Astro 596/496 NPA
Lecture 35
April 24, 2019

Announcements:

- **Problem Set 6 due Friday** penultimate!
  Q1 typos: use **Table 3** and **Fig 13** of Bouchet+ (1991)
  Q3b typo: you should find $(T_1/T_2)_{\rm ad} \gg (T_1/T_2)_{\rm obs}$
- Office Hours after class today, or by appointment
- Physics Colloquium today: David Spergel, Princeton & Flatiron
  "Repurposing a Spy Telescope for Studying Dark Energy and Exoplanets"

Last time: unveiling the engines of gamma-ray bursts

- long bursts *Q: engine? how do we know?*
- short bursts *Q: engine?*
- GW/GRB 170817: a landmark in multimessenger astronomy
- *Q: what did the gravitational radiation tell us? gamma rays? other EM?*

Kilonova/Macronova

theory predictions for binary neutron star merger outcome
merger matter sorted by angular momentum

- **central object:** lowest angular momentum matter
  black hole, or
  hypermassive neutron star
- magnetized, spinning → **relativistic magnetized jet**

- **accretion disk:** drives hot, low-density polar wind
  of expanding neutron star matter: expected EM signal!

- **dynamically ejected matter**: $v \sim 0.10 - 0.3c$
  expanding neutron star matter: expected EM signal!

key question:
What happens to decompressing neutron star matter?

Beyond the Iron Peak

Beyond the Iron Peak

`www: Solar Abundances vs` A

if all heavy elements made only in
  burning to nuclear statistical equilibrium
then should follow Fe peak, fall dramatically at high A
→ would have much less of the very heavy elements

How to synthesize nuclei above the iron peak?

- Coulomb barrier $E_\mathrm{C} = Z_1 Z_2 e^2/r$ prohibitive
- fusion reaction *not* exothermic

Yet silver, gold, lead, uranium, ... all exist!
→ nature has found a way

Q: Suggestions?

Neutron Pathways to Nucleosynthesis

Solution: **neutrons**

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

`www: Solar Abundances vs` N

- abundance peaks at neutron magic numbers, and just below
- so: production favors nuclei with neutrons in closed shells
- strong abundance drop *just above* closed shells

Today: nuclear physics of n capture processes

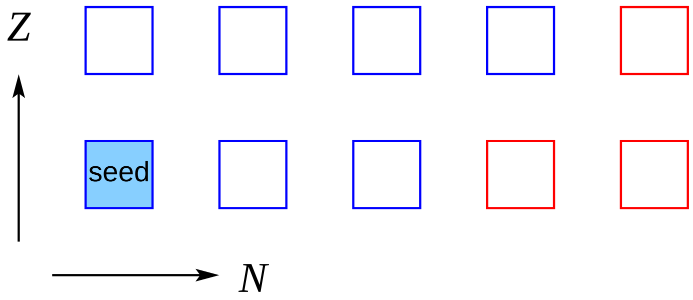
Then: astrophysical sites for appropriate conditions

Neutron Capture Processes

nuclear physics of n capture understood in 60+ years ago!
summarized in B^{2}FH (1957) and Cameron (1957)

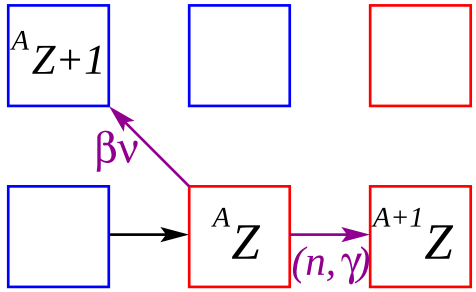
Simplifying assumptions for first approximation:
(1) "let there be neutrons"
(2) a pre-existing "seed" nucleus is presnt (e.g., ^{56}Fe)
(3) can ignore charged particle reactions (Coulomb suppressed)
(3) (n,γ) reactions (radiative capture) dominate (n,p) and (n,α)
all increase neutron richness, but the latter moreso

Q: (n,γ) reaction on chart?
Q: if bombard seeds with neutrons,
what can happen?
Q: competing processes? regimes?
`www: chart of nuclides`



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: $\boxed{r\text{-process}}$

decay rate $\gg$ capture rate

$\Rightarrow$ slow capture: $\boxed{s\text{-process}}$

Detective story:

- do these limiting cases occur? (*Yes!*)
- what are astrophysical sites?

n Capture Rates

n-capture cross sections: typically, $\sigma_{(n,\gamma)} \propto 1/v$

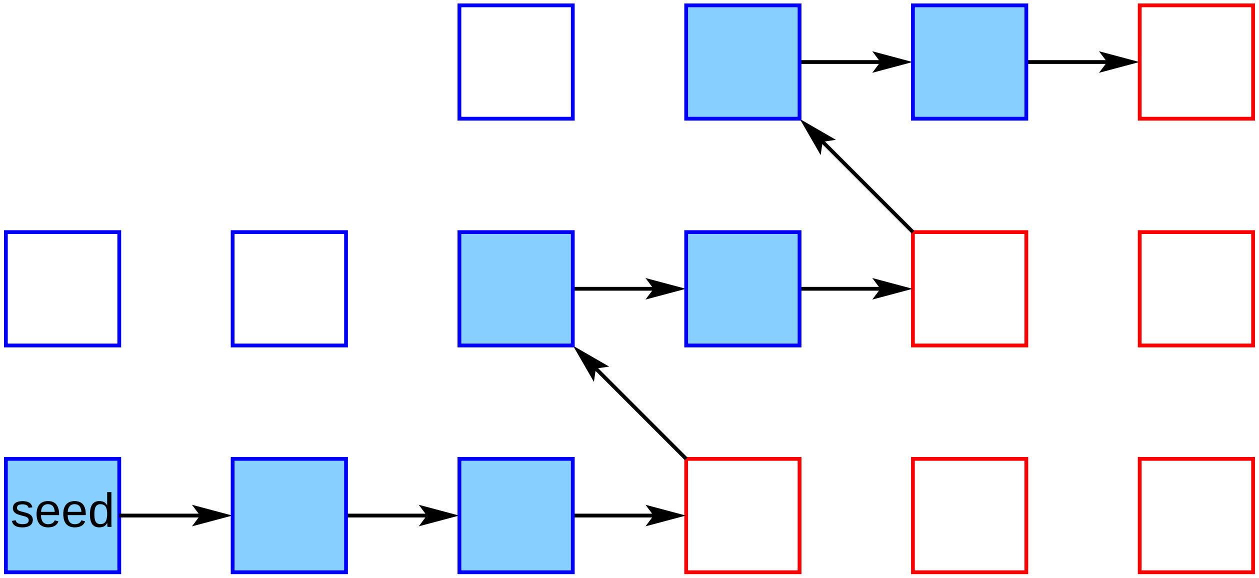
- enhanced at low energies!
- $\sigma v = \langle \sigma v \rangle = const$ → T-indep!
- for nuclei with "magic" N: closed neutron shells
  tightly bound → small $\sigma_{(n,\gamma)}$

Implications if neutron capture is slow?

The s-Process: Basic Physics

slow n capture: $\Gamma_{n\gamma} \ll \Gamma_{\beta}$

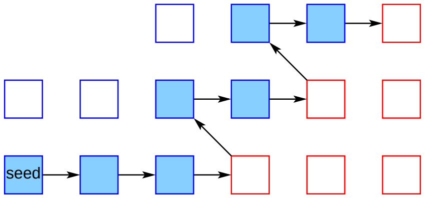
$\Rightarrow$ path in chart of nuclides



- follow n-rich edge of β-stability
- one s-process species per A (i.e., per isobar)

  with exception of long-lived radioactive “branch points”

s-Process Abundance Evoution



for isobar A

$$\frac{dn_A}{dt} = -\langle \sigma v \rangle_A n_n n_A + \langle \sigma v \rangle_{A-1} n_n n_{A-1} \tag{1}$$

except for seed (e.g., ^{56}Fe)

$$dn_{\text{seed}}/dt = -\langle \sigma v \rangle_A n_n n_{\text{seed}} \tag{2}$$

Q: what behavior expected for n_A?

put neutron exposure: $d\tau = n_n(t)\ v_T\ dt$
$\tau =$ time-integrated n flux $= n$ "fluence"
where $v_T = \sqrt{2kT/\mu_n}$, $\mu_n = m_n m_A/(m_n + m_A)$.
Then

$$\frac{dn_A}{d\tau} = -\sigma_A n_A + \sigma_{A-1} n_{A-1} \tag{3}$$

where $\sigma_A = \langle \sigma v \rangle_A / v_T$: thermal n capture cross section

evolution is another example of *self-regulating* equation
→ expect abundance driven to equilibrium, $dn_A/dt = 0$
$\Rightarrow \sigma_A n_A = \sigma_{A-1} n_{A-1}$

$$\frac{n_A}{n_{A-1}} = \frac{\sigma_{A-1}}{\sigma_A} \tag{4}$$

⇒ the "local approximation"
only holds for non-magic nuclei
⇒ good between magic numbers

Solar Abundances and the s-Process

For elements beyond Fe peak:
plot $N_A \sigma_A$ vs A
if *s*-process reaches equilibrium, predict flat curve `www: ` $N_A \sigma_A$ `plot`

for adjacent nuclides, local approximation excellent
between magic N: good
but globally, fails
$\Rightarrow$ need distribution of τ

Roughly: exponential distribution of τ needed
i.e., imagine series of n bursts of different intensities
Q: how does nature do this?

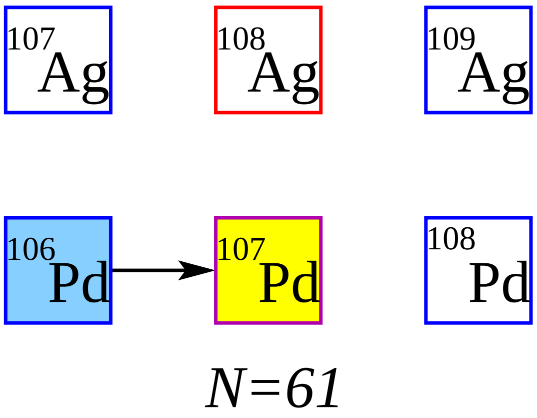
The s-Process: Characteristic Scales

typically, $\langle \sigma v \rangle \sim 3 \times 10^{-17}\ \mathrm{cm}^3/\mathrm{s}$

capture timescale $\tau(n) = 1/(n_n \langle \sigma v \rangle)$

if $\tau(n) > \tau_\beta^{\mathrm{min}} \sim 10\ \mathrm{yr}$ shortest lifetime on *s* path

$\Rightarrow n_n < 10^8$ neutrons cm^{-3}



but also must pass through

$N = 61$: no stable nuclei!

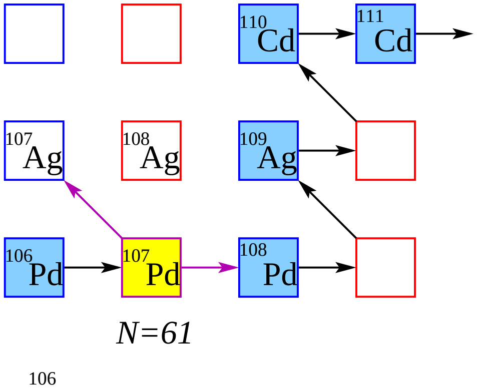
but ${}_{61}{}^{107}\mathrm{Pd}$: $\tau_{107} \sim 10^7$ yr

Q: how do we save the s-process?

s-Process Branches and Neutron Density

must pass throught ^{107}Pd before decay:

$\tau(n) < \tau_{107} \quad \longrightarrow \quad \Rightarrow n_n > 10^2$ neutrons cm^{-3}



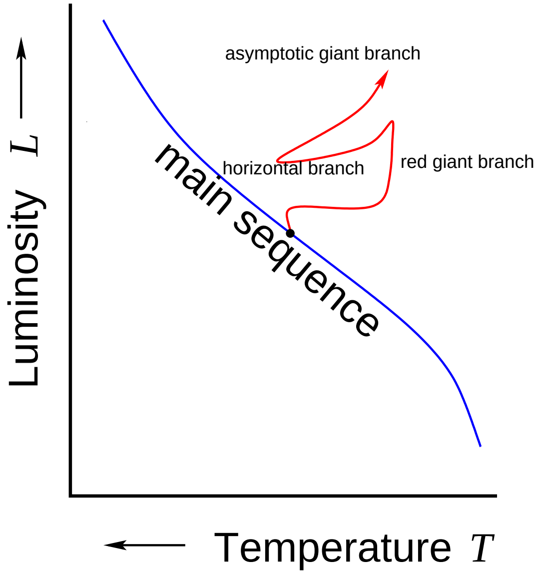
compare with typcial neutron densities in nuclear reactors:

$n_n \sim 10^7$ cm^{-3}

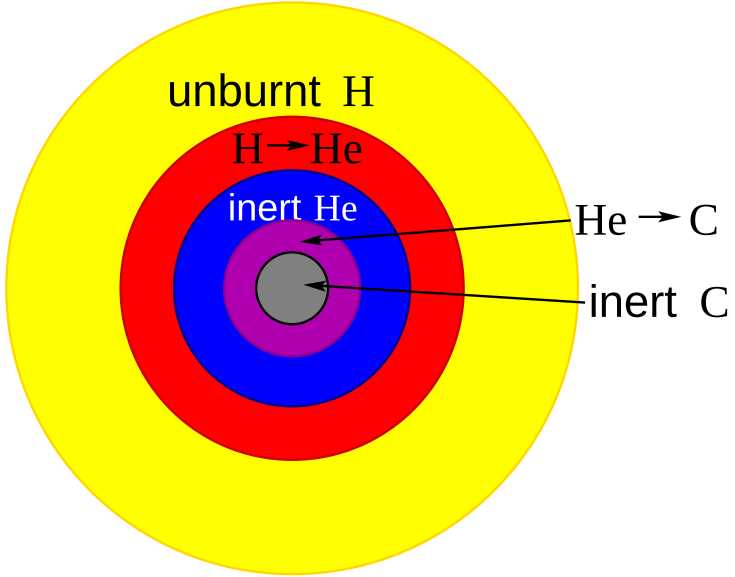
Q: Guesses as to astrophysical site?

s-Process: Astrophysical Site

Intermediate mass stars: $\sim 3 - 8 \ M_\odot$
recall–after main seq:
1. H shell burn → RGB
2. He ignition → core He burn
3 He shell burn → asymptotically approach RGB again
"asymptotic giant branch" $=$ AGB



On AGB:
two burning shells: H, He
instability → thermal pulses (TP)



TP-AGB stars observed to have

- $C/O > 1$ – “carbon stars”
- high *s*-process! – “*S*-stars”

s-Process: The Crown Jewel

technetium seen in AGB stars (Merrill 1952)

`www: Tc lines`

no stable isotopes!

longest-lived $\tau(^{98}\mathrm{Tc}) = 6$ Myr

⇒ 1st direct evidence for ongoing nucleosynthesis in stars!

⇒ *s*-process must occur in AGB!

s-process occurs in pulsing AGB stars

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

AGB neutron sources:

- ^{13}C from CNO cycle: $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$
- ^{14}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

n created during, between pulses

⇒ repeated n exposure of different intensities

⇒ can fit observed exposure distribution

...but now can make detailed, realistic models

in context of stellar evolution