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

Alex Zylstra

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Collaborators

**LANL**
- H. Herrmann
- Y.H. Kim
- G. Hale
- M. Paris
- A. McEvoy

**MIT**
- J. Frenje
- M. Gatu Johnson
- F. Seguin
- C. K. Li
- H. Sio
- R. Petrasso

**LLE**
- C. Forrest
- V. Glebov
- C. Stoeckl
- R. Janezic
- J. Knauer
- T.C. Sangster

**LLNL**
- D. McNabb
- J. Pino
- D. Dearborn
- B. Tipton
- H. Robey

**Indiana U**
- A. Bacher

**Ohio U**
- C. Brune

**AWE**
- M. Rubery

**GA**
- A. Nikroo
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 $^3\text{He}(T,\gamma)^6\text{Li}$ reaction, relevant to big-bang nucleosynthesis (BBN), rule out that reaction as an explanation for anomalously high levels of $^6\text{Li}$ observed in the universe.

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

• New data on the $D(p,\gamma)^3\text{He}$ 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 $\sim$100ps over 30$\mu$m radius volume $\rightarrow 10^{30}$ n/cm$^2$/s
  - Direct neutron reactions [e.g. $(n,2n)$, $(n,\gamma)$, 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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The $^7\text{Li} + ^3\text{He}$ fusion reaction was studied at the OMEGA facility.

\[
\begin{align*}
T + ^3\text{He} &\rightarrow ^4\text{He} + ^d (9.5 \text{ MeV}) \\
&\rightarrow ^4\text{He} + ^p (<10 \text{ MeV}) + n \\
&\rightarrow ^5\text{He} + ^p (9.3 \text{ MeV}) \\
&\rightarrow ^5\text{He}^* + ^p (6.4 \text{ MeV}) \\
&\rightarrow ^5\text{Li} + n \\
&\rightarrow ^6\text{Li} + \gamma
\end{align*}
\]

$\sim 60\%$ from $d$ and $\gamma$ branches.

$\sim 40\%$ from $p$ branches.

$\sim 0.1\%$ from $\gamma$ branch.

Charged particles are measured with dipole magnetic spectrometers\textsuperscript{1,2}

Gammas measured with Cherenkov detector\textsuperscript{3}

The $\gamma$ branch has been hypothesized to potentially explain astrophysical $^6\text{Li}$ anomalies.

1: D.G. Hicks, PhD Thesis (1999)
2: J. Frenje et al., RSI 79, 10E502 (2008)
The $\gamma$ data give a S-factor for this reaction at the lowest CM energy ever (first relevant to BBN)

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

Madsen et al., PRD (1990)  
Fukugita et al., PRD (1990)  
Boyd et al., PRD (2010)

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

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

Spectral shape is important for understanding few-body physics, and for interpretation of accelerator data.
A comparison of proton spectra from $^3\text{He}^3\text{He}$ and $^T\text{He}$ to R-matrix theory shows an underprediction of the ground state ($^5\text{Li}/^5\text{He}$).
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 $D(p,\gamma)^3\text{He}$ reaction, relevant to protostars and brown dwarfs, was recently studied on OMEGA with a new Cherenkov detector\textsuperscript{1}

\begin{equation}
D + p \rightarrow ^3\text{He} + \gamma \ (5.5 \text{ MeV})
\end{equation}

Accelerator data\textsuperscript{2}

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

Charged-particle induced reactions:

- $^4\text{He}(t,2n)^3\text{He}$ (analogue to $^3\text{He}(^3\text{He},2p)^4\text{He}$) [1]
- $^3\text{He}(^{3}\text{He},np)^4\text{He}$, $^3\text{He}(^{3}\text{He},d)^4\text{He}$, $^3\text{He}(^{3}\text{He},\gamma)^6\text{Li}$ (BBN) [2]
- $^3\text{He}(^{3}\text{He},2p)^4\text{He}$ (pp-I) [3]
- $^3\text{He}(^{3}\text{He},2p)^4\text{He}$ (Brown dwarfs, protostars) [4]
- $^4\text{He}(d,\gamma)^5\text{He}$ [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)
- $^{11}\text{B}(p,\alpha)^9\text{Be}$ (Basic nuclear)
- $^{15}\text{N}(p,\alpha)^{12}\text{C}$ (CNO)

Current work

1: Casey et al., PRL 2012; Sayre et al., PRL 2013; Gatu Johnson et al., to be submitted.
2: Zyslstra 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

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 $(n,\gamma)$, $(n,2n)$ processes
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- Proton spectra from the $^3$He($T,np$)$^4$He and $^3$He($^3$He,2p)$^4$He reactions disagree with R-matrix predictions

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

- **Dense and hot plasma**
  - Thermal ions
  - Thermal electrons

- **Debye screening**

- **Accelerator experiments**
  - Cold Target
  - Ions
  - Electrons
  - Monoenergetic ion

**Graph**

- **S-factor [MeV b]**
  - **$E_{CM}$ [keV]**
  - **$D(^3\text{He},p)^4\text{He}$**

**References**

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

Predicted $^6\text{Li}$ abundance too low to explain observations$^{1,2}$

A BBN solution is elusive$^3$

$^3\text{He}(T,\gamma)^6\text{Li}$ has been hypothesized to be important, but this is contentious. Severe lack of data at low energy$^6$

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

2 B.D. Fields, Annual Review of Nuclear and Particle Science 61, 47 (2011)
New R-matrix analysis of the $^{T^3}\text{He}$ reaction $\gamma$ spectrum and S-factor have been performed.

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

16.19 MeV New resonance
Example Cherenkov data from the p+D experiment

\[ D + p \rightarrow ^3\text{He} + \gamma (5.5 \text{ MeV}) \]

15\,\mu m CH

12 atm HD

430\,\mu m

\( \text{Ti} \sim 5 \text{ keV} \)

\( E_{\text{cm}} \sim 16 \text{ keV} \)

Signal (V/DD-n) \times 10^{-10}

Time (ns)

D\(^3\)He

Calibration

HD

Data shots

DD

Background

Null shot (H\(_2\), no \(\gamma\))