Nuclear Structure and Reactions at NSCL and FRIB through the Lens of Astrophysics: Lecture 2

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Outline

• Lecture 1: History, stellar evolution & thermonuclear rates
• Lecture 2: Charged-particle reactions: direct measurements
• Lecture 3: Charged-particle reactions: indirect measurements
• Lecture 4: Slow neutron capture process: direct measurements
• Lecture 5: Rapid neutron capture process: indirect measurements
Direct measurements (stable reactants)

- Accelerator produces ion beam of one reactant at appropriate energy
- Beam directed on a chemically stable target composed of other reactant
- Reaction like \( A(a, \gamma) B \) or \( A(a, b) B \) takes place in target
- Reaction products (usually \( \gamma \) rays or light particles) measured in detector
- Reduce background as much as possible (pure beam, clean target, shielding, …)
Example: $^3\text{He}(\alpha, \gamma)^7\text{Be}$ reaction

Motivation 1: Big Bang Nucleosynthesis (BBN) & cosmological Li problem:
Why do we observe 3-4 times less $^7\text{Li}$ than BBN predicts?
$^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$ reaction

Motivation 2: Solar hydrogen burning and neutrinos

Nuclear Physics of Stars, Iliadis, 2nd Ed.
$^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction experiment

Setup

Spectrum at $E_{\text{cm}} = 0.43$ MeV

S factor

\[ Y(E_0) = n\sigma \]

$Y$ = yield (# reactions per ion)

$n$ = # target nuclei per unit area

$\sigma$ = nuclear cross section

Measured at University of Washington’s Center for Experimental Nuclear Physics and Astrophysics.


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Experimental Nuclear Astrophysics
Resonances in the $^{31}\text{P}(p,\alpha)^{28}\text{Si}$ reaction determine if there is a Si-P cycle during (explosive) hydrogen burning on accreting compact stars: rapid proton-capture (rp) process.
Narrow resonance reaction rates

For narrow, isolated resonances, thermonuclear rate is:

\[ N_A \langle \sigma v \rangle = N_A \left( \frac{2\pi}{m_{01} kT} \right)^{3/2} \hbar^2 e^{-E_r/kT} \omega \gamma \]

Depends on nuclear physics:
1. Resonance energy \( E_r = E_{01} = E_\gamma - Q \)
2. Resonance strength \( \omega \gamma \), which is like integral of \( \sigma(E) \) over resonance

Depends on astrophysical environment:
1. Temperature \( T \)
31\text{P}(p,\alpha)^{28}\text{Si reaction experiment}

Setup

Spectrum at $E_p = 390$ keV

Excitation function

\[ Y = \frac{\lambda^2}{2\pi} \frac{\omega\gamma}{\varepsilon_r} \]

\( Y = \) yield (\# reactions per ion)
\( \lambda = \) proton deBroglie wavelength
\( \varepsilon = \) stopping power
\( \omega\gamma = \) resonance strength

Measured at the Kellogg facility at Caltech.

Result: no strong SiP cycle

No strong SiP cycling below about 1 GK

Nuclear Physics of Stars, Iliadis, 2nd Ed.
Example: \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\) reaction

Weak s-process occurs in supergiant stars

The \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\) reaction is one of two major sources of neutrons for the slow neutron capture (s) process that produces half of the heavy elements.
$^{22}$Ne + $\alpha$ competition

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction experiment

Measured using similar techniques at many facilities.

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Experimental Nuclear Astrophysics

Nuclear Physics of Stars, Iliadis, 2\textsuperscript{nd} Ed.

Eg. M. Jaeger et al., PRL 87, 202501 (2001)
Result: $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ cross section
\( ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \) reaction rate uncertainties

Monte Carlo method employed to sample probability densities of all input parameters

He: helium burning
C: carbon shell burning

Longland \textit{et al.} (2012)
Conclusion: still need to improve $^{22}\text{Ne} + \alpha$ reaction rates

Note: calculated $s$-process yields subtracted from solar abundances to determine $r$-process abundances
Charged-particle nuclear cross sections are low at astrophysical energies, so background levels can determine the sensitivity of an experiment: need to mitigate them!
Cosmic-ray backgrounds

Primary cosmic rays:
90% p; 9% α; 1% H\(\text{I}\)
\((\approx 1000 \text{ m}^{-2} \text{ s}^{-1})\)

Upper atmosphere:
\(n\) \(e\) \(\nu\) \(p\) \(\mu\) \(\pi\)

Sea level:
\(\mu\) \(n\) \(e\) \(p\) \(\pi\)

Cosmic-ray induced BG
(absorbed by lead or concrete)
Passive background shielding

- Use material to block radiation from interacting with the detectors

High-Z material (e.g. Pb) to block gamma rays

Moderator for neutrons (e.g. polyethylene) with component to capture thermal neutrons ($^{10}$B, $^6$Li, Cd)

Large overburden of Earth to block cosmic-ray muons
Active background shielding

- Surround detector with a material like plastic scintillator
- Use anti-coincidence condition to veto events that were likely from cosmic rays
- Eg. SuNSCREEN at NSCL (left) to veto cosmic-ray muons

E. Klopfer et al., NIMA 788, 5 (2015)
Rare Isotope Beams (RIBs)

- Stars (especially exploding stars) produce radioactive nuclides that undergo reactions
- Can’t make a target for $p$ and $\alpha$ induced reactions out of short-lived radioactive nuclides
- Instead, use *inverse kinematics*: bombard H or He target with RIB
- Need high-quality, high-intensity, low-energy RIB

Core-collapse supernovae

Thermonuclear supernovae

Classical novae
Methods for RIB production

**Isotope Separator On Line (ISOL) method**

- **Primary Accelerator**
- **Ion source**
- **Separator**
- **RIB Accelerator**

- **Thick-target**
- **light/heavy ion beam**
- **CN/Spallation/fission/fragmentation of target nuclei**
- **Online**: primary accelerator & RIB accelerator operate simultaneously
- **Low energy RIB (<20 MeV/A)**
- **High beam purity, quality, But element dependent intensity, T_{1/2} limit ≥ 1 sec**

**In-flight separation method**

- **Primary Accelerator**
- **Thinner-target**
- **Projectile like fragments**
- **Separator**
- **High energy RIB (>100 MeV/A)**

- **>100 MeV/A**
- **Fragmentation of beam nuclei**
- **Isotones cannot be separated; rejection of primary beam a challenge**
- **No ion-source, so all elements transported, no half-life limit But lower beam purity, quality**
Example: $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ reaction

How are the 2 solar masses of $^{26}\text{Al}$ ($\tau \sim 1$ Myr) radioactivity observed across the Milky Way produced?

The reaction $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ destroys $^{26}\text{Al}$ in stars: need to know the rate.
ISAC is an operating ISOL facility
RIB from ISAC facility hits H gas target inducing $(p, \gamma)$ reaction.

Detect $\gamma$-rays at target position.

Separate reaction products from beam with electromagnetic separator.

Detect reaction products at the end of the separator.
Example: $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ with DRAGON

Energy of recoils combined with time-of-flight through separator used to distinguish reaction products from “leaky” beam at $E_{\text{cm}} = 0.184$ MeV resonance.

$Y(\infty) = \frac{\lambda^2}{2} \frac{M+m}{m} \epsilon^{-1} \omega \gamma$

$Y = \text{yield (# reactions per ion)}$

$\lambda = \text{proton deBroglie wavelength}$

$M, m = \text{masses of reactants}$

$\epsilon = \text{stopping power}$

$\omega \gamma = \text{resonance strength}$
NSCL/FRIB
National user facility for rare isotope science and education:
Nuclear structure, nuclear astrophysics, fundamental symmetries, societal applications

On Michigan State University campus
NSCL/FRIB Re-accelerator (ReA3)

In-flight separation method

Primary Accelerator
>100 MeV/A

Thinner-target
Heavy beam
Fragmentation of beam nuclei

Projectile-like fragments
Separator

Isotones cannot be separated; rejection of primary beam a challenge

High energy RIB
(>100 MeV/A)

No ion-source, so all elements transported, no half-life limit
But lower beam purity, quality

> 50 MeV/u
Beams from PF

Multi Harmonic Buncher

80.5 MHz RT-RFQ
\[ \beta = 4.1\% \]

80.5 MHz SRF-QWR
\[ \beta = 8.5\% \]

Charge state Breeder

Gas stopper

Mass separator

1^+ \rightarrow N^+

Q/A Separator

Experiments

Introduction to ISOL Target Stations, Alexander Gottberg, Bill Paley, June 22, 2015
O. Kester et al., Proceedings of SRF 2009
C. Wrede, HUGS, May 2019
Experimental Nuclear Astrophysics
Accelerate heavy ion beam with cyclotrons and bombard thin, light, target. Reaction products fly forward, are separated in flight, and delivered to experiments directly (fast beam), thermalized (stopped beam), or reaccelerated (ISOL-like beam)
RIBs from FRIB

Same production technique and experimental areas as NSCL, but replace cyclotrons with 400 kW linear accelerator.

Experiments with fast, stopped and reaccelerated beams.

Rare isotope production area and isotope harvesting.

400 kW superconducting RF linear accelerator.

Ion source.

Reaccelerator.
RIB production: fragmentation (FRIB)
FRIB at full power will deliver 1000x the rare isotope quantities as NSCL by ~2025
Civil construction complete

Technical construction and concurrent commissioning underway

First RIB delivery to users in 2022 (possibly as early as 2021)
SECAR at NSCL/FRIB ReA3

SECAR: Separator for Capture Reactions

Under construction
Completion end of 2021
Design: M. Couder, G. Berg
Notre Dame
H. Schatz, F. Montes MSU
J. Blackmon LSU
K. Chipps, M. Smith ORNL
U. Greife CSM
+ many other institutions

SECAR performs the same role as DRAGON, but several differences and improvements

SECAR: Separator for Capture Reactions
Summary

• Charged-particle reactions are strongly suppressed by the Coulomb barrier at astrophysical energies

• Cross sections and resonance strengths for stable species typically measured using light beams and heavy targets, being mindful of backgrounds and often extrapolating to astrophysical energies

• Cross sections and resonance strengths for unstable species typically measured in the laboratory using heavy RIBs, gas targets, and recoil separators

• Next: indirect measurements of charged-particle reactions
Thank you for your attention!