Nuclear astrophysics studies with charged particles in hot plasma environments

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Summary

- Accelerator based nuclear astrophysics reaches yield and background limits at very low energy
- Electron screening in accelerator based measurement are not fully understood
- Inertial fusion experiments provide thermonuclear plasma environments similar to those in stellar core
- NIF provides the opportunity to study effects relevant to nuclear astrophysics
- Recent work have demonstrated the possibility to perform experiments that present new/unique challenges
- Reaction $^{10}\text{B}(p,\alpha)^7\text{Be}$ is proposed to demonstrate feasibility
Galactic Chemical Evolution

How did we get from here to here?

(a) Big Bang

(b) Oldest stars

(c) Solar system
Nucleosynthesis in Stars

Hydrogen Burning: \(^{4}\text{He}, ^{14}\text{N}\)

Helium Burning: \(^{12}\text{C}, ^{16}\text{O}, ^{22}\text{Ne}, \text{n, s-nuclei}\)

Carbon Burning: \(^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg} \ldots \text{s-nuclei}\)

Ne-, O-, Si-Burning: \(^{56}\text{Fe} \text{but shell distributions}\)
1: Thermonuclear Reaction Rates

Characterize the engine of stars; determine the energy production, define the time scale of burning, set its seed production, and provide new signatures for observations!

\[ N_A \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{3/2} \int_0^\infty E \cdot \sigma(E) \cdot \exp\left(-\frac{E}{kT}\right) dE \]

\[ R_{i,j} = \frac{n_i \cdot n_j}{1 + \delta_{ij}} \cdot \langle \sigma v \rangle_{i,j} \]

\[ \sigma(E) = \frac{S(E)}{E} \cdot \exp(-2\pi \eta) \]

MB distribution

CROSS SECTION \( \sigma(E) \)

(log scale)

S(E) - FACTOR

(lin. scale)

ENERGY E

LOWEST ENERGY \( E_L \)

OF DIRECT MEASUREMENTS

COULOMB BARRIER \( E_C \)

EXTRAPOLATION

background

MEASUREMENTS
I NSTITUTE FOR S TUCTURE AND NUCLEAR A STROPHYSICS
N UCLEAR S CIENCE L ABORATORY

Solar Nuclear Reaction Network

pp-chain

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \] (pp)

99.75%

\[ ^2\text{H} + p \rightarrow ^3\text{He} + \gamma \] (pep)

0.25%

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \] (ppII)

86%

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \] (ppIII)

14%

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \]

99.89%

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

0.11%

\[ ^8\text{B} \rightarrow ^7\text{Be}^* + e^+ + \nu_e \]

ppI

CNO Cycle

ppII

ACS 2014
Solar Neutrino Sources

Critical nuclear reaction with large cross section uncertainties at stellar temperature.
Low energy accelerator studies with high beam intensity

At low energy, yield is decreasing and the signal is eventually overwhelmed by the background (Cosmic rays, environmental, beam induced)

Yield measurements with particle and/or gamma detector arrangements
Compact Accelerator System to Perform Astrophysics Research

Sanford Underground Research Facility
4850 ft underground in Homestake Mine, South Dakota

Highly reduced cosmic rays
2: Laboratory electron screening

R. Bonetti et al. PRL 82(1999)

\[ ^3\text{He}( ^3\text{He}, 2\text{p})\alpha \]


Adiabatic approximation

\[ ^3\text{He}(d, p) ^4\text{He} \]

\[ U_e = 219\pm7 \text{ eV} \]

\[ U_{\text{theo}} = 120 \text{ eV} \]

Coulomb potential

\[ E \]

\[ E_c \]

\[ R_n \]

\[ R_{\text{atomic}} \]

\[ R_t \]
Laboratory electron screening

Discrepancies between theoretical and experimental screening estimation can be large for reactions involving $^6\text{Li}(d, \alpha)\,^4\text{He}$; $^7\text{Li}(p, \alpha)\,^4\text{He}$; $^{11}\text{B}(p, \alpha)\,^4\text{He}$ and $^6\text{Li}(p, \alpha)\,^3\text{He}$.

Laboratory electron screening

Beside reaction yield, nuclear astrophysics relies on reaction mechanism theory to:
1. Extrapolate reaction rate at low energy
2. Extract bare nucleus reaction rate

A long “shopping” list of reactions that are too weak to get a reaction rate at a stellar temperature.
Inertial confinement facilities Conditions

Advantage: Star like environment (temperature and density)

Plot from Daniel CASEY, LLNL
Data analysis from Prav Patel
Stellar evolution simulations by Dave Dearborn
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NIF Simulations Harry Robey and Bob Tipton
OMEGA Simulation P. B. Radha
Using NIF to study reaction rate?

Advantage: Star like environment (temperature and density)

Question:
• Are the plasma condition sufficiently well understood to extract reaction rate?
• Is the plasma at thermodynamic equilibrium at its temperature and density peak?
• What can we measure?
• Can we use a known nuclear reaction to demonstrate we understand the plasma?

Success: \( T(T, 2n) \, ^4He \)

D. Sayre

Producing and detecting \(^7Be\) a perfect proof and useful proof of concept

\( T_{1/2} \approx 53 \) days makes it an interesting particle to use as a reaction rate diagnostic.

Produced in the pp-chain by reactions between low-Z element, i.e. low(er) coulomb barrier. Can be captured with RAGS (Radiochemical Analysis of Gaseous Samples) using Xe carrier gas injected in the NIF chamber before the shot.

C. Velsko & D. Shaughnessy
$^7\text{Be}$ production channels

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

Part of the pp-chain

Large experimental uncertainties or controversial data

Not appropriate for a first test

$^6\text{Li} + p \rightarrow ^7\text{Be} + \gamma$

Y. Xu et al, Nucl Phys A918 (2013)
$^7\text{Be}$ production channel

$^{10}\text{B} + p \rightarrow ^7\text{Be} + \alpha$

$^7Be$ production channel

$^{10}B + p \rightarrow ^7Be + \alpha$

Responsible for the destruction of $^{10}B$ in stellar environment

**Experimental reaction rate has been investigated**

Proposal at NIF for a $BH_3$ filled capsule in a direct drive pusher shot

- The $^7Be$ collection efficiency needs to be estimated
- The reaction rate uncertainty at NIF temperatures need to be improved to provide energy/density distribution
- High energy shot to compensate for radiative (bremsstrahlung) loss
- Plasma electron screening not present in this type of shot (low density, high temperature)
How much $^7Be$ could one get?

$^{10}B + p \rightarrow ^7Be + \alpha$

Assuming a plasma temperature of 20keV and $10^{16}$ molecules of BH$_3$

A density at maximum compression of 200 g/cm$^3$ of $2\times10^{16}$ Borane molecules

A total of $\sim10^{10}$ $^7$Be will take place BUT ... too optimistic according to my NIF friends

Total reactants should be lower, and density exaggerated
$10^6$ seems to be a more realistic number

Signature of reaction will depend on:
Collection efficiency
Gamma detector efficiency at 478 keV

$\sim500$ counts seems reasonable
Reaction producing shorter lifetime isotopes

\[ ^{17}O(p, \gamma)^{18}F \] (110 min. half life) 15-20% uncertainty in reaction rate at nova temperature

\[ ^{12}C(p, \gamma)^{13}N \] (10 min. half life) 30% uncertainty in reaction rate at stellar energies introducing a large uncertainty to the contribution of CNO reactions to the solar neutrinos

The slowest reaction of the CNO cycle \[ ^{14}N(p, \gamma)^{15}O \] could be another candidate on the long term but the 122 sec. half life of \[ ^{15}O \] may be pushing the limit of the method

And one day, collection of stable product and analysis of the collected gas with AMS 😊
Usage of $^7Be$ producing reaction in other plasmas based measurements

Recently two petawatt laser facilities measured reaction rates:
Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune, C. Baccou, S. Depierreux, C. Goyon, G. Loisel, V. Yahia, & J. Rafelski

We report proton-boron reaction rates that are orders of magnitude higher than those reported previously.

$^{11}\text{B}(p,\alpha)^4\text{He}$
Summary

- The conditions in the core of a NIF shot make it an ideal place to study nuclear reaction between charged particles.

- An experimental program to study such reaction requires a proof of concept: $^{10}\text{B} + \text{p} \rightarrow \alpha + ^7\text{Be}$
  - The rate of this reaction will be studied with accelerator-based techniques to reduce the rate uncertainty at NIF energies.

- It is proposed to study at NIF key reactions associated with the understanding of the solar neutrino flux.
  - The appropriate diagnostics are “already in place” (RAGS).

- Using reactions producing $^7\text{Be}$ as a diagnostic in other plasma-based experiments is suggested.