R-Process Nucleosynthesis And Its Site

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Outline

- Introduction.
- Nuclear physics and the r-process.
- Possible sites for r-process nucleosynthesis.
- Abundances in halo stars.
- Chemical evolution.
- Summary

Introduction

- Most of the H and He in the Universe was created shortly after the Big Bang (along with some lithium). Other elements like beryllium-9 and boron-11 are synthesized due to the interaction cosmic rays with the gas in the ISM.

- Most of the other elements in nature are formed through nuclear fusion inside stars.

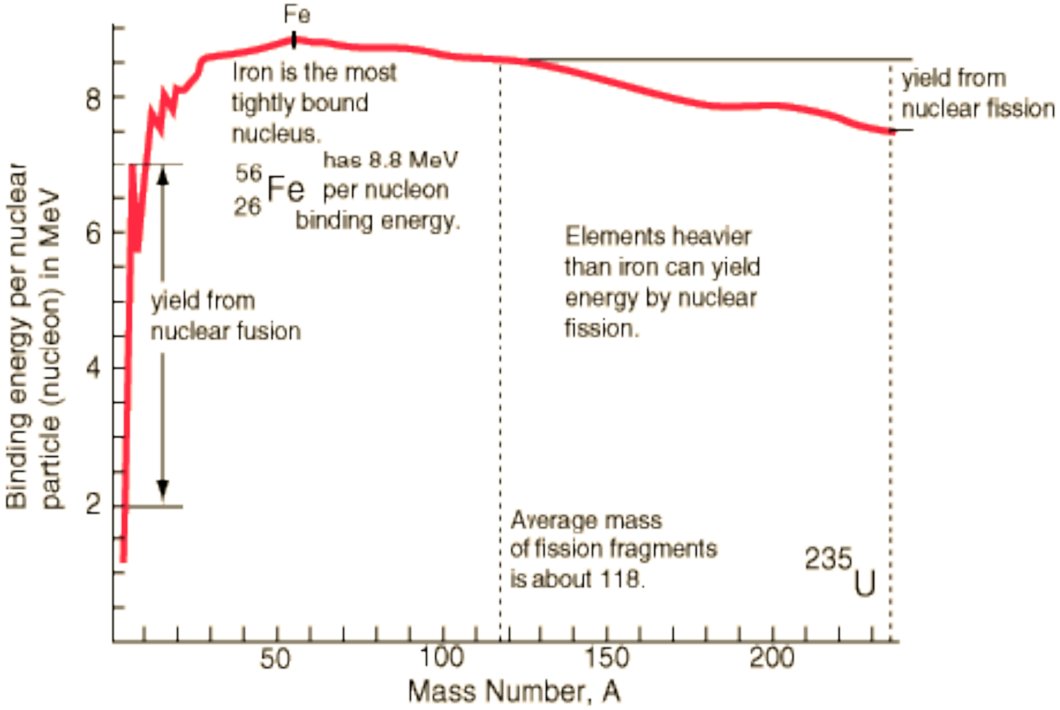
- Stars eject their material back into the space. Thus there is an intricate relationship between the life cycle of stars and the nucleosynthesis of elements.

Introduction

- Binding energy per nucleus increases only until iron-56. The product of heavier elements is endothermic.

- Also, as the proton number (Z) increases, the Coulomb barrier becomes an impediment for direct fusion.

- Heavier elements are synthesized through n-capture processes.



Introduction

- The two main n-capture processes were first identified by Burbidge et al. 1957.
- They are the slow (s) and rapid (r) processes:

  the s- and r-processes.
- In the s-process the neutron capture happens in a time scale (τ_{n}) much longer than the mean time for β-decay (τ_β), i.e., $\tau_{\mathrm{n}} >> \tau_\beta$.
- In the case of the r-process: $\tau_{\mathrm{n}} << \tau_\beta$.
- While τ_β depends only on the nuclear species, τ_{n} depends strongly on the environment, specifically on a strong neutron flux.

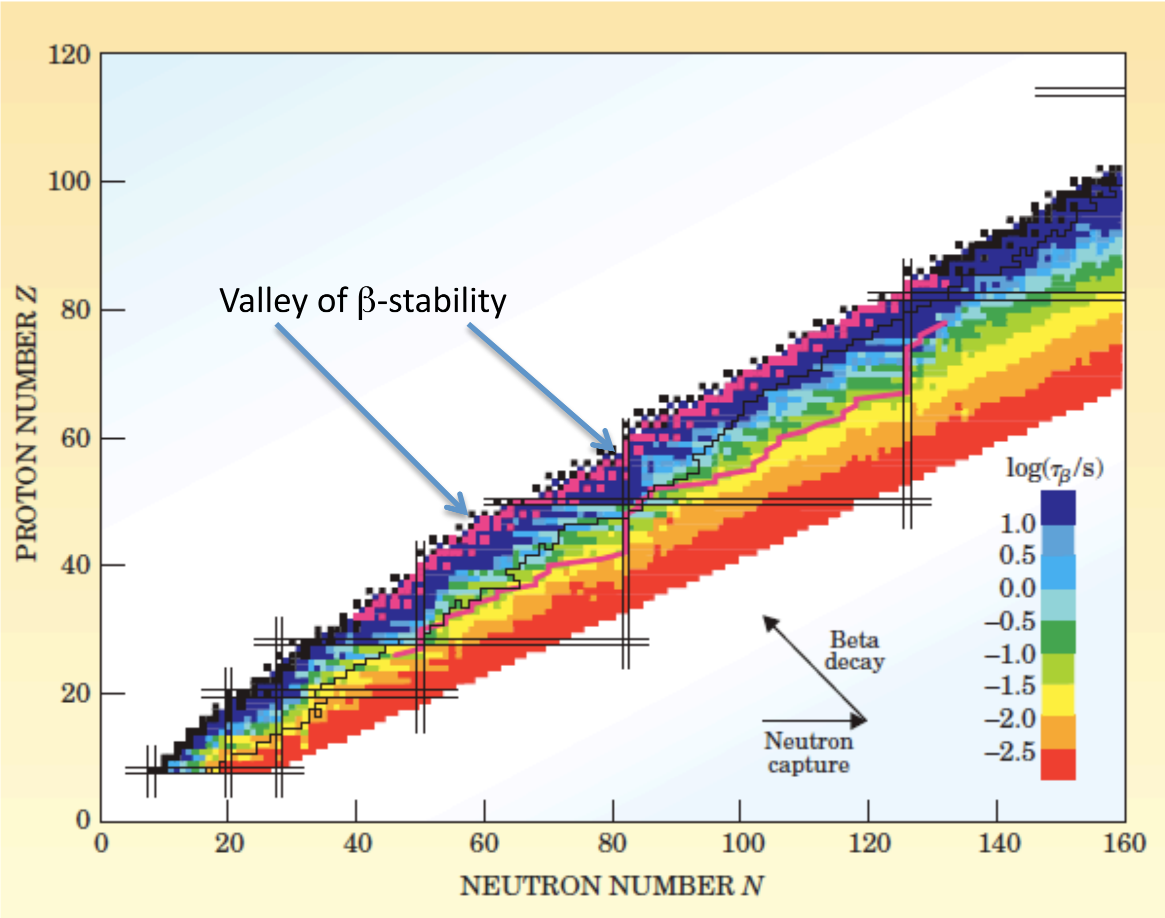
Introduction

- The figure shows the mean τ_β for different elements in terms of their proton- and neutron-numbers (Cowan et al. 2004).

- In the NZ plane, the elements are divide into β-decay stable and unstable.

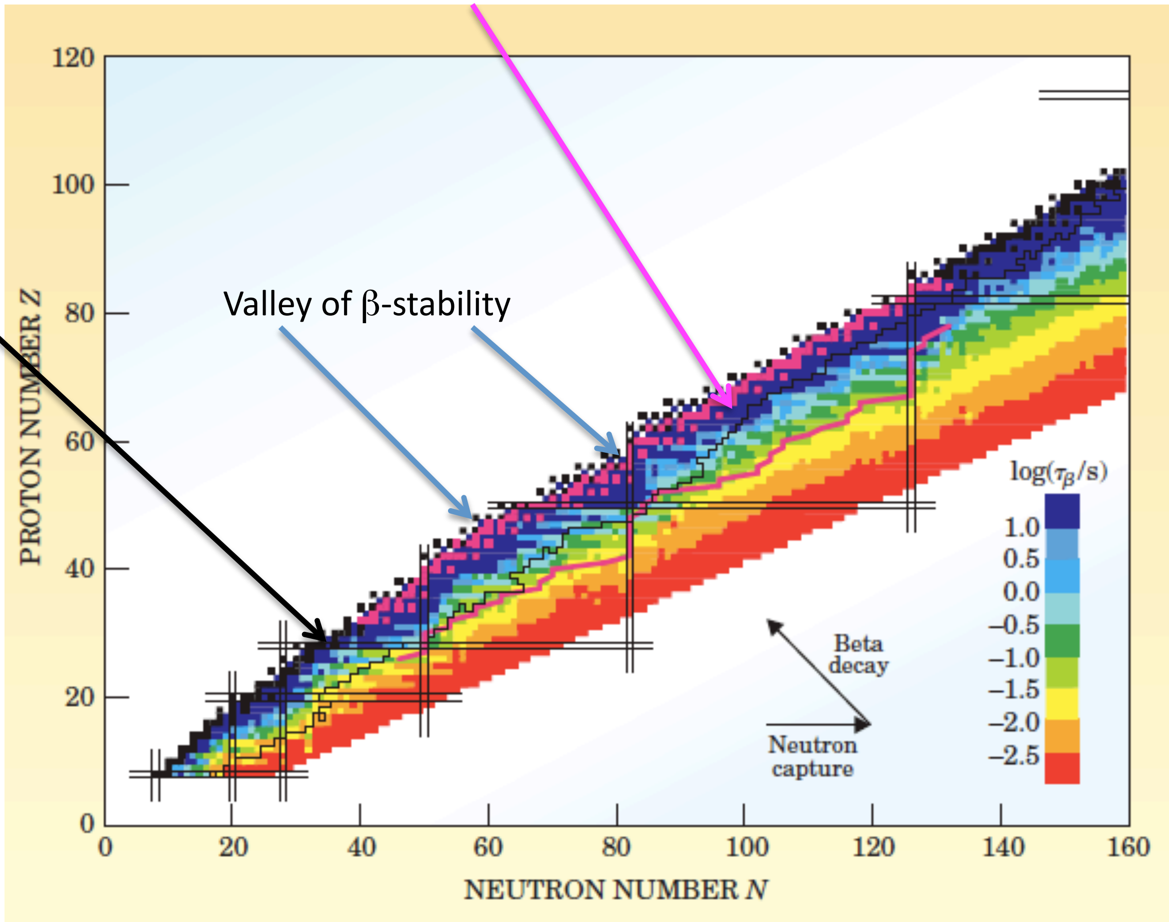
- The stable elements form the so-call “valley of β-stability”, which is marked by black and magenta points.

- The s-process path is close to the stability valley, while the r-process happens far from it.



Introduction

- The strong flux of neutron is a transient phenomena. After it stops, the nuclei will β decay until they reach the valley of stability. The magenta points show stable nuclei produced by the **r-process**.
- The black points mark the elements made by mainly the **s-processes**.
- The solar system elements are an admixture of s- and r-process elements (~50/50).
- Jeweler's elements like gold and platinum are made almost exclusively by the r-process.



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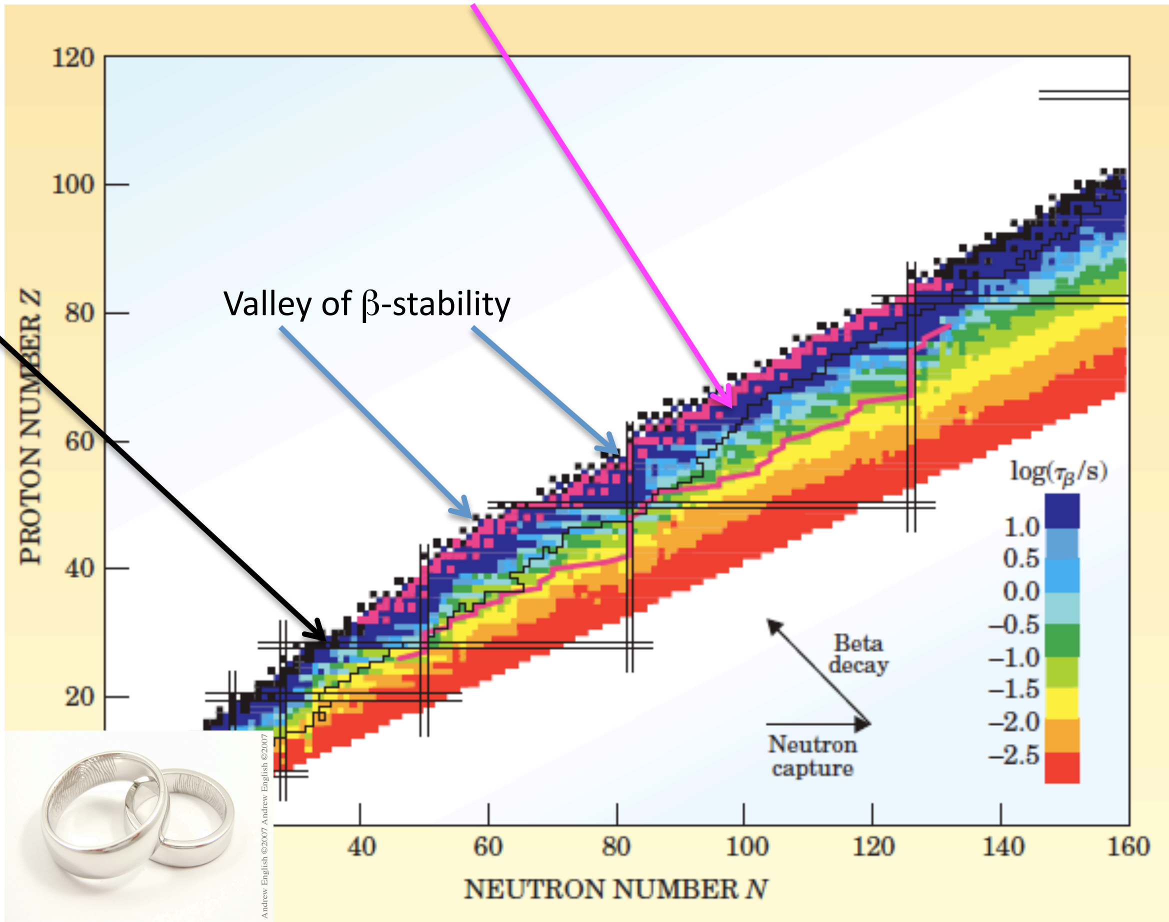


Introduction

- The s-process is relatively well understood.
- The nuclear properties of the involved species that are easier to measure in the lab than the ones of the r-process (longer τ_β).
- The site is also much better constrained: primarily low- and intermediate-mass stars (less than 8 solar masses).
- The r-process element formation is much more uncertain.
- The nuclear properties of the participating elements is much more difficult to measure.
- And the sites where the r-process take place are a mistery.
- R-process element formation requires large neutron fluxes that are associated to rather catastrophic events. The two main candidates are **type II (core-collapse) supernova explosions** and **neutron star mergers**. At present the astrophysical conditions of these two phenomena are not well understood (good review: Sneden et al. 2003).

Nuclear physics and the r-process

- Since in the r-process $\tau_n << \tau_\beta$, an element with a given proton-number (Z) should be able to capture many neutrons before a β-decay.
- In the environments of high fluxes there is typically large temperatures and therefore large quantities of gamma photons producing nuclear disintegration.

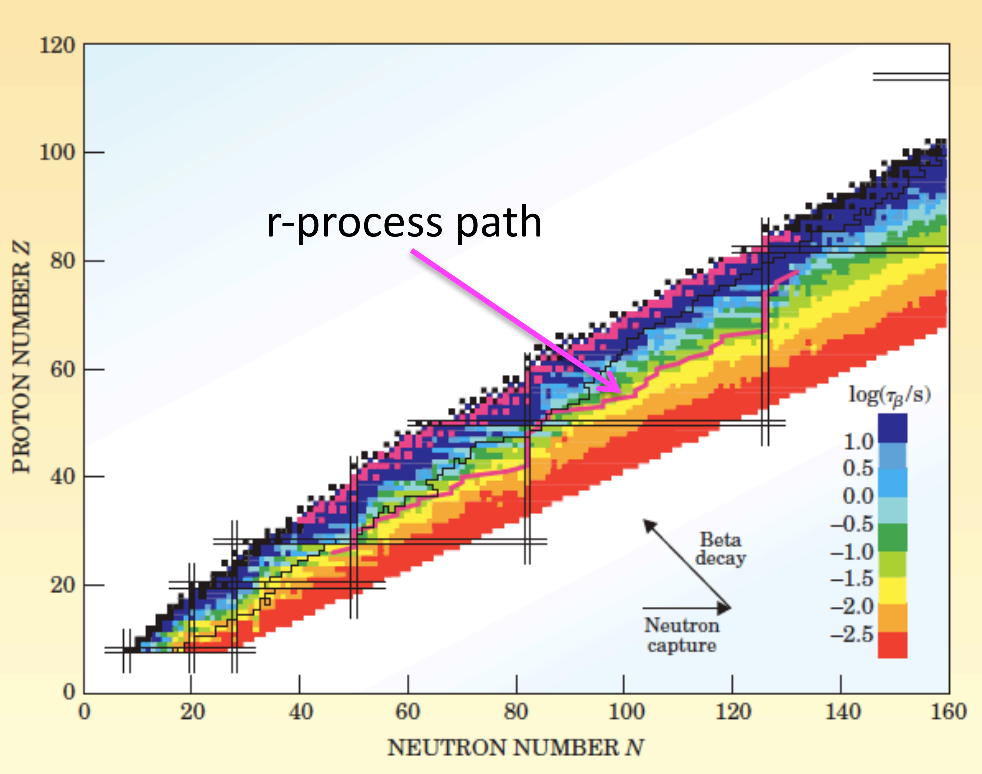
$$n + (Z, A) \leftrightarrow (Z, A + 1) + \gamma$$

- So the equilibrium abundances for a given isotopic chain will be determined by the neutron density and the temperature.

- This equilibrium implies that the maximum abundance of participating elements will be characterized by similar neutron energy separations (S_n), which is the energy released by the capture of a neutron.

Nuclear physics and the r-process

- To first order, the neutron energy separation, S_n, determines the maximum neutron abundance of each isotope, and defines a “path” in the NZ plane.
- In the figure, the magenta line shows an example of a r-process path (S_n = 2-3 MeV).
- When the flux of neutrons stops, the nuclei migrate towards the valley of β-stability, forming the r-process stable nuclei shown in magenta color.
- But knowing the path is not enough to make prediction about abundances of r-process elements.

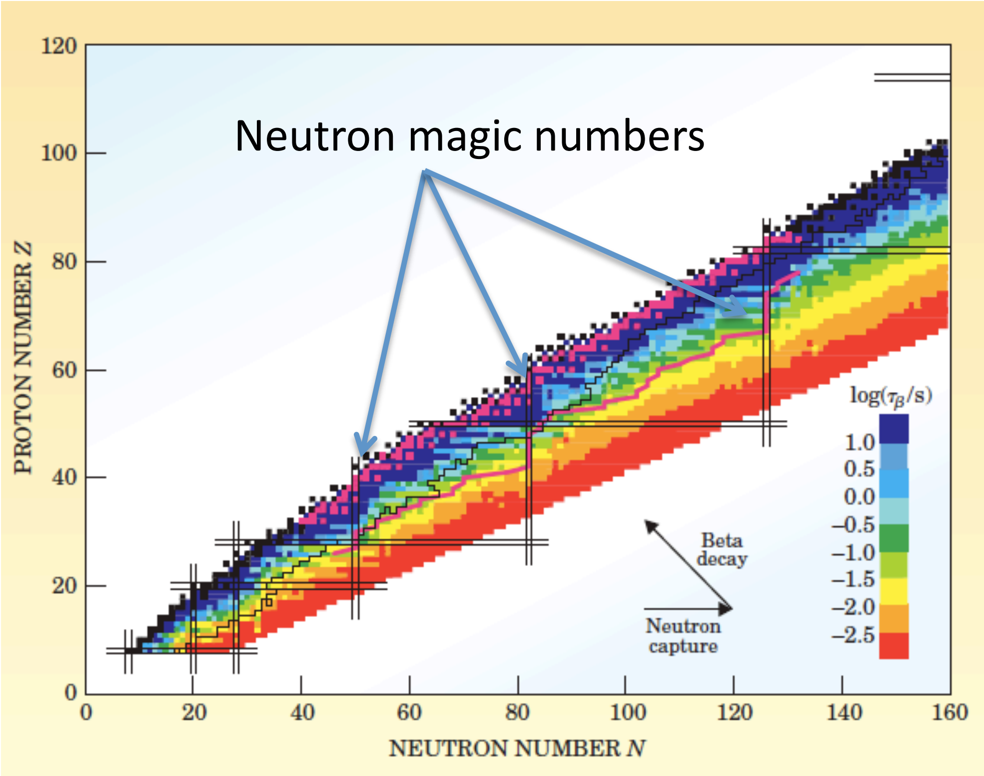


Nuclear physics and the r-process

- Indeed, the abundances will depend on the time that particles spend in each part of the path. This depends on τ_β.

- In fact, when the number of neutrons correspond to the so-called “magic numbers” (closed neutron shells) (2,8,20,28,50,…)the elements tend to be significantly more stable.

  The β-decay life can be one or two orders of magnitude larger. The n-capture cross-section is also smaller.
  So the nuclei tend to concentrate more around these regions, and produce peaks of abundance.

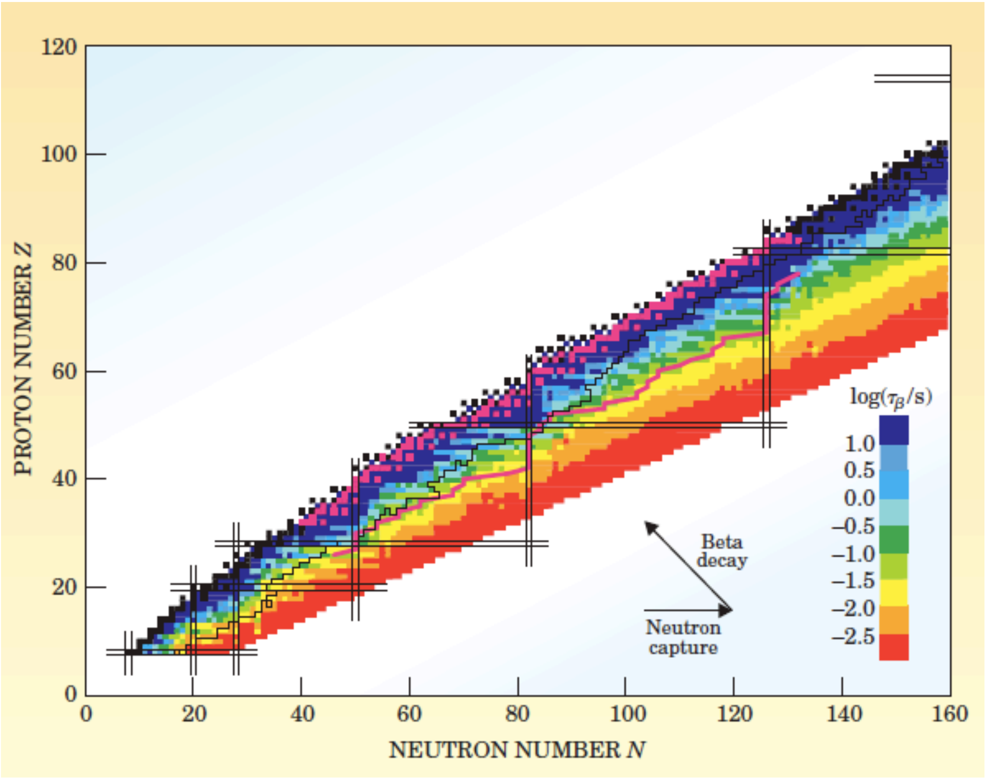

Neutron magic numbers

Nuclear physics and the r-process

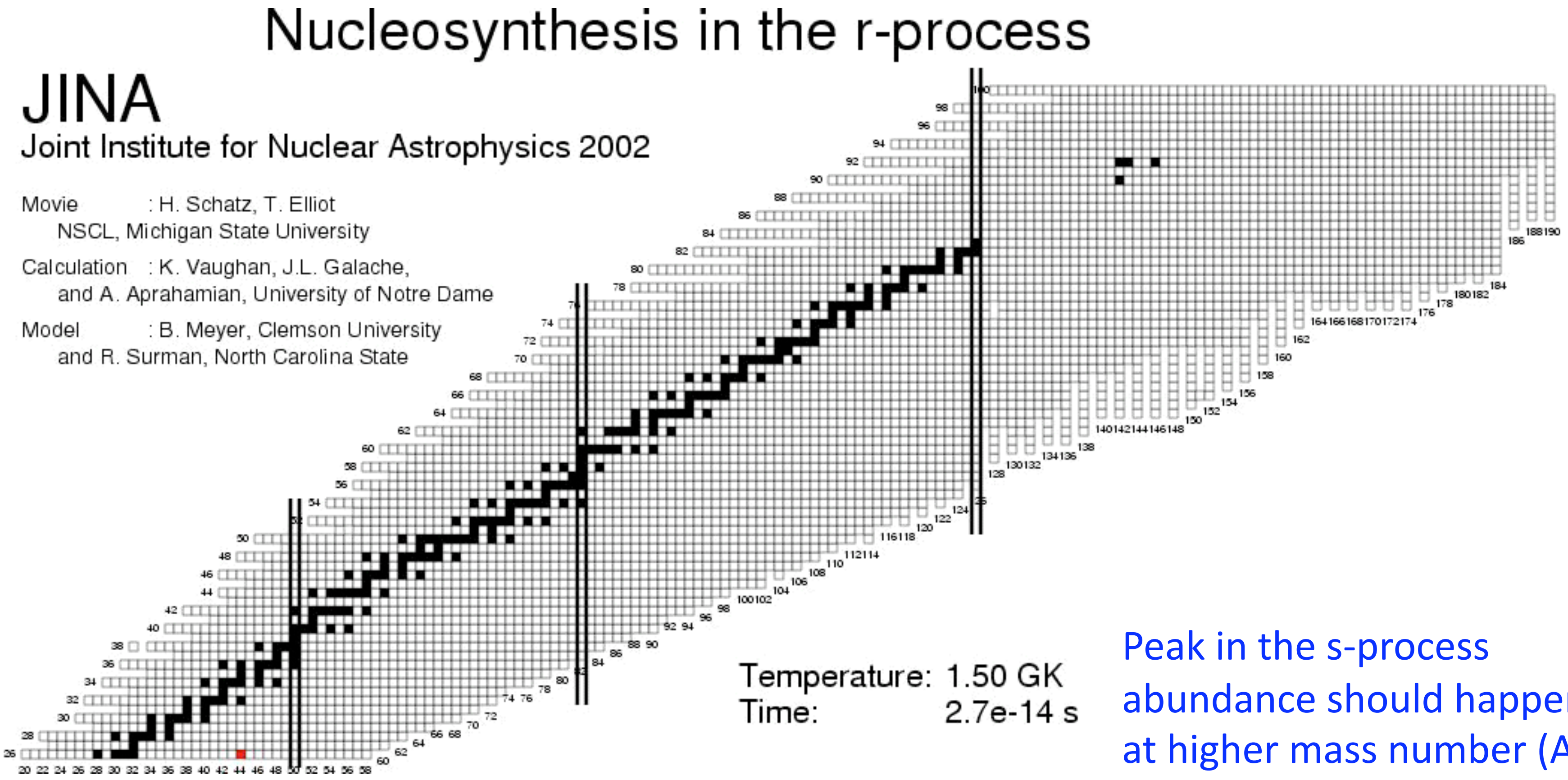
- This underscores the importance of knowing nuclear properties of the elements like S_n, τ_β, etc to be able to compare models with abundance observations.

- Fission also plays an essential role in the synthesis of r-process elements since, it determines the heaviest nuclei produced in an r-process (Cowan et al. 1991).

- Fission also contributes to the distribution of lighter elements.



Nuclear physics and the r-process



Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

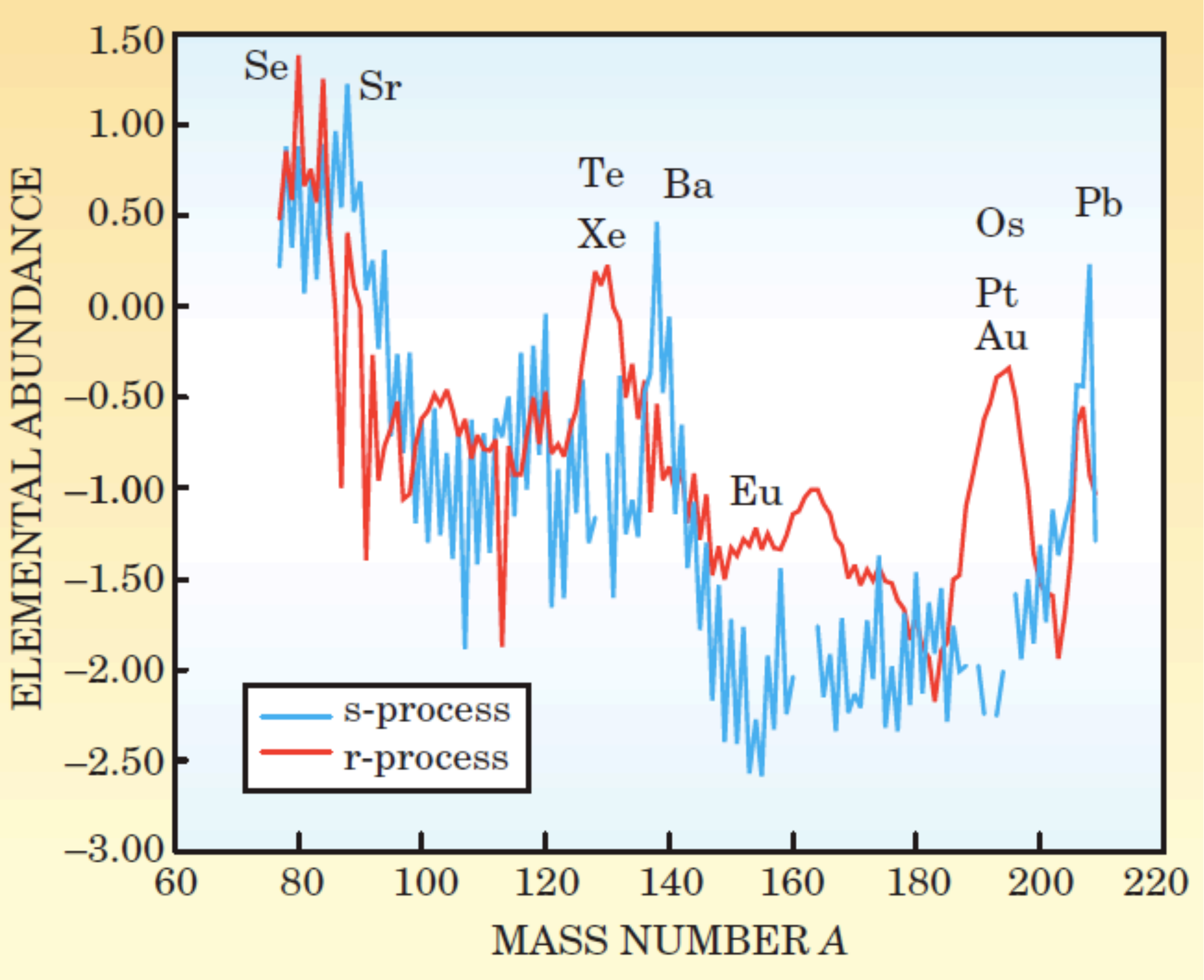
Temperature: 1.50 GK
Time: 2.7e-14 s

Peak in the s-process abundance should happen at higher mass number (A)

Nuclear physics and the r-process

- Peaks in s-process abundances are indeed shifted towards larger mass number (A).

  Example corresponds to solar system abundances.



Possible sites

- A critical parameter is the number of neutron per seed nucleus. In order to get to nuclei with A~200, it is necessary to have ~150 neutrons per seed nucleus (Fe being generally the lightest one).
- But where in nature does one find the appropriate conditions?
- Type II SNe.

  As the core collapses it would eject a rich flux of neutrons that would account for the formation of r-process elements.

  Many uncertainties remain: the explosion mechanism, the role of neutrino interaction, role of multidimensional hydrodynamic instabilities, the equation of state of ultradense matter, etc.

Possible sites

- Neutron star mergers.

  The enormous density of neutrons (~10^{33} cm^{-3}) available in the merger of neutron stars would build up heavy elements and lead to fission in very short time scales.

  It could produce "fission recycling" via subsequent n-capture (see calculation of Freiburghaus et al. 1999). It would be consistent with r-process elements in the solar system for A>130.

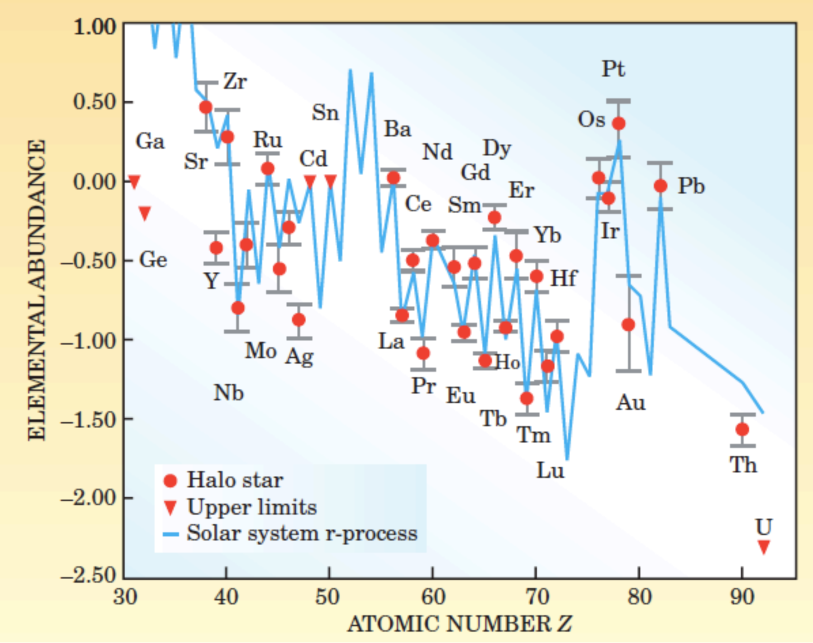
Abundances in halo stars.

- Much of the new knowledge about the formation of the heaviest elements has been gained through high resolution spectroscopy of stars in the Galaxy, specifically the so-called halo stars.
- The surface abundance of stars reflect the composition of the formation material.
- Halo stars are amongst the very oldest stars in the Galaxy, therefore they provide invaluable information about the chemical composition of the ISM at early times.
- A very well studied halo star is CS 22892-052, whose Fe abundance is about one thousandth of solar (very old; Sneden et at. 2003b).

Abundances in halo stars.

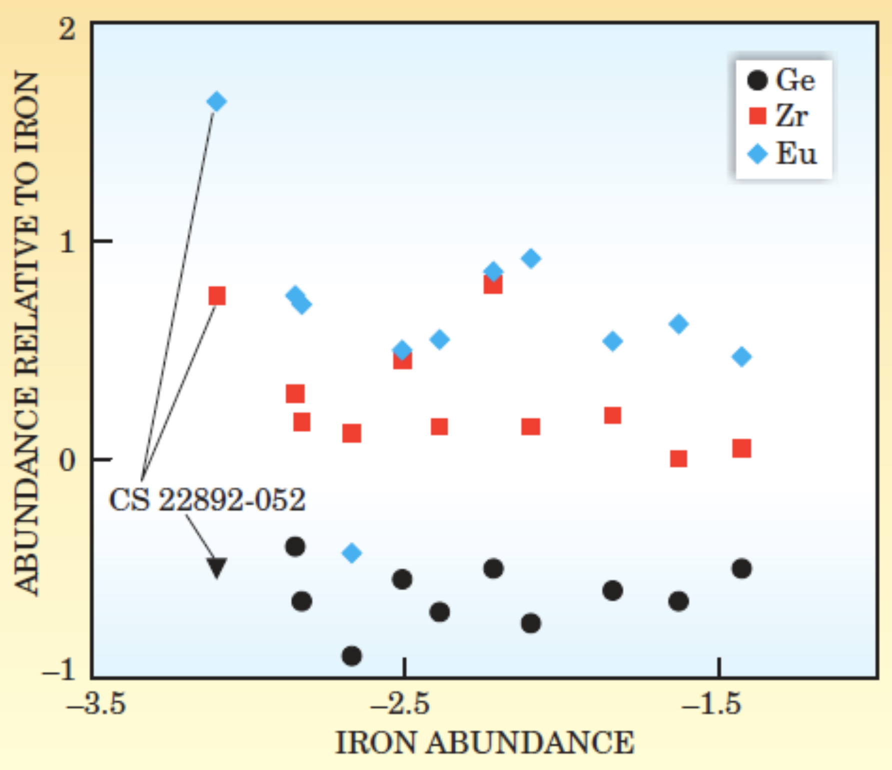
- An striking feature is the agreement between CS 22892-052 abundance and the r-process abundance of the solar system for Z > 56 (Ba).

- This is telling us mainly two things:
- First, the r-process seems to be a very robust process. Wherever and however is happening it is under well constrained astrophysical conditions.
- It happens very fast (few million years), before the formation of s-process elements.
- The disagreement for Z=40-50 is puzzling and might be suggesting different kind of r-process for light and heavy elements (Wassenburg et al. 2000).



Chemical evolution

- The possibility that light and heavy r-process elements are produced by different in different environments is supported by the chemical evolution of different halo stars.
- Figure shows the abundance as a function of “time” (Fe abundance) of different r-process elements. Ge (Z=36; light) shows a different evolution and much less scattering at early times compared to Eu (Z=63; heavy).
- The large scattering of Eu at early times suggests suggests that at first the r-process elements were spread inhomogeneously. This effect is less important if the element, like Ge, is produced in a larger range of sites/conditions.



Chemical evolution

- The short time in which the r-process elements should have been spread (few million years) points to type II SNe as the favored candidates (neutron star mergers would evolve too slowly).

- In the context of formation in core-collapse SNe, observations point to more than one site/condition for the formation of r-process.

Summary

- Elements heavier than Fe require endothermic nuclear reactions.
- They are formed by neutron-capture, in s- and r-processes (~50/50 in the solar system).
- The astrophysical site for the r-process is an open question.
- Possibilities: Type II core-collapse SNe and neutron star mergers.
- Observation of abundances in halos stars show an striking agreement with solar system r-process elements for Z>56.
- Chemical evolution shows that heavier elements were formed more slowly.
- This is telling us: R-process is very robust.
  Its site evolves quite rapidly (few million years).
  There could be different sites/conditions for heavy and light r-process elements.
- This favors the type II core-collapse SNe instead of neutron star mergers as the site. But the question of the where in the supernova or the effect of the progenitor mass in the kind of r-process element is still open.