Radioactive nuclei play an important role in stellar explosions:

- Novae, $t \sim 10$ minutes
- X-ray bursts, $t \sim$ minute
- Supernovae, $t \sim$ few seconds

thermonuclear events → source of the heavy elements
Nuclear astrophysics
A survey in 6 parts
Jeff Blackmon, Physics Division, ORNL

Nuclear physics plays an important role in astrophysics:
- Energy generation
- Synthesis of elements
  - astronomical observables

1. Introduction
2. Big Bang
3. Stellar structure & solar neutrinos
4. Stellar evolution & s process
5. Supernovae & r process
6. Binary systems
Creation of elements in the early Galaxy

Now many observations of unmixed supernova nucleosynthesis 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 >2x10^6 selected halo stars
 Expect ~ 1% with Fe/H < 0.001 solar

~36 known r process stars
11 with r/Fe > 10 solar
Distribution Fe/H puzzling
Lowest Fe/H stars intriguing

Z>55 pattern matches solar

Z<50 abundances vary
The r process site

Galactic chemical evolution arguments favor supernovae as the dominant source for elements early in the history of the Galaxy → an r process

NS mergers

Supernovae

Model star average with error

Average ISM

observations


Dots: model stars
**Core-collapse supernovae**

- Stars > 10 solar masses
  - Higher gravity
  - Faster burning stages
  - Less mass loss

- C burning
- O burning
- Si burning

  In rapid succession

- Fermi degeneracy initially supports core
- Shell Si burning increases core size of
- Electron capture on nuclei in core begins to reduce pressure support
- Core undergoes runaway collapse
- Reaches supernuclear densities & shock rebounds -- EOS important
- Mechanism involves interplay of hydrodynamics and nuclear physics
- Spherical models fail to explode
- Multidimensional effects important?
- Influence of nuclear reactions on dynamics?

**Standing Accretion Shock Instability**
The weak interaction in supernovae

- Electron capture rates affect formation of shock wave.
- Neutrino interactions play a role in driving the explosion.
- Neutrino induced reactions alter nucleosynthesis.
- Weak rates in this mass region are not well understood: GT strength distributions first-forbidden contribution

Abundances relative to solar
- ● with $\nu$ reactions
- ○ without $\nu$ reactions

Fröhlich et al., PRL 96 (2006)
Charge exchange reactions such as \((t,^3\text{He})\) are sensitive probes for GT strength at 100 – 200 MeV/u.

Needed for:
- core collapse supernova models
- type Ia supernova models
- neutron star crust processes

Special case or systematic issue? Need systematic measurements for entire relevant range (especially beyond fp shell where nuclear models become much simpler)
→ can help decide which theoretical model to use and can help to improve theoretical models for supernova usage
→ Need to develop technique for inverse kinematics and radioactive beams
A proposal has been submitted to DOE to construct a facility for neutrino reaction measurements at the Spallation Neutron Source.

15 ton (fiducial) target/detector
20 m from SNS spallation target

\[ \nu_e + O \rightarrow F + e^{-} \] (450 events/yr)
\[ \nu_e + Fe \rightarrow Co + e^{-} \] (1100 events/yr)
\[ \nu_e + Al \rightarrow Si + e^{-} \] (1100 events/yr)
\[ \nu_e + Pb \rightarrow Bi + e^{-} \] (4900 events/yr)
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 \( S_n \)

\((\gamma,n) \gg (n,\gamma) \gg t_{1/2}\)

\[\Rightarrow\] Free parameters \( n_n, kT, t \)

\[\Rightarrow\] Instantaneous freezeout & decay to stability

Only masses, \( t_{1/2} \), and \( P_n \) needed
Calculated r process

Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie: H. Schatz, T. Elliot
NSCL, Michigan State University
Calculation: K. Vaughan, J. G. Calache,
and A. Arshamian, University of Notre Dame
Model: B. Meyer, Clemson University
and H. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s
Results of r process calculations

▷ Many different n densities needed
▷ Reasonable fits to A=130, 190 peaks
▷ Not so nice reproduction of intermediate nuclei

Evidence for quenching of the shell gaps? (Kratz et al.)

Astrophysical environment?

Freezeout effects?

Surman & Engel 2001
**NSCL fast beam r-process campaign**

$t_{1/2}(^{78}\text{Ni})$: $110^{+100}_{-60}$ ms

Effect of new $t_{1/2}$ on r process abundances

Shorter $^{78}\text{Ni}$ half-life leads to greater production of $A=190$ peak

The properties of neutron-rich nuclei are crucial for understanding the site(s) of the r process and the chemical history of the Galaxy

- Particle identification in rare isotope beam
- Half-life of $^{78}\text{Ni}$ measured with 11 events.
Mass measurements

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

Experimental Storage Ring:
$$\frac{\Delta m}{m} = \gamma_i^2 \frac{\Delta f}{f} + (\gamma_i^2 - 1) \frac{\Delta v}{v}$$

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

Matos, Ph.D. Univ. Giessen

Measurements now crossing into regime of light $r$ process
The Chart of the Nuclides

The Chart of the Nuclides


- half-life measurements since 2000 (6th ed.)
  (neutron-rich nuclei only)
The Chart of the Nuclides


- Only a few measurements in r process path
- Z=82, N=126
- Z=50, N=82
- Z=28, N=50
- Z=0, N=0

= half-life measurements since 2000 (6th ed.)
(neutron-rich nuclei only)
Structure \textit{n-rich nuclei and the r process}

Masses, half-lives and $P_n$ are crucial $\rightarrow$ direct impact on r process abundances. Must rely on theory.

Properties like level energies and B(E2) values provide some direct benchmarks.

Understanding the structure of neutron-rich nuclei is crucial to improving extrapolations to more neutron-rich (unmeasured nuclei).
CARIBU

Intense $^{252}$Cf fission source under construction at ATLAS
Gas stopping technology
Neutron-rich RIBs will push the boundaries of our knowledge
Different region on nuclei → complementary to HRIBF

CPT measurements of very neutron-rich nuclei

Intense beams and high energy will allow unique structure studies, e.g. (p,t)
Next-generation RIB Facilities

RIBF (RIKEN), FAIR (GSI), SPIRAL-II (GANIL), RIA (USA)

Ground state properties of nearly all r process nuclei up to the A=190 peak can be measured.

Nuclear structure studies far from stability will greatly improve our ability to extrapolate to the unknown.

Understanding observations of the oldest stars and the origin of the heavy elements in our Galaxy.
**Recommendations of 2007 NSAC LRP**

- We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.

- We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.

- We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.

- The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.
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   Energy generation
   Synthesis of elements
          \{ \text{astronomical observables} \}

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Discovering Novae

➢ The most common stellar explosion
  • About 3 dozen per year in Milky Way

➢ Characterized by increase in brightness of 8-15 magnitudes ($10^3$-$10^6$ times)
  • Peak reached in < 24 h
  • Much slower decay (weeks)
  • Recur after t >1000 yr ?
  • Discovered by amateurs
  • 100’s observers networking around the world
  • Usually discovered photographically

➢ Nova Ophiuchi 2006 No. 2
  • Discovered April 6, 2006
  • Peter Williams, Sydney Australia
  • Visual discovery (Magnitude 10)
  • Peak brightness 9.2
  • Confirmation:
    – William Liller (Chile)
    – Tom Krajci (US)
    – Jaciej Reszelski (Poland)
**RS Ophiuchi**

- "Recurrent Nova" (one of few known)

- **Feb. 12, 2006**
- Reached Magnitude 4.8
- Swift observations began less than 3 days after onset (observations only after 3 weeks in 1985)
- Observed by 4 space observatories and variety of ground-based instruments on the same day (Feb. 26)
- First observed in 1898
  - Williamina Stevens Flemming (1857-1911)
Novae mechanism

- Hydrogen-rich gas from companion accretes onto white dwarf & burns: **hot-CNO cycle**
- Electron degeneracy $\rightarrow$ pressure
- Thermonuclear runaway

- Rates of nuclear reactions determine energy generation and nucleosynthesis
- Source for $^{13}$C, $^{15}$N, $^{17}$O
- $^{18}$F: largest source of 511 keV $\gamma$-rays
- Most important nuclear physics problems
  - $^{13}$N(p,$\gamma$)$^{14}$O
  - $^{17}$F(p,$\gamma$)$^{18}$Ne
  - $^{17}$O(p,$\alpha$)$^{14}$N
  - $^{18}$F(p,$\alpha$)$^{15}$N
- $^{22}$Na

Part of initial HRIBF Program

TRIUMF-ISAC
Complex, multidimensional problem

- Many ejecta substantially enriched in S

<table>
<thead>
<tr>
<th>Element</th>
<th>Abbreviation</th>
<th>Atomic Number</th>
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<tbody>
<tr>
<td>Ar</td>
<td>(18)</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>(17)</td>
<td></td>
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<tr>
<td>S</td>
<td>(16)</td>
<td></td>
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<tr>
<td>P</td>
<td>(15)</td>
<td></td>
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<tr>
<td>F</td>
<td>(9)</td>
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<tr>
<td>O</td>
<td>(8)</td>
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<tr>
<td>N</td>
<td>(7)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(6)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>(5)</td>
<td></td>
</tr>
</tbody>
</table>

- $^{26}$Al ($7 \times 10^5$ y) $E_\gamma = 1.275$ MeV
- $^{22}$Na (2.6 y) $E_\gamma = 1.809$ MeV
- $^{18}$F (110 m) $E_\gamma = 0.511$ MeV

- More violent than expected
  - High abundance of heavier elements
  - Elements as heavy as sulfur
  - High ejected mass
  - Substantial mixing of accreted material with core?

Complex hydrodynamical models required

- Multidimensional models using adaptive coordinate mesh
- Nuclear physics typically decoupled or simplified
- Nucleosynthesis tracked in detail in a post-processing approach
- Frontier is now coupling of better nuclear physics with more realistic hydrodynamical models


[Image of CO density gradient]
Advances in observation


511 keV


$^{26}\text{Al}$

2±1 supernovae/century

RS Ophiuchi
Feb. 12, 2006

Osborne et al. 2006
Over 100 sources in the Milky Way
- Do not confuse with Gamma ray-bursts
- Recur on a semi-regular time scale
- Thermonuclear explosion on surface of a neutron star
- Observations provide crucial insights into neutron star properties

http://heasarc.gsfc.nasa.gov/xte_weather/
X-ray Bursts

- Like nova, but on neutron star
- Started by hot CNO cycle
- \( \alpha \)-burning ignited
- Reactions close to the proton drip line


\[ t = 150 \, \mu s \]

- Nuclei up to Sn
- Waiting points crucial
  - \(^{64}\)Ge
  - \(^{68}\)Se
  - \(^{72}\)Kr
  - \(^{76}\)Sr

Most reaction rates very uncertain
X-ray Bursts & Superbursts


First observation in 2000

Orders of magnitude greater energy release and duration
Ignition of carbon from unburned ashes of previous bursts
Composition of rp process ashes is very important

Ginga 1826 over 5 years
More frequent and intense bursts
Increasing burning between pulses
Trends not fit with consistent models

Neutron Star Surface
X-ray burst
H, He fuel
rp process
H, He ashes
gas
ocean
outer crust
inner crust
core

Schatz et al.
\[ ^{18}\text{F}(p,\alpha)^{15}\text{O} \]

- Largest uncertainty in \(^{18}\text{F}\) production in novae
  - Largest source of potentially observable \(\gamma\) rays
  - Flux uncertain by \(~300\times\) just due to \(^{18}\text{F}(p,\alpha)^{15}\text{O}\)
- Complicated (uncertain) level structure

\[ ^{18}\text{O},^{18}\text{F} \]

\[ ^{18}\text{O} > 10\times (^{18}\text{F}) \]

- Coincidence allows reaction to be distinguished with highly contaminated beam.
**Results**

Significant progress ... but 3 significant outstanding issues

---

**Need**

Better technique
Greater beam intensity
New technique developed with $^{17}$O(p,$\alpha$)$^{14}$N


- Extended windowless hydrogen gas target
- Reaction yield increased by 3x relative to using CH$_2$
- Target thickness matched to resonance width by pressure → reduced background
- Narrow states → low P

183-keV resonance in $^{17}$O(p,$\alpha$)$^{14}$N reaction measured with an accuracy of 9%
Measurement of $^{18}$F(p,$\alpha$)$^{15}$O approved by HRIBF PAC

See talk by B. Moazen, Thursday July 19
(p,γ) at ISAC

H₂ gas target

30 BGO detectors

recoil+γ coincidences provide sensitive selection of events

http://dragon.triumf.ca

S. Engel et al., NIM A553 (2005) 491.

$^{21}\text{Na}(p,\gamma)^{22}\text{Na}$ with DRAGON

2.6 yr half-life and 1.27 MeV gamma ray make $^{22}\text{Na}$ a prime observational target.


$\omega_\gamma = 556 \pm 77$ meV

$\Gamma = 16$ keV


Higher rate for 206 keV resonance → ~25% less $^{22}\text{Na}$

Uncertainty~25%
That’s great, but ...

- Radioactive ion beam intensities are typically very low.
  - Expensive to produce
  - Beam time limited
- Cross sections for reactions of interest are low:
  - $(p, \gamma) \sigma < \mu b$
  - $(p, \alpha) \sigma < \mu b$
- Wide range of energies important in explosive environments.
- Measurement of complete excitation function over energy range of interest is usually not practical.
- Need alternative approaches to measure nuclear structure properties:
  - Stable beam measurements
  - Elastic scattering with RIBs
  - Direct reactions with RIBs

Keiser, Azuma & Jackson, NPA331 (1979) 155.
Elastic scattering with low energy beams

$^{17}F(p,\gamma)^{18}\text{Ne}$ via $^{17}F+p$


- $E_F = 599.8 \pm 2.5$ keV
- $\Gamma = 18.0 \pm 2.2$ keV
- $E_X = 4523.7 \pm 2.9$ keV

- 3$^+$ state predicted from mirror symmetry, but not observed in transfer reactions
  - $^{20}\text{Ne}(p,t)^{18}\text{Ne}$
  - $^{16}\text{O}(^{3}\text{He},n)^{18}\text{Ne}$

- Discovered via $^{17}F+p$ elastic scattering to be too high in energy to contribute significantly at nova temperatures.
The $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction & X-ray binaries

Lifetime of most important state ($E_x = 4.03$ MeV) measured → $\Gamma_{ND}$

$^{17}$O($^3$He,n)$^{19}$Ne

$\tau = 13^{+16}_{-9}$ fs (2$\sigma$)

TRIUMF

$^3$He($^{20}$Ne,$\alpha$)$^{19}$Ne

$\tau = 11^{+7}_{-8}$ fs (2$\sigma$)

Combined

$\tau = 12^{+7}_{-6}$ fs (2$\sigma$)

Despite great efforts, only upper limit on $\Gamma_{\alpha}$


$^3$He($^{20}$Ne,$\alpha$)$^{19}$Ne→$^{15}$O+ $\alpha$

$B_\alpha < 6 \times 10^{-4}$


Uncertain lower limit on $\Gamma_{\alpha}$ results in substantial, qualitative changes in X-ray burst models
Measuring partial widths

$^{15}$O($\alpha,\gamma$)$^{19}$Ne rate is important for "break-out" of CNO cycle and X-ray burst ignition $\rightarrow$ $\Gamma_\alpha$'s are major uncertainties

$^{15}$O($\alpha,\gamma$)$^{19}$Ne

$^{21}$Ne(p,t)$^{19}$Ne

**Big Bite Spectrometer**

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_\alpha$/$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.033</td>
<td>&lt; 0.0004</td>
</tr>
<tr>
<td>4.379</td>
<td>&lt; 0.004</td>
</tr>
<tr>
<td>4.549</td>
<td>0.16±0.04</td>
</tr>
<tr>
<td>4.6</td>
<td>0.32±0.04</td>
</tr>
<tr>
<td>4.712</td>
<td>0.85±0.04</td>
</tr>
</tbody>
</table>
Recent Notre Dame Measurement


\[ B_\alpha = (2.9 \pm 2.1) \times 10^{-4} \]
Homework problem - $^{15}$O($\alpha,\gamma$)$^{19}$Ne

The $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction is one of the most important reactions in X-ray binaries (see Lecture #3). The $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction rate is dominated by the contribution from a single 4.03 MeV ($E_{cm}$=504 keV, $J^{n}$=3/2$^+$) resonance in $^{19}$Ne. Plot the density as a function of temperature where the $^{15}$O($\alpha,\gamma$)$^{19}$Ne rate is equal to the beta decay rate. Use the narrow-resonance approximation for the $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction rate:

$$\langle \sigma v \rangle \approx \hbar^2 \left( \frac{2\pi}{\mu kT} \right)^{3/2} (\omega \gamma)_{\alpha} e^{-E_{\gamma}/(kT)}$$

The number of alpha particles/cm$^3$, $N_{\alpha}$, is given by:

$$N_{\alpha} = \rho X_{\alpha} \frac{A}{w_{\alpha}}$$

where $\rho$ is the density (g/cm$^3$), $A$ is Avogadro's number, and $w_{\alpha}$ is the molecular weight of helium (4 g/mole). Take the mass fraction of $^4$He, $X_{\alpha}$, to be 25%.

Assume the alpha-decay branching ratio of the 4.03 MeV resonance to be 4x10$^{-4}$, the upper limit from Davids et al., PRC 67 (2003). The $^{15}$O ground state has $J^{n}$=1/2$^+$. What is the orbital angular momentum of the captured alpha particle?

The maximum temperature and density in nova explosions is 4x10$^8$ K and 10$^6$ g/cm$^3$. Is this reaction important in novae?
Homework solution

\[ N_\alpha N_{15} \langle \sigma v \rangle = \lambda N_{15} \quad \longrightarrow \quad \rho X_{\alpha} \frac{A}{w_\alpha} \langle \sigma v \rangle = \frac{\ln 2}{122 s} \]

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

\[ (\omega\gamma)_r = \frac{2J+1}{(2J_\alpha+1)(2J_{15}+1)} \frac{\Gamma_{\alpha}\Gamma_{\gamma}}{\Gamma} = \frac{2^{3/2}+1}{(2\cdot0+1)(2\frac{1}{2}+1)} \left(4 \times 10^{-4}\right)(50meV) = 4 \times 10^{-5} \text{eV} \]

\[ \langle \sigma v \rangle \approx \left(6.6 \times 10^{-16} \text{eV} \cdot \text{s} \right)^2 (2\pi)^{3/2} \left( \frac{19}{60 \times 0.931 \times 10^9 \text{eV}} \right)^{3/2} \left(3 \times 10^{10} \text{cm/s} \right)^3 \left(4 \times 10^{-5} \text{eV} \right)(kT)^{-3/2} e^{-E_r / (kT)} \]

\[ \langle \sigma v \rangle \approx 4.64 \times 10^{-17} (kT)^{-3/2} e^{-E_r / (kT)} \text{cm}^3 / \text{s} \quad \text{(with kT in eV)} \]

\[ \rho(0.25) \frac{6 \times 10^{23}}{4g} 4.64 \times 10^{-17} (kT)^{-3/2} e^{-E_r / (kT)} \text{cm}^3 / \text{s} = 0.0057 / \text{s} \]
\[ \rho = 3.3 \times 10^{-9} (kT)^{3/2} e^{504000/(kT)} \text{ g/cm}^3 \]  

With \( kT \) in eV

<table>
<thead>
<tr>
<th>( T ) (10^9 K)</th>
<th>( \rho ) (g/cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>6.5x10^{22}</td>
</tr>
<tr>
<td>0.2</td>
<td>3.7x10^{10}</td>
</tr>
<tr>
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<td>3500</td>
</tr>
<tr>
<td>1.0</td>
<td>29</td>
</tr>
</tbody>
</table>
Resonance energies via $(p,d)$ reactions & fast beams at NSCL

$^{36}\text{Ar}$

150 MeV/u

$^{34}\text{Ar}$

84 MeV/u

plastic target

d

$^{33}\text{Ar}^*$

$\gamma$ rays detected by SeGA

$\gamma$ in $^{33}\text{Ar}$

$^{32}\text{Cl}(p,\gamma)^{33}\text{Ar}$

reaction rate (cm$^3$/s/mole)

Uncertainty reduced from $10^4 \rightarrow 3x$

level energies in $^{33}\text{Ar}$

$\rightarrow$ resonance energies in $^{32}\text{Cl}+p$
Reaccelerated beams at NSCL

Bollen, Morrissey, Shatz et al.

So far <10 proton-rich accelerated species have been used in experiments

Promising new technology for efficient stopping of fragmentation beams is under development

Would allow a broad range of beams to be accelerated for astrophysics measurements: unique capability

Direct measurement of many \((p,\gamma)\) reactions important for novae

\[^{23}\text{Mg},^{25}\text{Al},^{30}\text{P},^{35}\text{Ar},^{38}\text{K}\]

Scattering & transfer reactions important for understanding iron-group nuclei in supernovae

\[^{44}\text{Ti},^{45}\text{V},^{46}\text{Cr},^{56}\text{Ni}\]

Direct measurement of \((\alpha,p)\) reactions for X-ray burst ignition

\[^{14}\text{O},^{18}\text{Ne},^{22}\text{Mg},^{26}\text{Si},^{30}\text{S}\]

Proton elastic scattering with crucial \textit{rp process} waiting points

\[^{57}\text{Cu},^{68}\text{Se}\]
Conclusion

➢ Nuclear physics plays an important role in astrophysical objects.
➢ Nuclear astrophysics aims to supply nuclear data needed to help understand astrophysical objects, especially:
   ➢ Energy generation
   ➢ Nucleosynthesis
➢ Big bang nucleosynthesis and stellar hydrogen burning are relatively well understood thanks to sensitive measurements, but there are important outstanding open questions. For example:
   ➢ $^7$Li production in Big Bang
   ➢ Precise determination of neutrino production rates in sun
➢ The $^{12}$C($\alpha,\gamma)^{16}$O has a strong influence on all late stages of stellar evolution. Measurements (especially indirect approaches) have improved our understanding, but further work is very important.
➢ Measurements of (n,γ) reactions on radioactive s process branch points are important for understanding heavy element production.
➢ Measurements of nuclear reactions and nuclear structure properties using short-lived radioactive beams are beginning to provide data that is helping to improve our understanding of nucleosynthesis in stellar explosions, but next-generation radioactive ion beam facilities are needed.