

R-Process Nucleosynthesis And Its Site

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Theoretical Seminar - Fall 2009

Outline

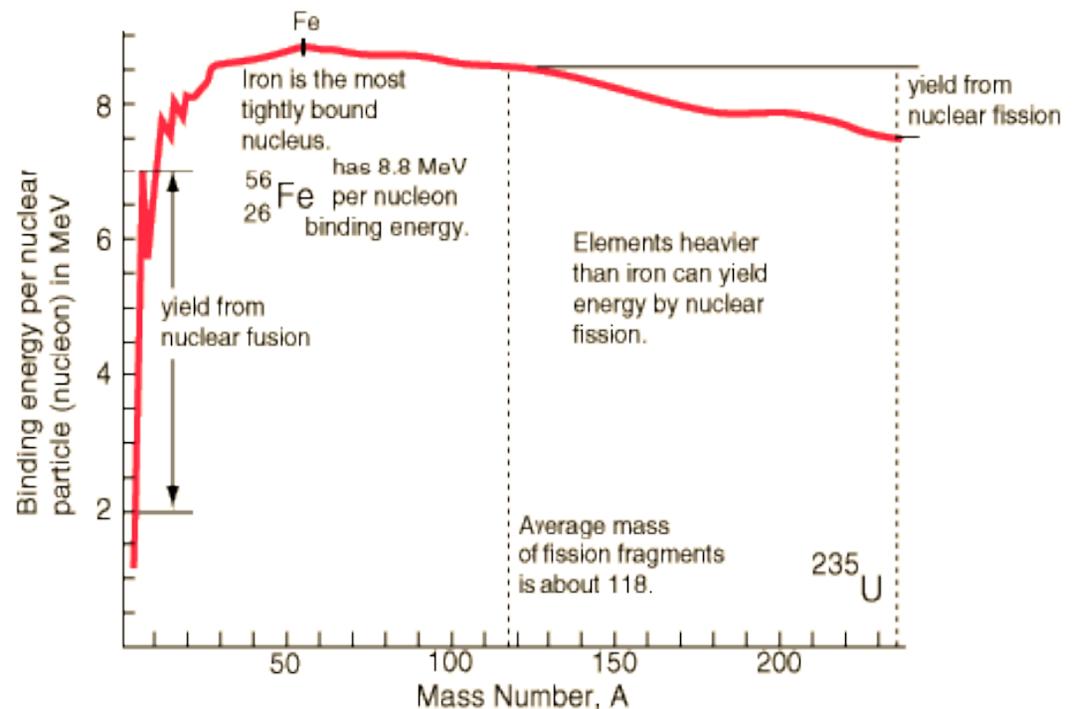
- Introduction.
- Nuclear physics and the r-process.
- Possible sites for r-process nucleosynthesis.
- Abundances in halo stars.
- Chemical evolution.
- Summary

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**.

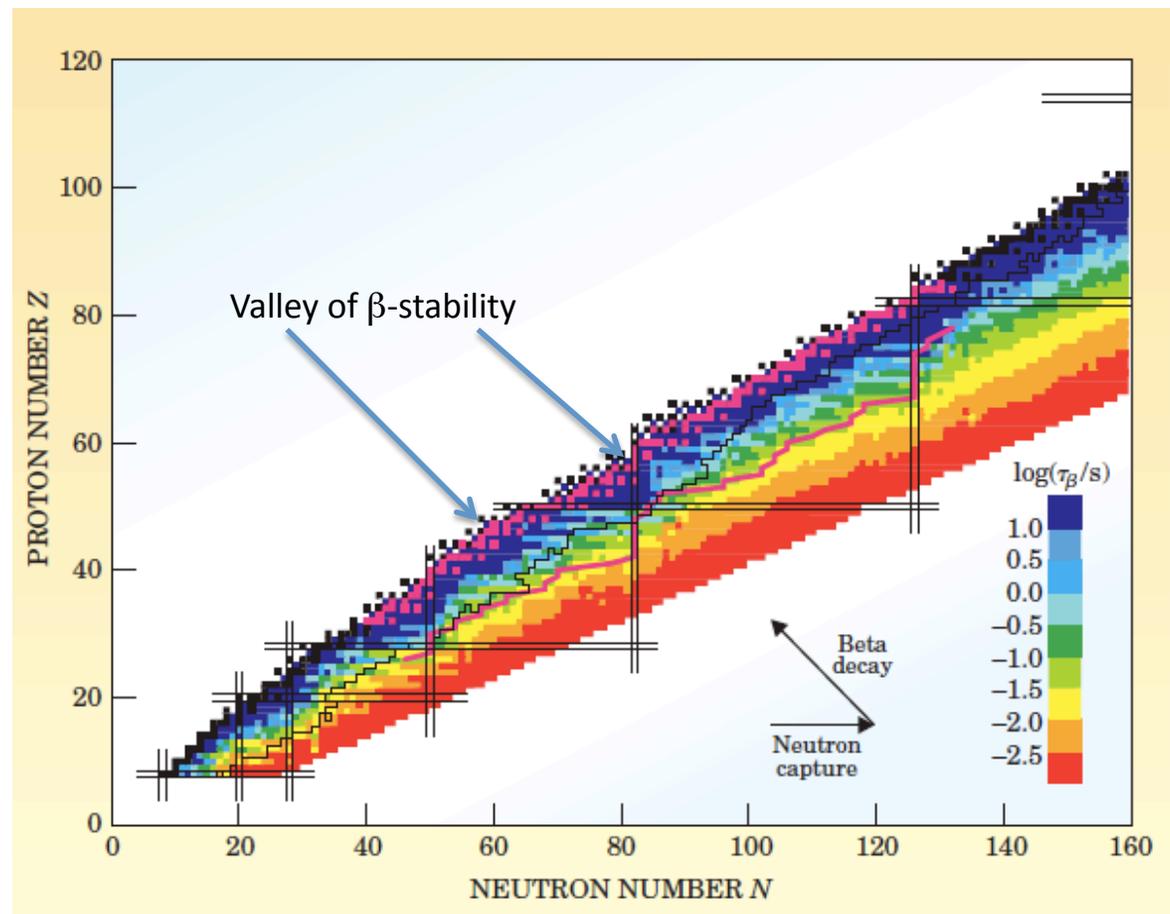


Introduction

- 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., $\tau_n \gg \tau_\beta$.
- In the case of the **r-process**: $\tau_n \ll \tau_\beta$.
- While τ_β depends only on the **nuclear species**, τ_n depends strongly on the **environment**, specifically on a **strong neutron flux**.

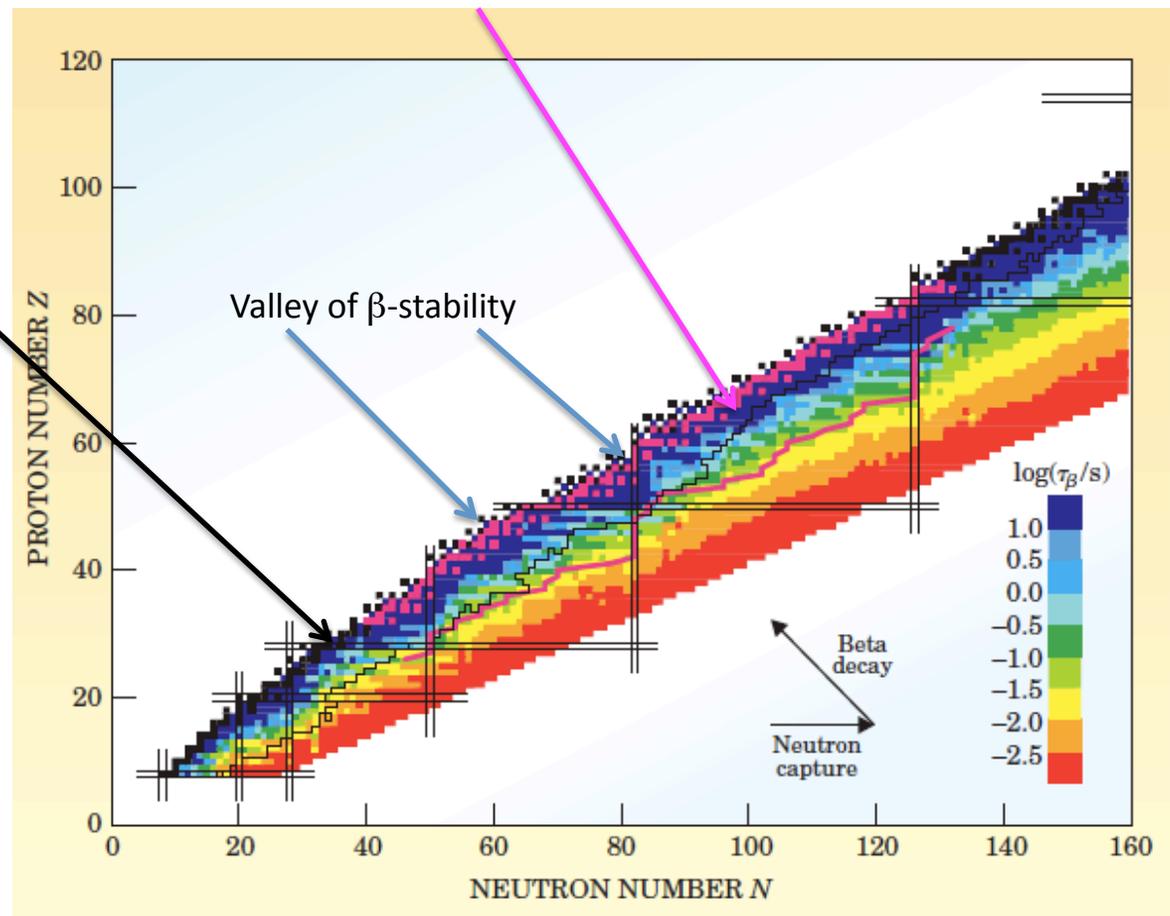
Introduction

- 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 divided into β -decay stable and unstable.
- The stable elements form the so-called “**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.



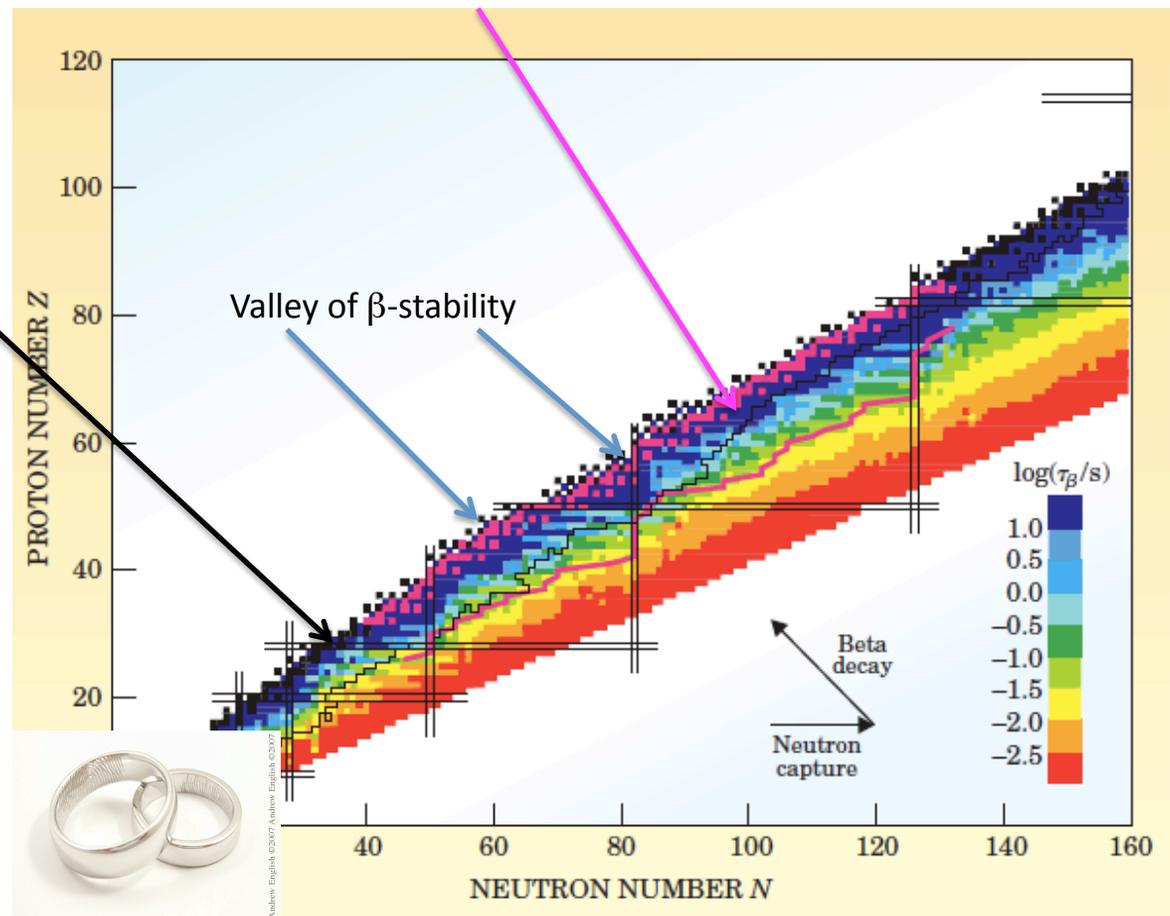
Introduction

- 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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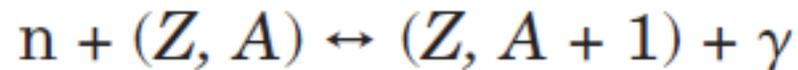


Introduction

- 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 mystery**.
- 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

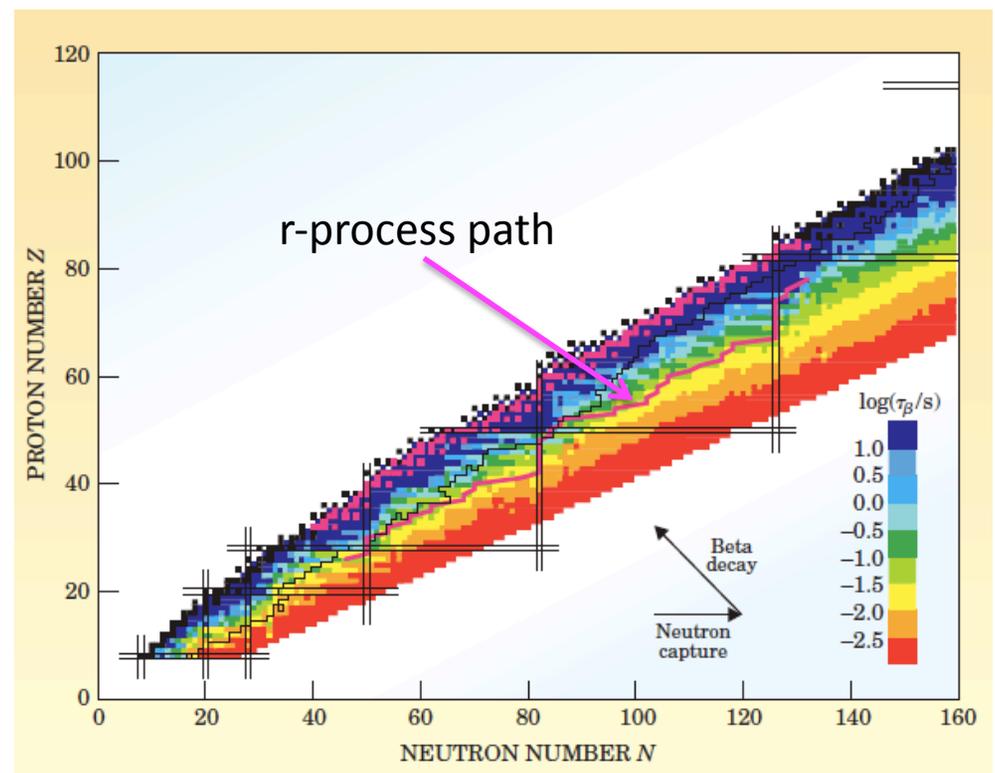
- Since in the **r-process** $\tau_n \ll \tau_\beta$, an element with a given proton-number (Z) should be able to **capture many neutrons before a β -decay**.
- In the environments of high fluxes there is typically **large temperatures** and therefore **large quantities of gamma photons** producing nuclear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



- 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.



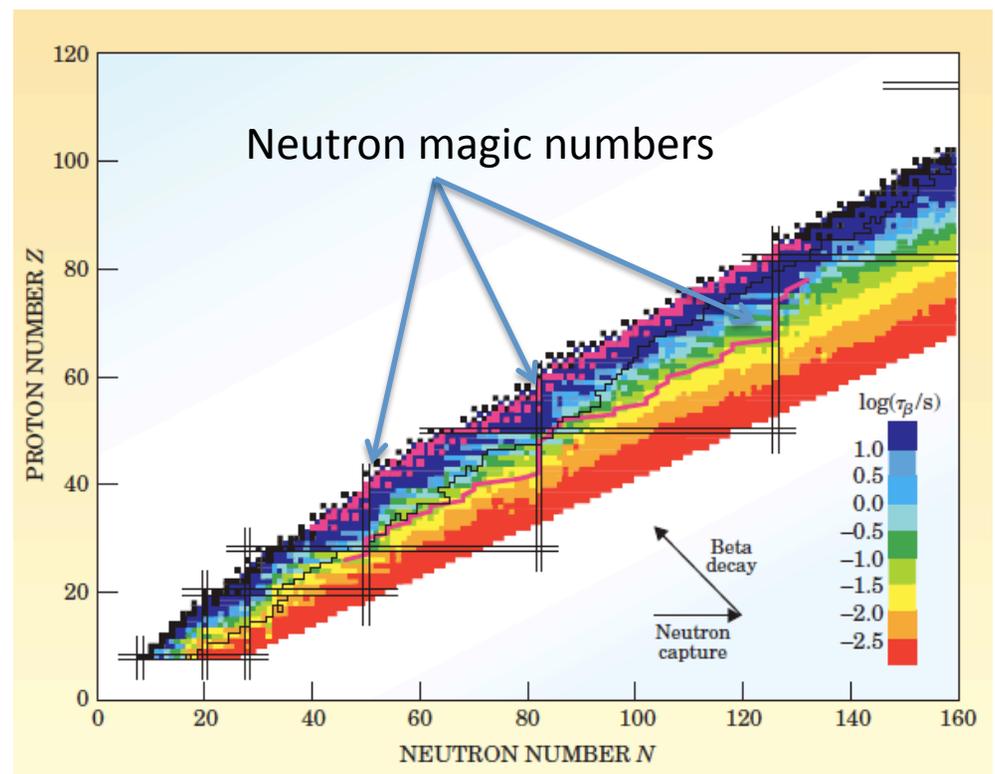
Nuclear physics and the r-process

- 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**.

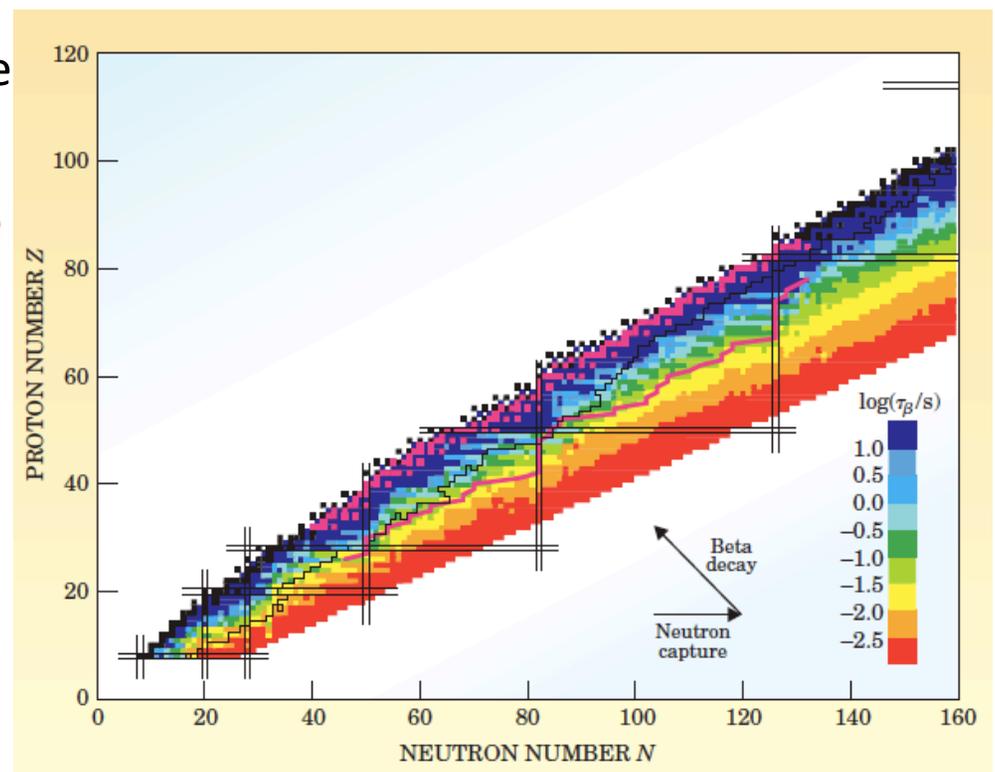
The **n-capture cross-section** is also **smaller**.

So the nuclei tend to concentrate more around these regions, and produce **peaks of abundance**.



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

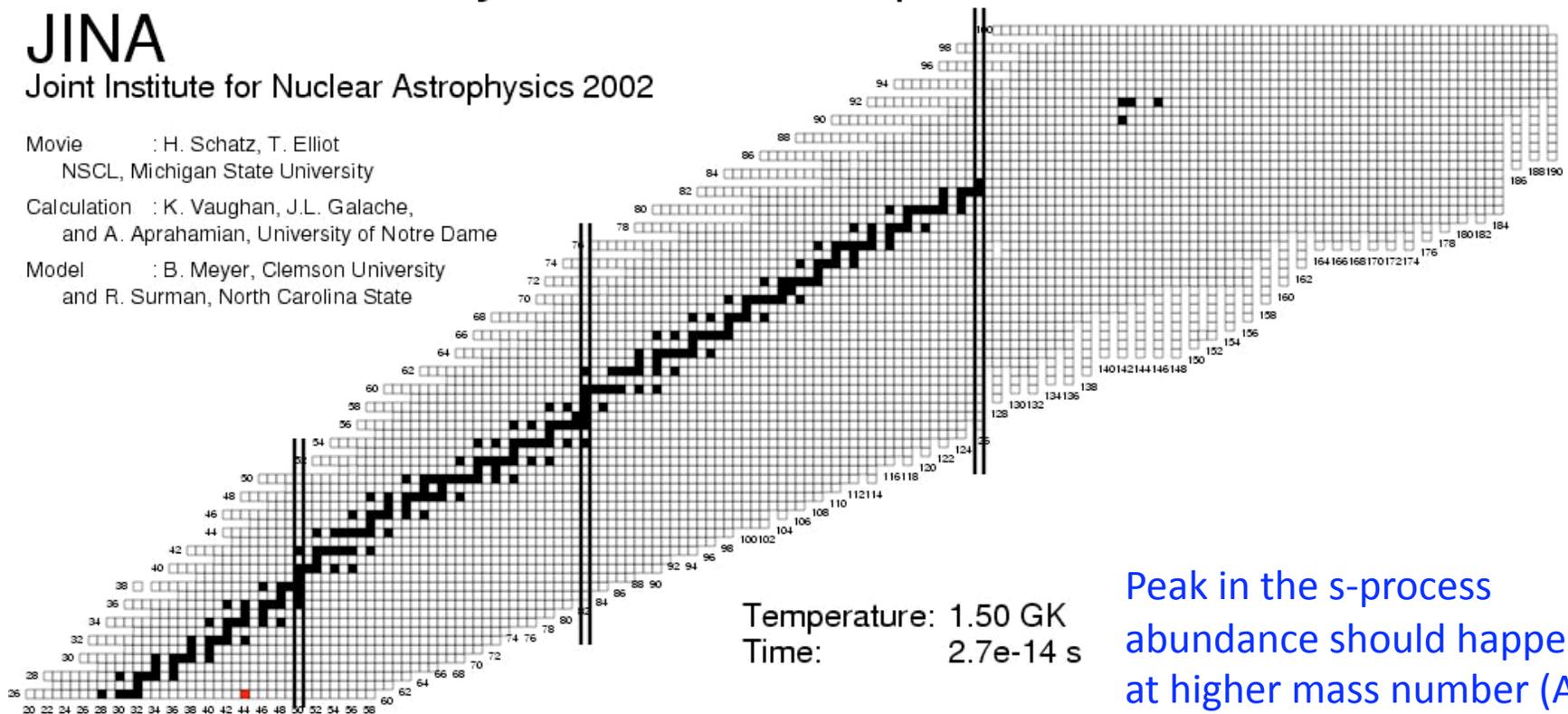
JINA

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



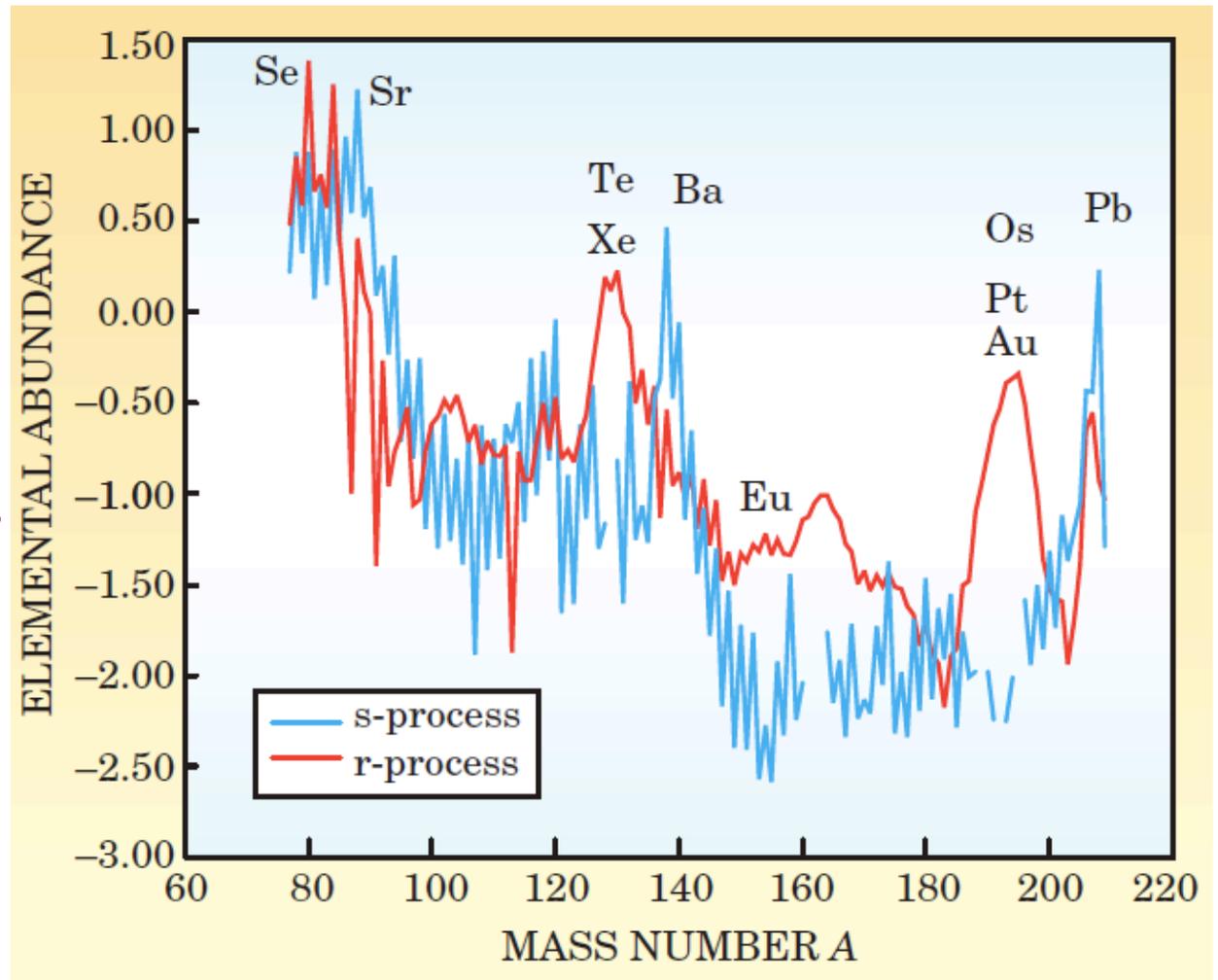
Temperature: 1.50 GK
Time: 2.7e-14 s

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 **$A \sim 200$** , 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 ($\sim 10^{33} \text{ cm}^{-3}$) available in the merger of neutron stars would build up heavy elements and lead to fission in very short time scales.

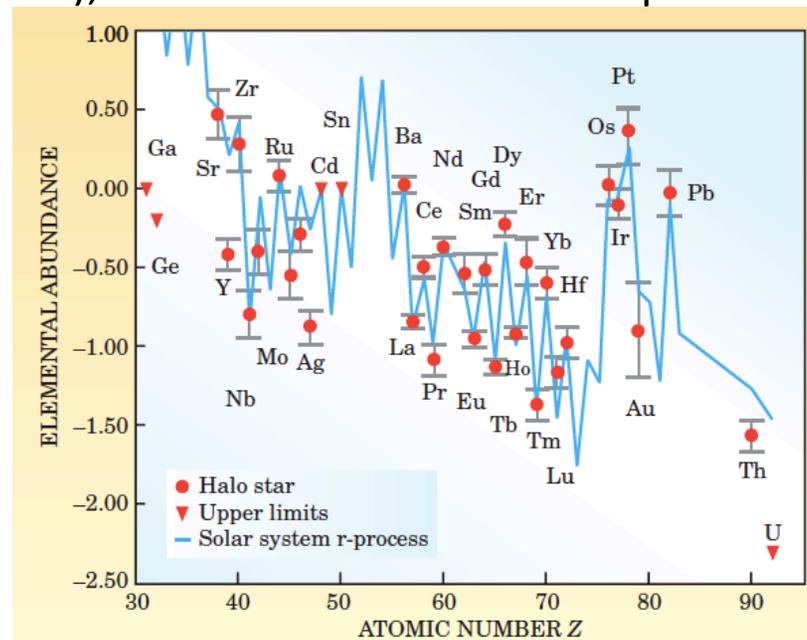
It could produce "fission recycling" via subsequent n-capture (see calculation of Freiburghaus et al. 1999). It would be consistent with r-process elements in the solar system for $A > 130$.

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 al. 2003b).

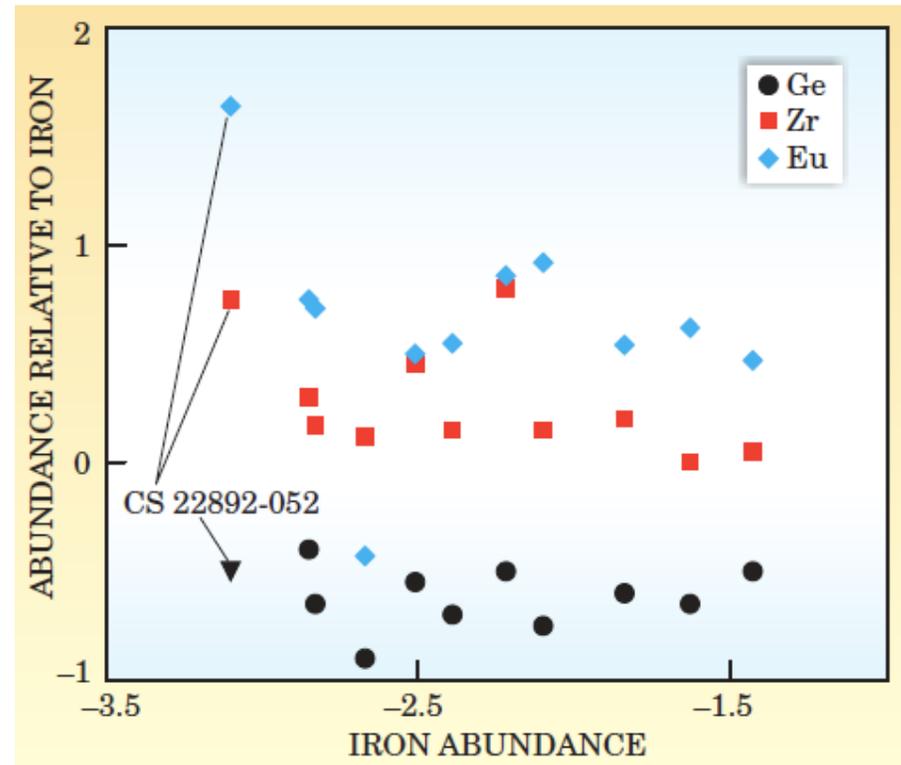
Abundances in halo stars.

- 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 halo 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.