Nuclear Astrophysics

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1. Introduction, Formalism, Big Bang and H burning
2. He burning, Heavy elements & s process
3. Stellar Explosions
**CNO Cycle**

- Dominant source of energy generation in stars heavier than the sun
- What is CNO contribution to energy production in the sun? Few%?
- CNO abundances in sun uncertain
- Stellar photospheric metallicity disagrees with helioseismology

![Diagram of the CNO cycle](image)
Resonances are important

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

\[
\sigma(E) = \pi \lambda^2 \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E - E_r)^2 + (\Gamma/2)^2}
\]

If resonance is narrow

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

Keiser, Azuma & Jackson, NPA331 (1979) 155.

Keiser, Azuma & Jackson, NPA331 (1979) 155.
Example: $^{18}\text{O}(p,\alpha)^{15}\text{N}$

Accessible with high intensity proton beams

Magnetic Spectrograph

$(^3\text{He},d)$

Champagne and Pitt (1986)

Accurate $E_x$

$\ell$, $J^\pi$ inferred

$$\Gamma_p = 2 \left( \frac{\hbar^2}{\lambda\mu R} \right) \left( \frac{\theta_p^2}{F_{\ell}^2 + G_{\ell}^2} \right)$$

with 1 mA $p + ^{18}\text{O}$

1 event / $3 \times 10^5$ years

$\theta_p = 0.12$
$^{14}\text{N}(p,\gamma)^{15}\text{O}$

- Slowest reaction in CN cycle
- Determines rate of energy generation and relative abundances

Mass log (abundance)
Can the sun synthesize heavier elements?

4He + p → ?

4He + 4He → ?

No atoms exist in nature with an A = 5 or 8

8Be lifetime ~ 10^{-16} s

4He + 4He + 4He → 12C

Only possible if 12C has a very large resonance at perfect energy

Red Giant Star

H burn

He burn

CO core
He burning & the "Hoyle" state

t_{1/2}(^{8}\text{Be})=9.7\times10^{-17}\text{ s}

^{8}\text{Be} \leftrightarrow \alpha+\alpha

\frac{N(^{8}\text{B})}{N(\alpha)} \approx 5 \times 10^{-10}

0^+\text{ resonance near the Gamow energy was predicted by Hoyle}

*Phys Rev 92 (1953) 1095.*

Numerous complementary techniques

\(^{12}\text{C}(p,p')^{12}\text{C}^*\quad \gamma\gamma, 3\alpha, e^+e^-

\(^{13}\text{C}(\text{^3He},\alpha)^{12}\text{C}^*\quad

\text{Largest uncertainty } \Gamma_{ee} \sim 12\%
The $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction rate fixes ratio of $^{12}\text{C}/^{16}\text{O}$ following helium burning.

Abundance ratio of $^{12}\text{C}/^{16}\text{O}$

The $^{12}\text{C}/^{16}\text{O}$ ratio governs subsequent evolution of the star:

- Size of Fe core & supernova dynamics

Subthreshold states influence → uncertain interference with other states

- Contribution of both E1 and E2 contributions are important → need to measure angular distributions

Stuttgart: Eurogam (HPGe)
Assuncão et al., PRC 73 (2006)

Karlsruhe: BaF$_2$
Plag et al., PRC 86 (2012)

Gai, PRC 88 (2013)
12C(α,γ)16O

Inverse reaction studied from 16N beta-delayed alpha emission

- Pushing direct measurements to lower energies is crucial but challenging
- Use indirect techniques to study properties of subthreshold states

Sub-Coulomb alpha transfer determines alpha-like part of asymptotic wavefunction

Brune et al. PRL 83 (1999)

France et al., PRC 75 (2007)

$S_{E2}(300\text{keV}) = 40 \pm 20 \text{keV} \cdot b$
AGB Stars – Fate for $M < 8 \, M_\odot$

Thermally unstable: mixing, convection, mass loss → nebulae

$^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta\nu)^{13}\text{C}(\alpha,n)^{16}\text{O}$

Neutrons drive synthesis of heavy elements

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

Convective pocket

He intershell

Neutron drive synthesis of heavy elements
Challenging measurements at lower energies needed to understand important reaction rates.
CASPAR (Compact Accelerator for Performing Astrophysical Research)

Sanford Underground Facility in Homestake Mine, South Dakota
High current JN accelerator

Windowless gas target
Underground accelerator project DIANA for low energy studies

High luminosity, low background experiments

p, α, HI beams
100 x LUNA luminosity
Generally only one combination of protons and neutrons is stable for each A (smallest mass)

“Beta decay” is a form of radioactivity that nature uses to change a nucleus into the most stable combination of Z and N

Too many protons
protons $\rightarrow$ neutrons

$$ p \rightarrow n + e^+ + \nu $$

Fusion only effective up to $\sim$Fe region

Too many neutrons
neutrons $\rightarrow$ protons

$$ n \rightarrow p + e^- + \bar{\nu} $$
Slow neutron capture (s) process

- Produced about half of matter that is heavier than iron
- Series of slow neutron captures
- Pattern of isotopes produced is generally well understood
- Most $\sigma$'s measured

Käppeler et al. Rev. Mod. Phys. 83 (2011)
(n,γ) cross sections for the s process

Good data on most stable isotopes
Spallation n sources
TOF techniques
Good energy resolution
Usually high level densities

Some outstanding issues

- Influence of low-energy levels at low temp
- Direct capture near closed shells
- Effect of thermal excitations in stellar environment
- Branch point isotopes
- Lighter elements – “weak s process”
What can AGB stars produce?

Relative abundances of s process isotopes well understood

Subtract s abundances from solar system to get remainder
**Rapid neutron process**

Temperature: 1.50  
Time: 2.7e-
Cartoon r process

\[
\frac{Y(A + 1)}{Y(A)} \approx \frac{1}{2} \left( \frac{2\pi \hbar^2}{m_u kT} \right) n_n e^{S_n/(kT)}
\]

Large \(S_n\)
\[(n,\gamma) \gg (\gamma,n) \gg t_{1/2}\]

Small \(S_n\)
\[(\gamma,n) \gg (n,\gamma) \gg t_{1/2}\]

Free parameters \(n_n, kT, t\)

freezeout relatively fast & decay back to stability

Most important: masses, \(t_{1/2}\), and \(P_n\)
Synthesis of heavy elements

- **s process**
- **r process**
  - Produces about half of matter heavier than iron
  - High neutron flux
  - Reactions on unstable isotopes
  - Site unknown
r process in the early Galaxy

New observations of unmixed abundances early in the Galactic halo

CS22892-052
Fe/H = (8x10^{-4}) solar = very old
r/Fe = 50 solar
Only 2 known in 2000
Now extensive surveys
  e.g. see Frebel et al., ApJ 652 (2006) 1585
  SEGUE (Sloan DSS)
Spectra of >2x10^5 selected halo stars
  Expect ~ 1% with Fe/H < 0.001solar
~36 known r process stars
  11 with r/Fe > 10 solar
Distribution Fe/H puzzling
Lowest Fe/H stars intriguing

An additional process (besides r/s) must contribute significantly to elements from Fe-Sn

Z>55 pattern matches solar

Z<50 abundances vary

r process, where?

*Neutron star mergers?*

- 10 systems known in our Galaxy
- Believed to be origin of gamma-ray bursts
- Potentially explains dispersion in Eu
- High output in rare event
- Calculations produce a robust r process
- Huge uncertainties due to nuclear data
r process: masses and reaction rates

- Some \((n,\gamma)\) capture rates are important
- Abundances are very sensitive to most atomic masses and decay properties
- Most mass models do not reliably extrapolate away from stability
- Need measurements of nuclear properties in neutron-rich nuclei
Atomic masses

- About 2400 isotopes have measured masses
- Average precision better than 0.1 ppm

Results from 6 Penning trap programs

Courtesy Dave Lunney
Penning Traps: In a Nutshell

- Trap electrodes in a hyperboloid geometry \( r_0/z_0 \approx 1.16 \)
- Placed inside uniform magnetic field
- Three types of motion: Axial \( (\omega_z) \), Reduced cyclotron \( (\omega_r) \), Magnetron motion \( (\omega) \)
- Drive trapped ions into an excitation using RF signal
- Ions are ejected from the trap and measure their time-of-flight to a detector
- Resonant enhancement at the ion cyclotron frequency: \( \omega_c \)

The mass of the trapped ions are measured indirectly by determining the cyclotron frequency:
\[
\omega_c = \frac{qB}{m}
\]

Time-of-Flight vs. Applied Frequency

132Sn iswrc

±3.7 keV
Canadian Penning Trap
Argonne National Laboratory
ATLAS Accelerator Facility
Precision Mass Measurements

\[ \text{Precision} = \frac{\Delta m}{m} \propto \frac{m}{T_q B \sqrt{N}} \]

Conversion Time
Time spent exciting the ion in the trap. \textit{Limited by isotope half-life!!!}

Ion Charge State
Typically \( q=1^+ \)
For some isotopes \( q=2^+ \); More precise measurement

Magnetic Field
Measured with a reference ion \((^{133}\text{Cs}^+)\) of known mass in between mass measurements

Statistics
The longer you acquire data, the better the measurement.
\textit{CARIBU transport efficiency!}

Many of the most neutron-rich nuclei produced at CARIBU have short half lives \((\leq 150 \text{ ms})\) as well as small fission branches from \(^{252}\text{Cf}\) \((\leq 10^{-4} \%)\)

Improvements in both CARIBU and the CPT systems are required to perform mass measurements of influential \(r\)-process nuclei to \(\Delta m/m \leq 10^{-7}\)
Mass measurements – storage rings

2 modes:
- Schottky - slow, more precise
- Isochronous - fast, less precise

Experimental Storage Ring:
\[ \Delta m/m = \gamma_{t}^{2} \Delta f/f + (\gamma_{t}^{2} - \gamma^{2}) \Delta v/v \]

Yu. Litvinov et al., NPA756 (2005) 3.

Matos, Ph.D. Univ. Giessen
NO dependence on lifetime!
Path length ~ 58m
Time resolution ~ 30ps

**B_ρ = \frac{m}{q} \quad mass**

Nov 2011 – Fragmentation of $^{76}$Ge
Estrade, George, Matos, Schatz et al.
Masses of 30+ neutron-rich nuclei near Ni measured with precision better than 1:200,000

New approved exp.
Fragmentation of $^{124}$Sn
Beta Decay Example: RIBF @ RIKEN

- Isotopes produced by fragmentation
- EM separated and implanted into Si detector stack (9)
- Identified by TOF and $\Delta$E-E
- Decay $\beta$ and $\gamma$ measured
- Dozens of isotopes studied

The r process

mass uncertainty [keV]

G. Audi, NPA729, 1
B. Singh, nuclearmasses.org
On existing NSCL Site

- New gas stopping technology + post accelerator
- New Powerful driver LINAC
  → 200 MeV/u for U
  → 400 kW
- 9/01/10 CD-1
  → $614M TPC
  → $520 DOE
- CD-4 ~FY2020

Wide variety of intense beams at low energies

- First access to many of the r process isotopes
- Direct measurements of many reactions for the first time
- Detailed study of all neutron-rich nuclei important for astrophysics possible up to Sn
- Masses and half-lives possible for most nuclei
  - Including A~190 mass peak
  - Pin down r process site