The role of Fe and Ni for s-process nucleosynthesis and innovative nuclear technologies

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OUTLOOK

-Motivation:synthesis of heavy elements
 with A<90
-(n,γ) measurements:n_TOF facility and PHWT
- Data analysis
- Conclusion

MOTIVATION

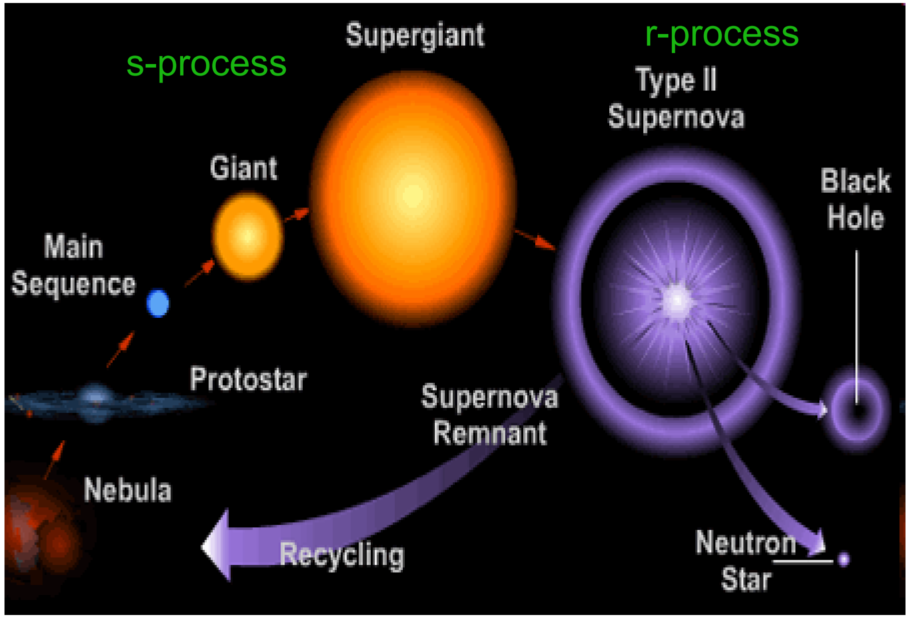
Understanding nucleosynthesis of heavy elements in the universe

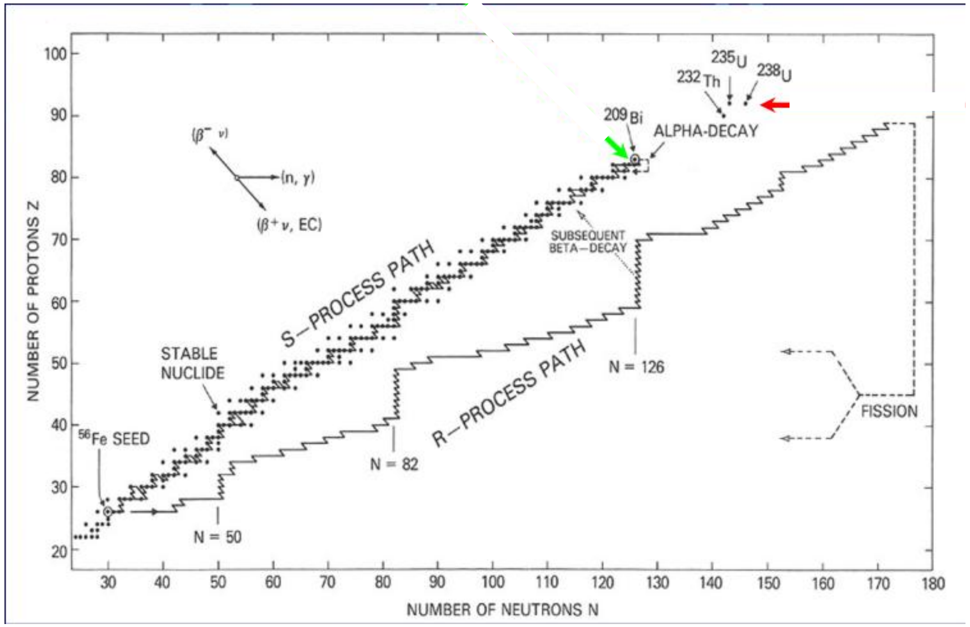
Neutron capture is the main process in the formation of elements heavier than iron in the universe.

-slow(s)-process

-rapid(r)-process

Both processes contribute in about equal amounts to the total heavy element budget although notable differences exist for individual isotopes or particular stars.





s-Process

-Low neutron density and intermediate temperature

-Very long neutron capture time

- s process works its way along the valley of beta stability

-main s-process ⟹ Asymptotic Giant Branch (AGB) stars.
Steady neutron flow: isotopic abundances are inversely proportional to the σ_{CAP}

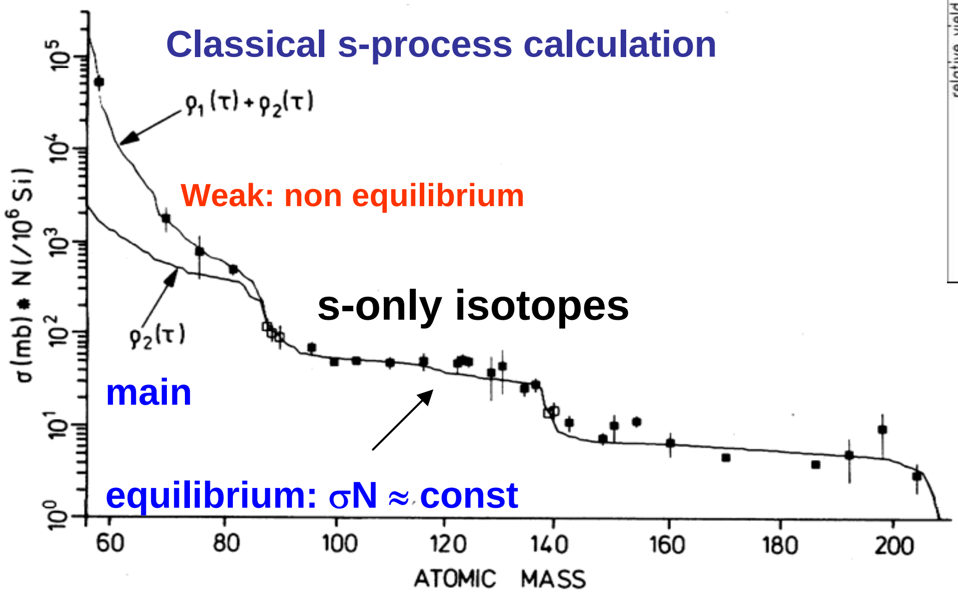
-weak s-process ⟹ Mass region <90 during Red Giant phase of massive stars
Non equilibrium condition

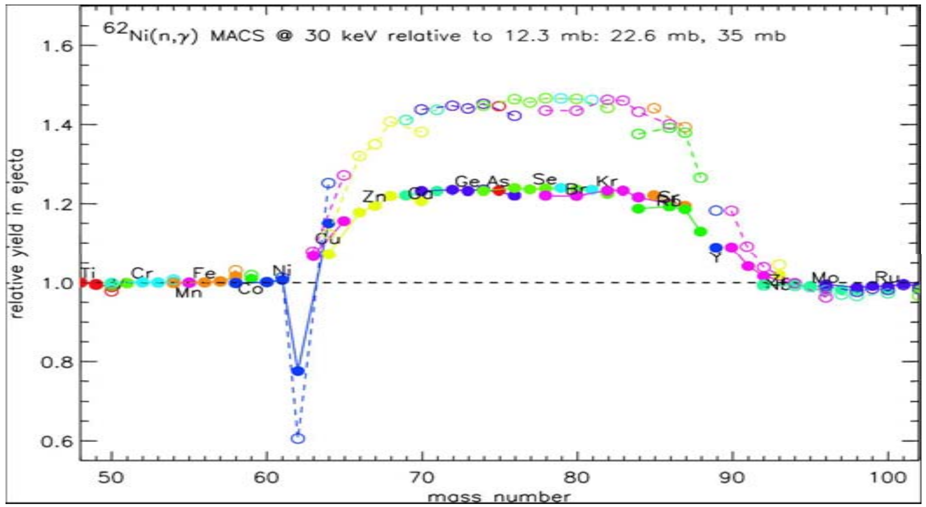
The s-process: n-capture along the β-stability valley

	weak (A<90)	main (A>90)
site	He-core burning massive stars	He-shell pulses low mass AGB stars
n source	$^{22}Ne(\alpha,n)$	$^{13}C(\alpha,n)$ / $^{22}Ne(\alpha,n)$
temperature (K)	3×10^{8}	10^{7} / 3×10^{8}
n density (cm^{-3})	7×10^{5}	10^{7} / 10^{10}

For A>90 the isotopic *s* abundances are well established by the fact that they are determined by their respective (n,γ) cross sections, which can be determined in laboratory experiments, and the assumption of constant neutron flux in a star, so that the ratio of abundances is inversely proportional to the ratio of neutron-capture cross-sections.
For A<90 there is not such simple relationship because cross-section influences the abundances of heavier nuclei but it can be still calculated.

$^{62}Ni(n,\gamma)$ cross section

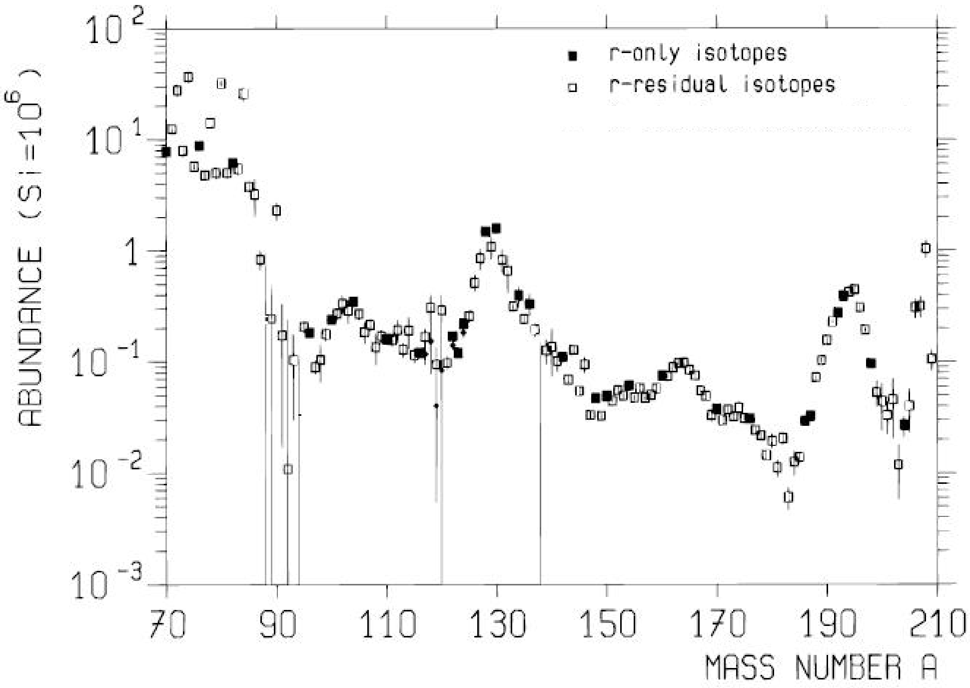


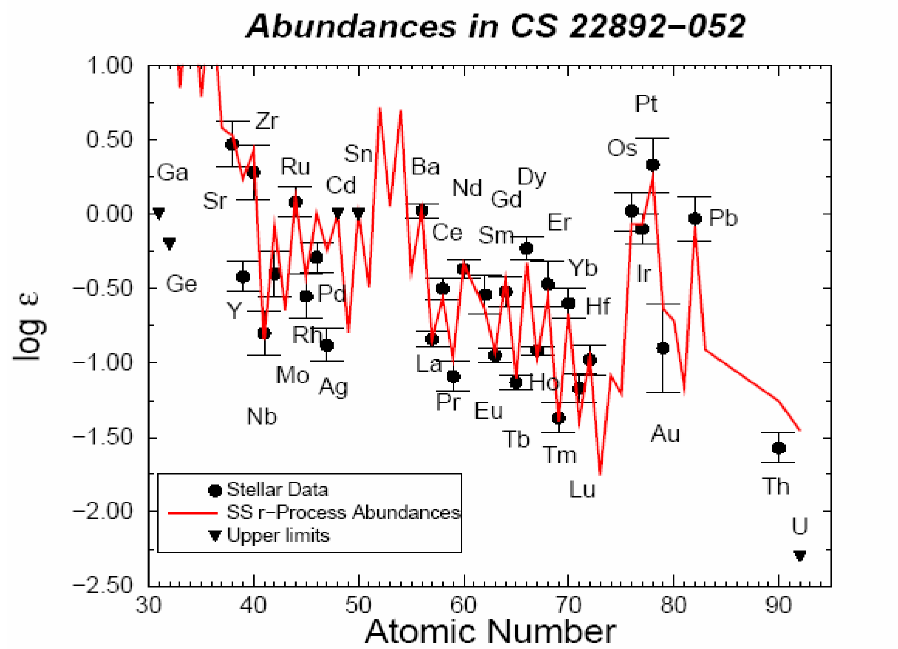


Consequence of the non-equilibrium condition: cross section influences abundances of many elements

r-Process

- High neutron density
- neutron capture time less than a seconds
- **r-process “experimental”** abundances are determined as residuals: Nr=N☼-Ns
- r-process abundance calculations are difficult and require a lot of nuclear physics input data(masses, half-life, neutron emission probabilities,…) largely unknown.
- Some ultra-metal-poor (UPM) stars show an elemental abundance which matches the standard r-process abundance. This is interpreted as a very old star collecting the ejecta from a single nearby supernova explosion. However the perfect match only happens for A>100: it is propose that this is an indication for a secondary r-process.

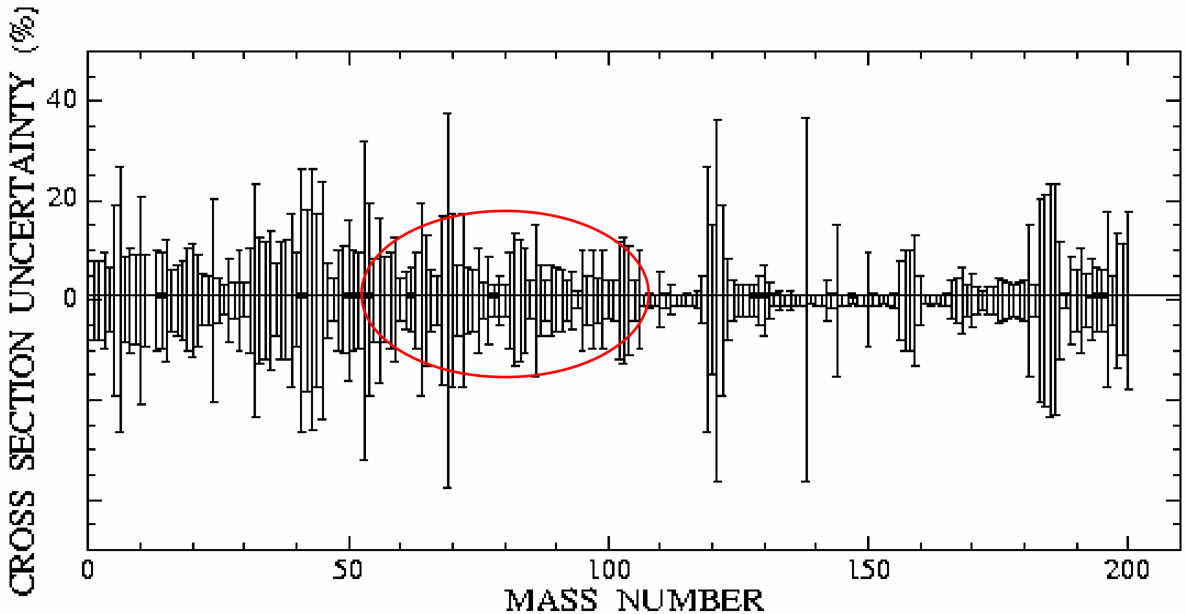


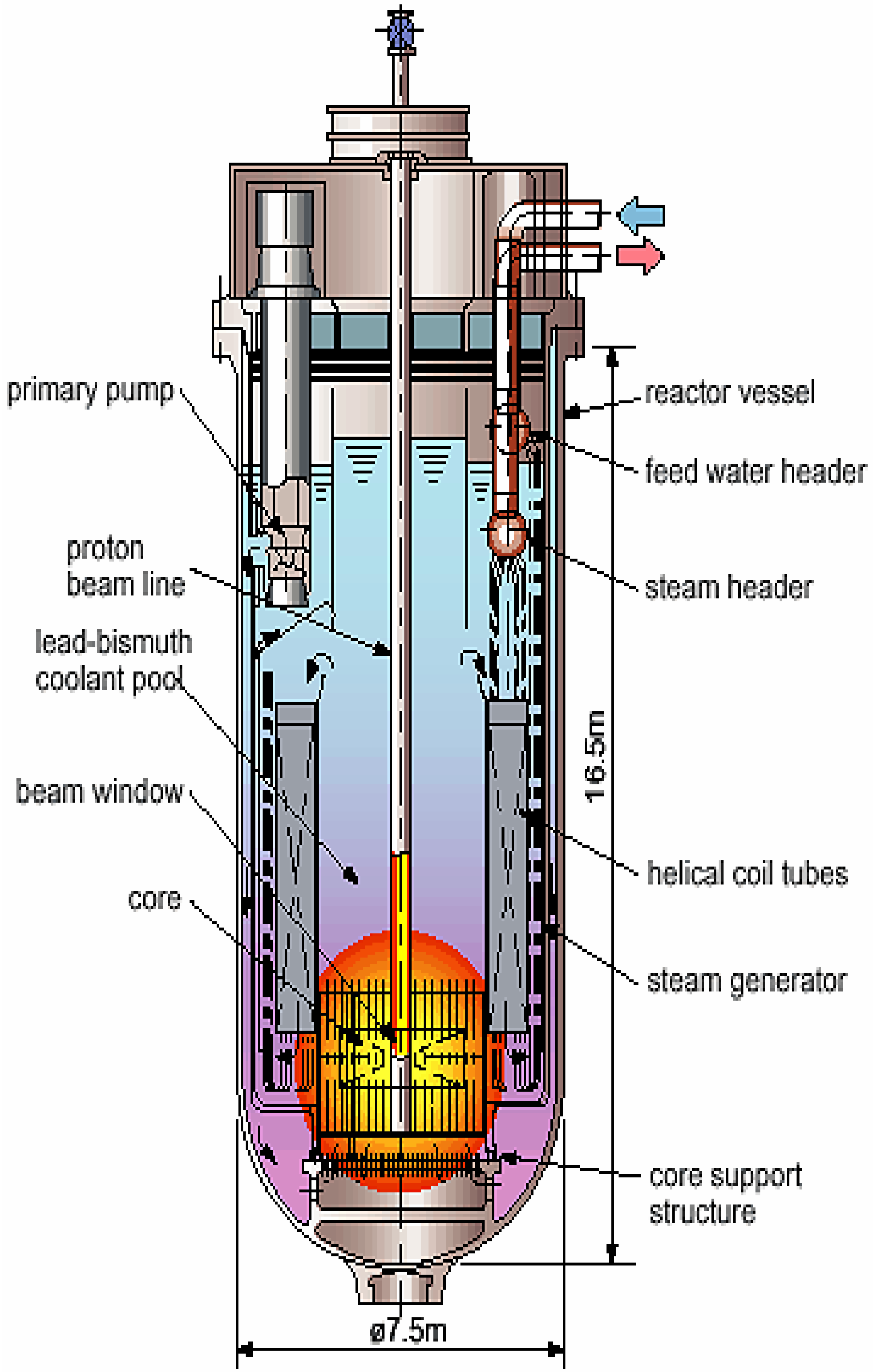


However if we look to the status of (n,γ) cross-section for elements with A<120 we can see that the uncertainties are quite large.

If the measured cross-section in this region are wrong than this could explain the discrepancies between the r-process residual and the UPM abundances.

So there is a need to measure with improved accuracy (n,γ) cross-section 56<A<120.





Additional motivation

Fe and Ni are part of the fuel cladding material and reflector for ADS systems
Accurate neutron cross section are required for most abundant element for limiting a choise of structural material.

Quoted uncertainties of σ_{CAP} for most abundant isotopes in 1-500keV range are 8-12 %.
Differences largely outside the uncertainty has been found for other isotopes.

Short and long activation level of structural material comes determined from:

^{58}Ni(n,γ)^{59}Ni T1/2=7.5x10^{4} yr

^{62}Ni(n,γ)^{63}Ni T1/2=100 yr

↓

(n,γ) cross section are poorly know

^{62}Ni about 50% in keV region

In view of this problem we are performing accurate state-of-the art measurements on highly enriched samples of the stable Fe and Ni isotopes at the n_TOF facility

Samples used:

^{54}Fe: 99.84%
^{56}Fe: 99.93%
^{57}Fe: 96.06%
^{58}Ni: 99.5%
^{60}Ni: 99.31%
^{62}Ni: 97.95%

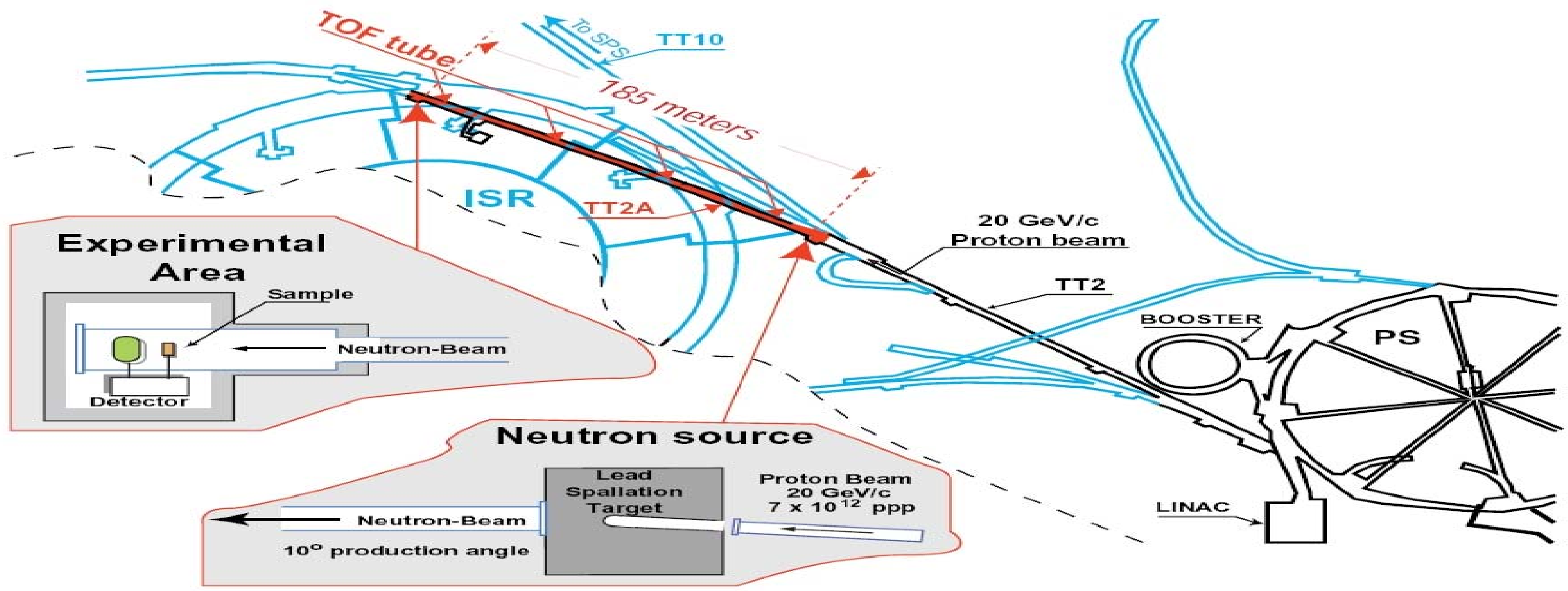
2009 measurement: ^{56}Fe and ^{62}Ni
2010 measurement: ^{54}Fe

The n_TOF facility

Neutron are produced via spallation of 20GeV/c protons from CERN PS on a lead target (80x80x60 cm^3).

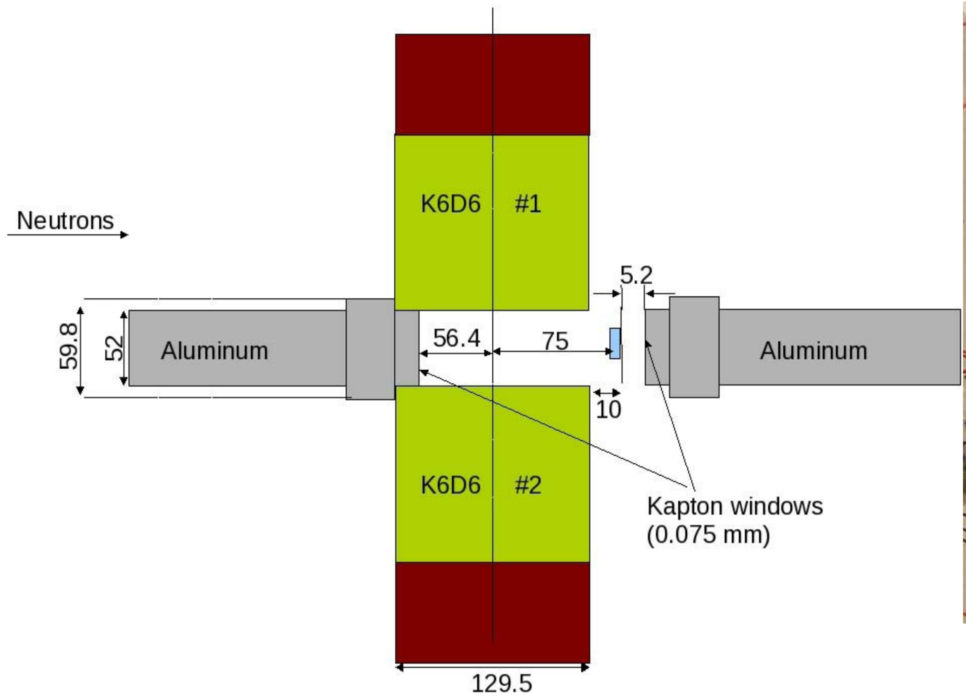
The 15 ns wide proton bunch with 7x10^{12} ppb produce a high instantaneus neutron flux.

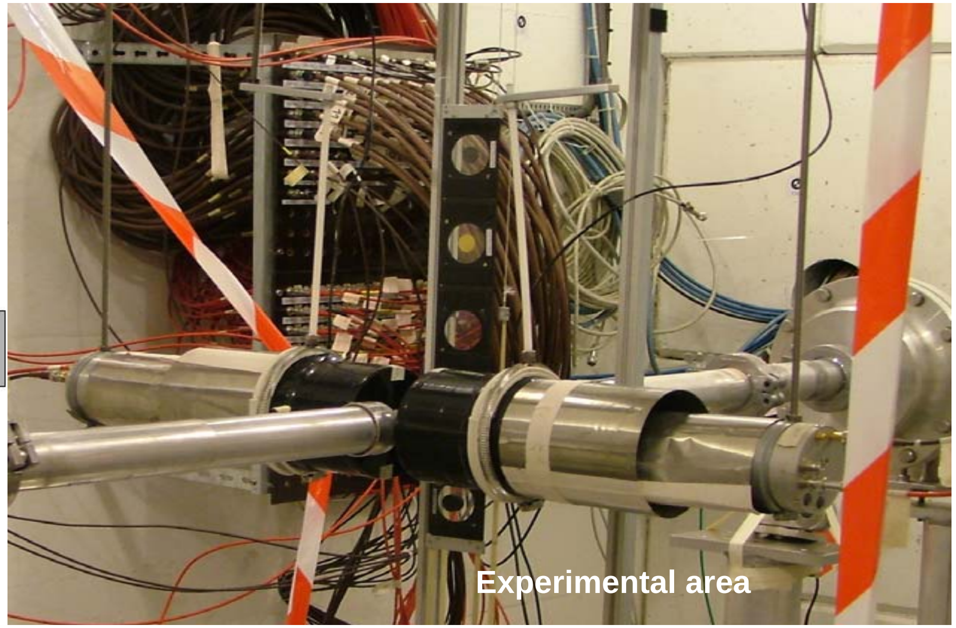
A flight path of 185m guarantees a very high energy resolution.



THE MEASUREMENTS

Experimental set-up of the Fe-56 measurement with K6D6 (n_TOF-Ph2)





The measurement were performed using two deuteraded benzene(C6D6) scintillation detectors with a low neutron sensitivity.

Problem:How do we count correctly the number of γ-rays cascade?

Using the Pulse Height Weigthing Technique

PULSE HEIGHT WEIGHTING TECHNIQUE

PHWT is based on the use of a γ ray detection system with very low efficiency. Only one gamma ray of the capture cascade is registered

$$\varepsilon^{\gamma} << 1$$

this detection efficiency is proportional to the photon energy

$$\varepsilon^{\gamma} = \alpha \mathbf{E}^{\gamma}$$

Under these conditions the efficiency for detecting a cascade *Ec* will be proportional to the known cascade energy and independent of the actual cascade path.

$$\varepsilon_c = \sum_j \varepsilon_{\gamma j} = \alpha E_c$$

The proportionality between efficiency and γ-ray energy is obtained by software manipulation of the detector response (Maier-Leibniz):

If Rij represents the response distribution for a γ-ray of energy $E\gamma j$:

$$\boxed{\sum_{i=1} R_{ij} = \varepsilon_{\gamma j}}$$

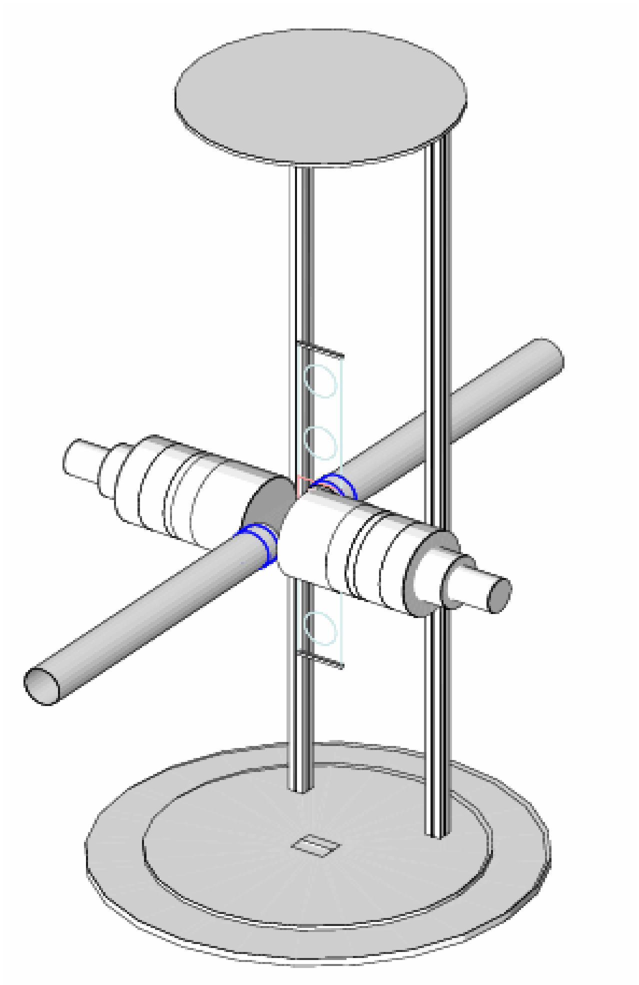
it is possible to find a set of weighting factors W_i dependent on energy deposited, which fulfil the proportionality condition

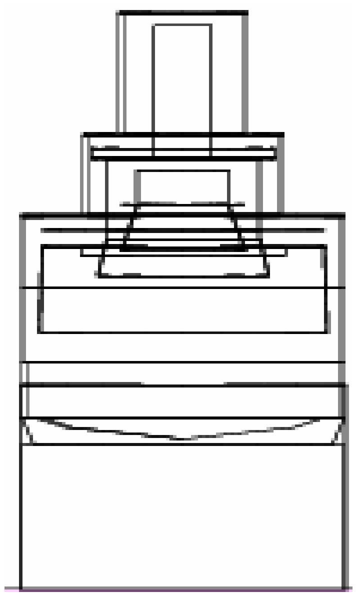
$$\boxed{\sum_{i} W_i R_{i\,j} = E_{\gamma j}}$$

The PHWT require the precise knowledge of the detector response as a function of γ energy. The latter is obtained from very detailed MC simulation using Geant4 with a complete description of the experimental setup.
From this information a counting weight as a function of deposit energy can be calculated.
It has been shown that an accuracy of 2% can be achieved in this way
The PHWT is used to count properly the number cascade.

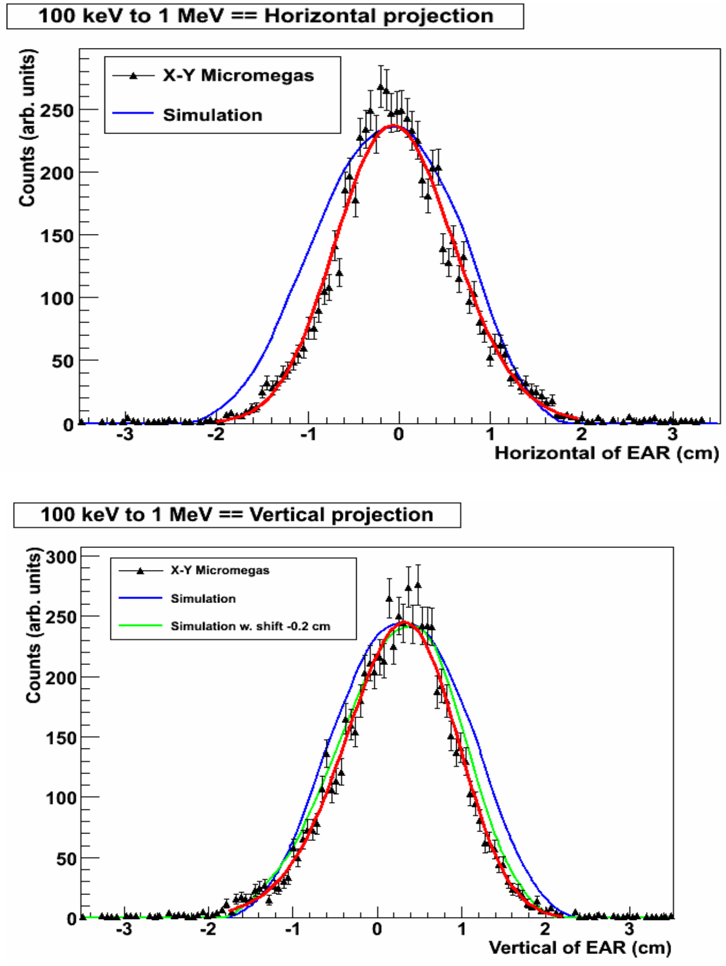
A detailed geometrical description setup was implemented using Geant4. We assumed that the beam have a gaussian profile, and we also took into account a exponential depth profile.

Experimental setup



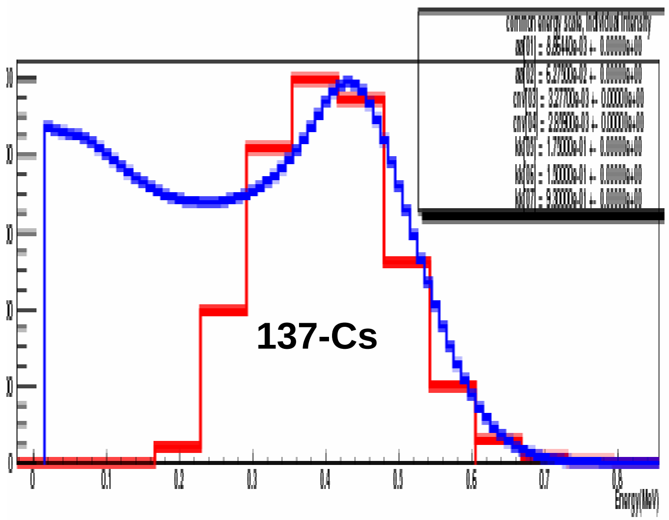


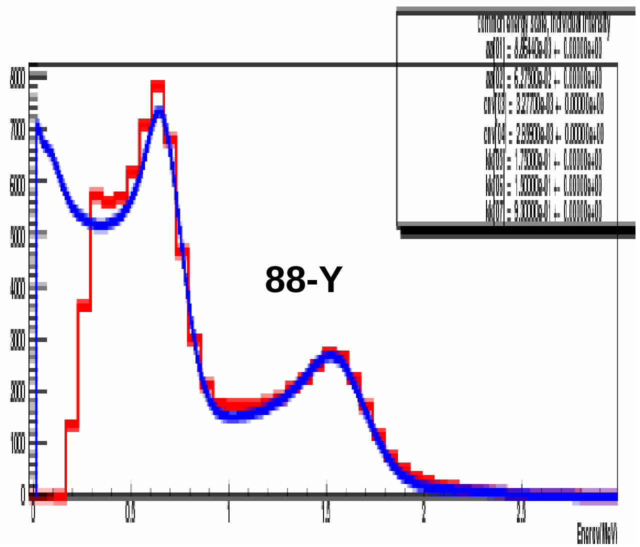
C6D6 detector

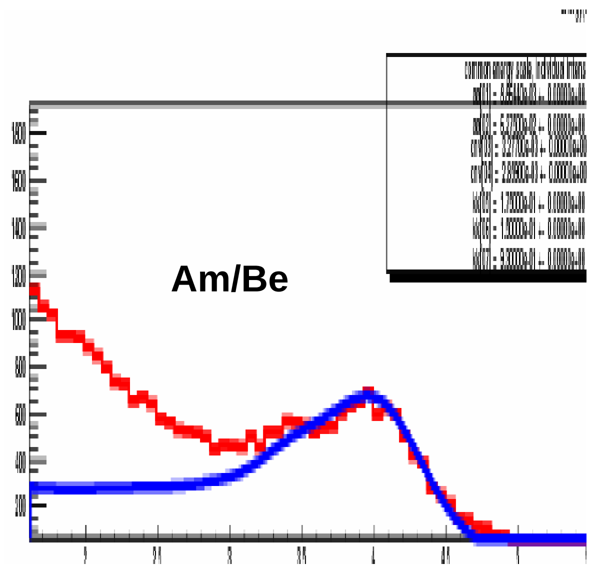


ENERGY AND WIDTH CALIBRATION

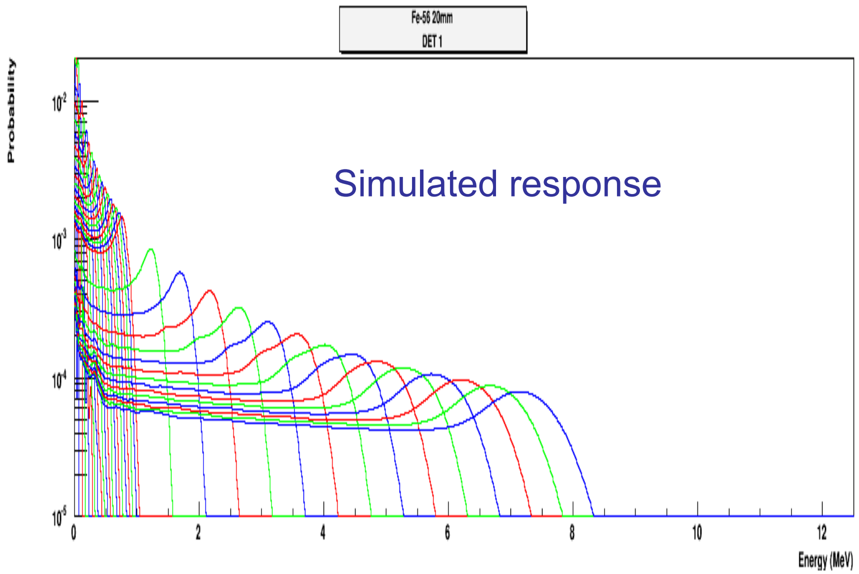
- A good calibration is needed because the weighting function is obtained from a MC simulation as function of deposited energy.
- The C6D6 detectors were calibrated using three different radioactive sources:
  - 137-Cs with $\gamma=662$ keV
  - 88-Y with $\gamma=898$ keV and 1.4MeV
  - Am/Be source with $\gamma=4.4$MeV

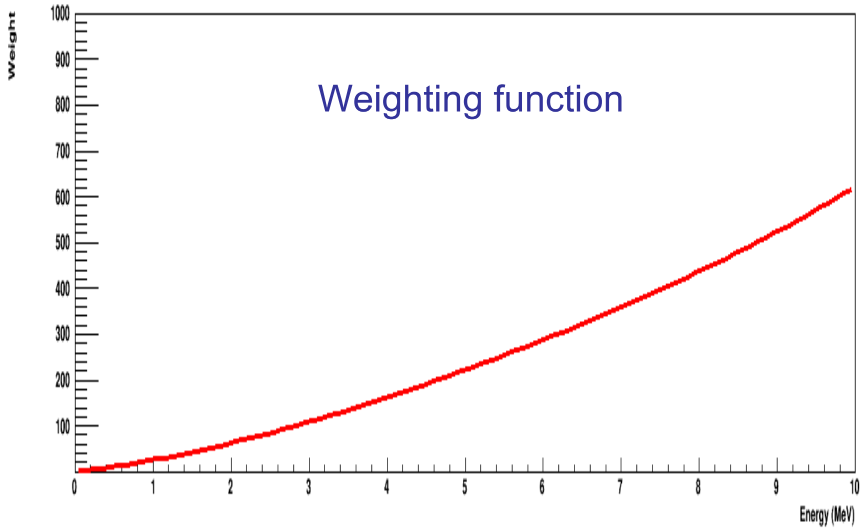




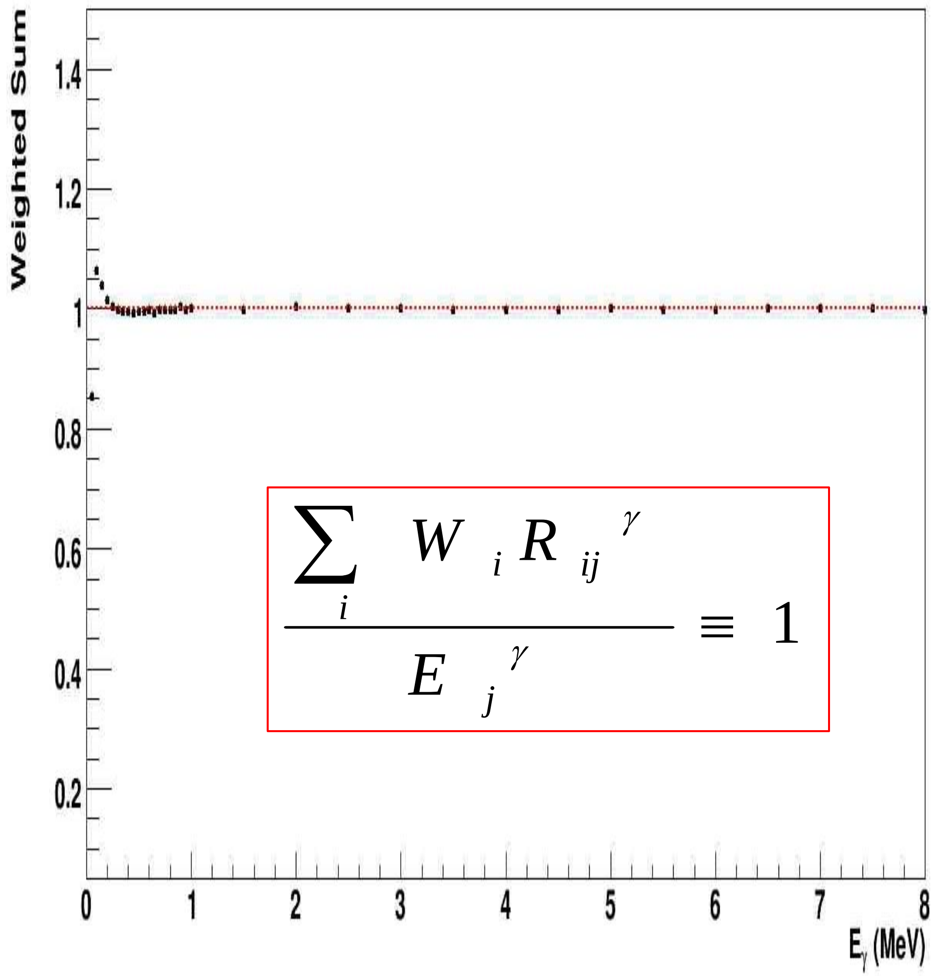


• A set of 34 monoenergetic gamma-rays with energies 0.05, 0.1, 0.15, 0.2, ...2, 2.5, 3, ….8 MeV were simulated. For each energy 5 e+6 photons were simulated.





To verify the correctness of the shape of the WF we calculate the ratio:

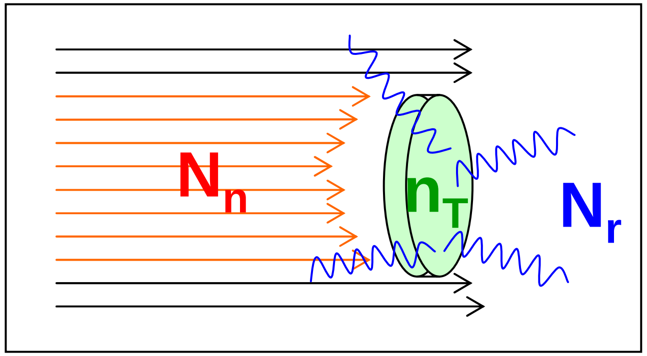


DATA ANALISYS

Cross-section: Probabilty that a nuclear reaction will occur

$$\sigma_r(E) = \frac{\textbf{Number of reactions}}{\textbf{Number of target nucleus per unit area} \times \textbf{Number of neutrons of energy E}}$$

$$\sigma_r(E) = \frac{N_r}{n_T\left[barn^{-1}\right] \cdot N_n(E)}$$



Needs:

- **sample of known mass and dimensions**
- **count the number of incident neutrons of energy E**
- **count the number of reactions**

Yield: Fraction of neutron beam wich undergoes a capture reaction in the sample

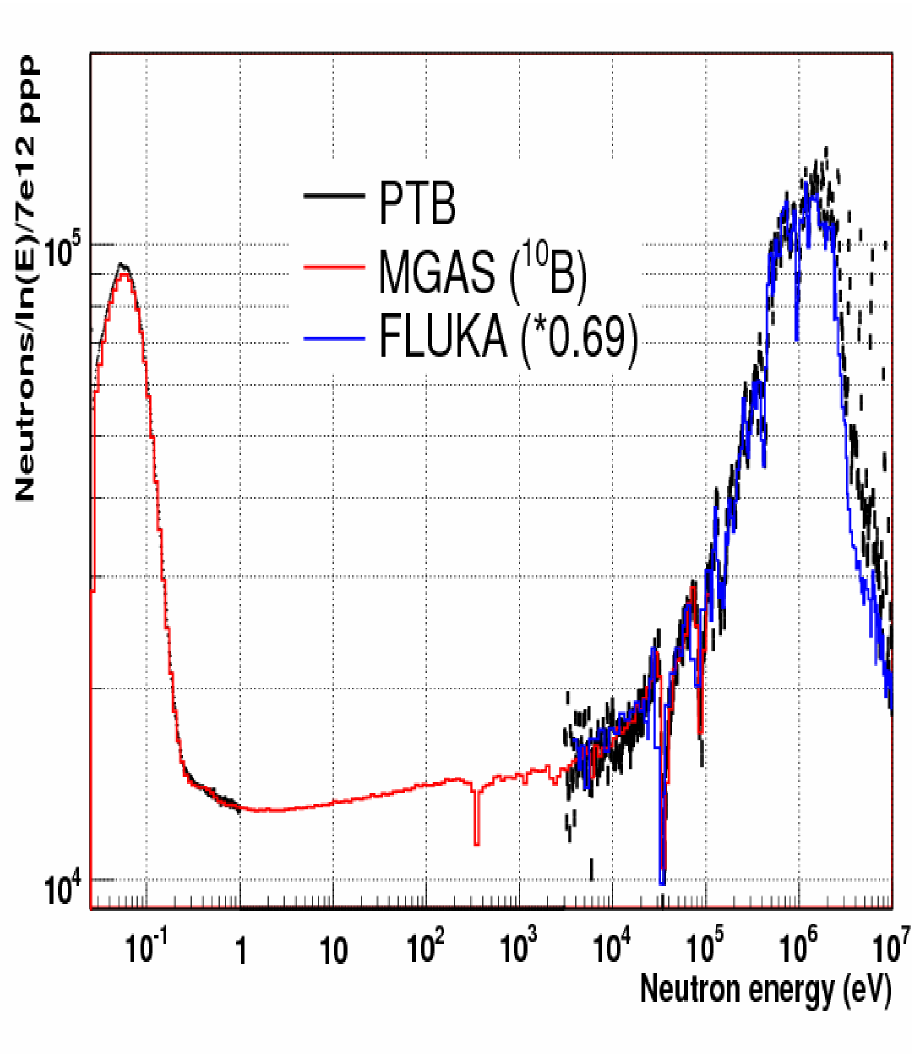
$$Y_r(E) = \frac{N_r}{N_n(E)}$$

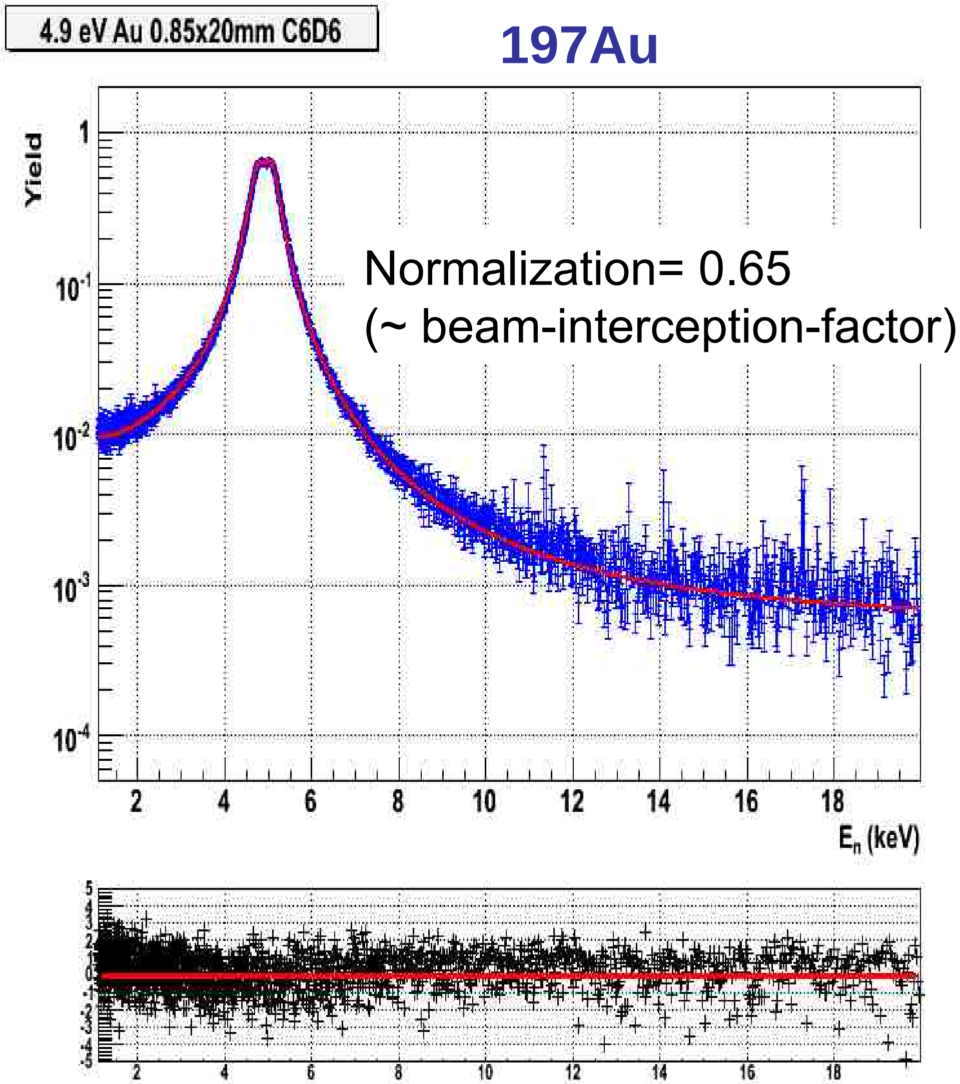
The total weighted spectrum was converted into yield using the relation:

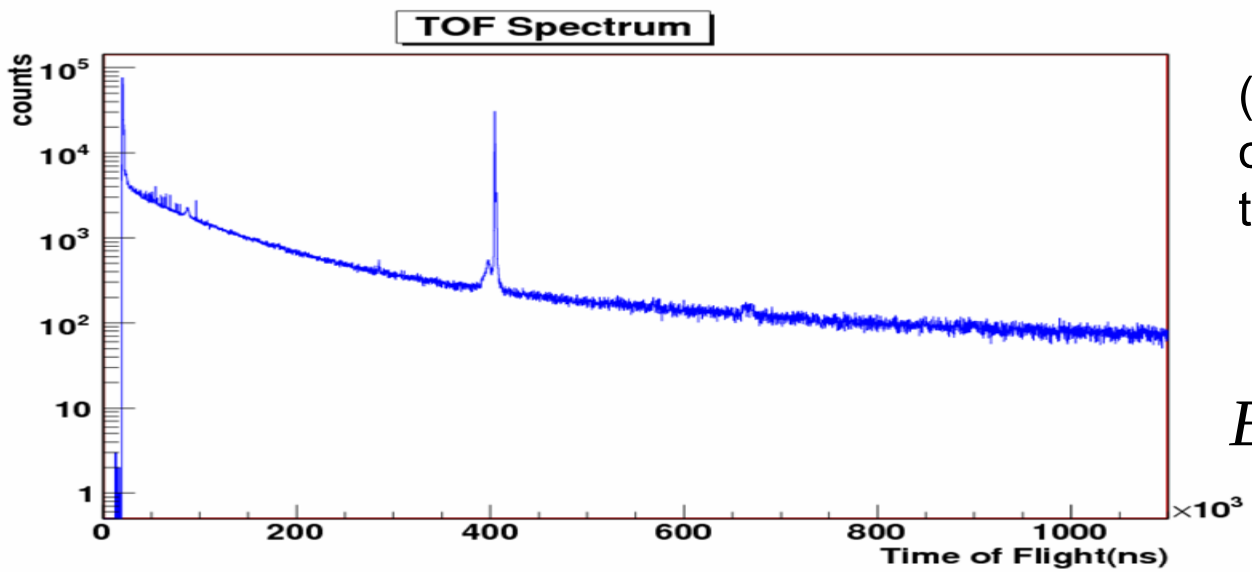
$$Y(E_n) = \frac{N^W(E_n)}{N_n(E_n) \times (S_n + E_n)}$$

The number of neutrons for each energy bin was obtained from neutron flux monitor data(Micromegas detector and PTB fission chamber) and from FLUKA MC simulation.

Normalization of neutron flux was obtained with saturated resonace method

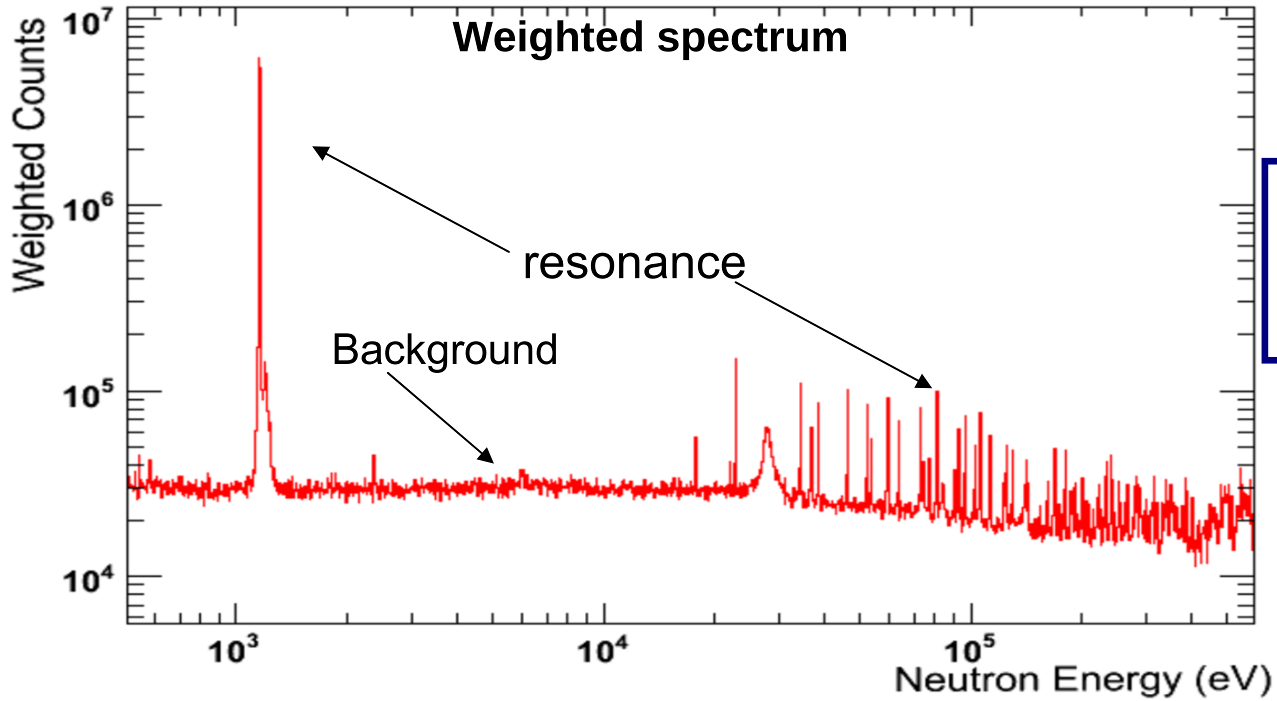






(n,γ) is measured as a function of time of flight, which is related to neutron energy

$$E_n = \frac{1}{2} m_n v^2 = \left(\frac{72.2977 L_0}{t + t_0} \right)$$



t is measured from the istant when n are produced till the effective reaction (n,γ) occurs

Background:γ rays scattered in the sample[E_γ=2.2MeV from H(n,γ) in water moderator]

Example of resonance analisys with SAMMY code

The analisys is performed with R-matrix analysis code SAMMY that include all the effects to describe cross section data.

Resonance are calculated using R-matrix formalism (the simplest is the Breit-Wigner formula)

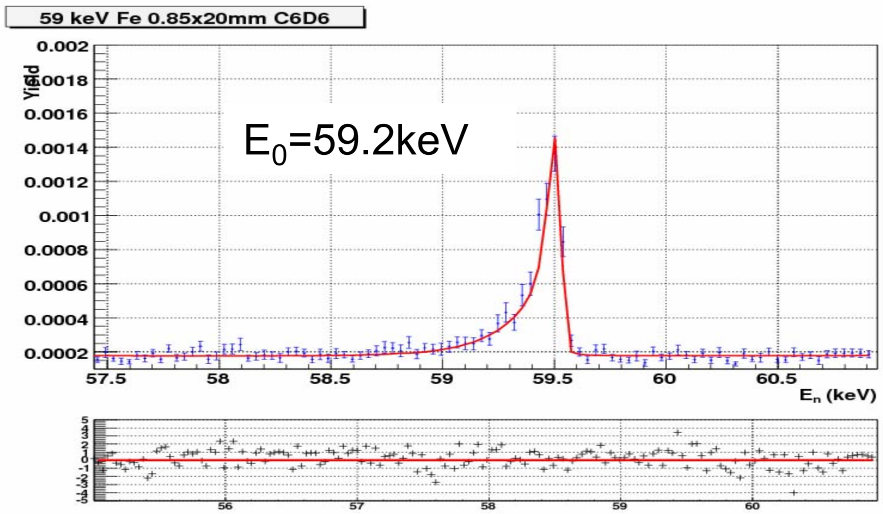
$$\sigma(E) = \pi\Delta^2 g_J \frac{\Gamma_n \Gamma}{(E-E_R')^2 + \frac{1}{4}\Gamma^2}$$

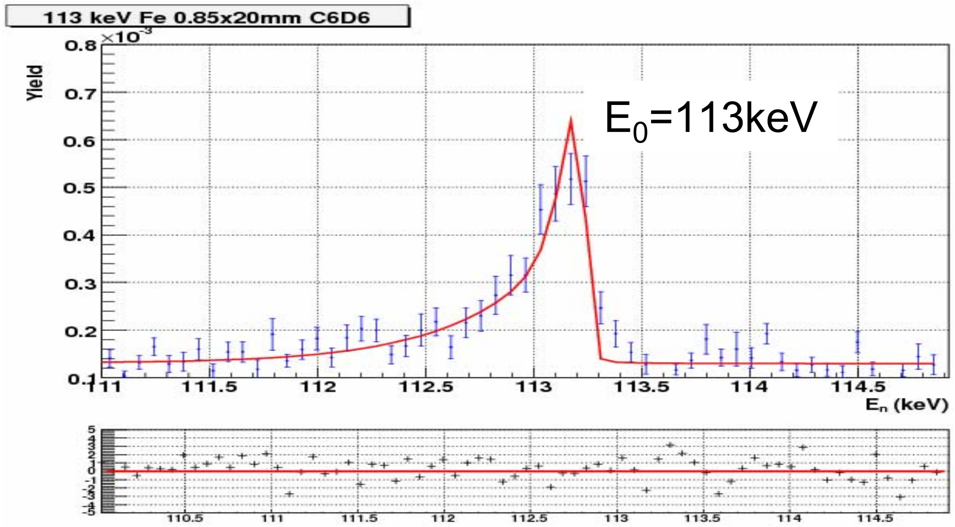
Resolution function: **TOF distribution of neutrons of a given energy**

Reproduce the simulated n-time response distribution

Using SAMMY code we can fit the data and extract the parameters:

$$E_R, \Gamma_\gamma, \Gamma_n, \ldots$$





Conclusion

The analisys on the data in term of resonance parameters is ongoing

With the improved experimental cross sections, the astrophysical consequences for the weak *s*-process component related to element production in massive stars of different mass and metallicity will be worked out. These results will then be used for a detailed discussion of the abundance patterns in UMP stars and for investigating the consequences for galactic chemical evolution.

The new lead target allows the use of borated water moderator to reduce beam γ-rays scattered background.The 54Fe measurement this year was made with this improvement