Astrophysics with unstable nuclei at FAIR and FRANZ

Preparatory talk for René Reifarth

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Abstract by R. Reifarth

The Gesellschaft fuer Schwerionenforschung mbH (GSI) offers opportunities for direct and indirect measurments with astrophysical interest at radioactive nuclei. Direct measurements, including (p, γ) and (A, γ) reactions, are possible at the experimental storage ring, while the LAND facility allows to determine reaction rates via Coulomb-breakup and charge-exchange reactions.

The "Frankfurter Neutronenquelle am Stern-Gerlach-Zentrum" (FRANZ), which is currently under development, will be the strongest neutron source in the astrophysically interesting energy region in the world. It will be about 3 orders of magnitude more intense than the well-established neutron source at the Research Center Karlsruhe (FZK), which allows the direct measurment of neutron-induced reactions with radioactive samples.

After an introduction to several astrophysical sites, recent and future experiments will be discussed contributing to the needs for nuclear reaction rates under the respective conditions. The experiments discussed cover a broad range of stellar sites –from p-process to s-process and experimental techniques– from experiments using radioactive samples to measurements with radioactive ion beams.


COSMOLOGY MARCHES ON
Where did it all come from?
Where did it all come from?

Part I
Nuclear physics, and nuclear physics in stars

Nuclide –

atomic nucleus characterised by a specific constitution, *i.e.*, proton number Z, neutron number N, and nuclear energy level

- Isobar: same $Z + N (\equiv A)$ – *e.g.*,

  $^{\mathbf{40}}_{16}$S, $^{\mathbf{40}}_{17}$Cl, $^{\mathbf{40}}_{18}$Ar, $^{\mathbf{40}}_{19}$K, $^{\mathbf{40}}_{20}$Ca

- Isotope: same Z, different N – *e.g.*,

  $\underbrace{^{8-11}_{\mathbf{6}}\text{C}}_{\text{unstable}}$, $^{12}_{\mathbf{6}}$C, $^{13}_{\mathbf{6}}$C, $\underbrace{^{14-22}_{\mathbf{6}}\text{C}}_{\text{unstable}}$

- Isotone: different Z, same N – *e.g.*,

  $^{36}_{16}$S, $^{37}_{17}$Cl, $^{38}_{18}$Ar, $^{39}_{19}$K, $^{40}_{20}$Ca (same $N = 20$)

- Isomere: same Z, same N, different energy level – *e.g.*,

  $\underbrace{^{234}_{91}\text{Pa}}_{\tau_{1/2}=6.7\text{ hr}}$, $\underbrace{^{234\text{m}}_{91}\text{Pa}}_{\tau_{1/2}=1.2\text{ min}}$

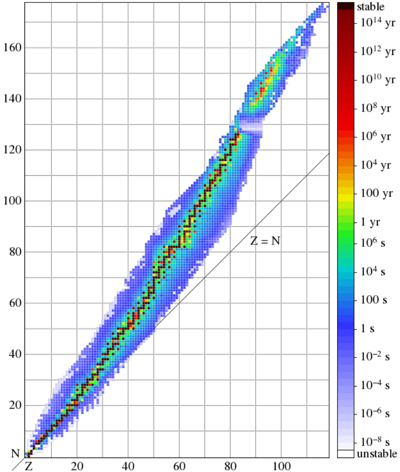
339 naturally-occurring nuclides
> **3000** radionuclides artificially produced

Radionuclide? –

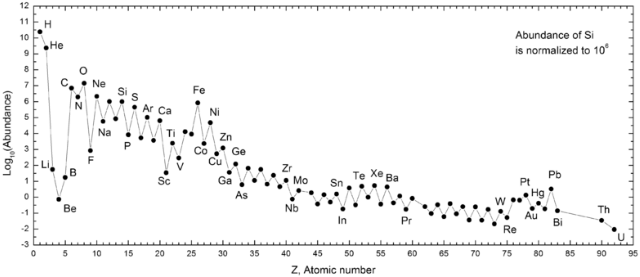
a radioactive nuclide which decays, emitting γ-rays, α's, β's
(**fact:** $\gtrsim$ 2400 with $\tau_{1/2} < 60$ min)

Natural radionuclides:

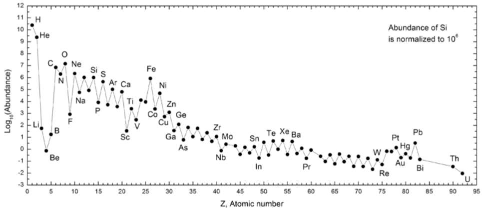
- Primordial: pre-Solar System remnants of nucleosynthesis (*e.g.*, ^{238}U with $\tau_{1/2} = 4.5 \times 10^9$ yr)
- Radiogenic: from radioactive decay (*e.g.*, ^{226}Ra from U, Th decay)
- Cosmogenic: from natural nuclear reactions – n bombardment from cosmic rays (*e.g.*, ^{14}C), spontaneous fission (*e.g.*, ^{239}Pu), etc.

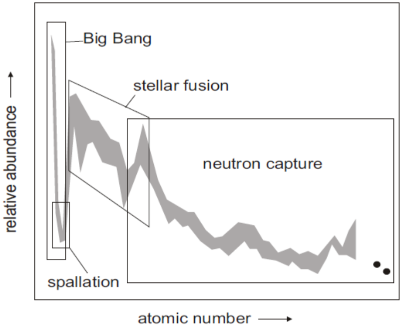


The observed abundance of elements in the Solar System,



is the result of four different classes of processes ►





- Big Bang nucleosynthesis: created ^{4}He (+ isotopes) and ^{7}Li
- Thermonuclear reactions: fusion in stars creates heavier elements up to ^{56}Fe – further fusion is endothermic
- Neutron spallation: formation of Li, Be, B due to fragmentation of nuclei by cosmic ray impact
- Neutron capture: produces all of the elements heavier than Fe, in astrophysical sites

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

We will now focus on neutron capture

Some evidence for neutron capture:

1. Large neutron fluxes exist in stars at certain stages of their evolution
2. Neutron capture cross sections for heavy elements ($\lesssim 10^3$ b) are very large compared to light elements ($\lesssim 1$ b) [1 b = 10^{-24} cm^2]
3. Enough seed material exists: only 3$\%$ of iron-peak elements are needed to synthesise all $A > 60$ heavy elements
4. Observaion of Tc in stellar atmospheres: $\tau_{1/2} \sim 10^6$ yr $\ll$ star lifetime, so it must have been created in the star (no Tc on Earth)

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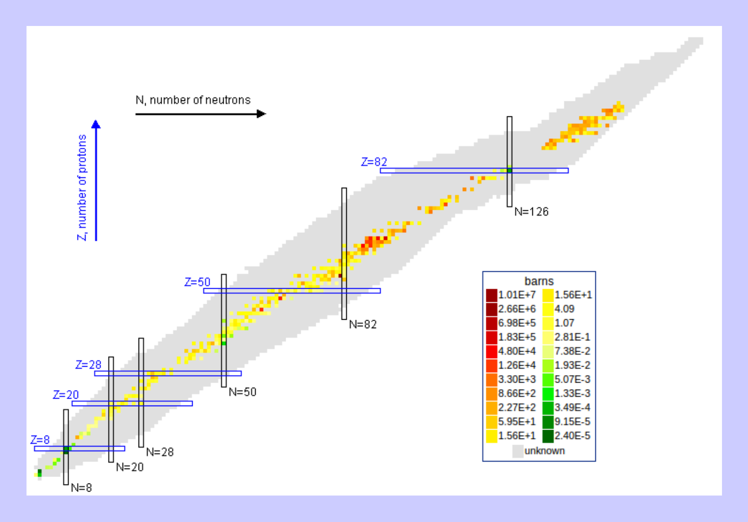

are

^{2}]

are

rth)

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There are two competing processes:

1. Neutron capture:

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

2. Beta decay:

$$(Z, A+1) \rightarrow (Z+1, A+1) + e^- + \bar{\nu}_e$$

Depending on the relative timescales, capture is slow or rapid:

s-process

if $t_\beta \gg t_{\text{capture}}$
(only few neutrons accumulated before β-decay occurs)

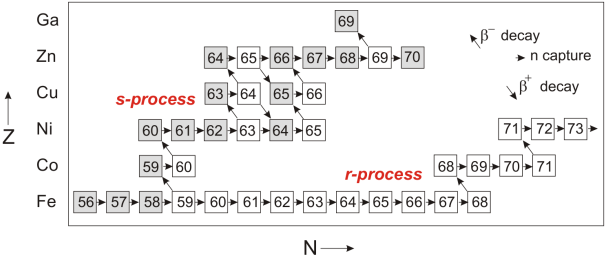
or

r-process

if $t_{\text{capture}} \gg t_\beta$
(many neutrons accumulated before β-decay occurs)

Producing the heavier elements

An example



$$^{56}\text{Fe} + n \rightarrow {}^{57}\text{Fe} \quad \text{(stable)}$$
$$^{57}\text{Fe} + n \rightarrow {}^{58}\text{Fe} \quad \text{(stable)}$$
$$^{58}\text{Fe} + n \rightarrow {}^{59}\text{Fe} \quad (\tau_{1/2} = 45 \text{ days})$$

if n flux is moderate (late red-giant stars)

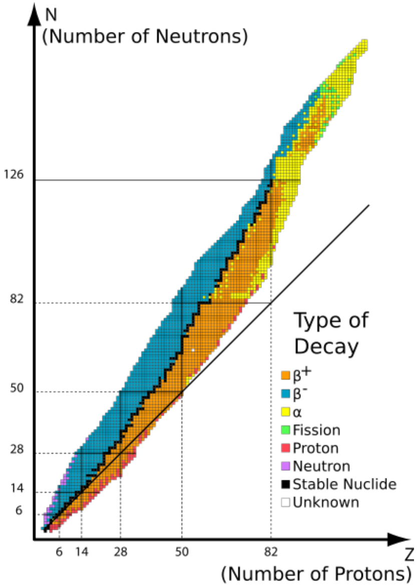
if n flux is very high (supernovae)

s-process

$$^{59}\text{Fe} \rightarrow {}^{59}\text{Co} + e^- + \bar{\nu}_e$$
$$^{59}\text{Co} + n \rightarrow {}^{60}\text{Co} \; (\tau_{1/2} = 5 \text{ yr})$$
$$^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e \; ({}^{60}\text{Ni stable})$$

r-process

$$^{59}\text{Fe} + n \rightarrow {}^{60}\text{Fe} \; (\tau_{1/2} = 3 \times 10^5 \text{ yr})$$
$$^{60}\text{Fe} + n \rightarrow {}^{61}\text{Fe} \; (\tau_{1/2} = 6 \text{ min})$$
$$^{61}\text{Fe} \rightarrow {}^{61}\text{Co} + e^- + \bar{\nu}_e \; (\tau_{1/2} = 1.65 \text{ hr})$$
$$^{61}\text{Co} \rightarrow {}^{61}\text{Ni} + e^- + \bar{\nu}_e \; ({}^{61}\text{Ni stable})$$


N
(Number of Neutrons)
126
82
50
28
14
6
6
14
28
50
82
Z
(Number of Protons)
Type of
Decay
β+
β-
α
Fission
Proton
Neutron
Stable Nuclide
Unknown

Neutron capture cross sections (valid for s- and r-process velocities):

$$\sigma \propto 1/v$$

Typical values:

$$\sigma \sim 100 \text{ mb} = 10^{-25} \text{ cm}^2 \,, \quad v \sim 10^8 \text{ cm s}^{-1}$$

For a heavy nucleus,

$$\sigma v \sim 10^{-17} \text{ cm}^3 \text{ s}^{-1} \ (\approx \text{constant})$$

For a n density N_n (cm^3), the nucleus captures a neutron in the time

$$t = (N_n \sigma v)^{-1} \simeq 10^9 \, (1/N_n) \, \text{yr}$$

- s-process: characteristic $t \approx 100$ yr $\Rightarrow N_n \sim 10^7$ cm^{-3} required
- r-process: characteristic $t \sim$ ms $\Rightarrow N_n \sim 10^{19}$ cm^{-3} required

The s-process

Rate of production of nucleus A:

$$\frac{dN_A}{dt} = N_n [\underbrace{(\sigma_{A-1} v)\, N_{A-1}}_{\text{production}} - \underbrace{(\sigma_A v)\, N_A}_{\text{destruction}}]$$

The r-process

The p-process

Abundance

Instead of the number density of a nucleus n (in cm^{-3}), use the abundance,

$$Y \equiv n/(\rho_{\text{pla}} N_{\text{Av}})$$

ρ_{pla}: density of the plasma (in g cm^{-3})

For N nuclides, the abundances are determined by solving an equation matrix of size N^2:

- thousands of nuclides, tens of thousands of reactions
- non-linear
- plus, coupled to a set of hydrodynamical equations
- vastly different timescales involved $\Rightarrow$ stiff equations

$\therefore$ overall, a tough problem

In general, a reaction network can be written as

$$\dot{Y}_i = \frac{\dot{n}_i}{\rho_{\text{pla}} N_{\text{Av}}} = \frac{1}{\rho_{\text{pla}} N_{\text{Av}}} \{ \underbrace{\sum_j {}^1_j K_j \, {}_i\lambda_j}_{①} + \underbrace{\sum_j {}^2_j K_j \, {}_i r_j}_{②} + \underbrace{\sum_j {}^3_j K_j \, {}_i \hat{r}_j}_{③} + \dots \}$$

①: ${}_i\lambda_j$ is the jth reaction rate (s^{-1} cm^{-3}) for destruction (${}^1_j K_j < 0$) of creation (${}^1_j K_j > 0$) of the ith nucleus without a nuclear projectile involved (spontaneous decay, lepton capture, photodisintegration)

②: ${}_i r_j$ is the rate involving one nuclear projectile

③: ${}_i \hat{r}_j$ is the rate involving two nuclei

Reactions with more participants are unlikely at astrophysical sites.

${}^1_j K_j, {}^2_j K_j, {}^3_j K_j$: integers specifying the number of nuclei i destroyed/created

1. **One-body rates:** ${}_i\lambda_j$ contains only the abundance Y_j
2. **Two-body rates:** ${}_ir_j$ contains two abundances

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