Outline – nuclear astrophysics experiments

• Astrophysics motivation – where does nuclear physics play a role?
• Reaction rate formalism – turning laboratory measurements into astrophysical input
• Brute force measurements – how our forefathers did nuclear astrophysics
• Direct measurements today
• Indirect techniques using stable beams

• Saturday : exotic beam measurements
Scientific Motivation
Overview of Nuclear Astrophysics

Nuclear Astrophysics plays a part in:

- explaining the tranquil beauty of the night sky
- explaining the violent events that occur throughout the cosmos - exploding stars
- explaining our ORIGINS - we are all made of stardust
astrophysics observations

- LIGO
- SuperK
- SIMS
- Auger
- SIRTF (infrared)
- Chandra (X-rays)
- Hubble (visible)
- INTEGRAL ($\gamma$-rays)
- WMAP (microwave)
- Keck, Subaru, ESO
- LIGO
- SuperK
- SIMS
as nuclear scientists, we have tools that enable studies of the cosmos that are impossible with any telescope!

we can use accelerators to recreate – and measure – one at a time the nuclear reactions that power the stars & create elements of life.
The Origin of the Elements

Observations provide picture of elemental abundance over time

Schatz, Physics Today (2008)

Must understand nucleosynthesis sites and events to explain the abundances
Overview of main astrophysical processes

- **Nova**
- **X-ray bursts**
- **Red Giant Stars**
- **p-process**
- **s-process**
- **n-star mergers**
- **Inhomogeneous Big Bang**

Nuclear Astrophysics Studies
Thermonuclear Reaction Rates

Nuclear Measurements

- Nuclear Theory
  - nuclear properties nuclei in a plasma reaction rate formalism

Astrophysics Theory

- Stellar Structure
- Stellar Evolution
- Hydrodynamics

Astrophysical Observations

Goal: make simulation accurately represent working of stars

Repeat to improve models

Astrophysical Observations

Computer Simulation

Predictions

nuclear astrophysics studies (more in Luke Roberts’ lecture)
nuclear astrophysics studies
Thermonuclear Reaction Rates

Reactions / cm$^3$ / s =

relative flux particles “1” (cm$^{-2}$ s$^{-1}$)

• (number of particles “2” cm$^{-3}$)

• effective area of each particle “2” for a reaction (cm$^2$)
Thermonuclear Reaction Rates

Define

\[ N_1 = \text{number of particles of type "1" per volume (cm}^{-3}\text{)} \]
\[ N_2 = \text{number of particles of type "2" per volume (cm}^{-3}\text{)} \]
\[ v = \text{relative velocity (cm s}^{-1}\text{)} \]
\[ \sigma(v) = \text{effective cross sectional area of each particle "2" for a reaction (cm}^2\text{)} \]

Then

\[ N_1 \cdot v = \text{relative flux of "1" relative to "2" (particles cm}^{-2}\text{ s}^{-1}\text{)} } \]

Reactions / cm\(^3\) / s =

relative flux particles “1” ( cm\(^{-2}\) s\(^{-1}\))

\[ \cdot \text{(number of particles "2" cm}^{-3}\text{)} \]

\[ \cdot \text{effective area of each particle "2" for a reaction (cm}^2\text{)} \]

Reactions / cm\(^3\) / s = \((N_1 \cdot v) \cdot N_2 \cdot \sigma(v) = N_1 N_2 \sigma(v) v\)

\[ \frac{dN_1}{dt} = -N_1 N_2 \sigma(v) v \]
At any given temperature, there is a distribution of relative velocities (relative energies) between any pair of particles in the star.

Need to average over these relative velocities to determine the interaction rate at a given temperature.
velocity averaged cross section

What you are used to in the lab:

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

In astrophysical events:

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

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

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

\[
\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_{0}^{\infty} \sigma E e^{-E/(kT)} dE
\]
Gamow window

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

$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}} \quad E_G \equiv \frac{2\mu}{\hbar^2} \left( \pi Z_1 Z_2 e^2 \right)^2$$

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

<table>
<thead>
<tr>
<th>Reaction</th>
<th>site</th>
<th>$T$ ($10^6$ K)</th>
<th>$kT$ (keV)</th>
<th>$r_{\text{turn}}$ (fm)</th>
<th>$r$ (fm)</th>
<th>$E_0$ (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>$^{4}$He+$^{12}$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>$^{16}$O+$^{30}$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>
For many reactions, MOST of the energy dependence in $\sigma(E)$ is described by the penetrability & nuclear size terms.

$S(E)$ is very slowly varying.

Advantageous to work with $S(E)$ rather than $\sigma(E)$. 

**Non-Resonant Reactions**
measure the cross section at all energies

- Accelerator produces ion beam of one reactant at an 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, ...)

Spectrum at $E_{cm} = 0.43$ MeV

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

CROSS SECTION $\sigma$ (nb)

ENERGY $E_{cm}$ (keV)
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: Experimental status of the art

Available data extend down to 1 MeV, well above the Gamow peak energy (about 200-300 keV) corresponding to the stellar temperatures experienced within the core of Helium burning stars (100 to 200 MK).

Gamow peak for helium burning stars

$10^{-8}$ nb at 300 keV
Research Highlights – Nuclear Astrophysics

LENA 240-keV ECR accelerator

Magnet upgrade planned, late 2018

H⁺ beam on target:
~ 5.2 mA @ 200 keV

See:
Laboratory for Underground Nuclear Astrophysics

LNDS
(1400 m rock shielding = 4000 m w.e.)

Radiation
Muons
Neutrons

10^{-6}
10^{-3}
Luna recent

<table>
<thead>
<tr>
<th>reaction</th>
<th>Q-value (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>completed</td>
<td></td>
</tr>
<tr>
<td>$^{17}\text{O}(p,\gamma)^{18}\text{F}$</td>
<td>5.6</td>
</tr>
<tr>
<td>$^{17}\text{O}(p,\alpha)^{14}\text{N}$</td>
<td>1.2</td>
</tr>
<tr>
<td>just started</td>
<td></td>
</tr>
<tr>
<td>$^{18}\text{O}(p,\gamma)^{19}\text{F}$</td>
<td>8.0</td>
</tr>
<tr>
<td>$^{18}\text{O}(p,\alpha)^{15}\text{N}$</td>
<td>4.0</td>
</tr>
<tr>
<td>just started</td>
<td></td>
</tr>
<tr>
<td>$^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$</td>
<td>11.7</td>
</tr>
<tr>
<td>completed</td>
<td></td>
</tr>
<tr>
<td>$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$</td>
<td>8.8</td>
</tr>
<tr>
<td>completed</td>
<td></td>
</tr>
<tr>
<td>$D(\alpha,\gamma)^{6}\text{Li}$</td>
<td>1.47</td>
</tr>
</tbody>
</table>

$^{3}\text{He}(^{3}\text{He},2p)^{4}\text{He}$
Bonetti et al. (1999)
CASPAR Status

CASPAR (Compact Accelerator System for Performing Astrophysical Research) initiated with NSF, ND, CSM, SDSM&T & SURF funding.

First underground accelerator in the U.S.

D. Robertson
M. Couder
M. Wiescher

JN accelerator moved from NSL.

Commissioned March 2018.

First operating deep-underground accelerator in the U.S.
The search for these resonances and measurement of their properties is extremely important.
resonance reaction rates

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

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

If resonance is narrow

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

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

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

“resonance strength”
Indirect Approach – Measure $E_x$ With Alternative Reaction

$A(a,b)B^*$ - energies of ejectiles (b’s) imprinted with quantized energies populating $E_x$ in $B^*$

Magnetic Spectrometers can precisely measure ejectile $E$

Grand Raiden Spectrometer (Osaka)

Matic et al. (2010)
In the U.S., Enge spectrometers at TUNL, Florida State, and Notre Dame. Other spectrometers at Texas A&M and Michigan State.

- Advantages: High resolution, Scattered beam steered away from detectors.
- Disadvantage: low acceptance, long counting times, difficult to measure angular distribution
High Efficiency Detector Arrays

Main Advantages:
• 16 angles measured simultaneously – to extract angular distribution only need relative solid angle of strips
• 16 independent energy measurements – average to reduce uncertainties

Disadvantage: limited energy resolution

Extract angular distribution of strips
Average to reduce uncertainties
If studying a transfer reaction that proceeds in a single step, Distorted Wave Born Analysis (DWBA) can be used to extract angular momentum transfer from angular distributions. Can be used to constrain spins.
Measuring decay $\gamma$-rays to determine level scheme

Hall et al. (2019) – $^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}^{*}(\gamma)$ reaction with GODDESS.

21 New transitions observed.

GODDESS – Gammasphere ORRUBA Dual Detectors for Structure Studies
If resonance is narrow

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

$E_r$ & $J^\pi$ are most important

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

“resonance strength”

If $\Gamma = \Gamma_x + \Gamma_y$ then factor $\Gamma_x \Gamma_y / \Gamma$ can be re-written in terms of

Branching ratio of one decay $B_x = \Gamma_x / \Gamma$ and

Lifetime = $\tau = \hbar / \Gamma$ as

$$\frac{\Gamma_x \Gamma_y}{\Gamma} = \frac{B_x (1 - B_x) \hbar}{\tau}$$

If we measure decay branching ratios and lifetimes for astrophysically important states, we can estimate the reaction rate.
Measuring $\alpha$ branching ratio of important $^{19}$Ne state

$^{19}$F($^3$He,$^3$H)$^{19}$Ne$^+(\alpha)$

Target CaF$_2$/C

Stripping Foil

12" Chamber

TwinSol

$\Delta E$-$E$ Telescope

Counts

Triton Energy (MeV)

$^{15}$O(\alpha, \gamma)$^{19}$Ne Breakout Reaction and Impact on X-Ray Bursts

W. P. Tan, J. L. Fisker, J. Górr, M. Couder, and M. Wiescher
(\(^3\)He, d) on stable targets to determine (p, γ) rates

\[ \Gamma_p = 2 \times 10^{-19} \text{ eV} \]

1 mA p + \(^{18}\)O \rightarrow 1 \text{ event / } 3 \times 10^5 \text{ years}
Hall et al. (2019) 

\[ ^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}^* (\gamma) \]

\[ \begin{align*} 
1536 \text{ keV, } \tau &= 16 \text{ fs} \\
1507 \text{ keV, } \tau &= 1200 \text{ fs} \\
1298 \text{ keV} \\
1269 \text{ keV} \\
238 \text{ keV} 
\end{align*} \]

- \(^{19}\text{Ne}\) kinetic energy ranged from 0.5 to 4 MeV
- \(\beta\) ranged from 0.005 to 0.025
Mythili et al. (2007)

FIG. 5: (Color online) The Doppler shifted transition of the 1536 keV level to the 238 keV level in $^{19}$Ne. The lifetime of this state was determined to be $19.1^{+0.7}_{-0.6} \pm 1.1$ fs.

FIG. 6: (Color online) Doppler shifted line shapes due to two transitions of the 4035 keV level. The experimental data are shown along with the calculated line shape and background that best fit them. Panel a) shows the decay to the ground
Conclusions

• Nuclear astrophysics involves a wide array of tools and techniques to explain the world around us.
• Nuclear physics plays a critical role. Many astrophysical events show a direct impact of nuclear physics.
• Laboratory measurements are necessary ingredients to astrophysical models.
• Both direct and indirect measurements are useful.
• Next time: Focus on exotic beams…