Nuclear reactions and nuclear properties determine:

- Energy generation
- Nucleosynthesis
  - Origin of the elements
  - Test between models and observations
Interdisciplinary research
New tools drive progress

Laboratory measurements
New beams & experimental techniques

Nuclear theory and data
Improved reaction theory, large-scale shell model calc, & reaction rate libraries

Observations
New orbiting instruments, increased optical power, presolar grains

Astrophysics
Advancing computing power → more realistic simulations
The sun’s energy is produced by nuclear fusion in its core

Result is $4p \rightarrow 4\text{He} + 2e^+ + 2\nu + 27 \text{ MeV}$

27 MeV = 4 x $10^{-12}$ J  \hspace{1cm} * $10^{38}$ fusions/s = 4x$10^{26}$ Watts
What are the origins of the elements?

Mass vs. log (abundance) graph showing AGB + Core Collapse. Types of supernovae:
- Core-collapse Supernovae
- Type Ia Supernovae

AGB stars and convective envelope.
Nuclear reactions in the lab & in space

What you are used to in the lab:

In astrophysical environments:

**cross section**

\[
\text{reactions/s} = \frac{\text{ions/atoms}}{\text{cm}^2} \sigma
\]

**reaction rate**

\[
\frac{\text{reactions}}{\text{cm}^3 \text{s}} = \int \frac{n_x}{\text{cm}^3} \frac{n_y}{\text{cm}^3} v \sigma(v) \phi(v) dv
\]

\[
\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)
\]

\[
\frac{\text{reactions}}{\text{cm}^3 \text{s}} = \frac{n_x}{\text{cm}^3} \frac{n_y}{\text{cm}^3} \langle \sigma v \rangle
\]

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

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

\[
\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G / E}}
\]

\[
E_G \equiv \frac{2\mu}{\hbar^2} \left( \pi Z_1 Z_2 e^2 \right)^2
\]

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

### Reaction site

<table>
<thead>
<tr>
<th>Reaction</th>
<th>site</th>
<th>(T) ((10^6 \text{ K}))</th>
<th>(kT) ((\text{keV}))</th>
<th>(r_{\text{turn}}) ((\text{fm}))</th>
<th>(r) ((\text{fm}))</th>
<th>(E_0) ((\text{keV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>sun</td>
<td>15</td>
<td>1.3</td>
<td>1100</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>p+(^{14})N</td>
<td>CNO</td>
<td>30</td>
<td>2.6</td>
<td>3900</td>
<td>4.3</td>
<td>42</td>
</tr>
<tr>
<td>(\alpha+^{12})C</td>
<td>red giant</td>
<td>190</td>
<td>16</td>
<td>1060</td>
<td>4.8</td>
<td>300</td>
</tr>
<tr>
<td>p+(^{17})F</td>
<td>nova</td>
<td>300</td>
<td>26</td>
<td>500</td>
<td>4.5</td>
<td>230</td>
</tr>
<tr>
<td>(\alpha+^{30})S</td>
<td>x-ray burst</td>
<td>1000</td>
<td>86</td>
<td>500</td>
<td>5.9</td>
<td>1800</td>
</tr>
<tr>
<td>(^3)He+(^4)He</td>
<td>big bang</td>
<td>2000</td>
<td>170</td>
<td>33</td>
<td>3.8</td>
<td>580</td>
</tr>
</tbody>
</table>
We have a fairly good understanding of hydrogen fusion in stable stars

Good observations (e.g. sun)

The astrophysical environment is not too complicated

We have directly measured most of the reactions in the laboratory
The S-factor

Example: $^3\text{He}(\alpha,\gamma)^7\text{Be}$

Important for:

The sun ($\nu$ production)
Big Bang (Li production)

$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}}$$

Previous experimental limit

Need $\sigma$ here for sun


New measurements

Stellar range 10-20 keV

Csoto

Kajino

Descouvemont

Laboratory
Underground
Nuclear
Astrophysics
“S4” Proposal Funded
Initial suite of experiments for DUSEL
Resonances

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

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

If resonance is narrow

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

\( E_r \) & \( J^\pi \) are most important

\[ \omega \gamma = \frac{2J + 1}{(2J_x + 1)(2J_y + 1)} \frac{\Gamma_x \Gamma_y}{\Gamma} \]

"resonance strength"

Keiser, Azuma & Jackson, NPA331 (1979) 155.
The cataclysmic death of a star

- Interacting binaries
  - Novae, X-ray bursts, Type Ia Sne
  - Most common stellar explosions
  - Thermonuclear events
- Core-collapse Supernovae
  - Site for the r process?
  - p process νp process?
- Asymptotic Giant Branch (AGB) stars
  - Site for s process
  - Source of ~half the heavy elements
- Others?
Novae and X-ray bursts

- The most common stellar explosions in the Galaxy
  - Thermonuclear events
  - About 3 dozen novae/year in Milky Way
  - Over 100 known Type 1 X-ray bursts

- Novae:
  - Recur after $t \gg 1000$ yr
  - Increase in brightness by $10^3$-$10^6$ times
  - Usually discovered by amateurs
  - Explosion on white dwarf

- X-ray bursts:
  - Recur on scale from hours to months
  - Don’t confuse with gamma-ray bursts
### Thermonuclear runaway under degenerate conditions

#### Some recent measurements:

- $^{13}\text{N}(p,\gamma)^{14}\text{O}$
- $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$
- $^{17}\text{O}(p,\alpha)^{14}\text{N}$
- $^{18}\text{F}(p,\alpha)^{15}\text{N}$
- $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$

#### Example Reactions:

- **$^{13}\text{N}(p,\gamma)^{14}\text{O}$**
  - $^1H + ^{12}\text{C} \rightarrow ^{13}\text{N} + ^0\gamma$
  - $Q = 0.511\text{MeV}$
  - Half-life: $2\text{h}$

- **$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$**
  - $^1H + ^{16}\text{O} \rightarrow ^{17}\text{F} + ^0\gamma$
  - $Q = 1.66\text{MeV}$
  - Half-life: $40\text{Myr}$

- **$^{18}\text{O}(p,\alpha)^{15}\text{N}$**
  - $^1H + ^{17}\text{O} \rightarrow ^{18}\text{O} + ^4\alpha$
  - $Q = 2.50\text{MeV}$
  - Half-life: $490\text{yr}$

- **$^{19}\text{F}(p,\alpha)^{16}\text{O}$**
  - $^1H + ^{18}\text{O} \rightarrow ^{19}\text{F} + ^4\alpha$
  - $Q = 3.00\text{MeV}$
  - Half-life: $1560\text{yr}$

- **$^{20}\text{Ne}(p,\alpha)^{17}\text{O}$**
  - $^1H + ^{19}\text{O} \rightarrow ^{20}\text{Ne} + ^4\alpha$
  - $Q = 3.47\text{MeV}$
  - Half-life: $2000\text{yr}$

#### Important Considerations:

- Thermonuclear runaway under degenerate conditions can occur under specific conditions, often in environments such as neutron star mergers or supernovae.
- Some reaction rates are very uncertain and require further investigation.

#### X-ray bursts

- X-ray bursts are transient phenomena observed in accreting neutron stars.
- The RXTE All-Sky Monitor Movie captures such events, providing valuable data on these bursts and their associated physics.

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**References:**

Knödlseder et al. (2005)
Very powerful experimental techniques have been developed to allow measurements of the weakest rates with minimum incident beam intensity.
\(^{21}\text{Na}(p,\gamma)^{22}\text{Na}\) with DRAGON

\[ \omega_\gamma = 556 \pm 77 \text{ meV} \]

\[ \Gamma = 16 \text{ keV} \]

\[ \omega_\gamma = 1.03 \pm 0.21 \text{ meV} \]

\[ E_r = 205.7 \pm 0.5 \text{ keV} \]

\[ ^{21}\text{Na}(p,\gamma)^{22}\text{Mg} \]

uncertainty now only 20%

Where are the resonances?

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

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

Resonance energy and width accurately determined from $^{17}\text{F}+p$ elastic scattering
- Only \textit{s-wave} resonances have strong signatures at low energies
**Classic Example: $^{18}\text{O}(p,\alpha)^{15}\text{N}$ via ($^3\text{He},d$)**

Accessible with high intensity proton beams

Champagne and Pitt (1986)

\[
\Gamma_p = 2 \left( \frac{\hbar^2}{\lambda \mu R} \right) \left( \frac{\theta_p^2}{F^2 + G^2} \right) \\
\Gamma_p = 2 \times 10^{-19} \text{ eV}
\]

$1 \text{ mA } p + ^{18}\text{O} \rightarrow 1 \text{ event / } 3 \times 10^5 \text{ years}$

- Accurate $E_x$
- Unambiguous $\ell, J^\pi$ inferred
- $\Gamma$ if broad
- $\Gamma_x$ sometimes, but can be model dependent
Recent example: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction

The $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction rate produces substantial qualitative changes in the X-ray burst light curve.

- Direct measurement of the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ rate would require $\sim\mu\text{A}$ beam intensities.
- Crucial quantities are $\Gamma_\alpha$‘s of resonances, particularly state at $E_x=4.03$ MeV.
- Populate state using another reaction and measure $B_\alpha$.

$$B_\alpha = \frac{\Gamma_\alpha}{\Gamma}$$
$^{19}$Ne Excitation Energy (MeV)

Counts / 40 keV

$^{1}$Ne-triton coincidence ($\gamma$ decay)

Counts / 20 keV

$^{19}$Ne Excitation Energy (MeV)

$^{15}$O-triton coincidence ($\alpha$ decay)

$E_x$ (MeV) $\Gamma_x/G$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_x/G$</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>


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

Somewhat similar measurement about the same time at ANL using the Enge splitpole:


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

$B_\alpha < 6 \times 10^{-4}$
$3^{rd}$ reaction

$18^F(3^He,3^H)19^Ne*(alpha)$


$B_\alpha = (2.9 \pm 2.1) \times 10^{-4}$
Exercise for the student: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

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

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

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 $^4\text{He}, X_{\alpha}$, to be 25%.

Assume the alpha-decay branching ratio of the 4.03 MeV resonance to be $4 \times 10^{-4}$, about the current upper limit. The $^{15}\text{O}$ ground state has $J^\pi=1/2^-$. What is the orbital angular momentum of the captured alpha particle?

The maximum temperature and density in nova explosions is $4 \times 10^8$ K and $10^5$ g/cm$^3$. Is this reaction important in novae?
Synthesis of elements heavier than iron

- **s process**
  - ~ 80% of isotopes
  - Most (n,γ) rates known
  - Branch points crucial

- **r process**
  - ~ 70% of isotopes
  - Far from stability
  - Supernovae?

- **p process**
  - ~ 10% of isotopes
  - Very low abundance
  - Secondary process

“What is the origin of the heavy elements?”
One of the top 11 questions
Neutron capture on long-lived nuclei

<table>
<thead>
<tr>
<th>Source</th>
<th>ORELA</th>
<th>Lujan</th>
<th>n TOF</th>
<th>SNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>flight path (m)</td>
<td>40</td>
<td>20</td>
<td>180</td>
<td>20</td>
</tr>
<tr>
<td>resolution (ns/m)</td>
<td>0.2</td>
<td>6.2</td>
<td>0.05</td>
<td>18</td>
</tr>
<tr>
<td>power (kW)</td>
<td>8</td>
<td>64</td>
<td>45</td>
<td>2000</td>
</tr>
<tr>
<td>flux (n/s/cm²)</td>
<td>2x10⁴</td>
<td>5x10⁶</td>
<td>3x10⁵</td>
<td>2x10⁸</td>
</tr>
<tr>
<td>FOM (n/s/cm²)</td>
<td>5x10⁵</td>
<td>6x10⁹</td>
<td>5x10⁸</td>
<td>9x10¹⁰</td>
</tr>
</tbody>
</table>

Experiments now possible with samples of only \( \sim 10^{16} \) atoms/cm².

High efficiency detector arrays
High segmentation to handle rate from radioactive sources

4π BaF array

Important s process brach points

\( ^{63}\text{Ni} \quad ^{79}\text{Se} \quad ^{81}\text{Kr} \quad ^{83}\text{Kr} \quad ^{147}\text{Nd} \quad ^{147}\text{Pm} \quad ^{148}\text{Pm} \quad ^{151}\text{Sm} \quad ^{154}\text{Eu} \quad ^{155}\text{Eu} \quad ^{153}\text{Gd} \quad ^{160}\text{Tb} \quad ^{163}\text{Ho} \quad ^{170}\text{Tm} \quad ^{171}\text{Tm} \quad ^{179}\text{Ta} \quad ^{185}\text{W} \quad ^{204}\text{TI} \)

status: ●
feasible: ●
New observations are allowing us to study the early evolution of the heavy elements in the Galactic halo.

Stars with:
- Fe/H < (0.001) solar → very old
- heavy/Fe = 50 solar

Only 2 known in 2000
Now extensive surveys

SEGUE (Sloan DSS)
Spectra of >2x10^5 selected halo stars
Expect ~ 1% with Fe/H < 0.001 solar

Usual suspect: Core collapse supernovae

- Explosion mechanism is not well understood.
- Electron capture rates affect formation of shock wave.
- Neutrino interactions play a role in dynamics and nucleosynthesis.
- Weak rates in this mass region are not well understood:
  - GT strength distributions
  - first-forbidden contribution

Weak interaction plays an important role in

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

Fröhlich et al., PRL 96 (2006)
Charge exchange reactions such as (t,³He) and (p,n) have been measured on some stable nuclei and provide sensitive probes of Gamow-Teller strength at 100 – 200 MeV/u.

Shell model calculations using the best interactions do not do an adequate job in predicting electron capture rates.

Measurements on radioactive nuclei are very important, but require new experimental techniques.

The LENDA neutron detector array is being developed at the NSCL for measurements of the (p,n) reaction in inverse kinematics.
Calculated r process

Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliott
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s
\[ \frac{Y(A+1)}{Y(A)} \approx \frac{1}{2} \left( \frac{2\pi \hbar^2}{m_u kT} \right) n_n e^{S_n/(kT)} \]

**r process cartoon**

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

- **Large \( S_n \)**
  - \((n,\gamma) \gg (\gamma,n) \gg t_{1/2}\)

- **Small \( S_n \)**
  - \((\gamma,n) \gg (n,\gamma) \gg t_{1/2}\)

- Dynamics: \( n_n, kT, t \) from astrophysical model
- Freezeout is relatively fast, followed by decay to stability

**Masses, \( t_{1/2} \), and \( P_n \) are crucial**
Mass measurements

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

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

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

Matos, Ph.D. Univ. Giessen

Measurements now crossing into regime of light r process
NSCL fast beam r-process campaign: the half-life of $^{78}\text{Ni}$

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

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

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

$^{78}\text{Ni}$ half-life measured with 11 events.

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


Only a few measurements in r process path

= half-life measurements since 2000 (6th ed.)
(neutron-rich nuclei only)
Not all masses and half-lives can/will be measured.

Our understanding of the synthesis of nuclei in the r process must depend upon nuclear theory.

Measurements of light isotopes have shown surprises, including modifications to the magic numbers.

What is expected in heavier nuclei near the r process?

Nuclear structure studies are crucial to improving the reliability with which nuclear models can extrapolate to more neutron-rich isotopes.
States populated using the (d,p) neutron-transfer reaction in inverse kinematics at the HRIBF.

Angular distributions of protons measured in coincidence with recoiling heavy ions.

States in $^{133}$Sn found to be strongly single-particle in nature, showing that $^{132}$Sn is a good “doubly-magic” nucleus.
The current frontiers of experimental nuclear astrophysics

- Direct measurements of cross sections with intense stable ion beams deep underground
- Direct measurements of charged particle induced reactions using proton-rich radioactive ion beams
- Innovative indirect approaches using both stable and radioactive ion beams
- Mass and decay property measurements of the most neutron-rich nuclei
- Nuclear structure studies to improve our understanding of the evolution of nuclear structure with isospin
- New capabilities to produce a much larger variety of isotopes are required