Astro 596/496 NPA
Lecture 37
Nov. 20, 2009

Announcements:

- Problem Set 6 due Dec 2 (Wed after break)

Last time: *s*-process
physics: slow neutron capture $\Gamma_{n,\gamma} \ll \Gamma_{\beta}$
  i.e., $\tau_{n,\gamma} \gg \tau_{\beta}$
origin: thermal pulses, dredge-up events in AGB stars
evidence: $N_A \sigma_{nA} \sim const$ good rough fit to solar abundances
but: *s*-pattern does not explain all abundances beyond Fe
  $\rightarrow$ need *r*-process!

Q: basic physics? `www: chart of nuclides`

The *r*-Process: Basic Physics

Sketch:

- Rapidly add n to seeds (e.g., ^{56}Fe)
- populate n-rich nuclei far from β-stability
- later: decay back to β-stable isotopes

Transp: r-*process path*

In general, heavy nuclei can have both
r-process and *s*-process contributions.
But if have multiple stable states
at fixed A, then bifurcates:
the higher N state gets *r*-process
the lower N is "shielded": *s*-only

`www: s-process path`

$\Rightarrow$ very useful in sorting out processes

The *r*-Process: In More Detail

1. Increase A at fixed Z
Transp: r-*process path*
reach $(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium
Saha: $n_{Z,A+1}/n_{Z,A} \sim n_n\,(mT)^{-3/2}\,e^{S_n(Z,A+1)/T}$
with n *separation energy*

$$S_n(Z,A+1) = m(Z,A+1) - m(Z,A) - m_n$$

- distribution in A fixed by n_n, T
- peak A_{max} when $n_{Z,A+1} \simeq n_{Z,A}$
  for *r*-process conditions, occurs at $S_n \sim 2$ MeV
- "waiting point" till A_{max} can β-decay

2. Increase Z at fixed A
Put $n_Z = \sum_A n_{Z,A}$
$\mathrm{d}n_Z/\mathrm{d}t \simeq -\lambda_{\beta,Z}\,n_Z + \lambda_{\beta,Z+1}\,n_{Z+1}$
in equilibrium, $\mathrm{d}n_Z/\mathrm{d}t = 0$:

$$n_{Z+1}/n_Z = \lambda_{\beta,Z}/\lambda_{\beta,Z+1} = \tau_{\beta,Z+1}/\tau_{\beta,Z} \quad (1)$$

Result:

During *r*-process: populate nuclides far from stability
($S_n \sim 2$ MeV)

Pileups around long $\tau_\beta \Rightarrow$ magic N

Transp: r-*process path*

After *r*-process: β decay to stability

Magic $N \longrightarrow$ nonmagic, lower A:

r-peaks lie below *s*-peaks

Characteristic Scales for the r-Process

Timescale

must overcome neutron-magic β-bottleneck $\Rightarrow t \sim \tau_{\rm max} \sim 1$ s

Temperature

need $T \sim$ neutron sep. energy $\sim$ MeV $\Rightarrow T \gtrsim 10^9$ K

Free Neutron Density

need $\tau_{n\gamma} < \tau_\beta$ for each of ~ 100 *r*-process path nuclides:
$t/100 \gtrsim \tau_{n\gamma} \sim n_n \sigma v_T \Rightarrow n_n \gtrsim 10^{20}\ {\rm cm}^{-3}$

Neutron-to-Seed Ratio

start from seeds with $A \sim 56-80$ to make actinides (e.g., ^{238}U)
$\Rightarrow$ neutron/seed ~ 100

Q: so where might these conditions occur?

Candidate Astrophysical Sites for the r-Process

Core Collapse Supernovae

old ideas: outer layers of NS (near mass cut)?
helium-burning shell: n from $\neq 22(\alpha, n)^{25}$Mg
seeds are pre-existing ^{56}Fe

new ideas:

- in hot propto-NS, νs drive baryonic "wind" near mass cut
  rich in n, α
  "high-entropy bubble" high n/seed $\rightarrow$ can get *r*-process
- in *collapsar*, accretion disk also drives ν wind
  which could produce n and *r*-process
  ejected in GRB and/or accompanying Type Ic explosion?
  if true: *r*-process origin in long/soft GRB

Neutron Star – Neutron Star Mergers

neutrons are abundant! if eject:
cold NS matter expands, heats → *r*-process
mergers rarer than SN:
need larger *r*-production per event

if true: *r*-process origin in short/hard GRB

New Twist: r-Process in Halo Stars

CS 22982–052

- halo star, $[Fe/H] = -3.1$

$\Rightarrow$ expected to sample few (1?) nuke events

no *s*-process sources yet *Q: why?*

- Although "metal" poor, very rich in *r*-process:

$$\left(\frac{\mathrm{Eu}}{\mathrm{Fe}}\right)_\star = 50 \left(\frac{\mathrm{Eu}}{\mathrm{Fe}}\right)_\odot \tag{2}$$

- "heavy *r*" ($\geq$Ba) in solar ratios to each other

  e.g., $(\mathrm{Eu/Pb})_\star = (\mathrm{Eu/Pb})_\odot$

  and $(\mathrm{Pb/Ir})_\star = (\mathrm{Pb/Ir})_\odot$, etc. ...

Transp: *abundance pattern*

∞

Q: what do these results imply?

r-Process Universality?

r-process-enriched halo stars:
same *r*-process ratios as in solar system

"one size fits all"?! amazing!

- this star: a few, maybe ONE nuke event
- the Sun: many (1000?) events, averaged ...but *r*-process ratios are the same!

$\Rightarrow$ Universal *r*-process?

- "light *r*" (Ge–Zr) *anomalous*

i.e., non-solar

r-Rich Halo Stars: Implications

1. supersolar *r*/Fe:
   not all SN produce both *r*-pro and Fe
   r-site very short-lived

2. heavy-*r* in solar ratios:
   universal (heavy) *r*-process site

3. nonsolar light-*r* ratios:
   multiple production mechanisms?

Crown Jewels: Uranium and Thorium

U and Th:

- *r*-process only
- unstable:

$$\tau(\mathrm{Th}) = \tau(^{232}\mathrm{Th}) = 20.2\ \mathrm{Gyr}$$

$$\tau(\mathrm{U}) = \tau(^{238}\mathrm{U}) = 6.446\ \mathrm{Gyr}$$

Thorium found in many halo stars

Uranium found in ~ 2 halo stars

Transp: *spectra and abundance patterns*

Can do nucleocosmochronology!

From observed and initial U,Th

$t \sim 12 \pm 3$ Gyr

Possible fly in ointment:

most r-ratios in solar pattern

but: heaviest stable elements (Os, Ir, Pb) *not*

$\Rightarrow$ universal *r*-process only approximate?