Week 12, Lecture 3 – Neutrons in Space

Nuclear Reactions in Space

-- Overview
-- Observational Information
--- Elemental distributions
--- EM distributions
-- Nuclear Synthesis
--- Big Bang
--- Stellar processes
---- simple proton burning
---- catalytic cycles
---- neutron capture, r&s
---- sun viz. other stars

8th Homework
due Monday

Type 1a Supernova Explosion
at the edge of a galaxy in the Virgo Cluster (NYTimes, 22Feb2010)

Overview of Nuclear Production Processes

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Observations of stable-element abundances:

- Odd-even staggering
  - -- odd-Z elements have only 1 or 2 stable isotopes, even-Z have several
- Logarithmic decline with Z or A
  - -- ?
- Very little Be, Li, B
  - -- "fragile" relative to ^{4}He, no significant production in Big Bang or stars
- Peak at Fe
  - -- highest binding energy, end point of stellar fusion processes
- Peak near Pb
  - -- ?

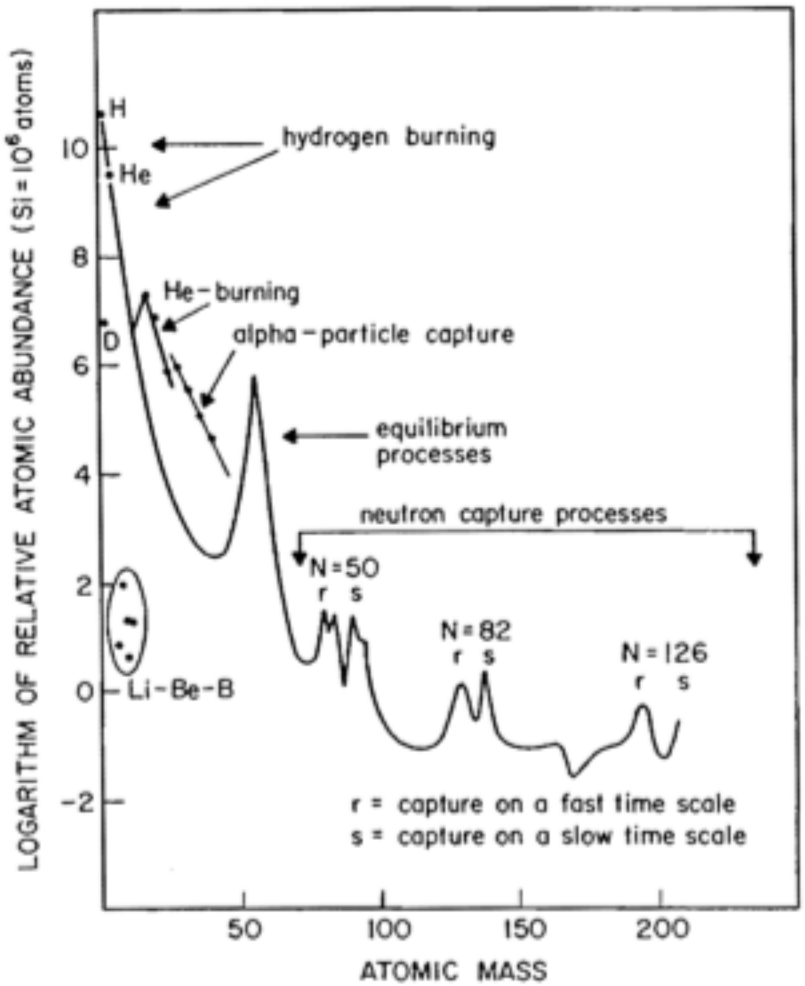

Figure 12.4 Atomic abundances of the elements in the solar system and the major nucleosynthetic processes responsible for the observed abundances. [From E. M. Burbidge, et al., *Rev. Mod. Phys.* **29**, 547 (1957). Copyright (1957) by the American Physical Society.]

Slow Neutron-Capture

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A process that can produce many of the isotopes heavier than iron is the slow neutron-capture process. This process can work in large stars with reprocessed material because:

Requirements: (1) seed nuclei in the iron region
(2a) (hot) helium burning on left-over $\boxed{\text{CNO}}$ nuclei
(2b) (hotter) helium burning residues in massive star

Sources of neutrons:

$$^{4}He^{2+} + {}^{14}N^{7+} = {}^{18}F^{9+} + \gamma$$
$$\hookrightarrow {}^{18}O^{8+} + e^{+} + \nu$$
$$^{4}He^{2+} + {}^{18}O^{8+} = {}^{22}Ne^{10+} + \gamma$$
$$^{4}He^{2+} + {}^{22}Ne^{10+} = {}^{25}Mg^{12+} + {}^{1}n$$

$$^{4}He^{2+} + {}^{13}C^{6+} = {}^{16}O^{8+} + {}^{1}n$$

$$^{1}p^{+} + {}^{20}Ne^{10+} = {}^{21}Na^{11+} + \gamma$$
$$\hookrightarrow {}^{21}Ne^{10+} + e^{+} + \nu$$
$$^{4}He^{2+} + {}^{21}Ne^{10+} = {}^{24}Mg^{12+} + {}^{1}n$$
$$^{4}He^{2+} + {}^{22}Ne^{10+} = {}^{25}Mg^{12+} + {}^{1}n$$

The time scale is thought to be on the order of 10^4 - 10^5 years between captures and would occur after the longer period (few 10^9 y depending on size) of hydrogen burning in a star.

Slow Neutron Capture Path

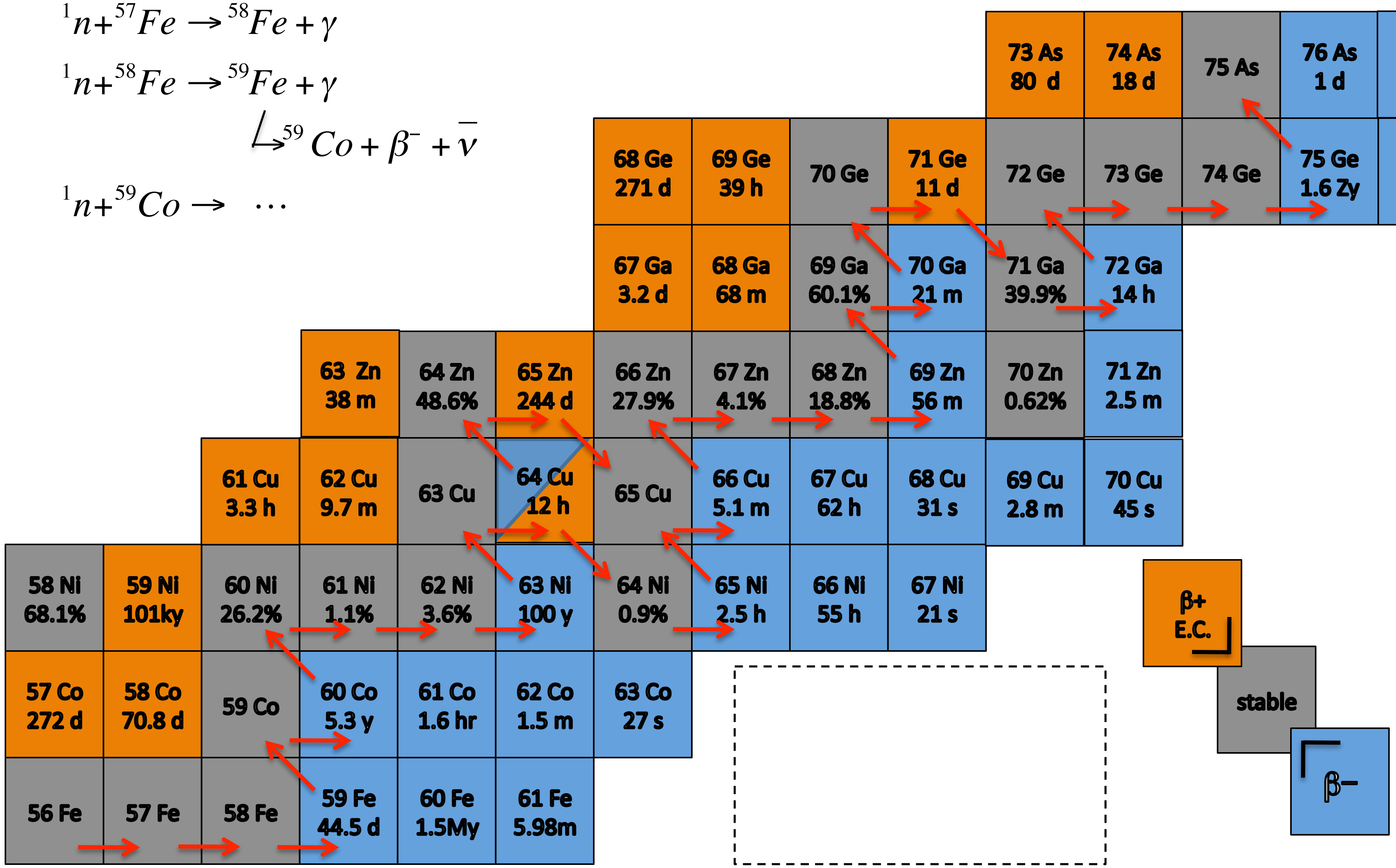
$$^{1}n + {}^{56}Fe \rightarrow {}^{57}Fe + \gamma$$

$$^{1}n + {}^{57}Fe \rightarrow {}^{58}Fe + \gamma$$

$$^{1}n + {}^{58}Fe \rightarrow {}^{59}Fe + \gamma$$

$$\hookrightarrow {}^{59}Co + \beta^{-} + \bar{\nu}$$

$$^{1}n + {}^{59}Co \rightarrow \quad \cdots$$



s-process Yields

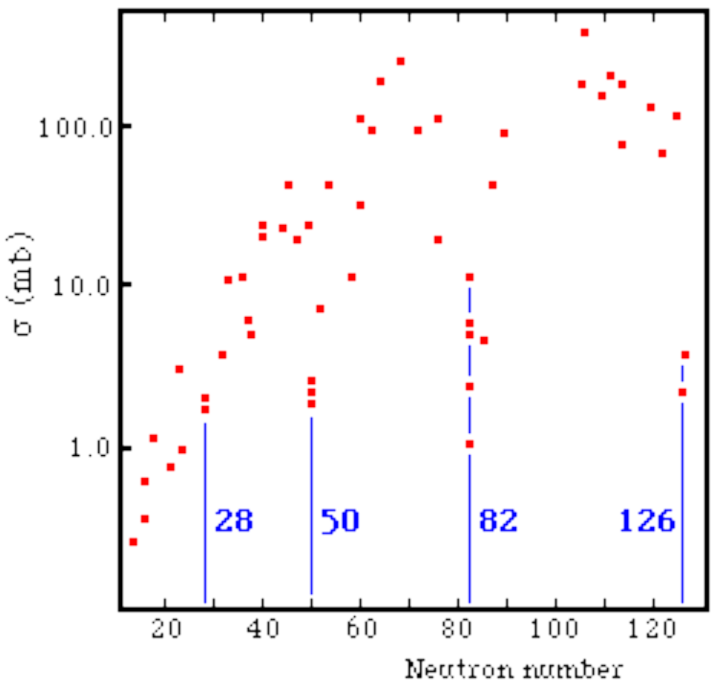
If we start with seed nuclei in the iron region and we have a successive capture of neutrons on the products, interspersed with beta-decays, then we would expect the products to fall in yield as we get further and further from the starting point.

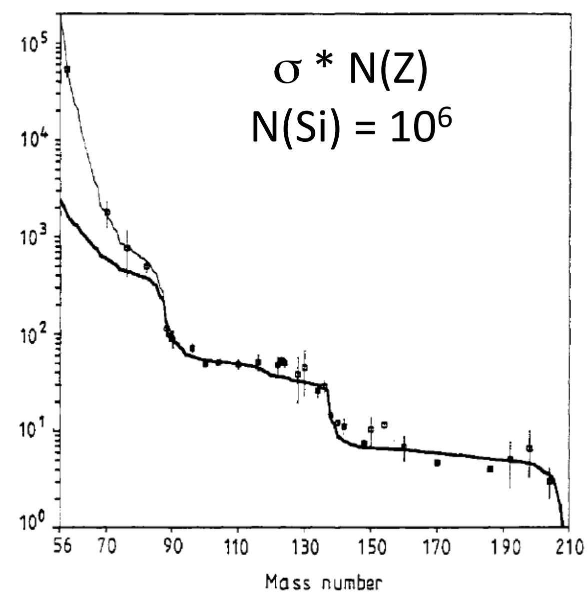
The s-process is cut off at ^{209}Bi by alpha decay.

There are two small modification due to nuclear structure effects:

(1) The neutron capture cross section generally increases with mass number due to the increasing nuclear size.

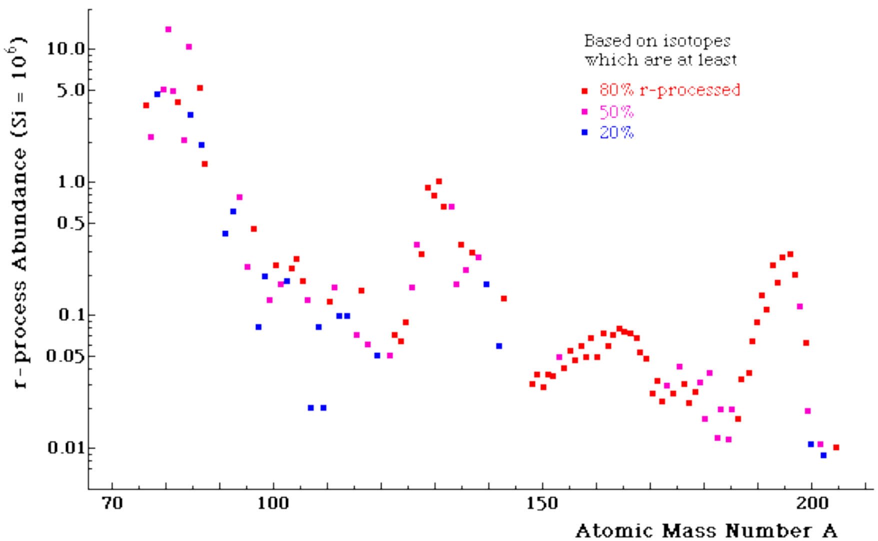
(2) The isotopes that are along the closed neutron shells will have reduced neutron capture cross sections as shown below.





Keppeler, et al. Rep. Prog. Phys. 52 (1989) 945

Rapid Neutron-Capture



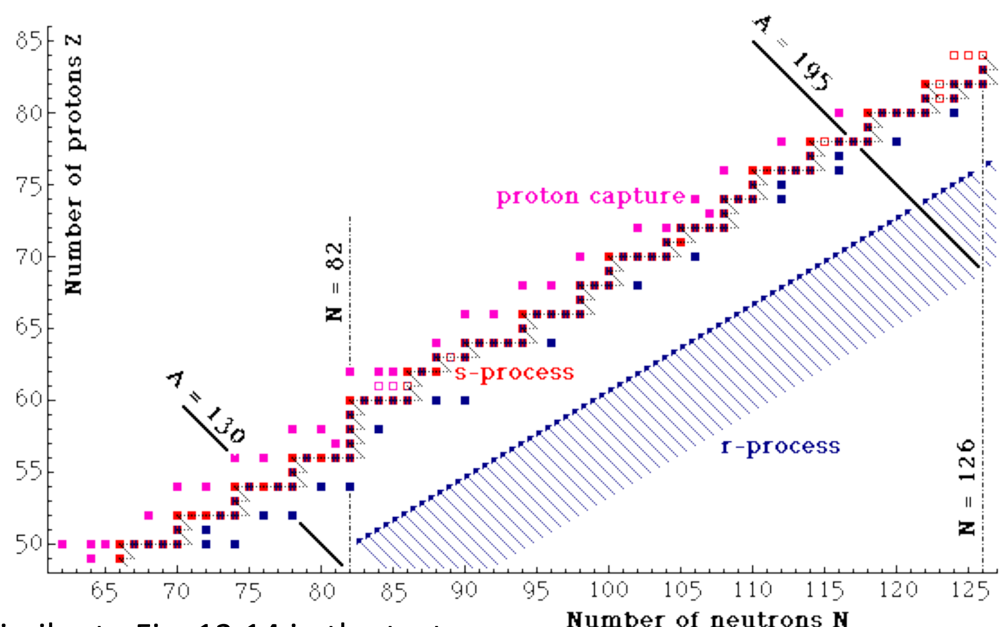
The calculated yields from the s-process can be removed with the neutron-deficient nuclei to leave the set of isotopes that are thought to have been produced in a rapid neutron capture process. For example, where did U and Th come from? The peak near A~195 (gold) and a peak near A~135 (tin) are more pronounced that in the raw data.

The site of this process is under debate but its general features can be established based on the nuclear reaction. [some kind of explosion]

The main features of the r-process are that the seed nuclei get exposed to a very high neutron flux for a short time. In this case only very fast beta-decays can compete with the high neutron capture rate.

Rate(β^- decay) ~ Rate(n-capture)

The nuclei are far from stability and their properties have not been measured and have only been calculated at present.



Similar to Fig. 12.14 in the text

r-process in the Cosmos

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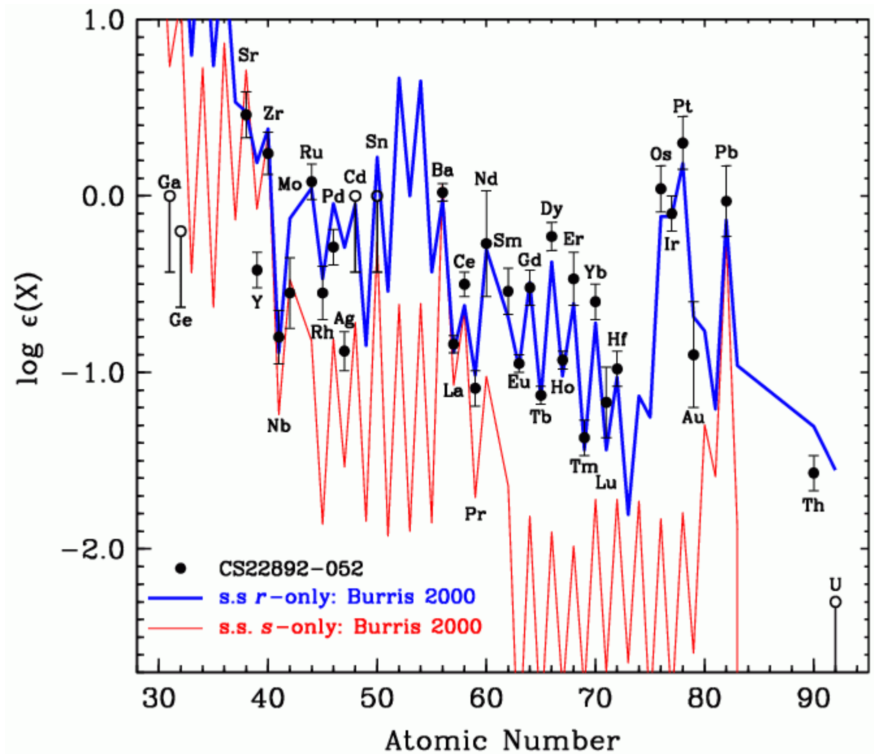
In current work astronomers are comparing the elemental abundances observed in distant stars with the s- and r- process calculations.

In general, it looks like the r-process is rather similar in other parts of the universe. And this star does not seem to have had the benefit of the s-process.

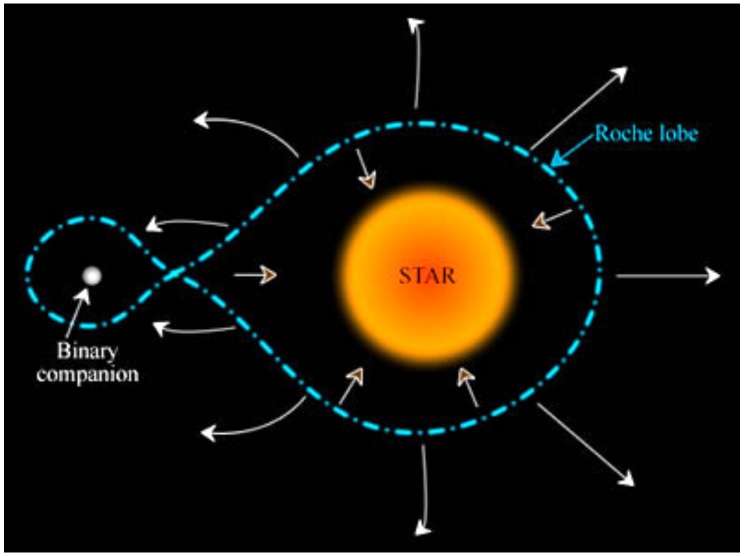


From Sneden et al. (2003, ApJ, 591, 936). The black symbols are the observed abundances in a particular star, the blue curve is the solar-system (meteoritic) r-process abundance distribution normalized to the observed europium (Eu) abundance, and the red curve is the solar-system s-process distribution roughly normalized to the observed Sr-Y-Zr element group. The abundance units are logarithmic number densities on a standard scale in which log ε(H) = 12

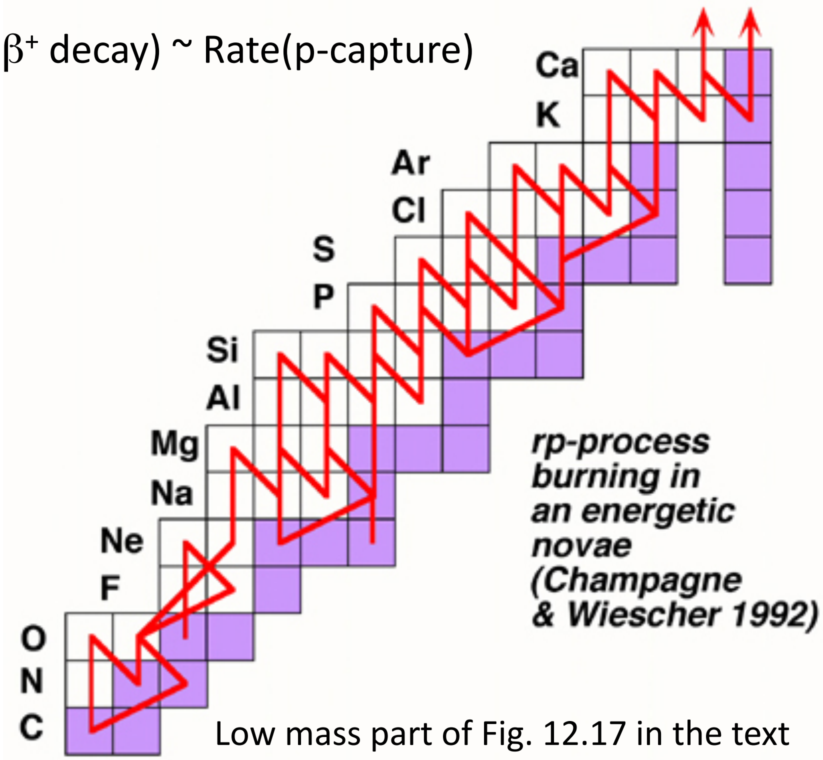
Rapid Proton Capture

The production of the stable isotopes that are "hanging out" by themselves on the neutron deficient side of the chart of nuclides are thought to be produced in a rapid proton capture process similar to rapid neutron capture. The nuclear reaction network is relatively well established because a lot is known about the intermediate nuclei and there are proposed astrophysical sites for the processing, the difficulty is that the material doesn't get dispersed.

The scenarios involve a binary star system with a compact, burned out star, and a main sequence star. If the burned out star is a white dwarf then the collection of material from the companion and burning in flashes are called novae or if it is a neutron star (much more massive) then the burning leads to x-ray bursts.



Rate(β^+ decay) ~ Rate(p-capture)



Low mass part of Fig. 12.17 in the text

Overall View of Production

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So the elements/isotopes that we have in our solar system are the result of a number of different processes. The lightest elements (mostly in the sun) are left over from the big bang and the rest of the elements had to be produced in five or six very different processes, including explosions of some sort to eject the material before it was recombined into our solar system. There was plenty of time for this to happen but it is a little surprising.

Big Bang
Proton Burning
Helium, etc. Burning
s-process
r-process
(p or rp-process)