Measurements of Stellar and Big-Bang Nucleosynthesis Reactions Using Inertially-Confined Plasmas

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Basic nuclear physics and nuclear astrophysics are being studied using inertial fusion implosions

- Inertial fusion implosions create high-temperature high-density plasmas, in which thermonuclear reactions occur at conditions comparable to astrophysical systems.

- Data on the ^{3}He(T,γ)^{6}Li reaction, relevant to big-bang nucleosynthesis (BBN), rule out that reaction as an explanation for anomalously high levels of ^{6}Li observed in the universe.

- Proton spectra from the ^{3}He(T,np)^{4}He and ^{3}He(^{3}He,2p)^{4}He reactions disagree with R-matrix predictions.

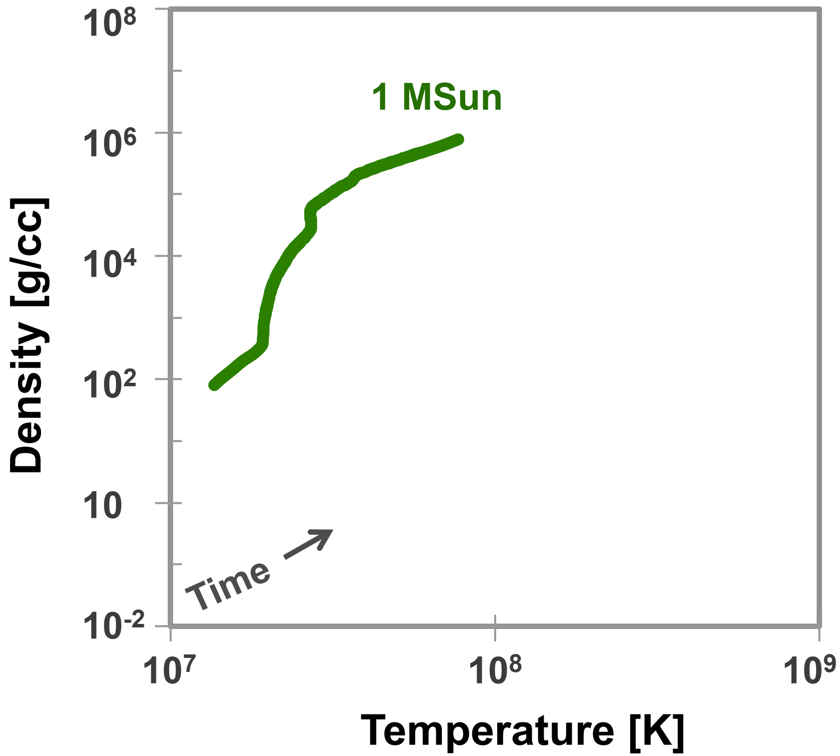
- New data on the D(p,γ)^{3}He reaction, relevant to brown dwarfs and BBN, will be directly compared to accelerator data.

- This technique has broad future applications for nuclear physics.

Several 'classes' of nuclear experiments can be done using implosions at these facilities

- **Thermonuclear reactions**
  - Instead of DT, capsules can be filled with various fuels to study different reactions
  - Can study spectra produced, or cross sections (usually by ratio to a better-known reaction)
- **Implosion as an intense neutron source**
  - 10^{16} neutrons in ~100ps over 30μm radius volume -> 10^{30} n/cm^2/s
  - Direct neutron reactions [e.g. (n,2n), (n,γ), etc] or reactions of knock-on products [elastic scattered D or T]
- **Plasma-nuclear effects (not yet)**
  - Screening effects

ICF capsule implosions can create densities and temperatures similar to stellar cores



Stellar evolution simulations by Dave Dearborn
NIF Simulations Harry Robey and Bob Tipton
OMEGA Simulation P. B. Radha

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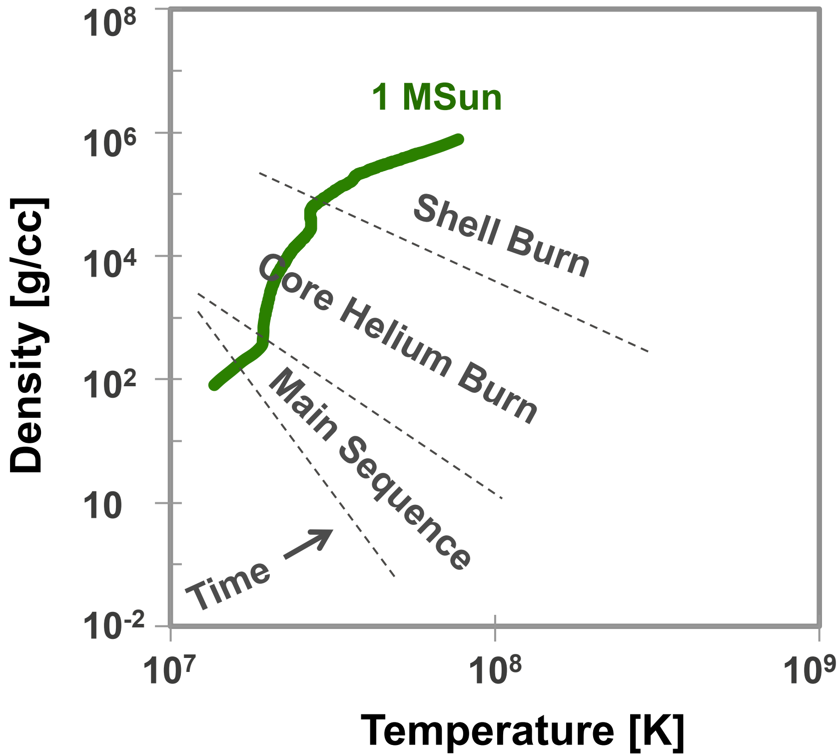

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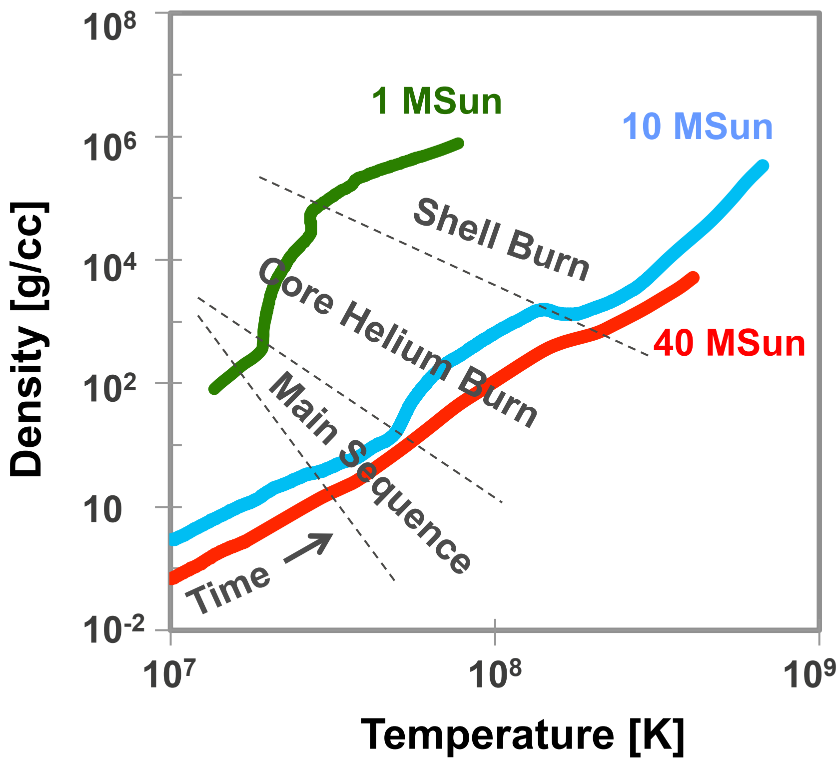

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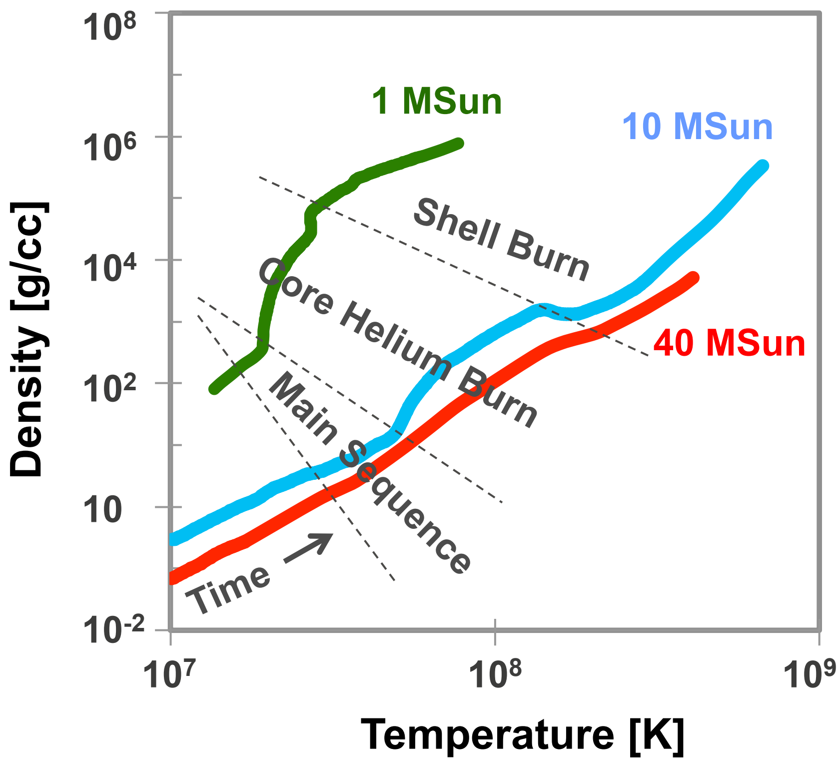

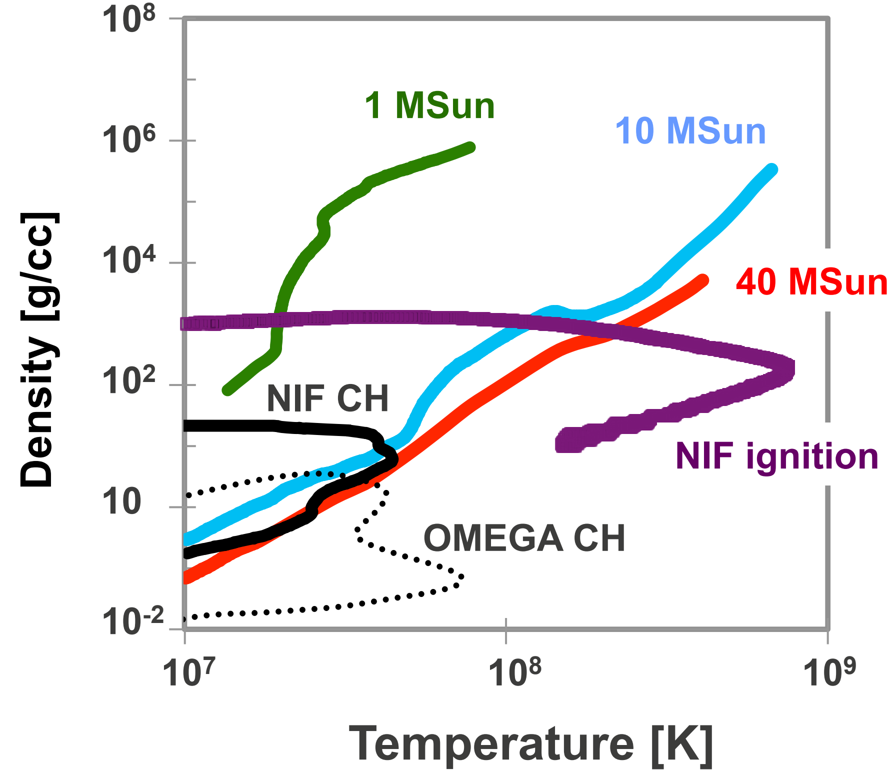

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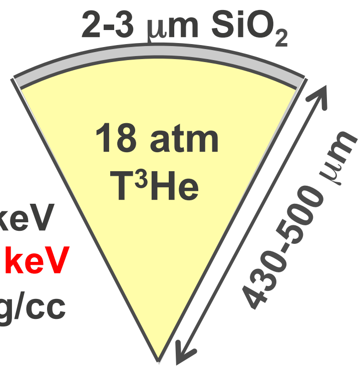
The T+^{3}He fusion reaction was studied at the OMEGA facility



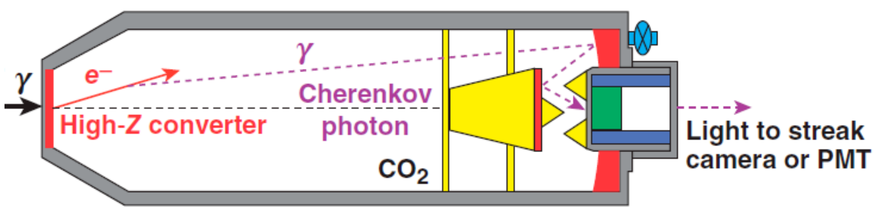
Ti ~ 19 keV
E_{cm} ~ 80 keV
ρ ~ 0.1 g/cc

T + ^{3}He	→ ^{4}He + d (9.5 MeV)		~60%
	→ ^{4}He + p (<10 MeV) + n		
	→ ^{5}He + p (9.3 MeV)	→ ^{4}He + p + n	~40%
	→ ^{5}He* + p (6.4 MeV)	→ ^{4}He + p + n	
	→ ^{5}Li + n	→ ^{4}He + p + n	
	→ ^{6}Li + γ		0.1%

The γ branch has been hypothesized to potentially explain astrophysical ^{6}Li anomalies

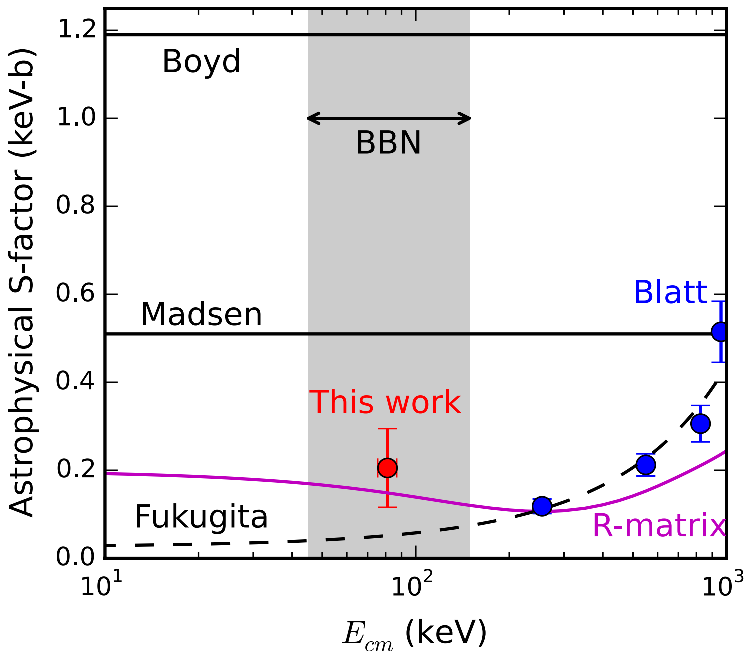
Charged particles are measured with dipole magnetic spectrometers[1,2]

Gammas measured with Cherenkov detector[3]



1: D.G. Hicks, PhD Thesis (1999)
2: J. Frenje et al., RSI 79, 10E502 (2008)
3: J. Mack et al., NIMA 513, 566 (2003)

The γ data give a S-factor for this reaction at the lowest CM energy ever (first relevant to BBN)



A.B. Zylstra et al., Phys. Rev. Lett. 117, 035002 (2016)

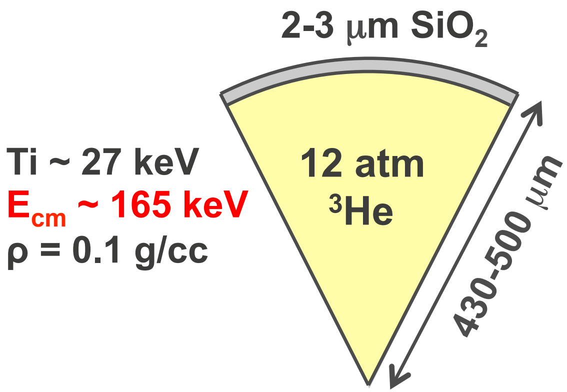
OMEGA
Accelerator
Theory Fit
Astrophysics

$$\sigma(E_{CM}) = S(E_{CM})\frac{\exp\left(-\sqrt{E_G/E_{CM}}\right)}{E_{CM}}$$

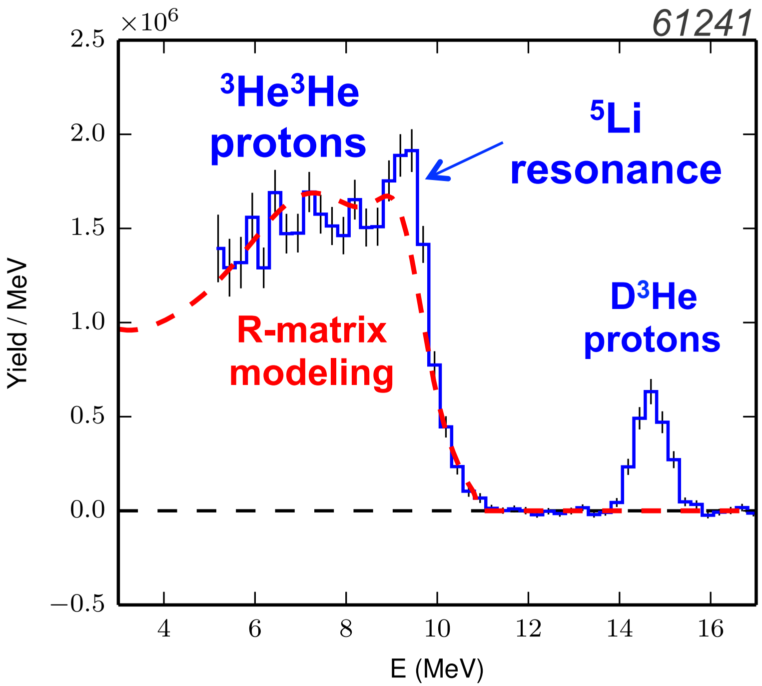
This reaction rate cannot explain high ^{6}Li levels in primordial material.

S.L. Blatt et al., Phys. Rev. (1968)
Fukugita et al., PRD (1990)
Madsen et al., PRD (1990)
Boyd et al., PRD (2010)

The $^3He(^3He,2p)^4He$ reaction, relevant to the solar proton-proton chain, has also been studied at OMEGA

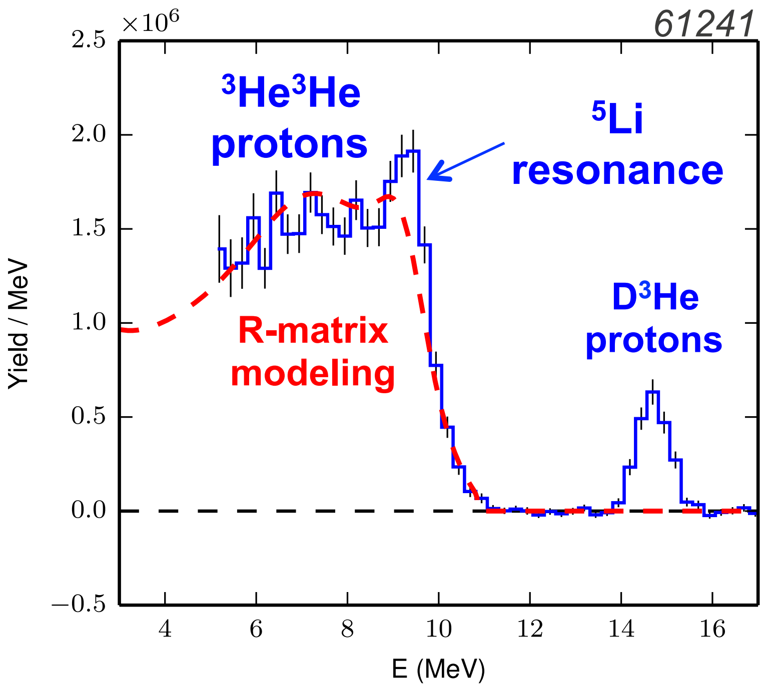


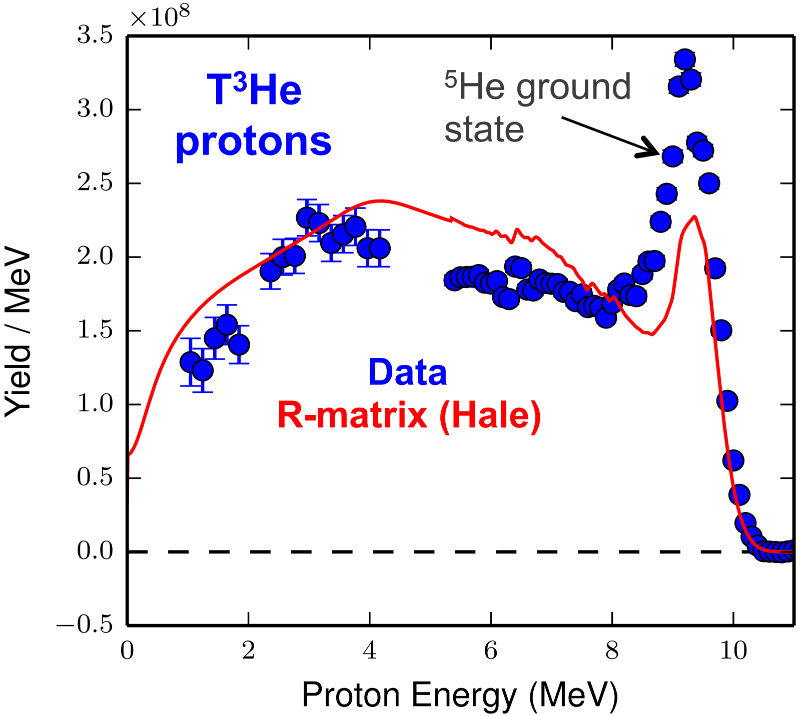
$^3He + {}^3He$	→	$^4He + 2p$ (0-10.8 MeV)
	→	$^5Li + p$ (9.2 MeV)
	→	$^5Li^* + p$



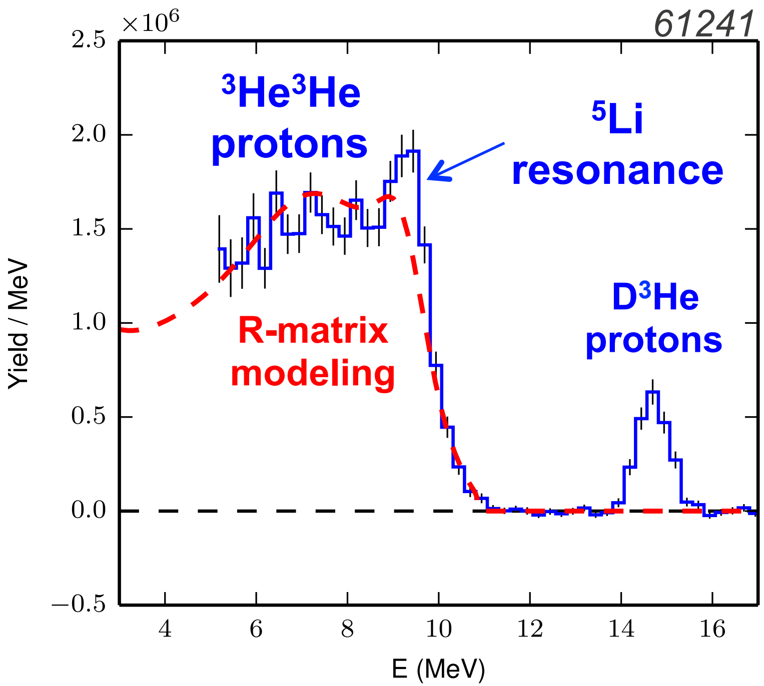
Spectral shape is important for understanding few-body physics, and for interpretation of accelerator data

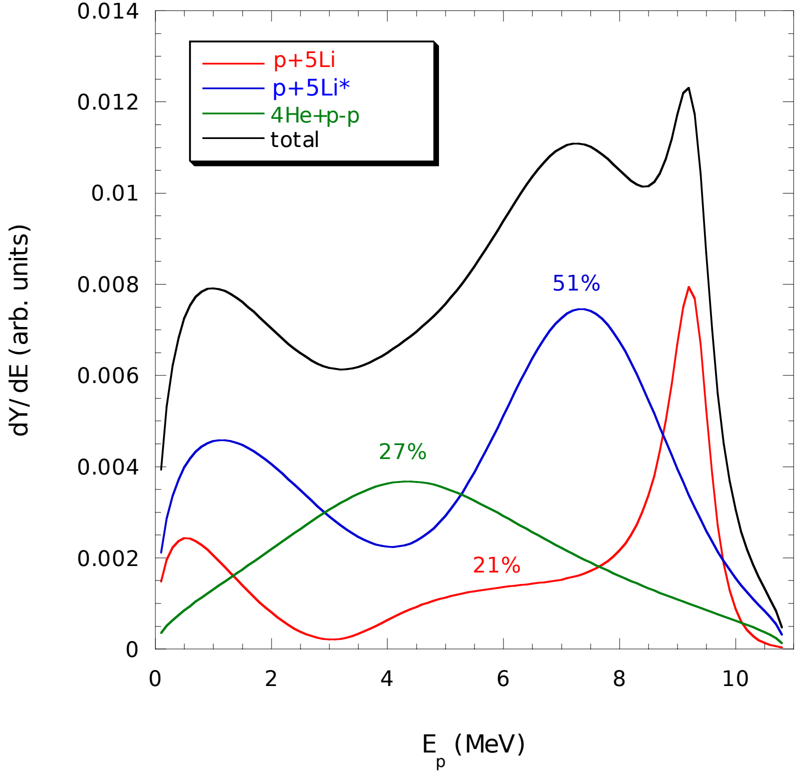
A comparison of proton spectra from ^{3}He^{3}He and T^{3}He to R-matrix theory shows an underprediction of the ground state (^{5}Li/^{5}He)





Components in the R-matrix calculation suggest it is underestimating the ^{5}Li ground state contribution

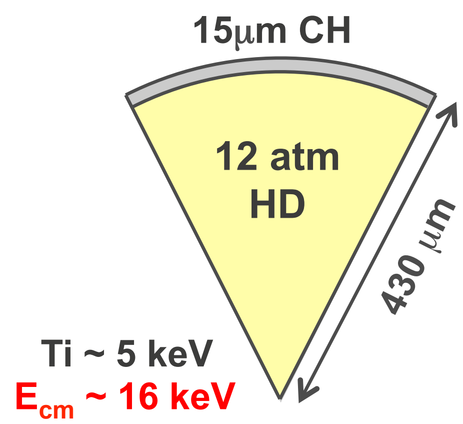


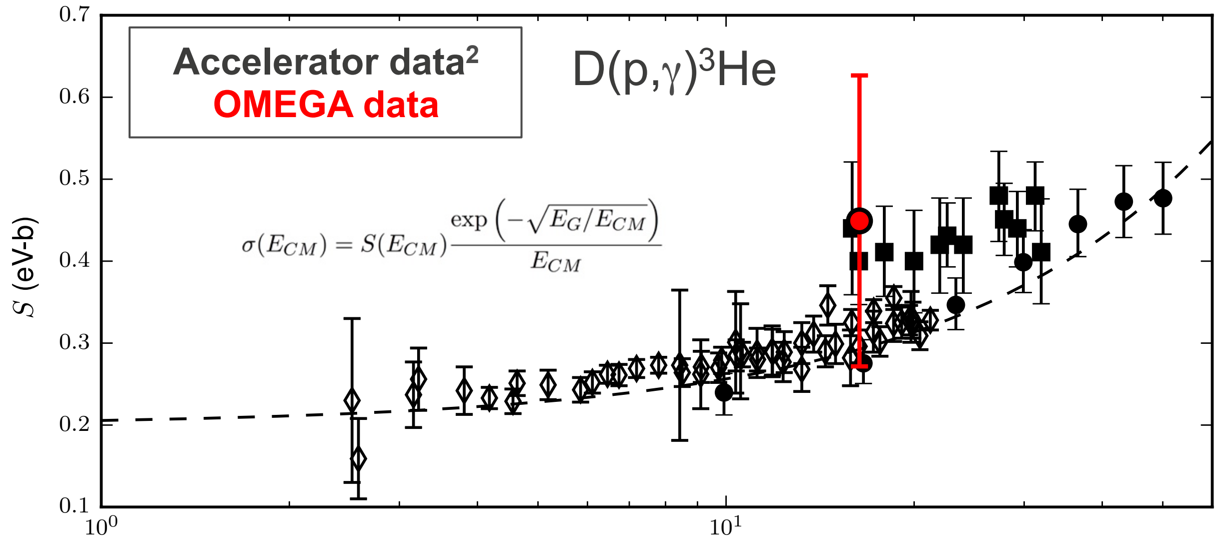


Spectral shape is important for basic few-body physics and also accelerator data interpretation – many papers in the literature assume elliptical shape

The $D(p,\gamma)^3He$ reaction, relevant to protostars and brown dwarfs, was recently studied on OMEGA with a new Cherenkov detector[1]

$D + p \rightarrow {}^3He + \gamma$ (5.5 MeV)





First direct plasma-accelerator comparison for an astrophysical reaction, agreement validates both techniques. With improved calibrations (in progress), error will be reduced.

1: H.W. Herrmann et al., RSI 85, 11E124 (2014)
2: G.M. Griffiths et al., Can. J. Phys. 41, 724 (1963); G.J. Schmid et al., PRC 52, 1732 (1995); C. Casella et al., Nuclear Physics A 706, 203 (2002)

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

Charged-particle induced reactions:

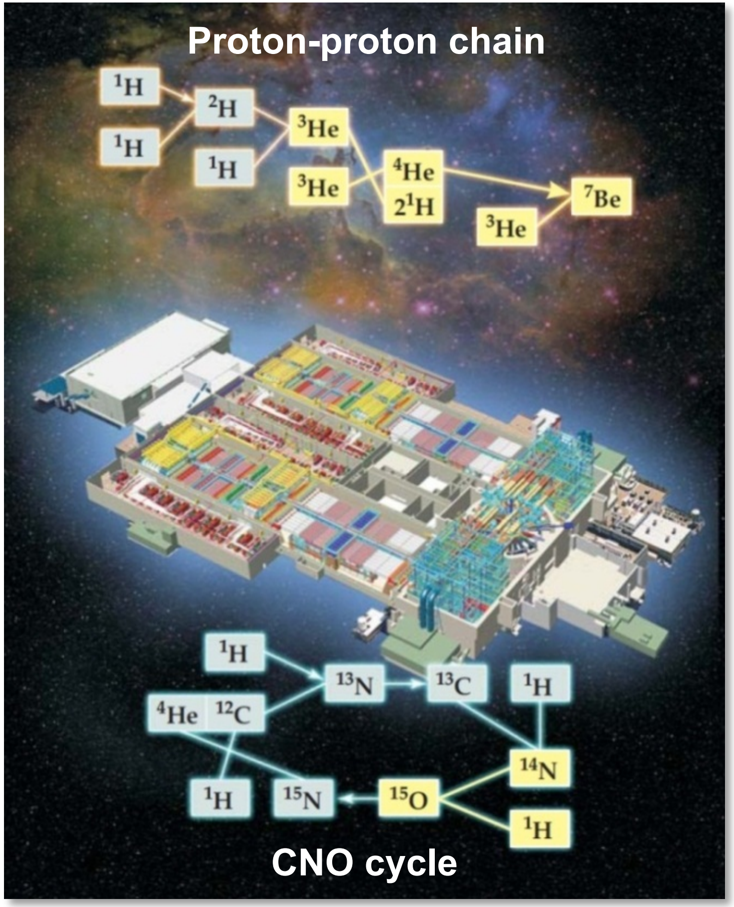
- **$T(t,2n)^4He$** (analogue to $^3He(^3He,2p)^4He$) [1]
- **$T(^3He,np)^4He$, $T(^3He,d)\,^4He$, $T(^3He,\gamma)^6Li$** (BBN) [2]
- **$^3He(^3He,2p)^4He$** (pp-I) [3]
- **$D(p,\gamma)^3He$** (Brown dwarfs, protostars) [4]
- **$T(d,\gamma)^5He$** [5]
- **$^4He(D,\gamma)^6Li$** (BBN)
- **$^4He(T,\gamma)^7Li$**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

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), (n,2n) processes

Current work

1: Casey et al., PRL 2012; Sayre et al., PRL 2013; Gatu Johnson et al., to be submitted.
2: Zysltra et al., PRL 2016
3-4: Zylstra et al., to be submitted
5: Kim et al., PoP and PRC (2012)
6: Frenje et al., PRL 2011
7: Forrest et al., to be submitted



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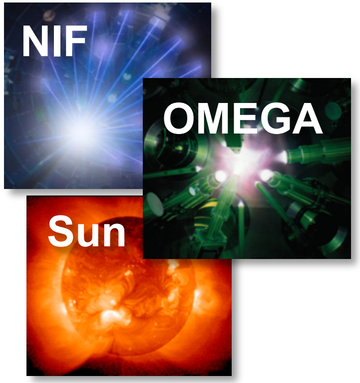
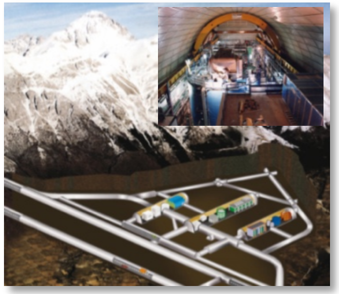
- This technique has broad future applications for nuclear physics

EXTRA SLIDES

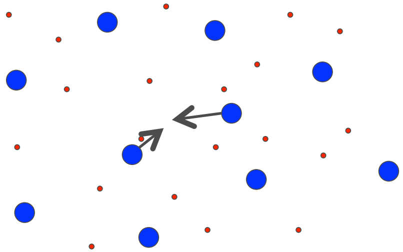
The conditions created in ICF (and astrophysical) plasmas are different from accelerator experiments



Accelerator experiments

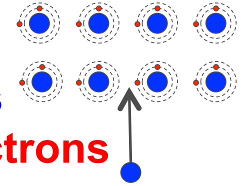


Dense and hot plasma



Thermal ions
Thermal electrons

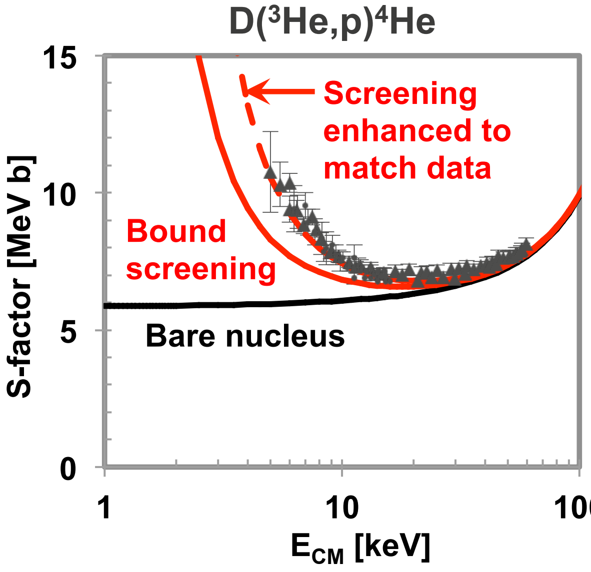
Cold Target



Ions
Electrons

Monoenergetic ion

Debye screening



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

An anomaly exists in the abundance of ^{6}Li in primordial material, could be produced by big-bang nucleosynthesis (BBN)?

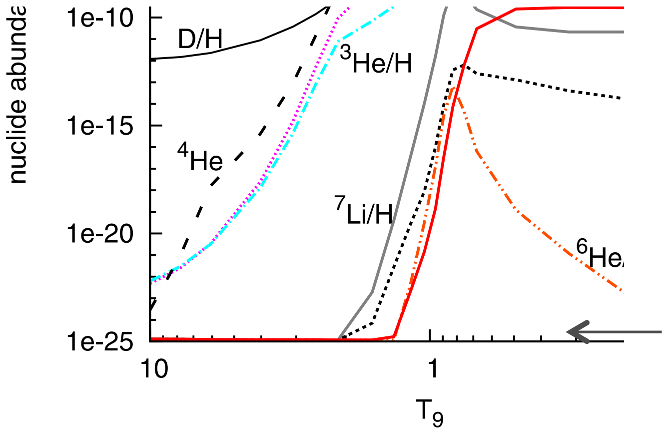


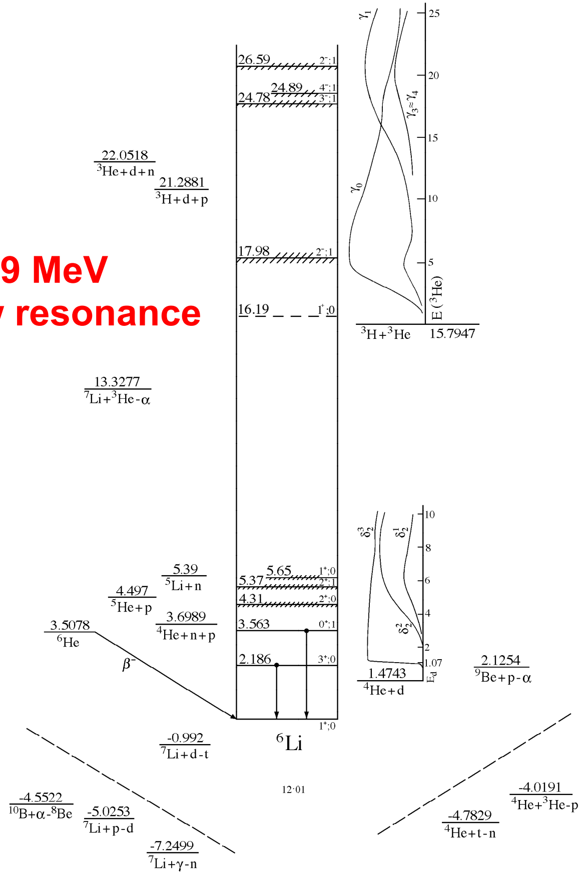
FIG. 2 (color online). Nuclear abundance as a temperature T_9, where $T_9 = T/10^9$ K. Abundance as mass fraction for ^{4}He and number abundance hydrogen for all others.

Predicted ^{6}Li abundance too low to explain observations[1,2]
A BBN solution is elusive[3]
^{3}He(T,γ)^{6}Li has been hypothesized to be important, but this is contentious.
Severe lack of data at low energy[6]

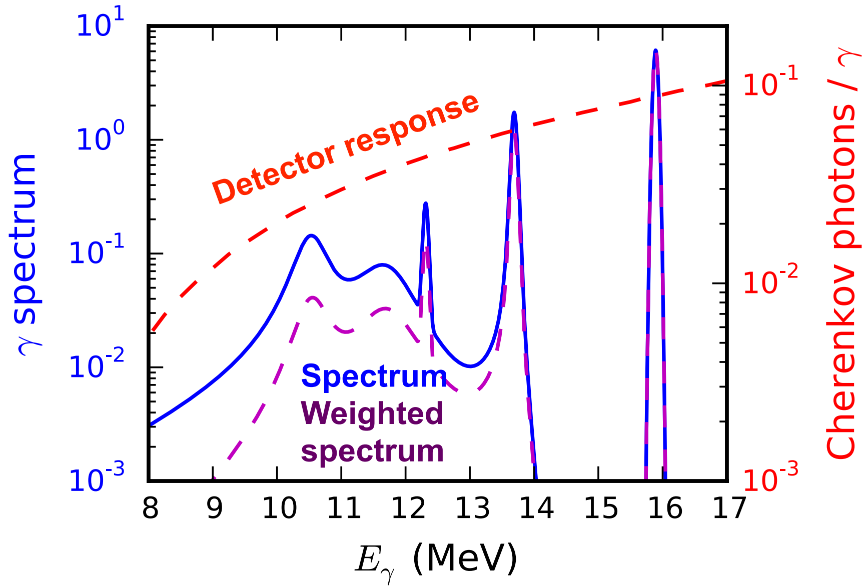
1 M. Asplund et al., Astrophysical Journal 644, 229 (2006)
2 B.D. Fields, Annual Review of Nuclear and Particle Science 61, 47 (2011)
3 Boyd et al., Phys. Rev. D 82, 105005 (2010)
4 J. Madsen, Phys. Rev. D 41, 2472(1990)
5 M. Fukugita et al., Phys. Rev. D 42, 4251 (1990)
6 S.L. Blatt et al., Phys. Rev. 176 1147 (1968)

New R-matrix analysis of the T^3He reaction γ spectrum and S-factor have been performed

Level Diagram



16.19 MeV
New resonance



A more careful treatment of ^{6}Li excited states has been done for this work than previous literature

Example Cherenkov data from the p+D experiment

D + p → ^{3}He + γ (5.5 MeV)