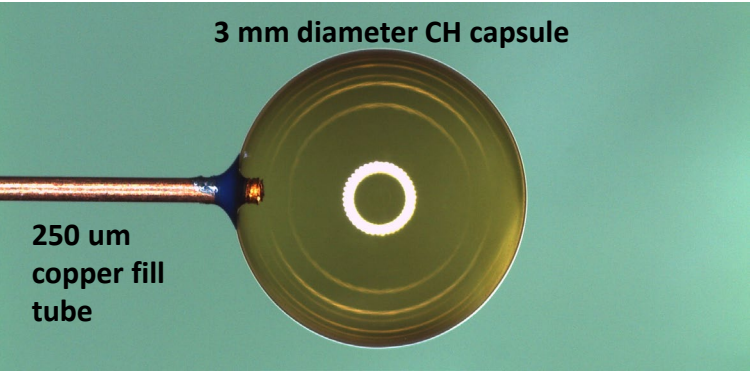


$$\frac{\sigma_{\text{screened}}}{\sigma} \approx e^{Z_1 Z_2 \tilde{z} \Lambda_0}$$

Might require development of a new higher-efficiency gamma detector

Proposed work aims to address neutron capture cross sections on s-process branch point nuclei in plasma environment

Coat inner shell with ^{171}Tm ($\sim 10^{15}$ atoms) and ^{89}Y ($\sim 10^{16}$ atoms)



Vary plasma conditions to tune ^{171}Tm ground state/ 1^{st} excited state ratio

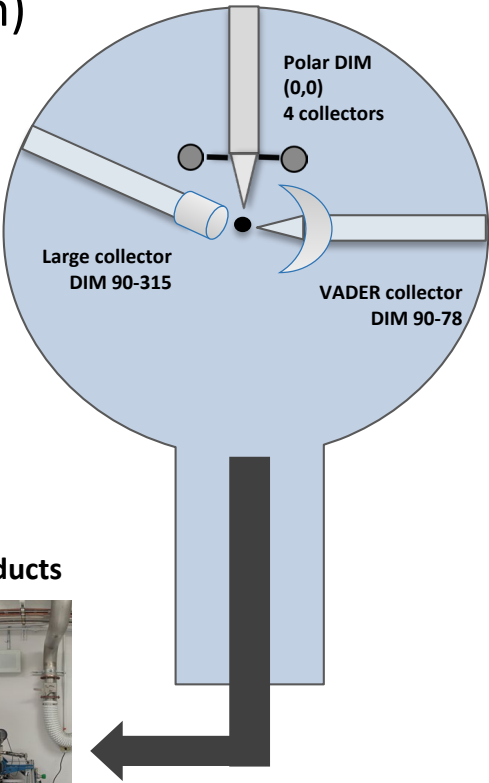
$^{171}_{69}\text{Tm}$							
E^*	$2J^\pi$	$2J^\pi$	C^2S	σ (τ, d)	S_N	σ (α, t)	$T_{1/2}$ or
[keV]		(τ, d)	(τ, d)	$\mu\text{b/sr}$	(α, t)	$\mu\text{b/sr}$	Γ_{cm}
0.0 ^a	1 ⁺	1 ⁺		30.6		64.5	1.92(1) yr
5.0361(11) ^a	3 ⁺	3 ⁺	$\langle 0.67 \rangle$	incl	$\langle 0.65 \rangle$	incl	4.77(8) ns
116.657(1) ^a	5 ⁺	5 ⁺	0.37	17.8	0.28	29.8	55(13) ps
129.054(1) ^a	7 ⁺	7 ⁺	0.28	3.6	0.15	3.1	415(20) ps
326.811(1) ^a	9 ⁺	9 ⁺	0.07	1.6	0.04	1.2	
347.800(8) ^a	11 ⁺						

Challenge: accurate knowledge of neutron spectrum

Measure reaction products using solid radiochemistry



Large area solid radiochemistry collector, 1-5%



Collection of noble gas products



Radiochemical Analysis of Gaseous Species (RAGS)

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

Charged-particle induced reactions:

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

Published
Ongoing
Proposed
Near future?

Proposed for
NIF

Neutron-induced reactions:

- $n\text{-d}$ and $n\text{-T}$ at 14 MeV [6]
- $D(n,2n)$ at 14 MeV [7]
- $T(n,2n)$ at 14 MeV
- Various (n,γ) processes
- $\text{Li}(n,2n)$, $\text{Be}(n,2n)$, 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

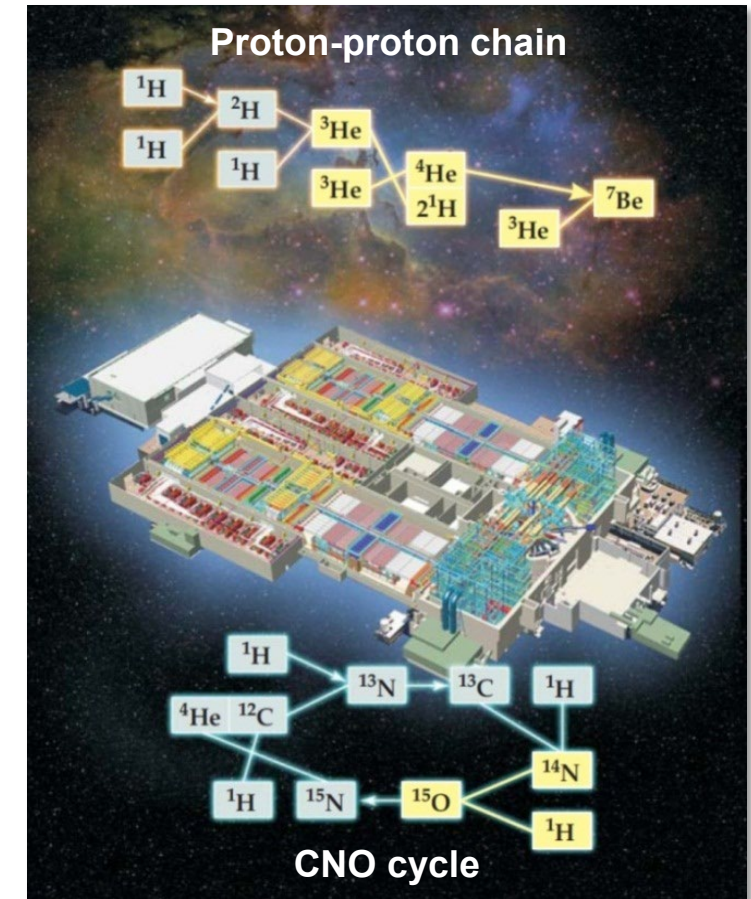
2-4: Zylstra et al., PRL 2016; Zylstra et al., PRL 2017

5: Kim et al., PoP and PRC (2012)

6: Frenje et al., PRL 2011

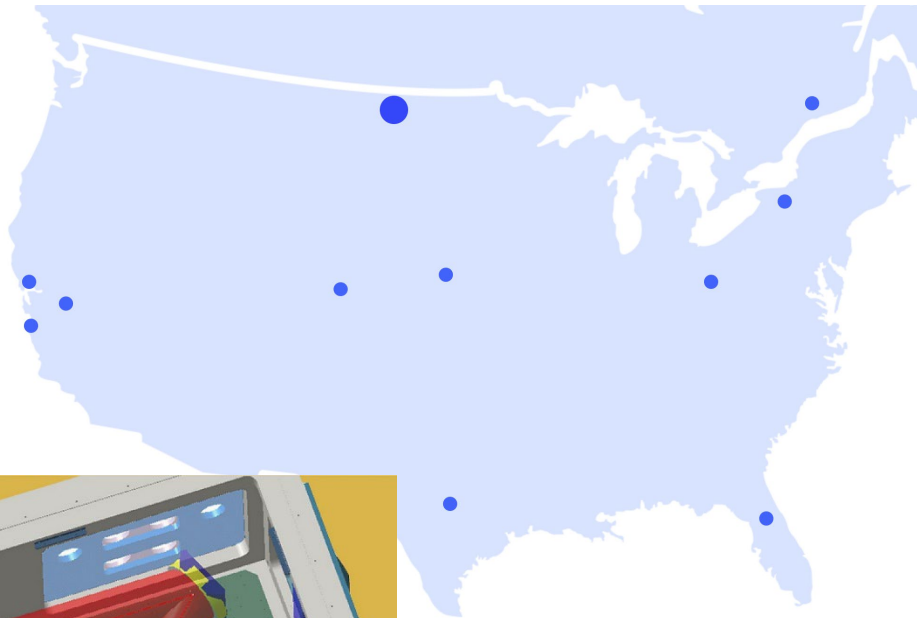
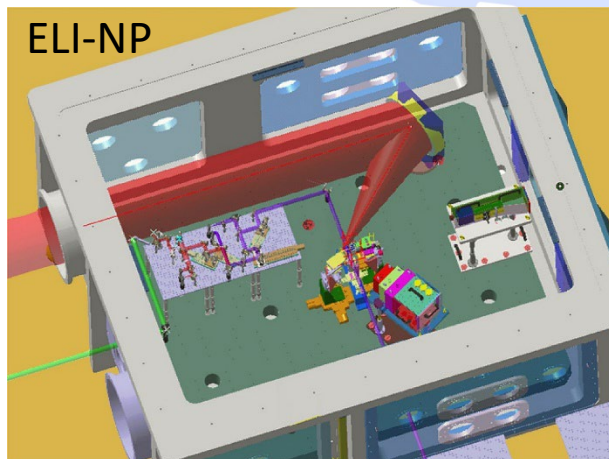
7: Forrest et al., NIM A 2018

8: Wiescher et al., Front. Phys 2022



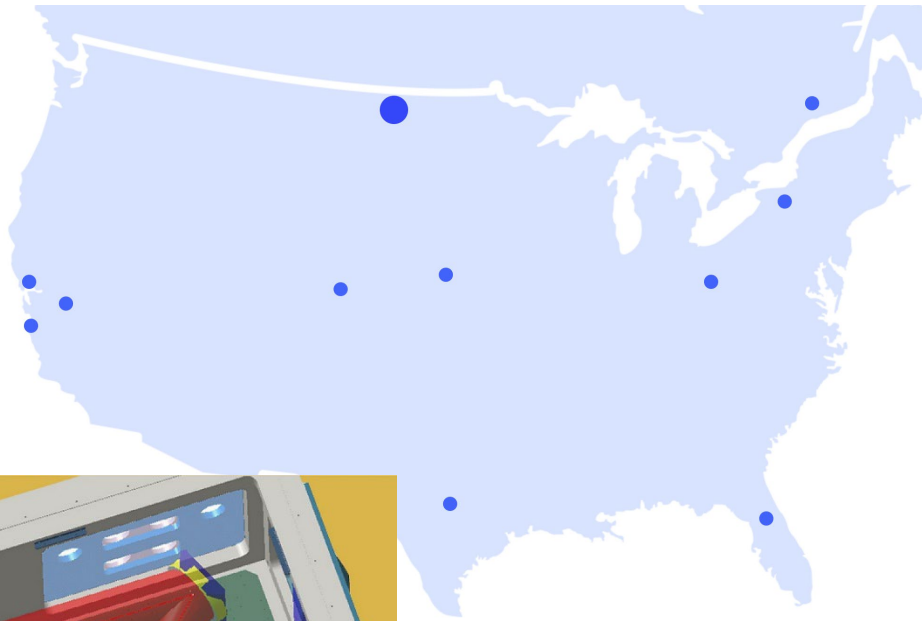
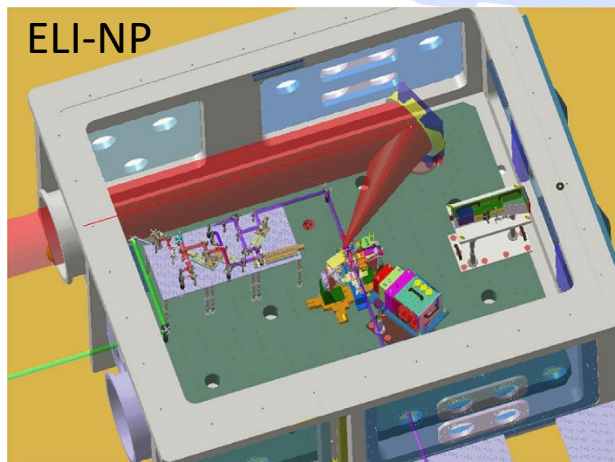
Short pulse lasers are another category of laser facilities potentially useful for nuclear astrophysics-relevant experiments

- LaserNet (US/Canada)
- Extreme Light Infrastructure
 - ELI-Nuclear Physics (Romania)



Short pulse lasers are another category of laser facilities potentially useful for nuclear astrophysics-relevant experiments

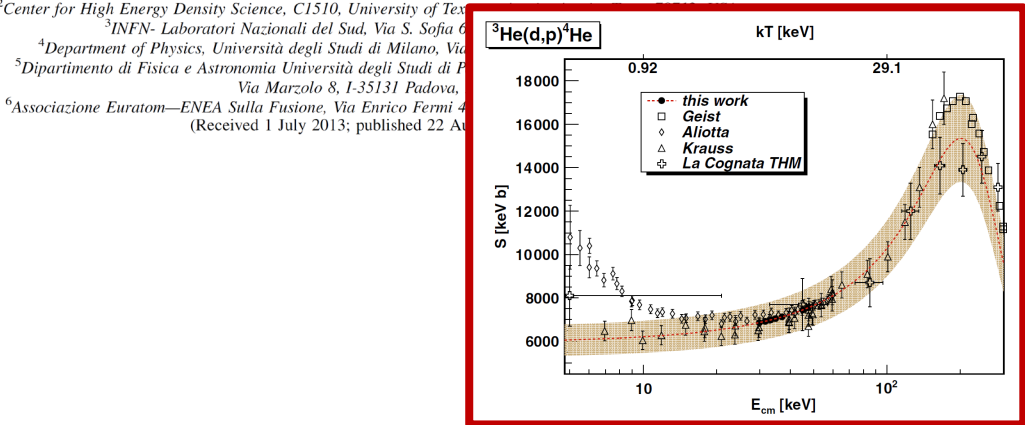
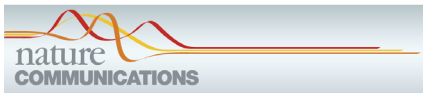
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- Extreme Light Infrastructure
 - ELI-Nuclear Physics (Romania)



PRL 111, 082502 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Measurement of the Plasma Astrophysical S Factor for the ${}^3\text{He}(d,p){}^4\text{He}$ Reaction in Exploding Molecular Clusters

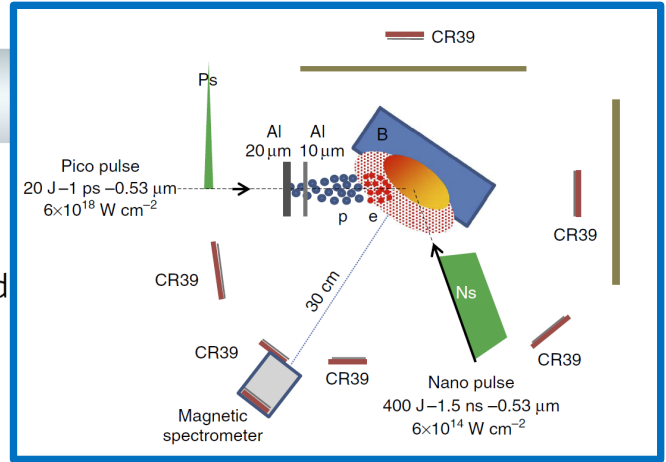
M. Barbui,^{1,*} W. Bang,^{2,†} A. Bonasera,^{3,1} K. Hagel,¹ K. Schmidt,¹ J. B. Natowitz,¹ R. Burch,¹ G. Giuliani,¹ M. Barbarino,¹ H. Zheng,¹ G. Dyer,² H. J. Quevedo,² E. Gaul,² A. C. Bernstein,² M. Donovan,² S. Kimura,⁴ M. Mazzocco,⁵ F. Consoli,⁶ R. De Angelis,⁶ P. Andreoli,⁶ and T. Ditmire²
¹Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
²Center for High Energy Density Science, C1510, University of Texas
³INFN- Laboratori Nazionali del Sud, Via S. Sofia 6
⁴Department of Physics, Università degli Studi di Milano, Via
⁵Dipartimento di Fisica e Astronomia Università degli Studi di Padova, Via Marzolo 8, I-35131 Padova, Italy
⁶Associazione Euratom-ENEA Sulla Fusione, Via Enrico Fermi 4



ARTICLE
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DOI: 10.1038/ncomms3506

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune¹, C. Baccou¹, S. Depierreux², C. Goyon², G. Loisel¹, V. Yahia¹ & J. Rafelski³



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

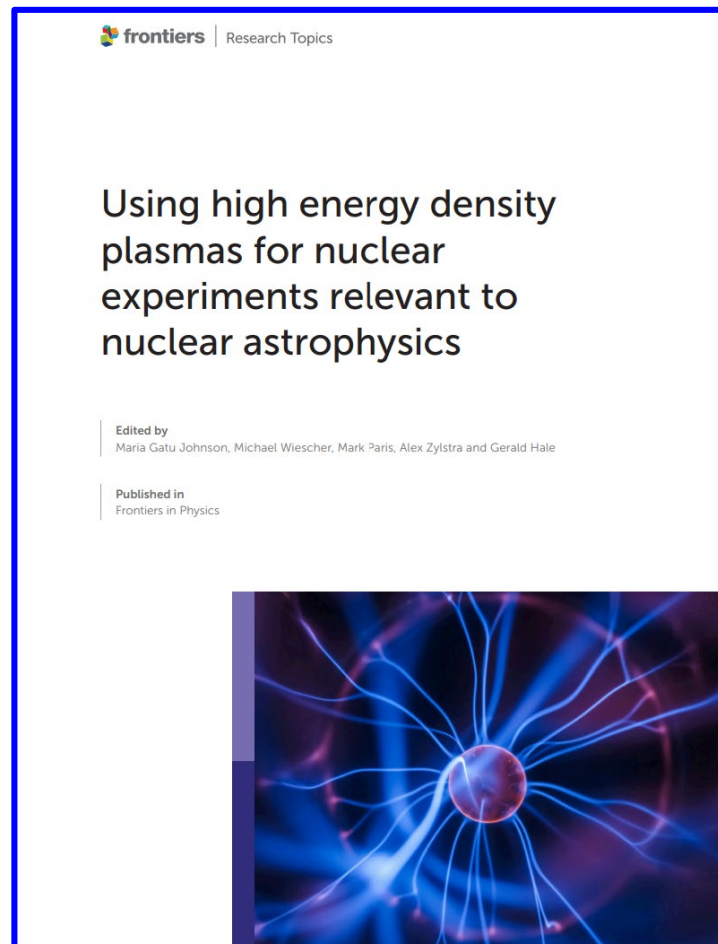


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<https://www.frontiersin.org/research-topics/29357/using-high-energy-density-plasmas-for-nuclear-experiments-relevant-to-nuclear-astrophysics>

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- Near-term work includes platform development for studying CNO-relevant reactions and electron screening effects; broad opportunities exist for additional efforts