Astro 596/496 NPA
Lecture 36
April 26, 2019

Announcements:

- **Problem Set 6 due today** ... or Monday
  Q1 typos: use **Table 3** and **Fig 13** of Bouchet+ (1991)
  Q3b typo: you should find $(T_1/T_2)_{\rm ad} \gg (T_1/T_2)_{\rm obs}$
- last Astro colloquium Tuesday, 3:45pm, NCSA
  Charles Gammie, "First EHT Results"

Yesterday: LIGO detected a second binary neutron star merger!

- distance ~ 150 Mpc
- no gamma-ray burst seen by *Fermi* or *Swift*
- EM searches ongoing

Last time: nucleosynthesis beyond the iron peak

Q: what's the magic ingredient? why is it needed?

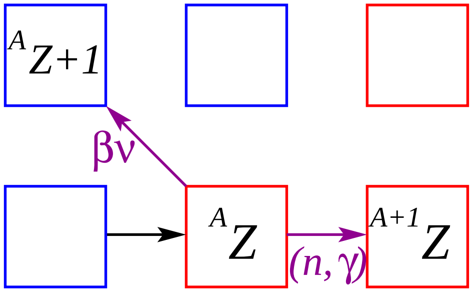
Q: main competing reactions?

Q: limiting cases?

Q: s-*process path on chart of nuclides?*

nucleosynthesis via neutron captures

- no Coulomb barrier
- capture reactions occur even at small thermal speeds



Neutron capture physics set by **competition**

- **neutron capture** $n + (A,Z) \rightarrow (A+1,Z) + \gamma$
- β **decay** $(A,Z) \rightarrow (A,Z+1) + e^{-} + \bar{\nu}_e$

Two regimes (BBFH 1957; Cameron 1957):

capture rate $\gg$ decay rate

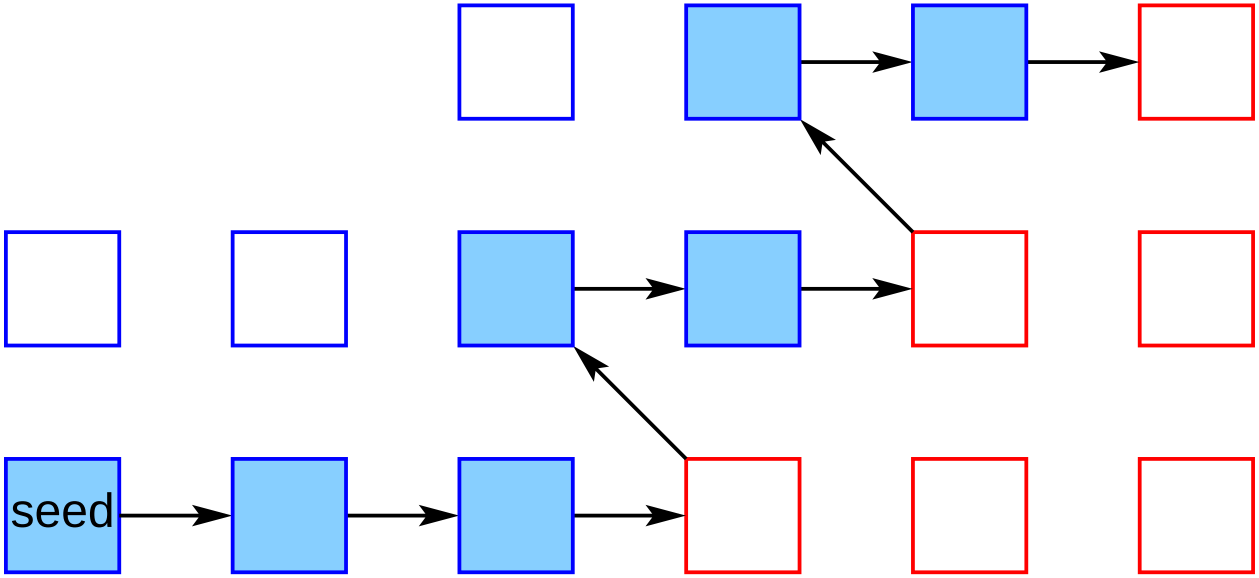
$\Rightarrow$ rapid capture: *r*-process

decay rate $\gg$ capture rate

$\Rightarrow$ slow capture: *s*-process

The s-Process: Basic Physics

slow n capture: $\Gamma_{n\gamma} \ll \Gamma_{\beta}$
$\Rightarrow$ path in chart of nuclides



`www:  chart of nuclides--neutron capture cross sections`

$\sigma_{n,\gamma}$ small at closed n shell/magic N
Q: why? implications for abundances?

Magic Numbers and s-process Peaks

$\sigma_{n,\gamma}$ small at closed n shell/magic N
tightly bound/highly stable, resistant to add another n

but this means *capture rate*

$$\Gamma_{n,\gamma} = n_n \langle \sigma_{n,\gamma} v \rangle$$

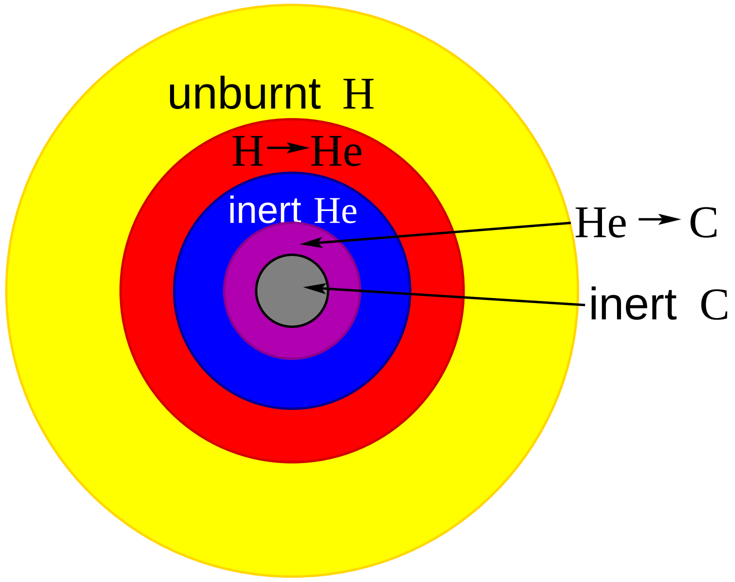
is *small at magic neutron numbers*

thus:
- n capture "flow" slows at magic N
- abundances of magic N nuclides accumulate
- expect peaks in solar pattern at magic N

`www:  solar abundances vs` A **`and vs`** N

observed! these are the *s*-process peaks!

The s-Process: Astrophysical Site



Site: AGB stars

two burning shells: H, He

instability → thermal pulses (TP)

“S-stars” – high *s*-process! contain technetium!

Q: where did the stars get the neutrons? the seeds?

AGB neutron sources:

- $^{13}\mathrm{C}$ from CNO cycle: $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$
- $^{14}\mathrm{N}$ from CNO cycle burnt to $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ then $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

occurs in intershell region
between $p\longrightarrow{}^{4}\mathrm{He}$ and $^{4}\mathrm{He}\longrightarrow{}^{12}\mathrm{C}$ zones
n created during, between pulses
$\Rightarrow$ repeated n exposure of different intensities
$\Rightarrow$ can fit observed exposure distribution
...but now can make detailed, realistic models
in context of stellar evolution

s-Process Residuals: Solar Abundances

for isotopes above Fe peak
s-process distribution well-determined
accounts for $\sim 50\%$ of isotopes above the iron peak!

what's left? look at residual (leftover) solar abundances:

$$N_r(A,Z) = N_{\mathrm{obs}}(A,Z) - \frac{f(A)}{\sigma_A} \tag{1}$$

where $f(A)$ set by s-theory curve

`www:  r-process abundances`

∞ *Q: what patterns do you notice?*

The r-Process: Solar Abundances

solar *r*-process patter from *s*-process residuals:

- *r*-process peaks at $A \sim 80, 130, 195$
- appear *below* *s*-process peaks:
  $A_{s,\text{max}} - A_{r,\text{max}} \sim 10$
  Why?

Also: *s*-process terminates at ^{208}Pb:
$A > 208$ are β-unstable
$\Rightarrow$ ^{232}Th, ^{235}U, and ^{238}U are *r*-process only
demand something else: *r*-process

The *r*-Process

Same song, second verse:

- let there be a **lot** of neutrons
- and pre-existing heavy element seed(s)
- capture n **rapidly**, without time for β decay

Q: how will this proceed?

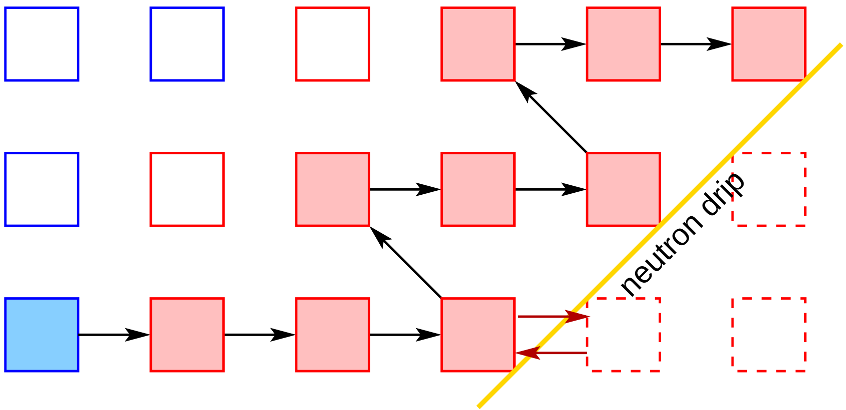
Q: what limits how far up the chart we can go?

`www: chart of nuclides`

The *r*-Process: Basic Physics

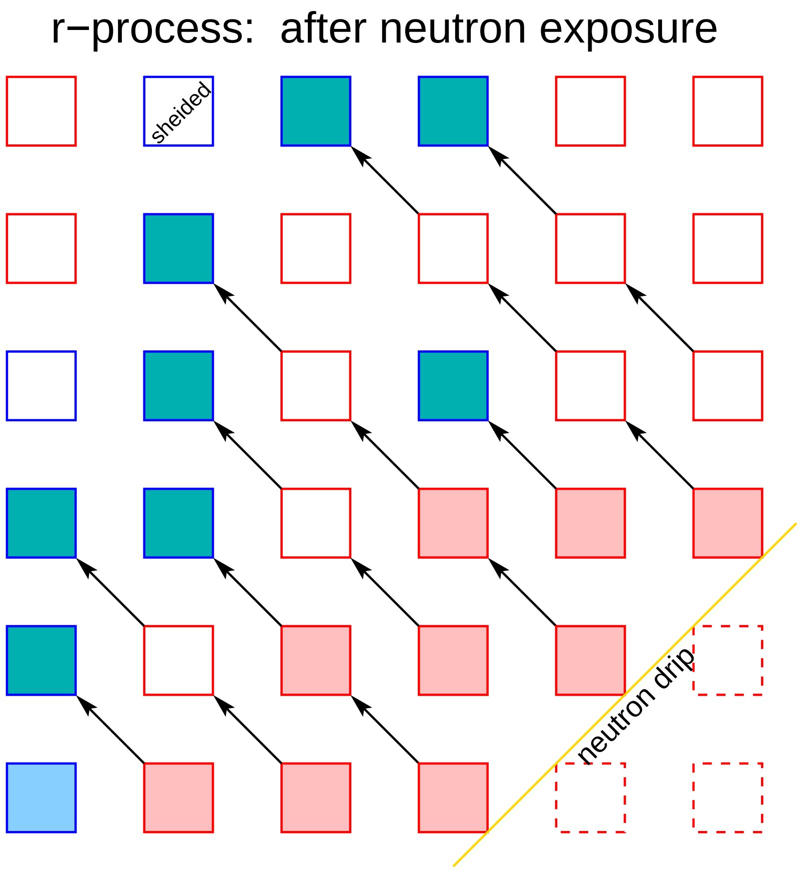
- Rapidly add n to seeds (e.g., ^{56}Fe)
- populate n-rich nuclei far from β-stability
- n enrichment finally limited by (γ, n) reactions
  and ultimately by *neutron drip*:
  extremely n-rich nuclei that decay via n emission
- process stops when all neutrons captured
  or reach to actinides (U, Th, Pu) and fission

r−process: during rapid neutron blast



Q: what happens after neutron blast is over?

r-Process: Decays Back to Stability



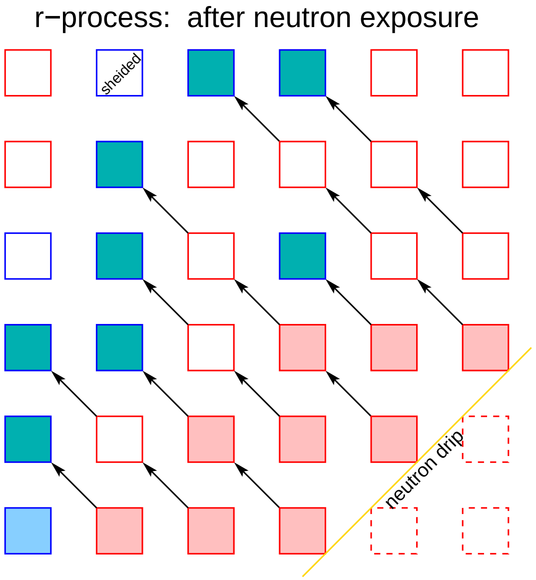
during rapid neutron blast:
r-process path of n captures
populates *extremely* n*-rich isotopes*
near neutron drip line
→ *highly unstable!*

after blast: return to stability via repeated β decays

Combining r and s Processes

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”



shielded *s*-only nuclei very useful in
spararting *r* and *s* processes

The *r*-Process: In More Detail

1. Increase A at fixed Z

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* `www: chart of nuclides`

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

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

2. Increase Z at fixed A

Put $n_Z = \sum_A n_{Z,A}$

$dn_Z/dt \simeq -\lambda_{\beta,Z}\,n_Z + \lambda_{\beta,Z+1}\,n_{Z+1}$

in equilibrium, $dn_Z/dt = 0$:

$$n_{Z+1}/n_Z = \lambda_{\beta,Z}/\lambda_{\beta,Z+1} = \tau_{\beta,Z+1}/\tau_{\beta,Z} \quad (2)$$

Result:

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

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

`www: 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 $\Rightarrow t \sim \tau_{\text{max}} \sim 1 \text{ s}$

Temperature

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

Free Neutron Density

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

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 $\longrightarrow$ 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! it's right there in the name!

if neutron star matter ejected:
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, $[\mathrm{Fe/H}] = -3.1$

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

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

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

$$\left(\frac{\mathrm{Eu}}{\mathrm{Fe}}\right)_{\star} = \boxed{50} \left(\frac{\mathrm{Eu}}{\mathrm{Fe}}\right)_{\odot} \tag{3}$$

- "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. ...

`www: 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!

⇒ 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:

$$\tau(\mathrm{Th}) = \tau(^{232}\mathrm{Th}) = 20.2 \text{ Gyr}$$
$$\tau(\mathrm{U}) = \tau(^{238}\mathrm{U}) = 6.446 \text{ Gyr}$$

Thorium found in many halo stars
Uranium found in several halo stars

Can do nucleocosmochronology!

From observed and initial U,Th

$$\boxed{t \sim 12 \pm 3 \text{ Gyr}}$$

Possible fly in ointment:

most r-ratios in solar pattern

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

⇒ universal *r*-process only approximate?