THE R-PROCESS IN HALO STARS

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Matter & Energy in the Universe: from Nucleosynthesis to Cosmology
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Abundance Clues and Constraints

- New observations of n-capture elements in low-metallicity Galactic halo stars providing clues and constraints on:
  1. Synthesis mechanisms for heavy elements early in the history of the Galaxy
  2. Identities of earliest stellar generations, the progenitors of the halo stars
  3. Suggestions on sites, particularly site or sites for the r-process
  4. Galactic chemical evolution
  5. Ages of the stars and the Galaxy chronometers

Solar System Abundances
• Metal-poor Halo Stars are "fossils" of the Early Universe
• These Stars are Relatives of the First Stars in the Universe
Solar System (``Cosmic'')
Abundances

r-Process Nucleosynthesis

- For the r-process:
- $T_{nc} \ll T_\beta$ decay (typically 0.01–0.1 s)
- Site for the r-process still not identified
The Nuclear Isotopes in Nature
SS isotopic deconvolution by s- and r-process

\[ \log \varepsilon(A) = \log_{10}(N_A/N_H) + 12 \]
Total Abundances in CS 22892-052: A Metal-Poor Halo Star

Heavy n-capture elements greatly enhanced (≈ 40-50) over iron abundance.

[Fe/H] = -3.1

Light elements mostly scale with [Fe/H].

\[ [X/H] = \log_{10} \left( \frac{X}{H} \right)_{\text{star}} - \log_{10} \left( \frac{X}{H} \right)_{\text{sun}} \]
n-Capture Abundances in CS 22892-052

Even s-process elements like Ba made in r-process early in the Galaxy.

Historical (~ 1996)

Very old star. Robust r-process over the history of the Galaxy.

Stellar elemental abundances consistent with scaled SS r-process only
Eu Isotopic Abundances in Three Metal-Poor Halo Stars

$^{151}\text{Eu}$:
- 100%
- 65%
- 48%
- 35%
- 0%

Many more examples of Eu isotopes in other stars. Same ratio found.

Ba now seen as well in one star: isotopes appears to be consistent with SS ratios.

Sm & others in progress

Sneden et al. (2002)
Focus On Individual Elements:
Nd, Sm, Gd & Ho

Previous abundance determinations based upon older atomic data.

Reduce abundance uncertainties with new experimental atomic physics data.
Focus On Individual Elements: Nd, Sm, Gd & Ho

New experimental atomic physics data:
- Nd done (Den Hartog et al. 2003)
- Ho done (Lawler et al. 2004)
- Pt done (Den Hartog et al. 2005)
- Sm done (Lawler et al. 2006)
- Gd done (Den Hartog et al 2006)
- Hf done (Lawler et al. 2007)

Working our way through the Periodic Table! (Ce, Dy, Er)
CS 22892-052 Abundances
(with new atomic and stellar data, JC et al. 2005)

\[
\log \varepsilon(A) = \log_{10}(N_A/N_H) + 12
\]

57 elements observed. More than any star except the Sun.

Germanium

Platinum
(64 HST Orbits)
Observational Summary of Total Abundances

6 r-process rich stars

Same abundance pattern at the upper end and ? at the lower end.
Observational Evidence for a Second (Weak) r-process?

- Only recently any detections of elements, $Z = 40-50$
  - Best previous evidence CS 22892-052
- Heavier element ($Z \geq 56$) abundances seem to follow SS r-process curve, not so for the lighter elements
  - Now seeing (?) similar pattern for light n-capture elements in several other r-process rich stars
- What about new observations of HD 221170?
- Two separate sites based upon SS meteoritic data (Wasserburg, Busso & Gallino): strong and weak r-process (two types of SNe or SNe and NS mergers) or
- One site (different epochs or regions)

More evidence?
HST Abundance Observations

- Dominant transitions for elements such as Ge, Os, and Pt in NUV requires HST
- New abundance determinations of these elements (and Zr) in 11 metal-poor halo stars
- Attempt to identify abundance trends and correlations
Ge Abundances in Halo Stars

$[A/B] = \log_{10}(A/B)_{\text{star}} - \log_{10}(A/B)_{\text{sun}}$

[Image of a graph showing the relationship between [Ge/H] and [Fe/H] with data points and a trend line labeled as $[\text{Ge/H}] = [\text{Fe/H}] - 0.85$ and additional points for HD 122563 and CS 22892–052.]

Ge $\propto$ Fe

Challenge to theorists.

$\nu$-process?

What happens at higher [Fe/H] with the s-process?

JC et al. (2005)
If Ge and Eu are both n-capture elements and both synthesized in the same process they should be correlated?

\[ [A/B] = \log_{10}(A/B)_{\text{star}} - \log_{10}(A/B)_{\text{sun}} \]
Zr and Eu Abundances in Halo Stars

Both n-cap elements but not from same source?

LEPP? SN models?
n-Capture Element Correlations: 3\textsuperscript{rd} r-Process Peak

3\textsuperscript{rd} r-process peak elements correlate with Eu.
New atomic data refines Hf and La abundances in Sun and 10 metal-poor stars.

Observed ratios of La/Eu and Hf/Eu larger than previous estimates of SS r-only values suggests larger contribution to La and Hf from r-process.

Lawler et al. (2007)
R- and S-Process Abundance Trends

Simmerer et al. (2004)
Trend is upward due to increasing s-process contribution to La

O’Brien et al. (2003)
Burris et al. (2000)
Arlandini et al.
r-process only

[Graph showing La/Eu vs. Fe with data points labeled bd-012582, g140-46, and g126-36.]
Cosmochronometers

THE RADIOACTIVE AEON GLASSES

\[ \begin{align*}
\text{Thorium-232} & : \quad T_{1/2} = 14.05 \times 10^9 \text{y} \\
\text{Uranium-238} & : \quad T_{1/2} = 4.47 \times 10^9 \text{y} \\
\text{Uranium-235} & : \quad T_{1/2} = 0.70 \times 10^9 \text{y} 
\end{align*} \]

[irrelevant; decays too quickly]

Rolfs & Rodney (1988)
Th Detections in Four Halo Stars and the Sun

Note the strength of the Th lines independent of metallicity

More Chronometers?

No

Yes
Some Concluding Thoughts on: Nucleosynthesis Early in the Galaxy

- r-process elements observed in very metal-poor (old) halo stars
- Implies that r-process sites, earliest stellar generations
  - rapidly evolving: live and die, eject r-process material into ISM prior to formation of halo stars
- Elements (even s-process ones like Ba) produced in r-process early in Galaxy
- Robust for heavy end:
  - places constraints on sites for the r-process
More Deep Thoughts on: Element Synthesis

- Ge and Zr complicated element formation: challenge to theorists
- Evidence for a second r-process? LEPP?
- Os, Ir & Pt correlated (and scatter) with Eu
- s-process onset at low [Fe/H]: how?
- Detections of radioactive elements (Th & U) allow age estimates for oldest stars: putting limits on the age of the Galaxy & Universe
With Collaborators at:

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