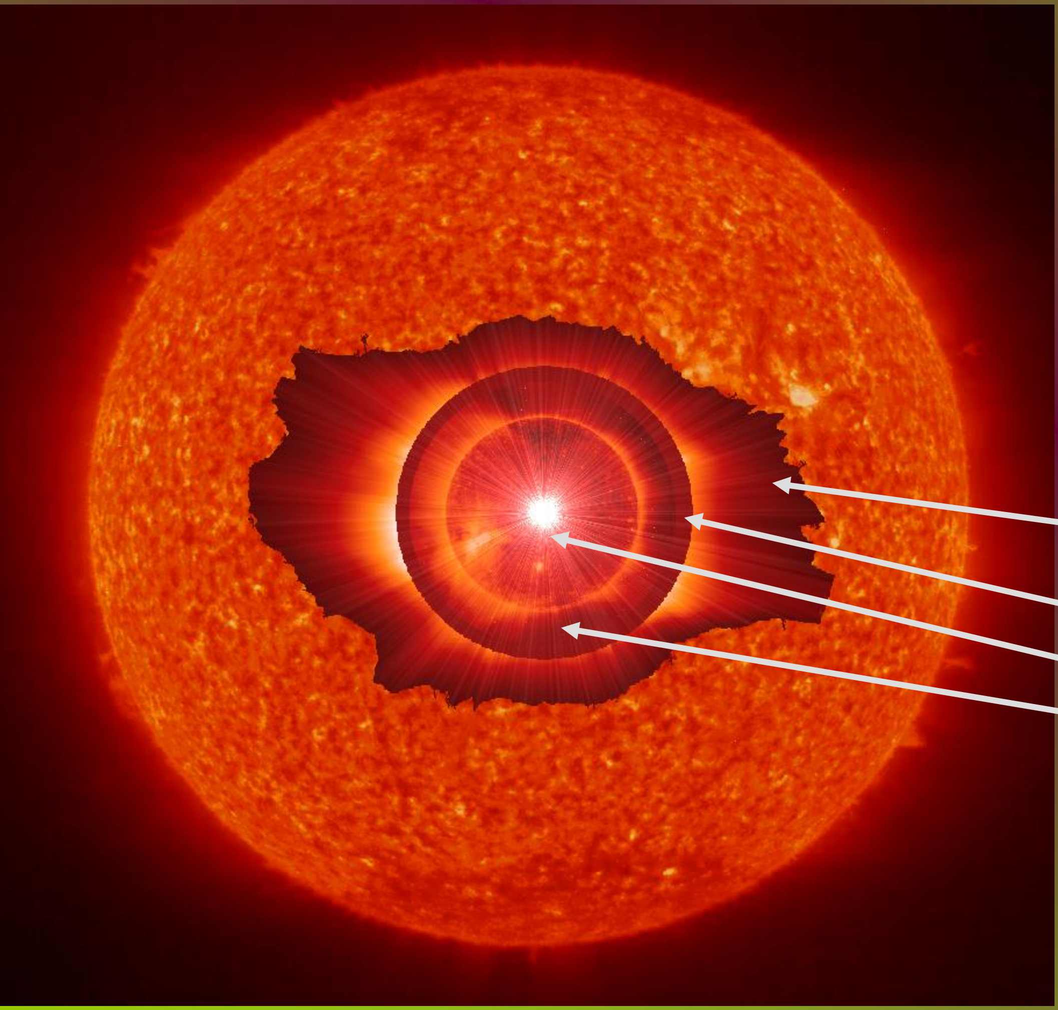
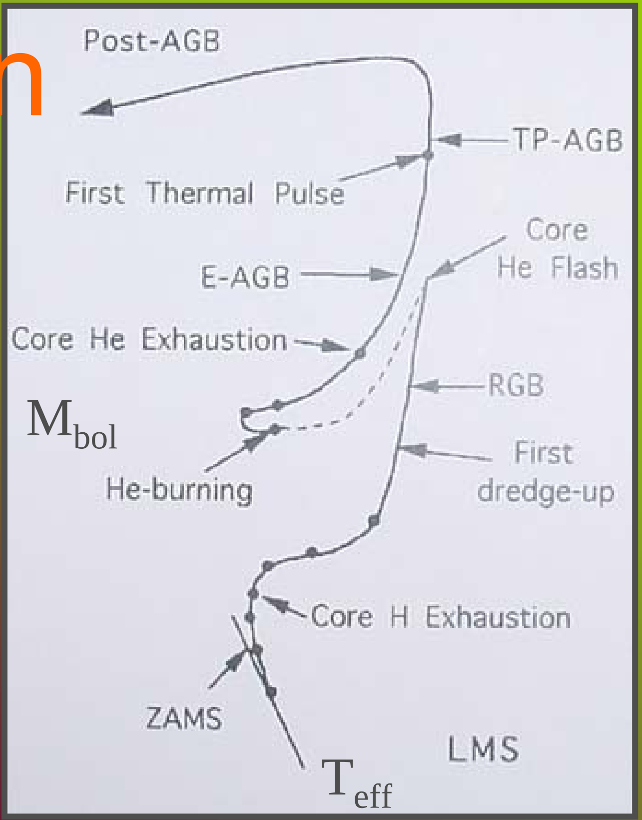
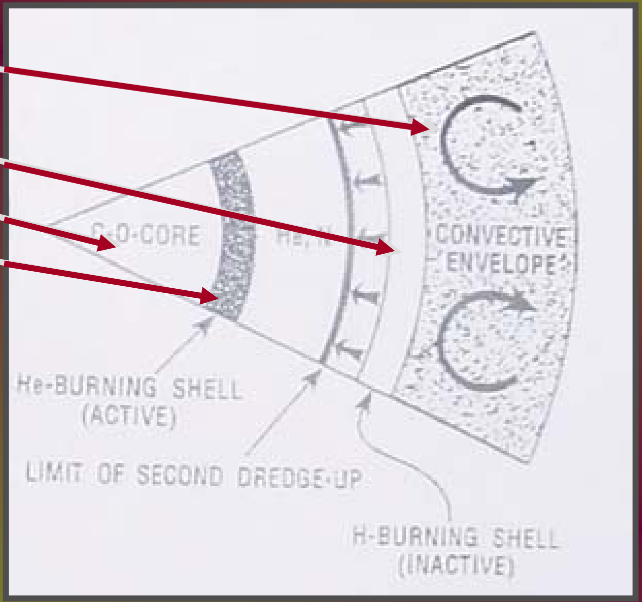
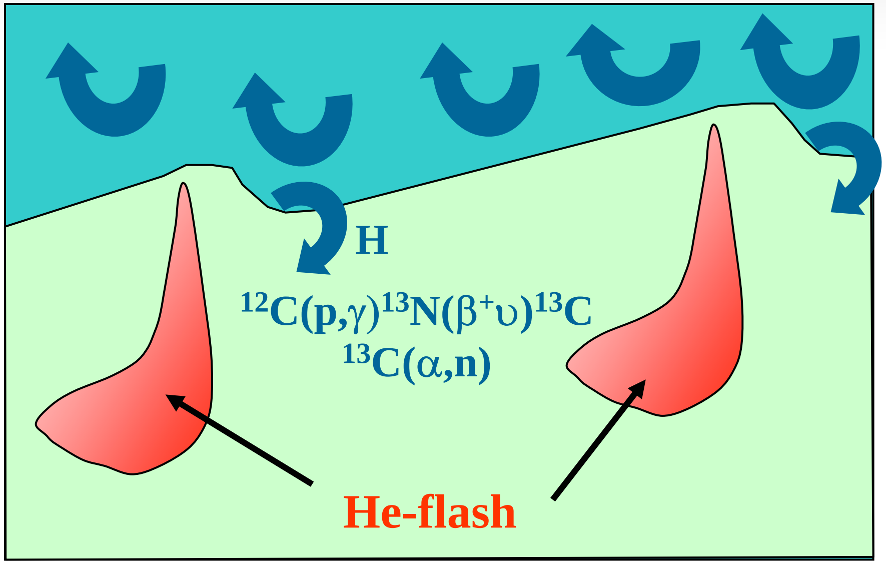
Structure and evolution of AGB stars







The main s-process in AGB stars



H

$^{12}C(p,\gamma)^{13}N(\beta^{+}\upsilon)^{13}C$

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

He-flash

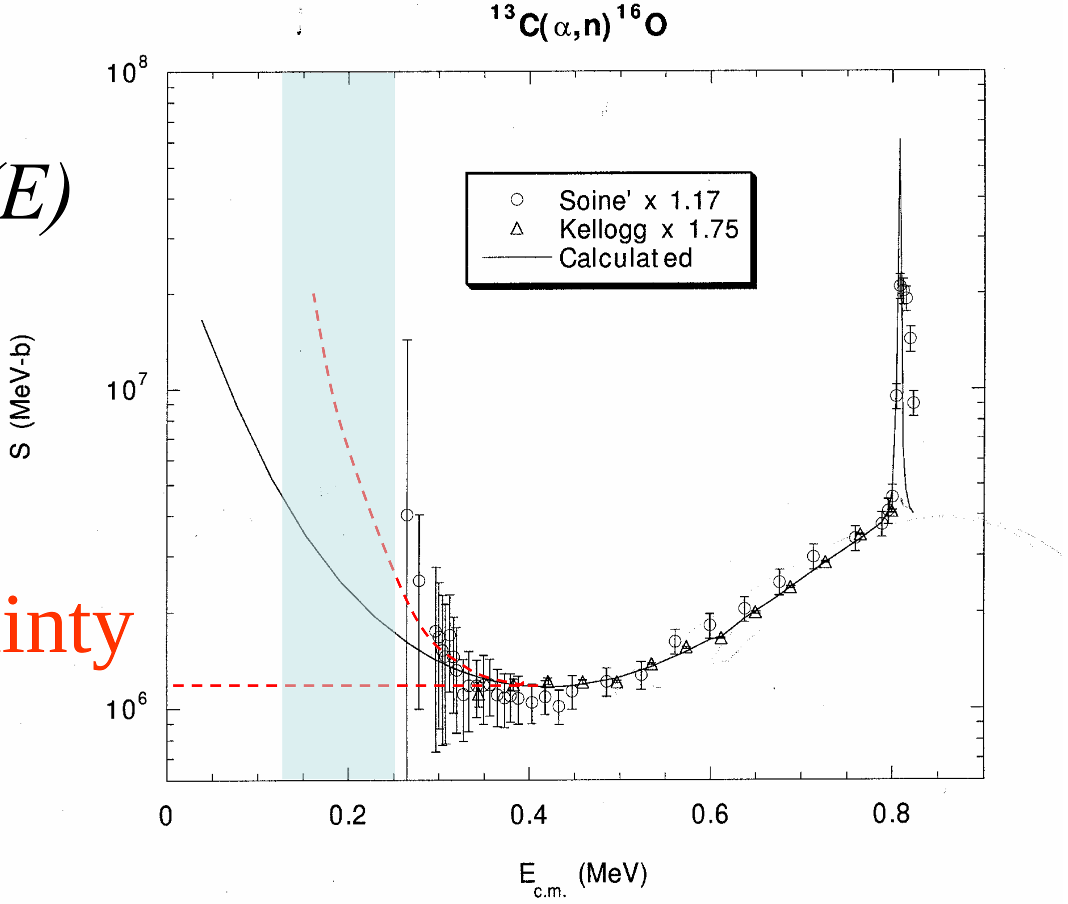
neutron source $^{13}C(\alpha,n)^{16}O$

$$\frac{dY_{^{13}C}}{dt} = -Y_{^{13}C} \cdot Y_{^{4}He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(\alpha,n)} + Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)}$$

$$\frac{dY_n}{dt} = -\sum_x Y_X \cdot Y_n \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{X(n,\gamma)} + Y_{^{13}C} \cdot Y_{^{4}He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(\alpha,n)}$$

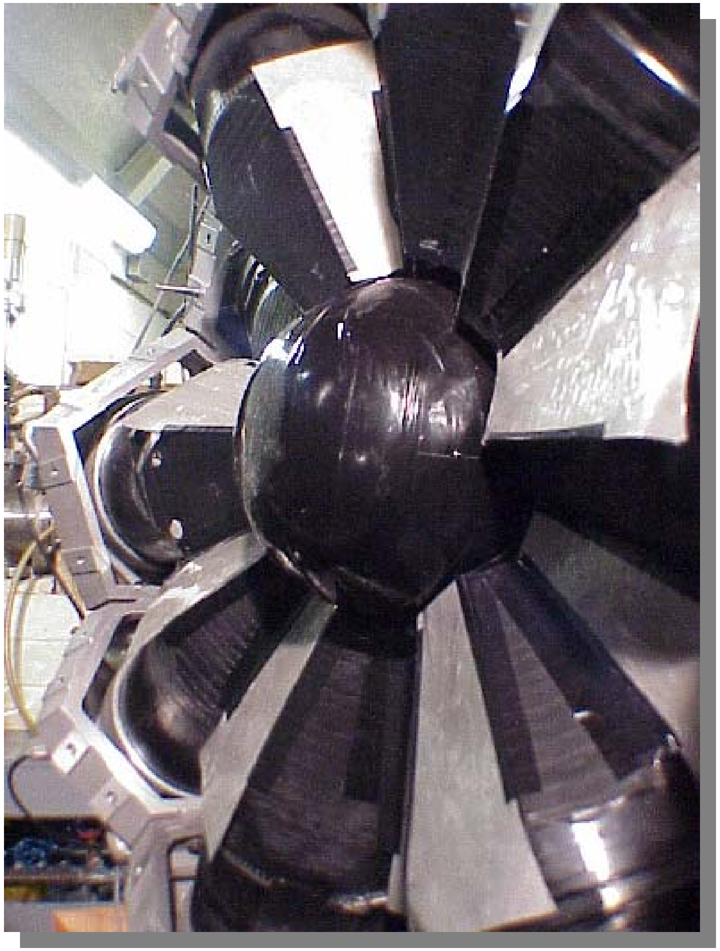
Present status on $^{13}C(\alpha,n)^{16}O$

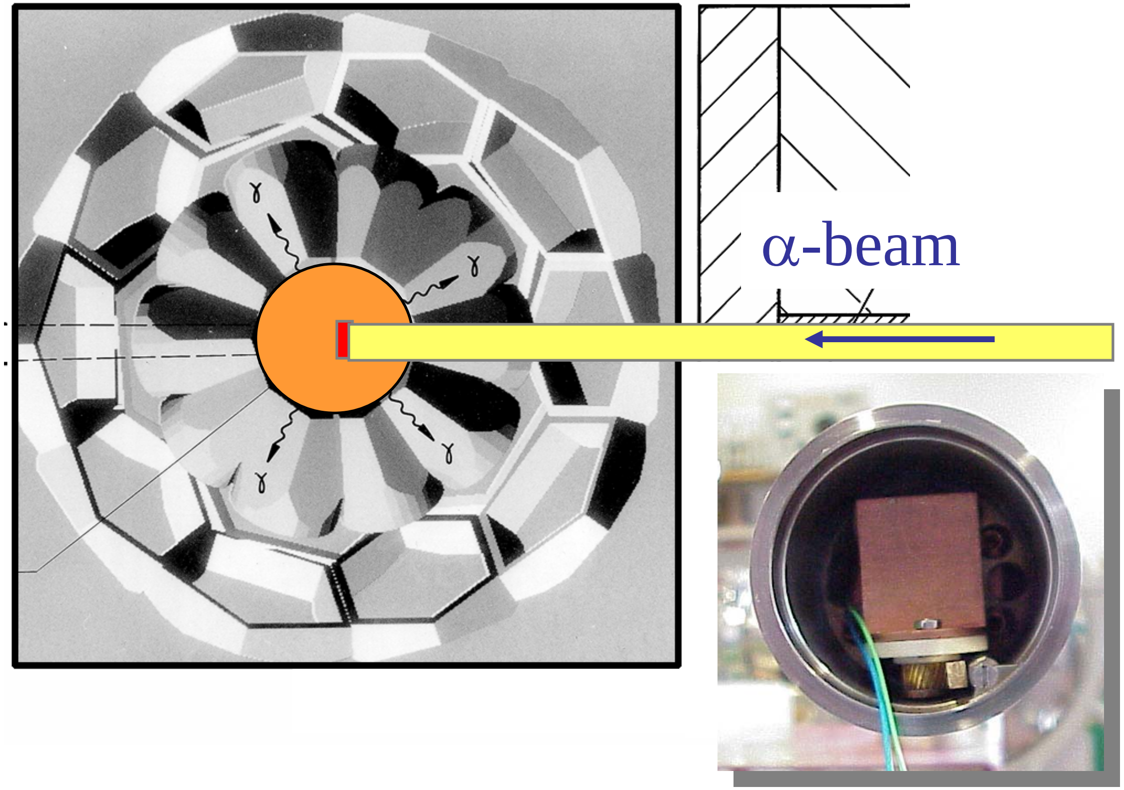
$$\sigma(E) = \frac{1}{E} \exp(2\pi\eta)\, S(E)$$



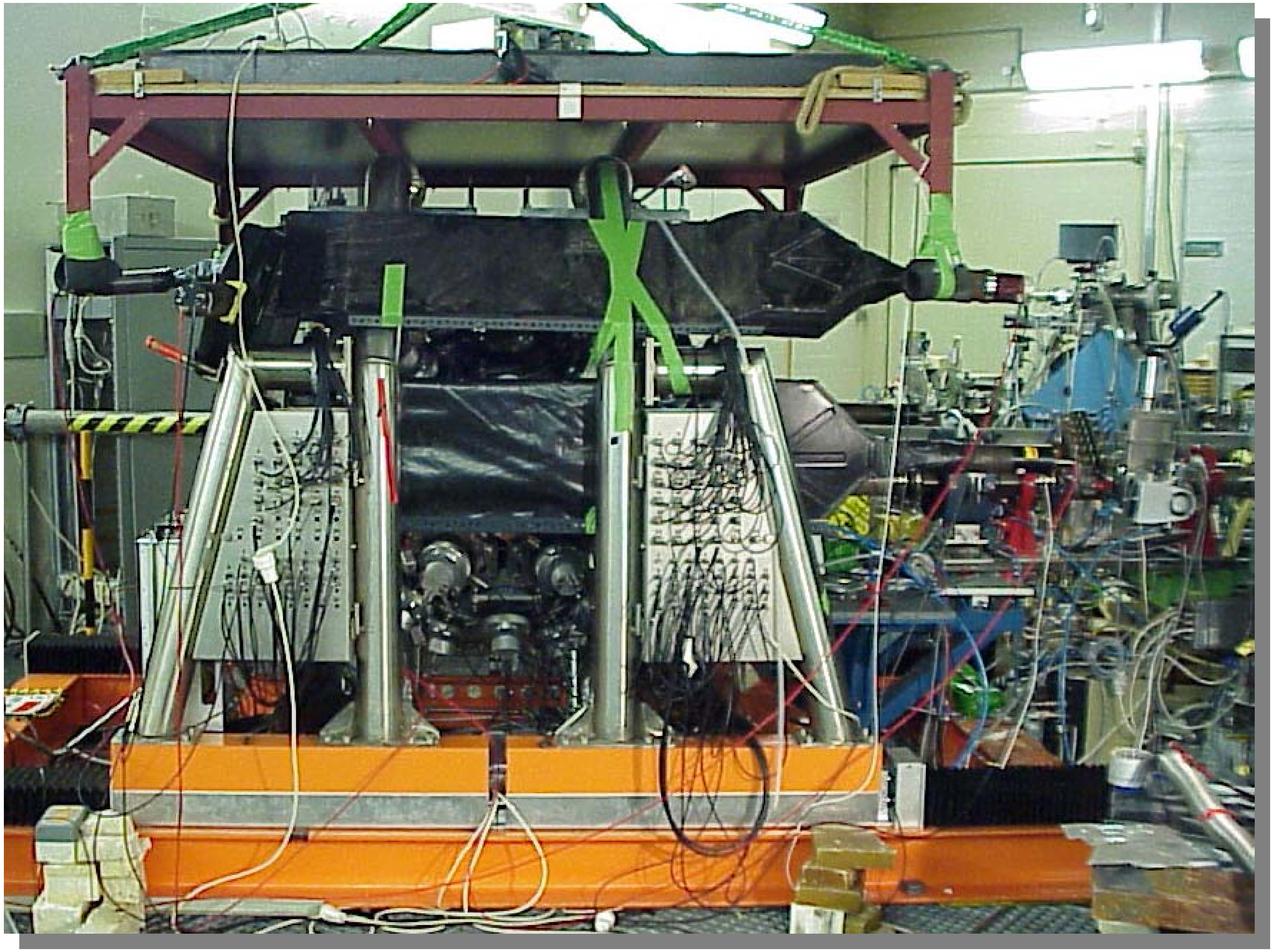
Previous experiments
Indicate large uncertainty
In low energy range!

Low-energy, low-background Experiment with 4π BaF_2 γ-array





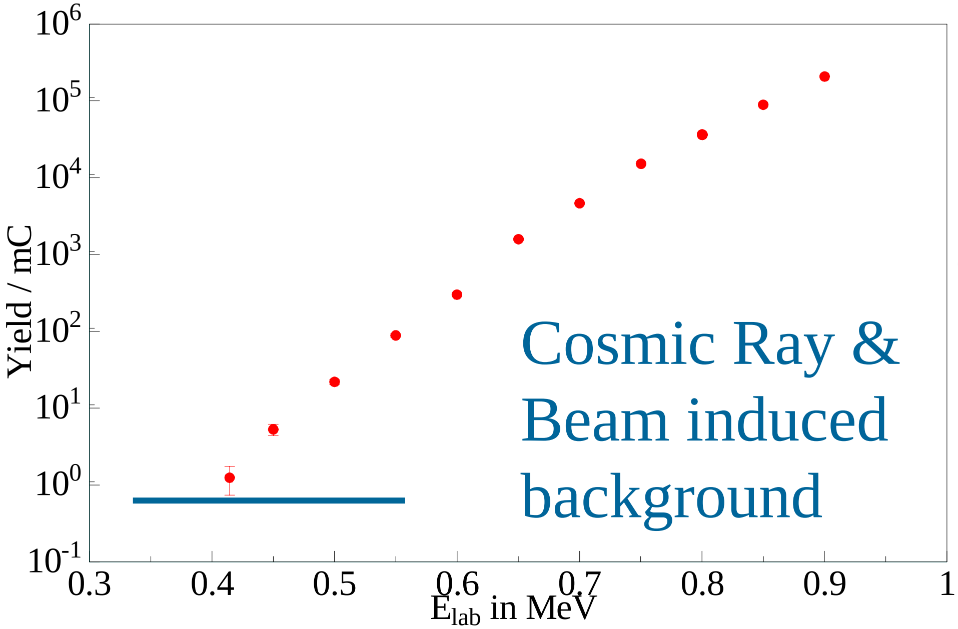
Experimental Set-Up@FZ-Karlsruhe



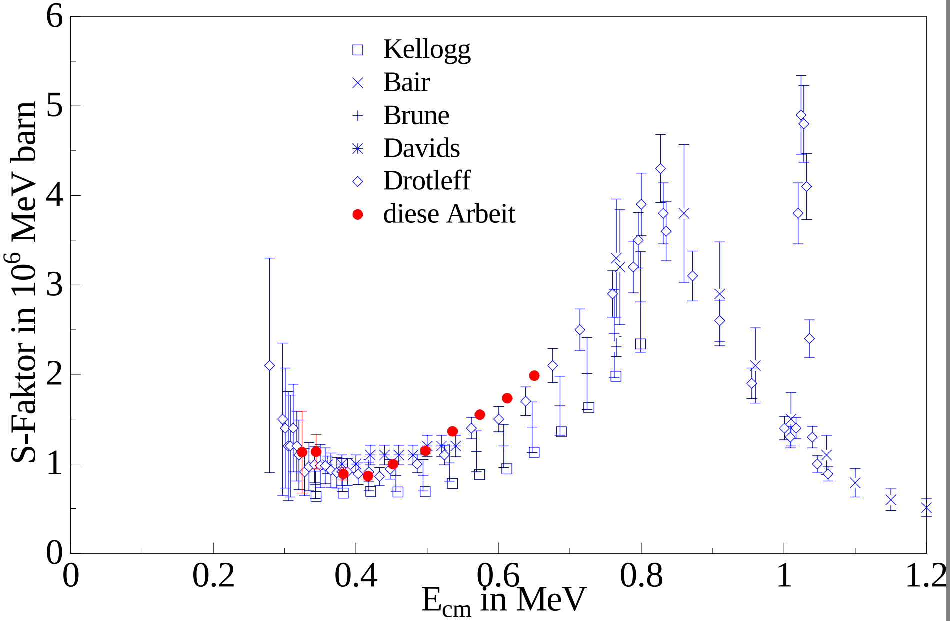
Active shielding techniques;

Pulse shape analysis;

Low energy reaction yield of $^{13}C(\alpha,n)^{16}O$

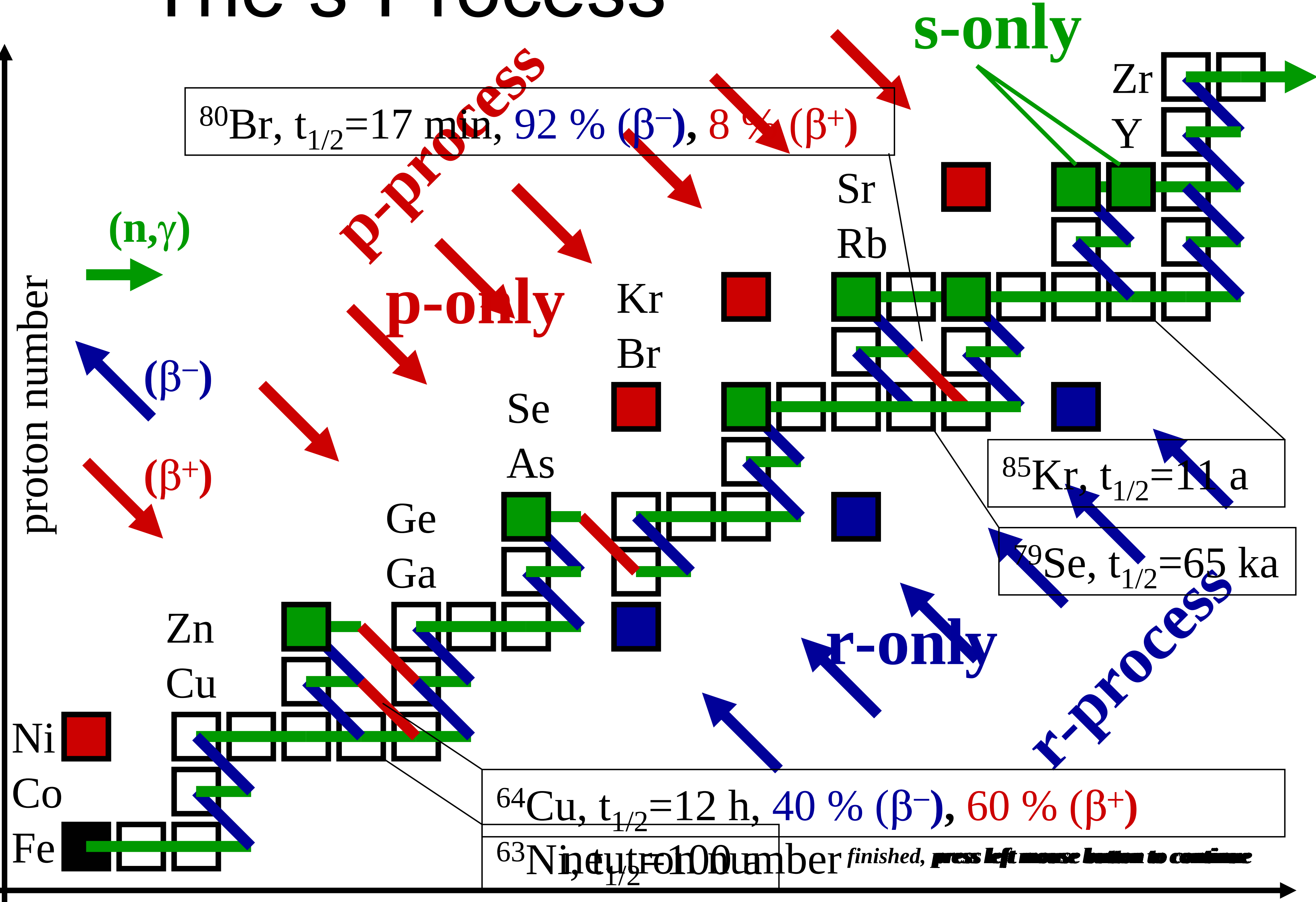


Cosmic Ray & Beam induced background



1 order of magnitude improvement in background reduction necessary!

The s-Process



^{80}Br, $t_{1/2}$=17 min, 92 % (β−), 8 % (β+)

^{85}Kr, $t_{1/2}$=11 a

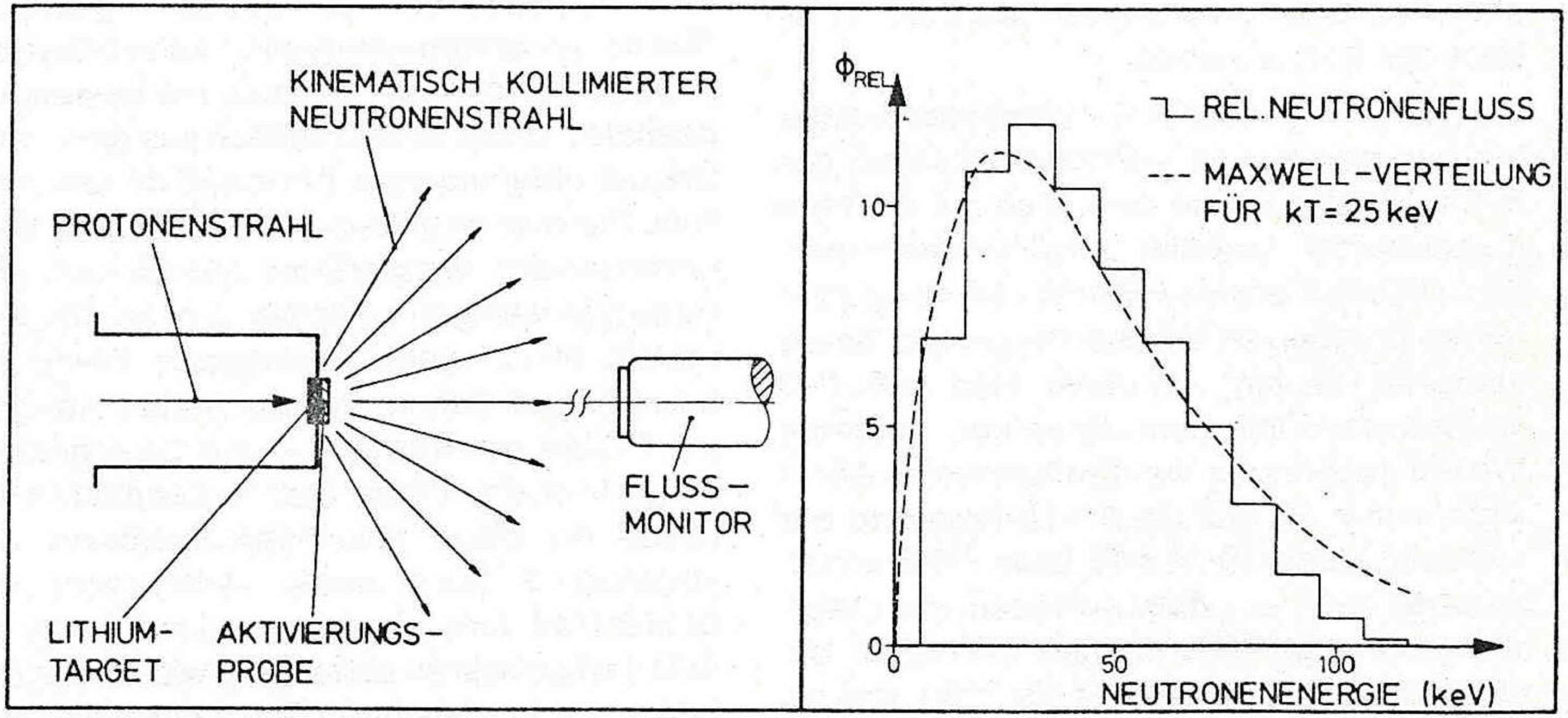
^{79}Se, $t_{1/2}$=65 ka

^{64}Cu, $t_{1/2}$=12 h, 40 % (β−), 60 % (β+)

^{63}Ni, $t_{1/2}$=100 a

finished, ***press left mouse button to continue***

s-process studies in lab

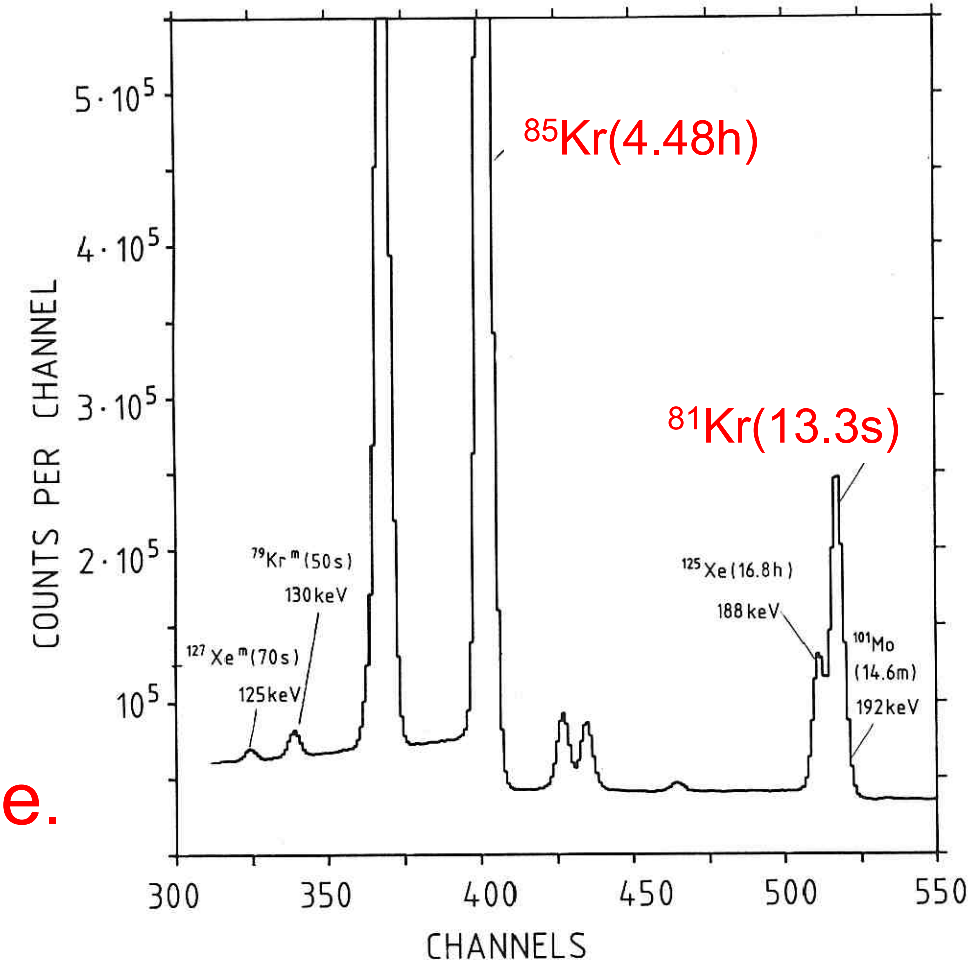


Neutron production by ^{7}Li(p,n) reaction at 1.98 MeV: Neutron spectrum resembles a kT=30keV Maxwell Boltzmann spectrum!

Activation Method

MB neutron spectrum bombardment of natural sample (mg) e.g. Krypton gas.

^{80}Kr(n,γ)^{81}Kr(β--γ)
^{84}Kr(n,γ)^{85}Kr(β^--γ)
^{86}Kr(n,γ)^{87}Kr(β^--γ)



Measurement of resulting γ-activity yields cross section & reaction rate.

Cross section determination by activation method

$$A\left(t_{irr}\right)=P\cdot\left(1-e^{-\lambda\cdot t_{irr}}\right)$$

$$\boxed{\sigma_{(n,\gamma)}=\frac{1}{\eta}\cdot\frac{I\left(t_c\right)}{N\cdot f\cdot\phi_n\cdot\left(1-e^{-\lambda\cdot t_{irr}}\right)}\cdot\frac{\lambda\cdot e^{\lambda\cdot t_w}}{\left(1-e^{-\lambda\cdot t_c}\right)}}$$

$$P=N\cdot f\cdot\phi_n\cdot\sigma_{(n,\gamma)}$$

$$A\left(t_w\right)=A\left(t_{irr}\right)\cdot e^{-\lambda\cdot t_w}$$

$$I\left(t_c\right)=\eta\cdot\int_0^{t_c}A\left(t_w\right)\cdot e^{-\lambda\cdot t_c}\cdot dt=\eta\cdot\frac{\left(1-e^{-\lambda\cdot t_c}\right)}{\lambda}\cdot A\left(t_w\right)$$

N: number of target atoms/cm^2

t_{irr}: irradiation time

t_w: waiting (transport) time

t_c: counting time

η: efficiency of detection system

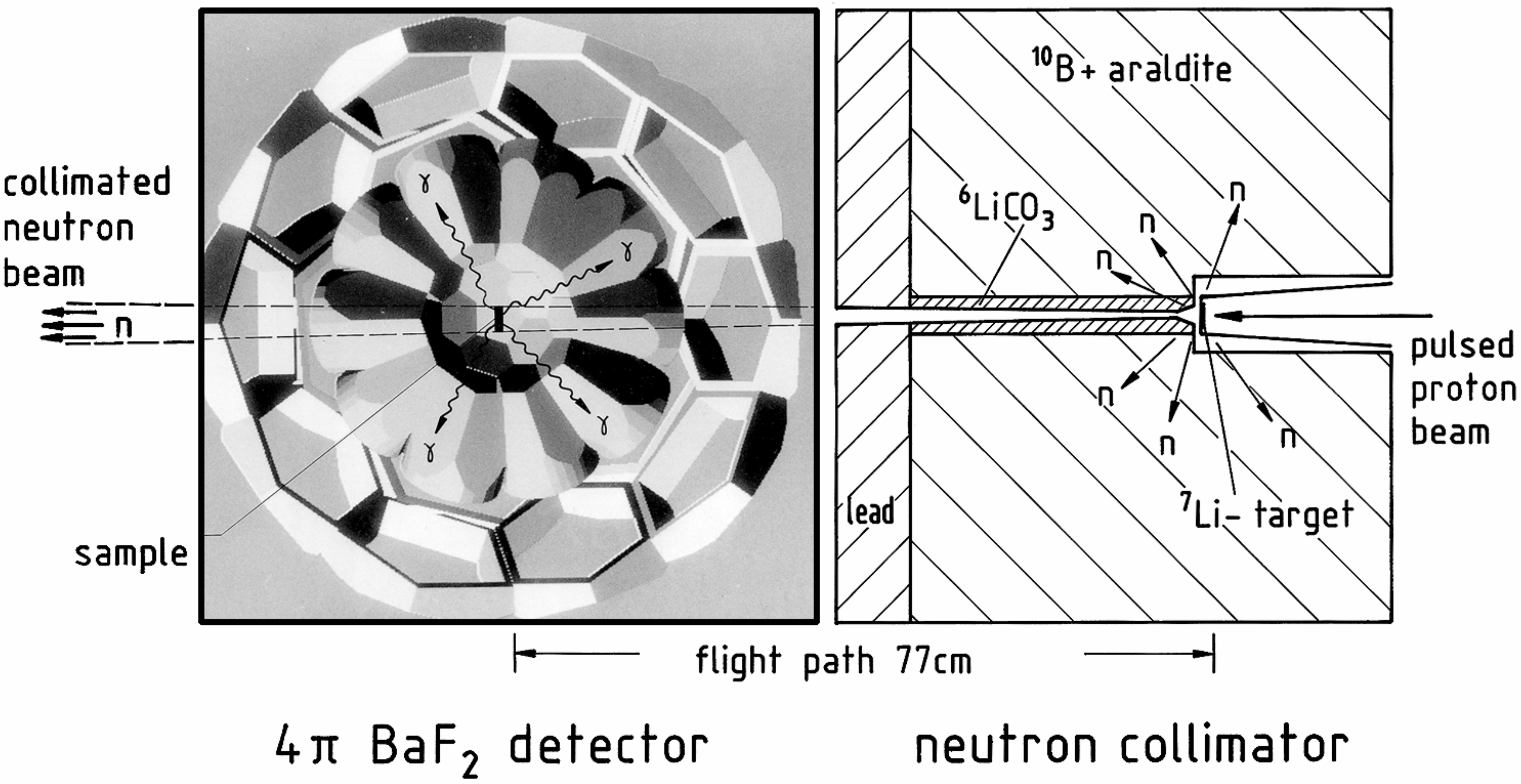
f: neutron absorption factor

$\sigma_{(n,\gamma)}$: energy averaged cross section

ϕ_n: time integrated neutron flux

$I(t_c)$: yield

Neutron sources VdG



In-beam γ-measurement for $^{A}X(n,\gamma)^{A+1}X$

In beam cross section

$$I_\gamma = \phi_n \cdot \sigma_{(n,\gamma)} \cdot N \cdot b \cdot \eta$$

I_γ: *gamma yield*

$\sigma_{(n,\gamma)}$: energy averaged cross section

ϕ_n: time integrated neutron flux

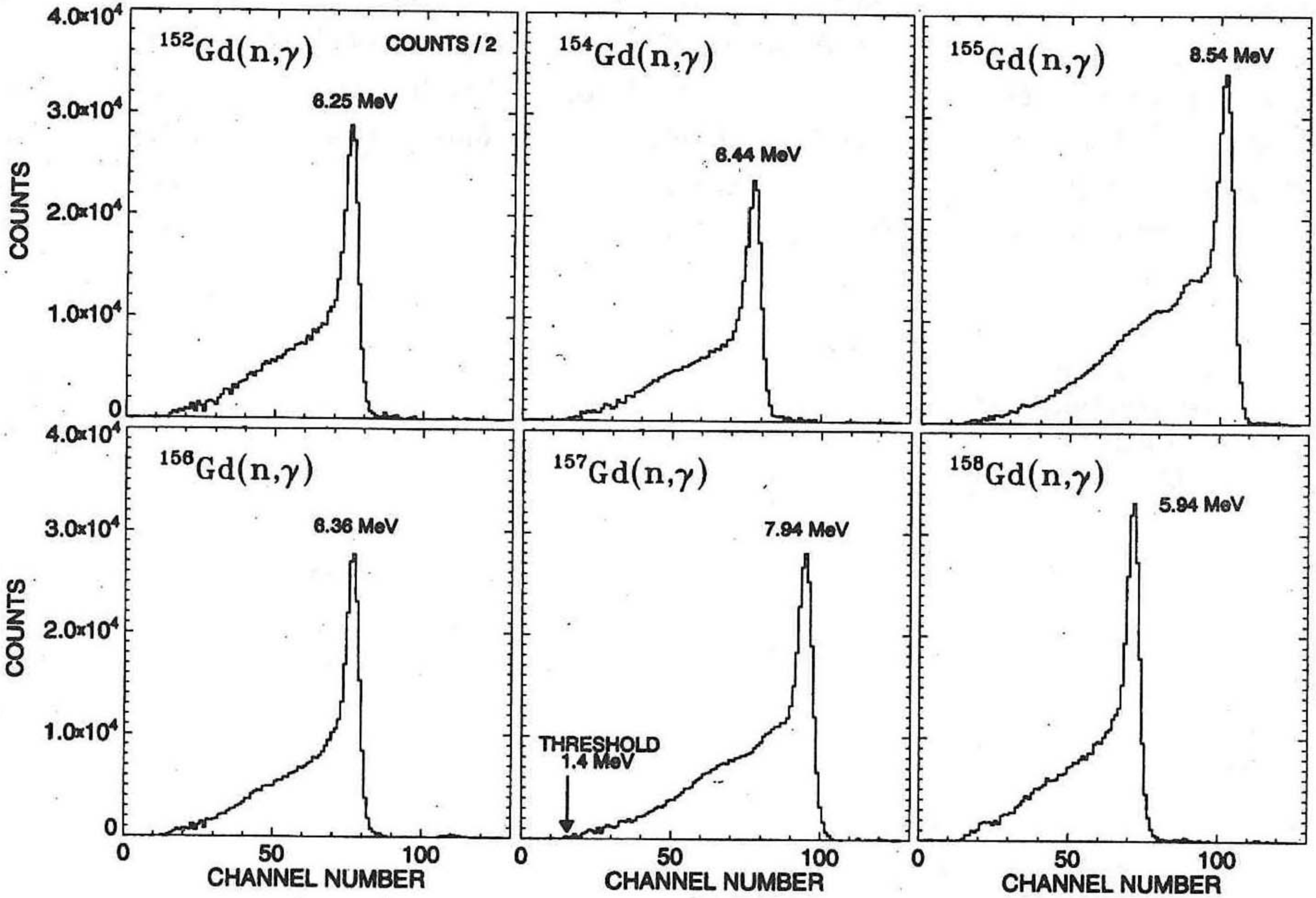
N: number of target atoms/cm^2

η: detector efficiency

b: gamma branching

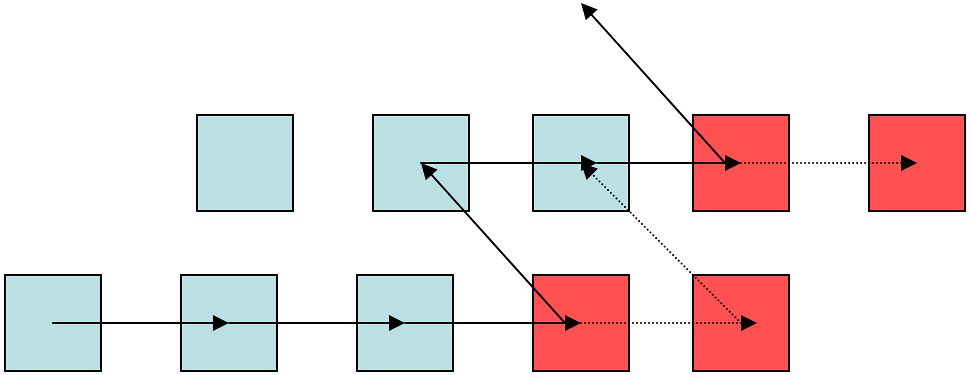
Through summing effects
~90% efficiency
In large detectors

In-Beam γ-Spectra



Neutron induced nucleosynthesis

$$\frac{dN_{A,Z}(t)}{dt} = -n_n \cdot N_{A,Z}\langle\sigma\upsilon\rangle_A - \lambda_{A,Z}\cdot N_{A,Z} + n_n \cdot N_{A-1,Z}\langle\sigma\upsilon\rangle_{A-1,Z}\left(+\lambda_{A,Z-1}\cdot N_{A,Z-1}\right)$$



Approximation for s-process network for A neglecting branching points

$$\frac{dN_A(t)}{dt} = -n_n \cdot N_A\langle\sigma\upsilon\rangle_A + n_n \cdot N_{A-1}\langle\sigma\upsilon\rangle_{A-1}$$

Cross section and abundance

$$\boxed{\frac{dN_A(t)}{dt} = -n_n \cdot N_A \langle \sigma \upsilon \rangle_A + n_n \cdot N_{A-1} \langle \sigma \upsilon \rangle_{A-1}}$$

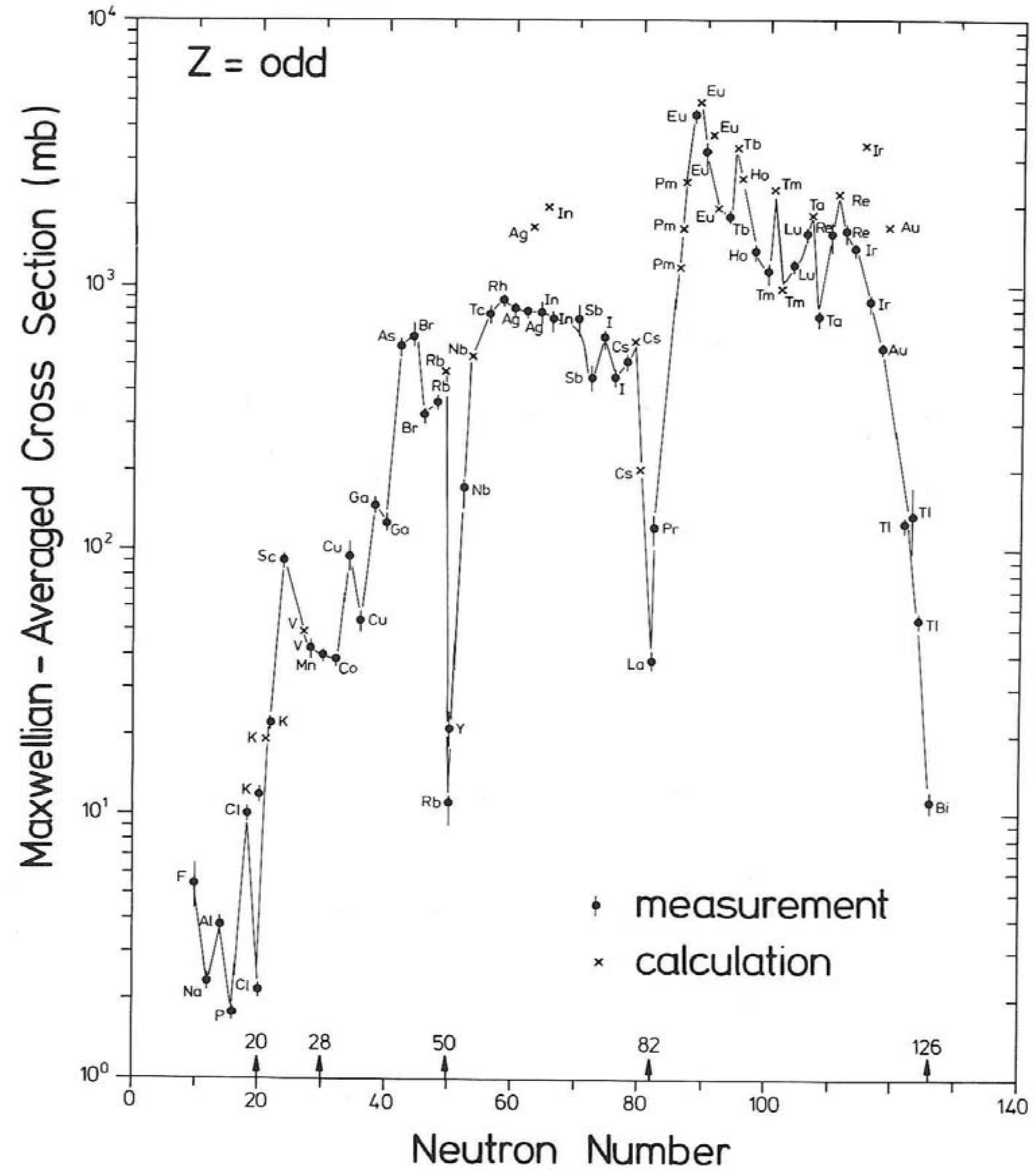
For time integrated neutron exposure $\tau \equiv \int n_n \cdot \langle \upsilon \rangle \cdot dt$

And relation for s-wave neutron capture $\langle \sigma \upsilon \rangle = \sigma \cdot \langle \upsilon \rangle$

$$\frac{dN_A(t)}{d\tau} = -N_A \sigma_A + N_{A-1} \sigma_{A-1}$$

For equilibrium: $\boxed{\frac{dN_A(t)}{d\tau} = 0; \qquad N_A \sigma_A = N_{A-1} \sigma_{A-1} = const}$

s-process results

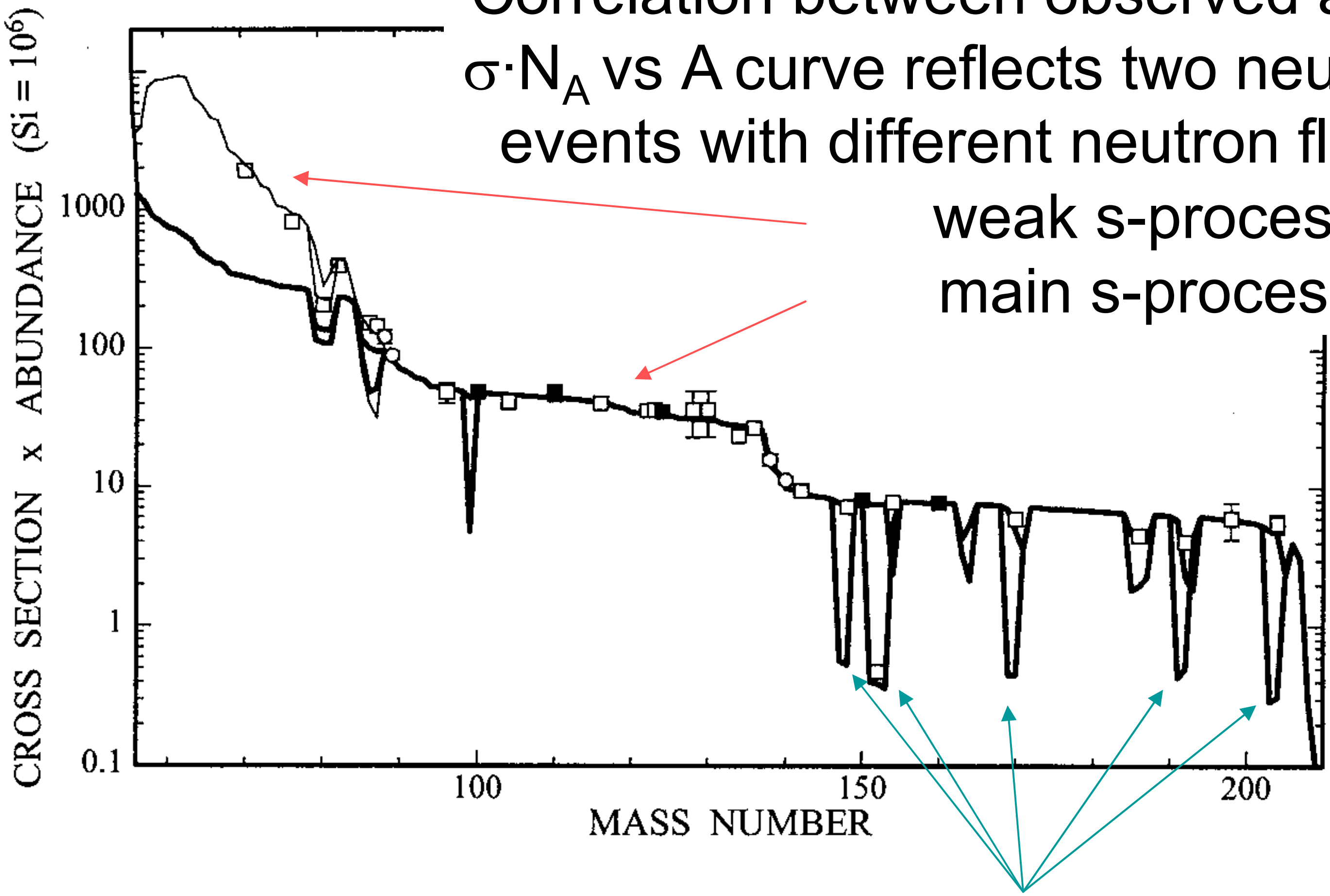


Low neutron capture cross section at closed shell nuclei, N=50, 82, 126

$\Rightarrow$ enrichment of closed shell nuclei,

$\Rightarrow$ s-process peaks!

The classical s-process model

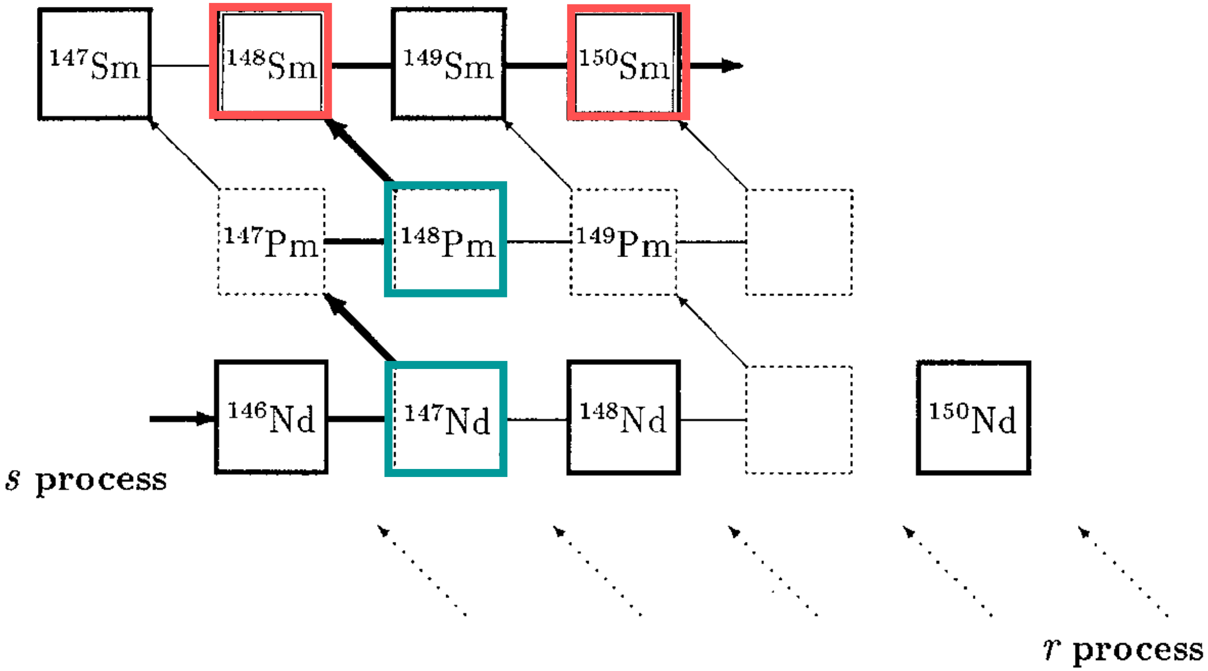


Correlation between observed and calculated $\sigma \cdot N_A$ vs A curve reflects two neutron exposure events with different neutron flux exposure:

weak s-process: $\tau_w = 4\text{mb}^{-1}$,

main s-process: $\tau_m = 0.3\text{mb}^{-1}$

Indication for s-process branchings



oint analysis
portant information
s conditions
ity, temperature

🟥 r-process shielded

🟩 branching point

⬚ β-unstable

^{148}Pm branching point is reflected in the observed abundances of the s-isotopes ^{148}Sm and ^{150}Sm.

$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + n_n \langle \sigma \upsilon \rangle} \approx \frac{\langle \sigma_{^{148}Sm} \rangle N_{^{148}Sm}}{\langle \sigma_{^{150}Sm} \rangle N_{^{150}Sm}} \approx 0.9$$

Neutron flux: ~$(4.1\pm0.6)\cdot10^{8}$ cm^{-3}

$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + n_n\langle\sigma\upsilon\rangle_{^{148}Pm}} \approx \frac{\langle\sigma_{^{148}Sm}\rangle N_{^{148}Sm}}{\langle\sigma_{^{150}Sm}\rangle N_{^{150}Sm}} \approx 0.9$$

$$n_n = \frac{1-f_\beta}{f_\beta}\cdot\frac{\lambda_\beta}{\langle\sigma\upsilon\rangle_{^{148}Pm}} = \frac{1-f_\beta}{f_\beta}\cdot\frac{1}{\upsilon\cdot\langle\sigma_{^{148}Pm}\rangle}\cdot\frac{\ln 2}{t_{1/2}\left(^{148}Pm\right)}$$

Accurate analysis of the neutron density depends on:

- accuracy In the cross section measurements (<1%) and in the abundances for the determination of the branching factor f_β.
- cross section measurement on radioactive ^{148}Pm isotope (>20%)
- stellar decay rate of ^{148}Pm
  (not necessarily identical with laboratory decay rates
  – e-capture, thermally induced decays …

Additional s-process parameters deduced from branching point analysis

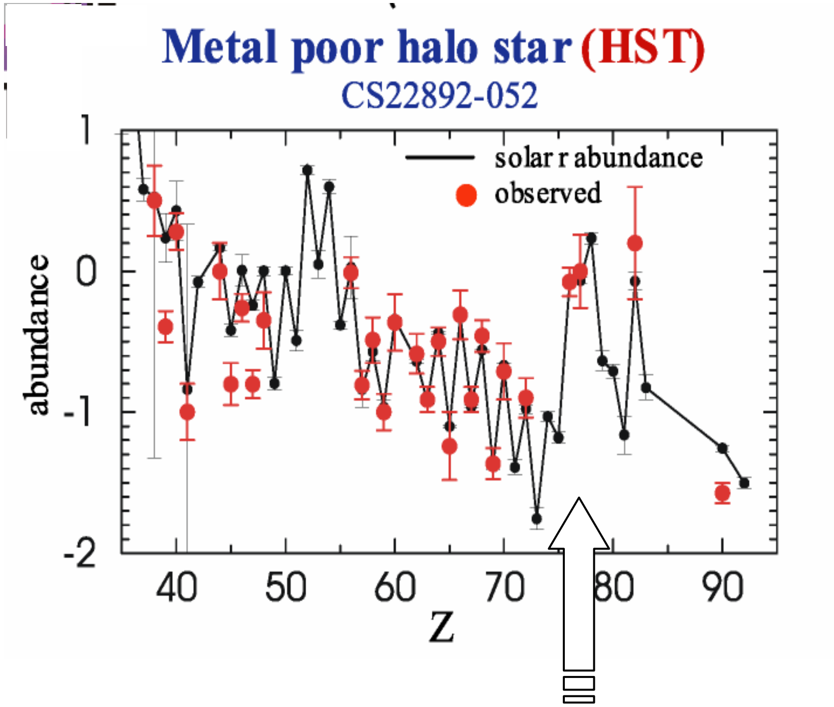
Branch point isotope	Deduced *s*-process parameter	
^{147}Nd/^{147}Pm/^{148}Pm	$n_n = (4.1 \pm 0.6) \cdot 10^8\ \mathrm{cm}^{-3}$	
^{151}Sm/^{154}Eu	$T_8 = 3.5 \pm 0.4$	Temperature dependent $t_{1/2}$
^{163}Dy/^{163}Ho	$\rho_s = (6.5 \pm 3.5) \cdot 10^3\ \mathrm{g\ cm}^{-3}$	Density dependent (e-capture) $t_{1/2}$
^{176}Lu	$T_8 = 3.1 \pm 0.6$	Temperature dependent $t_{1/2}$ through isomer population
^{121}Sn/^{122}Sb	$T_8 > 2.4$	
^{134}Cs	$T_8 = 1.9 \pm 0.3$	
	$T_8 = 1.7 \pm 0.5$	
^{185}W/^{186}Re	$n_n = (3.5^{+1.7}_{-1.1}) \cdot 10^8\ \mathrm{cm}^{-3}$	

$kT = 8.62 \times T_8\ \mathrm{keV}$

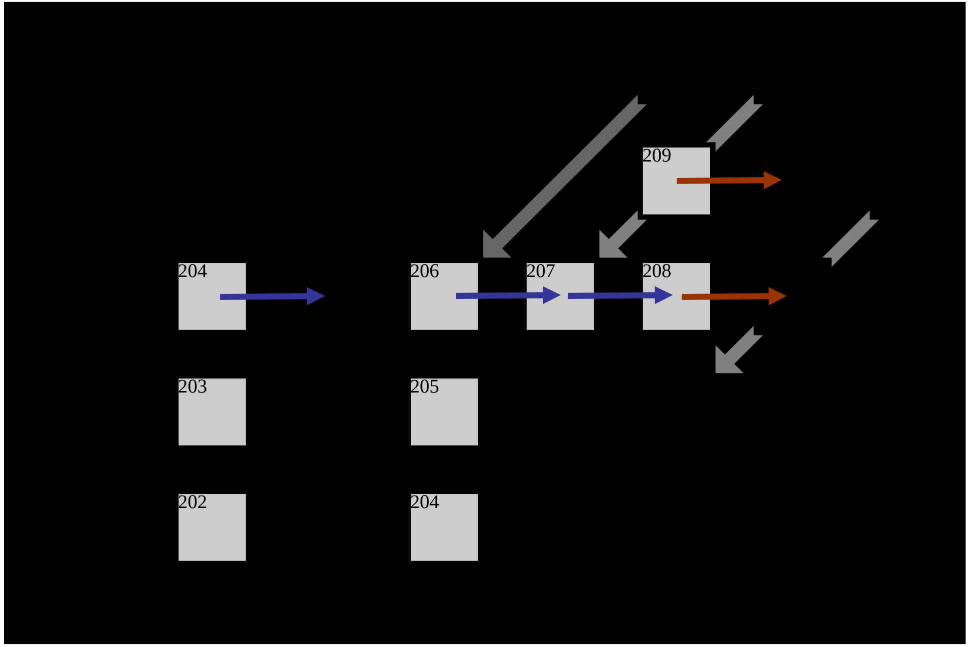
End-points of s-process Pb

First tests at n-ToF neutron source

$^{204,206,207,208}\mathrm{Pb}(n,\gamma)^{205,207,208,209}\mathrm{Pb}$, $^{209}\mathrm{Bi}(n,\gamma)^{210}\mathrm{Bi}$



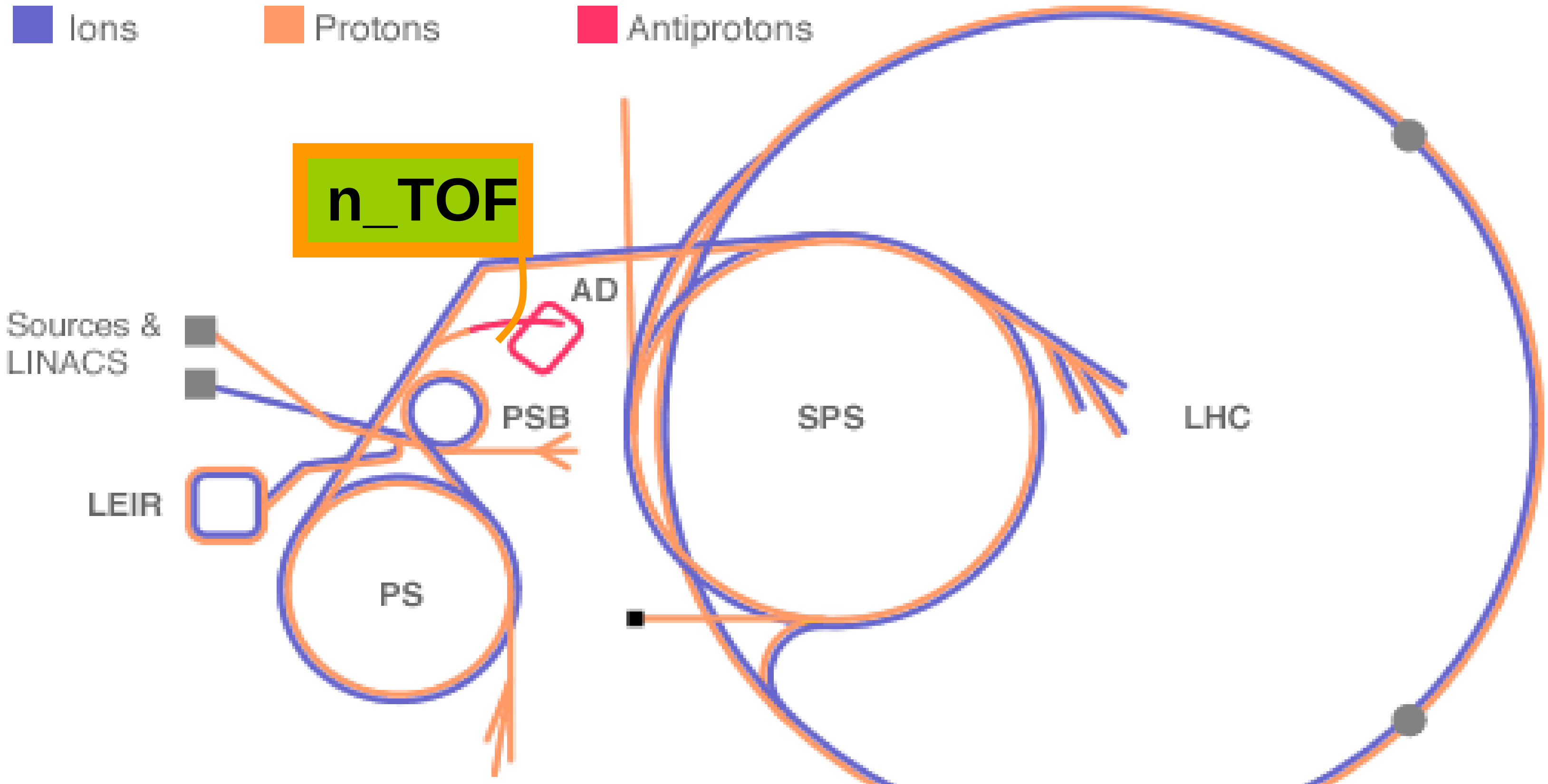
Metal poor halo star (HST)
CS22892-052



Old star abundance distribution points to r-process origin of Pb

n-capture on stable Pb isotopes needed!

CERN accelerator Complex



Linac(s): up to 50 MeV PSB: up to 1 GeV PS: up to 24 GeV

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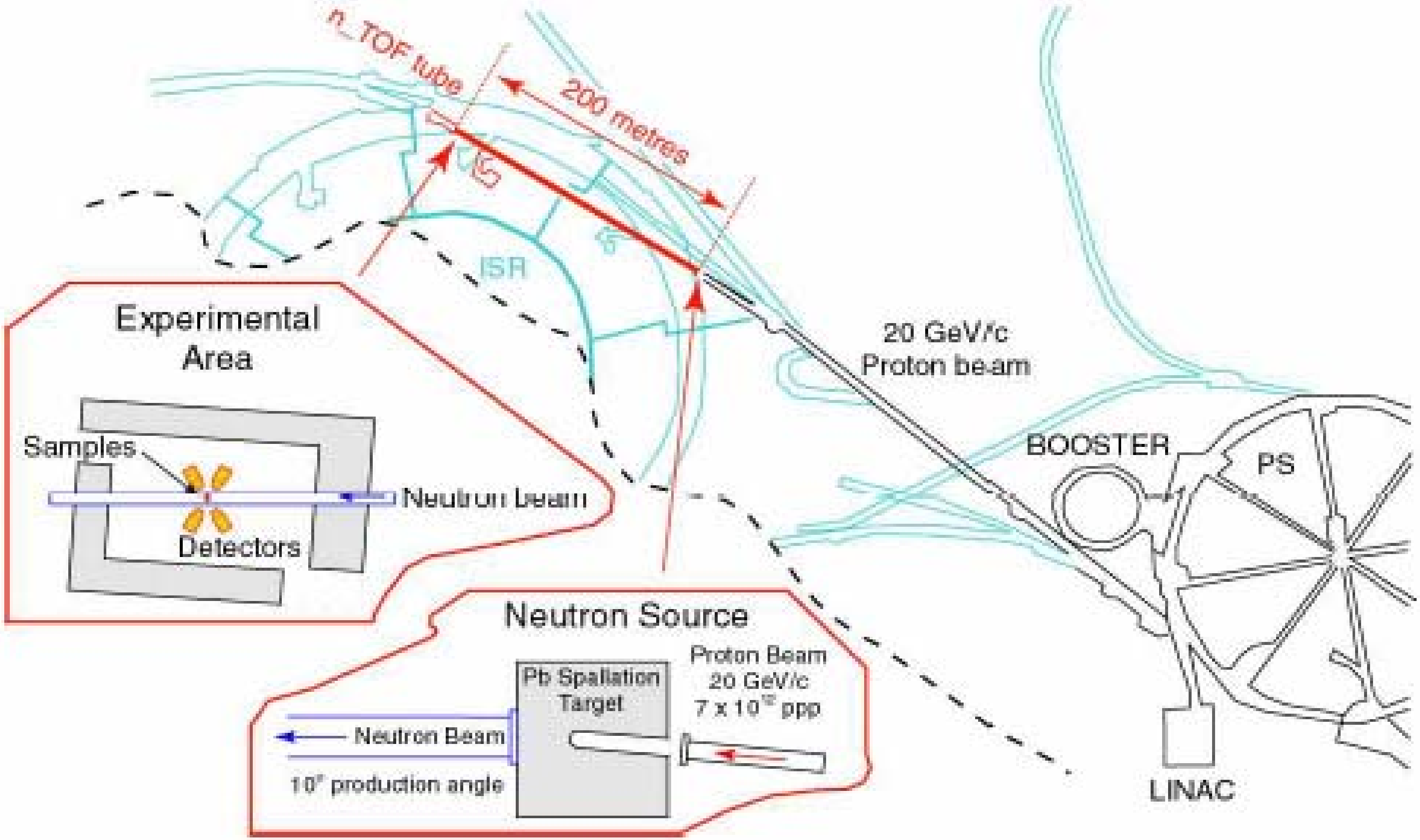
CERN accelerator Complex: n_TOF



1 pulse/2.5 s

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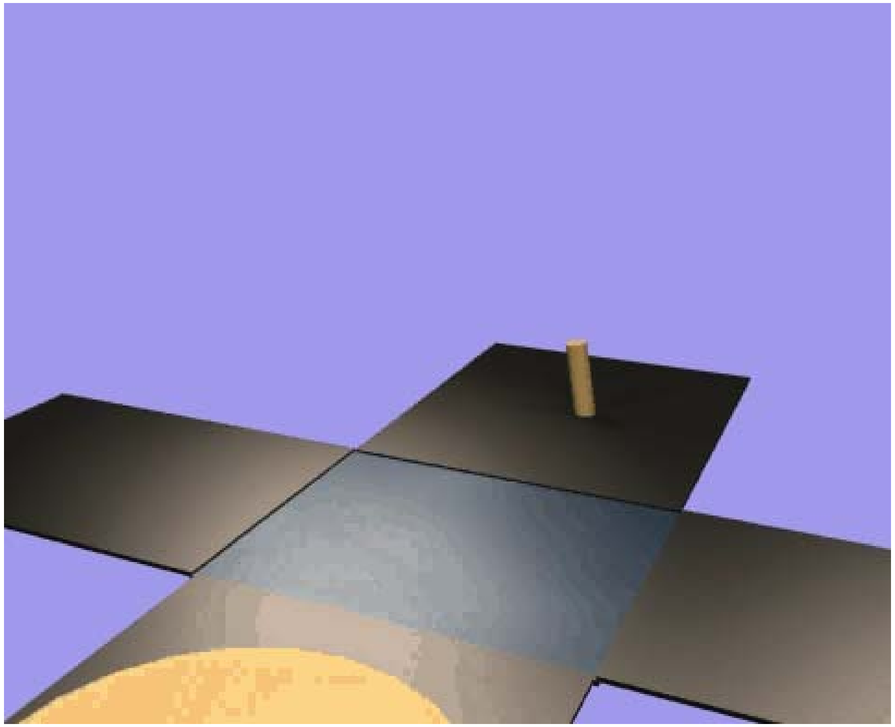
CERN n_TOF Facility

- Design: the n_TOF Target
- The Tunnel

movie by V Vlachoudis

Pb target 80x80x60 cm^3
In water (3cm) filled Al container
Production 300 n/p



Shielding required for γ,μ,π absorption

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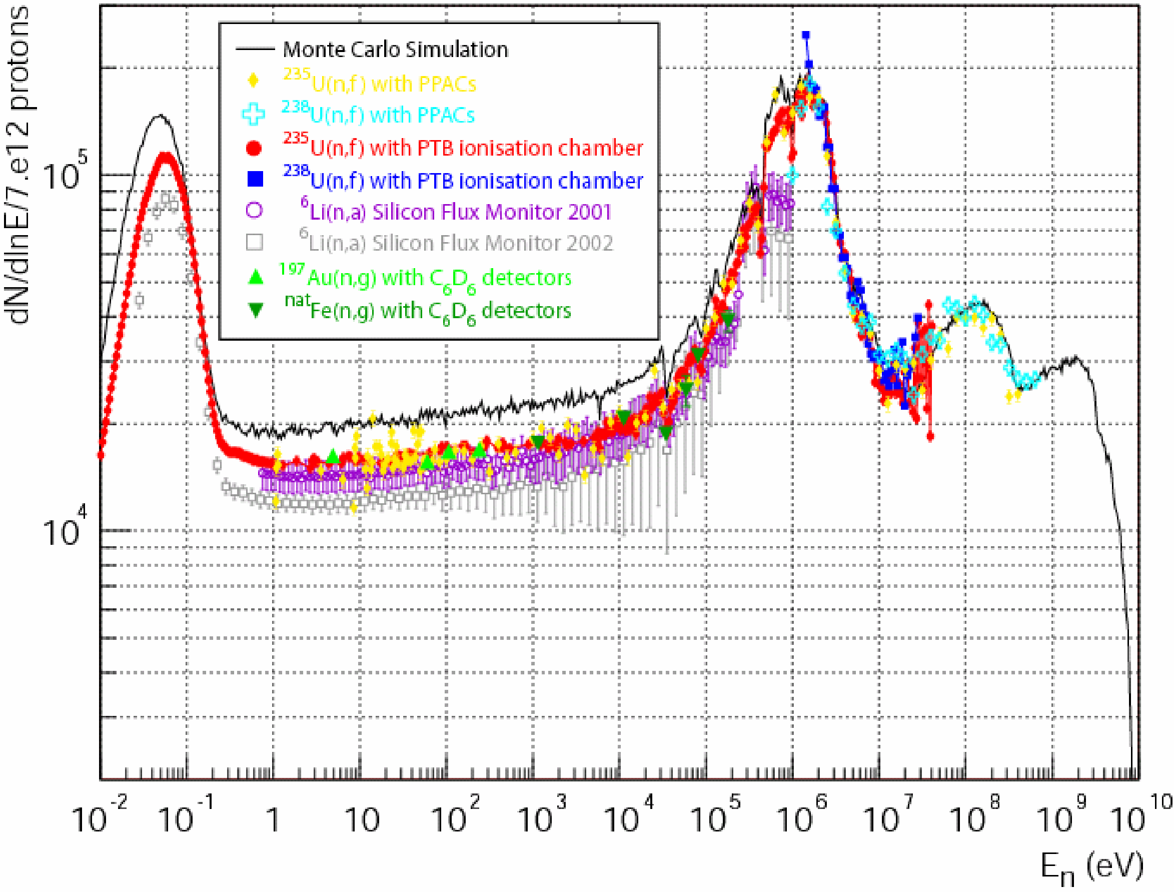
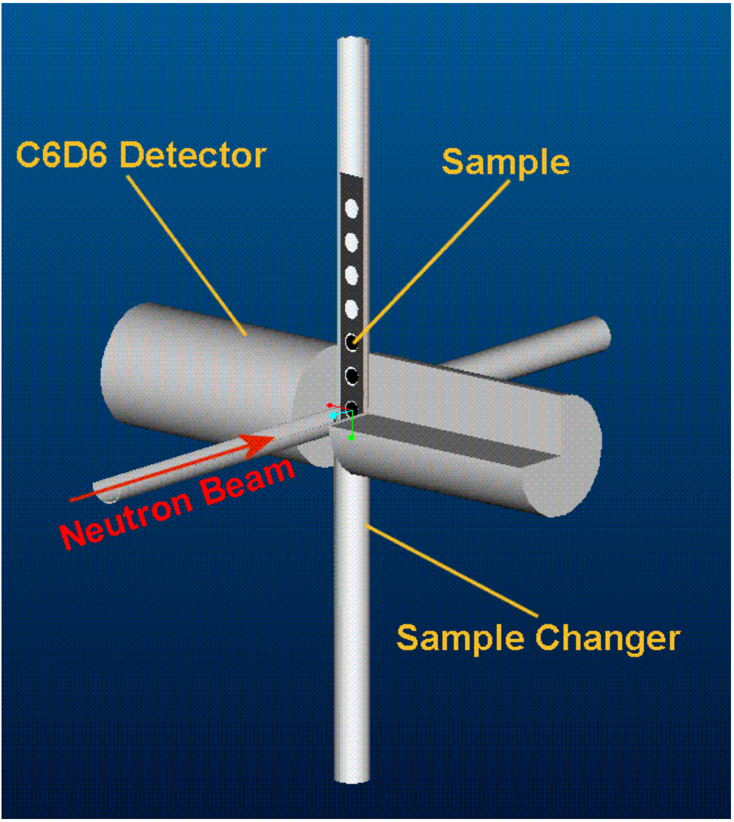
Neutron flux distribution @ n-Tof





Time of flight technique

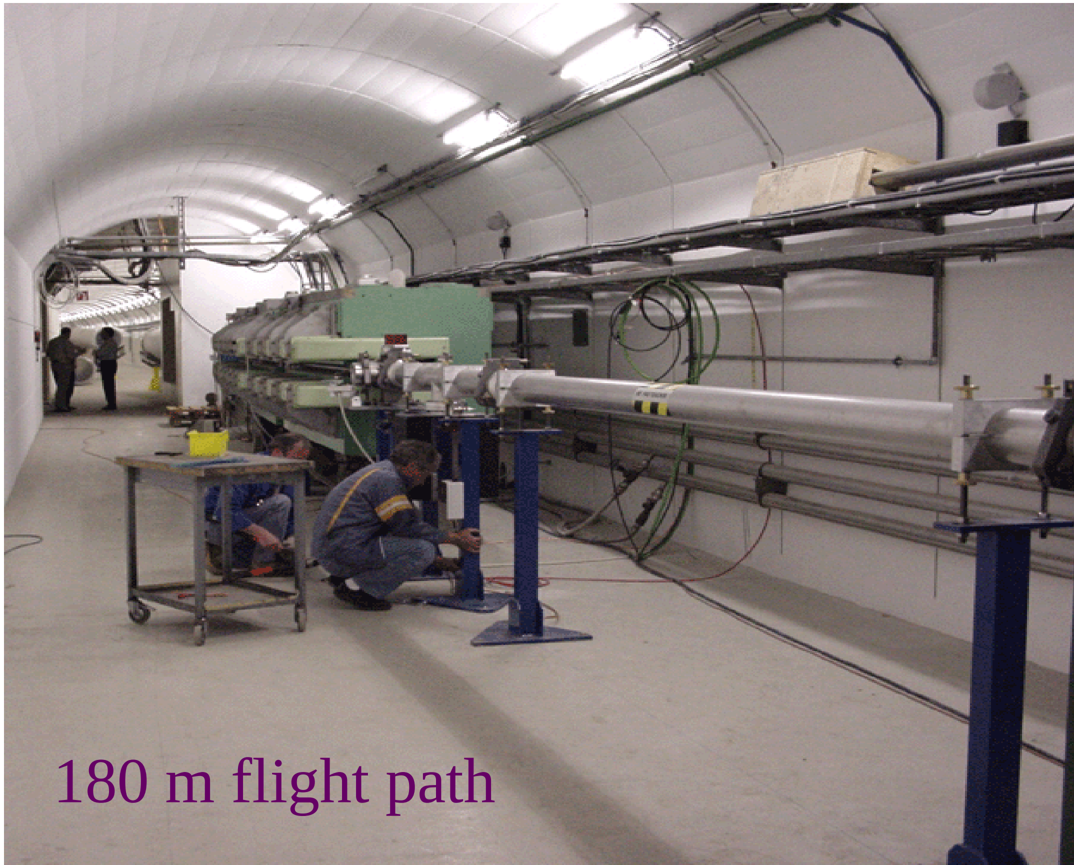
Neutron energy

$$E_n = 0.5 \cdot m_n \cdot \left(\frac{L}{t}\right)^2 \qquad t = \sqrt{\frac{0.5 \cdot m_n}{E_n}} \cdot L = \sqrt{\frac{0.5 \cdot 939.59 MeV}{E_n[MeV] \cdot c^2}} \cdot L = \frac{7.23 \cdot 10^{-10}[s] \cdot L[cm]}{\sqrt{E_n[MeV]}}$$

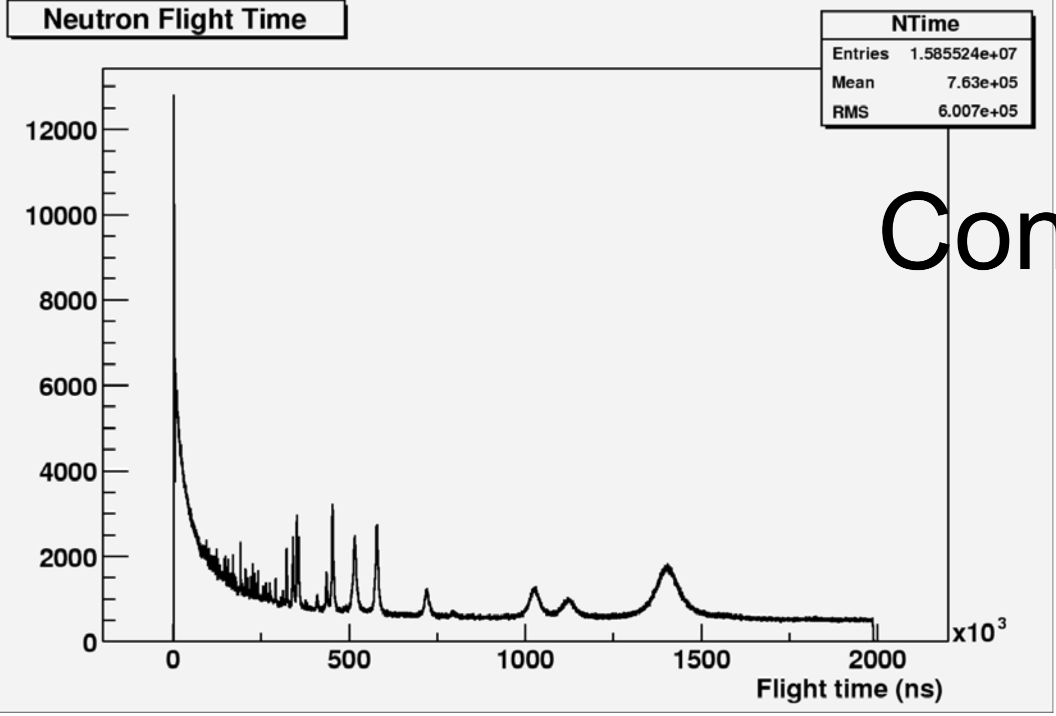
$$\frac{\Delta E_n}{E_n} = \frac{2}{L} \cdot \sqrt{(\Delta L)^2 + (\upsilon_n \cdot \Delta t)^2}$$

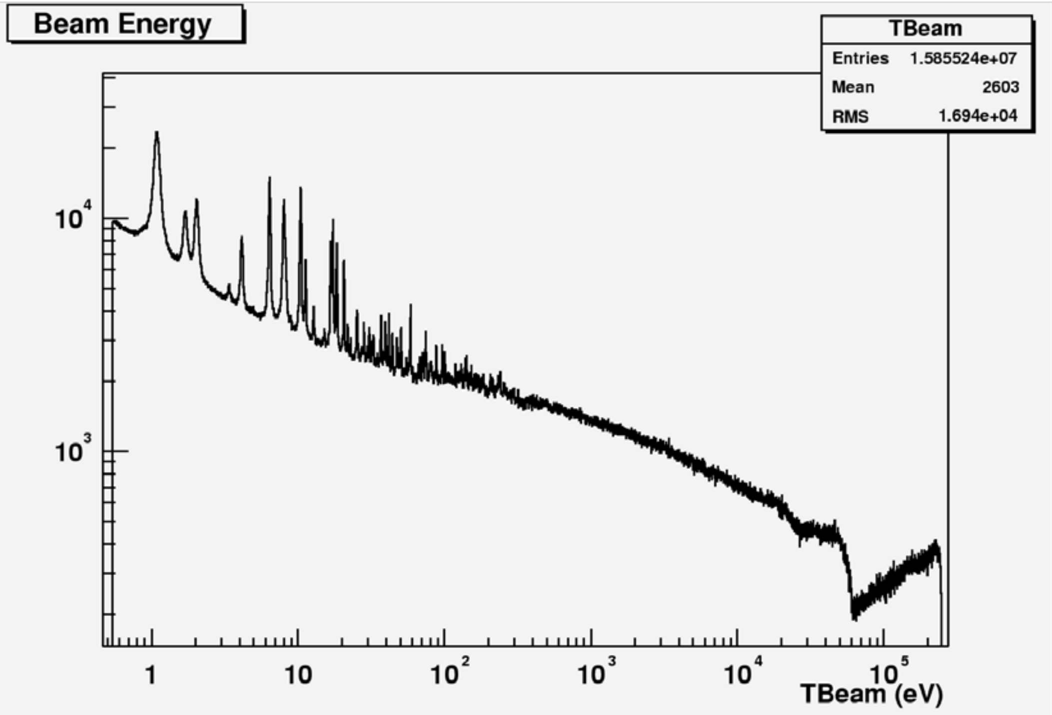
Energy resolution

For 180 m flight path
a 10keV neutron has
a flight time of $t=41\mu s$
$\Delta E_n/E_n \approx 10^{-3}$



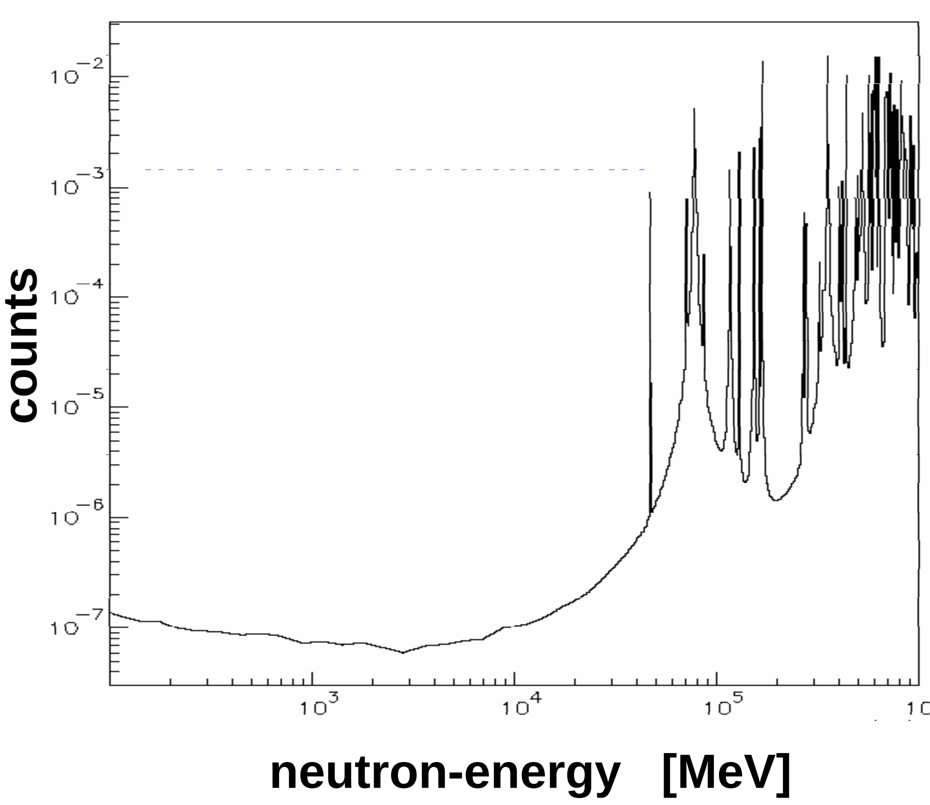
Conversion example

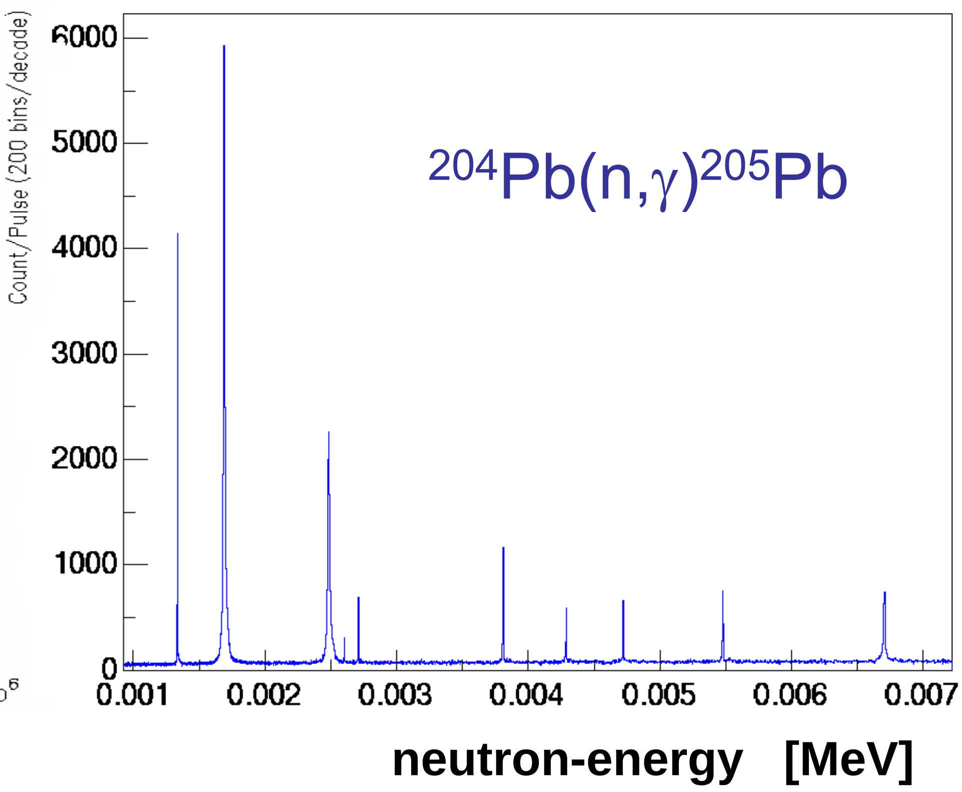




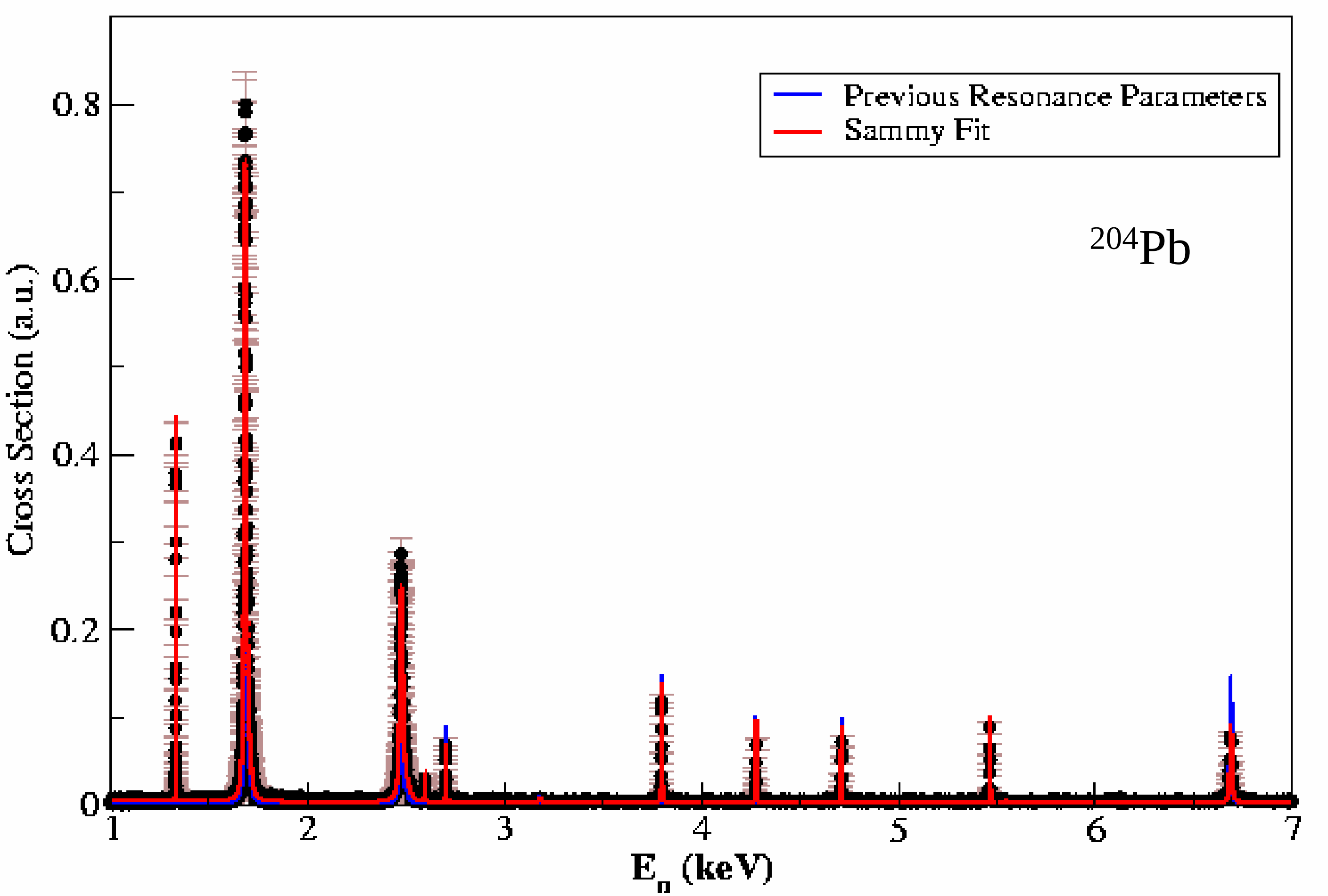
Conversion of time of flight spectrum into the neutron energy spectrum for the n capture reaction ^{151}Sm(n,γ)

n-capture on Pb - first results



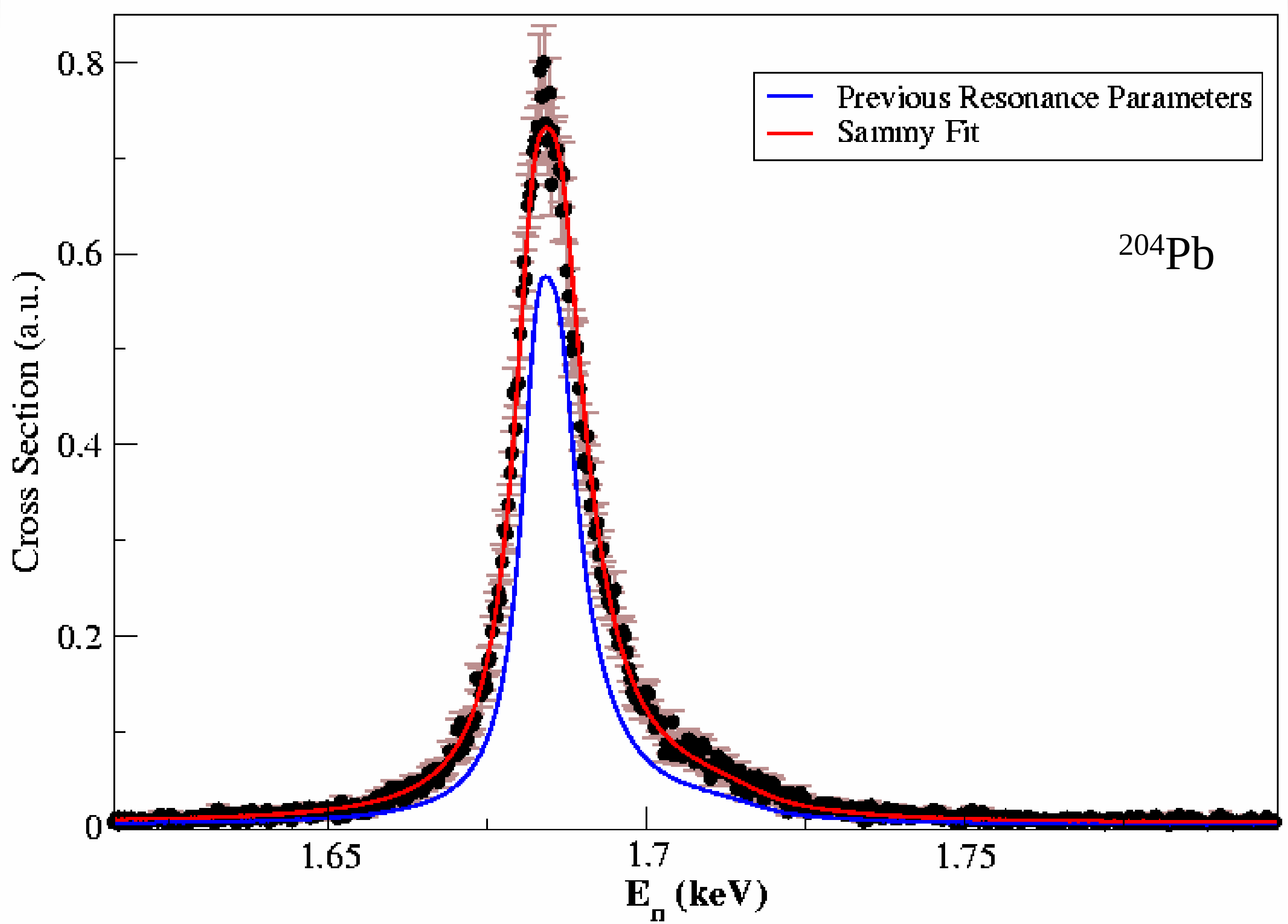


Pb analysis with r-Matrix



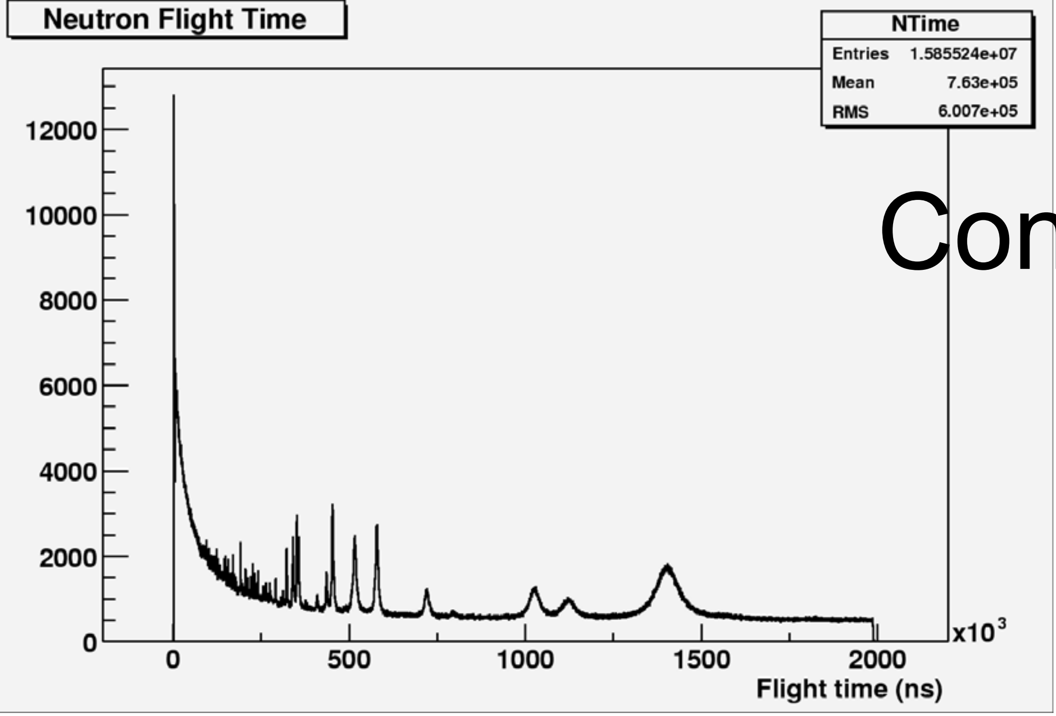
In general, good agreement with previous parameters. But, only 4 resonances below 7 keV have complete resonance parameters in literature

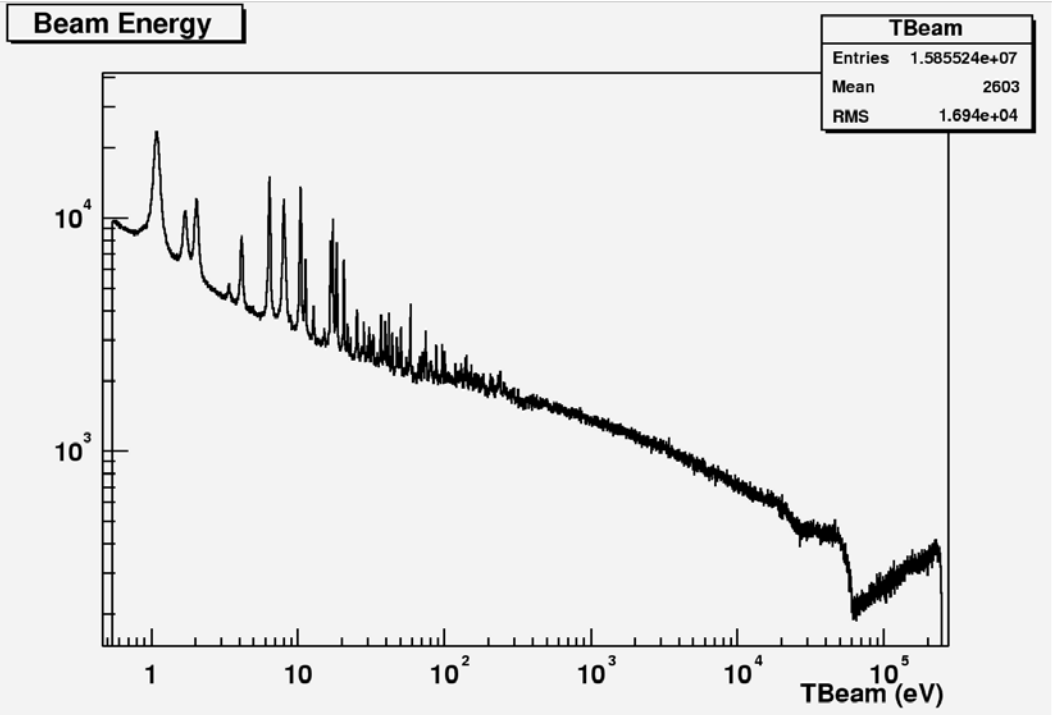
Detail of Pb analysis



Analysis still underway… but results indicate that previously adopted resonance parameters need improvement!

Conversion example





Conversion of time of flight spectrum into the neutron energy spectrum for the n capture reaction $^{151}Sm(n,\gamma)$

Multitude of open questions!

- impact of threshold cluster states in He burning
- low energy contributions to neutron sources
- neutron capture on light nuclei – neutron poison
- neutron capture on long-lived radioactive nuclei for branching point analysis
- end-point of s-process (n-capture on Pb, Bi isotopes)

The accuracy of stellar s-process abundance distribution limits the accuracy of the predicted r-process abundance distribution and the identification of the r-process site!