Neutron Producing Reactions in Nucleosynthesis

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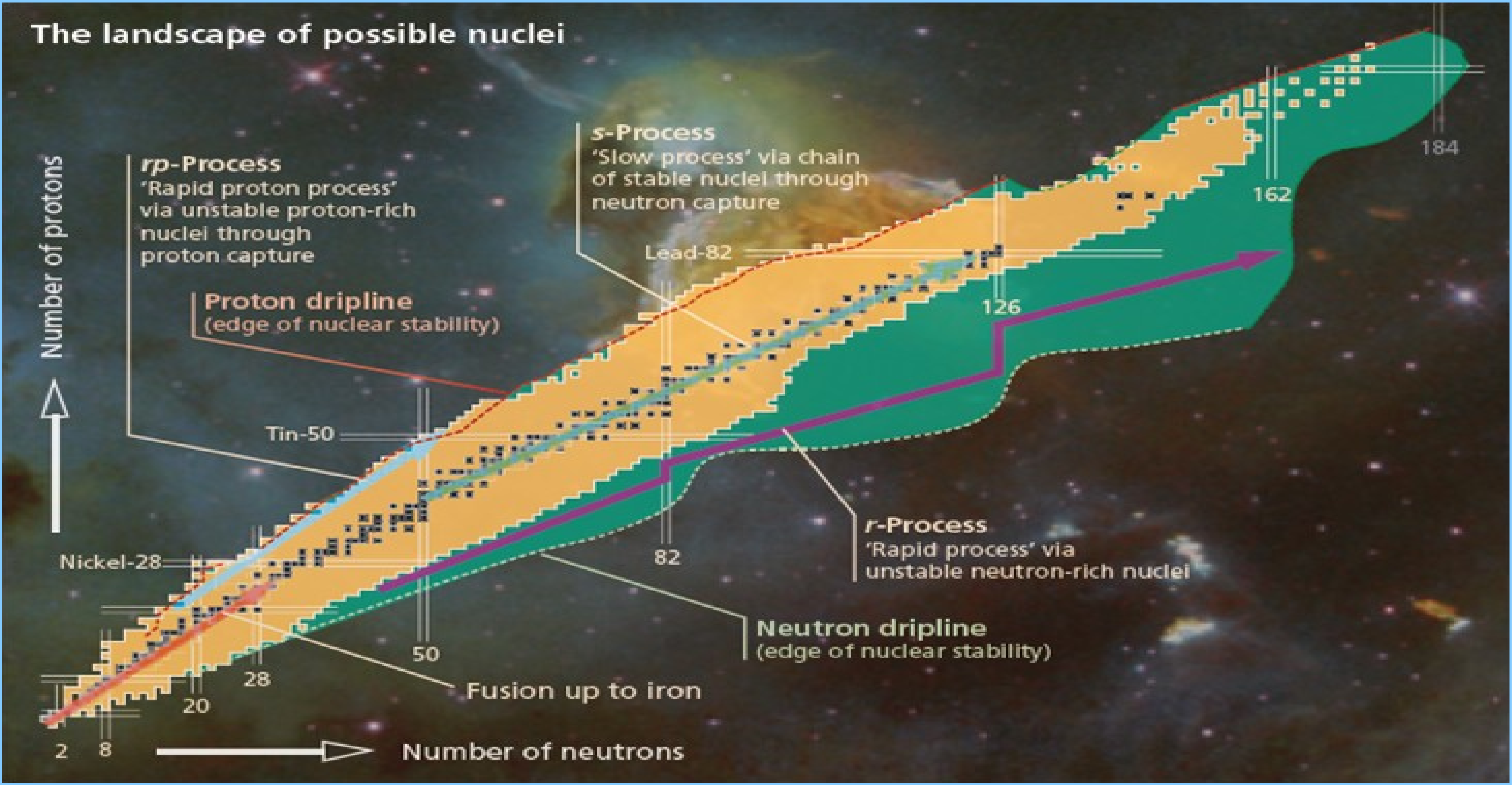
The landscape of possible nuclei
rp-Process
'Rapid proton process' via unstable proton-rich nuclei through proton capture
s-Process
'Slow process' via chain of stable nuclei through neutron capture
Proton dripline
(edge of nuclear stability)
Number of protons
Tin-50
Lead-82
Nickel-28
184
162
126
82
50
28
20
2
8
r-Process
'Rapid process' via unstable neutron-rich nuclei
Neutron dripline
(edge of nuclear stability)
Fusion up to iron
Number of neutrons

NUCLEOSYNTHESIS

- The process of creating new atomic nuclei from pre-existing nucleons

BIG BANG

$T \leq 2 \cdot 10^{12}\,\mathrm{K}$ **primordial nucleons formed from the quark-gluon plasma**

→ protons and neutrons built up to Li and Be

500 million years **H and He condensed to the first stars**

→ inside stars: **successive nuclear fusion processes** create elements up to Fe and Ni

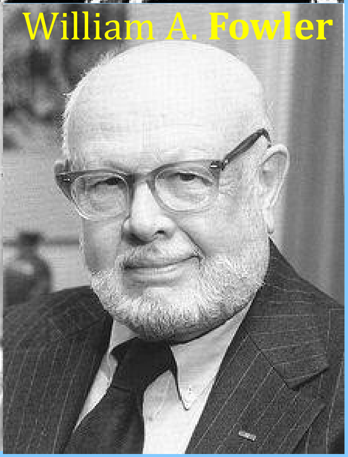
hydrogen burning,
helium burning,
carbon burning,
oxygen burning,
silicon burning

→ elements beyond Fe formed by **neutron capture processes**, or different reactions in explosives environments, e.g. in supernovae


Geoffrey **Burbidge**


E.Margaret **Burbidge**


Fred **Hoyle**


William A. **Fowler**

Why **neutron capture**?

<u>Relevant Processes:</u>

Slow Neutron-Capture-Process	**s process**
Rapid Neutron-Capture-Process	**r process**
Photodisintegration Process	**p process**

→ processes according to the isotopic pattern in the chart of nuclides

1952 Spectroscopy of unstable element Tc as evidence for active neutron-capture nucleosynthesis

1957 Paper “Synthesis of the Elements in Stars” :
successful model of the s process, the **classical model**.

The s process : Classical Model

assumption: All beta-decays of the radioactive nuclei are quite rapid compared to the rate for capturing neutrons.

if nucleus $(Z,A+1)$ produced by $(Z,A)+n\rightarrow(Z,A+1)+\gamma$ radioactive,
$\rightarrow$ decay to stable nucleus $(Z+1,A+1)$ in $(Z,A+1)\rightarrow(Z+1,A+1)+\beta^-+\bar{\nu}$

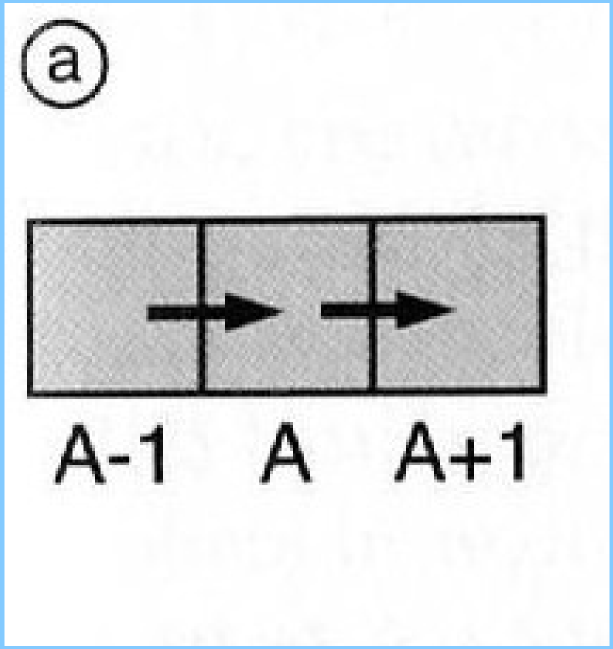
presumption: Some heavy elements are in some interior region of a star with T=const.

- **Seed Nuclei:** $^{56}\mathrm{Fe}$
- s-process follows path close to the group of stable nuclei
- $^{209}\mathrm{Bi}$ most massive stable nucleus

Differential Equation for abundance evolution of any stable nucleus:

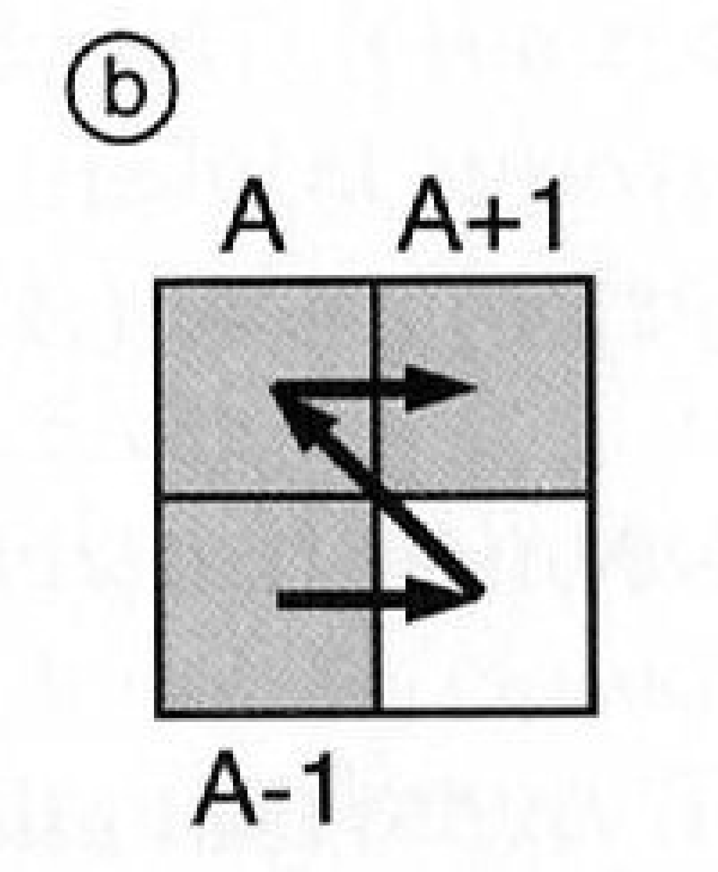
$$\boxed{\begin{aligned}\frac{d\,N_s(A)}{dt} &= -\langle\sigma v\rangle_A n_n(t) N_s(A) + \langle\sigma v\rangle_{A-1} n_n(t) N_s(A-1)\\ &= -\langle\sigma\rangle_A v_T n_n(t) N_s(A) + \langle\sigma\rangle_{A-1} v_T n_n(t) N_s(A-1)\\ &= v_T n_n(t)\left[-N_s(A)\langle\sigma\rangle_A + N_s(A-1)\langle\sigma\rangle_{A-1}\right]\end{aligned}}$$

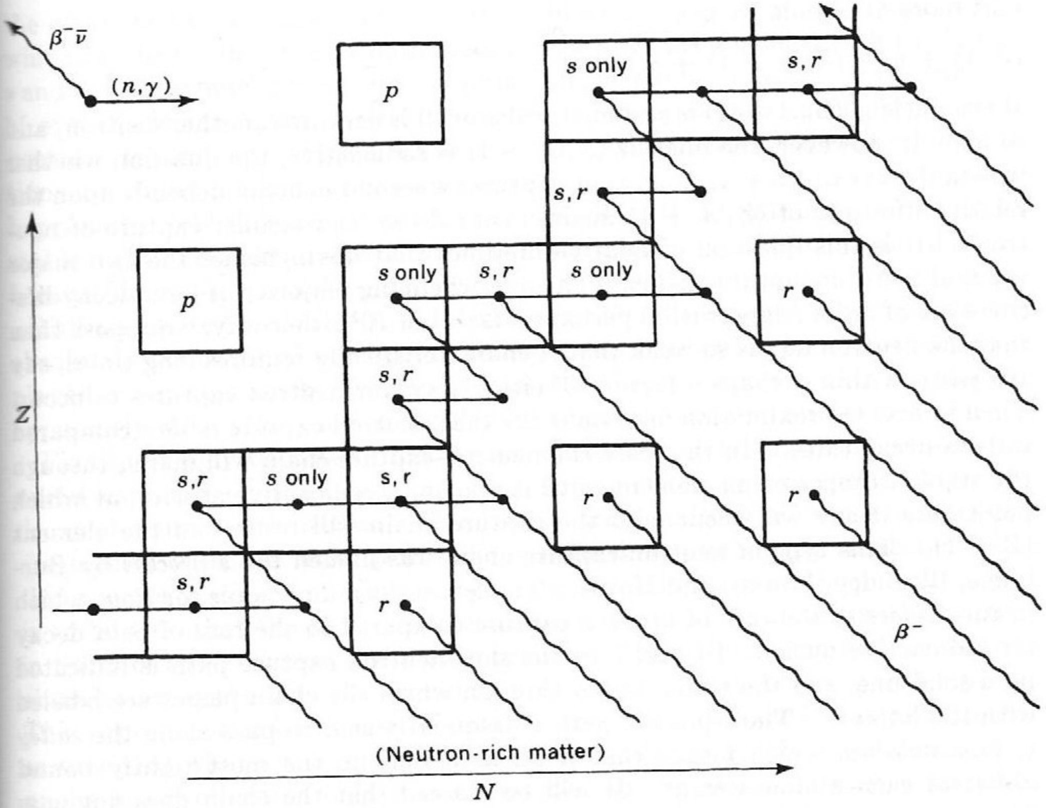
$N_s(A)$ number density of the nucleus with mass number A
free neutron-number density $n_n(t)$ uniform over the region
$\langle\sigma v\rangle_A$ neutron-capture rate per particle pair of nucleus A

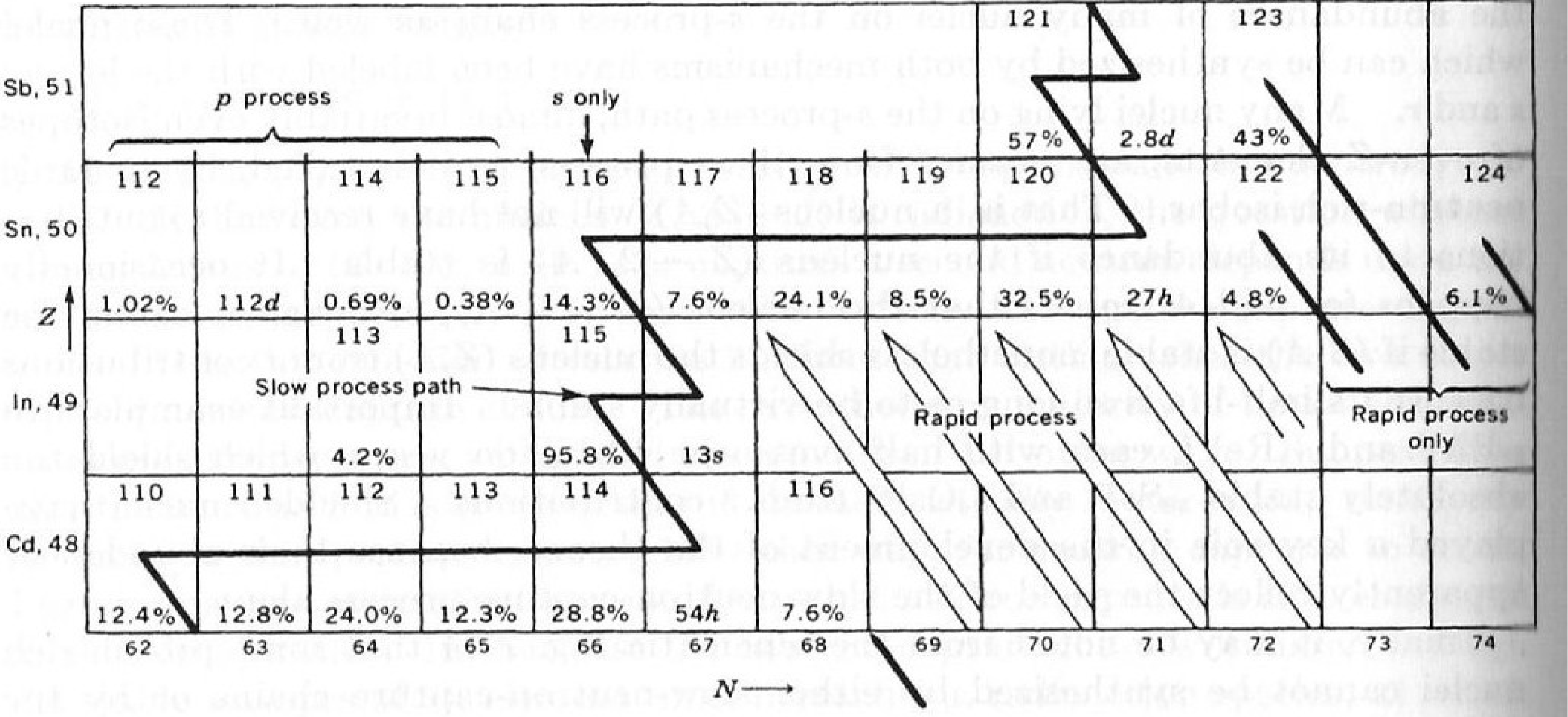


→ Nucleus A is destroyed by neutron capture
→ Nucleus A is produced by neutron capture on (A-1)

→ Nucleus A is destroyed by neutron capture
→ Nucleus A is produced by neutron capture on (A-1)
and subsequent β -decay




$\beta^-\bar{\nu}$
(n,γ)
p
s only
s, r
s, r
p
s only
s, r
s only
r
s, r
s, r
s only
s, r
r
r
s, r
r
β^-
Z
(Neutron-rich matter)
N


Sb, 51
Sn, 50
In, 49
Cd, 48
p process
s only
121
123
57%
2.8d
43%
112
114
115
116
117
118
119
120
122
124
1.02%
112d
0.69%
0.38%
14.3%
7.6%
24.1%
8.5%
32.5%
27h
4.8%
6.1%
113
115
Slow process path
Rapid process
Rapid process only
4.2%
95.8%
13s
110
111
112
113
114
116
12.4%
12.8%
24.0%
12.3%
28.8%
54h
7.6%
62
63
64
65
66
67
68
69
70
71
72
73
74
Z
N

With **Neutron Exposure**: $\boxed{\tau = v_T \int n_n(t)dt \leftrightarrow d\tau = v_T n_n(t)dt}$

==> $$\boxed{\begin{aligned} \frac{dN_S(A,t)}{d\tau} n_n(t) v_T &= v_T n_n(t)\left[-N_S(A,\tau)\langle\sigma\rangle_A + N_S(A-1,\tau)\langle\sigma\rangle_{A-1}\right] \\ \frac{dN_S(A,t)}{d\tau} &= -N_S(A,\tau)\langle\sigma\rangle_A + N_S(A-1,\tau)\langle\sigma\rangle_{A-1} \end{aligned}}$$

Boundary Conditions: $N_S(56,0) = f\, N_S^{seed}(56)$ and $N_S(A>56,0) = 0$

f is fraction number of the $^{56}\mathrm{Fe}$ seed that are subjected to a neutron exposure

Behaviour of the self-regulating coupled equations:

$$\frac{dN_S(t)}{d\tau} < 0 \quad \text{for} \quad N_S(A,\tau) > \left[\frac{\langle\sigma\rangle_{A-1}}{\langle\sigma\rangle_A}\right] N_S(A-1,\tau)$$

$$\frac{dN_S(t)}{d\tau} > 0 \quad \text{for} \quad N_S(A,\tau) < \left[\frac{\langle\sigma\rangle_{A-1}}{\langle\sigma\rangle_A}\right] N_S(A-1,\tau)$$

$$\boxed{\frac{dN_S}{d\tau} \approx 0} \rightarrow \boxed{\begin{gathered} N_S(A,\tau)\langle\sigma\rangle_A \approx N_S(A-1,\tau)\langle\sigma\rangle_{A-1} \\ N_S(A,\tau)\langle\sigma\rangle_A \approx \text{const.} \end{gathered}}$$

local (equilibrium) approximation

→ mass numbers removed from closed neutron shells ($A = 84, 138, 208$)

→ abundance up to: destruction rate ≈ production rate

→ steady flow along the s-process path

FUNCTION OF NEUTRON EXPOSURE: $N_S(A)\langle\sigma\rangle_A$

assumption: exponential distribution of neutron exposures $\boxed{p(\tau)=\frac{f\,N_S^{seed}(56)}{\tau_0}e^{-\tau/\tau_0}}$

($p(\tau)d\tau$ is the fraction of ^{56}Fe seed nuclei having received an exposure in the range between τ and $\tau+d\tau$)

→ **total number of irradiated seed nuclei:** $\int_0^\infty p(\tau)d\tau = f\,N_s^{seed}(56)\left[-e^{-\frac{\tau}{\tau_0}}\right]_0^\infty = f\,N_s^{seed}(56)$

→ **resulting abundances:** $\overline{N_s(A,\tau_0)}=\frac{\int_0^\infty N_s(A,\tau)p(\tau)d\tau}{\int_0^\infty p(\tau)d\tau}=\frac{\int_0^\infty N_s(A,\tau)}{\tau_0}e^{-\frac{\tau}{\tau_0}}d\tau$

$$==> \boxed{\langle\sigma\rangle_A\overline{N_s(A,\tau_0)}=\frac{f\,N_s^{seed}(56)}{\tau_0}\prod_{i=56}^{A}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_i}\right]}} \quad (1)$$

for two nuclides with adjacent mass numbers: $$\langle\sigma\rangle_A \overline{N_s(A,\tau_0)} = \frac{\langle\sigma\rangle_{A-1} N_s(A-1,\tau_0)}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_i}\right]}$$

between closed neutron shells: $\langle\sigma\rangle_A$ and $\tau_0\langle\sigma\rangle_A$ large

→ equilibrium in the neutron capture flow

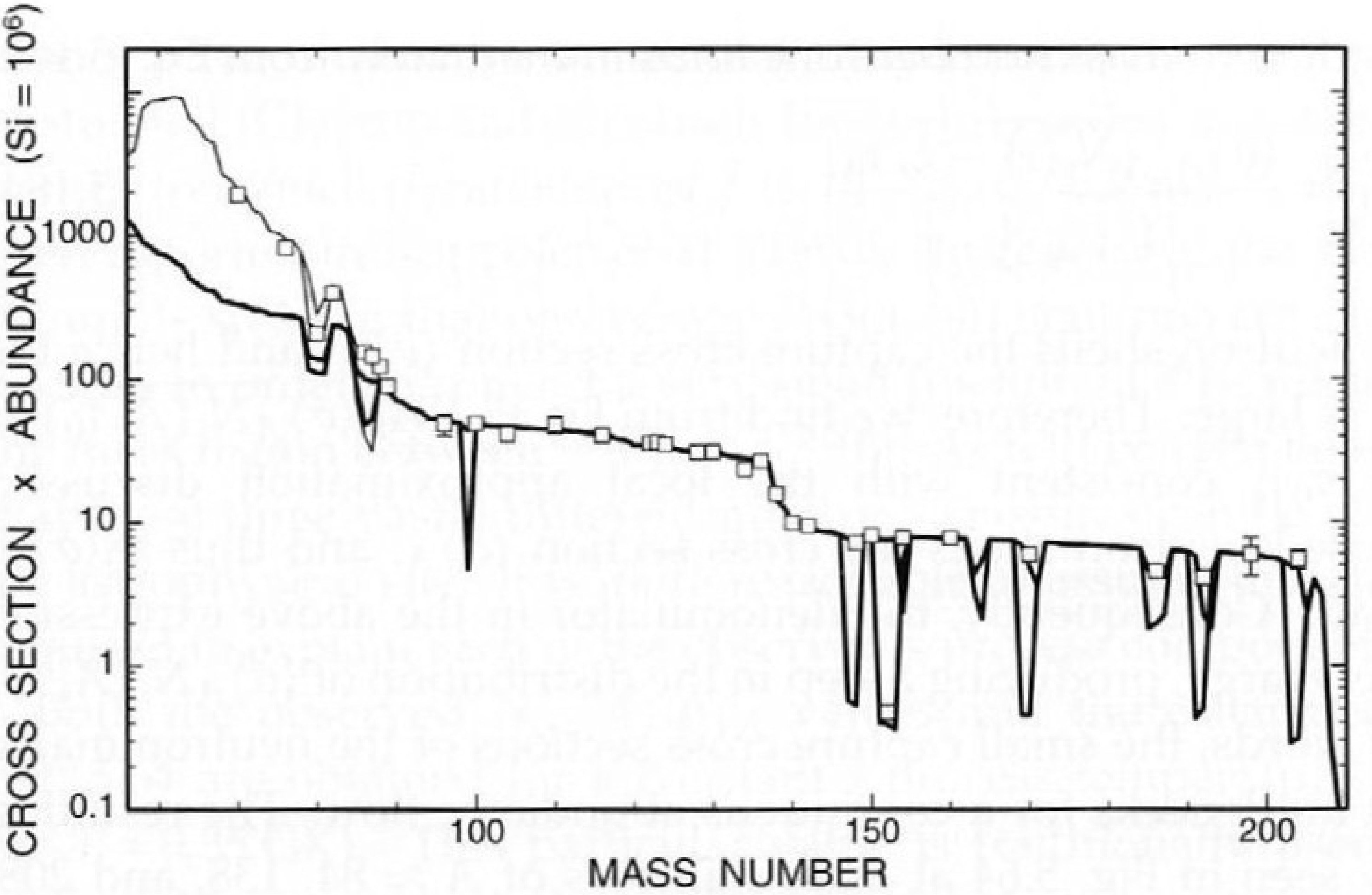
→ $\langle\sigma\rangle_A \overline{N_s(A,\tau_0)} \approx \langle\sigma\rangle_{A-1} \overline{N_s(A-1,\tau_0)}$ local approximation

→ curve $\langle\sigma\rangle_A \overline{N_s(A,\tau_0)}$ is almost constant

near closed neutron shells: $\langle\sigma\rangle_A$ and $\tau_0\langle\sigma\rangle_A$ relatively small

→ the denominator in the above expression becomes relatively large, producing a step in the distribution of $\langle\sigma\rangle_A \overline{N_s(A,\tau_0)}$ values

==> Small capture cross section of the neutron magic numbers/closed neutron shells are bottlenecks for a continuous abundance flow.



The product $N_{\odot}(A)\langle\sigma\rangle_A$ of solar system s-process abundances and MACS versus mass number A.

Important constraints on the physical environment and the history of s-process nucleosynthesis:

$$\boxed{n_c = \frac{\sum_{A=56}^{209} (A-56)\,\overline{N_s(A,\tau_0)}}{f\,N_s^{seed}(56)} = \frac{1}{\tau_0}\sum_{A=56}^{209}\frac{(A-56)}{\langle\sigma\rangle_A}\prod_{i=56}^{A}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_i}\right]}}$$

average number of neutrons captured per $^{56}\mathrm{Fe}$ seed nucleus

f fraction of the number of $^{56}\mathrm{Fe}$ seed nuclei, $N_S^{seed}(56)$, that has been subjected to an exponential distribution of neutron exposures

τ_0 mean neutron exposure that determines how rapidly the exposure distribution falls off

Evaluation of the classical s-process model

- simple
- satisfactory description of most observed $N_{\odot}(A)\langle\sigma\rangle_A$ values for s-only nuclides
  → small number of adjustable parameters
  → as long as neutron capture cross section large enough
  → fit to s-process only nuclei and to abundances predicted by AGB models
  → comparison to solar system s-process components
- **no information on specific neutron source reactions**

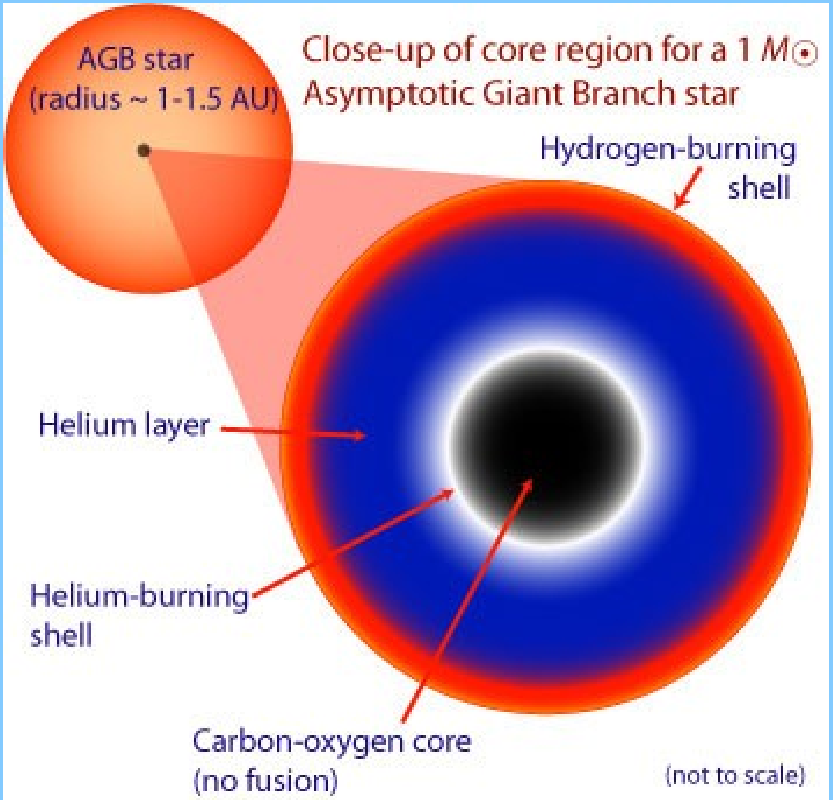
PROBLEM:

description of abundance patterns **at and near magic numbers**, e.g. s-only ^{142}Nd, **below A = 90** and **for stellar models of low-mass AGB stars**

→ small cross sections

Thermally Pulsing Asymptotic Giant Branch (AGB) stars

→ Evolved Red Giants $1 \leq M \leq 3\,M_\odot$ that have already burnt all the H and He in their core to C and O
→ Alternate Activation of the H- and He-burning shells
→ Separation of shells by thin zone in radiative equilibrium: He-intershell ($\sim 75\,\%\,^4\mathrm{He}, \sim 25\,\%\,^{12}\mathrm{C}$)



H-BURNING SHELL:

erosion of the bottom layers of the envelope and production of He

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He-INTERSHELL:

growth of intershell in mass, density, temperature

He-BURNING SHELL:

ignition of He at the bottom of the shell

==> Trigger of Quasi-Explosion: **Thermal Pulse TP**

→ sudden release of energy → higher temperatures $T \approx 0.27\, GK\, (kt \approx 23\, keV)$

→ production of lots of $^{12}\mathrm{C}$ by He-burning

→ expansion of stellar envelope

→ convection in the whole intershell for a short period of time

→ temporary extinction of H-burning

→ initiation of sequence $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$

→ **activation of the neutron source** $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$

→ **lower neutron burst**:

neutron exposure: $\approx 0.01\,\mathrm{mb}^{-1}$

peak neutron density $\mathrm{n_n} \leq 10^{11}\,\mathrm{cm}^{-3}$

→ **efficient operations of branchings**

==> He-shell burning for a few thousand years,
then He-shell almost extinct and inactive, contraction of the envelope

==> again H burning

H-BURNING SHELL:

ignition of H-shell

He-INTERSHELL:

mixing of protons below the H-rich envelope into restricted mass layers of the carbon-rich intershell

→ **initiation of sequence** $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+}\nu)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$

→ development of two separate regions rich in $^{13}\mathrm{C}$ and $^{14}\mathrm{N}$, the $^{13}\mathrm{C}$ pocket and $^{14}\mathrm{N}$ pocket

→ $T \approx 0.09\,\mathrm{GK}\,(kt \approx 8\,\mathrm{keV})$

mean lifetime of $^{13}\mathrm{C}$ versus destruction by $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ -reaction smaller than the time between two TP

→ **activation of the neutron source** $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$

==> release of neutrons within $^{13}\mathrm{C}$ -pocket

neutron flux:

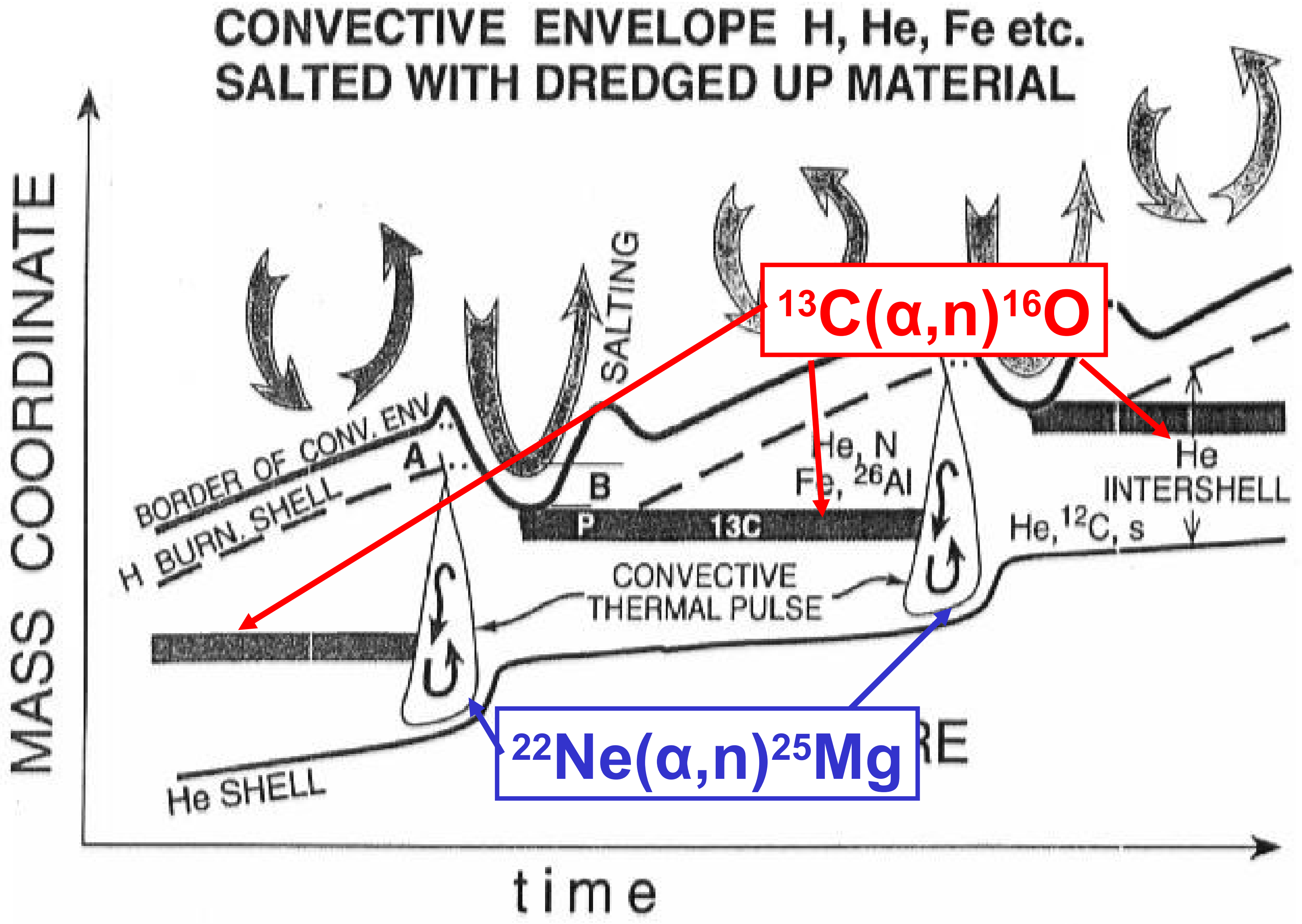
duration: 20 000 years (until the entire $^{13}\mathrm{C}$ is consumed)

locally high neutron exposures: $\approx 0.1\,mb^{-1}$

average neutron density $n_n \leq 10^8\,\mathrm{cm}^{-3}$

==> production of the nuclides in the main s-process component $90 \leq A \leq 209$ **via neutron capture by pre-existing seed nuclei (mainly Fe)**

==> 95% of the total neutron exposure



$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

H-BURNING SHELL:

after a number of TP: H-exhausted core $\approx 0.6\,M_\odot$ → H-shell inactive

recurrent TDU-Episodes (third dredge-up)
→ penetration of the convective core into the He-intershell
→ mixing newly synthesized material to the surface of the star
→ enrichment of the envelope in primary ^{12}C and in s-process elements

==> chemical discontinuity between H-rich envelope and He-intershell: only few protons come into top layers of intershell
renewed burning: protons captured by abundant ^{12}C forming ^{13}C
$^{12}C(p,\gamma)^{13}N(\beta^+\ \nu)^{13}C$ in the small intershell region, the ^{13}C pocket

→ repetition of the cycle tens to hundreds of time
→ change of the initial CNO abundances at the surface because of the TPs and TDUs

==> successful description of the abundance distribution of the main s-components

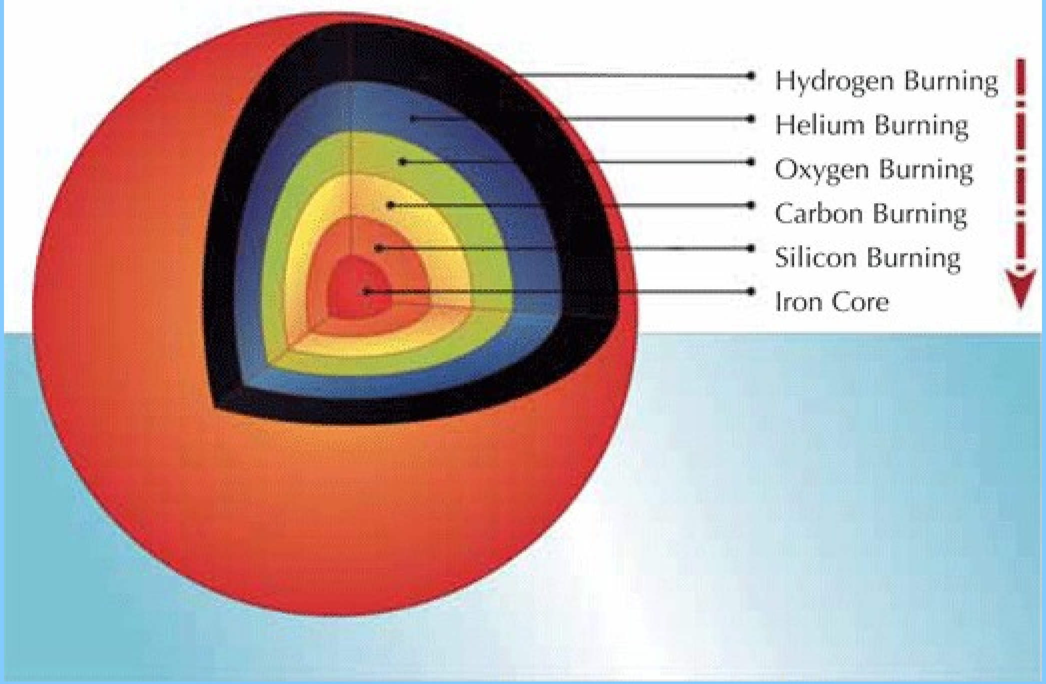
BUT: A single s process does not satisfactorily explain all the observed Solar System abundances, e.g. uncertainties in the region of ^{208}Pb and ^{209}Bi.
THEREFORE: main, weak and strong s process

Massive Stars $M \geq 8\, M_\odot$

s process in two steps in different evolutionary phases

production of ^{14}N by the **CNO cycles in H-burning phase**
→ rapid transformation: $^{14}N(\alpha,\gamma)^{18}F(\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne$

at the beginning of the He-burning phase:
competition between neutron source $^{22}Ne(\alpha,n)^{25}Mg$ and $^{22}Ne(\alpha,\gamma)^{26}Mg$
→ most important neutron poison: $^{25}Mg(n,\gamma)^{26}Mg$ followed by $^{22}Ne(n,\gamma)^{23}Ne$



1) **neutron exposure during convective core He-burning**: $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

$T = 0.30\,\mathrm{GK}\,(kT = 26\,\mathrm{keV}),\ n_n = 10^6\,\mathrm{cm}^{-3},\ 10^4$ years

→ He exhaustion
→ carbon burning

2) **neutron exposure during later convective carbon burning** $^{12}\mathrm{C}(^{12}\mathrm{C},n)\mathrm{Mg}^{23}$

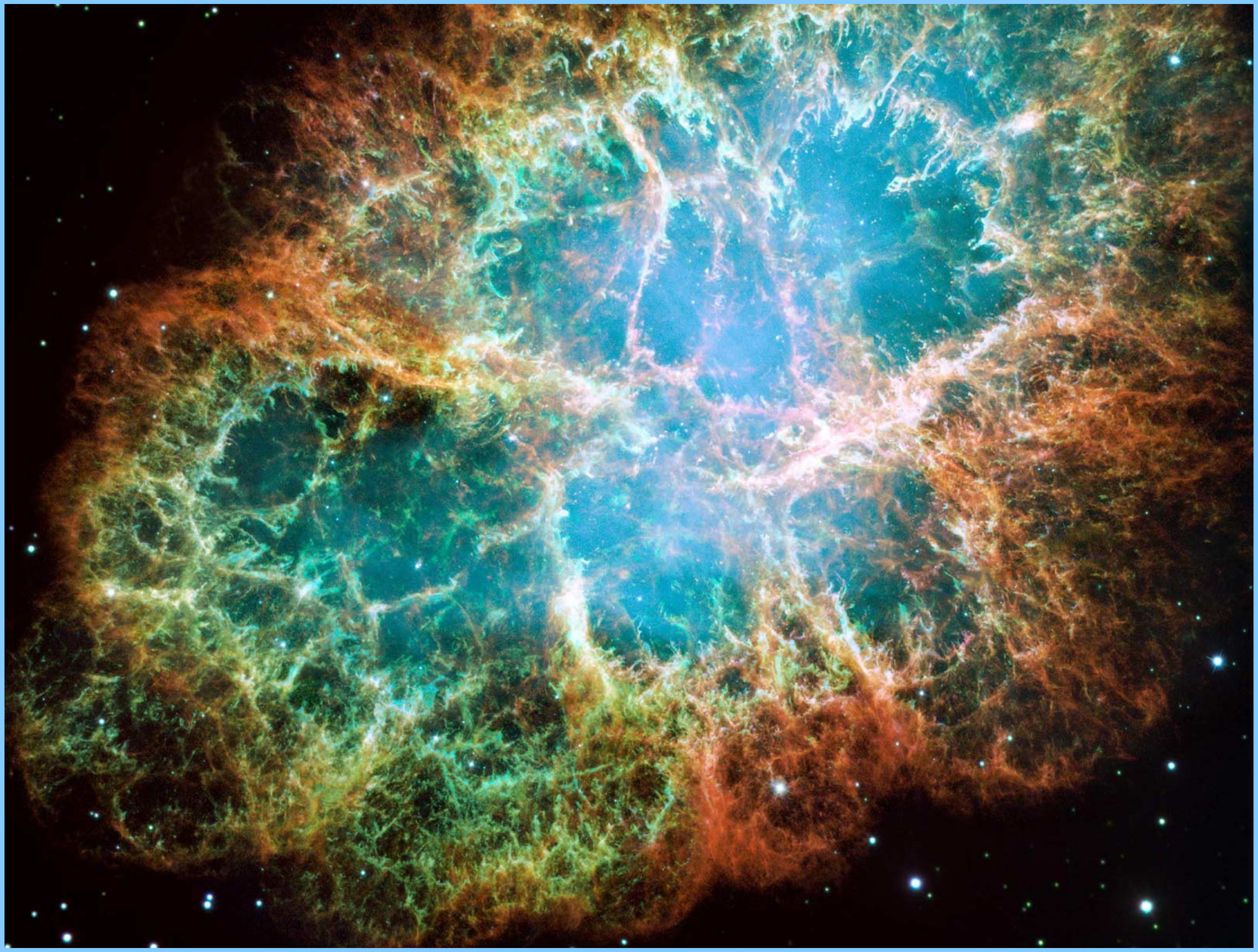
exposure of part of the material synthesized by the first production

$T = 1\,\mathrm{GK}\,(kT = 91\,\mathrm{keV}),\ n_n = 10^{11}$ to $10^{12}\,\mathrm{cm}^{-3}$, 1 year

→ since not all $^{22}\mathrm{Ne}$ is consumed, neutron production via $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ continues
(α-particles via $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ -reaction channel)

→ contributing to weak s-process component, $A \leq 90$
→ **small neutron exposure during He-burning, higher during C-burning**
→ **reprocessing of most of the synthesized material** by following burning stages

→ destruction of previous s-process signature in mass fraction up to $3.5\,M_\odot$ during explosive nucleosynthesis of supernova II
→ preservation of s-process abundances in mass fraction of $2.5\,M_\odot$



Neutron Economy during s-process Nucleosynthesis

Dependence on:

- (I) abundance of the neutron source nuclei $^{22}\mathrm{Ne}$ and $^{13}\mathrm{C}$
- (II) abundance of the seed nuclei $^{56}\mathrm{Fe}$ and other iron-peak species
- (III) abundances of any neutron poison
- (IV) cross section of the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ - and the $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ -reaction
- (V) initial stellar mass
- (VI) stellar metallicity
- (VII) strength of the $^{13}\mathrm{C}$ pocket
- (VIII) choice of mass loss rate

neutron poison: process of capturing and hence removing neutrons so that these neutrons will not contribute to the production of s-process nuclei

relevant reaction:

- $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ with $^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}$ followed by $^{22}\mathrm{Ne}(\mathrm{n},\gamma)^{23}\mathrm{Ne}$
  → $^{25}\mathrm{Mg}$ has large neutron capture cross section

- $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ with $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}$ and $^{16}\mathrm{O}(\mathrm{n},\gamma)^{17}\mathrm{O}$
  → $^{12}\mathrm{C}$ no neutron poison because of $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$
  → $^{16}\mathrm{O}$ potential neutron poison because of the competition of $^{16}\mathrm{O}(\mathrm{n},\gamma)^{17}\mathrm{O}(\alpha,\mathrm{n})^{20}\mathrm{Ne}$
  with $^{16}\mathrm{O}(\mathrm{n},\gamma)^{17}\mathrm{O}(\alpha\gamma)^{21}\mathrm{Ne}$

What is Branching?

→ competition between neutron capture and β^- -decay at unstable isotopes if half-life comparable to the neutron capture time

Mathematical Explanation: $\langle\sigma\rangle_A \overline{N_s(A,\tau_0)} = \frac{f\,N_s^{seed}(56)}{\tau_0} \prod_{i=56}^{A} \frac{1}{[1+\frac{1}{\tau_0\langle\sigma\rangle_i}]}$

former assumptions: s-process path is unique at each mass number A, i.e. $\lambda_\beta \ll \lambda_{n\gamma}$ or $\lambda_\beta \gg \lambda_{n\gamma}$

BUT sometimes: $\lambda_\beta \approx \lambda_{n\gamma}$ ==> path splits into two branches

$$\boxed{f_\beta = \frac{N_s(A,\tau)\langle\sigma\rangle_A}{N_s(A+1,\tau)\langle\sigma\rangle_{A+1}} = \frac{\lambda_\beta(A')}{\lambda_\beta(A')+\lambda_{n\gamma}(A')}}$$

<u>"branching factor"</u>

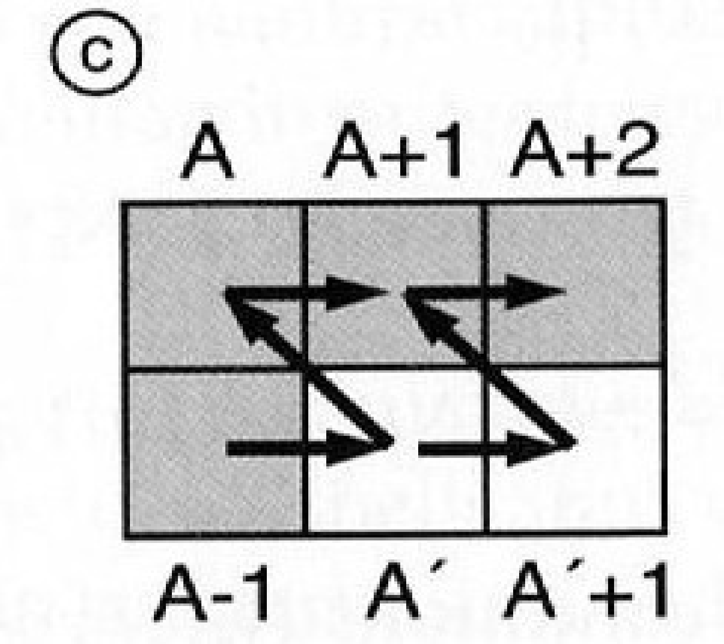
$\beta-$decay rate: $\lambda_\beta = \frac{\ln 2}{t_{1/2}}$

neutron capture rate: $\lambda_n = n_n\, v_T \langle\sigma\rangle$

n_n: neutron density

v_T: mean thermal velocity

$\langle\sigma\rangle$: MACS for the radioactive branch point nucleus



→ path split in two parts at unstable A'
→ entire path through stable (A+1)

APPLICATION:

- test of the s-process prescriptions
- providing informations about characteristic physical parameters/constraints:

→ branching informations: (n_n, T, ρ)

$$n_n = \left[\frac{N_s(A+1,\tau)\langle\sigma\rangle_{A+1}}{N_s(A,\tau)\langle\sigma\rangle_A} - 1 \right] \frac{1}{\langle\sigma\rangle_{A'} v_T} \frac{\ln 2}{t_{1/2}(A')} = \frac{1-f_\beta}{f_\beta} \frac{1}{\langle\sigma\rangle_{A'} v_T} \frac{\ln 2}{t_{1/2}(A')}$$

→ global fit to the observed $N_\odot(A)\langle\sigma\rangle_A$ distribution for s-only nuclides $(f, \tau_{0,} n_c)$

Neutron Capture Cross Section

-Maxwellian Averaged Neutron Cross Section MACS-

assumption:

Maxwell-Boltzmann distribution of the neutron energy distribution $\Phi = \frac{dN}{dE_n} \sim \sqrt{E_n} \exp\left(\frac{-E_n}{kT}\right)$

$\boxed{\langle \sigma \rangle = \frac{\langle \sigma v \rangle}{v_T}}$ and approximation $\boxed{\langle \sigma v \rangle \approx \text{const.}}$ (especially heavy elements)

with $\langle \sigma v \rangle$: product of the average cross section with the average thermal velocity

$$\langle \sigma v \rangle = \int_0^\infty \sigma v \phi(v) dv$$

$$v_T = \sqrt{\left(\frac{2kT}{\mu_n}\right)} \; ; \; \mu_n = \frac{M_n M_A}{M_n + M_A} \; ; \; \phi(v) dv = \frac{4}{\sqrt{\pi}} \left(\frac{v}{v_T}\right)^2 \exp\left[-\left(\frac{v}{v_T}\right)^2\right] \frac{dv}{v_T} \quad \text{with} \quad \phi = \frac{2}{\sqrt{\pi}} n_n v_T$$

$$\Longrightarrow \boxed{\langle \sigma \rangle_{kT} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma(E_n) E_n e^{-\frac{E_n}{kT}} dE_n}{\int_0^\infty E_n e^{-\frac{E_n}{kT}} dE_n}}$$

MACS (for kT = 30keV)

example of estimation:

characteristic cross section: $\langle \sigma \rangle \approx 100\,\mathrm{mb}$

characteristic thermal velocity $v_T \approx 3 \cdot 10^8 \dfrac{\mathrm{cm}}{\mathrm{sec}}$

$\rightarrow \langle \sigma v \rangle \approx 3 \cdot 10^{-17} \dfrac{\mathrm{cm}^3}{\mathrm{sec}}$

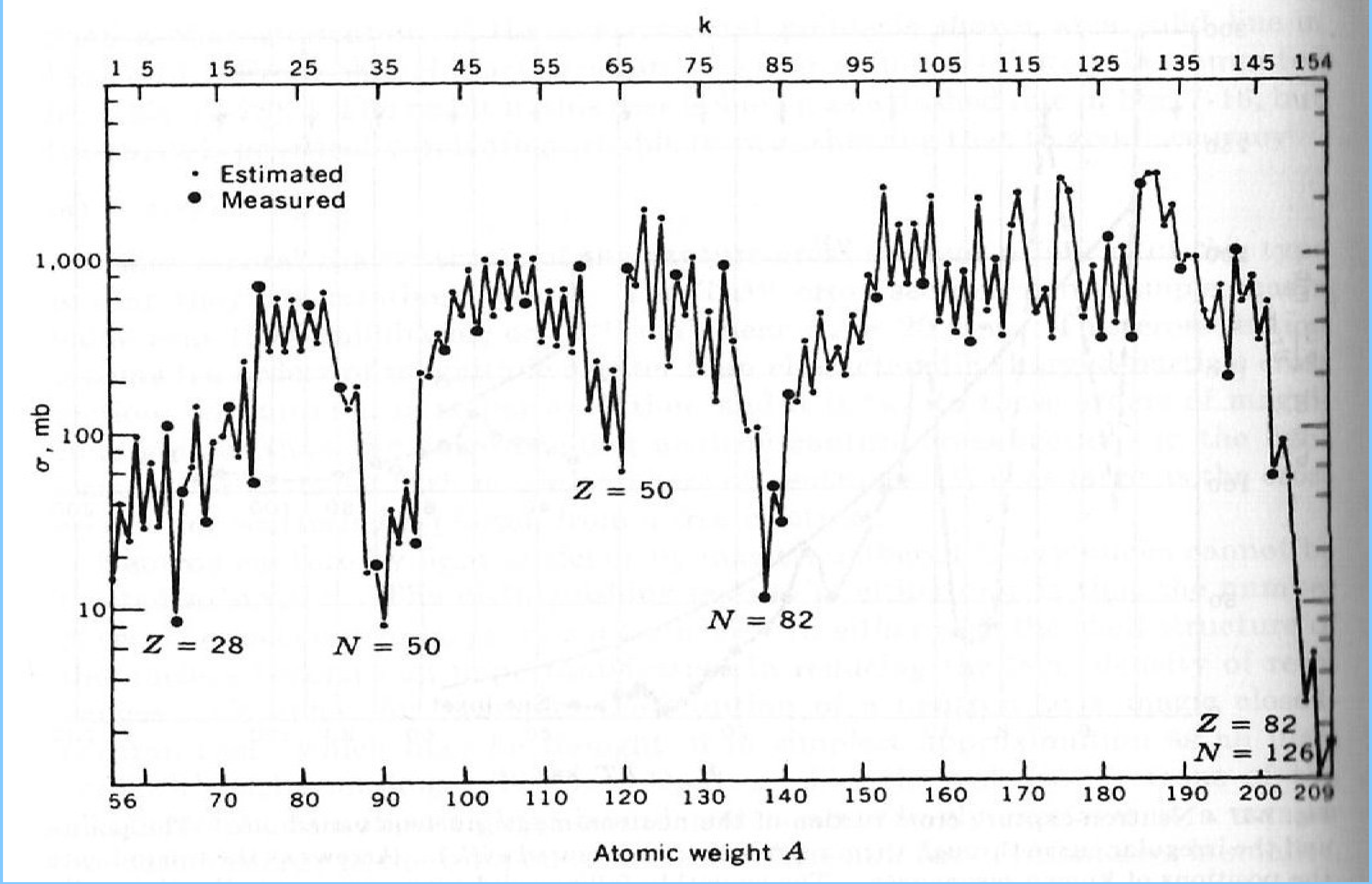
lifetime of nucleus against neutron capture $\boxed{\tau_n = \dfrac{1}{n_n \langle \sigma v \rangle}}$

here $\approx \dfrac{3 \cdot 10^{16}}{n_n} \mathrm{sec} \approx \dfrac{10^9}{n_n} \mathrm{years}$

s process: $\tau_n \approx 10^4\,\mathrm{years}$, $n_n \approx 10^5\,\mathrm{cm}^{-3}$
p process: $\tau_n \leq 1\,\mu\mathrm{sec}$, $n_n \approx 10^{23}\,\mathrm{cm}^{-3}$
cf. thermal neutron density in reactor $n_n \approx 10^7\,\mathrm{cm}^{-3}$

ATTENTION: real energy range is from 8keV up to 90keV

→ missing experimental data gaps filled by cross section calculations
→ extrapolation with methods like R-Matrix method



general: even A-nuclei (even Z, even N) → small MACS

- smallest MACS: magic neutron numbers

  N=50: Sr^{88}, Y^{89}, Zr^{90}

  N=82: $Ba^{138}, La^{139}, Ce^{140}, Pr^{141}$

  N=126: Pb^{208}, Bi^{209}
- small MACS: light elements $56 \le A \le 90$

Measuring MACS: The Time-of-flights Method

aim: measurements of neutron-capture cross sections over a sufficiently large neutron energy rang

experimental method:
spallation reactions induced by energetic particle beams
for example at **LANSCE at Los Alamos** **or** **at n_TOF at CERN**

data:
proton beam energy: $800\,\mathrm{MeV} \le E_p \le 20\,\mathrm{GeV}$
highest neutron flux: $5 \cdot 10^5\,\mathrm{s}^{-1}$

detectors:

- 4π -detectors
- Moxon-Rae-type detectors
- PHWT pulse height weighting technique proportionality
  (off-line weighting function+Monte Carlo)

PROBLEM: response to neutrons scattered in the sample and background from isotope activity
→ solution: absorber shell around the sample

EXAMPLE: **FRANZ**

Frankfurt Neutron Source at the Stern-Gerlach-Zentrum by University of Frankfurt

short neutron pulses by bombardment of a $^{7}\mathrm{Li}$-target with an intense proton beam

proton energy: $E_p \leq 2.0 \pm \mathrm{MeV}$

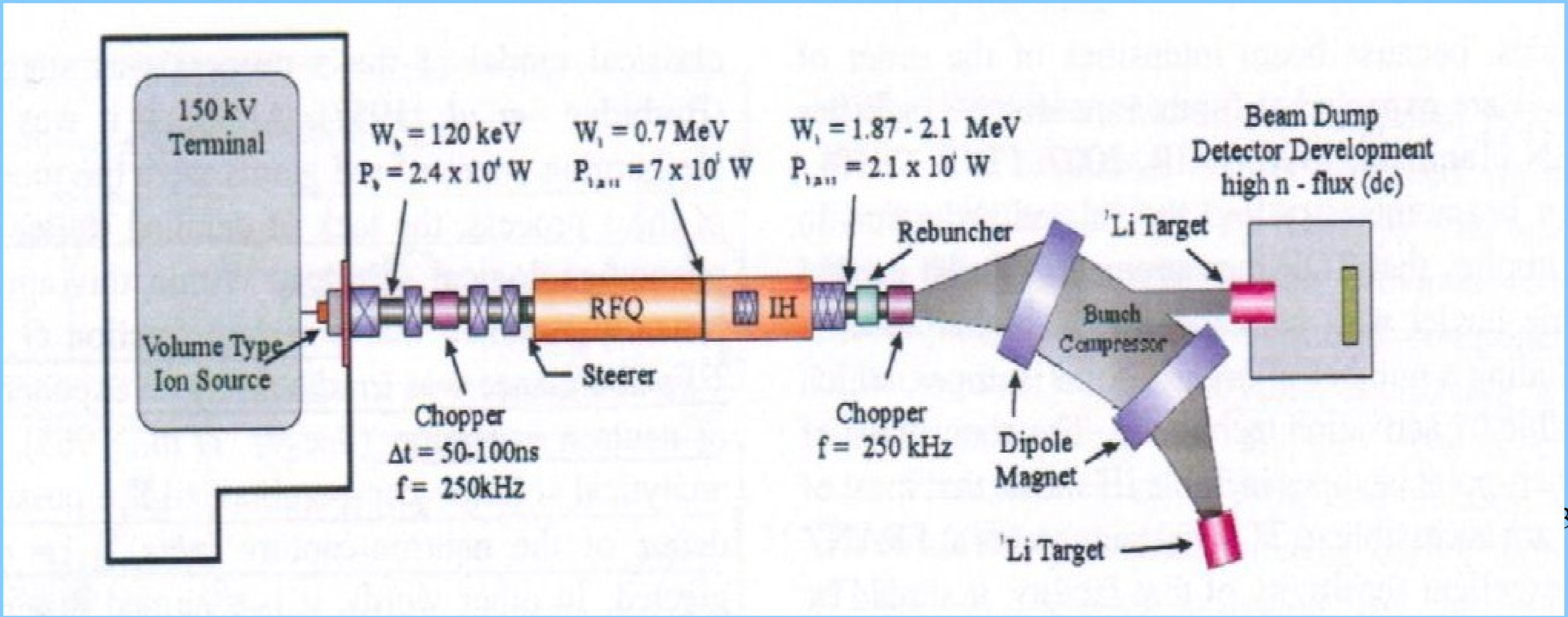
pulse rate: 250 kHz

pulse intensity: $I \leq 5 \cdot 10^{10} \frac{\mathrm{protons}}{\mathrm{ns}}$

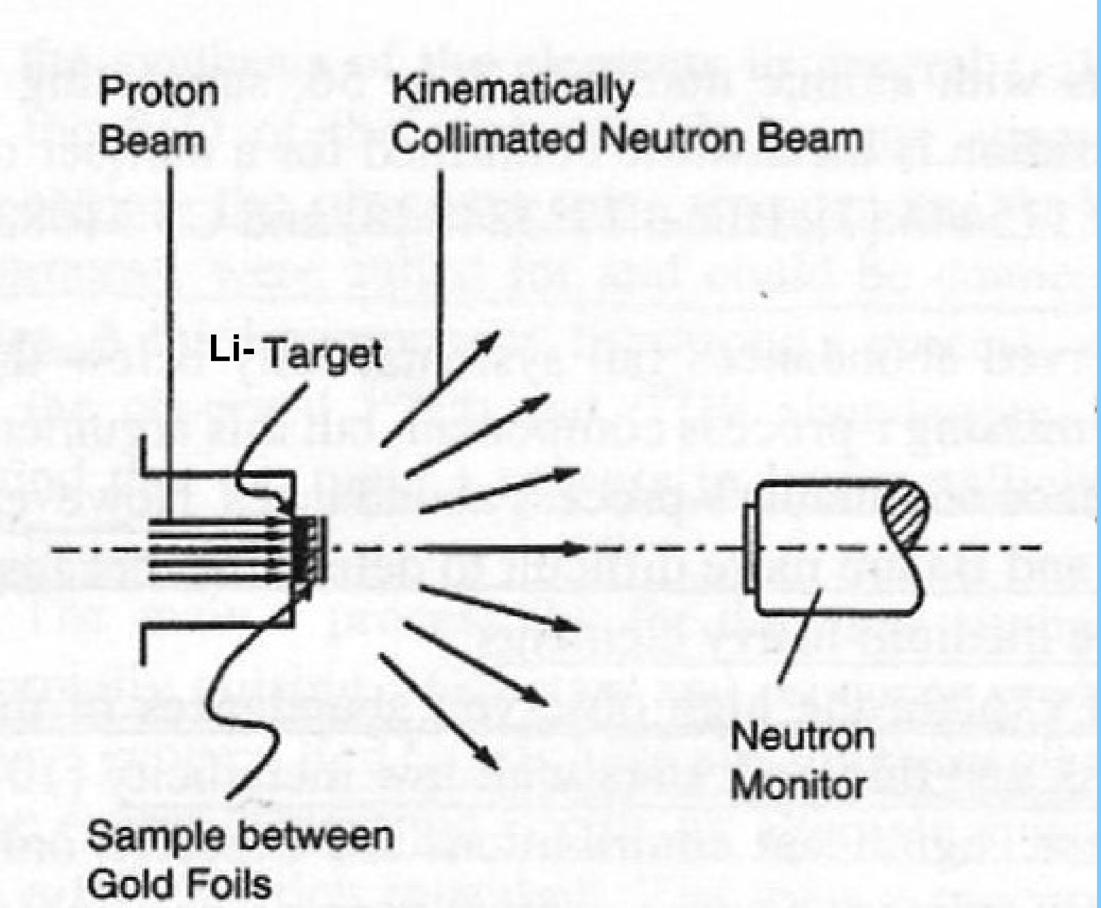
beam current: 2mA

→ little samples (unstable isotopes with higher activity, number of branch-point isotopes, which are not accessible by activation method)

→ simulation of stellar neutron spectra via $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction



Measuring MACS: Activation Method



Determination of MACS at kT = 25 keV
→ quasistellar neutron spectrum produced by $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction

Karlsruhe 3.7 MV van de Graaff accelerator

proton beam $E_p = 1912\,\mathrm{keV}$

intensity $I = 100\,\mu\mathrm{A}$

→ $n_n \leq 10^9\,s^{-1}$ achieved for the (p, n) reactions

→ all neutrons are emitted in forward direction

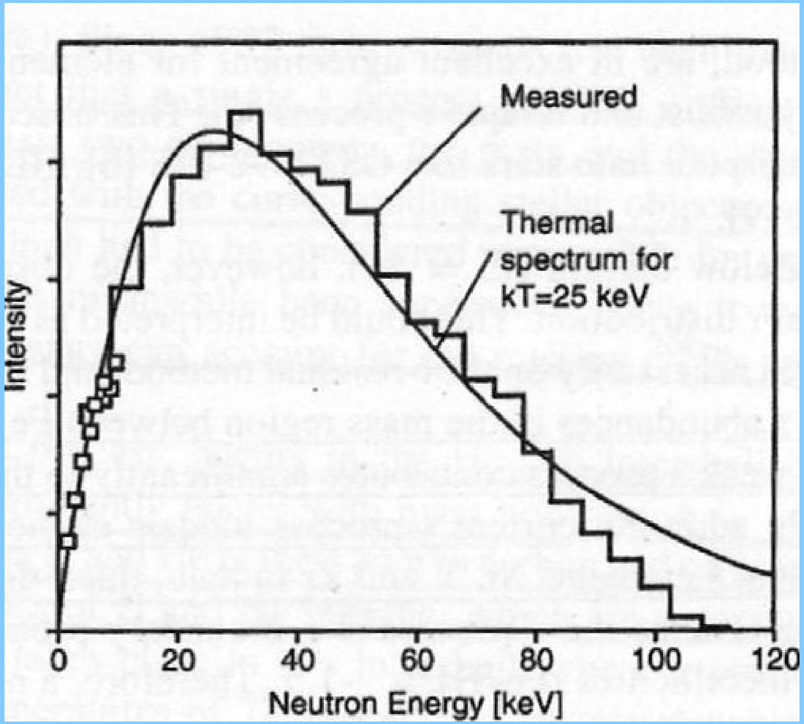
→ backgrounds from scattered neutrons are negligible

total number of activated nuclei A : $\boxed{A = \Phi \cdot N \cdot \sigma \cdot f_b}$

Φ : time integrated neutron flux
N : number of sample atoms per cm²
σ : spectrum averaged neutron capture cross section
f_b : factor for variation of neutron flux and for the decay during the activation

the number of counts in a characteristic γ-ray line: $\boxed{C_\gamma = A \cdot K_\gamma \cdot \epsilon_\gamma \cdot I_\gamma \cdot (1 - \exp(-\lambda t_m)) \cdot \exp(-\lambda t_w)}$

K_γ : correction factor for γ − ray self − absorption
ϵ_γ : efficiency of the detector
I_γ : line intensity
t_m : duration of the activity measurement
t_w : waiting time between irradiation and counting

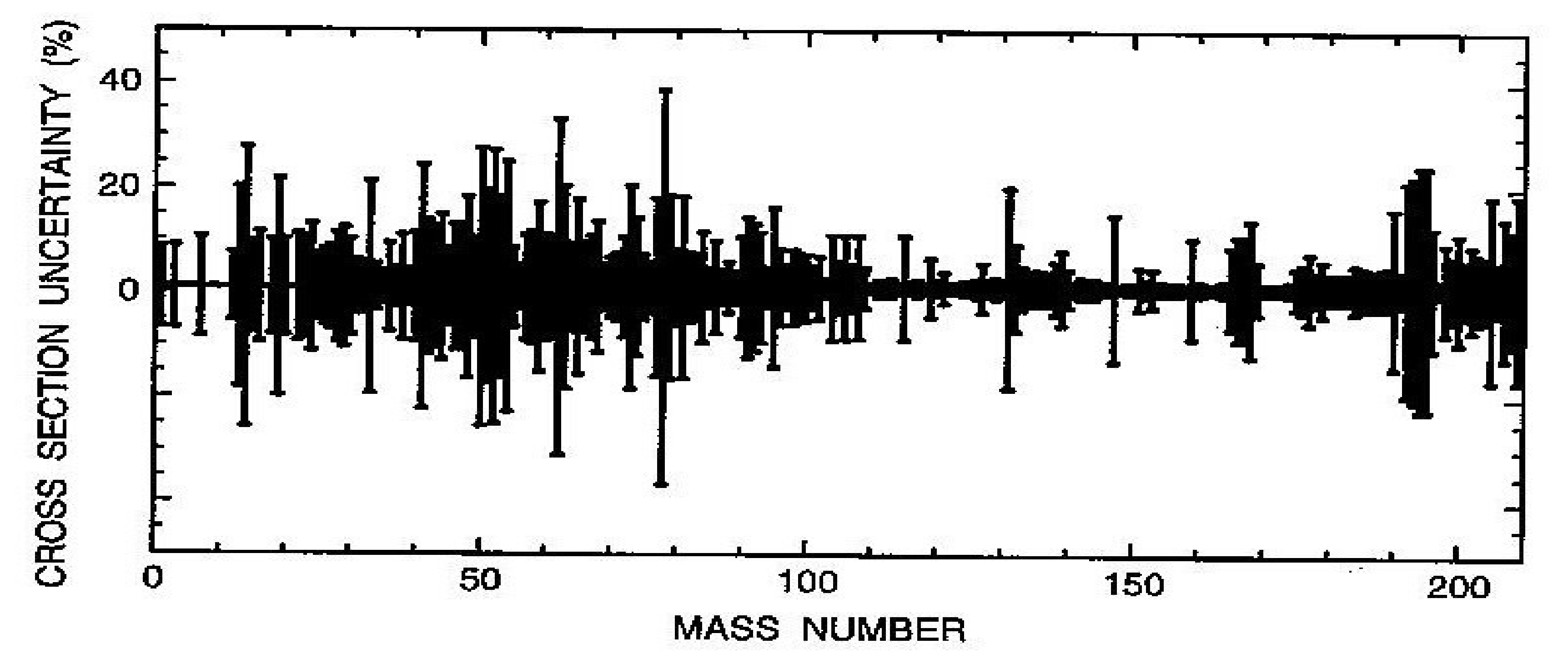


Comparison of the produced neutron spectrum and a thermal spectrum

Features:

- restricted to cases where the neutron-capture produces an unstable nucleus
- good approximation of stellar neutron spectra in laboratory
- simple realization
- great sensitivity
- unambiguous identification of reaction products
- insensitive to the reaction mechanism

==> Activation method represents the most sensitive method for (n,γ) measurements in the astrophysical energy range.



Uncertainties of the stellar (n,γ) cross section for s-process nucleosynthesis (at thermal energy kT = 30 keV)

Outlook

- **observational constraints** via abundances of elements with magic neutron numbers
of **Sr, Y, Zr (light s-process elements, ls)**
of **Ba, La, Ce, Nd, Sm (heavy s-process elements, hs)**
and Pb act as bottlenecks for the s-process reaction path
==> **[hs/ls] and [Pb/hs] ratios**

- **observation of AGB stars, post-AGB stars, planetary nebulae, binary systems**
by (high-resolution) spectroscopy, large telescopes

- **CEMP-s stars / CEMP-s/r stars**

- **galactic chemical evolution GCE**
→ other neutron capture processes: LEPP light element primary process

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