Outline

• Lecture 1: History, stellar evolution & thermonuclear rates
• Lecture 2: Charged-particle reactions: direct measurements
• Lecture 3: Charged-particle reactions: indirect measurements
• Lecture 4: Slow neutron capture process: direct measurements
• Lecture 5: Rapid neutron capture process: indirect measurements
Solar System $r$-process abundances

Obtained by subtracting $s$-process abundances
r process in metal-poor stars

Robust main r-process pattern (for $Z > 55$) identical over billions of years! What is the site?
r-process site(s): Neutron-star mergers!
Type II supernovae?

LIGO GW170817

Model: merging neutron stars
→ r-process
→ Kilonova

Kilonova observed!

https://www.aldebaran.cz/bulletin/2017_36/kilonova.jpg

Metzger, 2010
Wikipedia
r process: nuclear data needed

**Bold**: can measure directly

- Q values for \((n,\gamma)\) reactions
- \(\beta^-\) decay half lives
- \(\beta^-\) delayed neutron decay
- Partition functions
- Fission probabilities
- \(\alpha\)-decay half lives
- \((n,\gamma)\) reaction rates

*Generally, these properties are not known experimentally: need RIBs (eg. FRIB)*
Nuclear masses play a fundamental role in calculating most of nuclear properties needed to model the r process.

Most directly: if in \((n,\gamma)-(\gamma,n)\) equilibrium then successive application of the Saha equation along isotopic chain yields general expression for number density of isotope \(\chi_m\), which is \(m\) neutron captures away from isotope \(\chi_0\):

\[
N_{\chi_m} \approx N_{\chi_0} \left( \frac{N_n}{1.188 \times 10^{34} T_9^{3/2}} \right)^m \exp \left[ \frac{11.605}{T_9} \sum_{j=0}^{m-1} Q_{\chi_j(n,\gamma)} \right]
\]

Due to decrease of \(Q_{ny}\) as neutron drip line is approached and odd-even-\(N\) staggering, maximum abundance occurs at a particular even-\(N\) isotope with optimal \(Q_{ny}\) (given \(T, N_n\)).
r-process mass sensitivity

Black squares: stable nuclides
Grey squares: nuclides with measured masses in 2013 Atomic Mass Evaluation
Colored squares: nuclides with unmeasured masses affecting r-process abundances

Mumpower et al., PNPP 86, 86 (2016)

C. Wrede, HUGS, May 2019
Experimental Nuclear Astrophysics
Europium isotope masses

Nuclear theories don’t predict consistent masses: need to measure them!

Mumpower et al., PNPP 86, 86 (2016)
r-abundances from theoretical masses

Need to measure masses to about 100 keV uncertainty (darker-shaded bands)

Mumpower et al., PNPP 86, 86 (2016)
Nuclear masses: experimental approaches

FRIB researchers will employ most (potentially all) of the approaches above
Fission of 1 Ci $^{252}$Cf source at Argonne National Lab’s ATLAS facility is projected to produce 500 neutron-rich species at a rate of $>1/s$. 

J. A. Clark
One ion per second is sufficient for r-process mass measurements with the Canadian Penning Trap at ANL, for example.
Beta decay transfers material to isotopic chains of higher-Z chemical elements, where equilibrium is established again. Gives rise to r process path.
r-process $T_{1/2}$ sensitivity

Mumpower et al., PNPP 86, 86 (2016)
r-abundances from theoretical $T_{1/2}$

Need to measure half lives, too!

Mumpower et al., PNPP 86, 86 (2016)
RIBF at RIKEN is currently the world leading in-flight RIB facility: it has primary beam powers exceeding 10 kW and can produce very neutron-rich nuclides.

A. Estrade
Beta decay half lives: experiments

Example: fast beams produced by in-flight fission of $^{238}$U at RIBF.

Species to the right of the red line are newly-measured half lives.

Circled species are most neutron-rich isotopes measured of each element.

Half lives can be measured in bulk given RIB rates of a few per day.

Particle ID plot obtained by combining time-of-flight with energy loss

Correlating exotic ions with their $\beta$ decays

- Particle ID detectors: timing, position, $\Delta E$
- Energy degrader
- Double-sided silicon strip detector (DSSD)

$\rightarrow$

fast isotope

RIB implantation

- Signal ($V$) vs. time
  - $\Delta t$

RIB decay
RIKEN RIBF $T_{1/2}$ measurements

EURICA Ge array detects $\gamma$ rays emitted following $\beta$ decay

WASA3Bi Si stack detects RIB implantations and subsequent $\beta$ decays.

RIKEN RIBF $T_{1/2}$ measurements

$T_{1/2}$ of 110 neutron-rich nuclides were measured including 40 new ones in the vicinity of $N = 82$ r-process waiting point. Sensitivity to nuclides with $T_{1/2}$ as low as 15 ms.

Beta delayed gamma decay

\[ \beta\text{-decay: } \frac{A}{Z}X \rightarrow \frac{A}{Z+1}Y + e^- + \bar{\nu}_e \]
Beta delayed neutron decay

\[ \beta^{-}\text{-decay:} \quad \frac{A}{Z}X \rightarrow \frac{A}{Z+1}Y + e^- + \bar{\nu}_e \]

\[ \beta^{-}\text{-delayed neutron decay:} \quad \frac{A}{Z}X \rightarrow \frac{A-1}{Z+1}Y + n + e^- + \bar{\nu}_e \]

Probability for beta delayed neutron emission is called \( P_n \).
When r process ends, material $\beta$ decays back to stability to form the r-process abundance pattern.

$\beta$ decays can’t be assumed to proceed along an isobaric chain because $\beta$-delayed neutron emission branch can be significant.

Example: interpretation of $A = 130$ abundance peak is influenced by probabilities of $\beta$ delayed neutron emission, $P_n$. 
r-process $P_n$ sensitivity

Mumpower et al., PNPP 86, 86 (2016)
$P_n$ experiment example: BRIKEN @ RIBF

A. Estrade
A. Tolosa-Delgado et al, NIM A 925, 133 (2019)

C. Wrede, HUGS, May 2019
Experimental Nuclear Astrophysics
BRIKEN setup

High neutron detection efficiency: 64% up to 1 MeV

A. Estrade
A. Tarifeño-Saldivia et al, JINST 12 P04006 (2017)
A. Tolosa-Delgado et al, NIM A 925, 133 (2019)
BRIKEN collaboration has recently acquired data to measure over 100 $P_n$ values on or near the r-process path (also $P_{2n}$ and $P_{3n}$).
Things experimentalists won’t be able to measure in detail/bulk anytime soon

**Partition functions**: Needed to augment ground-state decay constants with thermal excitations. Requires complete spectroscopy of the low-lying excited states of nuclides on the r-process path.

**Fission probabilities**: When r-process path runs close to the drip line, fission cycling becomes important. Region of interest ($A\sim260$, $Z\sim94$) is far from anything RIB facilities can produce in the near future. Instead, experimentalists will measure fission where they can and use that information to constrain theoretical models, which can then be applied to the r process.

**($n,\gamma$) reaction rates**: Important when there is no ($n,\gamma$)-($\gamma,n$) equilibrium. Can’t make a sufficiently dense neutron target for use with RIBs. Maybe one day our grandkids will be able to fill a bottle with Avogadro’s number of ultra-cold neutrons. Until then, use indirect methods on selected reactions to constrain statistical-model calculations.
FRIB at MSU has been billed as the “r-process machine”: will facilitate measurements of all quantities discussed today for more exotic species.
Recent r-process measurements vs. FRIB

Horowitz et al., arxiv:1805.04637
Summary

• Astrophysical r-process produces about half of the abundance of elements heavier than iron in the Universe

• Renewed interest in r-process due to the clear observation of one r-process site: neutron star mergers

• r-process yield depends on astrophysical conditions, and nuclear properties such as masses, half lives, and beta delayed neutron emission probabilities of very neutron-rich isotopes

• We can measure all of these quantities directly in the lab given sufficient RIB intensities; facilities worldwide are beginning to make measurements on the r-process path

• FRIB will take us further
Thanks again for your attention!
There are about 35 heavy nuclides that can’t be produced by neutron capture processes: the p nuclides.
“Gamma process” likely produces many p nuclides from s,r-process seeds in supernovae. Can measure (p,γ) and (α,γ) reactions to learn about photodisintegrations.