Exploding stars and the synthesis of heavy elements

Artemis Spyrou

MICHIGAN STATE UNIVERSITY
Overview

• Nuclear Astrophysics
• Heavy Element Synthesis
• R-process
• Nuclear Physics Input
• Current Experiments
• New Opportunities
• Future - FRIB

Credit: Erin O’Donnel, MSU
Elements in nature

<table>
<thead>
<tr>
<th>Period 2</th>
<th>Period 3</th>
<th>Period 4</th>
<th>Period 5</th>
<th>Period 6</th>
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<tr>
<td>H (1)</td>
<td>Li (3)</td>
<td>Be (4)</td>
<td>B (5)</td>
<td>C (6)</td>
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<td>Na (11)</td>
<td>Mg (12)</td>
<td>Al (13)</td>
<td>Si (14)</td>
<td>P (15)</td>
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<td>Ca (20)</td>
<td>Sc (21)</td>
<td>Ti (22)</td>
<td>V (23)</td>
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<td>Sr (38)</td>
<td>Y (39)</td>
<td>Zr (40)</td>
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<td>La (57)</td>
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<td>Ta (73)</td>
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<td>Fr (87)</td>
<td>Ra (88)</td>
<td>Ac (89)</td>
<td>Pa (91)</td>
<td>U (92)</td>
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<td>Pd (106)</td>
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<td>Cd (108)</td>
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<td>Lu (71)</td>
<td>Er (68)</td>
<td>Tm (69)</td>
<td>Yb (70)</td>
<td>Lu (71)</td>
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</table>
Elements in nature

H$^1$
Li$^3$
He$^2$

BANG

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The rest… made in stars!!!

Elements in nature
Elements in nature

The rest... made in stars!!!

How can we tell?

Elements in nature

The rest... made in stars!!!

How can we tell?
Light from a red giant (s-process):

Star contains Technetium (Tc) !!!
(heavy element Z=43, T_{1/2} = 4 Million years
Merrill 1952)

Merril 1952: “It is surprising to find an unstable element in the stars”
...“(1) A stable isotope (of technetium) actually exists although not yet found on Earth; or (2) S-type stars somehow produce technetium as they go along; or (3) S-type stars represent a comparatively transient phase of stellar existence”
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Nuclear Landscape

Proton Number

- **p-process**
  - SNII or SNIa?

- **s-process**
  - AGB stars

- **r-process**
  - SNII or NS mergers?

Materials:
- $^{91}\text{Mo}$, $^{92}\text{Mo}$, $^{93}\text{Mo}$
- $^{94}\text{Mo}$, $^{95}\text{Mo}$, $^{96}\text{Mo}$, $^{97}\text{Mo}$
- $^{98}\text{Mo}$, $^{99}\text{Mo}$, $^{100}\text{Mo}$, $^{101}\text{Mo}$

Credit: Erin O’Donnell, MSU
Credit: NASA Goddard
Nucleosynthesis paths

- s-process
  - He-burning in AGB stars, massive stars
  - type II supernovae, merging neutron stars

- r-process
  - cosmic rays
  - pp chain

Margarite Burbidge
Geoffrey Burbidge
William A. Fowler
Fred Hoyle
B²FH, 1957

From M. Wiescher, JINA web
From St. John’s College, University of Cambridge
s/r-process paths and abundances

R-Process Simulation

Temperature = 5.70E+09 K
Density = 3.01E+07 g / cm³
Heating rate = 1.13E+13 erg / s / g
Entropy = 5.99E+00 kB / baryon
Ye = 0.130

Time = 1.06E-03 s
= 1.1 ms

Abundance

Mass fraction

Made with SkyNet by Jonas Lippuner

NSCL
National Science Foundation
Michigan State University
Made with SkyNet by Jonas Lippuner
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**Blue component:**
Light r-process elements
Optical
Bright and brief

**“Red” component:**
Heavy r-process elements
Lanthanides
Infrared
Longer-lasting

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Kilonova in GW170817
Neutron Star Merger

Credit: NASA Goddard

Watson et al., Nature 2019

Kasen et al., Nature 2017

Kilpatrick, et al, Science 2017

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More observations

**NUCLEAR ASTROPHYSICS**

129\(^{I}\) and 247\(^{Cm}\) in meteorites constrain the last astrophysical source of solar r-process elements

Benoit Côté\(^{1,2,3}\), Marius Eichler\(^{4}\), Andrés Yagüe López\(^{1}\), Nicole Vassh\(^{5}\), Matthew R. Mumpower\(^{6,7}\), Blanka Világos\(^{1,2}\), Benjámin Soós\(^{1,2}\), Almudena Arcones\(^{4,8}\), Trevor M. Sprouse\(^{5,6}\), Rebecca Surman\(^{5}\), Marco Pignatari\(^{9,11}\), Mária K. Pető\(^{1}\), Benjamin Wehmeyer\(^{1,10}\), Thomas Rauscher\(^{10,11}\), Maria Lugaro\(^{12,12}\)

The composition of the early Solar System can be inferred from meteorites. Many elements heavier than iron were formed by the rapid neutron capture process (r-process), but the astrophysical site where this occurred remain poorly understood. We demonstrate that the near-identical (\(\approx 15.6\) million years) of the radioactive r-process nuclei iodine-129 and curium-247 irrespective of the time between production and incorporation into the Solar System, suggests the last r-process source by comparing the measured meteoritic ratio \(^{129}\text{I}/^{247}\text{Cm} = 4\) to nucleosynthesis calculations based on neutron star merger and magneto-rotation simulations. Moderately neutron-rich conditions, often found in merger disk ejecta, are consistent with the meteoritic value. **Uncertain nuclear physics data limit our confidence in this conclusion.**
r-process in neutron-star mergers

• What is needed?
r-process in neutron-star mergers

- What is needed?

- [Image of a diagram showing processes like beta decay, neutron capture, and fission]

- Simplistic r-process path

- Fission
What’s known?

- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates

- fission rates
- fission product distributions
- neutrino interaction rates
- Equation of state

*figure by M. Mumpower*
Current \((n,\gamma)\) measurements
The trouble with Neutron Capture Reactions

- Regular kinematics
  - Light beam
  - Heavy nucleus (target)

- Inverse kinematics
  - Heavy beam
  - Light target
  - Heavy recoil

- Measuring Neutron Capture reactions on short-lived nuclei is challenging
- Cannot make a neutron target
- Cannot make a target out of a short-lived isotope
- Need indirect techniques
Neutron capture reactions

- Variation of theoretical predictions using TALYS code, changing model parameters
- Predictions diverge moving away from stability
R-process sensitivity to neutron captures

Monte-Carlo variations of \((n,\gamma)\) rates within a factor
100 – 10 – 2
light – darker – dark bands

Liddick, Spyrou, et al., PRL 2016
R-process sensitivity to neutron captures

Main r-process

Neutron-star merger

Supernova

Weak r-process

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

Neutron Capture – Uncertainties

Hauser – Feshbach (Statistical Model)

- Nuclear Level Density (NLD)
- $\gamma$-ray strength function ($\gamma$SF)
- Optical model potential

Dominate uncertainties
Large uncertainties further from stability

$\beta$-Oslo collaboration:
- Liddick, Spyrou (MSU)
- Larsen, Guttormsen (Oslo)

$\beta$-Oslo method:
- Combine traditional Oslo Method with Total Absorption Spectroscopy
- Use $\beta$-decay to populate the compound nucleus of interest
- Advantage: study nuclei far from stability
Neutron Capture – Indirect studies

• Populate the compound nucleus via β-decay
• Study nuclei far from stability
• Feasible with low beam intensities

Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

- **K500**
  - Production target
  - Stripping foil
  - Coupling line
  - Ion sources
  - $^{86}\text{Kr}^{14+}$, 12 MeV/u

- **K1200**
  - Stripping foil
  - Production target
  - $^{86}\text{Kr}^{34+}$, 140 MeV/u

- **A1900**
  - Focal plane
  - Wedge
  - Transmission of 65% of the produced $^{78}\text{Ni}$

**Fragment yield**
- After target
- After wedge
- At focal plane

$\Delta p/p = 5\%$
National Superconducting Cyclotron Lab

ReAccelerator Facility

“Stopped beam area”

Gas Stopper

Slow

Reaccelerated

Fast

K500 Cyclotron

A1900 Fragment Separator

S800 Spectrograph
Summing NaI – SuN and friends

SuN
γ-Total Absorption Spectrometer

SuNTAN
Tape Transport System

DSSD
Implantation-decay correlation

Fiber Detector
β-detection

Design by LSU and ANL

Hope College

Weak r-process measurements

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**Reactions and Reactions Rates**

- $^{68}\text{Ni}(n,\gamma)^{69}\text{Ni}$
- $^{73}\text{Zn}(n,\gamma)^{74}\text{Zn}$

**Impact on weak r-process abundance calculations**

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**References**

- Spyrou, Larsen, et al, JPG 2017
β-Oslo @ MSU

Stephanie Lyons, MSU
Alex Dombos, MSU
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Mallory Smith, MSU
Andrea Richard, MSU
Alex Dombos, MSU
Steinway Lyons, MSU

Science Foundation
State University

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Current Reach

$r$-process path

figure by M. Mumpower
Facility for Rare Isotope Beams

- Facility for Rare Isotope Beams (FRIB) Project constructs a $730 million scientific user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
  - DOE-SC $635.5 million
  - State of Michigan $94.5 million

- Planned FRIB completion date is June 2022, managing to early completion in 2021

- Upon FRIB completion, NSCL stops operation and FRIB Laboratory starts operation as a DOE-SC scientific user facility for world-class rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC
Facility for Rare Isotope Beams, FRIB
Michigan State University Campus

Experiments with fast, stopped, and reaccelerated beams

Reaccelerator

Ion source

400 kW superconducting RF linear accelerator

Rare isotope production area and isotope harvesting

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Summary - Conclusions

• Nuclear structure and reactions are important input in astrophysical calculations

• New techniques to solve the problem of unconstrained neutron-capture reactions far from stability

• FRIB will bring new capabilities and access to a lot more exotic nuclei