r-Process

Nucleosynthesis of the heavy elements

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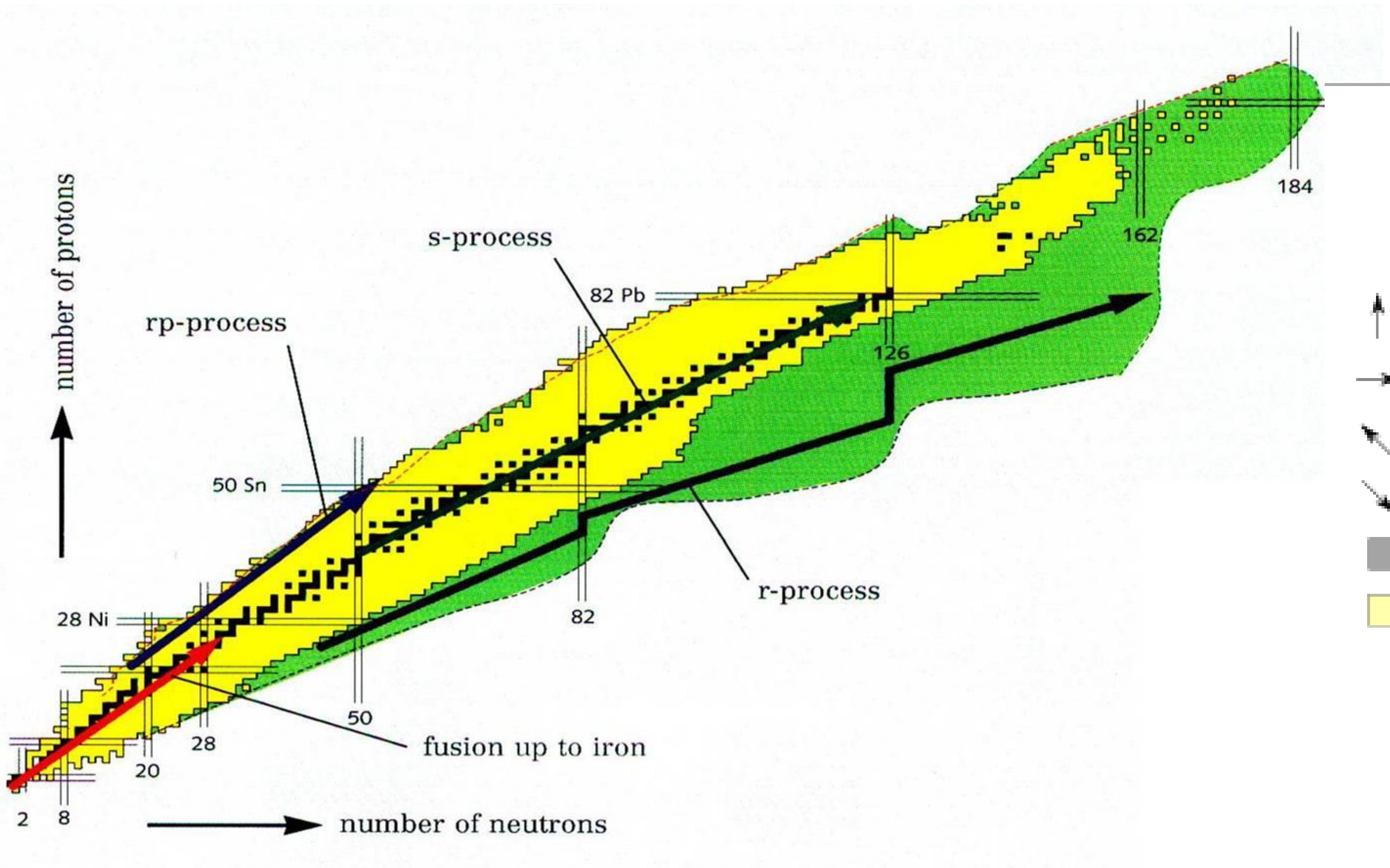
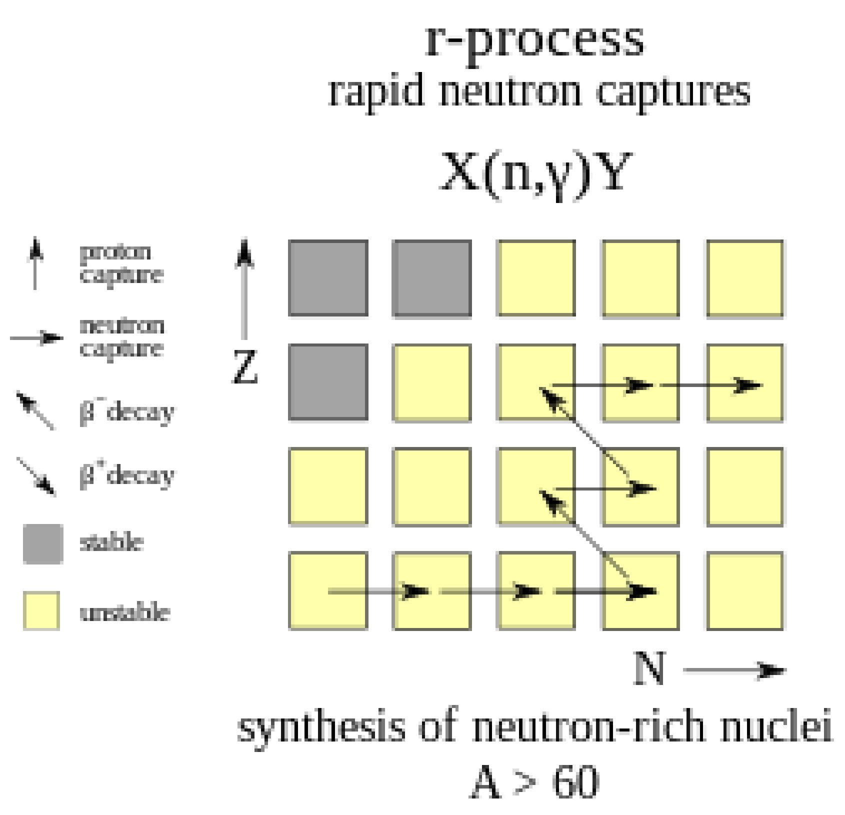
What is *r*-Process

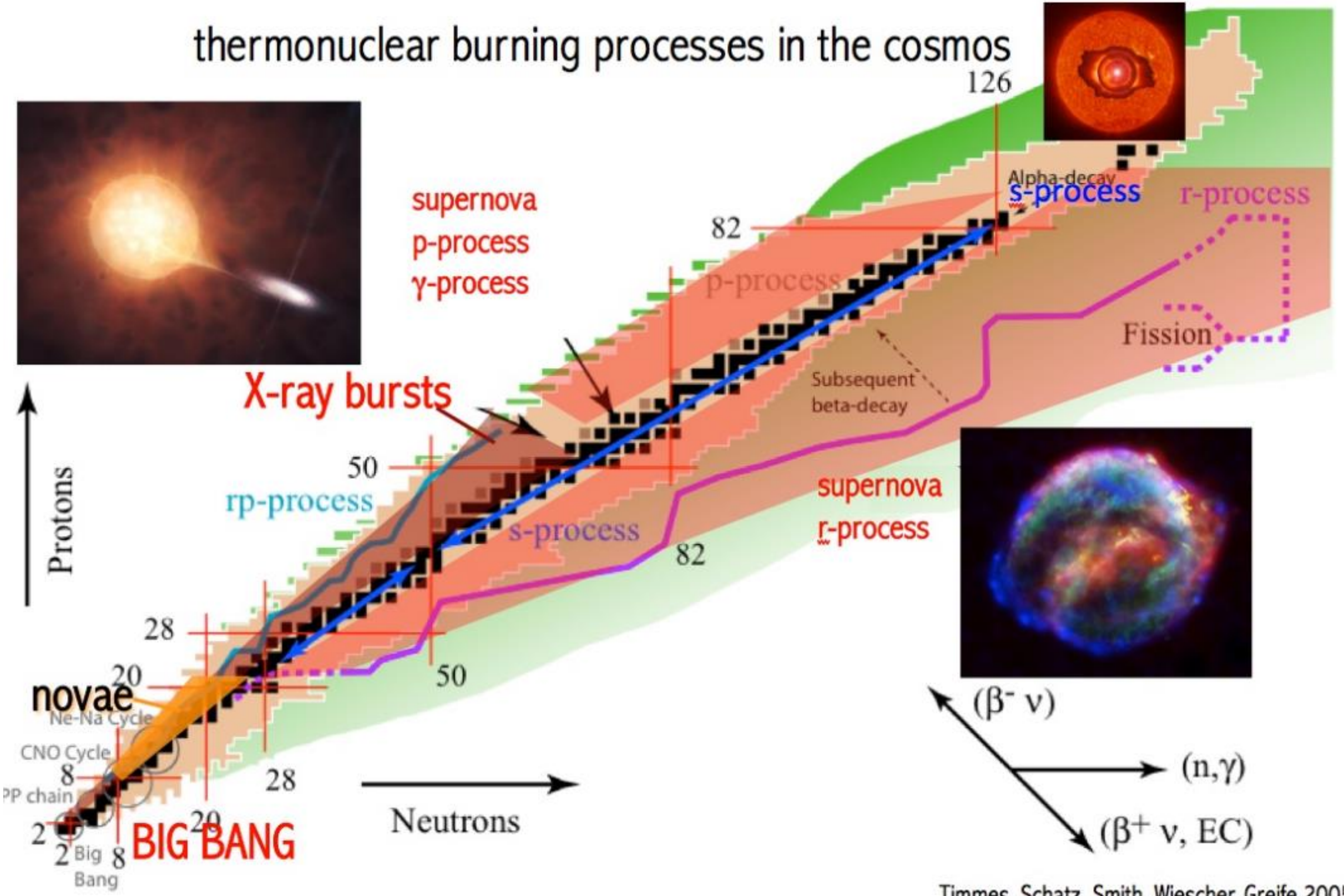
- Rapid neutron capture
- The dominant process through which elements heavier than iron are formed (also s-process or slow neutron capture)
- The exact site of r-process is still unconfirmed however due to the conditions necessary (high neutron density, high temperature) core collapse supernovae and neutron star mergers are the most likely candidates.

Chart of Nuclides



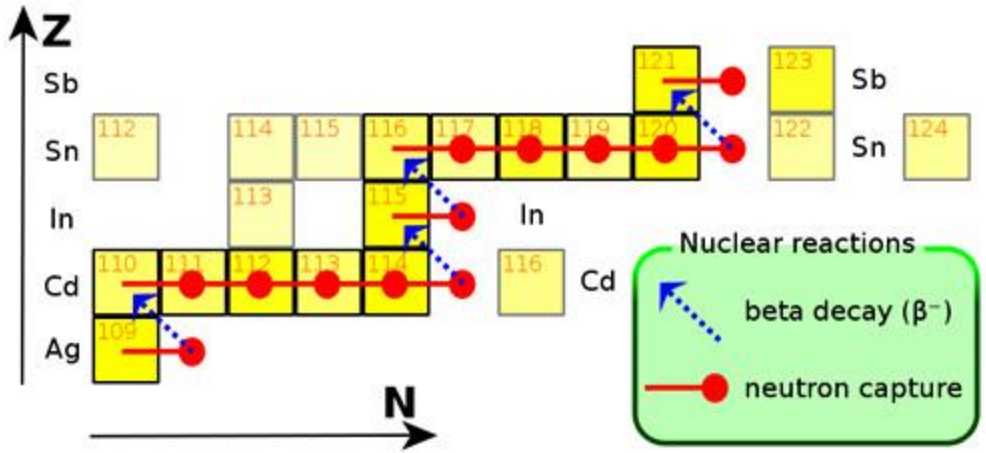


thermonuclear burning processes in the cosmos



Timmes, Schatz, Smith, Wiescher, Greife 2005

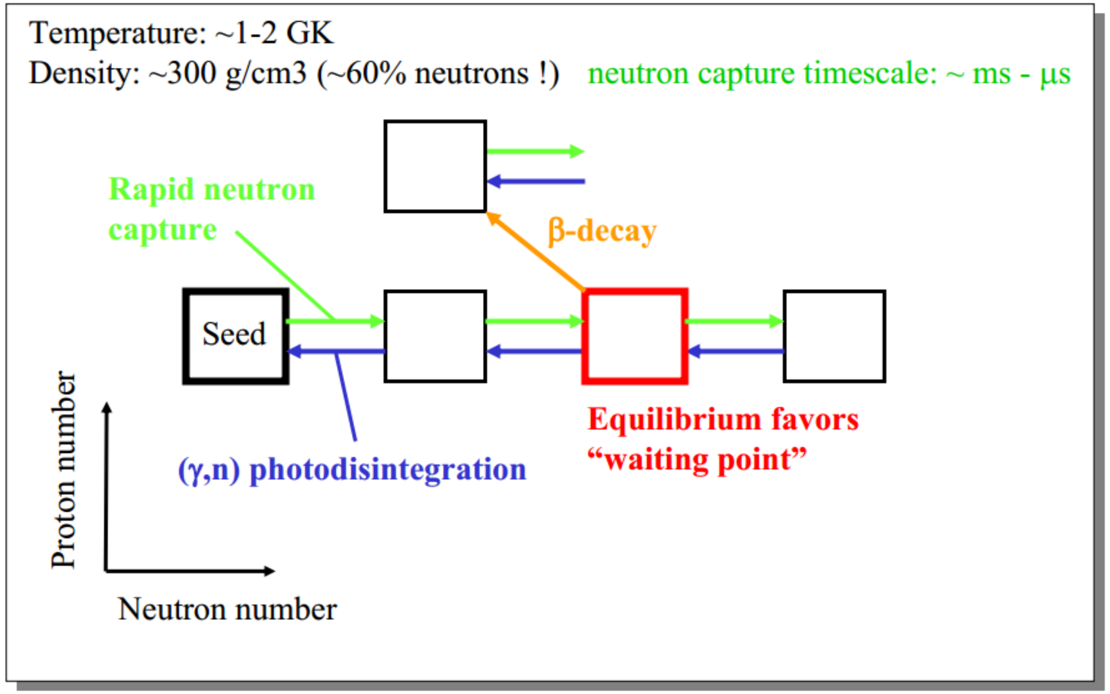
Mechanisms of r-process



- High T ($T > 10^9$ K)
- High neutron density ($n_n > 10^{22}$ cm^{-3})
- Nuclei are bombarded with neutrons.
- Neutrons **can** be absorbed until the neutron separation energy is less than or equal to zero. This is the Neutron drip line.
- Neutron rich isotopes are unstable to beta decay.
- After beta decay the new nucleus will have a new neutron drip line and in most cases be able to capture more neutrons.

(n,γ) and (γ,n) Equilibrium

- Photodisintegration can play an important role in the r-process path. In very these hot environments there will be high energy photons.
- The location of “waiting points” in r-process are points where an equilibrium between neutron capture rates and photodisintegration has been reached.



(n,γ) and (γ,n) Equilibrium

- Start with stable "seed" nucleus (A,Z)

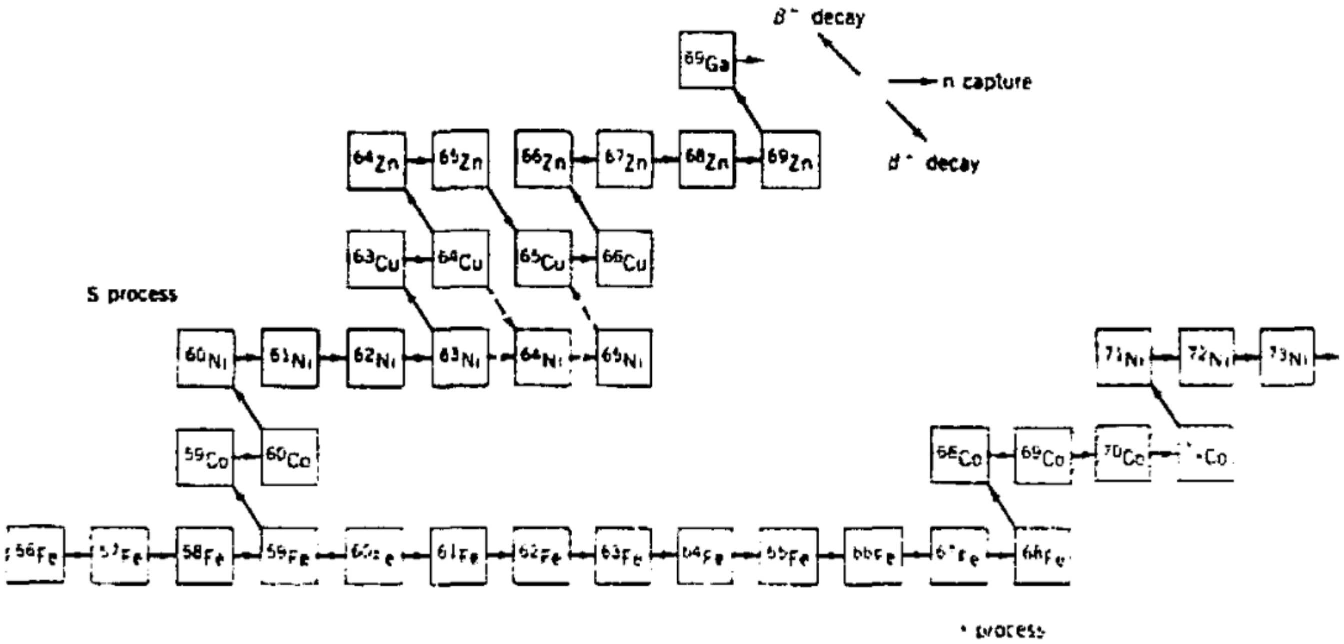
$$(A , Z) + n \rightarrow (A+1 , Z) + n \rightarrow (A+2 , Z) + n \ldots (A+i , Z)$$

- The more neutron rich the nuclei become
  - (n,γ) cross section goes down
  - (γ,n) cross section goes up
- When the rates for (n,γ) are equal to the rates for (γ,n) equilibrium is reached. This nucleus would be (A+i , Z) where i is the number of neutrons captured.
- At this equilibrium point the nuclei can beta decay

$$(A+i , Z) \rightarrow (A+i , Z+1)$$

r-process vs. s-process

- If the neutron capture rates are low enough then nuclei have time to beta decay before being hit by another neutron (s-process)
- If the neutron capture rates are high then once an equilibrium between neutron capture and photodisintegration has been reached beta decay will occur.

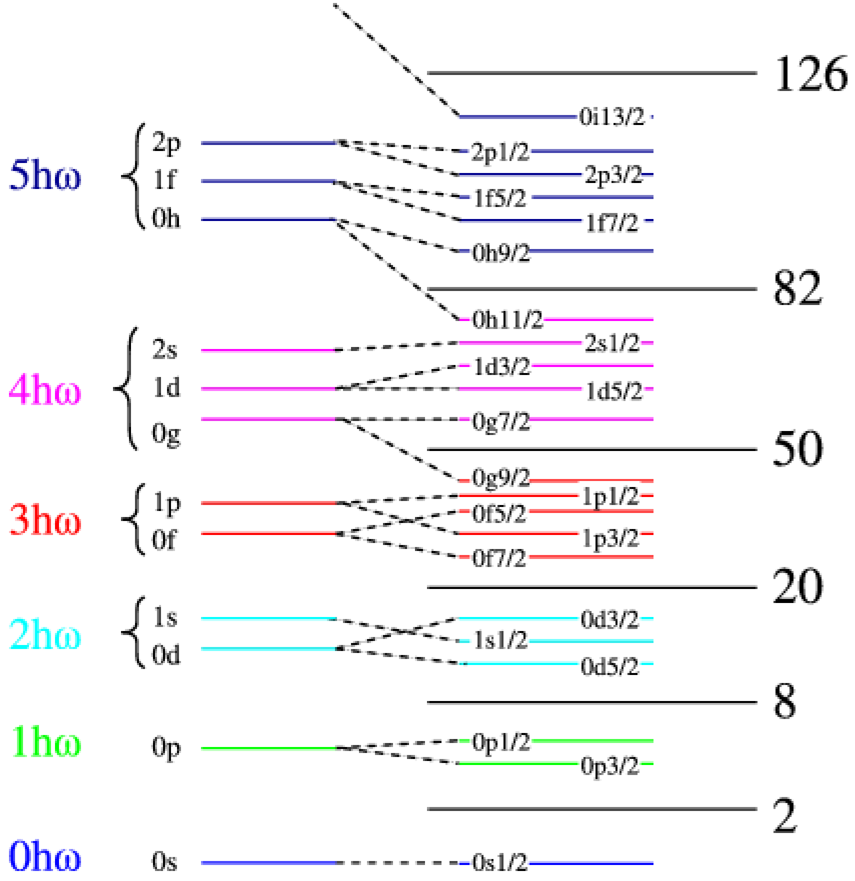


Kenneth Krane, *Introductory Nuclear Physics*, (1987)

Shell closures

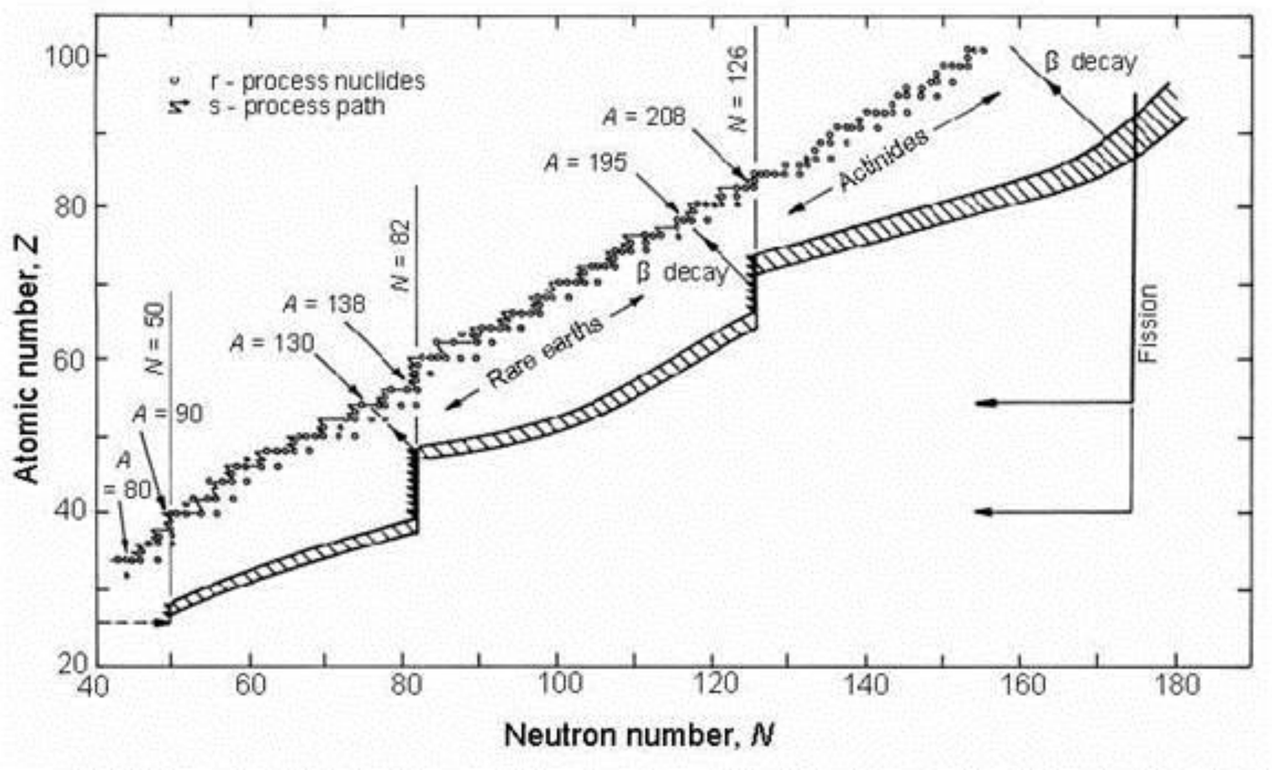
- Analogous to electron shell closures in atoms. There are certain numbers of nucleons that form particularly stable nuclei. These are known as magic numbers and magic nuclei.

- At neutron shell closures the rates for (n,γ) decrease and nuclei are able to live long enough to beta decay.
- Just past the shell closure (γ,n) rates are very large.
- After beta decay the nucleus will capture another neutron and once again be at a neutron shell closure.

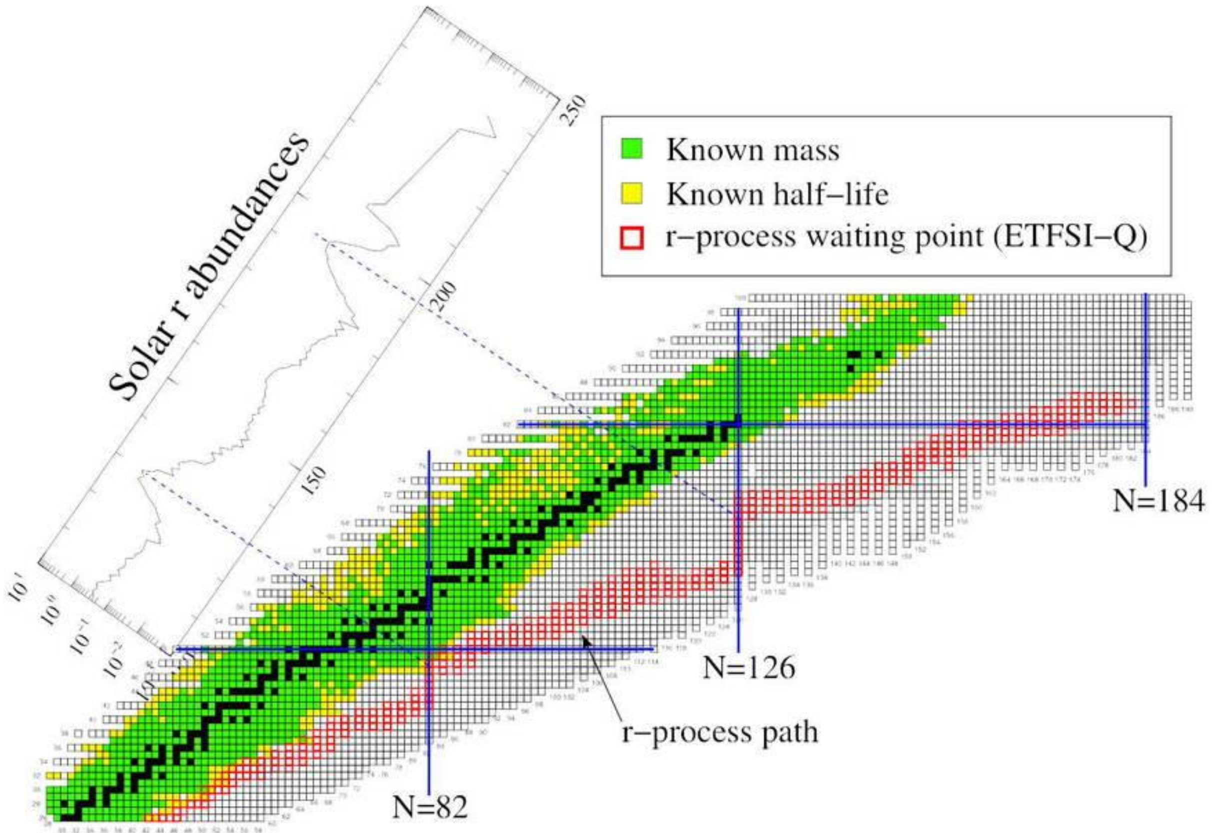


Shell closures and Abundance

- As a result of the r process path waiting at shell closures the abundance of nuclei in the corresponding mass range is increased.



Clayton, *Principles of Stellar Evolution and Nucleosynthesis*, (1983)



r-process vs. s-process abundances

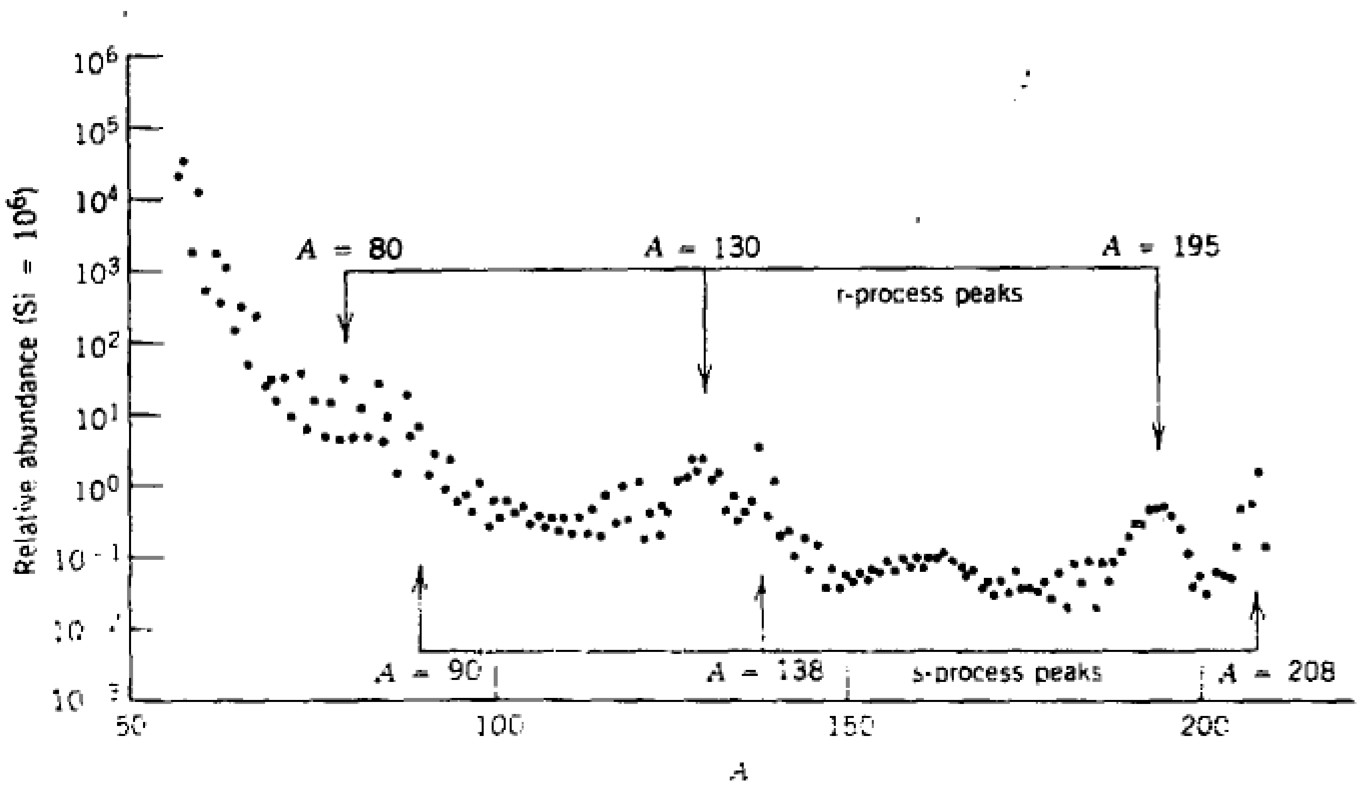
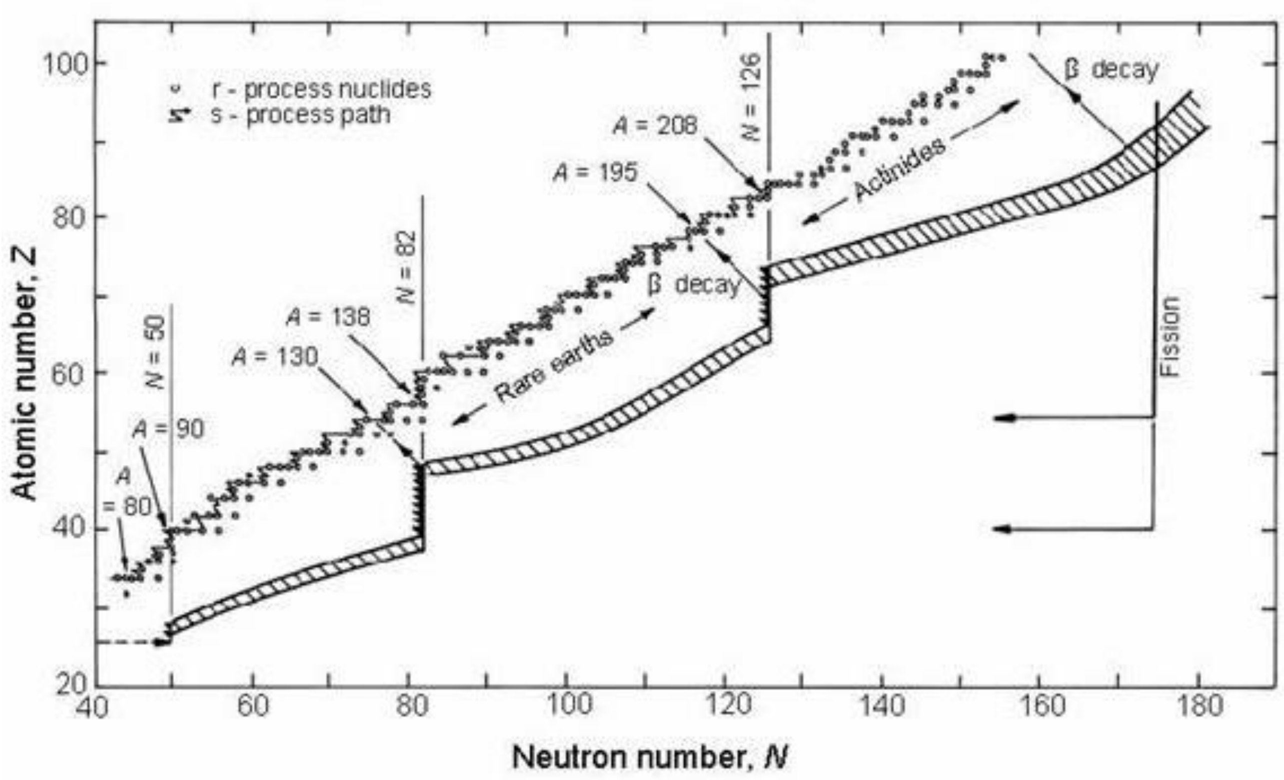


Figure 19.18 Abundances of isobars. The peaks near $A = 80$, 130, and 195 originate from the β decays of r-process progenitors with $N = 50$, 82, or 126. The peaks near $A = 90$, 138, and 208 result from s-process stable nuclei with $N = 50$, 82, or 126. Note the difference in abundance between odd-A and even-A nuclei.

Kenneth Krane, *Introductory Nuclear Physics*, (1987)

The end of r-process: Fission

- Eventually it is impossible to make a bigger nucleus. Trying to pack too many protons in a nucleus results in instability to spontaneous fission as well as neutron induced fission.
- Nuclei in the N = 175 region typically fission and terminate the r-process.
- The fission fragments from the heavy nucleus will re-seed the r-process



Modeling r-process

- To understand the abundance of elements in the universe it is important that we understand r-process
- Important parameters: neutron density, temperature, neutron capture cross sections, neutron magic numbers, beta decay half lives, and initial composition
- Models of r process are used to try and reproduce the abundance of elements observed in the universe
- Models are very sensitive to neutron capture cross sections and beta decay properties, both of which can be measured in the laboratory by nuclear physicists
- Current models do not reproduce the observed abundance of elements in the universe

Challenges of study (n,γ) in the Lab

- We want to use accelerators to create nuclear reactions relevant to r-process.
- The nuclei involved in r-process are very short-lived and therefore will decay on you during measurement.
- We can however create radioactive ion beams of these short lived nuclei.
- We cannot make a neutron target. (free neutrons are unstable)
- Next best thing is a deuteron. (1 proton, 1 neutron)
- To study (n,γ) on short-lived nuclei, we create beams of the nuclei and accelerate them at deuterium targets and look for the reaction (d,p). This is the surrogate reaction technique.
- The detection of an outgoing tells you the a neutron transfer reaction has taken place.