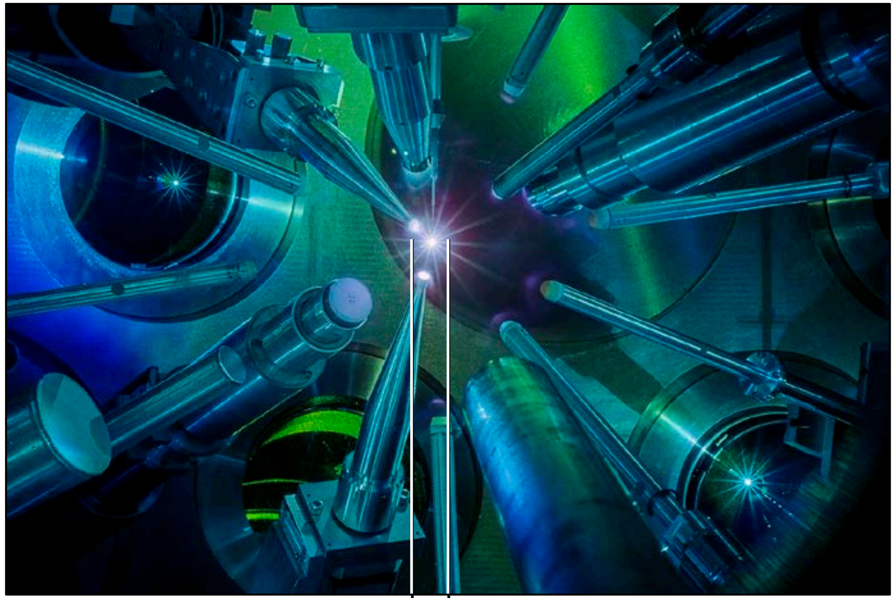
Nuclear Science at the University of Rochester's Omega Laser Facility



100-μm diam

C. J. Forrest
University of Rochester
Laboratory for Laser Energetics

Texas A & M University
College Station, TX
13 June 2019

Summary

Studying fundamental nuclear physics using high-energy-density plasmas complements experiments performed on accelerators

- Inertial confinement fusion (ICF) lasers have unique capabilities to
  - achieve plasma conditions to study nuclear reactions relevant for stellar nucleosynthesis (SN) and big-bang nucelosynthesis (BBN)
  - generate a bright neutron source with a luminosity of $L = 10^{24}\ s^{-1}$ to induce the breakup of light-z nuclei
  - perform measurements with a high signal-to-background from the short duration of the experiment (100 ps)
- Experiments using TNSA* have demonstrated nuclear reactions initiated by laser-accelerated ions onto solid targets using the OMEGA EP laser
  - explore light-ion nuclear reactions using an ion beam with the joint capabilities of OMEGA/OMEGA EP
  - study the six-nucleon system with a MeV triton beam (T-LIANS)**

* TNSA: target normal sheath acceleration
** T-LIANS: tritium laser ion acceleration for nuclear science

Collaborators

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Los Alamos National Laboratory

W. Martin and B. Augierre
Sandia National Laboratories

Outline

- Science of fusion—large lasers are used for high-energy-density physics (HEDP) (defined generally as pressures above 1 Mbar)
- Nuclear experiments to date
  - target ions in the fusing hot spot (DT, TT, $^3He^3He$)
  - target nuclei outside of the source target (deuterium breakup)
  - laser-accelerated ions (protons, deuterons)
- Upcoming experiments
  - laser-accelerated ion (tritons) onto tritiated foils

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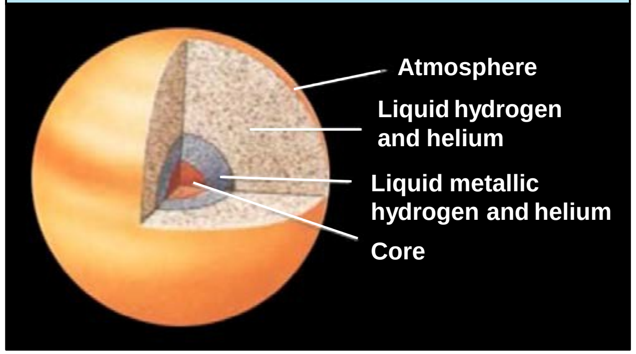
LLE is a university-based research center of scale with multiple missions supporting the Department of Energy (DOE)

Inertial confinement fusion (ICF)

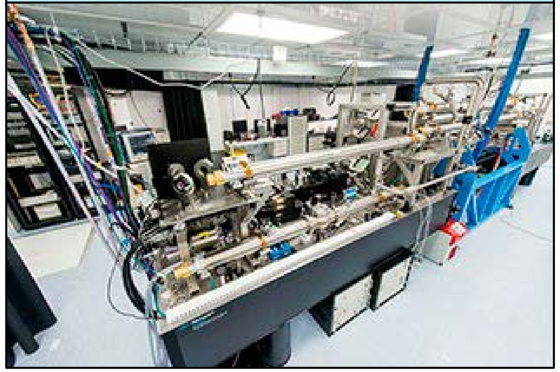
Experiments, modeling, diagnostics, and innovation

High-energy-density physics (HEDP)



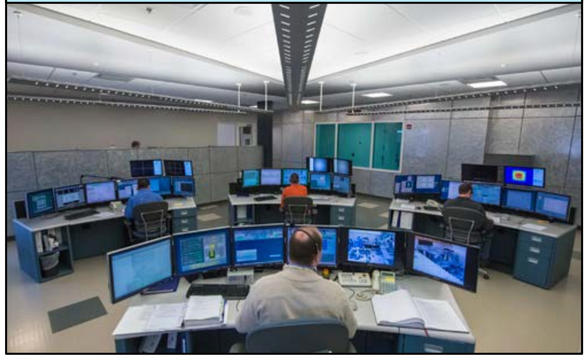
(P, ρ, T) of materials of interest to SSP and science (stars, planets, novel materials)

Laser technology



Dynamic Compression Sector (DCS) laser

Facility operations: 80% of the shots for ICF/HEDP research



OMEGA EP Control Room

Sustain the essential skills and develop future scientists

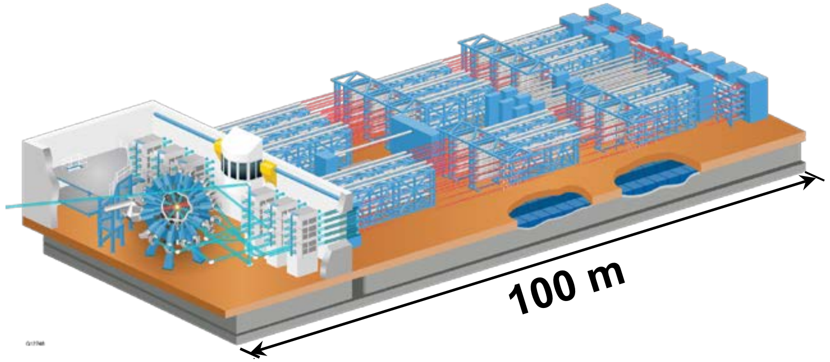
>500 Ph.D. degrees based on LLE-sponsored and OMEGA based research

LLE-trained national leaders

SSP: Stockpile Stewardship Program

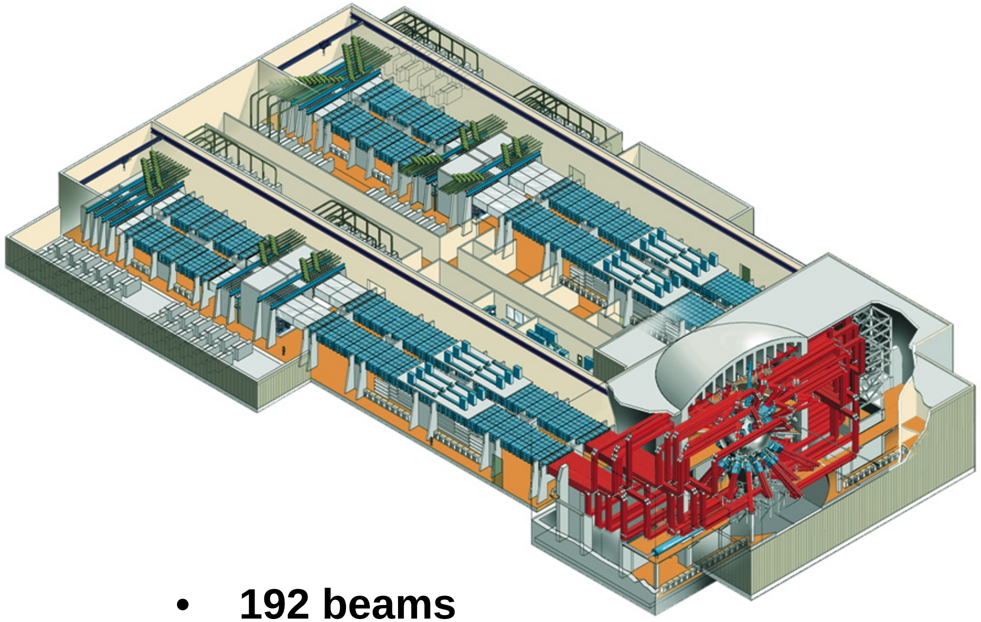
ICF lasers create pressures of ~100 Gbar or more and plasma temperatures up to 30 keV (E_{CM} ~ 100 keV)

The OMEGA Laser System



- 60 beams
- Symmetric configuration
- Maximum 30 kJ_{UV} on target
- Up to 16 shots/day (1600/yr)
- 3.2-m target chamber
- DT fusion Y_n up to 2×10^{14}
- <40-μm-diam hot spot
- <100-ps burn

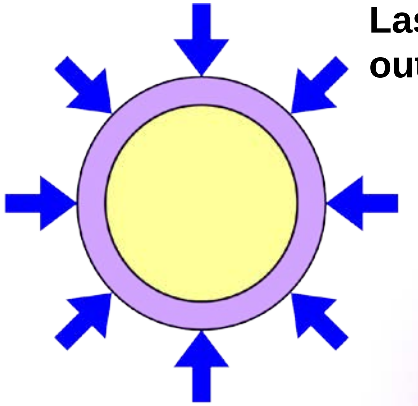
The National Ignition Facility



- 192 beams
- Polar configuration
- Maximum 1.9 MJ_{UV} on target
- Up to 3 shots/day (400/yr)
- 10-m target chamber
- DT fusion Y_n up to 1×10^{16}
- 40- to 50-μm-diam point source
- <100-ps burn

High-energy-density plasmas are created by spherically compressing a capsule using an ICF platform

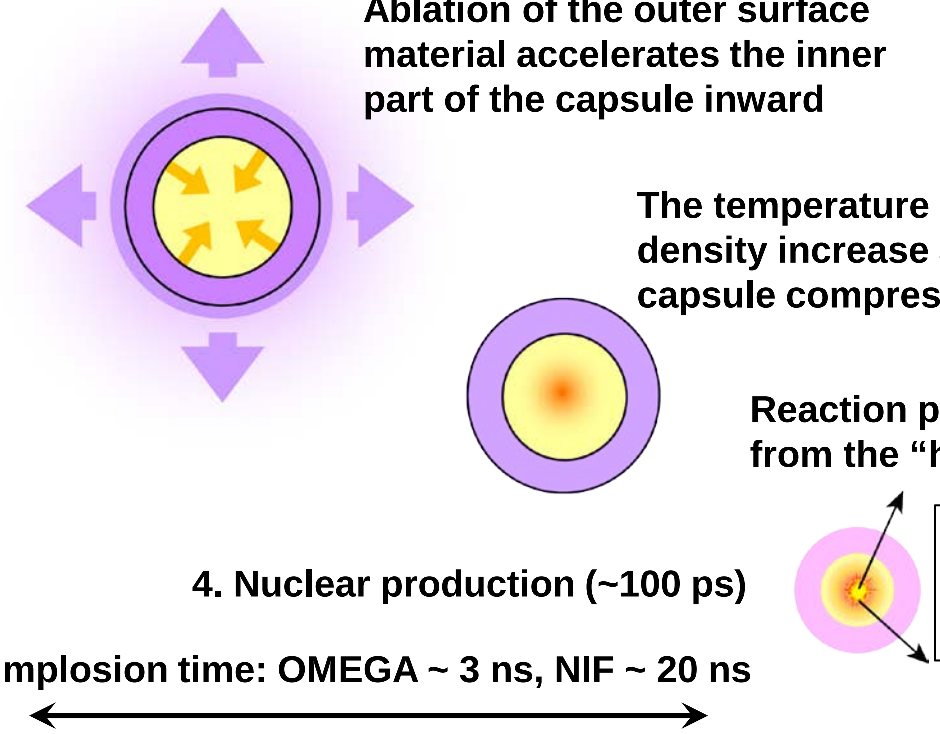
LLE
direct-drive target



Lasers (or x rays) irradiate and heat the outer surface of the capsule (CH, HDC,* Be)

DT, DD, D^{3}He with dopants

Ablation of the outer surface material accelerates the inner part of the capsule inward



The temperature and density increase as the capsule compresses

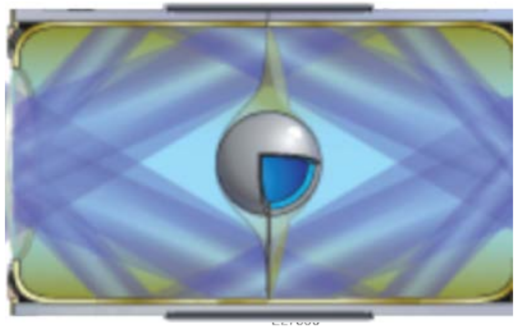
Reaction products from the "hot spot"

P ~ 100 Gbar
ρR: 250 mg/cm^2
T_i: 30 keV (E_{CM} ~ 100 keV)

4. Nuclear production (~100 ps)

Implosion time: OMEGA ~ 3 ns, NIF ~ 20 ns

NIF
indirect-drive target



* HDC: high-density carbon

An annual National Diagnostics Working Group (NDWG) meeting is dedicated to advancements in diagnosing high-energy-density plasmas

National Diagnostic Working Group
LLE, December, 2018

LLE = 32
LLNL = 30
LANL = 10
SNL = 10
CEA = 9
MIT = 8

Total = 127 (2018)

- **The challenge is to diagnose plasma conditions of the order of 10 ps to 100 ns (current mode)**
- **This is a very different approach as compared to accelerator-based measurements (single-particle counting)**

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Recent experiments exploring nuclear science and astrophysics with HEDP plasmas have been published using NNSA above ground facilities

To date HED plasmas have been used to probe

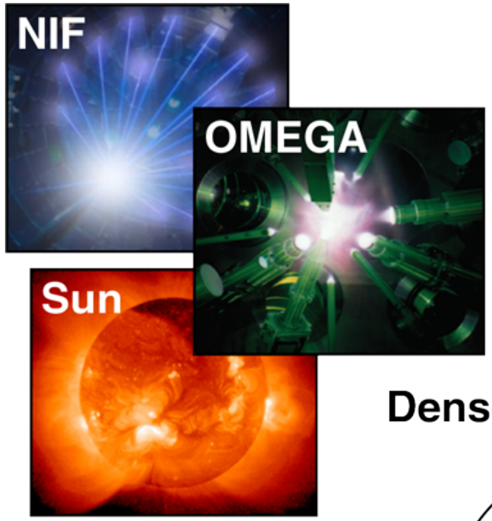
• (n, D) and (n, T) elastic scattering*	(target is the fuel)
• D(n, 2n) breakup reaction**	(shell is the target in 4π flux/external target in-line)
• T + T reaction†	(reaction rate)
• ^{3}He + ^{3}He reaction‡	(reaction rate; hydrogen-burning stars)
• T + ^{3}He reaction‡	(reaction rate for BBN and ^{6}Li abundance
• D(t, γ)^{5}He	(γ branching ratio; basic nuclear science)
• ^{9}Be(d, n)^{10}B	(induce direct reaction)
• ^{6}Li + T reaction	(nuclear structure of halo nuclei)

We can perform measurements with a high signal-to-background ratio as a result of the short duration of the experiment (100 ps).

NNSA: National Nuclear Security Administration

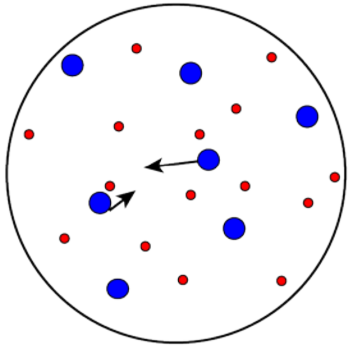
* J. A. Frenje *et al,* Phys. Rev. Lett. 107, 122502 (2011).
**C. J. Forrest *et al.,* Nucl. Instrum. Methods Phys. Res. A 888, 169 (2018).
† D. B. Sayre *et al.*, Phys. Rev. Lett. 111, 052501 (2013).
‡ A. B. Zylstra *et al*., Phys. Rev. Lett. 119, 222701 (2017).
Y. Kim *et al*., Phys. Plasmas 19, 056313 (2012).

The conditions in HEDP plasmas (and in stars) are quite different from those created by accelerators



Debye screening

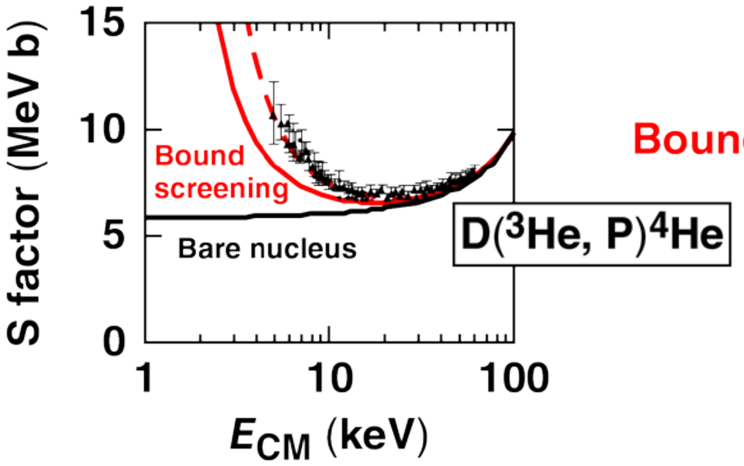
Dense and hot plasma



Thermal ions
Thermal electrons

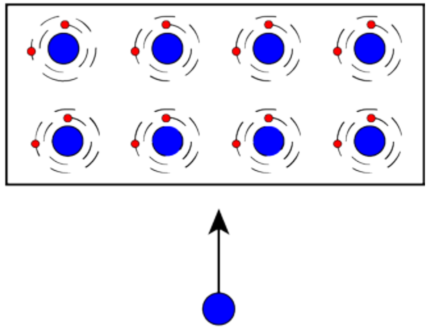
E27392

Screening potentional enhanced to match data



Cold target

Ions
Bound electrons

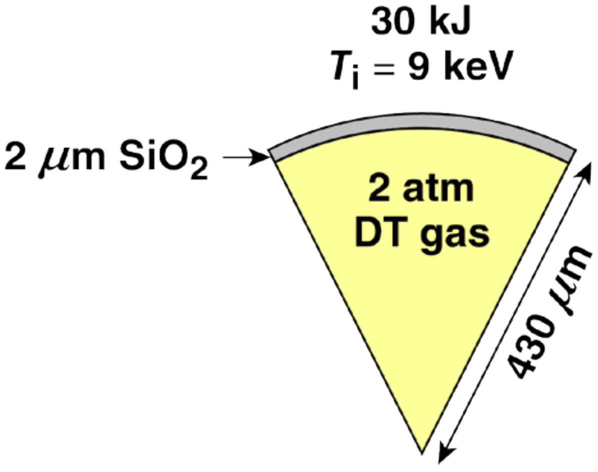


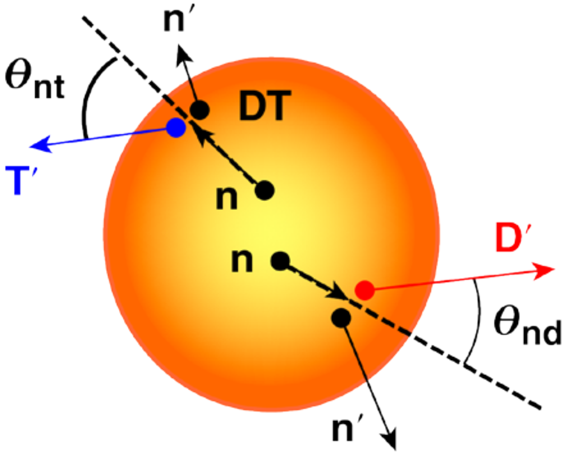
Monoenergetic ion

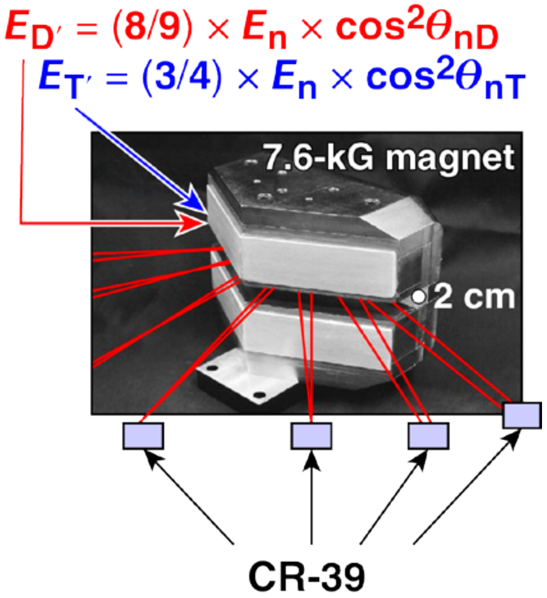
M. Aliotta *et al.*, Nucl. Phys. A 690, 7900 (2001);
U. Schröder *et al.*, Nucl. Instrum. Methods Phys. Res. B 40/41, 466 (1989);
H. J. Assenbaum, K. Langanke, and C. Rolfs, Z. Phys. A 327, 461 (1987).

First measurement of the $d\sigma/d\Omega$ for (n, D) and (n, T) elastic scattering at E_n = 14 MeV on the OMEGA Laser

UR LLE







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D + T → ^{4}He + n (source reaction)

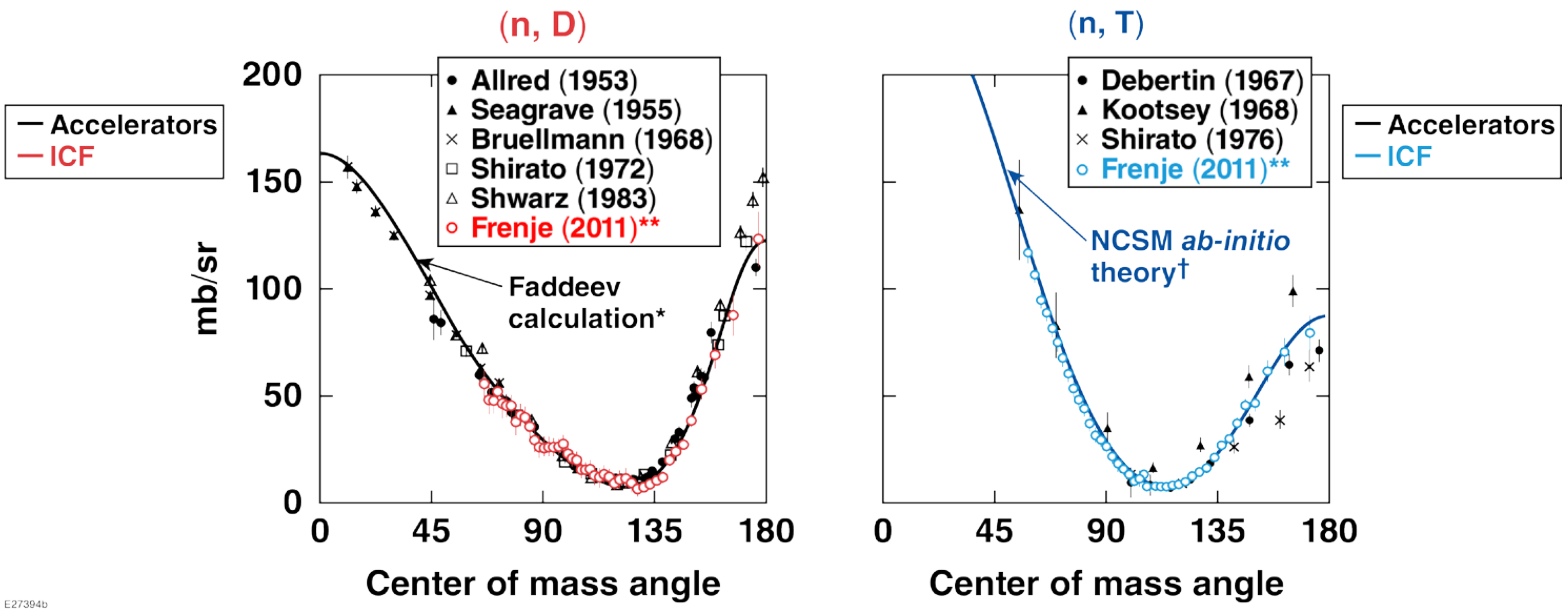
n(14 MeV) + D → n′(1.6 – 14 MeV) + D′(<12.5 MeV)
n(14 MeV) + T → n′(3.5 – 14 MeV) + T′(<10.6 MeV)

Charged-particle spectrometer (CPS)

The HED plasma serves as the neutron source and the target.

J. A. Frenje *et al,* Phys. Rev. Lett. 107, 122502 (2011).

The (n, T) and (n, D) elastic scattering cross sections were measured with higher quality than obtained in accelerator experiments

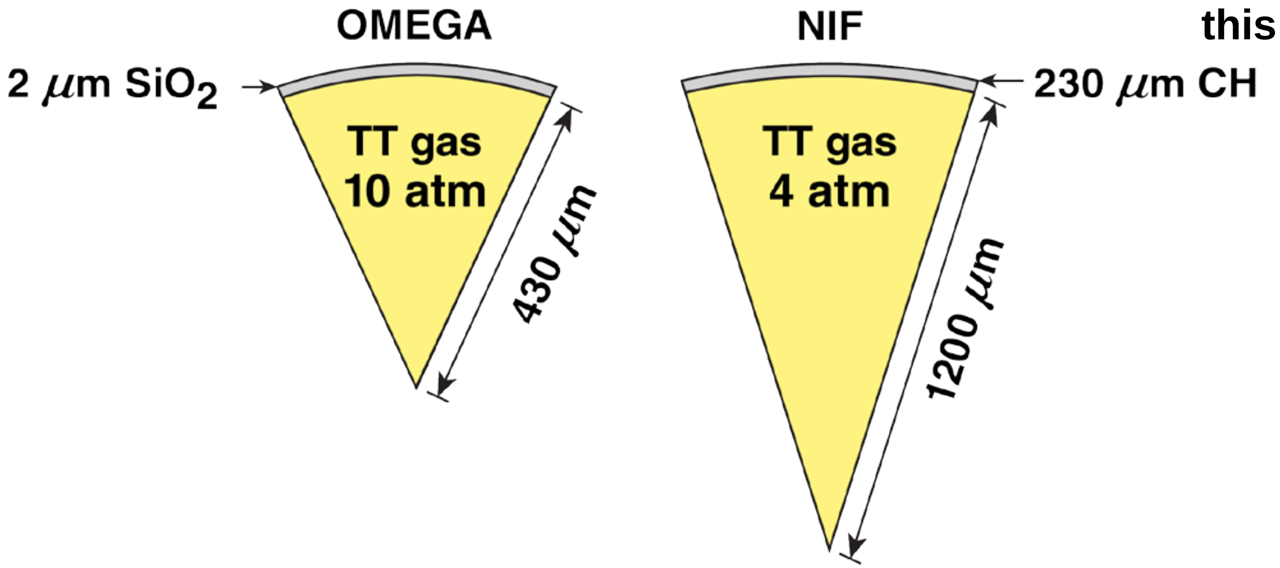


This experimental campaign was completed in a single shot day.

* E. Epelbaum *et al.*, Phys. Rev. C 66, 064001 (2002).
** J. A. Frenje *et al.*, Phys. Rev. Lett. 107, 122502 (2011).

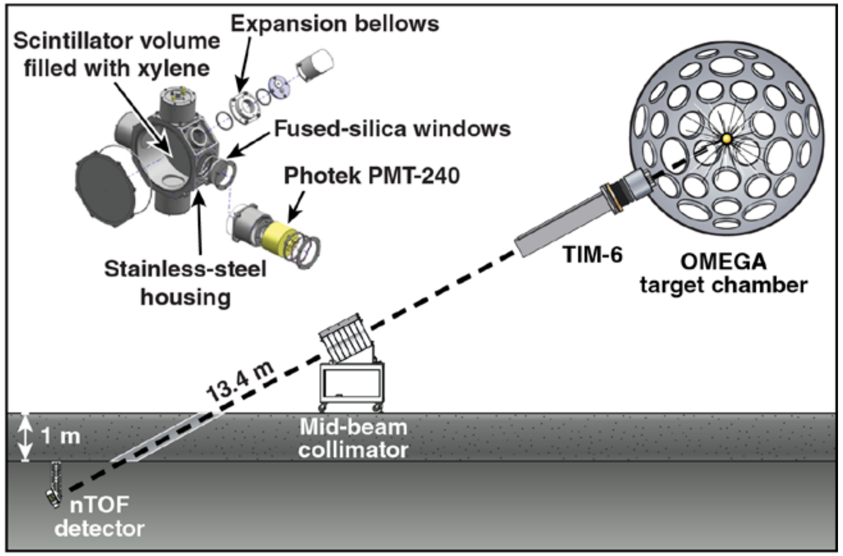
† P. Navrátil *et al.*, Lawrence Livermore National Laboratory, Livermore, CA, Report LLNL-TR-423504 (2010).

Full calculations of six-nucleon reactions with a three-body final state has been a long-standing physics issue



T + T	→	^{5}He (1.7 MeV) + n (8.7 MeV)
	→	^{5}He* (~4.4 MeV) + n (~6 MeV)
	→	^{4}He (0 to 3.5 MeV) + 2n (0 to 9.4 MeV)
	→	^{4}He + (nn)

A neutron transport code (*MCNP*)* was used to model this line of sight to increase the signal to background



Understanding the T + T reaction has important implications for
1. basic nuclear physics
2. stellar nucleosynthesis
3. inertial confinement fusion

* X-5 Monte Carlo Team, Los Alamos National Laboratory, Los Alamos, NM, Report LA-UR-03-1987 (2008).
nTOF: neutron time of flight
TIM: ten-inch manipulation

Measurements of the T + T fusion neutron spectrum have been made at E_{CM} ~ 16 keV on the NIF and E_{CM} ~ 16 to 50 keV on OMEGA

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]

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[6]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[7]*General Atomics, San Diego, California 92121, USA*
(Received 25 May 2013; published 2 August 2013)

First experimental evidence of a variant neutron spectrum from the T(T,2n)α 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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[2]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA
[3]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[4]Indiana University, Bloomington, IN 47405, USA
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[6]Ohio University, Athens, Ohio 45701, USA
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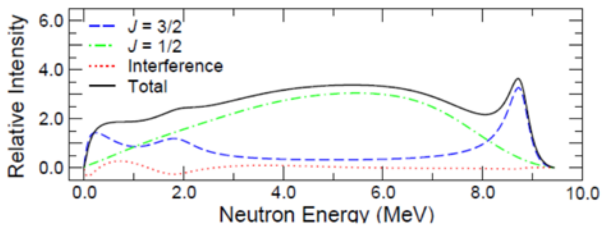
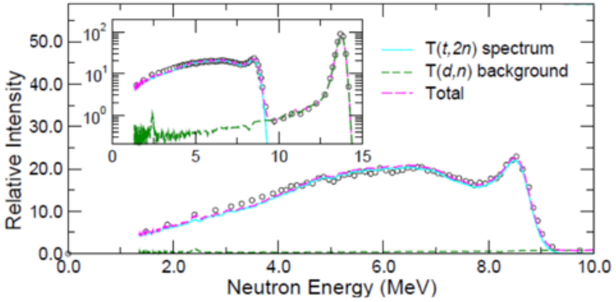
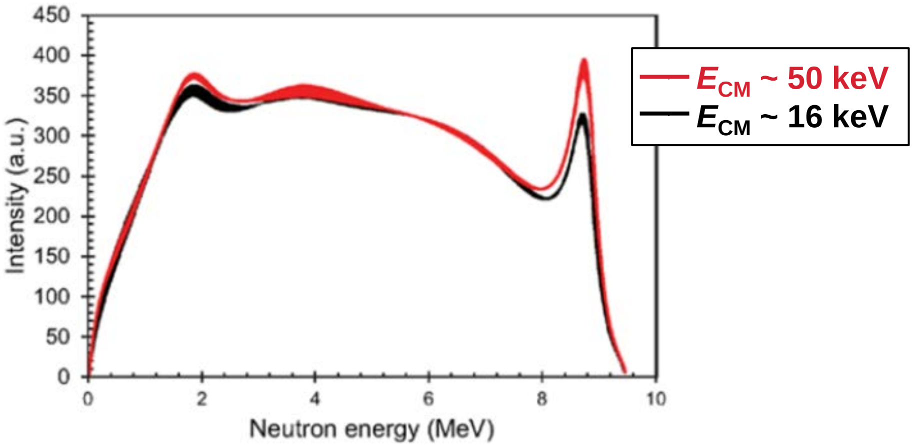




E_{CM} ~ 16 keV



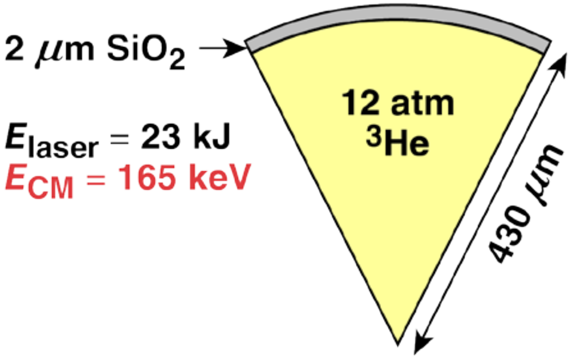
Presently there are two competing theories to describe the data

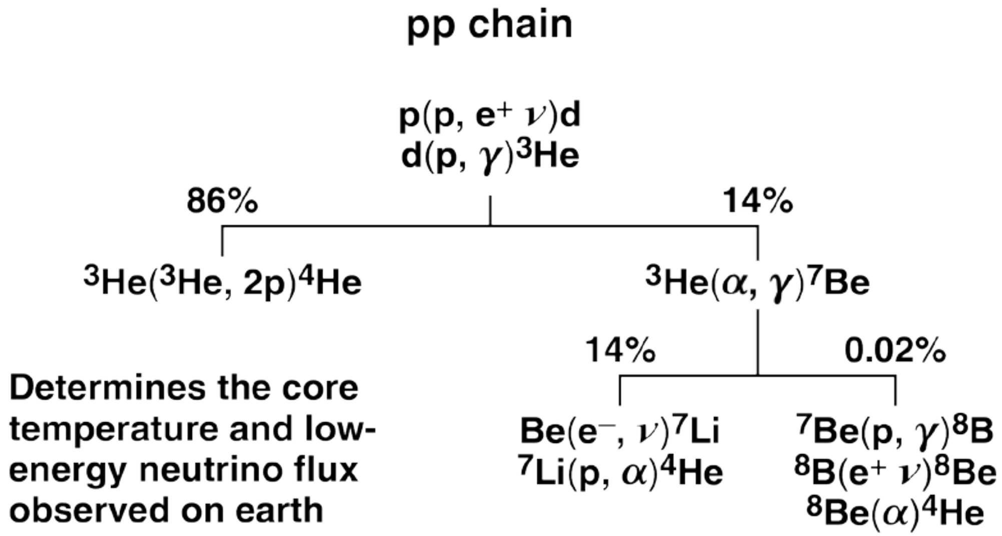
- R-matrix analysis
- wave-function amplitude

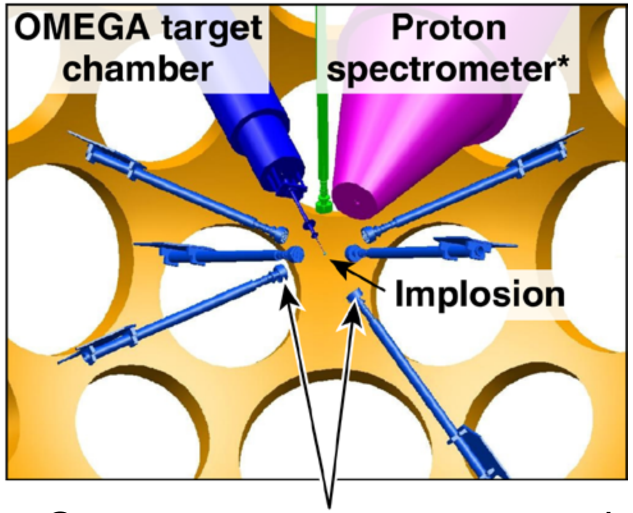
D. B. Sayre *et al.*, Phys. Rev. Lett. 111, 052501 (2013).

M. Gatu Johnson *et al.*, Phys. Rev. Lett. 121, 042501 (2018).

The ^{3}He + ^{3}He reaction is a main part of the proton–proton solar chain







Compact proton spectrometers*

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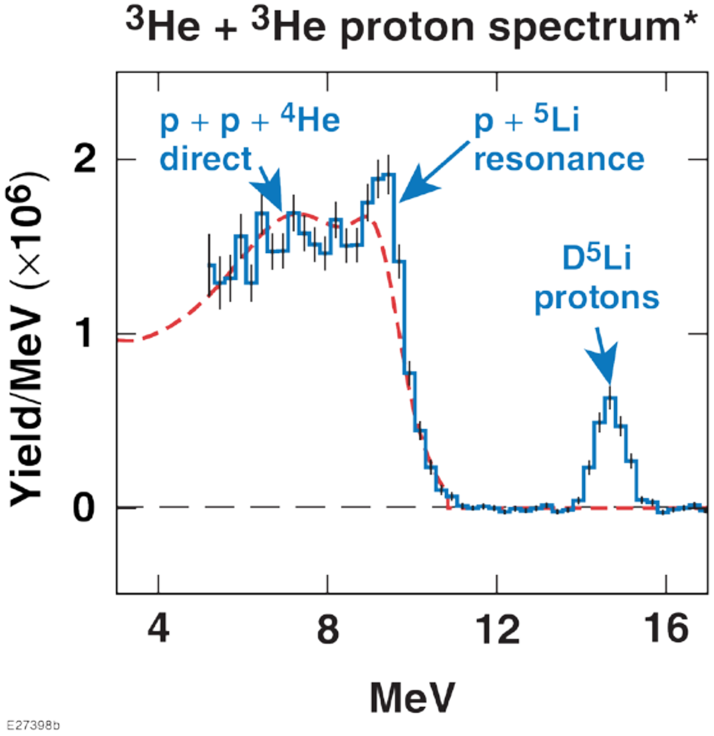
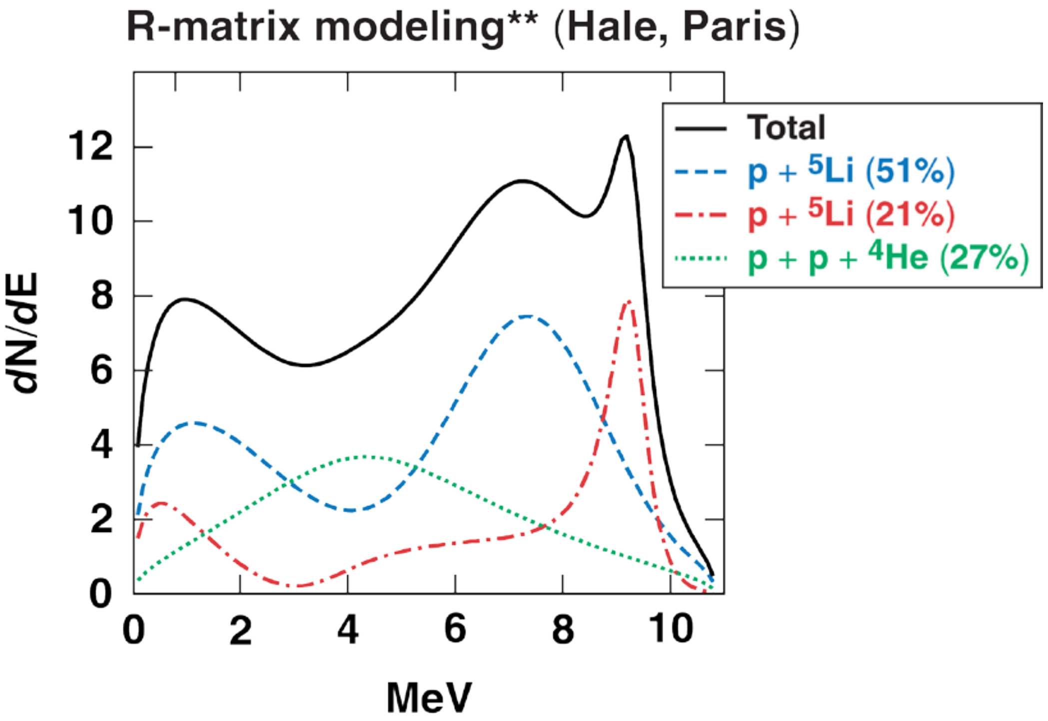
$$
\begin{aligned}
{}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + 2\mathrm{p}\ (0 \text{ to } 10.8\ \mathrm{MeV}) \\
&\rightarrow {}^5\mathrm{Li} + \mathrm{p}\ (9.2\ \mathrm{MeV}) \\
&\rightarrow {}^5\mathrm{Li}^* + \mathrm{p}
\end{aligned}
$$

*F. H. Séguin *et al.*, Rev. Sci. Instrum. 74, 975 (2003).

The measured ^{3}He + ^{3}He proton spectrum suggests p + ^{5}Li and p + p + ^{4}He components in final state at E_{CM} = 165 keV





The ^{3}He + ^{3}He reaction is a mirror of the T + T reaction.

A. B. Zylstra *et al.*, Phys. Rev. Lett. 119, 222701 (2017)
* Folded with CPS impulse response function and plasma thermal broadening.
** Uses feeding amplitudes determined from fit to 1965 Wong TT-n spectrum.

Outline

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  - target ions in the fusing hot spot (DT, TT, $^3He^3He$)
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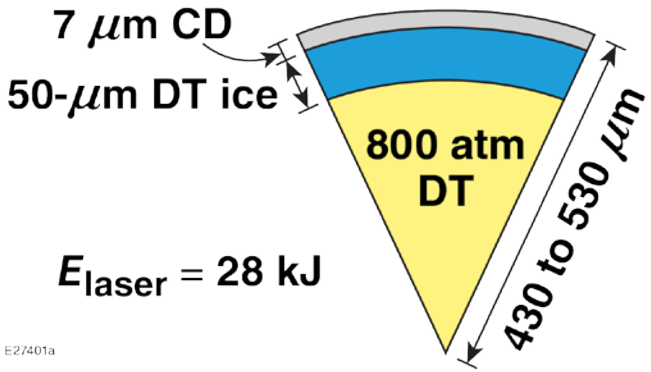
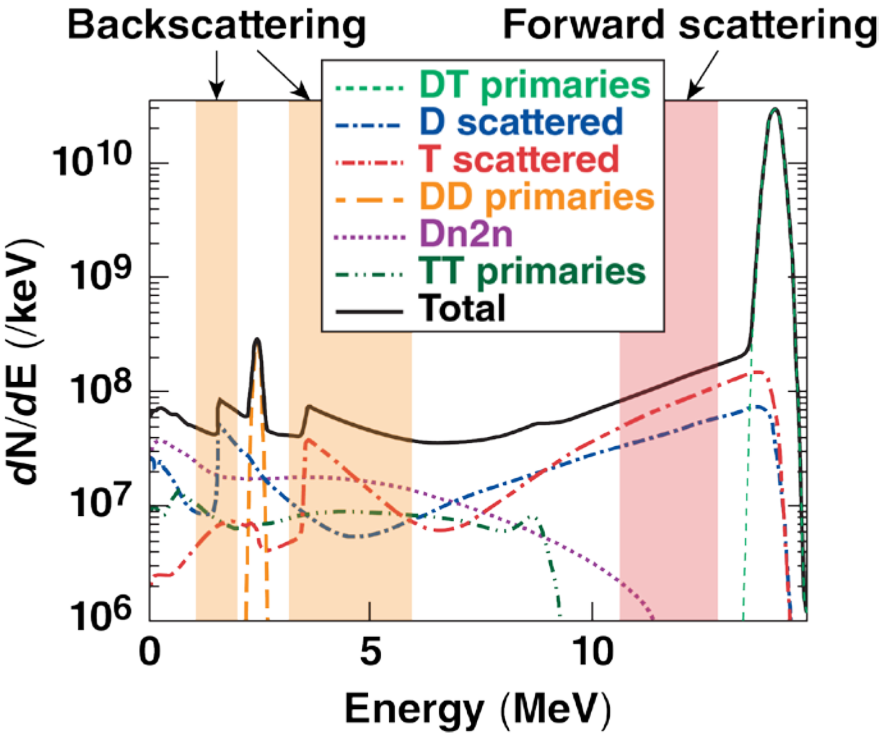
An accurate description of the neutron energy spectrum from direct-drive cryogenic DT experiments is crucial to infer the implosion performance

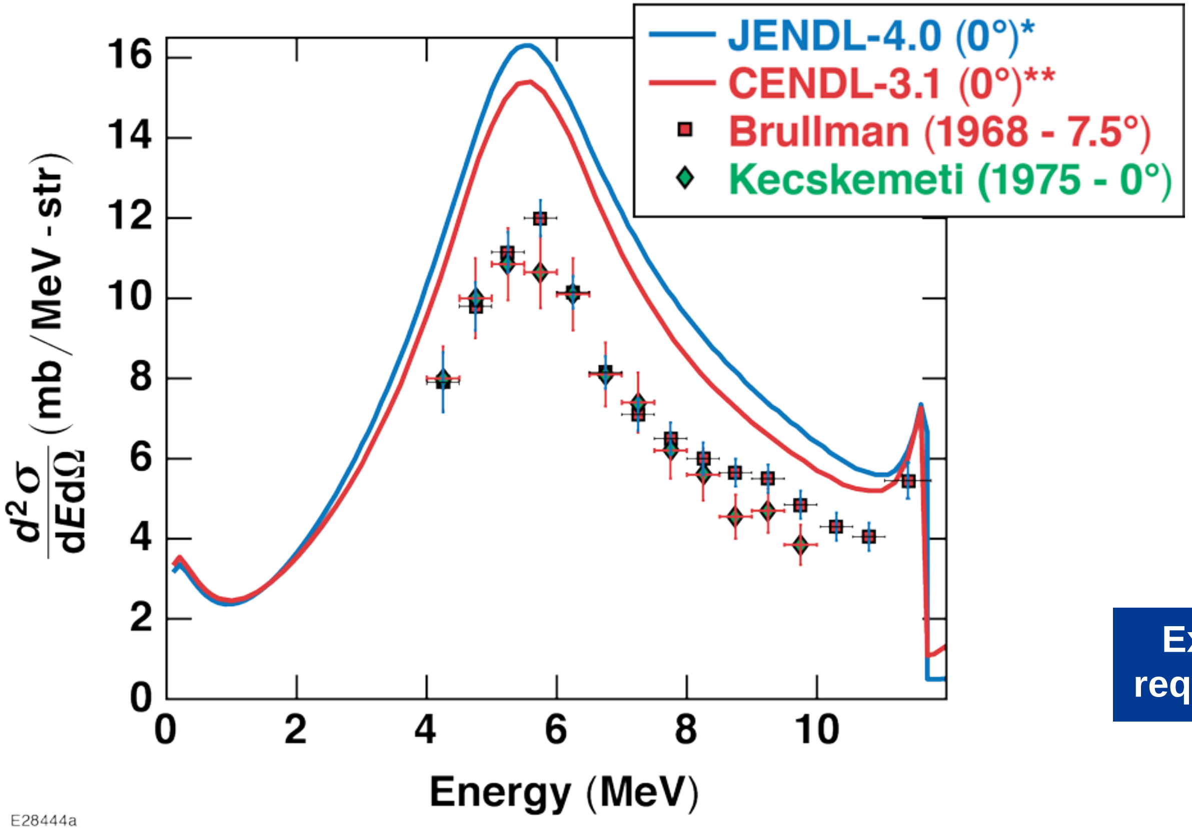




D + T	→	^{4}He (3.5 MeV) + n (14 MeV)
D + D	→	^{3}He (0.82 MeV) + n (2.45 MeV)
T + T	→	^{5}He (1.7 MeV) + n (8.7 MeV)
	→	^{5}He* (~4.4 MeV) + n (~6 MeV)
	→	^{4}He (0 to 3.5 MeV) + 2n (0 to 9.4 MeV)

n(14 MeV) + D → n′ (1.6 to 14 MeV) + D′ (<12.5 MeV)
n(14 MeV) + T → n′ (3.5 to 14 MeV) + T′ (<10.6 MeV)
n(14 MeV) + D → 2n (0 to 11.8 MeV) + ^{1}H (0 to 11.8 MeV)

Large discrepancies between measured spectra from the neutron-induced breakup reaction ($d^2\sigma/d\Omega dE$) and theoretical calculation still exist



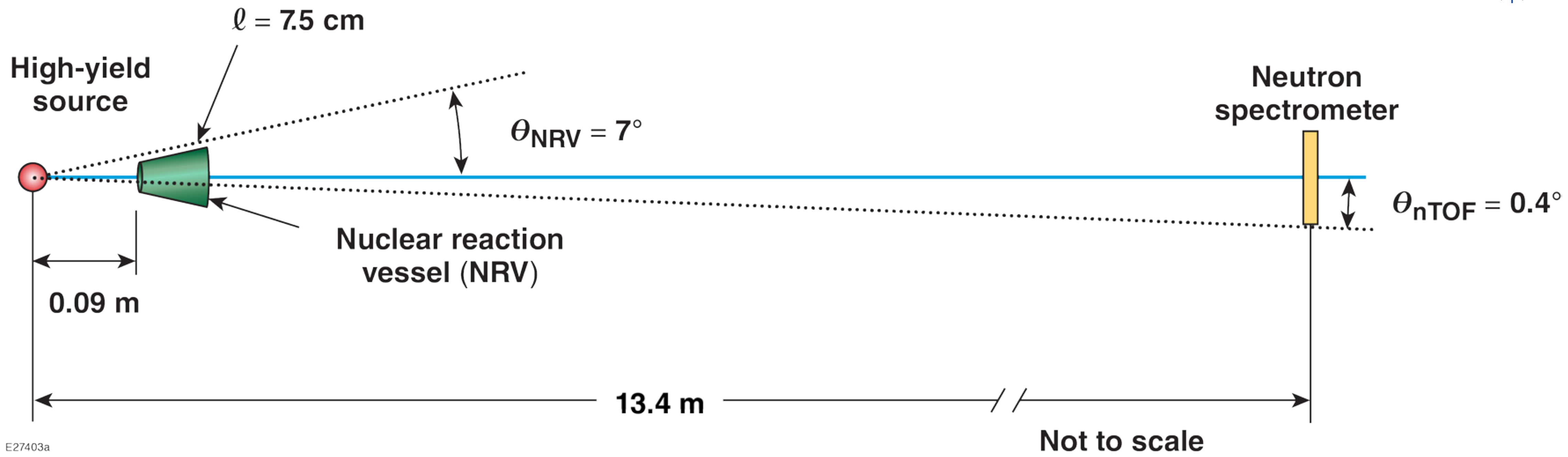
Experimental data in the literature has not measured the complete energy range of the breakup reaction below 10°

It is important to measure the in the region far from the FSI dominance where the 3NF is least sensitive to the final state configuration

Experiments to study neutron-induced breakup reactions are required since past measurements show significant differences.

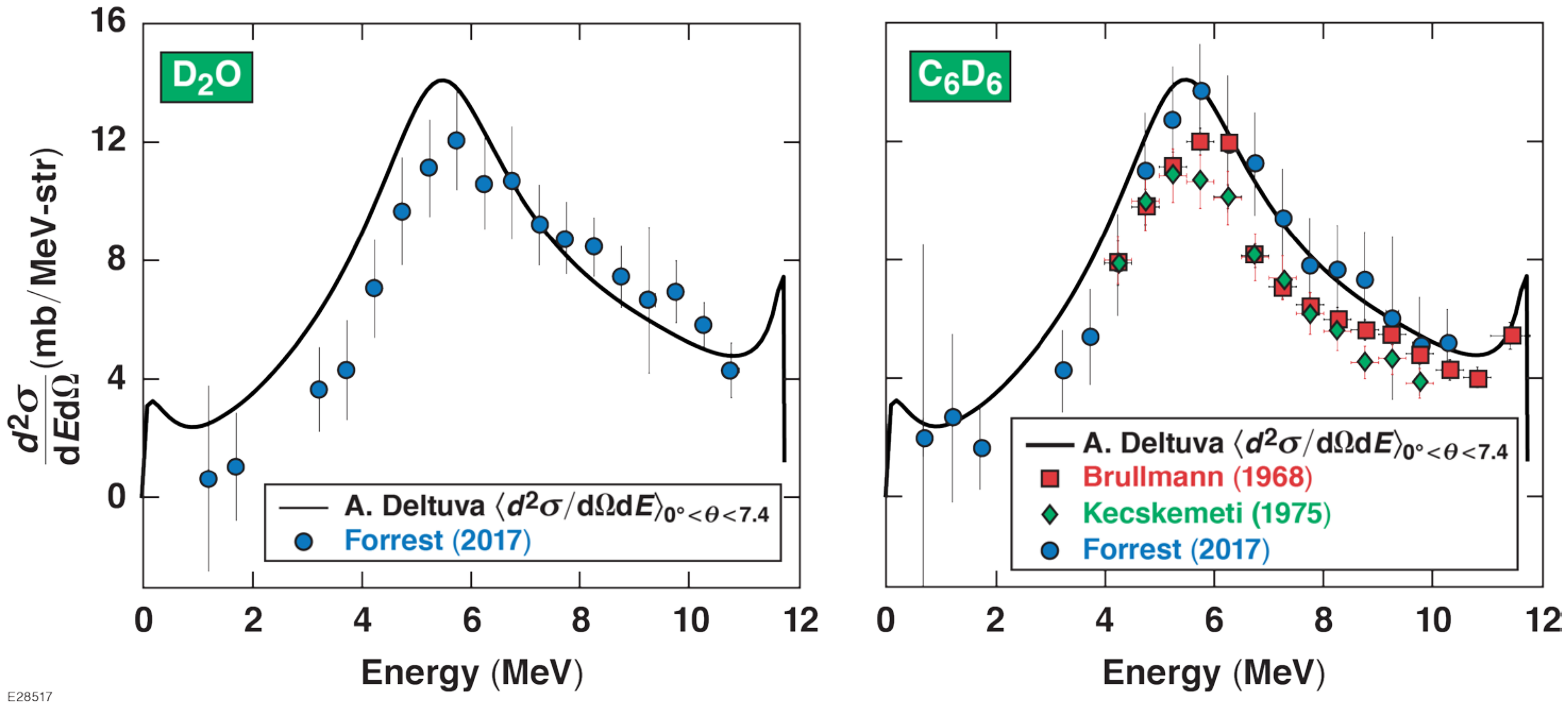
*K. Shibata et al., J. Nucl. Sci. Technol. 48, 1 (2011).
**Z. Youxiang et al., J. Nucl. Sci. Technol. 39, 37 (2002).

A novel new approach to measure the neutron-induced breakup of deuterium (light-*Z* ions) has been developed at the Omega Laser Facility



- The experimental platform consists of an ~100-ps, high-yield 14-MeV neutron pulse incident on a reaction vessel filled with the target compound
- A reaction vessel filled with deuterated compounds is located as close as possible to the implosion, maximizing the solid angle without interfering with the laser pulses required for illuminating the exploding pusher

The inferred double-differential cross section from OMEGA has been compared with available experimental data and recent theoretical calculations



Recent experiments have looked n2n reactions using vessels that contain ^{7}Li and ^{9}Be.

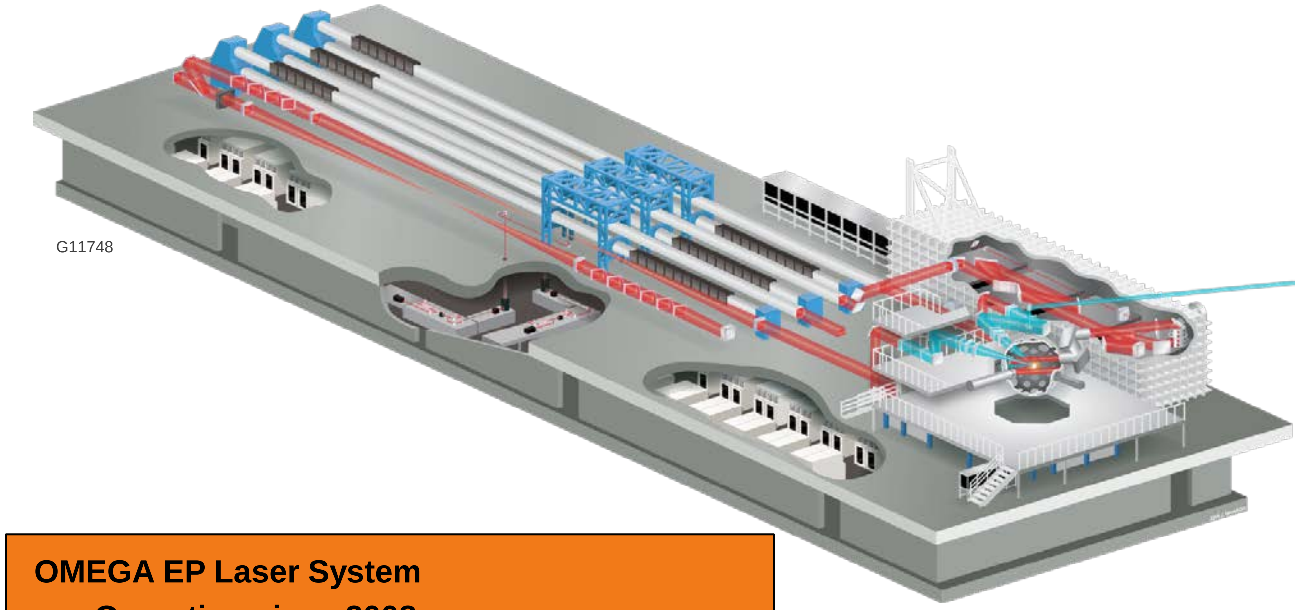
K. Shibata *et al.*, J. Nucl. Sci. Technol. 48, 1 (2011);
Z. Youxiang *et al.*, J. Nucl. Sci. Technol. 39, 37 (2002);
A. Deltuva, Institute of Theoretical Physics and Astronomy, Vilinus University, Vilinus, Lithuania, private communication (2016).

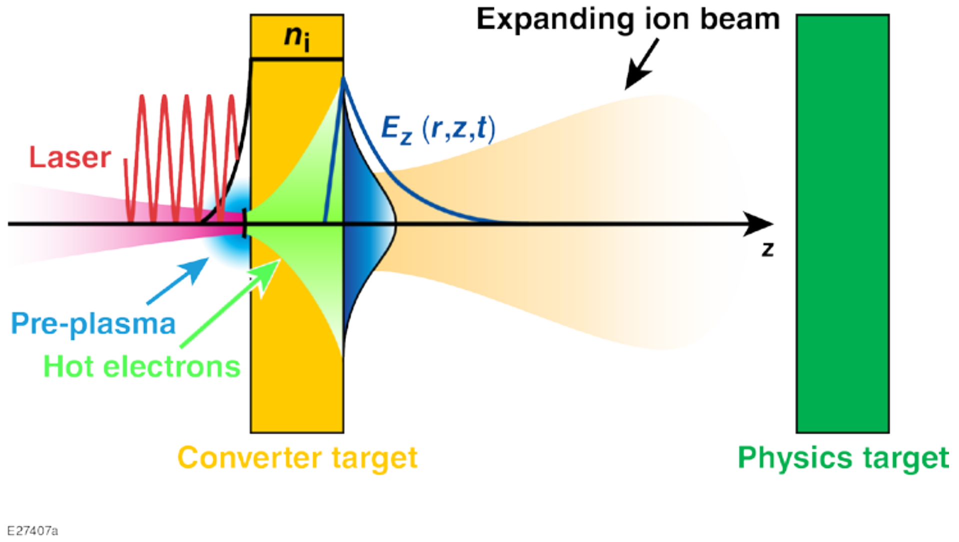
Outline

- Science of fusion—large lasers are used for high-energy-density physics (HEDP) (defined generally as pressures above 1 Mbar)
- **Nuclear experiments to date**
  - target ions in the fusing hot spot (DT, TT, $^3He^3He$)
  - target nuclei outside of the source target (deuterium breakup)
  - **laser-accelerated ions (protons, deuterons)**
- Upcoming experiments
  - laser-accelerated ion (tritons) onto tritiated foils

A nuclear physics platform using laser-generated light ions from target normal sheath acceleration (TNSA) has been developed on the OMEGA EP Laser System

- **Energetic protons (deuterons) are created off the back surface of a primary target irradiated by a short-pulse laser (τ = 10 ps)**





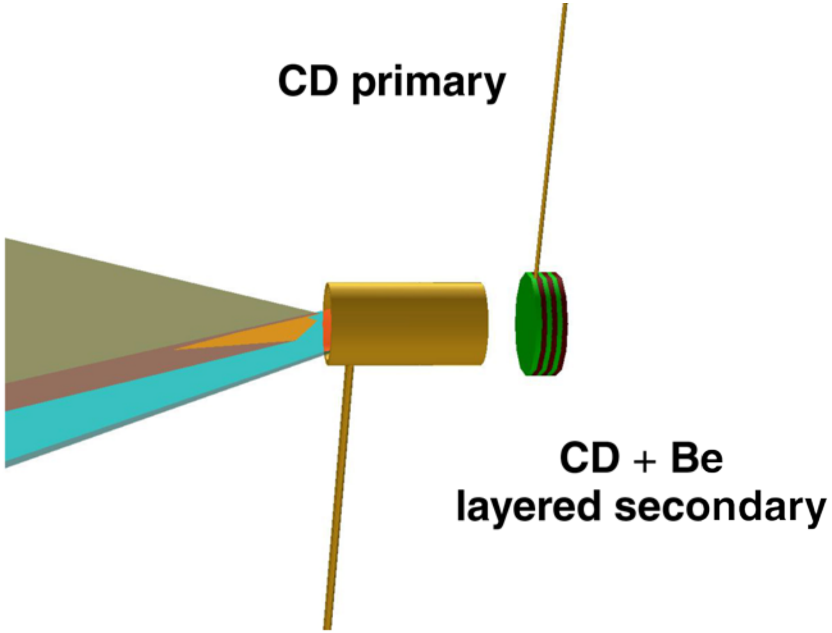
OMEGA EP Laser System

- **Operating since 2008**
- **Four NIF*-like beamlines; 6.5-kJ UV (10 ns)**
- **Two beams can be high-energy petawatt**
  - **2.6-kJ IR in 10 ps**
  - **can propagate to the OMEGA or OMEGA EP target chamber**

- **Protons beam up to 4 MeV**
- **Deuteron beam up to 5 MeV**

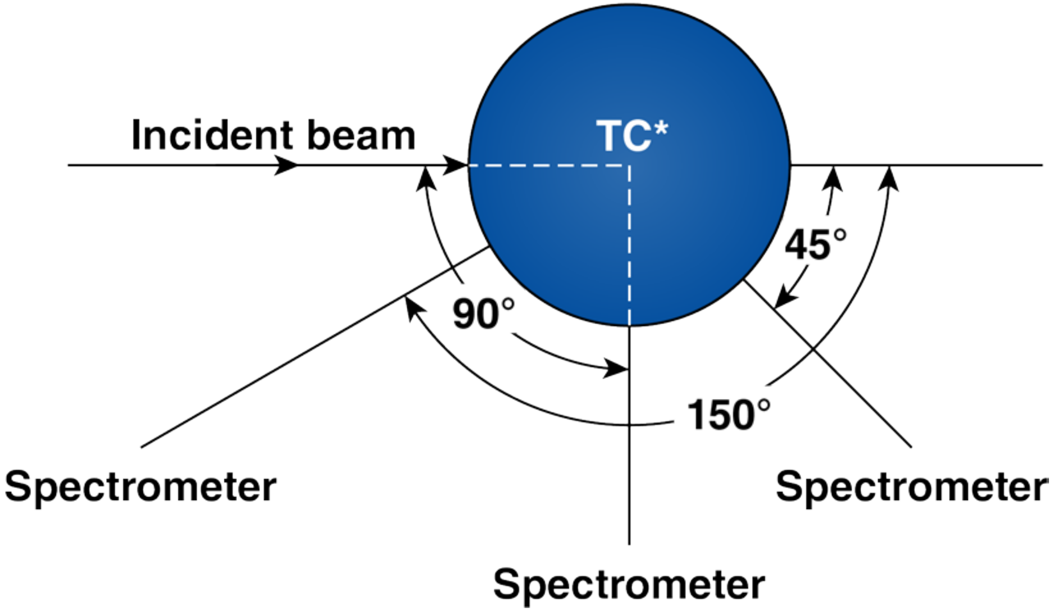
C. Stoeckl *et al*., Nucl. Instrum. Methods Phys. Res. B 453, 41 (2019).

The first experiment on OMEGA EP used a deuteron beam to induce the direct reaction $^{9}Be(d,n)^{10}B$



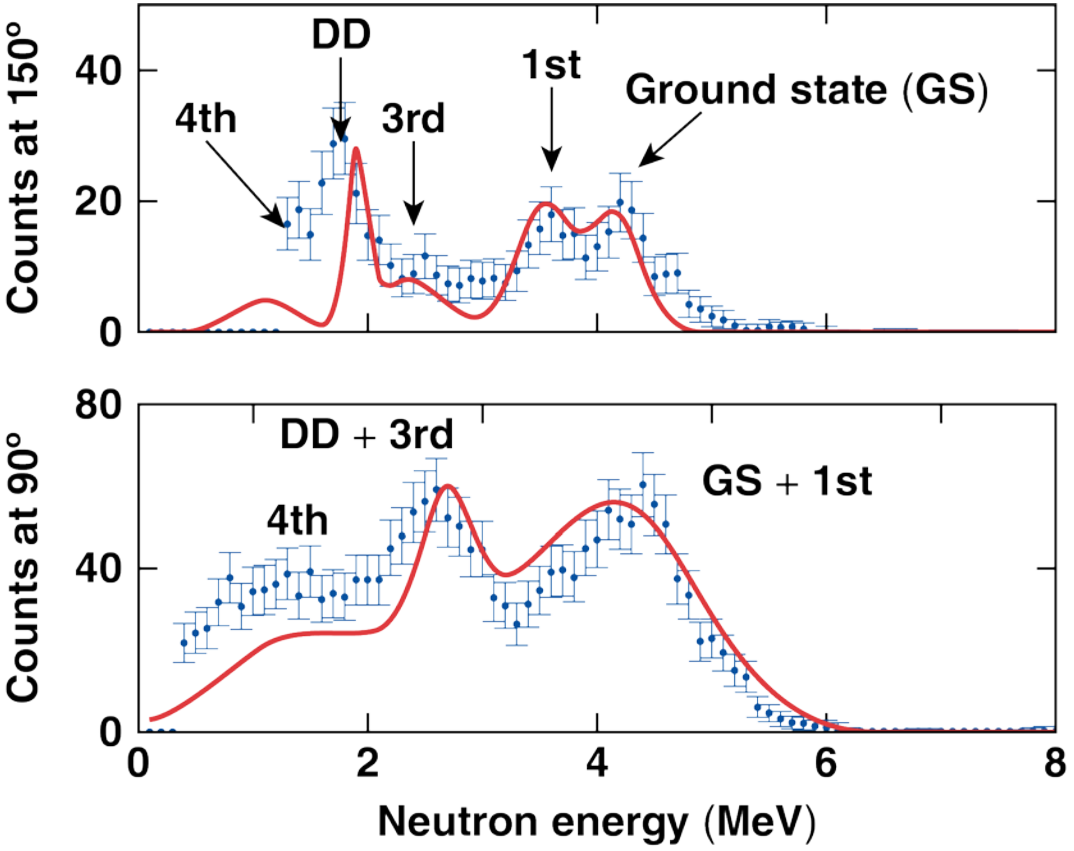
$^{9}Be + D \rightarrow {}^{8}Be$ (1.26 MeV) + T (3.34 MeV)
$^{9}Be + D \rightarrow {}^{10}B$ (0.40 MeV) + n (3.97 MeV)
$D + D \rightarrow {}^{3}He$ (0.82 MeV) + n (2.45 MeV)
$D + T \rightarrow {}^{4}He$ (3.5 MeV) + n (14 MeV)

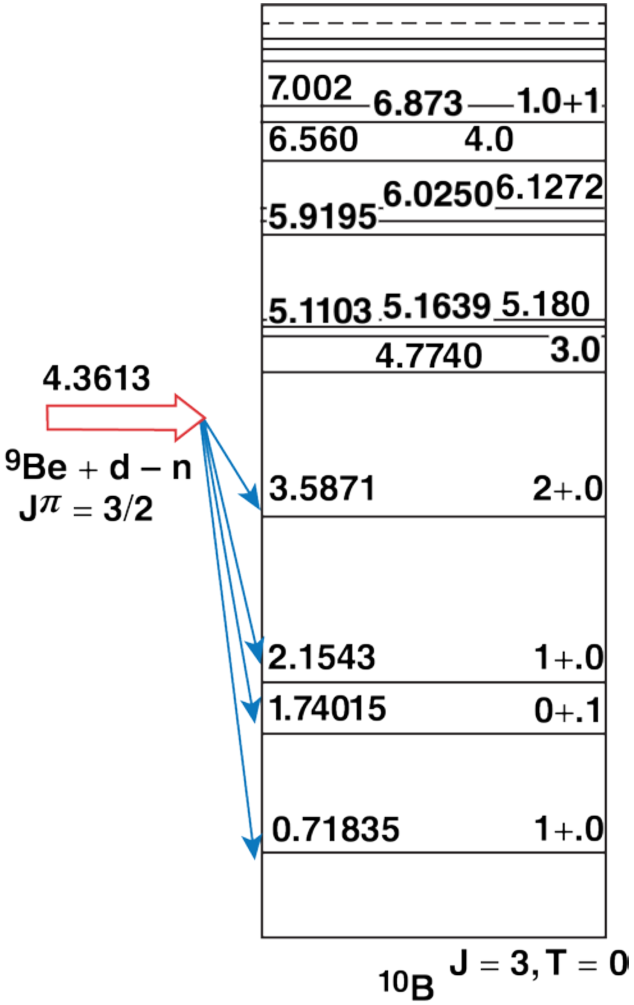
A small (100-J) UV pulse fired 0.5 ns before the short pulse was used to suppress p–n reactions off the front side of the target



* TC: target chamber

A first step in creating ion beams for nuclear experiments using the OMEGA EP short-pulse laser has been demonstrated





The D beam populated several different ^{10}B states and induced DD fusion.

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Outline

- Science of fusion—large lasers are used for high-energy-density physics (HEDP) (defined generally as pressures above 1 Mbar)
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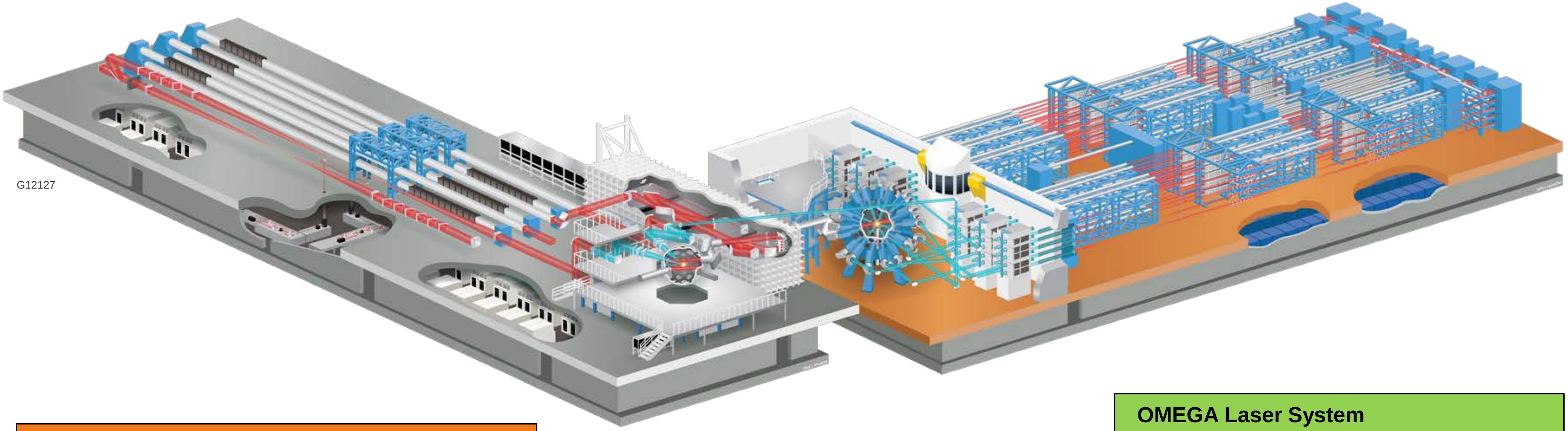
  - target ions in the fusing hot spot (DT, TT, $^{3}He^{3}He$)
  - target nuclei outside of the source target (deuterium breakup)
  - laser-accelerated ions (protons, deuterons)
- **Upcoming experiments**
  - **laser-accelerated ion (tritons) onto tritiated foils**

OMEGA EP provides short-duration and high-intensity laser pulses into the OMEGA target chamber



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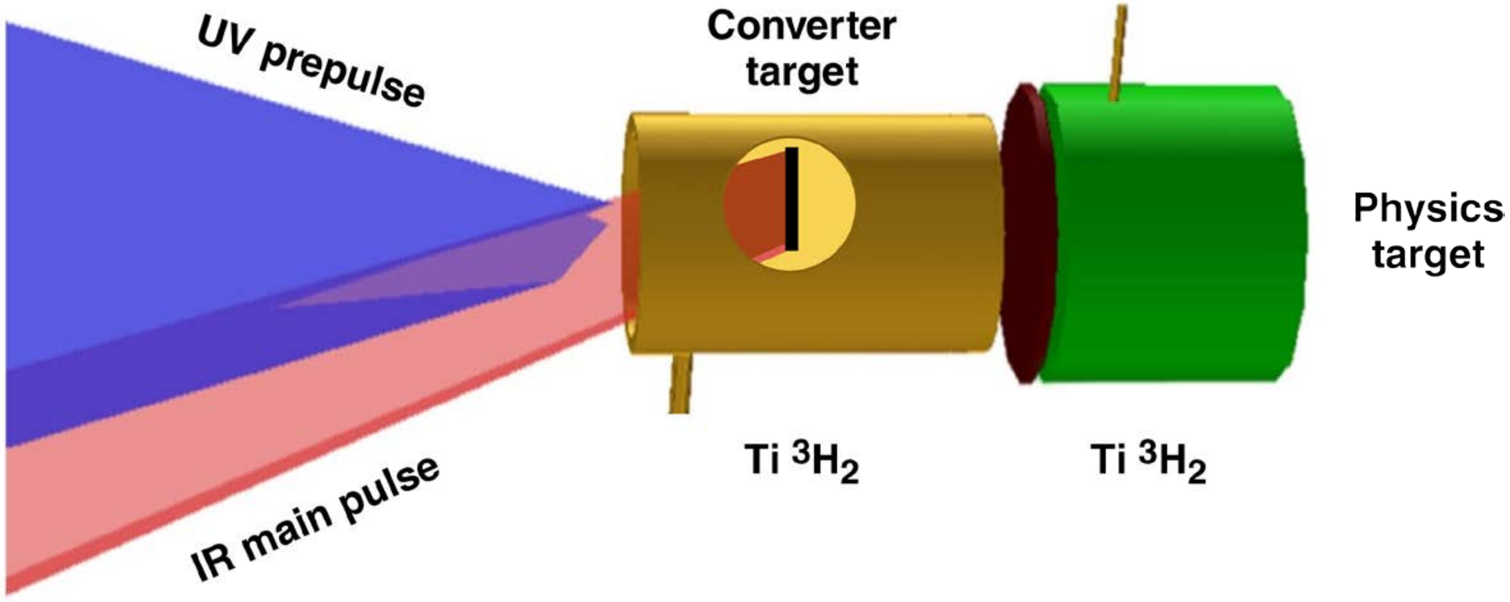
OMEGA EP Laser System
- Operating since 2008
- Four NIF*-like beamlines; 6.5-kJ UV (10 ns)
- Two beams can be high-energy petawatt
  - 2.6-kJ IR in 10 ps
  - can propagate to the OMEGA or OMEGA EP target chamber

OMEGA Laser System
- Operating at LLE since 1995
- Up to 1500 shots/year
- Fully instrumented
- 60 beams
- >30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

The nuclear structure of ^{6}He will be studied with the TT reaction



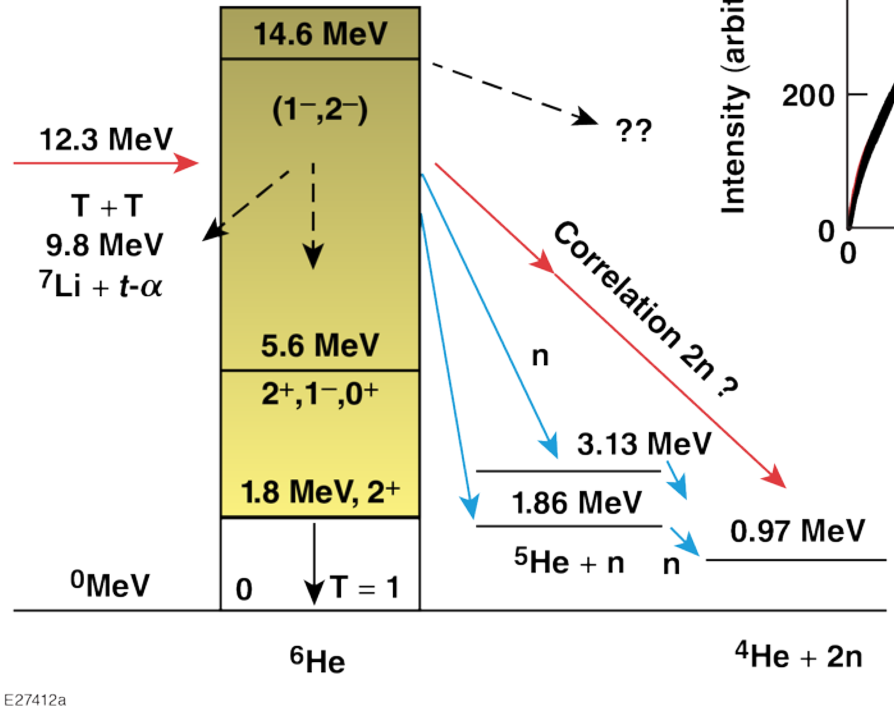
T + T	$\rightarrow$ ^{5}He (1.7 MeV) + n (8.7 MeV)
	$\rightarrow$ ^{5}He* (~4.4 MeV) + n (~6 MeV)
	$\rightarrow$ ^{4}He (0 to 3.5 MeV) + 2n (0 to 9.4 MeV)
	$\rightarrow$ ^{4}He + (nn)
^{6}Li + T	$\rightarrow$ ^{8}Li (0.15 MeV) + p (1.16 MeV)

- **The nuclear structure of halo nuclei ^{6}He, ^{8}Li and tritium, excited states**
- **Is the TT reaction a director compound reaction**

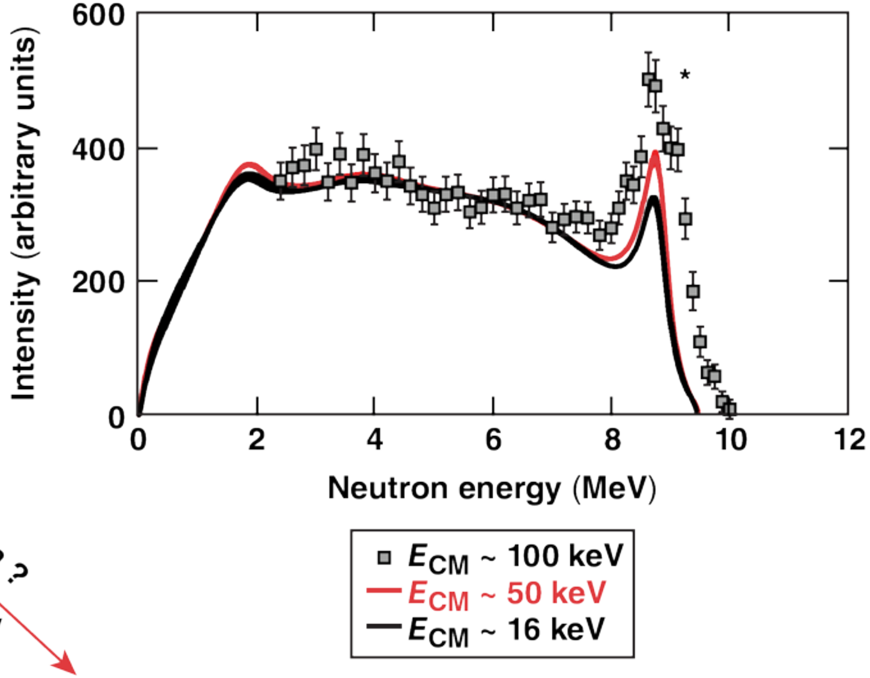
A measurement of the T + T fusion γ will confirm the formation of a compound nucleus

$^3H + {}^3H \rightarrow {}^6He\ [\rightarrow {}^4He + 2n]$

14.6 MeV excited states require $\Delta\ell = 0$

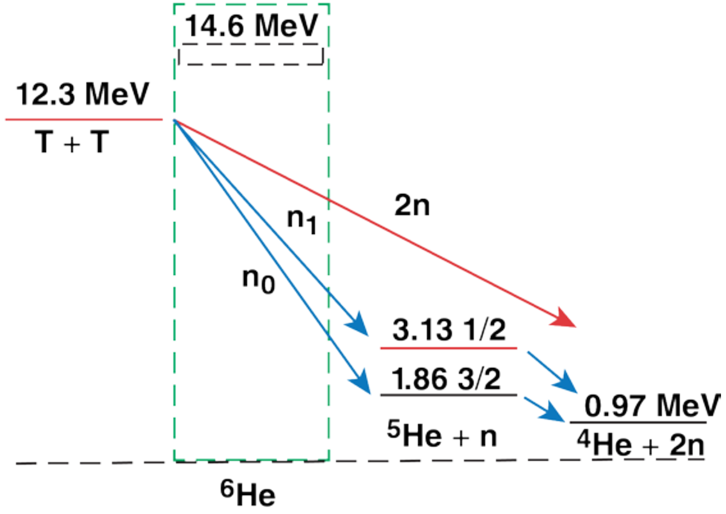


Compound nucleus formation



$^3H + {}^3H \rightarrow {}^6He\ [\rightarrow {}^4He + 2n]$

^{5}He states require $\Delta\ell = 1$



Direct reaction

*C. Wong *et al.*, Nucl. Phys. 71, 106 (1965).

Studying fundamental nuclear physics using high-energy-density plasmas complements experiments performed on accelerators

UR LLE

- Inertial confinement fusion (ICF) lasers have unique capabilities to
  - achieve plasma conditions to study nuclear reactions relevant for stellar nucleosynthesis (SN) and big-bang nucelosynthesis (BBN)
  - generate a bright neutron source with a luminosity of $L = 10^{24}$ s^{-1} to induce the breakup of light-z nuclei
  - perform measurements with a high signal-to-background from the short duration of the experiment (100 ps)
- Experiments using TNSA* have demonstrated nuclear reactions initiated by laser-accelerated ions onto solid targets using the OMEGA EP laser
  - explore light-ion nuclear reactions using an ion beam with the joint capabilities of OMEGA/OMEGA EP
  - study the six-nucleon system with a MeV triton beam (T-LIANS)**

* TNSA: target normal sheath acceleration
** T-LIANS: tritium laser ion acceleration for nuclear science