Astrophysics I: Stars and Stellar Evolution

AST 4001

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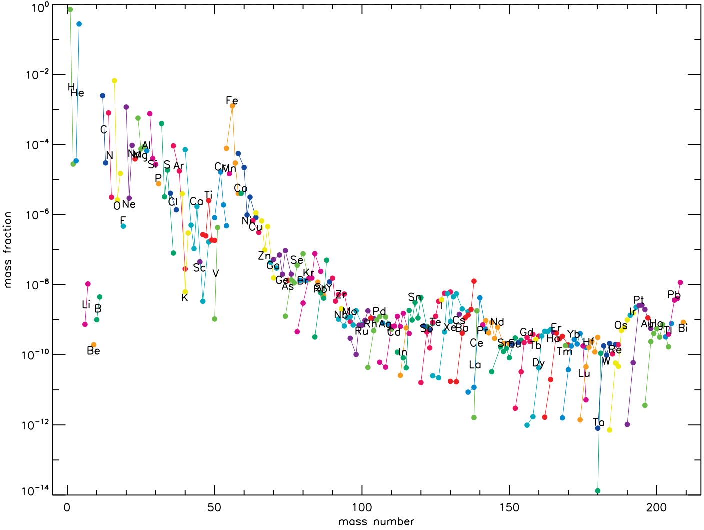
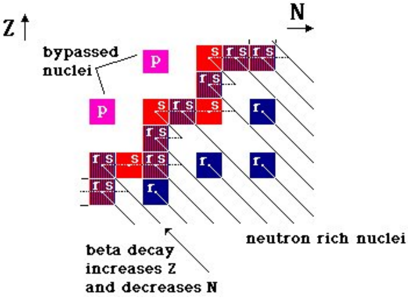
Stars and Stellar Evolution, Fall 2008

Overview

The Composition of the Sun

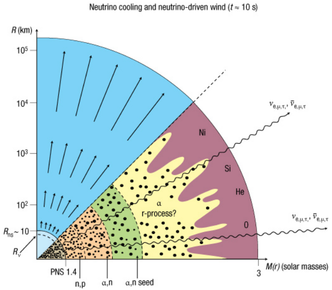


Creation of Heavy Elements



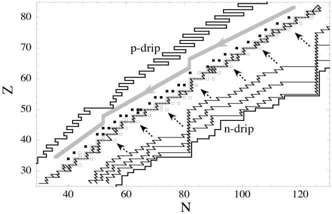
- Beyond iron the mass excess decreases.
- Fusing these heavy nuclei to even heavier does cost energy!
- But fusing a light "nuclei" (mostly neutrons) onto heavier still gives energy.
- Neutrons don't see the coulomb barrier!

r-Process



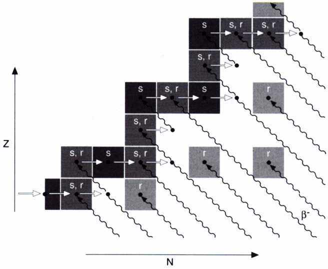
- Typical site: core collapse supernovae, hot neutron-rich environment
- Alternate site I: merger of neutron stars
- Alternate site II: explosive burning in helium shell during supernova explosion
- makes "heavy" nuclei including uranium and thorium (this is where these nuclei are made)
- is the dominant production mechanism for about half (by number) of the heavy isotopes beyond iron

r-Process Mechanism



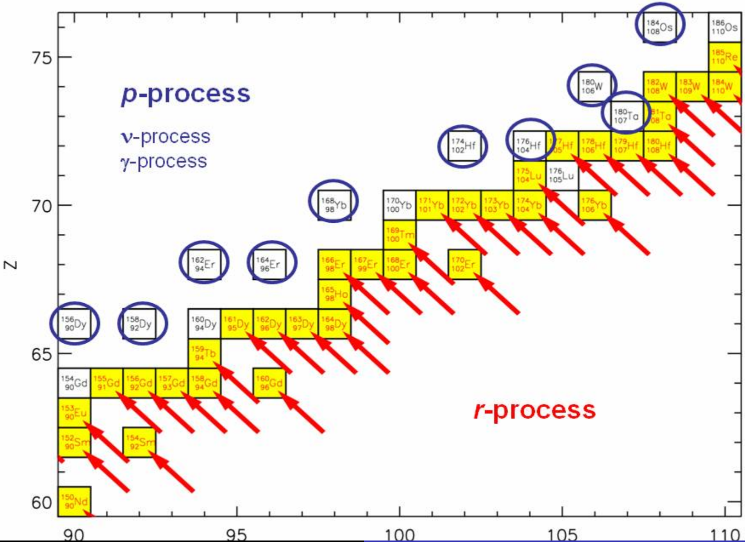
- runs on the neutron-rich side of valley of stability
- very high neutron "exposure"
- $(\mathrm{n},\gamma) \leftrightharpoons (\gamma,\mathrm{n})$ equilibrium (neutron capture balances photo-disintegration reaction - very fast)
- "wait" for β^- decays to build up heavier nuclei (slower)
- time scale: $1 - 100\,\mathrm{s}$

r-Process Production

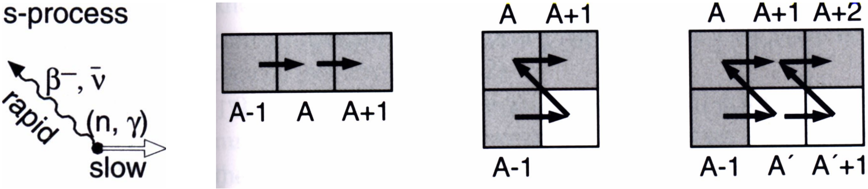


- β^- decays back to line of stability
- makes only nuclei not "shadowed" by other stable nuclei
- $\Rightarrow$ for each mass number A there is only one r-process isotope.

r- and *p*-Process



s-Process

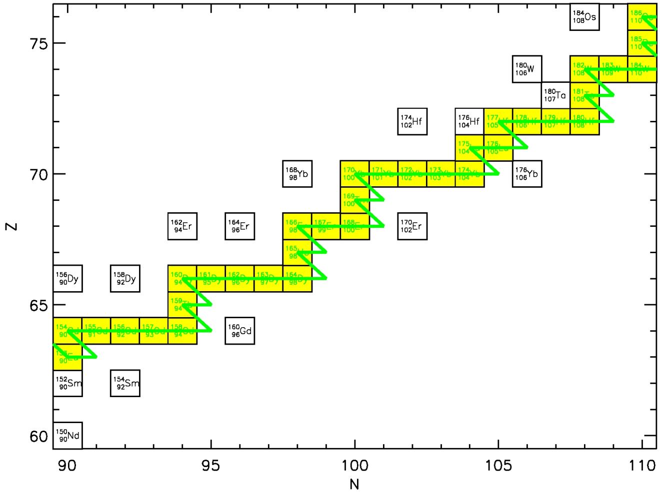


Two major contributions to *s*-process:

Weak component
Mostly in massive stars
weak neutron exposure
not in "equilibrium" - exponential decrease of abundances
Makes nuclei up to $A \sim 90$.

Strong component
Mostly in lower-mass stars, AGB stars
strong neutron exposure
in "equilibrium" - $Y_i \times \sigma_i$ constant (for extended ranges in A) Makes heavy nuclei up to lead (^{209}Bi).

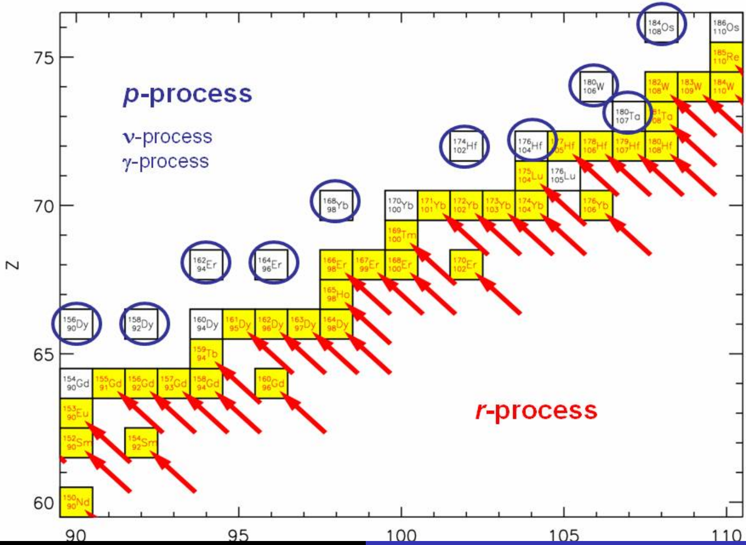
s-Process Path



Neutron Sources for the *s*-Process

- In massive stars:
  $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$
- $^{22}\mathrm{Ne}$ made from
  $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$
- In low-mass AGB stars (helium shell flashes) also $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$
- $^{13}\mathrm{C}$ made from
  $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{13}\mathrm{C}$

r- and *p*-Process



Overview

"*p*"-Process (γ-process, ν-process)

- Production of proton-rich nuclei
- Proton-rich heavy nuclei are rare in nature
- Typical site: core collapse supernovae
- Mechanism 1 (γ-process): photo-"evaporation" of neutrons by high-energy photons; (γ,n) reaction;
  at higher energy and for more proton-rich nuclei also (γ,p) and (γ,α) reactions
- Mechanism 2: excitation of nuclei by high-energy neutrinos from hot neutron star; de-excitation by nucleon emission;
  $\mathrm{N}(\nu,\nu')\mathrm{N}^*(\mathrm{n}|\mathrm{p}|\alpha|\ldots)$
- Mechanism 3: conversion of neutrons to protons by electron neutrinos from hot neutron star; $(\nu_\mathrm{e},\mathrm{e}^-)$ reaction
- decay of proton-rich nuclei back to stable nuclei by β^+ decays

"p"-Process (γ-process, ν-process)

- Limitation:
  production of "rare" isotopes from very abundant neighbors.
- light nuclei examples:
  ^{11}B from ^{12}C,
  ^{19}F from ^{20}Ne
- heavy nuclei examples:
  ^{180}Ta from ^{181}Ta
  ^{138}La from ^{138}Ba

νp-Process

- Production of proton-rich nuclei in early supernova ejecta
- high flux of electron neutrinos makes proton-rich environment
- allow fast build-up of proton-rich nuclei up to $A \sim 100$

"βn"-Process

- Production of neutron-rich nuclei at moderately high neutron fluxes
- competition of neutron capture and β^- decays
- runs only a "few" neutron numbers on the neutron rich side of valley of stability
- usually operates only for short time and shifts nuclei by a few mass and charge numbers

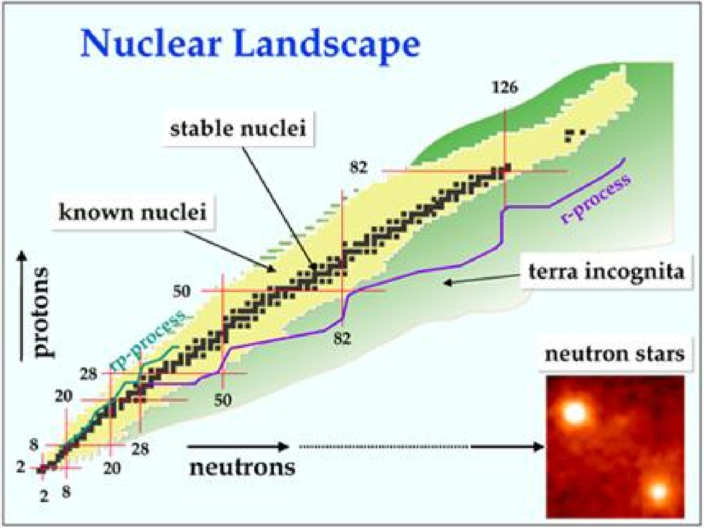
X-ray Bursts and Novae

- Site 1: thermonuclear runaway on the surface of a neutron star, accreting material from a companion in a binary star system
- Site 2: very hot burning during thermonuclear runaway on the surface of a white dwarf star, accreting material from a companion in a binary star system
- runs on the proton-rich side of the valley of stability
- αp-process to build up nuclei to below iron;
  sequence of (p,γ) and (α,p) captures;
  α-captures "catalyzed" by protons
- rp-process to build up nuclei to mass number $A \sim 106$
  sequence of (p,γ) captures and β^+ decays;
  ends in tin-tellurium-antimony cycle;
  in novae it does not reach to that heavy nuclei

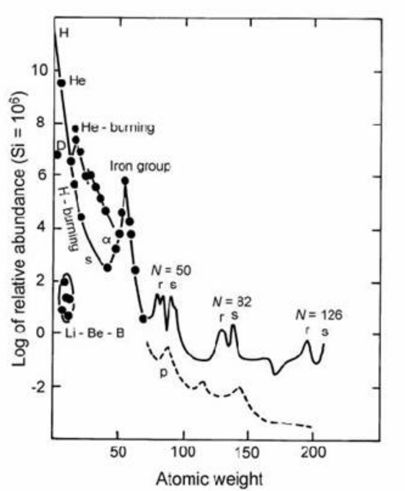
Classification of Nuclei by Origin

- Most heavy nuclei can be produced by several processes some, however, have only one contribution:
- *s*-only nuclei
  - only produced by *s*-process
  - shadowed from *r*-process contributions
- *p*(-only) nuclei
  - only produced by "*p*"-process
  - on proton-rich side of *s*-process path
- *r*-only nuclei
  - only produced by *r*-process
  - on neutron-rich side of *s*-process path
  - cannot be reached by *s*-process path

The Nuclear Landscape



Abundance Distributions



- Abundance peaks in *s*-process and *r*-process patterns due to nuclear physics effects (closed nuclear shells)
- much less abundant *p*-process nuclei
- low abundance of light elements (Li, Be, B)
- pronounced "iron" peak from burning in massive stars (explosive nucleosynthesis in supernova ejecta)

Overview

1. Recap
   - Where are the Heavy Elements and How are They Made?
   - r-, p-, and s-Process
2. Origin of the Heavy Elements
   - p-Process
   - Other Processes
   - Classification of Nuclei by Origin
3. Summary
   - Heavy Nuclei Production Mechanisms
   - Nucleosynthesis
   - Computer Class: Sign-up, Times & Dates

Summary Heavy Nuclei Production Mechanisms

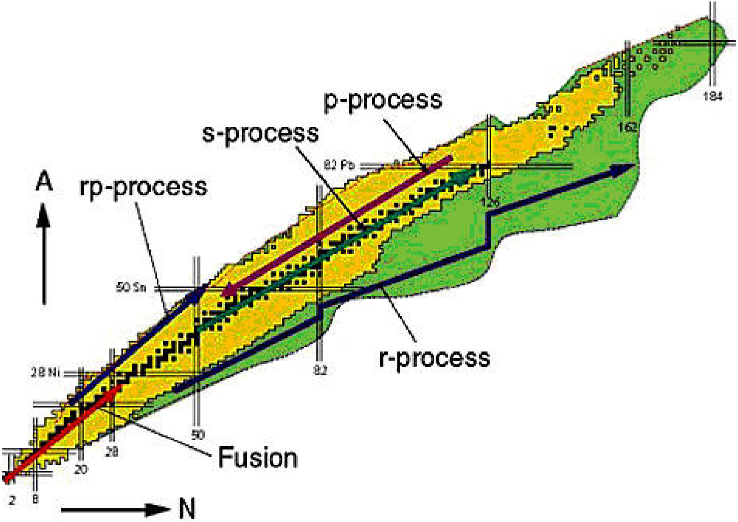
Main production mechanisms for heavy nuclei:

- *s*-process - *slow* capture of neutrons.
  "slow" is defined by compariosn with β-decays
  defines *s*-process path uniquely, except:
  in rare case "branchings" can occur for long-lived radioactive isotopes
- *r*-process - *rapid* capture of neutrons.
  "rapid" is defined by compariosn with β-decays
  decay of radioactive, neutron-rich nuclei gives unique abundace pattern; only production of certain isotopes
- *p*-process - production of proton-rich nuclei
  this can be due to interaction with photons or neutrinos from hot neutron star during supernova explosion
  makes nuclei not made by *r*-process of *s*-process

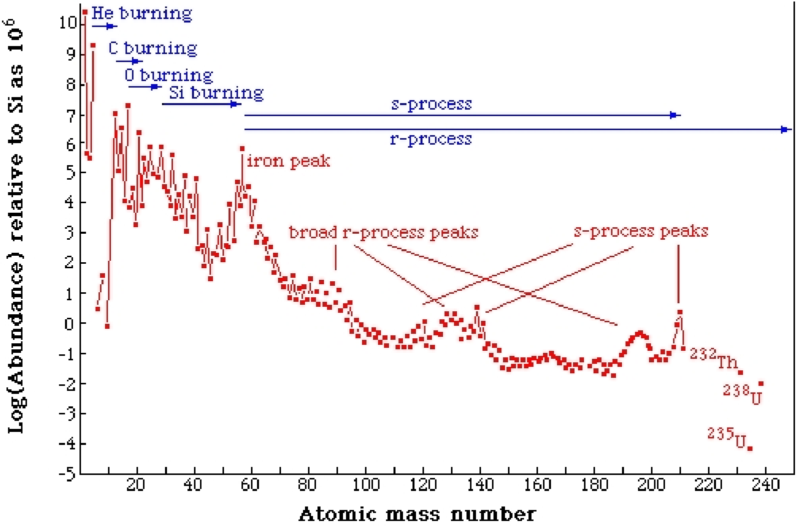
Summary Nucleosynthesis

- Production of helium by fusing protons; required two weak decays of protons to neutrons per ^{4}He formed.
- fuse ^{4}He to ^{12}C and ^{16}O
- heaviest significant direct reactions are $^{12}\mathrm{C} + {}^{12}\mathrm{C}$, $^{16}\mathrm{O} + {}^{16}\mathrm{O}$, and, to a minor extent, $^{12}\mathrm{C} + {}^{16}\mathrm{O}$
- photo-disintegration + α capture reaction in neon and silicon burning; the later builds up nuclei up to the "iron group" (iron, nickel, cobalt, etc.)
- build up of heavier nuclei by capture of neutrons (no coulomb barrier, *r*-process, *s*-process, νp-process)
- production of rare heavy proton-rich nuclei by "*p*"-process (γ-process, ν-process)

Nucleosynthesis Summary



Nucleosynthesis Summary



Computer Class

Room 575, Walter Library

Possible dates

- Friday, 90 min between 6am and 11:30am
- Friday, 13:15-14:45
- Monday, 13:30-15:00

Please let me know which dates and times work for you;
I will schedule class when most people can come.

I will need name, student ID, U Card number to have accounts created.