Nuclear Astrophysics and Exotics

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Overview

Lecture 1: Intro to Nuclear Astrophysics - reactions
Lecture 2: How to measure cross sections + activity
Lecture 3: Nuclear structure for astrophysics
Lecture 4: Exotic phenomena close to the drip lines
Abundances

stellar H-, He, C, O, Si-burning stars, supernovae

s-process
He-burning in AGB stars, massive stars

r-process
type II supernovae, merging neutron stars

cosmic rays

p-process
site disputed

From M. Wiescher, JINA web
Nucleosynthesis paths

Stellar burning

pp chain
Paths beyond Iron

Z

\( \rho \) process

s process

\( r \) process

\( \sim 10^8 \text{ n/cm}^3 \)

\( \sim 10^{20} \text{ n/cm}^3 \)
Nuclear Astrophysics Connections

- Solar system abundances
- Stellar observations – Abundances
- Meteoritic samples
- Light output / Energy production
- Time scales

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Nuclear input: What do we need?

- Basic nuclear properties
  - Mass
  - Half life
  - Binding energy
  - Nuclear radius/shape

- Level structure
- Angular Momentum
Nuclear Input

**vp-process**
- Close to proton drip line
- Masses, T1/2 mostly known
- Most important (p,n) reactions

**rp-process**
- Close to proton drip line
- Masses, T1/2 mostly known
- Proton capture reactions

**p-process**
- Close to stability
- Masses, T1/2 known
- γ-induced reaction rates

**s-process**
- Along stability
- Most properties known
- Missing neutron captures

**r-process**
- Far from stability
- Most properties not known
- Masses
- T1/2
- Pn
- Neutron captures

**i-process**
- Between s and r
- Mass, T1/2 known
- Missing neutron captures

**Burning**
- Nuclear reactions
- Resonance properties

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Nuclear Reactions in Stars

Main focus on capture reactions
Nuclear Reactions in stars

\[ r = N_X N_Y \nu \sigma(\nu) \]

\[ r = N_X N_Y \int_0^\infty f(\nu) \sigma(\nu) \nu d\nu \]

**Symbols:**
- \( r \): reaction rate
- \( N_X, N_Y \): number of particles
- \( \nu \): velocity
- \( \sigma(\nu) \): reaction cross section at \( \nu \)
- \( f(\nu) \): velocity distribution
- \( <\sigma\nu> \): reaction rate per particle pair

Rolfs and Rodney, “Cauldrons in the cosmos”
Maxwell – Boltzmann distribution

\[ f(v) = 4\pi v^2 \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{mv^2}{2kT}} \]

\[ \phi(E) = \frac{2}{\sqrt{\pi}} \left( \frac{1}{kT} \right)^{3/2} E^{1/2} e^{-\frac{E}{kT}} \]

\[ \langle \sigma v \rangle = \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^{\infty} \sigma(E) E e^{\left( \frac{-E}{kT} \right)} dE \]

Rolfs and Rodney, “Cauldrons in the cosmos”
Tunnel Effect – S-factor

Cross section has two components:
1. Interaction between particles (pure nuclear)
2. The Coulomb force

$$\sigma(E) = \frac{1}{E} e^{(-2\pi\eta)} S(E)$$

Astrophysical S-factor
Contains all the pure nuclear properties

$$\eta: \text{Sommerfeld parameter} \quad \eta = \frac{Z_1Z_2e^2}{\hbar \nu}$$

Potential $V(r)$
- Coulomb barrier
- Distance $r$
- Nuclear radius

Tunneling probability $P$

$$P = \frac{\left| \psi(R_n) \right|^2}{\left| \psi(R_c) \right|^2}$$

Tunneling probability -> increasing with energy

Rolfs and Rodney, “Cauldrons in the cosmos”
S-factor

The dangers of extrapolation

Astrophysical region

Coulomb Barrier

Extrapolation

Energy E

S(E) factor

Linear Scale

Cross Section σ(E)

Log Scale

The dangers of extrapolation
Gamow Window

Maxwell – Boltzmann distribution

\[ \propto \exp \left( -\frac{E}{kT} \right) \]

Tunneling probability

\[ \propto \exp \left( -\sqrt{\frac{E_C}{E}} \right) \]

Relative probability

Energy

Gamow peak

\[ \Delta E_0 \]

\[ E_0 \]
**Gamow Window**

- **Charged particles**

  Standard approximation

  \[ E_0 = 0.12204(Z_1^2 Z_2^2 \mu T_9^2)^{1/3} \] [in MeV]

  \[ \Delta E_0 = 0.237(Z_1^2 Z_2^2 \mu T_9^5)^{1/6} \]

  **Window:** \[ E_0 + \frac{\Delta E_0}{2} \]

- **Neutrons**

  No Coulomb barrier, angular momentum

  \[ E_{\text{eff}} = 0.172T_9(\ell + \frac{1}{2}) \] [in MeV]

  \[ \Delta E_{\text{eff}} = 0.194T_9 \sqrt{\ell + \frac{1}{2}} \]

  **Window:** \[ E_{\text{eff}} + \frac{\Delta E_{\text{eff}}}{2} \]

**Burning:** \( T = 0.01 - 0.1 \) GK
- \((p,\gamma)\): \( E_p = 0.02 - 0.2 \) MeV
- \((\alpha,\gamma)\): \( E_\alpha = 0.05 - 0.5 \) MeV

**p process:** \( T = 1.8 - 3.3 \) GK
- \((p,\gamma)\): \( E_p = 1 - 5 \) MeV
- \((\alpha,\gamma)\): \( E_\alpha = 4 - 12 \) MeV

**rp process:** \( T = 1.1 - 1.3 \) GK
- \((p,\gamma)\): \( E_p = 0.8 - 2 \) MeV

**vp process:** \( T = 1.5 - 3.0 \) GK
- \((p,\gamma)\): \( E_p = 1 - 4 \) MeV

**s process:** \( T \sim 0.3 \) GK
- \((n,\gamma)\): \( E_n = 25 - 75 \) keV

**i process:** \( T = 0.1 - 0.3 \) GK
- \((n,\gamma)\): \( E_p = 10 - 75 \) MeV

**r process:** \( T = 0.1 - 2.0 \) GK
- \((n,\gamma)\): \( E_p = 10 - 500 \) keV
Nuclear input: What do we need?

- Nuclear reactions/Astrophysical reaction rates

\[ a + A \rightarrow B^* \rightarrow B + \gamma \]

**Radiative capture reactions**

**Incoming channel**

**Resonant**

\[ A \rightarrow Q \rightarrow B \]

**Statistical**

\[ A \rightarrow Q \rightarrow B \]

**Direct**

\[ A \rightarrow Q \rightarrow B \]
Example: $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$
Nuclear input: What do we need?

- Nuclear reactions/Astrophysical reaction rates

\[ a + A \rightarrow B^* \rightarrow B + \gamma \]

Outgoing channel

or other particle channels (Competing channels)
Experiment
Accelerator Facilities
Facilities

Stable beam facilities (Intro Physics)
• Van de Graaff (single-ended or tandem)
• Cyclotrons
• LINACS
Basic Components

- Ion sources
- Accelerator
- Analyzing magnet
- Beam Lines

5MV tandem accelerator @ Institute of Nuclear Physics, “Demokritos”, Athens, Greece
Radioactive Beams

- **Fragmentation**: NSCL/FRIB, GSI/FAIR, RIKEN, ...
- **Isotope Separation On-Line (ISOL)**: TRIUMF, SPIRAL, ISOLDE, ...
- **Fission source**: CARIBU/ANL
- **Low energy reactions**: ANL, FSU, Texas A&M, Notre Dame, ...

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National Superconducting Cyclotron Laboratory

- K500 Cyclotron
- K1200 Cyclotron
- A1900 Fragment Separator
- S800 Spectrograph
- Gas Stopper
- ReAccelerator Facility
- "Stopped beam area"
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

- Ion sources
- Coupling line
- Stripping foil
- Production target
- $^{86}\text{Kr}^{34+}$, 12 MeV/u
- $^{86}\text{Kr}^{14+}$, 140 MeV/u
- $^{78}\text{Ni}$
- Fragment yield after target
- Fragment yield after wedge
- Fragment yield at focal plane
- $\Delta p/p = 5\%$
- Transmission of 65% of the produced $^{78}\text{Ni}$

Coupled Cyclotron Facility
Neutron Facilities

Time-of-Flight: e.g. nTOF@CERN, LANSCE@ Los Alamos, IRMM@Geel, Belgium, etc
- High energy protons on heavy target, broad energy distribution, pulsed beam.

Reaction-based, quasi-monoenergetic: Any low energy facility
- Reactions: $^2\text{H}(^2\text{H},\text{n})^3\text{He} - Q = 3.3 \text{ MeV} - E_\text{n} = 2.5 \text{ MeV}$
  $^3\text{H}(^2\text{H},\text{n})^4\text{He} - Q = 17.6 \text{ MeV} - E_\text{n} = 14.1 \text{ MeV}$
  $^7\text{Li}(\text{p},\text{n})^7\text{Be} - Q = - 1.64 \text{ MeV} - E_\text{n} = ?$ – How can you get 25 keV?
  ...

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In the Laboratory

- Yield of reaction: \( Y = \frac{\text{Number of reactions}}{\text{Number of beam particles}} \)

- Cross section: \( \sigma = \frac{\text{Yield of reaction}}{\text{Number of target particles}} = \frac{N_R}{N_b \cdot N_T} \)

To measure a cross section you need three things:

1. Number of target particles \((N_T)\) !!!
2. Number of beam particles \((N_b)\) !!!
3. Number of reactions \((N_R)\) !!!
Number of target particles

- Rutherford backscattering

\[ N_T = \frac{N_A \xi}{A} \]

- \( N_A \): Avogadro number
- \( A \): Atomic mass
- \( \xi \): target thickness in g/cm\(^2\)

- Simulation with SIMNRA
- Known detector geometry
- Known cross section
- Free parameter: target thickness/composition

\( ^{92}\text{Mo target} \)

\( E_d = 1.35 \text{ MeV} \)

Mo

Al backing

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Tools

Si surface barrier detector – Semi-conductor

http://nsspi.tamu.edu/nssep/courses/basic-radiation-detection/semiconductor-detectors/introduction/introduction
Number of target particles

- X-ray Fluorescence (XRF)

![Diagram of X-ray Fluorescence (XRF)]

- X-ray tube
- X-ray detector

![Graph showing energy vs. number of events]

Energy (keV) | # events
---|---
Pd - L | 1000
Fe - Kα | 100
Cu - Kα | 10
Cu - Kβ | 1
Tools

SiLi detector – Semi-conductor

- Cooling
- Addition of Li helps remove impurities

X-ray tube

http://nau.edu/cefns/labs/electron-microprobe/glg-510-class-notes/detection-of-signals/
http://www.schoolphysics.co.uk/age16-19/Medical%20physics/text/X_rays/index.html
Number of target particles

- Particle energy loss

$\Delta E_0$

- Many other techniques like resonance measurement, use of spectrometer or recoil separator, use a reaction, etc
- If radioactive sample: activity from decay
In the Laboratory

• Yield of reaction: \( Y = \frac{\text{Number of reactions}}{\text{Number of beam particles}} \)

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To measure a cross section you need three things:

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2. Number of beam particles (\( N_b \)) !!!
3. Number of reactions (\( N_R \)) !!!
Number of beam particles

- High beam intensities: measure deposited charge

![Diagram of beam particles with collimators, target, and detectors]

e.g. $^1\text{H}^+$ beam: each beam particle deposits $1.6 \times 10^{-19}$ Cb (e⁻ charge)

$^{84}\text{Kr}^{27+}$ beam: each beam particle deposits $27 \times 1.6 \times 10^{-19}$ Cb
• High beam intensities: measure deposited charge
• High beam intensities: measure deposited charge

Beam: positive charge $+1e$

Measurement 1: $+1e$

Measurement 2: $+2e = false$

How do we fix it?
Number of beam particles

- **Low beam intensities:** measure each particle in detector
  1. In beam detector upstream to measure continuously
  2. In beam detector upstream to insert every so often
  3. Scattering detector upstream
  4. Detector looking at target scattering
  5. Detector downstream after target
  6. Activation (especially for neutrons)

![Diagram of beam particle detection](image)
Overview

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In the Laboratory

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To measure a cross section you need three things:

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2. Number of beam particles \((N_b)\) !!!
3. Number of reactions \((N_R)\) !!!
Regular kinematics

- n, p, α - beam
- heavy nucleus (target)

**Facilities:** Stable beam (ATOMKI, Athens, Notre Dame, Cologne, Florida State, nTOF, Los Alamos, Karlsruhe, etc)

**Equipment:** Gamma-ray detectors, X-ray detectors, charged particle detectors

**Techniques:** Activation, Angular distribution, Summing

**Advantages:**
- High intensity stable beams
- Well developed techniques

**Disadvantages**
- Not applicable for all targets, in particular radioactive nuclei
Activation

- Irradiate for time according to half life
- Monitor beam intensity
- After irradiation move sample to low background area, HPGe
- Detect $\beta$-delayed $\gamma$-rays

Tools

High Purity Ge detectors inside shielding
Angular Distributions

- In beam γ-ray detection
- Measure at many angles
- High resolution system (HPGe)
- Create angular distributions
- Extract reaction yield
- Extract cross sections

E_{cm}

Entry state

A

Q

B

e.g. Galanopoulos, et al, PRC 67 (2003) 015801
Tools

HPGe ($\varepsilon = 100\%$)  BGO

RBS detector  cooling trap ($\text{LN}_2$)  13 HPGe (+5 BGO) detectors

suppression voltage $U_s = -400 \text{ V}$

independent current read-out


Georgina at ND
Angular Distributions

\[ W(\theta) = A_0 (1 + a_2 P_2(\cos \theta) + a_4 P_4(\cos \theta)) \]

\[ \sigma_T = \frac{A}{N_A \cdot \xi} \sum_j A_j^0 \]

e.g. Galanopoulos, et al, PRC 67 (2003) 015801
**Summing Technique**

- In beam γ-ray detection
- Sum all energy in a cascade
- Need very high efficiency detector
- Need highly enriched samples
- Efficiency dependence on the γ-multiplicity
- Simple analysis

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Spyrou et. al. PRC 76 (2007) 015802
Simon et. al. NIMA 703 (2013) 16
Tools

NaI

12”x12”

4π@Bochum

HECTOR
@Notre Dame

SuN@MSU

Spyrou et. al. PRC 76 (2007) 015802
Simon et. al. NIMA 703 (2013) 16
**Summing Technique**

- **${}^{92}\text{Zr}(p,\gamma){}^{93}\text{Nb}$**
  - Sum peak: 2614 keV

- **${}^{19}\text{F}(p,\alpha\gamma){}^{16}\text{O}$**

- **${}^{92}\text{Mo}(\alpha,\gamma){}^{96}\text{Ru}$**
  - $E_\alpha = 11$ MeV
  - $E_\alpha = 10.2$ MeV
  - $E_\alpha = 9.8$ MeV

**References:**
- Spyrou et al. PRC 76 (2007) 015802
- Simon et al. NIMA 703 (2013) 16
Summing Technique

Efficiency depends on energy AND γ multiplicity

Reactions = $\frac{I_{\text{SumPeak}}}{\epsilon}$

Spyrou et. al. PRC 76 (2007) 015802
Simon et. al. NIMA 703 (2013) 16
Comparison – Stable Beam

**Activation technique - Off line**
- Low energy $\gamma$-rays
- Natural targets
- Suitable half-life

**Angular Distributions – In beam**
- Decay scheme information
- High volume HPGe detector
- Time-consuming data collection and analysis

**Angle integrated measurements – In beam**
- High efficiency
- Simple analysis procedure
- Limited spectroscopic information
Inverse kinematics

Heavy beam

Light target (H, He)

Heavy recoil

Radioactive Beam Facilities: TRIUMF, MSU, GSI, GANIL, CERN, ANL?
Equipment: Dragon, SECAR, Storage ring, SuN, LiSE, ...

TRIUMF

MSU

GANIL
Recoil separators

- Many different separators in operation or under construction
- Main use: rejection of incoming beam while selecting recoils
- Gamma rays around target in coincidence with recoils
- Very clean measurements

DRAGON @ TRIUMF

SECAR @ MSU

St. George @ Notre Dame
Storage rings

\[ ^{96}\text{Ru}(p,\gamma)^{97}\text{Rh} \]

Mei, et. al. PRC 92 (2015) 035803
Summing in inverse kinematics

- Hydrogen gas target
- Heavy beam
- Doppler shift

Let’s put it all together!!!!

You learned:
• How to measure the number of target nuclei
• How to measure the number of beam particles
• How to measure the number of reactions that occurred

• Cross section: \[ \sigma = \frac{\text{Yield of reaction}}{\text{Number of target particles}} = \frac{N_R}{N_b \cdot N_T} \]
**p process example:** $^{74}\text{Ge}(p,\gamma)^{75}\text{As}$

### Table 2
Selected $(\gamma, p)$ or $(n, p)$ Reactions

<table>
<thead>
<tr>
<th>Reactions</th>
<th>$^{73}\text{Kr}$</th>
<th>$^{74}\text{Kr}$</th>
<th>$^{75}\text{Kr}$</th>
<th>$^{76}\text{Kr}$</th>
<th>$^{77}\text{Kr}$</th>
<th>$^{78}\text{Kr}$</th>
<th>$^{79}\text{Kr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{126}\text{Ba}(\gamma,p)^{127}\text{Cs}$</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>$^{110}\text{Sn}(\gamma,p)^{110}\text{In}$</td>
<td>72</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>$^{106}\text{Cd}(\gamma,p)^{106}\text{Ag}$</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>$^{104}\text{Cd}(\gamma,p)^{103}\text{Ag}$</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
</tr>
<tr>
<td>$^{100}\text{Pd}(\gamma,p)^{99}\text{Rh}$</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>$^{96}\text{Ru}(\gamma,p)^{95}\text{Tc}$</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
</tr>
</tbody>
</table>

[Image of a table showing selected $(\gamma, p)$ or $(n, p)$ reactions, including $^{75}\text{As}(\gamma,p)^{75}\text{Ge}$]
**p process example:** $^{74}\text{Ge}(p,\gamma)^{75}\text{As}$

Two measurements: Angular Distributions + Summing

Post-Processing Code NucNet Tools
*Brad Meyer, Clemson University*

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(n,γ) cross sections

Direct measurements: A lot of measurements along the valley of stability
Best resource: KADONIS library:  http://www.kadonis.org/

The new version KADoNiS v0.3 is finally online!

Version 0.3 provides data for 357 isotopes including 5 newly added isotopes, 42 updated MACS30, new stellar enhancement factors, and the MACS30 obtained from three different evaluated data libraries. More information below or in the logbook.

View Maxwellian-Averaged (n,γ) Cross Section

Isotope  Show

(Examples: Ba138, Ta180m, Se.)
Observationally confirmed: Asymptotic giant branch (AGB) stars

Classic s process

Weak s process

Seed: $^{56}\text{Fe}$
s process example: $^{63}\text{Ni}(n,\gamma)^{64}\text{Ni}$

“The $^{63}\text{Ni}$ sample was produced about 30 years ago by breeding a highly enriched $^{62}\text{Ni}$ sample in the ILL high flux reactor at Grenoble.”

- nTOF facility @ CERN
- Use resonance parameters to calculate Maxwellian Averaged Cross Section (MACS)
- New MACS is a factor of 2 higher than previous estimate
- $^{64}\text{Ni}$ increased by 20%
- $^{63}\text{Cu}$ decreased by 15%
- $^{63}\text{Cu}/^{65}\text{Cu}$ ratio changes

C. Lederer, et. al. (nTOF collaboration) PRC 89 (2014) 025810, PRL 110 (2013) 022501
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Indirect Measurements
Nova contribution to Galactic $^{26}\text{Al}$?

Last nuclear-physics uncertainty is $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ rate

Data from COMPTEL & INTEGRAL-SPI (MPE Garching / Roland Diehl)
$^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ resonance

Measured $g$ branch for first time to determine $3^+$ strength: up to 30% of Galactic $^{26}\text{Al}$ produced in novae.

The trouble with neutron capture

- Regular kinematics
- Measuring Neutron Capture reactions on short-lived nuclei is at best challenging
- Need indirect techniques
- Surrogate technique (d,p)-(n,γ)
- Measure NLD, γSF
- Can also be applied to (p,γ) – why?

- Inverse kinematics
- Colliding beams

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Surrogate technique

- Formation of compound nucleus (CN) independent of its decay
- Form same CN as \((n,\gamma)\) via \((d,p)\)
- Study its decay
- Inform the models
- Applicable in regular and inverse kinematics
- Applicable a few steps from stability

Validation: \(^{95}\text{Mo}(n,\gamma)^{96}\text{Mo}\)

Significant progress during the last couple of years

Calculate \((n,\gamma)\) Cross Section

**Hauser – Feshbach**

- **Nuclear Level Density**
  - Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic
- **\(\gamma\)-ray strength function**
  - Generalized Lorentzian, Brink-Axel, various tables
- **Optical model potential**
  - Phenomenological, Semi-microscopic

\[95\text{Sr}(n,\gamma)^{96}\text{Sr}\]

\[\text{TALYS}\]
Traditional Oslo method

- Use reaction to populate the compound nucleus of interest
- Measure excitation energy and $\gamma$-ray energy
- Extract level density and $\gamma$-ray strength function (external normalizations)
- Calculate “semi-experimental” $(n,\gamma)$ cross section
- Excellent agreement with measured $(n,\gamma)$ reaction cross sections

Unfolding
Iterative subtraction
Normalization

$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)T(E_\gamma)$

T.G. Tornyì, M. Guttormsen, et al., PRC2014
Example Oslo method

L. Crespo-Campo, et. al. PRC 94 (2016) 044321
• Populate the compound nucleus via $\beta$-decay (*large Q*-value far from stability)
• Spin selectivity – correct for it
• Extract level density and $\gamma$-ray strength function
• *Advantage:* Can reach $(n, \gamma)$ reactions with beam intensity down to 1 pps.

*Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014*
Example $\beta$-Oslo


$^{69}\text{Ni}(n,\gamma)^{70}\text{Ni}$

$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$

$Q_\beta = 12.3$ MeV

$S_n = 7.3$ MeV

$T_{1/2} = 11.2$ s

$N_a(ov)$ (cm$^3$ s$^{-1}$ mol$^{-1}$)

$E_\gamma$ (keV)

$E_x$ (keV)
Nuclear Structure
s/r-process paths and abundances


Cowan and Thielemann, Physics Today, 2004
Mass measurements

• Strong connection between nuclear mass (binding energy) and shell closures
• Two-neutron separation energies – example
Impact of mass to astrophysics


X-ray burst Luminosity

r-process abundances

Mass measurements

- Time-of-Flight (ToF)
- Multi-reflection ToF (MR ToF)
- Penning Traps (PT)
- Storage Rings – Schottky (SR-Sch)
- Storage Ring – Isochronous Mass Spectrometry (SR – IMS)
Penning Trap

- Triple motion in penning trap
- Used for measuring the mass of nuclei with very large accuracy
- Confining particles in electric and magnetic fields

Canadian Penning Trap @ANL
- LEBIT @ MSU
- ISOLTRAP @ ISOLDE, CERN
- TITAN @ TRIUMF
- JYFLTRAP @ Jyvaskula
- SHIPTRAP @ GSI

Example results: Penning Trap

- Canadian Penning Trap @ANL
- Collaboration ANL + Notre Dame
- Impact on r-process calculations

Time-of-Flight

- National Superconducting Cyclotron Laboratory @ MSU

90 meters

K500 Cyclotron

A1900 Fragment Separator

K1200 Cyclotron

S800 Spectrograph

Storage Rings

Schottky Mass Spectrometry

Cooled Fragments \( \frac{\Delta v}{v} \to 0 \)

Isochronous Mass Spectrometry

Hot Fragments \( \gamma \to \gamma_t \)

www.gsi.de

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Different types of MR-ToF

(a) Linear TOF-MS
(b) Reflector-TOF-MS
(c) Multiple-Reflection TOF-MS (closed Path)
(d) Multiple-Turn TOF-MS (closed path)
(e) Multiple-Reflection TOF-MS (open Path)
(f) Multiple-Turn TOF-MS (open path)

W. Plaß et. al., Intern. J. of Mass Spectrom. 349 (2013) 134
\( \beta \) decay properties

- Half life \( T_{1/2} \)
- \( \beta \)-delayed neutron emission probability \( P_n \)
- \( \beta \)-decay intensity
Impact of half-lives on r-process

Half life

- RIKEN recently completed a major upgrade
- Higher beam rates than other facilities
- Systematics of $T_{1/2}$
- Impact on r process

High resolution

- Mentioned that nuclear structure understanding is important for all astrophysical processes
- Many ways to study nuclear structure
- $\beta$ decay is typically the first view of a nucleus (low beam intensity)
- High resolution measurements for the low lying level scheme

**GRIFFIN @ TRIUMF**

**SeGA + BCS @ MSU**
Evolution of Nuclear Structure

Shell model

5\hbar\omega
- 2p
- 1f
- 0h
1f
0h9/2
2p1/2
2p3/2
1f5/2
1f7/2
82

4\hbar\omega
- 2s
- 1d
- 0g
1d
0g7/2
2s1/2
1d3/2
1d5/2
0g9/2
50

3\hbar\omega
- 1p
- 0f
1p
0f7/2
1p1/2
1p3/2
20

2\hbar\omega
- 1s
- 0d
1s
0d3/2
1d
0d5/2
8

1\hbar\omega
- 0p
- 0h
0p
0p1/2
0p3/2
2

0\hbar\omega
- 0s
- 0h9/2
0s1/2
2

E [MeV]
0
0.5
1
1.5

28
32
36
40

N=51

HPGe Clovers @ ORNL


Artemis Spyrou, Belfast 2017, 85
Why measure $\beta$-decay intensity?

- Model constraints for better input in r-process calculations (Cannot measure everything - we need to rely on model predictions)
- Nuclear structure information
  - $T_{1/2}$ sensitive to nuclear shape
  - Can get same $T_{1/2}$ for different shapes
  - $\beta$-decay strength: sensitive constraint

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Lucrecia @ CERN

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$^{76}$Sr $\beta$-decay

Total Absorption Spectroscopy

Small size – low efficiency detector

\[ I_\beta = I_\gamma^{\text{out}} - I_\gamma^{\text{in}} \]

Large size - high efficiency detector

\[ E_x = E_\gamma^1 + E_\gamma^2 + E_\gamma^3 + E_\gamma^4 + ... \]

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John Milton’s "Paradise Lost"
The Pandemonium in Action

$^{76}$Ga $\beta$ decay

$^{101}$Zr $\beta$ decay

$Q_\beta = 5717$ keV

A. Dombos, et al. PRC93 (2016) 064317
**r-process example: $^{70}$Co $\beta$-decay Intensity**

Double Sided Si Strip Detector
For ion and $\beta$ detection
Importance of $P_n$ values

$r$-process simulation results with and without $\beta$-delayed neutron emission

R. Surman, et. al. JPS Conf. Proc. 6 (2015) 010010
Measuring Pn values

- Integrated measurement - 3He counters (3Hen, NERO, BRIKEN)
- Time of flight – energy information (VANDLE, LENDA, DESCANT)
- New technique – Paul trap (@ ANL)

• Surround ion trap (Paul trap) with plastic scintillators (to detect β’ s) and MCPs (to detect decay recoils)
• Beta-delayed neutron decay measured without detecting neutron

N. Scielzo, et. al., Nucl. Data Sheets 120 (2014) 70
Example: Recent Pn measurements

- Installed at RIKEN Nishina Center in Wako/ Japan
- $148 \ ^3\text{He}$-filled neutron counters from Germany, Japan, Spain, USA and 2 HPGe clovers (Oak Ridge)
- Implantation detector AIDA (Edinburgh, Daresbury)
- First parasitic experiment – more to come 2017-2019

**BRIKEN**

- **Goal**: Measure >100 of the most exotic neutron-rich isotopes presently accessible
- More recent results – Ask Iris 😊
We covered A LOT of material but we didn’t cover EVERYTHING. Here’s what we didn’t cover:

- Isomers
- Charge Exchange Reactions
- \((p,n)\) reactions for \(\nu p\) process
- \((\alpha,n)\) reactions for neutron-star crusts
- Equation of State experiments
- Fission
- Photon beam
- ...
Overview

Lecture 1: Intro to Nuclear Astrophysics - reactions
Lecture 2: How to measure cross sections + activity
Lecture 3: Nuclear structure for astrophysics
Lecture 4: Exotic phenomena close to the drip lines
Reaching the limits

Proton halos
Diproton decay
Location of drip line

High Z Superheavies

Island of stability

Large Z/N
Large N/Z

Reaching the limits
Neutron halos
Neutron skins
Dineutron decay
Structure changes
New radioactivity
Location of drip line

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Structure Evolution
Nuclear Binding

Binding energy: $B(N,Z) = ZM_H c^2 + N M_n c^2 - M(N,Z) c^2$
Nucleon separation energies

Neutron Separation Energy: \[ S_n = B(N,Z) - B(N-1,Z) \]
Two neutron Separation Energy: \[ S_{2n} = B(N,Z) - B(N-2,Z) \]
Proton Separation Energy: \[ Sp = B(N,Z) - B(N,Z-1) \]
Two proton Separation Energy: \[ S_{2p} = B(N,Z) - B(N,Z-2) \]
Neutron separation energies


Artemis Spyrou, Belfast 2017, 100
"Dripline: The limit of the nuclear landscape where additional protons or neutrons can no longer be kept in the nucleus, they literally drip out”

B. Jonson
How to measure structure evolution

- Nuclear existence
- Mass measurements
- γ-ray spectroscopy – excitation energies
- Neutron spectroscopy – unbound states
- Reaction cross sections
- β-decay properties
- …
Isotope Discovery

National Superconducting Cyclotron Laboratory
Michigan State University, US

“Stopped beam area”
Gas Stopper
ReAccelerator Facility
S800 Spectrograph

K500 Cyclotron
S800 Spectrograph
K1200 Cyclotron
A1900 Fragment Separator

Energy Loss
Corrected ToF

RIKEN
RIKEN, RIBF, Japan


MSU
• 3 events of $^{40}$Mg in 7.6 days
• 23 events of $^{42}$Al
• 1 event $^{43}$Al

RIKEN
• About 1000 per day!!!
Yesterday we talked about γ-spectroscopy following β-decay
Today we will focus on reactions
The goal is the same: Study the evolution of single-particle levels
Reminder: Shell model

What can we learn?
- Location of levels
- Cross section of reaction
- Life time of levels
- Angular distribution – multipolarity
- Occupation of levels
γ-ray spectroscopy

Many different ways to populate a state:
- Excitation (Coulomb, inelastic)
- Nucleon transfer
- Knockout
- Fusion evaporation
- Charge exchange
- ...

Important note:
Some reactions are very selective so the structure of the initial nucleus matters.

Selective population

$^{26}\text{Ne}$

\[ Z = 10 \quad N = 16 \]

- 1d\( \frac{3}{2} \)
- 2s\( \frac{1}{2} \)
- 1d\( \frac{5}{2} \)
- 1p\( \frac{1}{2} \)
- 1p\( \frac{3}{2} \)
- 1s\( \frac{1}{2} \)

$^{25}\text{Ne}$

\[ Z = 10 \quad N = 15 \]

- 1d\( \frac{3}{2} \)
- 2s\( \frac{1}{2} \)
- 1d\( \frac{5}{2} \)
- 1p\( \frac{1}{2} \)
- 1p\( \frac{3}{2} \)
- 1s\( \frac{1}{2} \)

$^{26}\text{Ne}$

\[ Z = 10 \quad N = 16 \]

- 1d\( \frac{3}{2} \)
- 2s\( \frac{1}{2} \)
- 1d\( \frac{5}{2} \)
- 1p\( \frac{1}{2} \)
- 1p\( \frac{3}{2} \)
- 1s\( \frac{1}{2} \)

$^{27}\text{Na}$

\[ Z = 11 \quad N = 16 \]

- 1d\( \frac{3}{2} \)
- 2s\( \frac{1}{2} \)
- 1d\( \frac{5}{2} \)
- 1p\( \frac{1}{2} \)
- 1p\( \frac{3}{2} \)
- 1s\( \frac{1}{2} \)
Tools

DALI2 @ RIKEN

TIGRESS@TRIUMF
Example – Island of Inversion

- Local increase to $S_{2n}$ for $^{31,32}$Na (masses)
- $N=20$ shell closure would lead to decrease

- Low lying $2^+$ state in $^{32}$Mg ($\beta$-decay)
- $N=20$ shell closure would lead to a high-lying $2^+$

- $^{32}$Mg deformed (Coulomb excitation)
- $N=20$ shell closure would mean spherical shape

- $^{36}$Mg strong inverted component ($2p$ knockout)
- $N=20$ shell closure would mean

And many more...

Intruder configurations in the ground state of $Z=10-12$ and $N=20-22$ nuclei
Neutron separation energies

- Neutron unbound
- Neutron dripline

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Neutron spectroscopy

- The same reactions can be used to populate neutron-unbound states
- Detect neutron and remaining fragment
- Invariant mass analysis to extract the excitation energy

\[
m(^{15}\text{Be}) = m(^{14}\text{Be}) + m(n) - S_n(^{15}\text{Be})
\]

\[
E_d = \sqrt{M_f^2 + M_n^2 + (2E_f E_n - p_f p_n \cos \theta_{open})} - M_f - M_n
\]

- If \(S_n>0\): bound
- If \(S_n<0\): unbound

\(f\): Fragment

\(n\): Neutron
Example: $^{26}\text{O}$ – bound or unbound

- $^{26}\text{O}$ predictions for 30 years
- Calculations vary: from bound by 5 MeV to unbound by 4 MeV
$^{26}\text{O}$: Experiment@MSU

MoNA/Sweeper setup

Artemis Spyrou, Belfast 2017, 112
Example: $^{26}\text{O} – \text{bound or unbound}$

$^{26}\text{O}$ unbound by $<200$ keV


$^{26}\text{O}$ unbound by $<100$ keV


$^{26}\text{O}$ unbound by $<50$ keV

@RIKEN


$^{37}\text{F} \rightarrow ^{24}\text{O} + 2n$

@MSU

@GSI

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Halo Nuclei

Halo Nuclei

Borromean nuclei

1n - halo

2n - halo

Z=8

N=16

N=14

N=12

N=8

N=2

N=20

Z=2

Z=8

Z=16

Z=20

P. Mueller, PRL 2007


Artemis Spyrou, Belfast 2017, 115
Halo Nuclei

**Discovery**
Experiment: Very large interaction cross section for some light nuclei – large radius

Theory: Explain the matter radius experiments: Introduced term „halo”

**Characteristics of halo nuclei**
- Very low binding energy of the last nucleon(s)
- Large interaction cross section
- Narrow momentum distribution of the fragments in breakup reactions.
Example: $^{31}$Ne halo

- Large cross section of $^{31}$Ne Coulomb excitation
- Low angular momentum of valence neutron
- Weak binding of last neutron
- $^{31}$Ne inside the island of inversion


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2p radioactivity

- 2p radioactivity predicted by Goldansky *Nucl. Phys. 19* (1960) 482
- Single proton emission suppressed - Simultaneous emission of two protons
- Experimentally observed: $^{45}\text{Fe}$, $^{19}\text{Mg}$, $^{48}\text{Ni}$, $^{54}\text{Zn}$

**First observation: $^{45}\text{Fe}$**

2p radioactivity

Interesting detection approach: optical Time Projection Chamber
45Fe @ NSCL

Diproton observation hard to observe due to coulomb barrier

Di-neutron decay: $^{16}\text{Be}$

Di-neutron decay: $^{16}\text{Be}$

$^{16}\text{Be}$

$^{14}\text{Be}$, $^{16}\text{Be}$, $^{15}\text{Be}$, $^{17}\text{B}$, $^{18}\text{F}$, $^{19}\text{F}$, $^{20}\text{Ne}$, $^{21}\text{Ne}$, $^{22}\text{Ne}$, $^{23}\text{Na}$, $^{24}\text{Mg}$, $^{25}\text{Mg}$, $^{26}\text{Si}$, $^{27}\text{Al}$, $^{28}\text{Si}$, $^{29}\text{P}$, $^{30}\text{P}$, $^{31}\text{S}$, $^{32}\text{S}$, $^{33}\text{S}$, $^{34}\text{Ar}$, $^{35}\text{Ar}$, $^{36}\text{Ar}$, $^{37}\text{Cl}$, $^{38}\text{Ar}$, $^{39}\text{K}$, $^{40}\text{Ca}$

Energy (MeV)

Shell model

$1/2^+$

$3/2^+, 5/2^+$

$2^+$

$0^+$

Di-neutron decay: $^{16}\text{Be}$

- First observation of di-neutron decay
- Interpretation still under debate
  - Di-neutron in $^{16}\text{Be}$?
  - Initial state: pairing of neutrons in $^{17}\text{B}$ (2n halo)?
  - Final state interaction?

Summary

Proton halos
Diproton decay
Location of drip line

High Z Superheavies

Island of stability

Neutron halos
Neutron skins
Dineutron decay
Structure changes
New radioactivity
Location of drip line

neutrons, N

Large Z/N
Large N/Z