Rare Isotope Experiments with n-rich nuclei

Motivation: the origin of the heavy elements
r-rich (Eu) rich, s-poor star: Main r-process

- Sneden et al. 2003

r- poor, s - poor star: ??

- Honda et al. 2006 (Travaglio et al. 2004, Montes et al. 2008)

LEPP HD 122563

CS 22892-052

Find more such stars?

- Only 1:1.2 Mio halo stars r-process element enhanced
- Ongoing Surveys (e.g. SEGUE at Apache Point) might find 1000s of stars in relevant metallicity range
  → Will obtain a fossil record of chemical evolution
Nuclear masses in the r-process

Temperature: ~1-2 GK
Density: 300 g/cm³ (~60% neutrons !)  neutron capture timescale: ~ 0.2 µs

Rapid neutron capture

(γ,n) photodisintegration

β-decay

Equilibrium favors “waiting point”
A possible pathway of the r-process

Nucleosynthesis in the r-process

Compare calculated results with abundance observations?

→ Masses, half-lives, n-capture rates of very unstable, exotic nuclei need to be known

→ Need experiments and nuclear theory
New neutron star merger simulations

Korobkin et al. 2012

→ Breakthrough: Find robust r-process with no parameter tuning!
→ Have astronomical data that demonstrate robustness!
→ Wish we had the nuclear data to really test the model …
Rare earth peak – diagnostics of freezeout

r-process model calculations with different nuclear masses:

→ With experimental nuclear masses we could test r-process models

M. Mumpower et al. 2012
Recent r-process related experiments

Mass measurements (need 1:10^6)

- Penning Traps
- TOF (spectrometers, storage rings)

- ANL Trap
- Jyvaskyla Trap
- GSI ESR Ring
- TRIUMF Trap
- CERN/ISOLDE Trap
- NSCL TOF
- ORNL T_1/2_P_n
- RIKEN T_1/2
- CERN/ISOLDE T_1/2_P_n

Neutron capture rates:
- use transfer such as (d,p)
- ORNL (d,p)

Seed producing reaction rates:
- ^9Be(γ,n) with HlgS Neutrino physics

Future facility reach (FRIB)

β-decay studies:
- RIKEN T_1/2
- CERN/ISOLDE T_1/2_P_n
- ORNL T_1/2_P_n
- NSCL T_1/2_P_n
- GSI/Mainz T_1/2_P_n
- TRIUMF Trap
- Jyvaskyla Trap
- ANL Trap
- N=50
- N=82
- N=126
Fragmentation production of rare isotopes
$B\rho$ selection separates $m/q$

\[
B\rho = \frac{p}{q} = \frac{m}{q} \gamma v \quad \text{so for production at fixed velocity } v \ B\rho \sim m/q
\]
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

Fragment yield after Br selection
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

Fragment yield after Br selection

Fragment yield at focal plane
A1900 Fragment Separator
Event by event particle identification

Ion Source: $^{86}$Kr beam

$^{86}$Kr beam 140 MeV/u

Tracking

Measure $p/q$ by tracking at dispersive focus

$\frac{p}{q} = B \rho$

Time of flight measurement

Combine with TOF velocity measurement

$\frac{p}{qv\gamma} = \frac{m}{q}$ get $m/q$

Energy loss measurement

Measure energy loss in Si detector

$\Delta E \sim \frac{Z^2}{v^2}$ get $Z$

Implant beam in detector and observe decay

K1200 K500

gas catcher

4 pi

sweeper

neutron walls

S800

superball

A1900

RPMS
Particle Identification

78Ni
Doubly Magic!
(σ~20 fb)
11 per week
FRIB: 50 per second!

Fast RIB from fragmentation:
• no decay losses
• any beam can be produced
• multiple measurements in one
• high sensitivity 1:1014
Search for new isotopes – an example

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- Flight time of the order of 100s of ns. This requires neutron bound!

Observation -> n-bound

Non-observation -> n-unbound (if production sufficient)

- The dripline is a benchmark that all nuclear models can be measured against

- Sensitive to aspects of the nuclear force

1990: Guillemaud-Mueller et al., Z. Phys. A 332, 189

Lukyanov et al., J. Phys. G 28, L41

The existence of $^{42,43}\text{Al}$ indicates that the neutron dripline might be much further out than predicted by most of the present theoretical models, certainly out of reach at present generation facilities.
**New NSCL Neutron detector NERO**

Measure:
- β-decay half-lives
- Branchings for β-delayed n-emission

Detect:
- Particle type (TOF, dE, p)
- Implantation time and location
- β-emission time and location
- neutron-β coincidences

NERO efficiency: 30-38% for <2 MeV
• 4 cm x 4 cm active area
• 1 mm thick
• 40-strip pitch in x and y dimensions ->1600 pixels
NERO – Neutron Emission Ratio Observer

Specifications:
- 60 counters total (16 $^3$He, 44 BF$_3$)
- 60 cm x 60 cm x 80 cm polyethylene block
- Extensive exterior shielding
- 43% total neutron efficiency (MCNP)
Result for half-life: 110 $^{+100}_{-60}$ ms

Compare to theoretical estimate used: 470 ms
New data by Winger et al. PRL 102, 142502 (2009)

\[
\begin{align*}
\nu \rho_{1/2} & \quad 5/2^- & \quad 1.5 \\
\nu f_{3/2} & \quad 1/2^- & \quad 0.46 \\
\nu \rho_{3/2} & \quad 3/2^- & \quad 1.3
\end{align*}
\]

\[\begin{align*}
69\text{Cu}_{40} & \quad 71\text{Cu}_{42} & \quad 73\text{Cu}_{44}
\end{align*}\]

Results (Hosmer et al. 2005, Hosmer et al. to be published)

From talk by Georgiev 2009:

Evidence for 5/2^- gs for $^{75}\text{Cu}$, $^{77}\text{Cu}$ (Walters, Flanagan private communication)

Nuclear masses in the r-process

Temperature: ~1-2 GK
Density: 300 g/cm³ (~60% neutrons !)  neutron capture timescale: ~ 0.2 µs

Rapid neutron capture  β-decay

Seed  (γ,n) photodisintegration  Equilibrium favors “waiting point”

Proton number  Neutron number
In equilibrium abundance ratios in isotopic chain:

\[
\frac{Y(Z, A+1)}{Y(Z, A)} = n_n \frac{G(Z, A+1)}{2G(Z, A)} \left[ \frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp\left( \frac{S_n}{kT} \right)
\]

Exponential dependence on neutron separation energy

\[ S_n = m(Z,A)+m_n-m(Z,A+1) \]

\[ \rightarrow \text{Need masses to precision of } kT \sim 100 \text{ keV for } \sim 1-2 \text{ GK} \]

\[ \rightarrow \text{For } A=100 \text{ this is } 10^{-6} \]
Contains information about:
- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

But convoluted with nuclear physics:
- masses (set path)
- \( T_{1/2}, Pn \) (\( Y \sim T_{1/2_{prog}} \)), key waiting points set timescale
- n-capture rates
- fission barriers and fragments
Trends of the mass surface

From isotopic Sn difference: need mass uncertainty << 200 keV
For identification of “humps” << 1 MeV (10^-5 precision)
Measurement of Nuclear Masses: Precision need

\[ m(Z, N) = Zm_p + Nm_n - B / c^2 \]

\( m_p, m_n \sim 940 \text{ MeV} \)

\( B < 9 \text{ MeV/u} \)

\( \rightarrow \) Just counting Protons and Neutrons gives mass to 1%

\( \rightarrow \) Need 4 orders of magnitude more Precision!
What about mass models?
Penning Trap Mass Measurements (stopped beams)

\[ f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B \]

- **Cyclotron frequency**
- **PENNING trap**
  - Strong homogen. magnetic field
  - Weak electric 3D quadrupole field

Typical freq.
- \( q = e \)
- \( m = 100 \text{ u} \)
- \( B = 6 \text{ T} \)

\[ \Rightarrow f_+ \approx 1 \text{ kHz} \]
\[ f_- \approx 1 \text{ MHz} \]
Example: TRIGA Penning Trap (Mainz)
Example Results

**JYFLTRAP (Hakala et al. 2008)**

![Time of Flight Graph](image)

- \(^{83}\text{Ga}^+\)
- \(T_{1/2} = 300\,\text{ms}\)

**ISOLTRAP (Baruah et al. 2008)**

![Neutron Separation Energy Graph](image)

- Zn masses out to \(^{81}\text{Zn}\)
- Error: 2-5 keV
- (~10\(^{-7}\) to 10\(^{-8}\) precision)
- (and accuracy!)
The r-process at A=80

Precision masses from ion traps

Known n-emission branchings

> Unique region where main nuclear physics for the r-process is now experimentally constrained

Network calculation: when is $^{80}$Zn a waiting point?

Baruah et al. 2008
Example: Impact of Zn mass measurements

conditions for >90% $\beta$-branch ($^{80}\text{Zn}$ is waiting point)

Precision masses up to $^{80}\text{Zn}$

Precision masses up to $^{81}\text{Zn}$
Mass measurements of very neutron rich nuclei

$\sigma \sim 30$ ps

MSU/ORNL coll.
Matos, Estrade, …
George, Carpino, Meisel, …

Isotopes identified in one experiment

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Discriminate mass models

$Q_{EC}$ for $A=66$ chain (difference to FRDM)

Impact on crustal heating

Integrated heat release for superburst ashes

Masses in neutron star crust models

$^{66}$Ni $\rightarrow$ $^{66}$Fe

$^{66}$Fe $\rightarrow$ $^{66}$Cl

Less heating

Shallower heating
How to measure neutron capture on unstable nuclei?

\[ n + A \rightarrow B + \gamma \]

Direct transition from initial state \(|n+A\rangle\) to final state \(<f|\) in B

\[ \sigma \propto \pi \lambda_a^2 \cdot \left| \langle f \middle| H \middle| n + A \rangle \right|^2 \cdot P_l(E) \]

- Geometrical factor (deBroglie wave length of projectile - “size” of projectile)
  \[ \lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}} \]

- Interaction matrix element

- Penetrability: probability for projectile to reach the target nucleus for interaction. Depends on projectile Angular momentum \(l\) and Energy \(E\)

“Same” for neutron transfer: \(A + d \rightarrow B + p\)

BUT: might probe different parts of wave function at different energies
Neutron transfer reaction measurements at HRIBF at ORNL (K. Jones, J. Ciezczewski, et al.)
The magic nature of $^{132}$Sn explored through the single-particle states of $^{133}$Sn

r-rich (Eu) rich, s-poor star: Main r-process

Sneden et al. 2003

solar r-process

r-poor, s-poor star: ??
(Travaglio et al. 2004, Montes et al. 2008)

HD 122563

Honda et al. 2006

Major progress in astronomy – new processes found!

Find more such stars?
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- $T_{1/2}$, $P_n (Y \sim T_{1/2}^{\text{prog}})$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments