Understand nuclear processes that

• Power the stars
• Synthesize the elements
• Mediate explosive phenomena

Determine

• Nature of stellar evolution
• Sites of astrophysical processes
• Properties of universe
• Neutrino properties

For background, see http://www.nscl.msu.edu/~austin/nuclear-astrophysics.pdf
An Intellectual Opportunity

This is a special time

- Wealth of new astronomical observations—require new nuclear data for a credible interpretation
- New accelerators of radioactive nuclei to provide this data
- Growing computational power to simulate the phenomena
Cosmic History—a Long View

Universe began as a hot, sense primeval fireball-Big Bang

- It then cooled: $T \propto 1/t^{1/2}$
- Light elements were made
- Galaxies and stars formed

Creation of matter
Elementary particles

quark/gluon → hadron

Light elements
Stars
Now

TIME AFTER BIG BANG (seconds)

TEMPERATURE (K)

3°

10^10 years

10^10

10^20

10^30

10^40
Outline of the Lectures:

The observables: Cosmic abundances, abundances in the solar system and elsewhere

Nature of the nuclear processes involved:
- Reaction rates
- Resonant and non-resonant processes
- Technical details: Gamow peak, S-factor, etc.

The Big Bang and the Nature of the Universe
- Baryons, dark matter, dark energy

Stellar evolution with some digressions
- Quasistatic evolution, solar neutrinos, s-process, stellar onion
- Explosive phenomena: supernovae, r-process, neutrinos
- Binary systems: x-ray bursters and x-ray pulsars, the surface of neutron stars.
What nuclear physics do we need to know?

- Throughout the presentation
- Theoretical and experimental needs, and their coordination with astrophysicists

Nature of experiments at low and high energy facilities

- High energy approaches to low energy astrophysics
- The NSCL--an extant fast-radioactive-beam-facility
- The proposed RIA facility
Nuclear Astrophysics

- Supernovae
- Cataclysmic binaries
- Stellar evolution
- AGB stars

Origin and fate of the elements in our universe
Origin of radiation and energy in our universe

the 3rd minute
Simplicius (Greek 6th AD) on ideas of Leucippus (5th BC):
“The atoms move in the void and catching each other up jostle together, and some recoil in any direction that may chance, and others become entangled with on another in various degrees according to the symmetry of their shapes and sizes and positions and order, and they remain together and thus the coming into being of composite things is affected.”

King Lear, Act IV, scene 3:
“It is the stars, the stars above us govern our condition”

Arthur Eddington, 1928
I ask you to look both ways. For the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been reached through the stars”

Mark Twain, Life on the Mississippi
“There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.”

Willy Fowler:
“We got to get all this theory out of things”.
Cosmic Abundances (Really solar system, mainly)

A qualitative view-Suess-Urey Plot

- Very large range of abundances
- Names denote various creation processes

<table>
<thead>
<tr>
<th>Group</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{1,2}$H</td>
<td>0.71</td>
</tr>
<tr>
<td>$^{3,4}$He</td>
<td>0.27</td>
</tr>
<tr>
<td>Li, Be, B</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>CNO Ne</td>
<td>2x10^{-2}</td>
</tr>
<tr>
<td>Na-Sc</td>
<td>2x10^{-3}</td>
</tr>
<tr>
<td>A=50-62</td>
<td>2x10^{-4}</td>
</tr>
<tr>
<td>A=63-100</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>A&gt;100</td>
<td>10^{-7}</td>
</tr>
</tbody>
</table>
A More Detailed Picture

Solar abundances

Rapid n capture process

all processes

Makes most of Gold and Platinum

Makes Uranium
Populations I, II and III

What about elsewhere?

In the halo of the galaxy find (old) stars (Pop II stars) with small abundances of metals ($A > 4$) compared to the solar system values typical of Pop I stars.

Pop II stars
- Reflect processes in the early galaxy
- Investigation of Pop II stars is a hot area of astrophysics

What are Pop III stars?
- Stars that produce the material from which Pop II are made.
- Probably very large (> 100 $M_{\odot}$) fast evolving stars made from products of the Big Bang.
The Stars as Element Factories

Stars
Nuclear Reactions
Element Synthesis

Condensation
Ejection-Supernovae
Planetary nebulae

Interstellar
Gas
Dust

Supernova remnant
N132D-LMC

Star Forming Region
DEM192-LMC
Universe began as a hot, sense primeval fireball-Big Bang

- It then cooled: $T \propto 1/t^{1/2}$
- Light elements were made
- Galaxies and stars formed
Element Production in the Big Bang

Assumptions:
- General relativity
- Universe isotropic, homogeneous
- $T_{\text{now}} = 2.735$ K (CBR))

Production of elements
- 10-300 sec after BB
- $T \approx 10^{10}$ K, $\rho \approx 1$ g/cm$^3$
- Big Bang produces only $^1,^2\text{H},^3,^4\text{He}, ^7\text{Li}$
- Yield depends on density $\rho_B$ of baryons

Reaction network
Need to know noted reactions-

- $\bullet$ = Poorly known reactions
Can we Determine the Baryon Density from the Big Bang?

**Method**
- Find $\rho_B$ where predicted and observed abundances equal.
- If $\rho_B$ same for all nuclides, it assume it is the universal density

**Result**
OK, EXCEPT for $^7\text{Li}$. Perhaps predicted abundance wrong (poor cross sections) or primordial Li higher (star destroyed).

Nollett and Burles, PRD 61, 123505 (2000)
**It’s Close, Why Does It Matter?**

<table>
<thead>
<tr>
<th>Cosmic Background Radiation</th>
<th>Era of precision cosmology</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Surrounds us, Planck distribution (T~2.7 K), remnant of early BB</td>
<td>• Far reaching conclusions must be checked and the value of $\rho_B$ is the best possibility.</td>
</tr>
<tr>
<td>• Fluctuations (at $10^{-5}$ level) give information on total density of Universe and on $\rho_B$.</td>
<td>• Need more accurate cross sections for several reactions affecting $^7\text{Li}$.</td>
</tr>
<tr>
<td><strong>It implies</strong></td>
<td></td>
</tr>
<tr>
<td>Universe is just bound $\Omega_{\text{tot}} = 1$</td>
<td></td>
</tr>
<tr>
<td>• Baryon density $\rho_B \sim 0.05$</td>
<td></td>
</tr>
<tr>
<td>• Dark matter density, $\rho_D \sim 0.3$</td>
<td></td>
</tr>
<tr>
<td>perhaps WIMPS, weakly interacting massive particles</td>
<td></td>
</tr>
<tr>
<td>• Dark energy $\rho_{\Lambda} \sim 0.65$</td>
<td></td>
</tr>
</tbody>
</table>
What energy source powers the stars?

All energy comes from mass

\[ \text{Mass}_{\text{initial}} \rightarrow \text{Mass}_{\text{final}} \]

\[ \text{Reaction} \]

\[ \text{Mass}_{\text{converted}} = f \text{Mass}_{\text{initial}} \]

Energy released
\[ f \text{Mass}_{\text{initial}} c^2 \]

Must provide solar luminosity for \( >4.6 \times 10^9 \) yrs

\[ L_{\text{sun}} = 3.826 \times 10^{33} \text{ erg/sec} \]
\[ M_{\text{sun}} = 1.989 \times 10^{33} \text{ g} \]

Of the possibilities

- \( f_{\text{chemical}} \approx 1.5 \times 10^{-10} \Rightarrow 2200 \text{ yrs} \)
- \( f_{\text{gravity}} \Rightarrow 10^7 \text{ yrs} \)
- \( f_{\text{nuclear}} \approx 0.007 \Rightarrow 10^{11} \text{ yrs} \)

Only nuclear remains

Other evidence

Technetium is seen in stellar spectra. BUT the longest lived isotope is unstable--lifetime of \( 4 \times 10^6 \) yrs. Must have been synthesized in the star.
Reaction Rates and Energy Scales

**Reaction Rate**
- Ionized gas (plasma) with $N_i$ /cm$^3$ of species “$i$”
- Assume species $x$ moving at velocity $v$ through species $y$ at rest. Rate of reactions $r_{xy}$ is
  \[ r_{xy} = N_x N_y v \sigma_{xy} \]
- Average over velocity distribution (Max. Boltz.)
  \[ r_{xy} = N_x N_y (1 + \delta_{xy})^{-1} <v\sigma_{xy}> \]
  \[ \# \text{ of pairs/cm}^3 \]

**Environment**
- $k = 8.6171 \times 10^{-5}$ eV/K
- $T = 10^7-10^{10}$ K $\Rightarrow kT = 1-900$ keV
- Coulomb barriers MeV range
- Reactions are far sub-coulomb

\[ \sigma_{xy}(E) \propto \text{tunneling probability} \]

\[ \text{for point coulomb charge} \]
Example Reaction –$^7$Be(p,$\gamma$)$^8$B

Nature of Cross Sections

S Factor = $\sigma E \exp(b/E^{1/2})$

Increase Rapidly with Energy

Removes penetrability, nearly constant away from resonance
What Energies are Important?

S contains the nuclear structure information - At what energy do we need to determine it?

Gamow Peak:
Maximum in product of MB distribution and penetrability of Coulomb barrier

\[ E_0 = \begin{align*} 
5.9 \text{ keV} & \quad p + p \\
27 \text{ keV} & \quad p + ^{14}\text{N} \\
56 \text{ keV} & \quad \alpha + \alpha \\
237 \text{ keV} & \quad ^{16}\text{O} + ^{16}\text{O} 
\end{align*} \]

Cross sections at \( E_0 \) too small to be measured
# S for Resonant and Non-Resonant Phenomena

## Resonance in Gamow

- Peak dominates the rate
- Rate \( \propto \Gamma_p \Gamma_\gamma / (\Gamma_p + \Gamma_\gamma) \cdot \exp(-E_r/kT) \)
- Measure: \( \Gamma_s, E_r \Rightarrow \text{Rate} \)
- \( \Gamma_s \) may be strong functions of \( E \)

## No resonance--Rate

- Characterized by slowly varying S factor at low energy.
- Classic expts. with low-E accelerators: small \( \sigma \)'s at low-E
- Measure cross sections to low-E, extrapolate to \( E_o \) to extract S-Factor.

## Role of High-E facilities

- Long used for resonant rates, esp. \( E_r \)
- Recent emphasis on new techniques to measure non-resonant rates. Subject of this talk and several talks at this meeting.
How it looks!

Image of Sun: Goddard Space Flight Center
(http://antwrp.gsfc.nasa.gov/apod/image/9709/solprom1_eit_big.jpg)

How it works!
Gravity pushes inward, but the center of the sun in heated by nuclear reactions, making a high pressure that pushes outwards. They balance, and the sun just sits there burning its nuclear fuel. This has gone on for 4.5 billion years and will continue for another 5 billion years.
“Energy Production in Stars”

A Scenario-H.A. Bethe (CNO Cycles)

Physical Review 55, 103(L) 1939.

...for his contributions to the theory of nuclear reactions, especially his discoveries concerning energy production in stars.
The pp Chains and Neutrino Sources

\[ p( p, e^+ \nu) d \]
\[ d( p, \gamma) ^3\text{He} \]

86% 14%

\[ ^3\text{He}( ^3\text{He}, 2p) ^4\text{He} \]

14% 0.02%

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

\[ ^7\text{Be}(e^-, \nu) ^7\text{Li} \]
\[ ^7\text{Li}(p, \alpha) ^4\text{He} \]

\[ ^7\text{Be}(p, \gamma) ^8\text{B} \]
\[ ^8\text{B}(e^+, \nu) ^8\text{Be}^* \]

\[ ^8\text{Be}^*(\alpha) ^4\text{He} \]

**CHAIN I**

\[ Q_{\text{eff}} = 26.20 \text{MeV} \]

(2.0% loss)

**CHAIN II**

\[ Q_{\text{eff}} = 25.66 \text{MeV} \]

(4.0% loss)

**CHAIN III**

\[ Q_{\text{eff}} = 19.17 \text{MeV} \]

(28.3% loss)
### Observing the Center of the Sun with Solar Neutrinos

<table>
<thead>
<tr>
<th>Problem</th>
<th>Result:</th>
</tr>
</thead>
</table>
| - Can’t look with telescopes  
- Light is absorbed in $L$, re-emitted in random direction.  
- Drunkard’s walk: Distance covered = $(N)^{1/2} L$  
  - $N$ number of steps;  
  - $L$ length of a step. | For sun, $L = 0.1 \text{ cm}$, $D = 6.96 \times 10^{10} \text{ cm}$. Takes: $5 \times 10^{4} \text{ yr}$ |

#### Look at emitted neutrinos
- Made in solar cycle, escape without hindrance  
- $N_{\nu} \sim T^{18}$, measuring flux measures $T$ at center of sun

#### But it’s hard
- $\nu$s hardly interact  
- Need a huge detector
The Detector

- 100,000 gallons cleaning fluid (perchlorethylene $C_2Cl_4$), Homestake gold mine, S.D.
- $\nu + ^{37}Cl \rightarrow e + ^{37}Ar$ - Inverse $\beta$-decay
- Collect by bubbling He through tank (every 30 days)-count radioactive $^{37}Ar$

Motivation

“To see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.”
### Implications of the Davis Experiment

#### Results
- Expected 2 $^{37}$Ar per day. **Got 0.5/day-a shocker!**
- “Solar neutrino problem”, a *one-number* problem
- Solution in solar physics? nuclear physics? particle physics?
- Motivated a search for the cause: 1968 to present
- Better solar models, improved input nuclear physics.

#### New Experiments - different neutrino energy sensitivities
- Davis (Cl)---------8B, $^7$Be $\nu_e$
- Gallex/Sage (Ga)--p-p, $^7$Be $\nu_e$
- SNO (D$_2$O)--------8B $\nu_e$, $\nu_x$
- Super-K(H$_2$O)------8B $\nu_e$, ($\nu_x$)

**Others yet to come, see**
[http://www.sns.ias.edu/~jnb](http://www.sns.ias.edu/~jnb)
The Super-Kamiokande Detector Japan, US, Korea, Poland

Properties
• 50,000 tons H$_2$O, 11200 P.M.s
• 1000m underground, Mozumi mine, Kamioka Mining Co.
• Observe $\nu_e$-e scattering (mainly)-via Čerenkov light
**SNO—The Sudbury Neutrino Detector**

**Unique characteristics**
- 1000 tons heavy water ($D_2O$)
- See electron neutrinos and muon and tau neutrinos
- Charged current (CC)
  \[ \nu_e + D \rightarrow p + p + e^- \]
- Neutral current (NC)
  \[ \nu_x + D \rightarrow \nu_x + p + n \]
- $\nu_x + e \rightarrow \nu_x + e$ (ES)

**Location**
- 6800 feet under ground, Creighton mine Sudbury, Ontario.
- Canada, US, UK
It appears: different fractions of neutrinos arrive at the detectors

- All of p-p ν’s
- ~0.5 of $^8$B ν’s
- Few of $^7$Be ν’s

As compared to the standard solar model

Note: SNO differs from S-K because S-K sensitive to $\nu_x$
Neutrino oscillations

- Neutrinos have mass. Oscillate into another type of neutrino. ($\nu_e \rightarrow \nu_\mu$)
- Detector not sensitive to these neutrinos
- Probability of survival: $P(\nu_e \rightarrow \nu_e) = 1 - (\sin^2 \theta) \sin^2 (\frac{\Delta m^2 d}{E})$
- Passage through matter changes the constraints-resonant conversion.

Flaws in the physics input?

- Stellar physics--no, details to be settled. A check from Helioseismology
- Nuclear Physics--no, but better prediction of fluxes needed.
- Properties of neutrinos--the consensus culprit
**Determining $\Delta m^2$ and $\Theta_V$**

**Survival Probability**
- Show two cases: large mixing angle (now favored) and small mixing angle.
- Analysis is complex and subtle

**Example**
- Extracted values depend on reaction rates for
  - $^7\text{Be}(p,\gamma)^8\text{B}$, ($S_{17}$)
  - $^3\text{He}(\alpha,\gamma)^7\text{Be}$
Neutral Currents from SNO

First results (with S-K)
- Ascribe difference in SNO CC rate ($\nu_e$) and S-K ES rate ($\nu_e + \nu_x$) to $\nu_x$
- Extract $\nu_x$ – agrees with Standard Solar Model (SSM)

New from SNO
Combine all three SNO detection modes CC, NC, ES

Results
- $\phi(\nu_e) = 1.76 \times 10^6$ cm$^{-3}$sec$^{-1}$; $\phi(\nu_\mu + \nu_\tau) = 3.41 \times 10^6$ cm$^{-3}$sec$^{-1}$
- Good agreement with SSM- solar neutrino problem is no more
<table>
<thead>
<tr>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Explanation of solar neutrino problem is still imprecise</td>
</tr>
<tr>
<td>• Extracted values of $\Delta m^2$ and $\Theta_V$ depend on the cross sections for certain nuclear reactions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Important cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>• $^3\text{He}(\alpha,\gamma)^7\text{Be}$</td>
</tr>
<tr>
<td>• $^7\text{Be}(p,\gamma)^8\text{B}$, ($S_{17}$)</td>
</tr>
</tbody>
</table>
Core hydrogen burning ends
- Consumed central 10% of sun
- No heat source, pressure decreases, gravity wins
- Core collapses, releases gravitational energy which heats the core

Core helium burning starts
- Core hot-allows fusion of two a’s (Z=2)
- Helium fuses to $^{12}\text{C}$, $^{16}\text{O}$
- Hydrogen burns in shell

He Burning Core
- $T = 10^8$ K
- $r = 10^4$ g/cm$^3$

H burning shell

Non-burning envelop
What’s next for the Sun?

It’s the end of the line

• Helium burning ends after $10^8$ years, C and O core
• Gravitational collapse, BUT, never reach sufficient T to fuse C + C.
• Collapse continues to $10^7$ g/cm$^3$—electron pressure stops collapse

• Shells still burning, unstable, blow off planetary nebula

Star becomes a white dwarf (e.g. Sirius B).

<table>
<thead>
<tr>
<th>Property</th>
<th>Earth</th>
<th>Sirius B</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_{\text{sun}}$)</td>
<td>$3 \times 10^{-6}$</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>Radius ($R_{\text{sun}}$)</td>
<td>0.009</td>
<td>0.008</td>
<td>1.00</td>
</tr>
<tr>
<td>Luminosity ($L_{\text{sun}}$)</td>
<td>0.0</td>
<td>0.0028</td>
<td>1.00</td>
</tr>
<tr>
<td>Surface T (K)</td>
<td>287</td>
<td>27,000</td>
<td>5770</td>
</tr>
<tr>
<td>Mean r (g/cm$^3$)</td>
<td>5.5</td>
<td>$2.8 \times 10^6$</td>
<td>1.41</td>
</tr>
<tr>
<td>Central T (K)</td>
<td>4200</td>
<td>$2.2 \times 10^7$</td>
<td>$1.6 \times 10^7$</td>
</tr>
<tr>
<td>Central r (g/cm$^3$)</td>
<td>9.6</td>
<td>$3.3 \times 10^7$</td>
<td>160</td>
</tr>
</tbody>
</table>

Ring nebula in Lyra-NGC 6720—a planetary nebula
The Evolutionary Process for Heavy Stars

With this background can guess what happens for heavier stars.
But now, when He is exhausted in the core and the core collapses, it does get hot enough to burn carbon and oxygen.

The successive stages in the core are $H \rightarrow$ He, gravity, He $\rightarrow$ C,O, gravity, $\rightarrow$ C,O $\rightarrow$ Mg, Si, gravity, Si $\rightarrow$ Fe.
Fe (Iron) is special. Core of our stellar onion is “Fe”, most tightly bound nucleus. Result of fusing two “Fe's” is heavier than two “Fe's”; costs energy to fuse them. No more fusion energy is available.

Core collapses, keeps on collapsing, until reach nuclear density. Then nuclei repel, outer core bounces.

Outgoing shock wave forms
### Evolutionary Stages of a 25 M$_{\odot}$ Star

Weaver et al., 80

<table>
<thead>
<tr>
<th>Burning Stage</th>
<th>Time Scale</th>
<th>T(K) x 10$^9$</th>
<th>$\rho$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>7 x 10$^6$ y</td>
<td>0.006</td>
<td>5</td>
</tr>
<tr>
<td>He</td>
<td>5 x 10$^5$ y</td>
<td>0.23</td>
<td>700</td>
</tr>
<tr>
<td>C</td>
<td>600 y</td>
<td>0.93</td>
<td>2 x 10$^5$</td>
</tr>
<tr>
<td>Ne</td>
<td>1 y</td>
<td>1.7</td>
<td>4 x 10$^6$</td>
</tr>
<tr>
<td>O</td>
<td>0.5 y</td>
<td>2.3</td>
<td>1 x 10$^7$</td>
</tr>
<tr>
<td>Si</td>
<td>1 d</td>
<td>4.1</td>
<td>3 x 10$^7$</td>
</tr>
<tr>
<td>Core collapse</td>
<td>Seconds</td>
<td>8.1</td>
<td>3 x 10$^9$</td>
</tr>
<tr>
<td>Core Bounce</td>
<td>Millisec</td>
<td>34.8</td>
<td>3 x 10$^{14}$</td>
</tr>
<tr>
<td>Explosive</td>
<td>0-1-10 sec</td>
<td>1.2-7.0</td>
<td></td>
</tr>
</tbody>
</table>
What Next?

We know that

- Shock blows off outer layers of star, a supernova
- $10^{51}$ ergs (1foe) visible energy released (total gravitational energy of $10^{53}$ ergs mostly emitted as neutrinos).

Theoretically

- Spherical SN don’t explode
- Shock uses its energy dissociating “Fe”, stalls
- Later, $\nu$’s from proto-neutron star deposit energy, restart the shock. Still no explosion.

1-D model (T. Mezzacappa)
The Question—How do we get from here to an explosion?

SN 1987a in Large Magallanic Cloud
Non-Spherical Calculations

Is sphericity the problem?

- Now have 3-D calculations which explode, but have only a part of the detailed microphysics. Their stability against such changes is not known—we return to this later.
- Find 2-D, 3-D similar

Two views

Red upwelling
Blue sinking
What’s Produced in a Supernova

Model
- Evolve the Pre-SN star
- Put in a piston that gives the right energy to the ejecta (Don’t know how explosion really works).
- Calculate what is ejected
- Calculate explosive processes as hot shock passes.
- Example: Wallace and Weaver, Phys. Rep. 227, 65(93)

Find
- Elements, mass 20-50, generally reproduced at same ratio to solar.
- Modifications by explosive processes are small
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}—\text{an Important Reaction}$

**Helium Burning-** A two Stage Process

- $3\alpha$: $\alpha + \alpha \leftrightarrow ^{8}\text{Be}^* + \alpha \rightarrow ^{12}\text{C}^* \rightarrow ^{12}\text{C}$ (gs) Rate known to $\pm 12\%$
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Poorly known (20-30%)  
- Ratio affects $^{12}\text{C}/^{16}\text{O}$ after He burning—important resulting effects

**Element Synthesis in SN**

**Mass of Pre-SN Cores**

![Graphs showing element synthesis and core masses](image)
Some important Nuclear Rates for SN Synthesis

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
• $r_{3\alpha} = 170 \pm 20 \text{ keV-b}$ (300 keV) describes abundances (last slide)
• Experiment: 100-200, preference near 150, but uncertain.
• High priority reaction
$^{12}\text{C} + ^{12}\text{C}$ for Carbon burning
$^{22}\text{Ne}(\alpha,\gamma), ^{22}\text{Ne} (\alpha, n)$
Production of light slow neutron capture (s-process) nuclides--A= 60=88

Weak decay rates for gamma line emitters. E.g. $^{60}\text{Fe}$

Charged particle reactions on N=Z nuclei for production of p-process nuclei

For more details
R.Hoffmann et al. UCRL-JC-146202 and many references at:
http://www.ucolick.org/~alex/nucleosynthesis/
Weak Strength and Supernovae Core Collapse

Gamow-Teller (GT) Strength?
- Mediates $\beta$-decay, electron capture (EC), $\nu$ induced reactions
- GT (allowed) Strength $S=1; L = 0$, e.g. $0^+ \rightarrow 1^+; \text{GT}^+, \text{GT}^-$
- Lies in giant resonances;

Situation
- After silicon burning, $T_{\text{core}} \approx 3.3 \times 10^9 \text{ K}$, density $\approx 10^8 \text{ g/cm}^3$. $\text{e}^-$ Fermi energy allows capture into $\text{GT}^+$.
- At higher $T$, $\text{GT}^+$ thermally populated, $\beta^-$ decays back to ground state. $\beta^- \Leftrightarrow \text{E.C.}$
- $\text{GT}^+$ dominates the processes
How Weak Strength Affects the SN Core

Core size depends on $Y_e = \langle Z/A \rangle$

- Starts near 0.5
- Reduced by electron capture
- As $Y_e$ decreases, $\beta^-$ decay becomes important.
- Competition of EC and $\beta^-$ stabilizes $Y_e$ near 0.45
- When EC and $\beta^-$ compete we have the possibility of a cyclic process—the URCA process.

Urca process (named after a Casino da Urca in Rio de Janeiro that takes your money slowly but surely)

- $Z A + e^- \rightarrow Z^{-1} A + \nu$
- $Z^{-1} A \rightarrow Z A + e^- + \nu$
- Net result: production of two neutrinos removes energy from the core
- $T$ reduced

Compare WW, LMP rates

- WW standard Wallace-Weaver rates
- LMP—from large basis shell model calculations. Langanke and Martinez-Pinedo, NPA 673, 481(00)
- Compare results of pre-core-collapse calculations
- Significant differences

Si Ignition
Si depleted
Core contract
Core collapse
Effects

- Larger, lower entropy "Fe" pre-collapse core
- More e-'s ($Y_e$ larger), lower $T$ core.
- Larger homologous core

These changes tend to make explosions easier

How can we improve rates?

Heger results also determine which nuclei are most important
Most important nuclei - Heger et al.

- Generally closer to stability than predicted earlier.
- Stable and radioactive nuclei important

Can’t rely on exp’t

- Need many rates
- Some transitions are from thermally excited states

Need

- Reliable calculations
- Experiments to verify accuracy
- Measurements for the most crucial cases, if possible
Experimental data

- (n,p) measurements at TRIUMF
- $^{58,60,62,64}_{\text{Ni}}, ^{54,56}_{\text{Fe}}, ^{51,52}_{\text{V}}, ^{55}_{\text{Mn}}, ^{59}_{\text{Co}}$
- Resolution: 1MeV

Compare to Shell Model

Results fairly good, not perfect (?)

Need

- Data on other nuclei, some radioactive
- Better resolution and detail
The Experimental Possibilities

For stable targets

For EC, (t, $^3$He), (d,$^2$He) best candidate reactions E>120 MeV/nuc desirable

First (t, $^3$He)

- secondary t beams $10^6$/sec at MSU/NSCL, Daito et al., PLB 418, 27(98)
- Resolution: 160 keV, has been achieved at 117 MeV/nuc
- 50 keV resolution possible

(d, $^2$He)-KVI, 80 MeV/nuc
What About Radioactive Nuclei?

Use Inverse kinematics

Unusual kinematics

- Light particle has low E, few MeV, angle near 90°.
- Lab angle => $E_{c.m.}$
- Lab E => $\Theta_{c.m.}$
Some possibilities

- (p,n) expts are feasible. Require many small n detectors for good E resolution.
- EC expts have outgoing charged articles at low E. Detect heavy particle.
- Best possibility: \((^7\text{Li}, ^7\text{Be})\) \(^7\text{Li}(^{56}\text{Ni}, ^7\text{Be}(1/2^-))^{56}\text{Co}\), Coincidence with de-excitation \(\gamma\)-ray \(\Rightarrow S = 1\) (GT).

First experiment:
\(^6\text{He}\ (p,n)^6\text{Li}\), Brown, et al. \(^{93}\) MeV/nuc
High Resolution (from $\gamma$'s)
$^7\text{Li}(^{56}\text{Ni},^{56}\text{Co})^7\text{Be}(1/2^-) \rightarrow S=1$
- S800 spectograph: ID $^{56}\text{Co}$, determine $\Theta_{\text{c.m.}}$
- Detect $\gamma$'s from $^7\text{Be}$, $^{56}\text{Co}^*$ de-excitation, to reconstruct the $^{56}\text{Co}$ states reached
- $3 \times 10^6$ $^{56}\text{Ni}$/sec-present intensity

Low resolution
$^7\text{Li}(^{55}\text{Fe},^{55}\text{Mn})^7\text{Be}(1/2^-) \rightarrow S=1$
- Complex level structure of $^{55}\text{Mn}$ prevents reconstruction of levels reached
- Detect $\gamma$'s from $^7\text{Be}$
- S800: ID $^{55}\text{Mn}$, determine $\Theta_{\text{c.m.}}$, Measure $E \rightarrow$ thin target
**The r-Process**

**What is it?**
- Heavy elements formed by rapid neutron capture on seed nuclei
- Flow along path near neutron drip line till \((n,\gamma) = (\gamma,n)\)
- After explosion, decay back to stable region. \(N(Z) \propto t_\beta\)

**Where does it occur?**
In hot bubble just inside SN shock? Or in fusion of two neutron stars?
Properties of R-Process Nuclei

![Graph showing properties of R-process nuclei with labels and data points]

- **Proton Number Z**
- **Neutron Number N**
- **FRDM (1992)**
- **Log(T_\beta/s)**

**R-process abundance**
The r-Process and Nuclear Shells

**Predictions** (not verified by experiment)
- Shell gaps smaller near drip line
- Changes beta decay lifetimes, masses
- r-process abundance models are sensitive to gaps
- Need measurements of $t_\beta$, masses on r-process path to check
Experimental opportunities at Rare Isotope Facilities

Example: fast beams

Need:

- masses
- decay properties
- fission barriers
- neutron capture rates

Reach for at least a half-life measurement
Why fragmentation?

- Lifetime measurements can be done with beams from low energy facilities
- But, fragmentation facilities have advantages:
  - Use beams of mixed nuclides--Identification on event by event basis
  - Greater reach toward dripline-see figure
  - NSCL, RIKEN, and RIA will cover a large part of r-process path

Beams NSCL, RIA--N = 82,126
How to Measure Beta-Decay Lifetimes, Decay Properties

Beam from A1900

$^{129}$Ag

$\beta^-$

300 $\mu$m Si PINs

500 mm Si PIN

Gamma detectors

Neutron detectors

PPACs 40 x 40 pixilated Detector--1mm thick
Explosive Hydrogen Burning-Accreting Binary Systems

First **X-ray pulsar**: Cen X-3 (Giacconi et al. 1971) with UHURU

\[ T \sim 5 \text{s} \]

Today: ~50

First **X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS

Today: ~40

Total ~230 X-ray binaries known
Neutron stars:
1.4 $M_\odot$, 10 km radius
(average density: $\sim 10^{14}$ g/cm$^3$)

Typical systems:
• accretion rate $10^{-8}/10^{-10}$ $M_\odot$/yr (0.5-50 kg/s/cm$^2$)
• orbital periods 0.01-100 days
• orbital separations 0.001-1 AU’s
Mass transfer by Roche Lobe Overflow

Star expands on main sequence. when it fills its Roche Lobe mass transfer happens through the L1 Lagrangian point
Energy generation: thermonuclear energy

4H → $^4$He $\quad$ 6.7 MeV/u

3 $^4$He → $^{12}$C $\quad$ 0.6 MeV/u ("triple alpha")

5 $^4$He + 84 H → $^{104}$Pd $\quad$ 6.9 MeV/u (rp process)

Energy generation: gravitational energy

$$E = \frac{G M m_u}{R} = 200 \text{ MeV/u}$$

Ratio gravitation/thermonuclear $\sim 30 - 40$
Observation of thermonuclear energy:

Unstable, explosive burning in bursts (release over short time)

- Burst energy
- Persistent flux
- Gravitational energy
Nuclear reactions on accreting neutron stars

- **Thermonuclear burning (rp process)**
  - Why do burst durations vary? (10s – min)
  - What nuclei are made in the explosion?
    - Galactic nucleosynthesis contribution?
    - Start composition for deeper processes?

- **Deep H, C, … burning**
  - Origin of Superbursts? 100X stronger

- **Electron captures**
  - Pycnonuclear reactions
    - Gravitational wave emission?
    - Crust heating?
    - Dissipation of magnetic fields?

Need nuclear physics to answer and to understand observations
Visualizing reaction network solutions

Proton number

14

27Si

Neutron number

13

Lines = Flow = \[ F_{i,j} = \int \left( \frac{dY_i}{dt}_{i \rightarrow j} - \frac{dY_j}{dt}_{j \rightarrow i} \right) dt \]
Crust reactions in accreting neutron stars

From Haensel & Zdunik 1990

Need to measure:

- Masses (Exp 1035 Santi, Ouellette at S800)
- Electron capture rates (Exp 1038 Sherrill at S800)

(Charge exchange in inverse kinematics (\(^7\)Li, \(^7\)Be) )
Models: Typical reaction flows


Schatz et al. 1998

Wallace and Woosley 1981
Hanawa et al. 1981
Koike et al. 1998

Most calculations (for example Taam 1996)

rp process:
$^{41}\text{Sc} + p \rightarrow ^{42}\text{Ti}$
$+ p \rightarrow ^{43}\text{V}$
$+ p \rightarrow ^{44}\text{Cr}$
$^{44}\text{Cr} \rightarrow ^{44}\text{V} + e^+ + v_e$
$^{44}\text{V} + p \ldots$

αp process:
$^{14}\text{O} + \alpha \rightarrow ^{17}\text{F} + p$
$^{17}\text{F} + p \rightarrow ^{18}\text{Ne}$
$^{18}\text{Ne} + \alpha \ldots$

3α reaction
$\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}$
Endpoint: Limiting factor I – SnSbTe Cycle

The Sn-Sb-Te cycle

Known ground state α emitter
Nuclear data needs:

- Masses (proton separation energies)
- $\beta$-decay rates
- Reaction rates ($p$-capture and $\alpha,p$)

Some recent mass measurements
$\beta$-endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)

Separator energies
Experimentally known up to here

Many lifetime measurements at radioactive beam facilities
(for example at LBL, GANIL, GSI, ISOLDE, MSU, ORNL)

- Know all $\beta$-decay rates (earth)
- Location of drip line known (odd Z)

Indirect information about rates
from radioactive and stable beam experiments
(Transfer reactions, Coulomb breakup, …)

Direct reaction rate measurements
with radioactive beams have begun
(for example at ANL, LLN, ORNL, ISAC)
X-ray burst: Importance of waiting points—points where the flow is hampered by slow decay or weakly bound nuclei

- Luminosity:
- Abundances of waiting points
- H, He abundance
What Next?

Several Topics Briefly

- Trojan Horse measurements of low energy cross Sections
- ANC\textsubscript{S} and S-Factors
- L=1 Forbidden Weak Strength
- Is there a Chance that $\sigma(CEX) \propto B(L=1)$?
- Coulomb Breakup measurements (more detailed)
Trojan Horse Method (Bauer, Typel, Wolter)

**Principle**
- Obtain 2-body $\sigma$ from 3-body reaction
- Example: $^7\text{Li} ( p \alpha)\alpha$ from $^2\text{H}(^7\text{Li}, \alpha\alpha)n$

**Results** (Lattuada et al., Ap.J. tbl)

![Graph showing $S_b(E)$ vs. $E$ (MeV) with labels: Direct 2-body, Troj. Hor.-3 body.]

**Comments**
- Large rates, no screening correction
- Norm to 2-body, extend to low-E
- Compare to direct $\Rightarrow$ screening correction near 250 eV. Larger than usual theory.
Low Energy Measurements

Find: \( U_e = 290 \pm 47 \) eV
Adiabatic: 240 eV

M. Aliotta *et al*. NPA 690, 790 (2001)
Find: \( U_e = 219 \pm 7 \)
Adiabatic: 120 eV
ANCs and S-Factors

Measure ANC ⇒ $S(E=0)$ for $(p, \gamma)$, $(\alpha, \gamma)$ reactions

Principle:
- Low-E $(x,\gamma)$ reactions occur far from the nuclear surface
- $\sigma \propto |\psi(\text{large } r)|^2 \propto \text{ANC}^2$

Experiments: Transfer reactions at low energies measure ANC
- Detailed work: Texas A&M (Ajhari, Gagliagardi, Mukhamedzhanov, Tribble, et al.) $^7\text{Be}(p,\gamma)^8\text{B}$, $^{13}\text{C}(p,\gamma)$, $^{16}\text{O}(p,\gamma)$.
- Issues: Require accurate OM Potentials, limits accuracy to about 10%; checked to 10% against $^{16}\text{O}(p,\gamma)$
- Example $^{10}\text{B}(^7\text{Be},^8\text{B})^9\text{Be}$, $^{14}\text{N}(^7\text{Be},^8\text{B})^{13}\text{C}$ at 85 MeV ⇒ $S(^7\text{Be}(p,\gamma))$ to 10%, Ogata, 6 Dec.
Test case-known from Direct Capture

- ANC’s for $^{16}\text{O}(^{3}\text{He},d)^{17}\text{F}$
  - $(C^2)_{\text{gnd}} = 1.08 \pm 0.10 \text{ fm}^{-1}$
  - $(C^2)_{\text{ex}} = 6490 \pm 680 \text{ fm}^{-1}$
- Direct Capture data from Morlock, et. Al
- Agree within the relative errors-the 10% level
Forbidden (L = 1) Strength

Why we need to know

• Neutrino’s excite spin-dipole (L = 1, S =1) resonance--emitted nucleon(s) lead to formation of rare nuclides (\(^7\)Li, \(^{11}\)B, \(^{19}\)F…)

• Neutrino reactions modify distribution of r-process nuclides

• Need to calibrate flavor sensitive supernovae neutrino detectors

What’s known?

• For GT (L = 0) transitions, \(\sigma(p, n) \propto \text{B(GT)}\) within, typically, 5-10%. Little similar evidence for L = 1 transitions.

• The maximum strength of the SDR lies below the GDR

• Radioactive beams will permit measurements nearer the dripline
**Is there a Chance that $\sigma(\text{CEX}) \propto B(\text{L}=1)$?**

**Questions we ask (Dmitriev, Zelevinsky, Austin, PRC):**

- Is $\sigma(\text{CEX}) \propto B(\text{L}=1)$ when both are calculated with the same wave functions?

- What range of momentum transfer is important in the transition form factor $F(q')$?

**Sample case:** $^{12}\text{C}(p, n)^{12}\text{N}$ at $E_p = 135$ MeV

- Eikonal model taking into account real and imaginary parts of OM Potential (Compare to DWIA)

- Define sensitivity function: $T(q) = T_{PW} + \int dq' S(q,q') F(q')$

- Characterizes range of $q'$ in $F(q')$ which contribute at a given asymptotic momentum $q$. 
Cross section vs. B(L = 1, J = 0−, 1−, 2−)

\[\sigma(q)\]

1−

1.80 MeV
Calculations (x 0.2)

\[\frac{d\sigma}{d\Omega} (\text{mb/sr})\]

\[q \text{ (fm}^{-1}\text{)}\]

2−

4.3 MeV
Calculations (x 0.53)

\[\frac{d\sigma}{d\Omega} (\text{mb/sr})\]

\[q \text{ (fm}^{-1}\text{)}\]

\[\frac{\sigma_{\text{max}}}{B_0}\]

\[\frac{(2J+1)\sigma_{\text{max}}}{B_0}\]

\[B_0 \text{ (fm}^2\text{)}\]

\[\frac{3\sigma_{\text{max}}}{B_1}\]

\[\frac{(2J+1)\sigma_{\text{max}}}{B_1}\]

\[B_1 \text{ (fm}^2\text{)}\]
F(q’) and Sensitivity Function

Results

• For $B_J > 0.1 \text{fm}^2$, $B_J \propto \sigma(p,n)$ within 10-15%

• Sensitivity function $S(q, q’)$ shows main contribution is in range where the transition form factors have the same shape

To generalize to other systems

• Are $F_J(q’)$ similar for important $q’$?

• Is $S(q, q’)$ localized for heavier nuclei, strongly absorbed probes?
**Coulomb Breakup-Detailed Example**

**Principle**

- Breakup of fast projectile by Coulomb field of a high-Z nucleus.
- Inverse of radiative capture. Detailed balance $\Rightarrow$ S-factor for radiative capture. Inverse cross section is larger.
- Advantages-Thick targets, large $\sigma \Rightarrow$ high rates. Universal technique, accuracy probably 5-10%.
- Issues--Nuclear breakup if $E_\gamma$ large, contributions of other multipoles, complex theory.

**Early Experiments**

Motobayashi, *et al.*: $^{13}$N(p,$\gamma$)$^{14}$O, $^7$Be(p,$\gamma$)$^8$B, breakup of $^8$B, $^{14}$O

GSI, NSCL: $^7$Be(p,$\gamma$)$^8$B, $^8$Li(n,$\gamma$)$^9$Li
Radiative Capture and Coulomb Dissociation

Detailed balance theorem relates Coulomb dissociation and radiative capture cross sections for photons of a given multipolarity.

Contributions of E2 and M1 multipolarities must be gauged in order to extract E1 strength from Coulomb dissociation cross section.
Experimental Apparatus

SSO Spectrometer

at the National Superconducting Cyclotron Laboratory

Spectrometer set at 0° to detect $^7$Be fragments from breakup of 44 and 81 MeV/nucleon $^8$B on Ag and Pb targets
Low Energy Results

$^7$Be Longitudinal Momentum (MeV/c)

Longitudinal Momentum distribution of $^7$Be fragments produced in Coulomb dissociation of 44 MeV/nucleon $^8$B on Pb target

Curves: 1st-order perturbation theory convoluted with experimental resolution
Conclusions

Results interpreted with 1st-order perturbation theory; if higher-order effects are significant, larger E2 strength required to describe measurement

\[ S_{E2}/S_{E1} = 4.7 \times 10^{-4} \text{ at } E_{rel} = 0.6 \text{ MeV} \]
$^7$Be and proton fragments from Coulomb breakup of 83 MeV/u $^8$B on Pb dispersed by 1.5 T dipole magnet, detected in pairs of position-sensitive drift chambers and array of 16 plastic scintillators

Stainless steel plate intercepted direct beam
Theoretical Description of Breakup Energy Spectrum

1st-order perturbation theory calculation of E1+E2 using model of Esbensen and Bertsch with scaled E2 matrix elements, M1 from Filippone measurement

Angular cut corresponds to 30 fm impact parameter: minimizes E2 component, nuclear-induced breakup, and higher-order electromagnetic processes.
E1 Fraction of Total Breakup Cross Section

E1 transitions account for over 90% of cross section between 130 keV and 2 MeV, except near 640 keV M1 resonance.

E2 dominates at low relative energies excluded from analysis.
Extracting $S_{17}$—Some Issues

**Reaction Model**

- First order perturbation theory--Esbensen, Bertsch
- Continuum Discretized Coupled Channels (CDCC)--Thompson, Tostevin

**E2 Contributions**

- Use results from inclusive experiments
- For most of $E_x$ range < 5%, large for $E_x < 130$ keV

**Nuclear contributions**

- From CDCC, less than 4% for $E_x < 400$ keV
Continuum Discretized Coupled Channel Calculations

Basic Picture

- Breakup populates excitations up to $E_{\text{rel}} = 10$ MeV
- $E_{\text{rel}}$ range divided into bins-discretized
- Bin wavefunctions are orthonormal basis for coupled channels solution of $^7\text{Be}+p+\text{target}$ three-body w.f.

Details

- Partial waves: $L_{\text{max}} = 15,000$, radii to 1000 fm
- $l_{\text{rel}} \leq 3$, $\lambda \leq 2$
- Pure $p_{3/2}$ single particle state ($^7\text{Be}$ inert)
- Consider nuclear interactions
Beyond perturbation theory

- This analysis done in P. Theory
- Underestimates the E2-strength. (Esbensen-Bertsch)
- Recent calculations by Mortimer et al. in CDCC, find that E2 amplitude must be 1.6 times single particle estimate to fit asymmetries.
- Recent calculations (S. Typel) using the time dependent Schroedinger Eq., find a similar result.
Chi$^2$ for various E2 Scaling Factor

Pb, $E_p = 44$ MeV/nucleon, first order calculation

Pb, $E_p = 44$ MeV/nucleon, dynamical calculation
Minimizing $\chi^2$ for the data above 130 keV by varying normalization of E1+E2 calculation in perturbation theory yields best fits for 2 energy ranges

$$S_{17}(0) = 17.8 \,(+1.4,-1.2) \text{ eV b}$$
A Plea to Nuclear Theorists

Theoretical uncertainties for these difficult experiments are now comparable to experimental error even for extrapolations from 250 keV—can we get a better theory?

Tabulation-Junghans, et al.
Summary-Values of $S_{17}$

Wt. Mean* = 18.6 ± 0.5 eV b

Note: Fit includes * points.
New Expt-- $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$


Major uncertainty (8%) in fluxes of $^7\text{Be}$ and $^8\text{B}$ neutrinos (SNO, SuperK, Borexino).

Also $^7\text{Li}$ in Big Bang

Looks good: BUT

- Counting $\gamma$'s $\Rightarrow 0.507 \pm 0.016$ keV b
- Counting $^7\text{Be}$ decays $\Rightarrow 0.572 \pm 0.026$
New Experiment—Coulomb breakup of $^7$Be—Matt Cooper, et al.

$^7$Be breakup: $B_{\rho} = 1.5$ T.m.

Analysis should be straightforward—E2 cross section small.
Neutron star crust process

p process

rp process

r process

neutrons

protons

X-ray burst (RXTE)

4U1728-34

Frequency (Hz)

10 15 20

Time (s)

10 20 30

Wavelength (Å)

V382 Vel

Ne Nova (Chandra)

Metal poor halo stars (Keck, HST)

Supernova (HST)

Neutron star crust process

Mass known

Half-life known

nothing known

Nova (Chandra)

n-Star (Chandra)

protons

neutrons

E0102-72.3

4U1728-34

Metal poor halo stars (Keck, HST)
Production of radioactive beams

**ISOL (ISOLDE, ISAC, Oak Ridge, Louvain-la-Neuve, …):**

1. **Accelerator** → **Target** → **Ion source** → **Separator** → **Post Accelerator** → Low energy radioactive beam (<12 MeV/A)

   Spallation/fragmentation of target nuclei

**Fragmentation (NSCL, GSI, RIKEN, GANIL, …):**

1. **Accelerator** → **Target** → **Gas stopper** → **Separator** → **Post Accelerator** → Low energy radioactive beam (<12 MeV/A)

   High energy radioactive beam (50-2000 MeV/A)

   Fragmentation of beam nuclei
### Summary Fast/Slow beam experiments for nuclear astrophysics

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<tr>
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<th>slow</th>
<th>fast</th>
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<tr>
<td><strong>Direct rate measurements</strong></td>
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<td>Half-lives</td>
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If both techniques are applicable then consider on case by case basis:
- beam intensity (production cross section, release and transport times)
- target thickness (higher for fast beams)
- selectivity (signal/background) (fast: ~100%, slow: depends)
- method efficiency
• First fully accelerated beams, Oct/00!
• First Radioactive Ion Beams, Jun/01
• First PAC experiment, Nov/01
Installation of D4 steel, Jul/2000
Fragment Separators

Recall in B-field: $r = \frac{mv}{qB}$

Spacial Dispersion

Recall: $\frac{dE}{dx} \sim Z^2$

Primary Beam

Beam & All Fragmentation Products

Momentum Selection

Wedge-shaped Degrader

Secondary Beam

Isotope Selection

Focal Plane

Beam Analysis Tracking Detectors

One B $\frac{mv}{q}$

$\alpha c \leq \leq \frac{\alpha \epsilon N}{\epsilon}$
NSCL S800 Spectrometer

dp/p ~ $10^{-4}$ possible

SPEG GANIL achieved mass measurements at $10^{-5}$ level