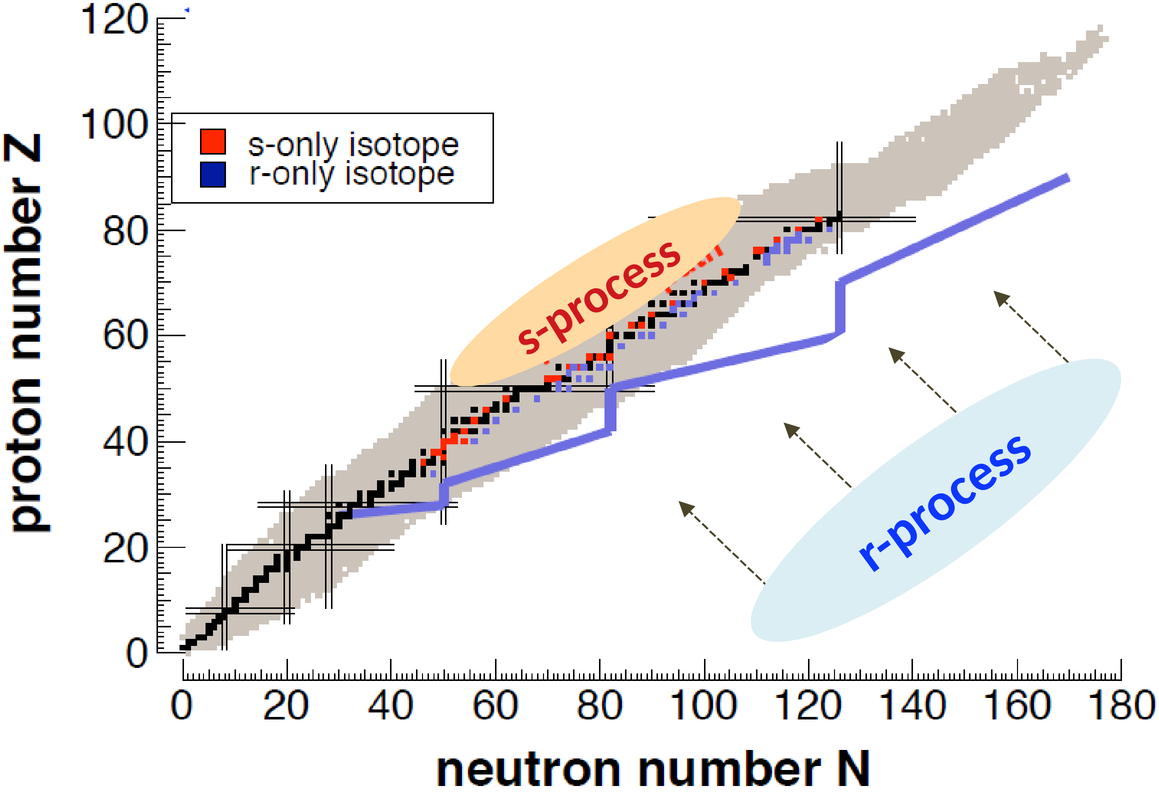
Measurement of the ^{140}Ce(n,γ) cross section at n_TOF

Stellar nucleosynthesis

The heavy elements (Z>26) are produced mostly via neutron captures followed by beta decays.



s-process

- Mainly AGB stars
- Capture times >> Decay times
- $N_n = 10^8$ n/cm^3 kT = 0.3-300 keV
- Near the valley of stability

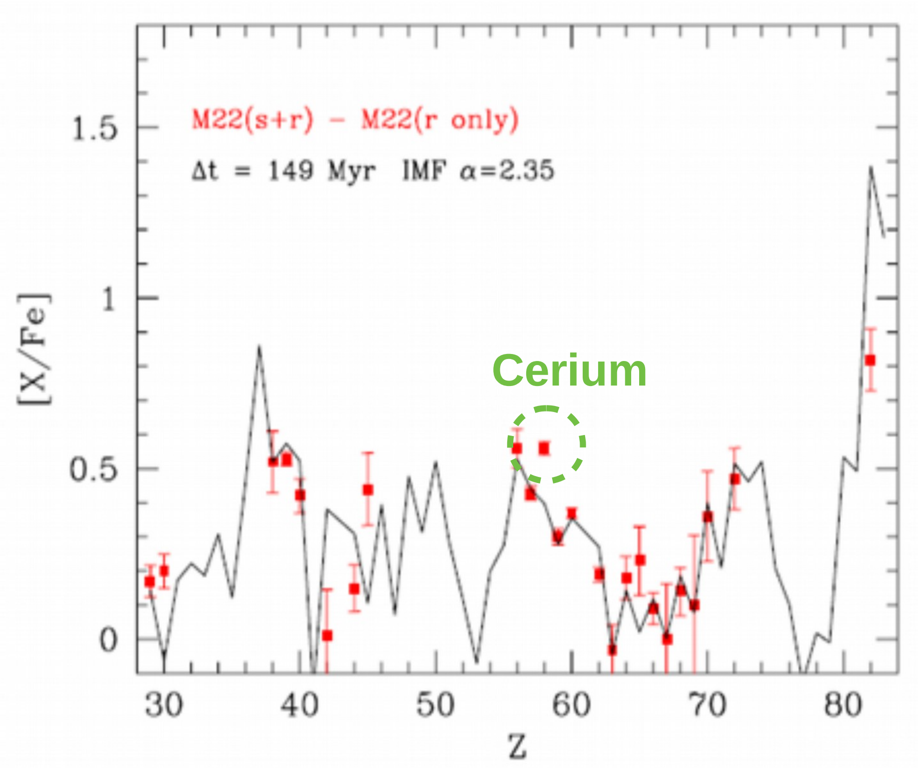
r-process

- Explosive environments
- Capture times << Decay times
- $N_n = 10^{20\text{-}30}$ n/cm^3 kT > 100 keV
- Far from stability

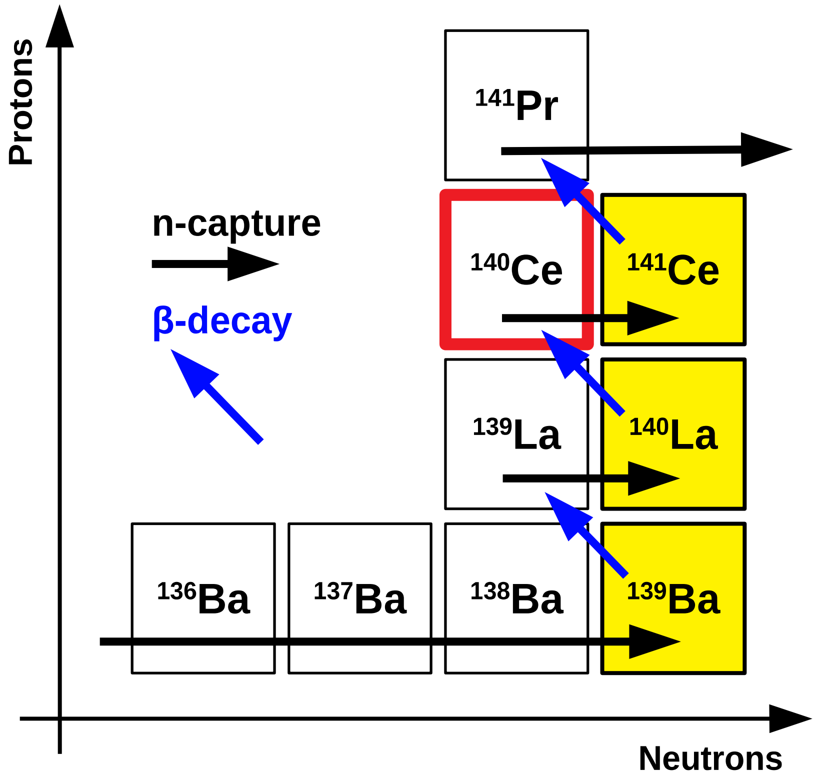
Why Cerium?

Cerium is mostly produced via **s-process**, the final abundance of ^{140}Ce (89% of natural cerium) predicted by stellar models strongly depends on its destruction channel ^{140}Ce(n,γ).

Small cross section (magic number of neutrons), the **MACS (Maxwellian average cross section) is determined by resonances in keV region**.



O. Straniero, S. Cristallo, L. Piersanti APJ **785** (2015) 77


Protons

Neutrons

n-capture

β-decay

^{141}Pr

^{140}Ce

^{141}Ce

^{139}La

^{140}La

^{136}Ba

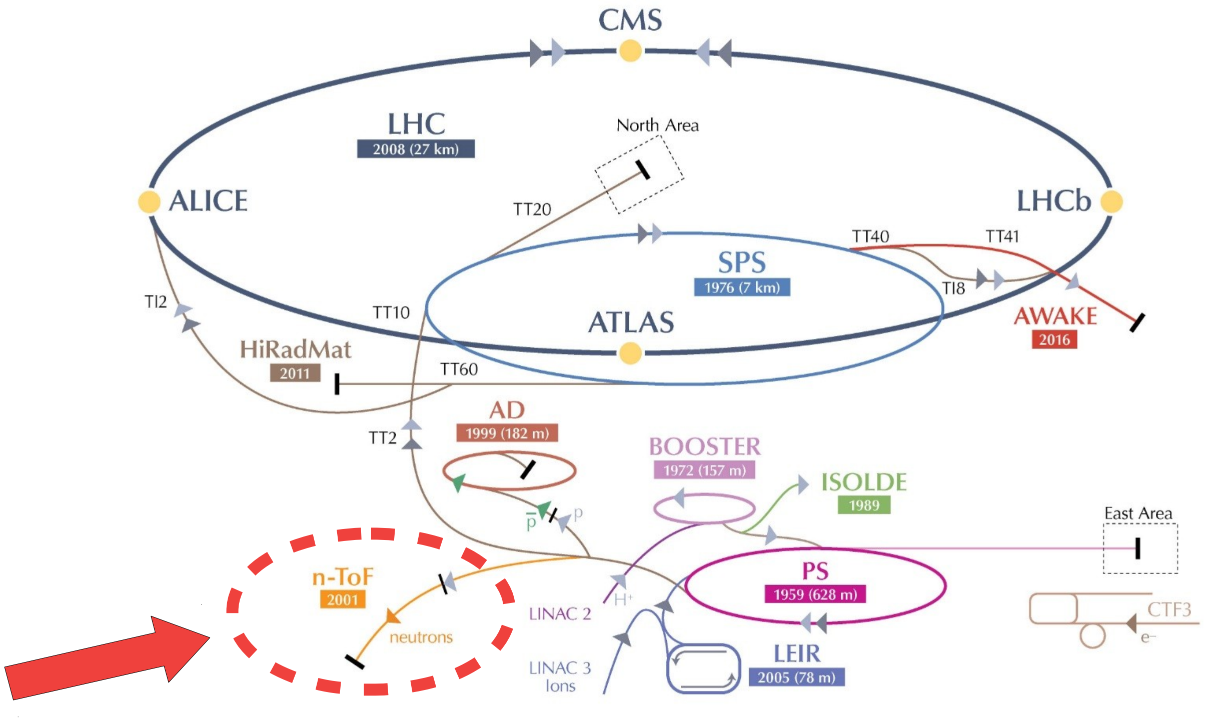
^{137}Ba

^{138}Ba

^{139}Ba

n_TOF facility

neutron_**T**ime**O**f**F**light

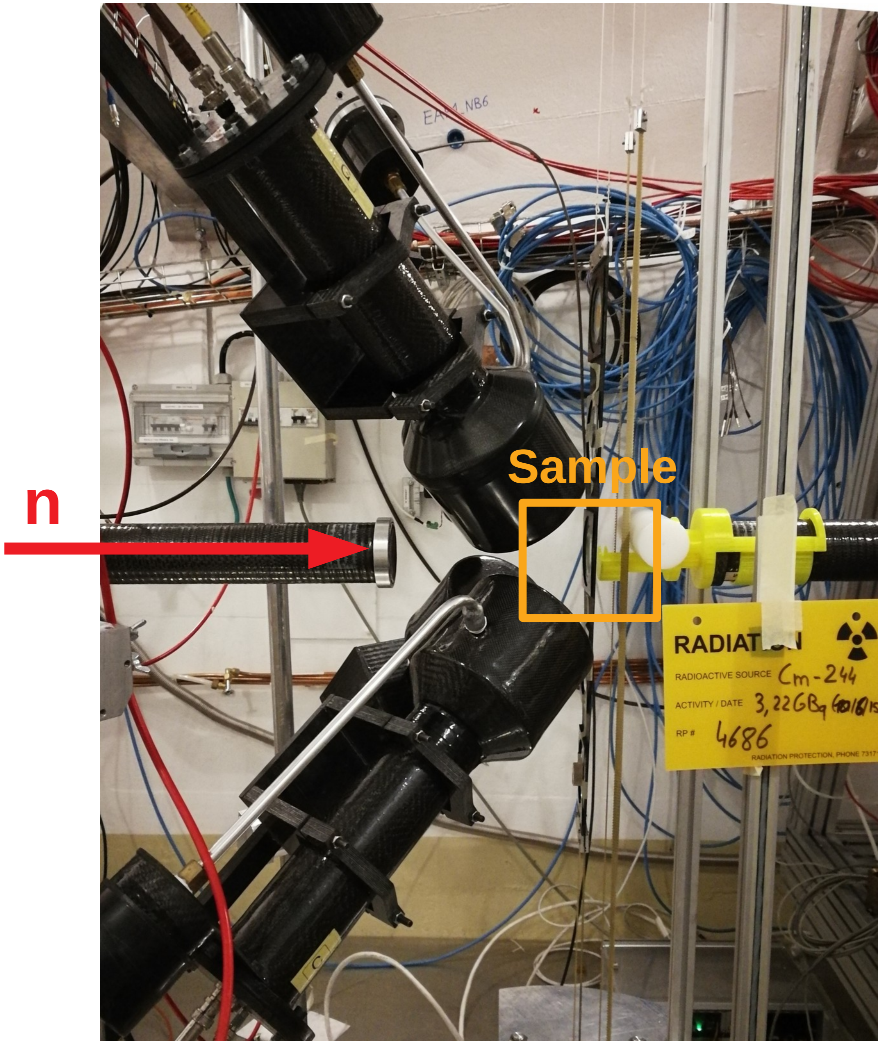


n_TOF is here

n_TOF facility has the **high instantaneous neutron flux**, the **wide energy range** and the **high energy resolution** (up to 10^{-4}) and low background needed for this accurate measurement.

For more details see talk from Cristian Massimi **“Nuclear astrophysics activities at the n_TOF facility at CERN”**.

Experimental setup for ^{140}Ce(n,γ)

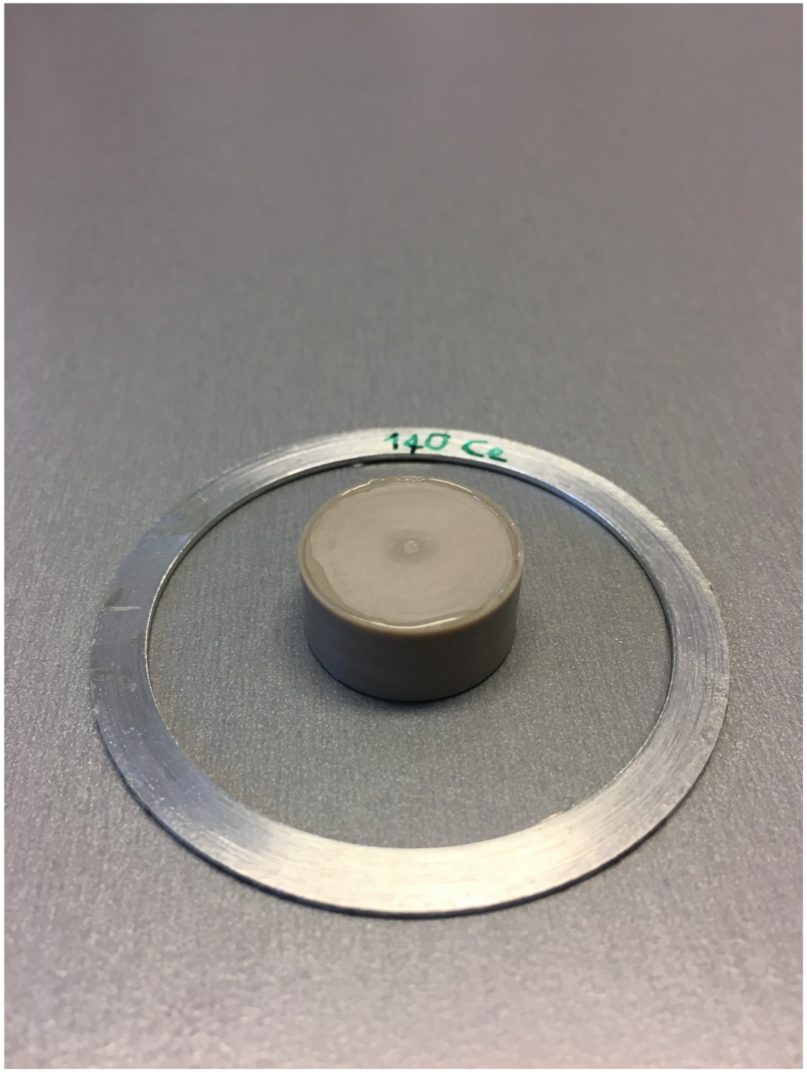


Liquid scintillator detectors containing C_6D_6 used to measure **(n,γ)** reaction cross sections.

Low neutron sensitivity and background thanks to the carbon fiber structure.

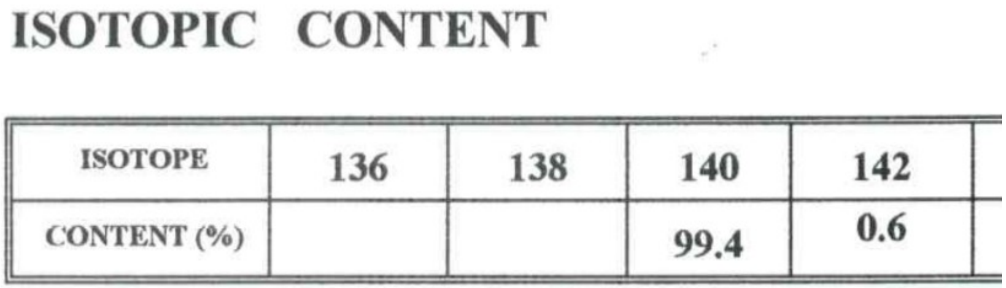
The neutron energy is measured with Time of Flight technique with a **energy resolution of 10^{-4}**.

^{140}Ce Sample



Sample made of CeO_2 powder, **enriched in ^{140}Ce (99.4%)**, total ^{140}Ce mass ~ 10 grams.

First capture measurement with a combination of high purity sample and high energy resolution.



ISOTOPIC CONTENT

ISOTOPE	136	138	140	142
CONTENT (%)			99.4	0.6

89% and 11% natural

Data analysis

The quantity we want to extract from a capture measurement is the experimental Yield, defined as:

$$Y_{exp}(E_n) = \underset{\textbf{Normalization}}{N}\,\frac{\overset{\textbf{Counts}}{C_w(E_n)} - \overset{\textbf{Background}}{B_w(E_n)}}{\underset{\textbf{Efficiency}}{\varepsilon(E_n)}\,\underset{\textbf{Neutron flux}}{\phi(E_n)}}$$

Data analysis

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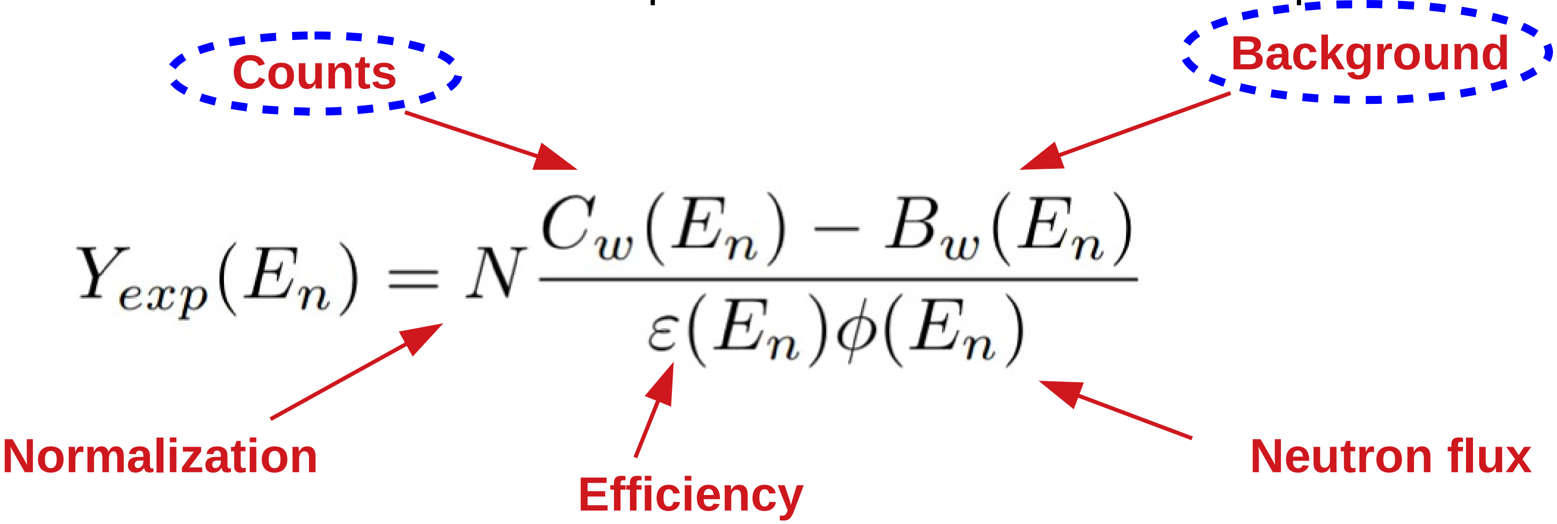


$$Y_{exp}(E_n) = N\frac{C_w(E_n) - B_w(E_n)}{\varepsilon(E_n)\phi(E_n)}$$

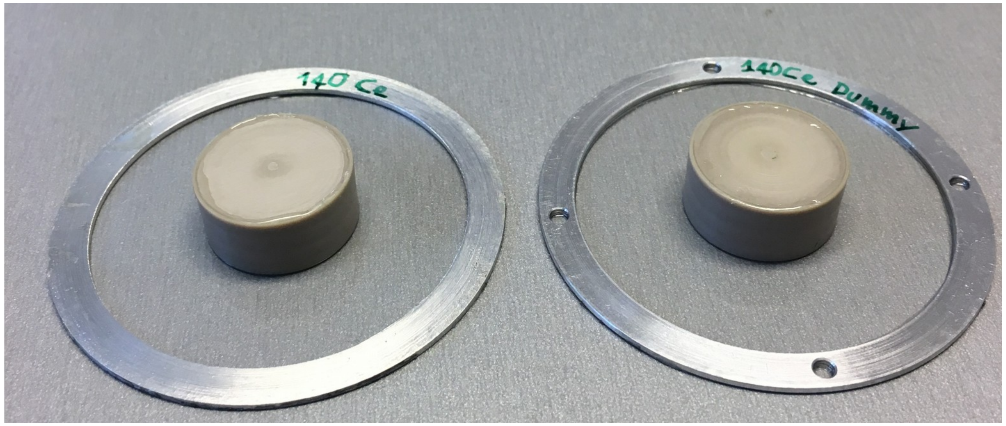
Counts

Background

Normalization

Efficiency

Neutron flux



Dedicated beam time with dummy samples to evaluate background

Data analysis

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Counts

Background

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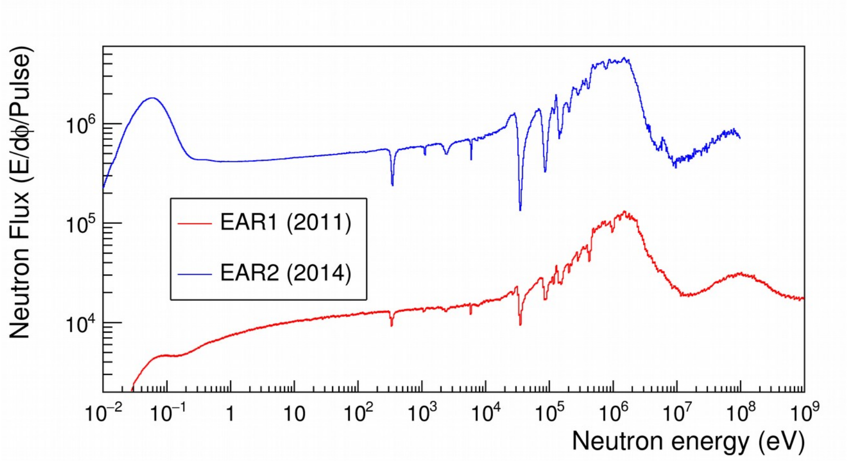
Normalization

Efficiency

Neutron flux

Official n_TOF neutron flux



M. Barbagallo et al., "High-accuracy determination of the neutron flux at n TOF" Eur. Phys. J. A (2013) 49: 156

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Background

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Normalization

Efficiency

Neutron flux

Efficiency to detect a cascade following the neutron capture, determined by the "Pulse Height Weight Technique"

$$\varepsilon_{\gamma} = \alpha E_{\gamma} \quad \Longrightarrow \quad \varepsilon_{(n,\gamma)} = \sum_{j} \varepsilon_{\gamma_j} = \alpha E_{(n,\gamma)}$$

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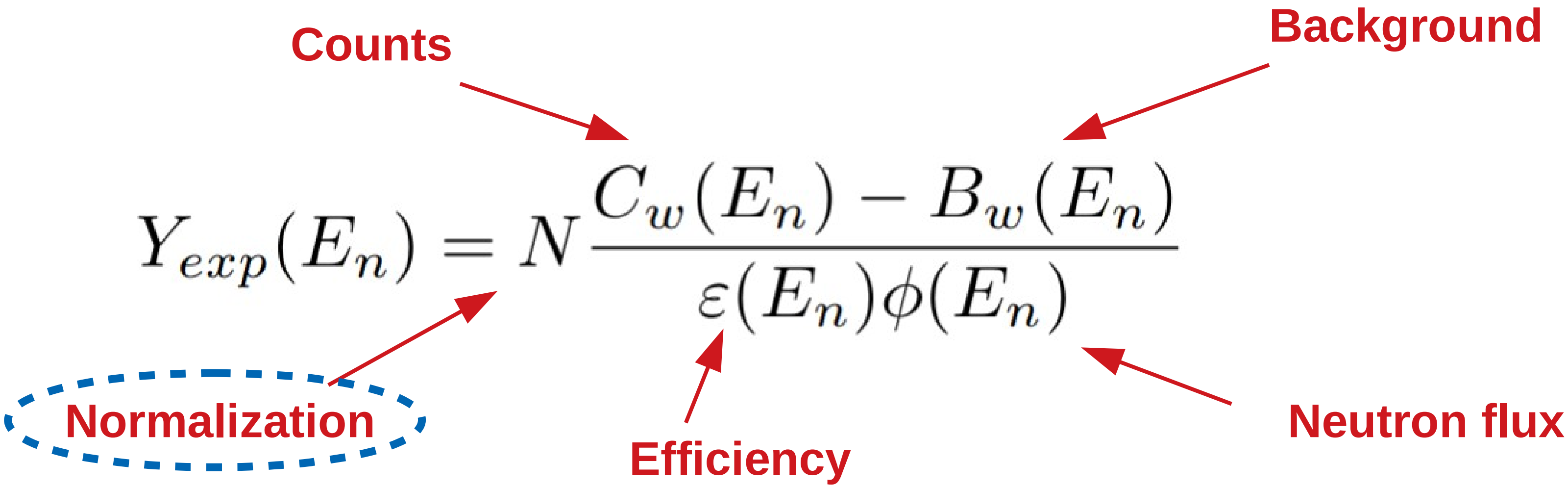


Counts

Background

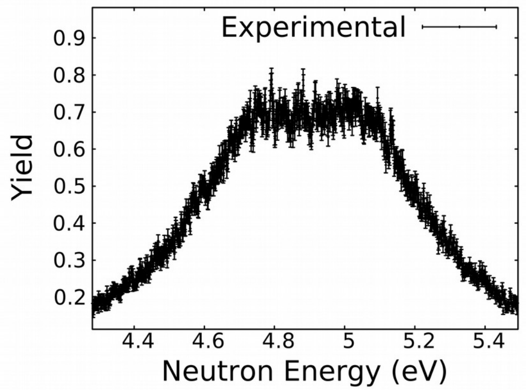
$$Y_{exp}(E_n) = N\frac{C_w(E_n) - B_w(E_n)}{\varepsilon(E_n)\phi(E_n)}$$

Normalization

Efficiency

Neutron flux

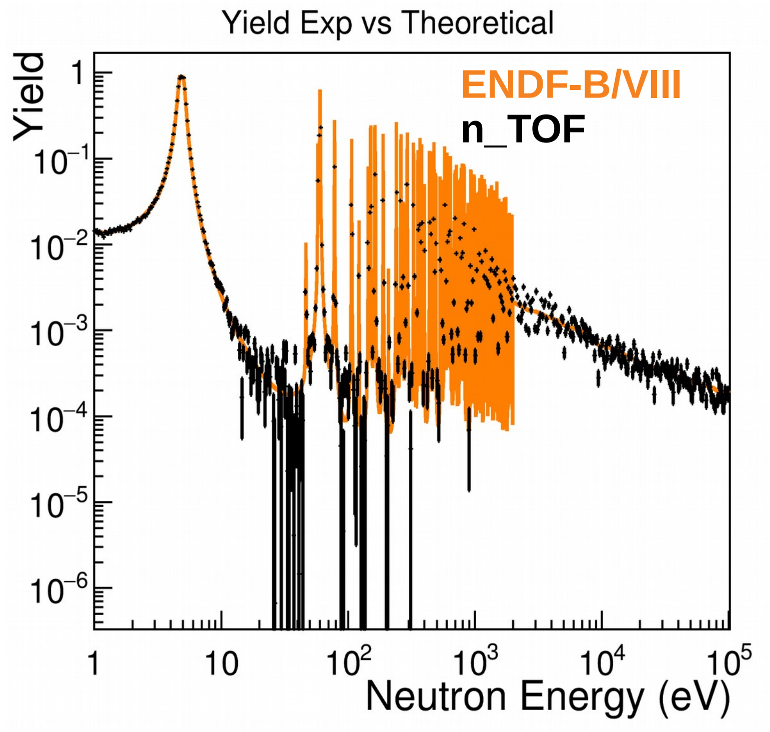
Geometrical factors including the Beam Interception Factor

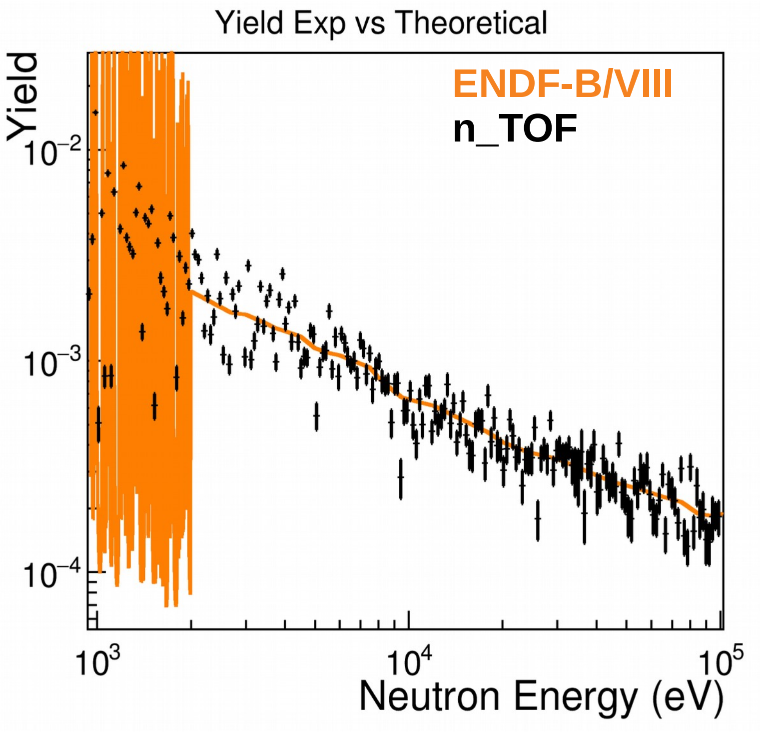


Cerium data are **normalized to ^{197}Au(n,γ)** in the “saturated resonance” and corrected by the different total energy of the two cascades.

Gold yield

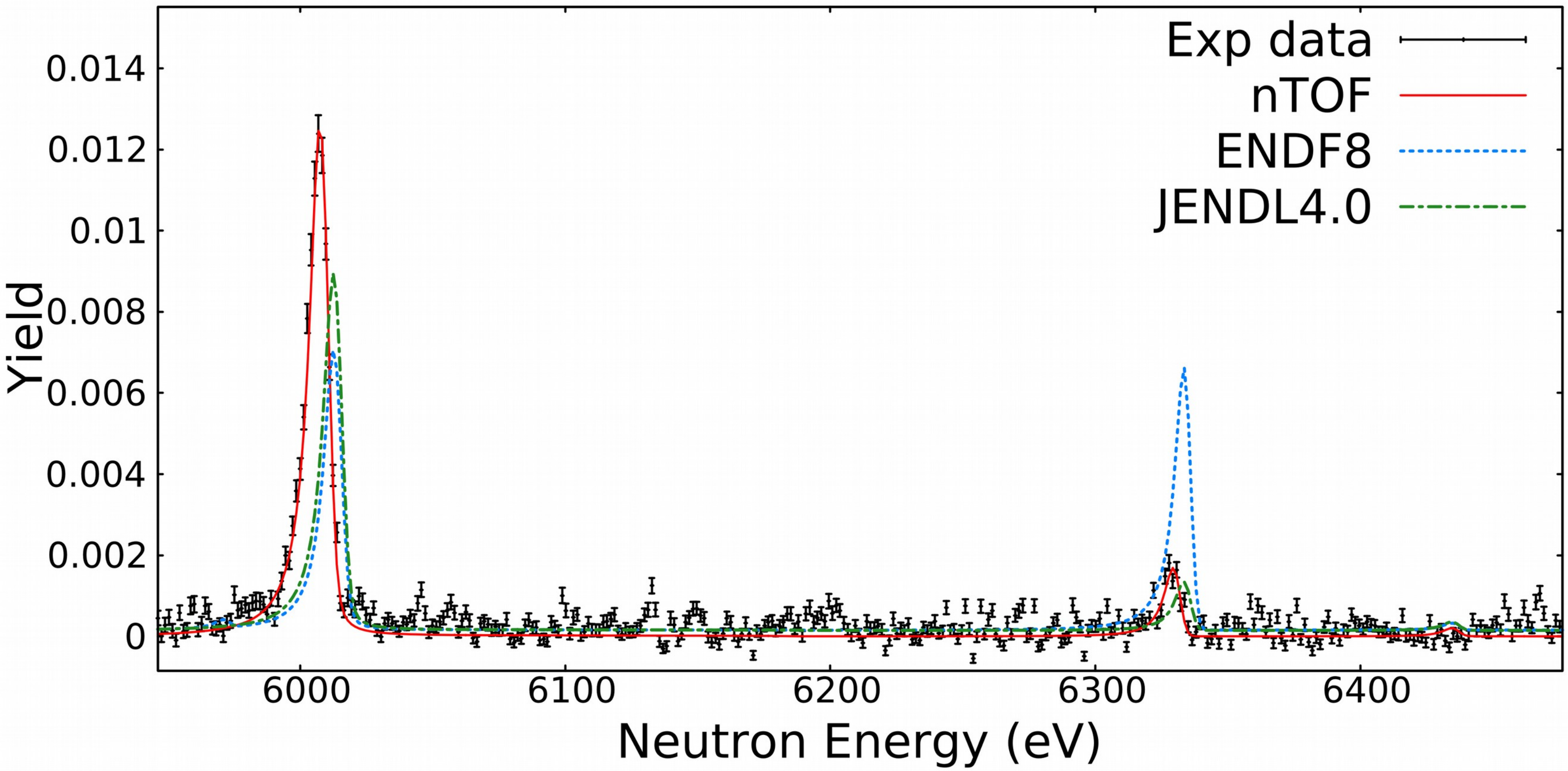
The gold sample allow as well to check the experimental data, in particular in the keV energy region where the resonance of ^{140}Ce are located. **A good agreement between n_TOF and nuclear libraries is observed**.





Resonances analysis

The resonance analysis has been performed with SAMMY **up to 65 keV**, using JENDL4.0 as reference library. The **two reaction width** (capture and scattering) are fitted at the same time, **together with the resonance energy**.



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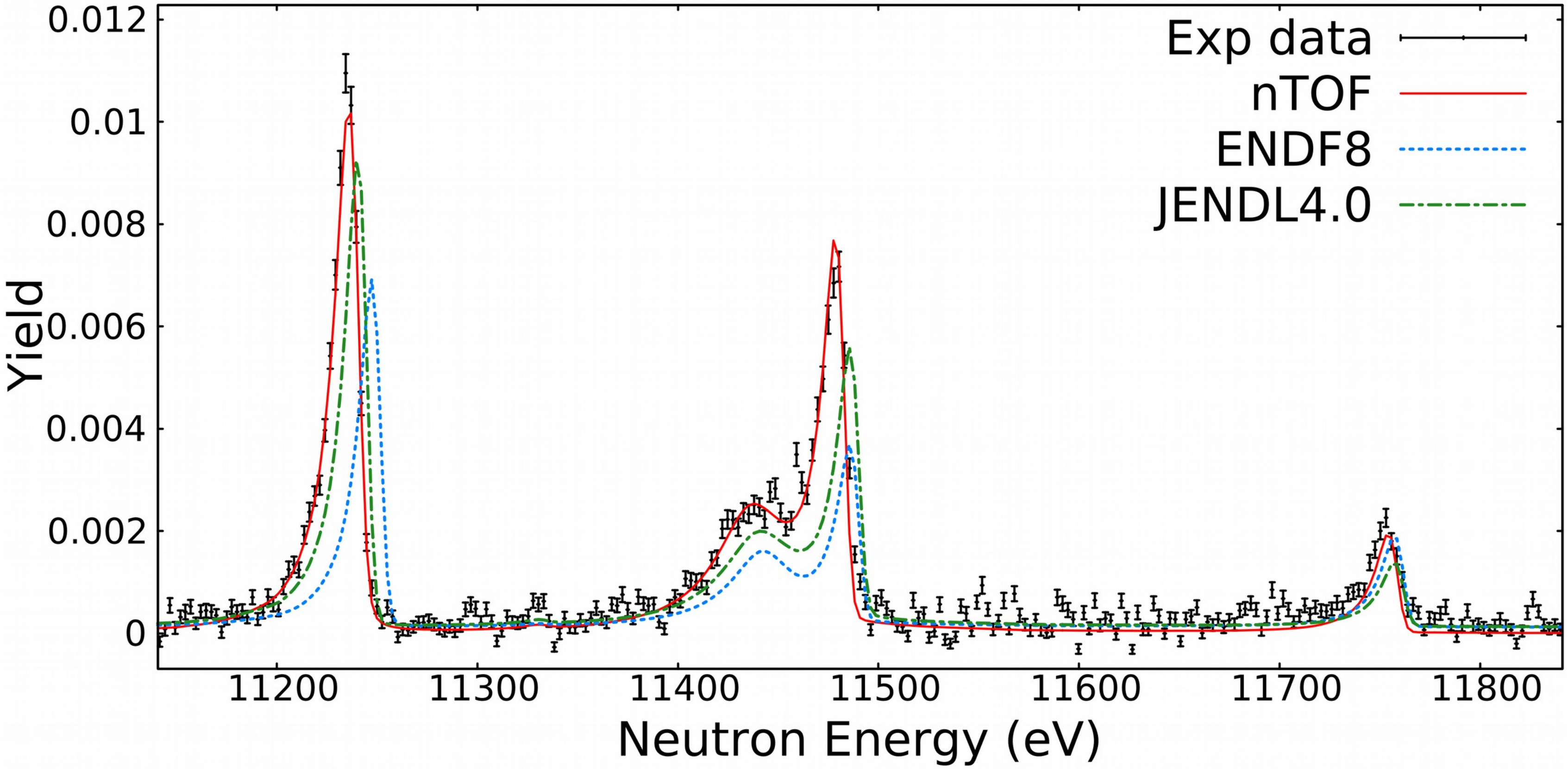
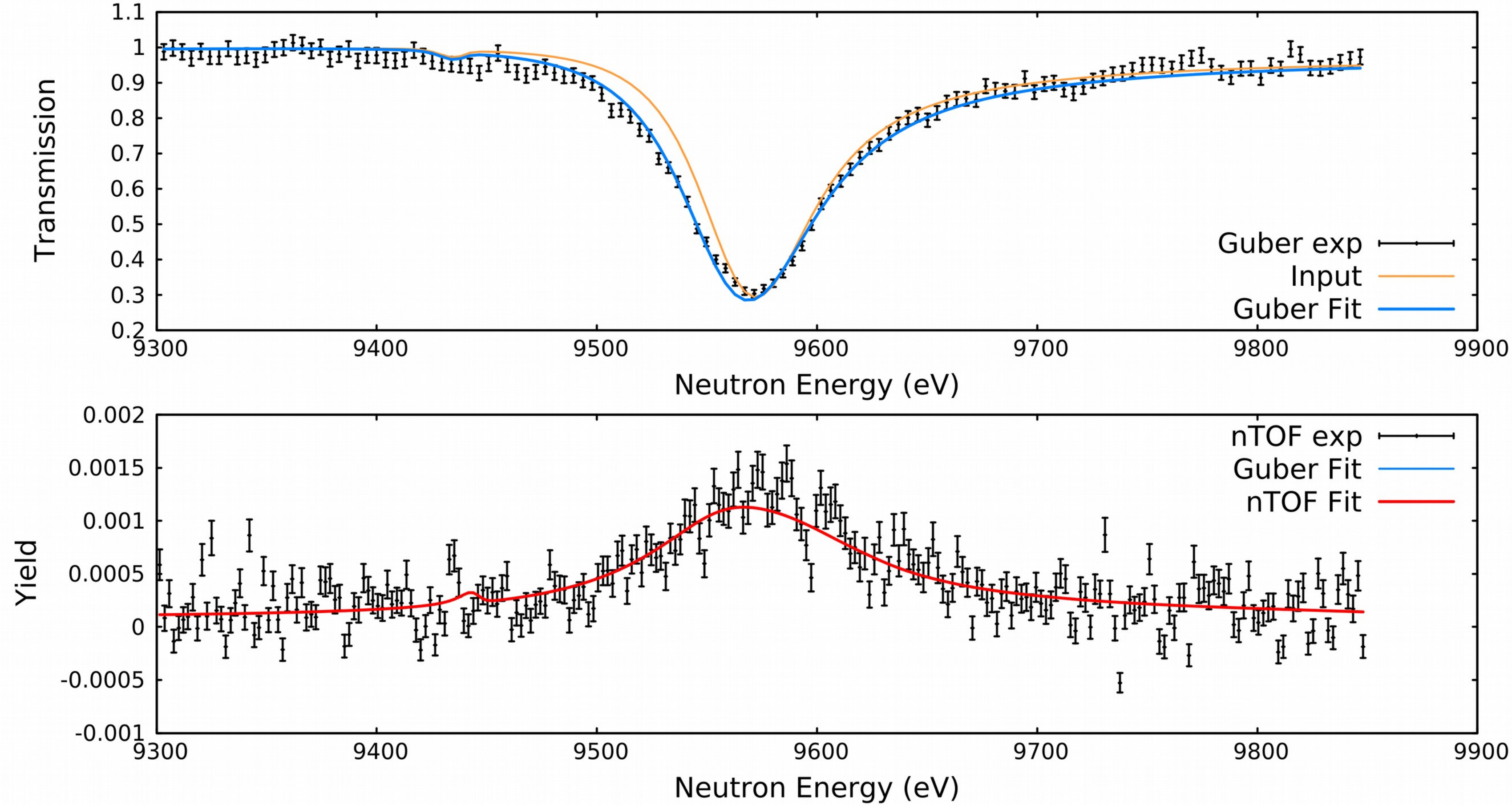


Resonances analysis

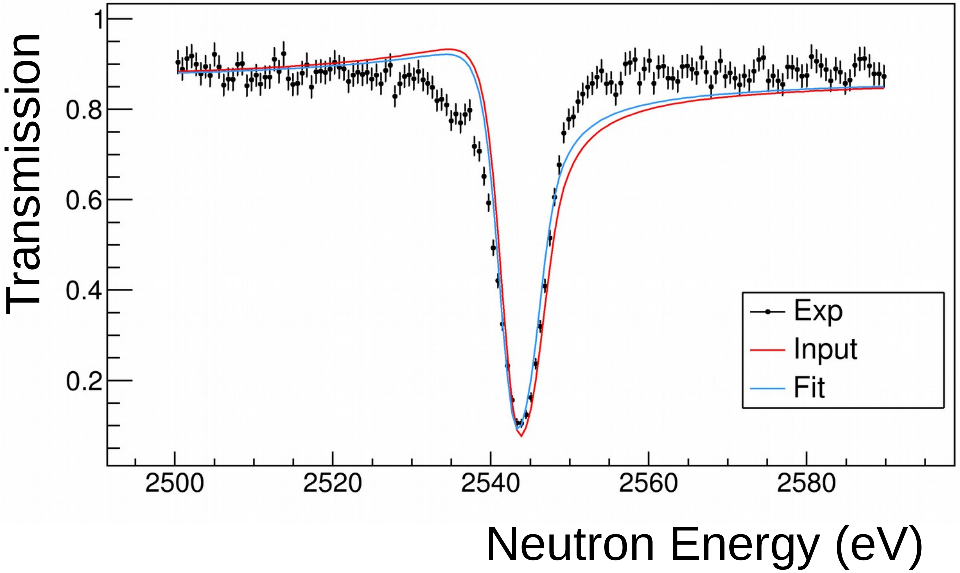
We **included in the analysis a transmission measurement** performed at GELINA in 2016 by Guber et al. with a natural sample (89% of ^{140}Ce). The combined fit provided a better estimation for the Γ_n of large resonances.



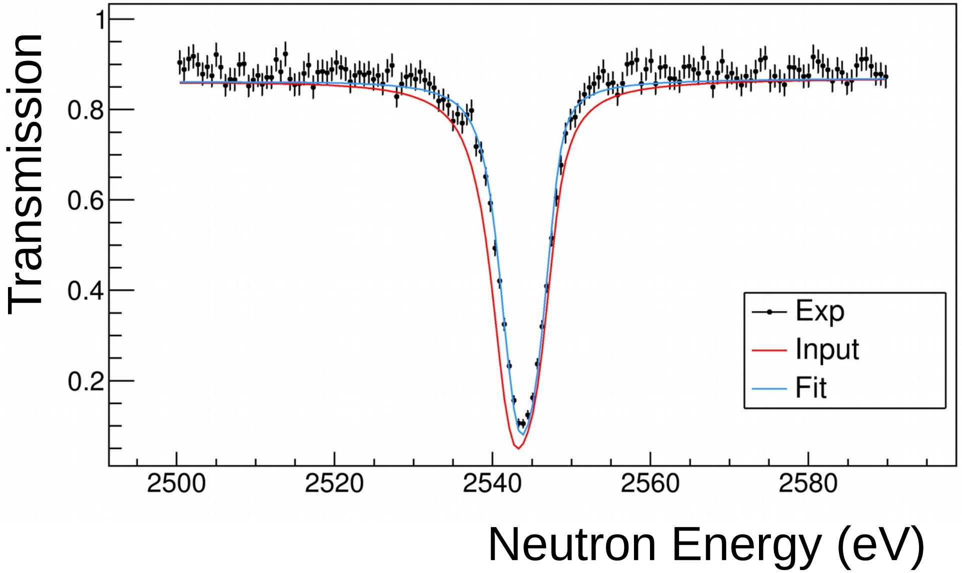
Wrong spin/parity in s-wave

Further looking to the transmission data with the thick target, we noticed that **3 of the 16 fitted s-waves are clearly p-waves**:

s-wave



p-wave



Clearly the reduction of s-wave number impacts the relative spacing.

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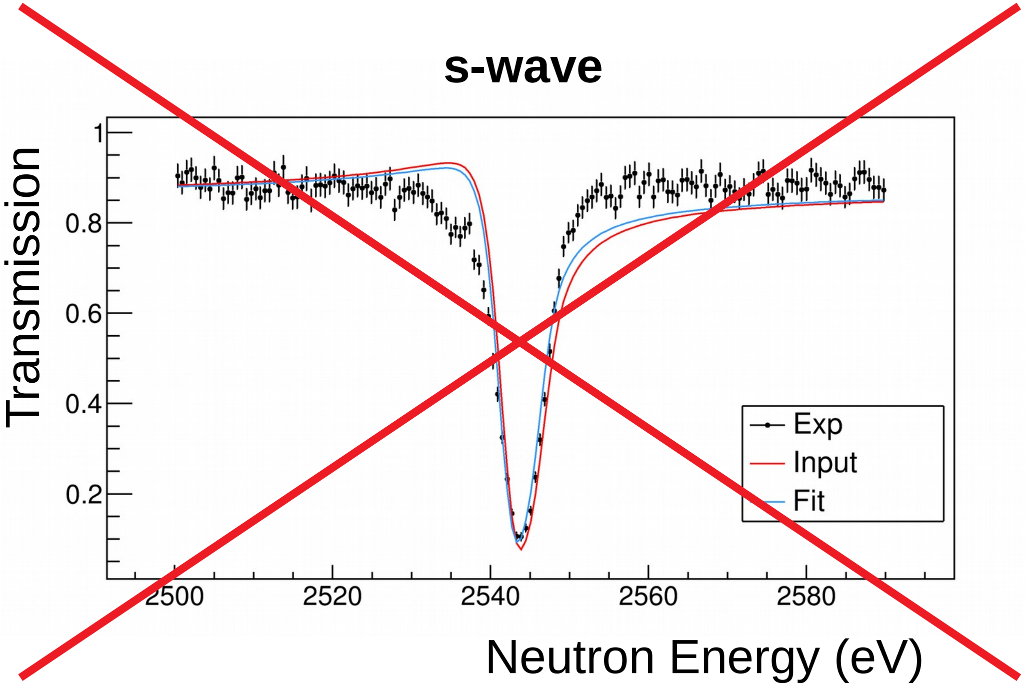
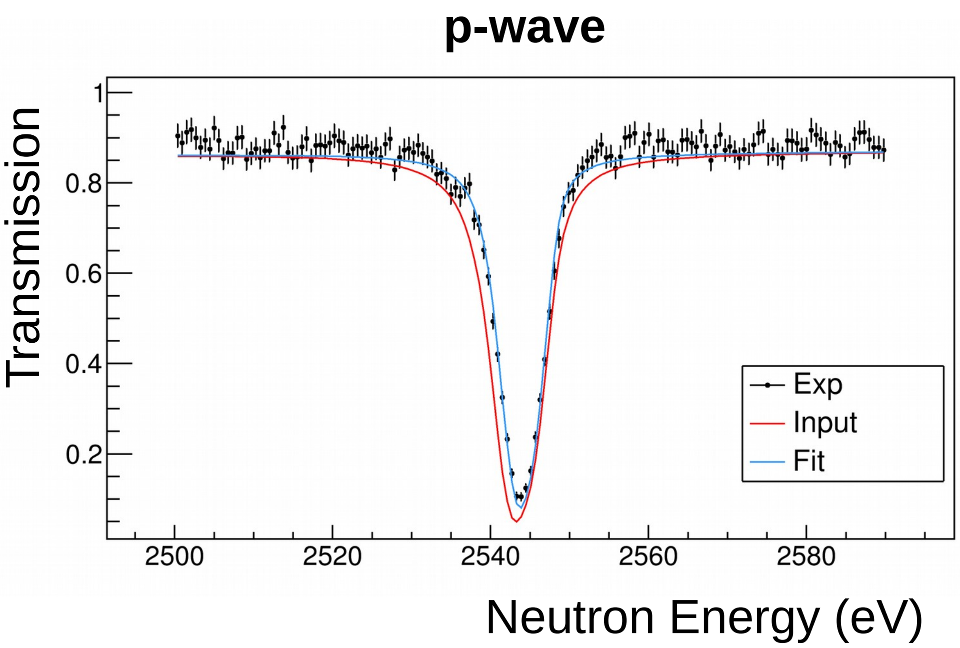


s-wave

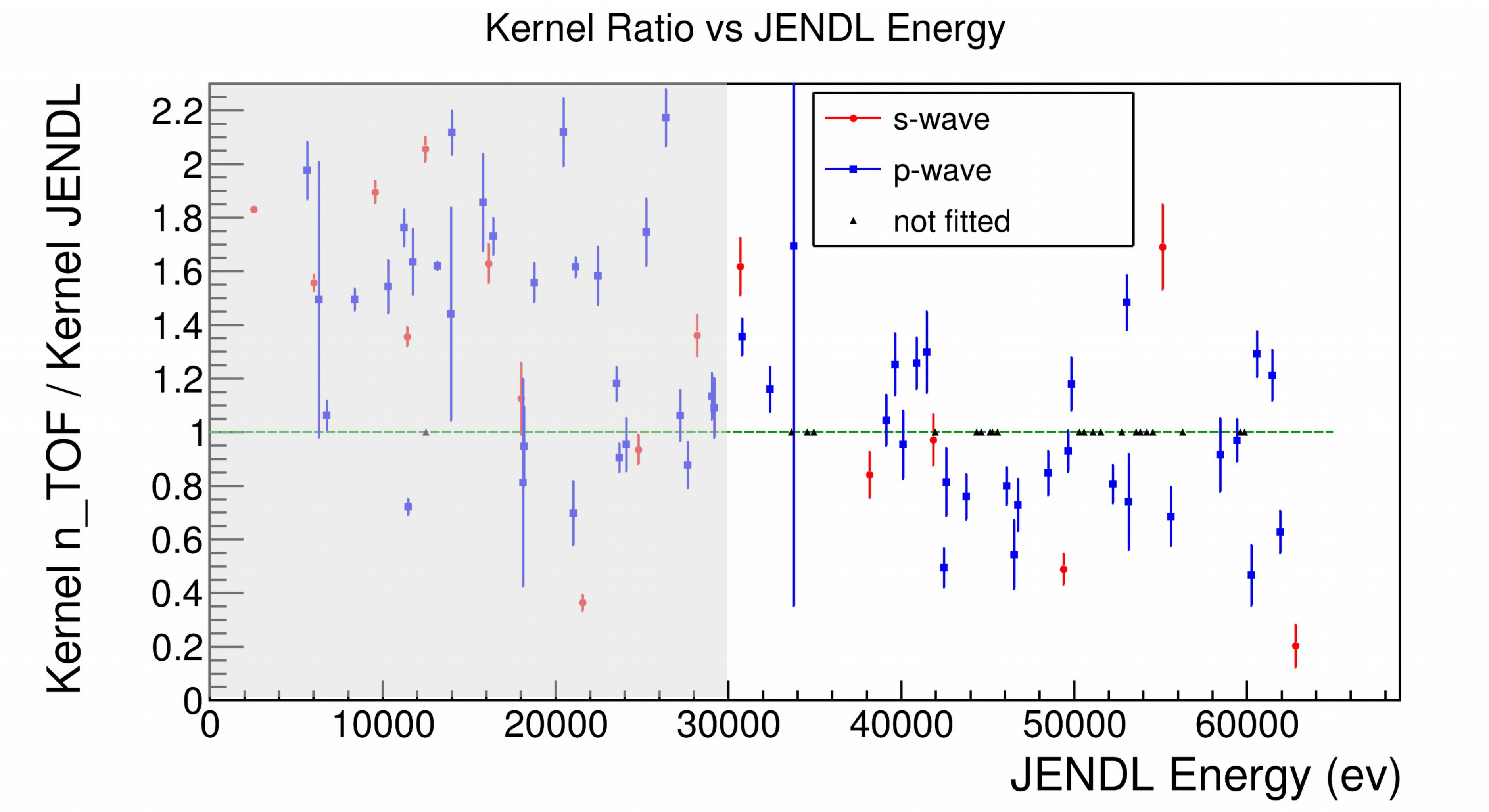


p-wave

The 3 resonance have been **fitted with the new spin** combining transmission&capture data.

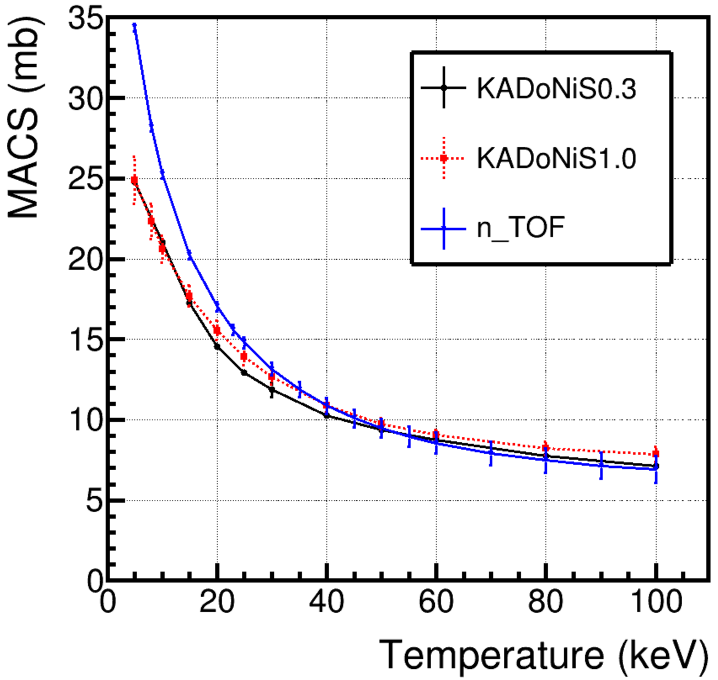
Kernel ratio vs JENDL Energy

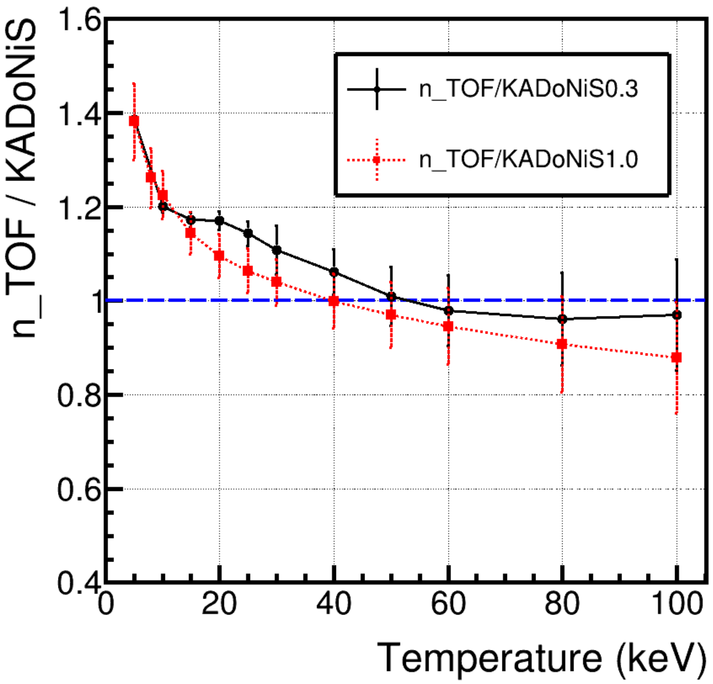
The kernel **ratio n_TOF/JENDL is systematically larger than 1**, for E_n<30 keV



MACS

The n_TOF MACS has been calculated combining the **n_TOF data and JENDL-4.0 library** (for the energy region that was not possible to measure).

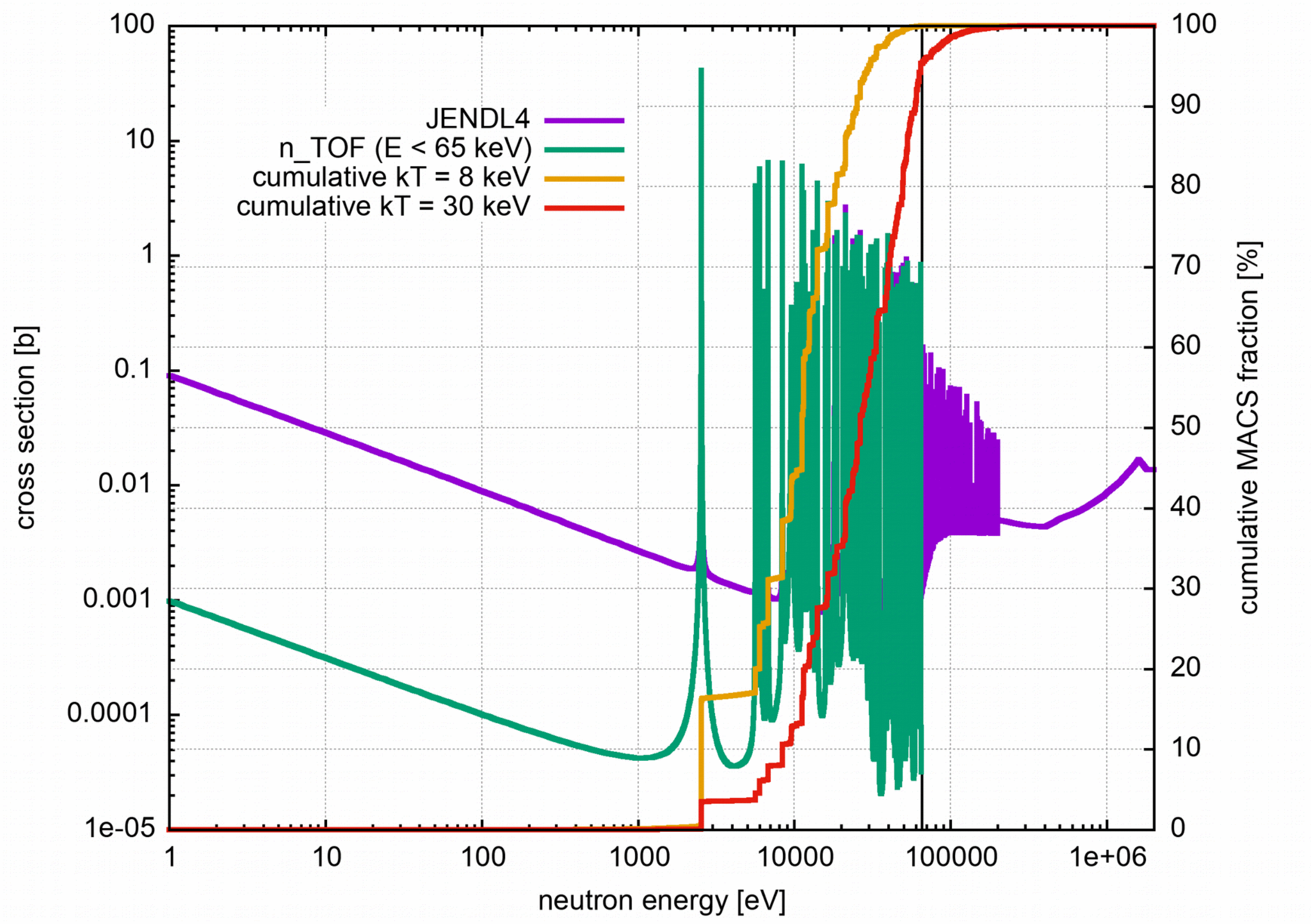




The n_TOF+JENDL-4.0 MACS is **higher than KADoNiS at low temperature** (contrary to what expected) but a **reasonable agreement is observed at 30 keV.**

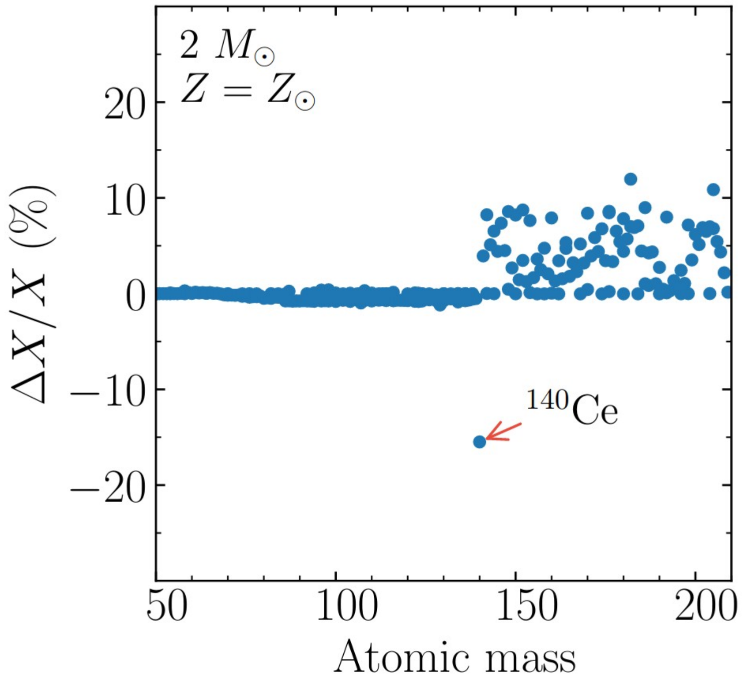
Contribution to the MACS

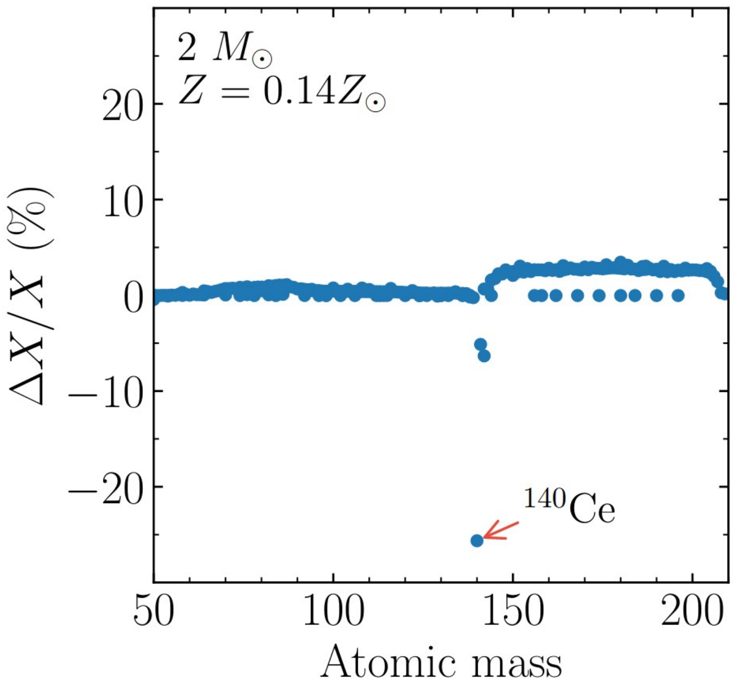
At the temperature of interest the MACS is determined almost entirely by the resonances **below 65 keV** (80% of the resonances has been fitted in this interval, the one with higher kernel thus providing the higher contribution).



Astrophysical impact

The impact has been evaluated calculating the **difference in the isotopic abundances** predicted by the stellar model with the new MACS with respect to the previous values.





The new values for the ^{140}Ce abundance are ~20% lower to the previous ones, in the opposite direction with respect to what originally expected from the observations.

An impact on the heavier nuclei is observed as well, since the **^{140}Ce acts as a bottleneck** of the s-process an increase of his MACS make easier to overcome it.

Conclusions

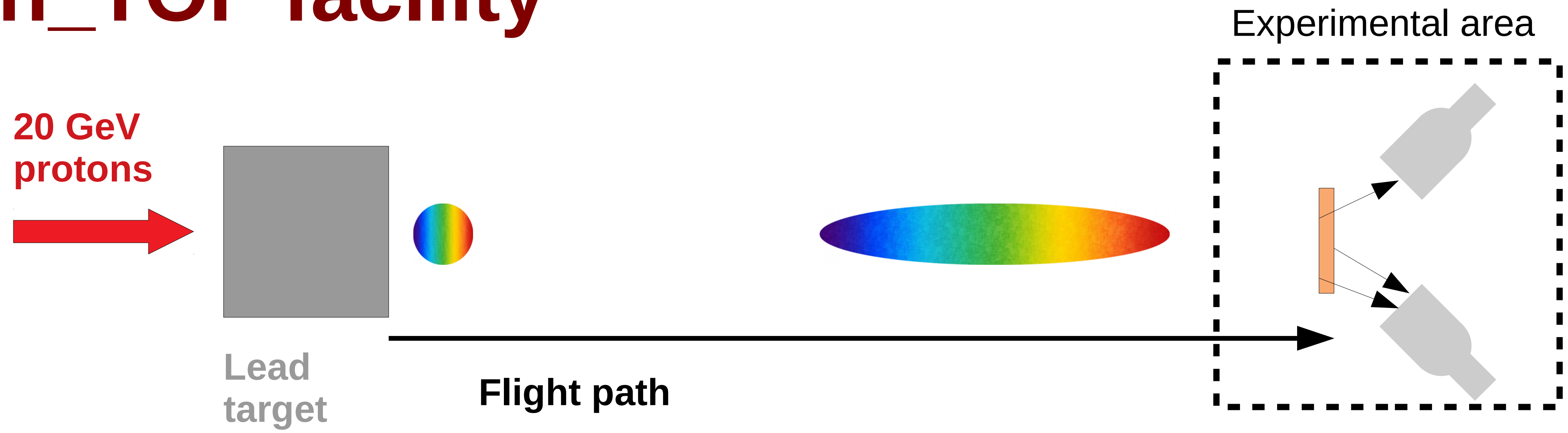
An accurate measurement of **^{140}Ce(n,γ) cross section has been successfully performed at n_TOF**, the resonance analysis has been carried out up to 65 keV and the parameters of s and p waves has been estimated.

The MACS calculated on the basis of the new parameters and JENDL library is in **good agreement with KADoNiS at 30 keV** (essentially the activation measurement by Käppeler et al.) while it is **higher at lower temperatures**.

As it reasonable, the **^{140}Ce produced by the main component of s-process** decreases causing an higher discrepancy with observations.

The easiness of overcoming ^{140}Ce bottleneck changes the neutrons available and influences the abundances of a large part of heavier elements.

n_TOF facility

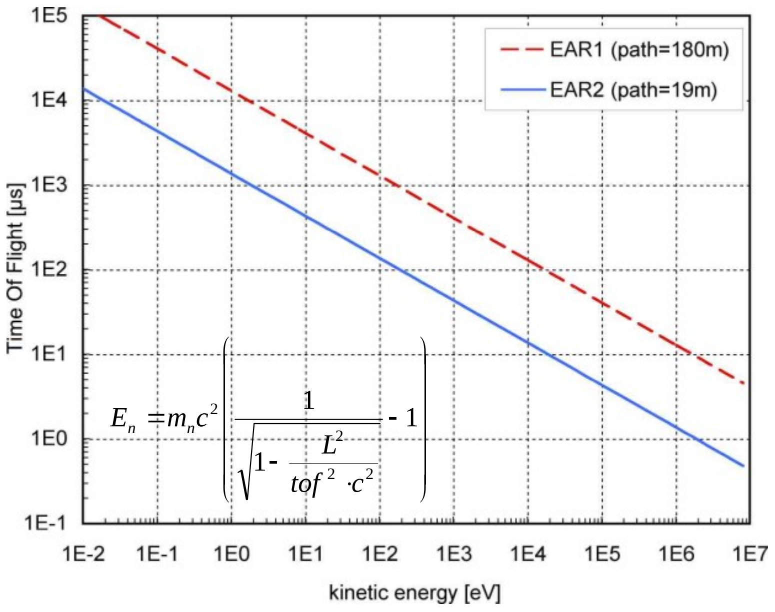


Experimental area

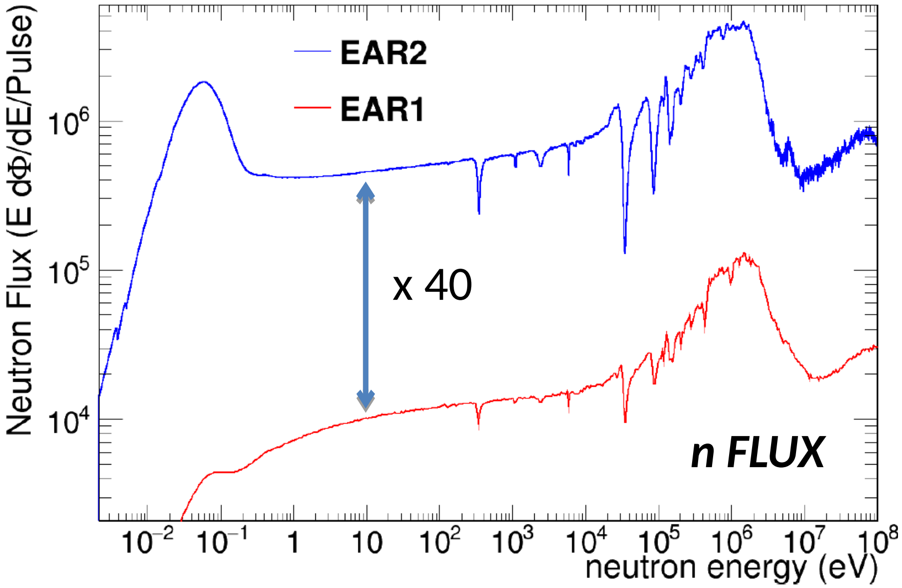
20 GeV protons

Lead target

Flight path

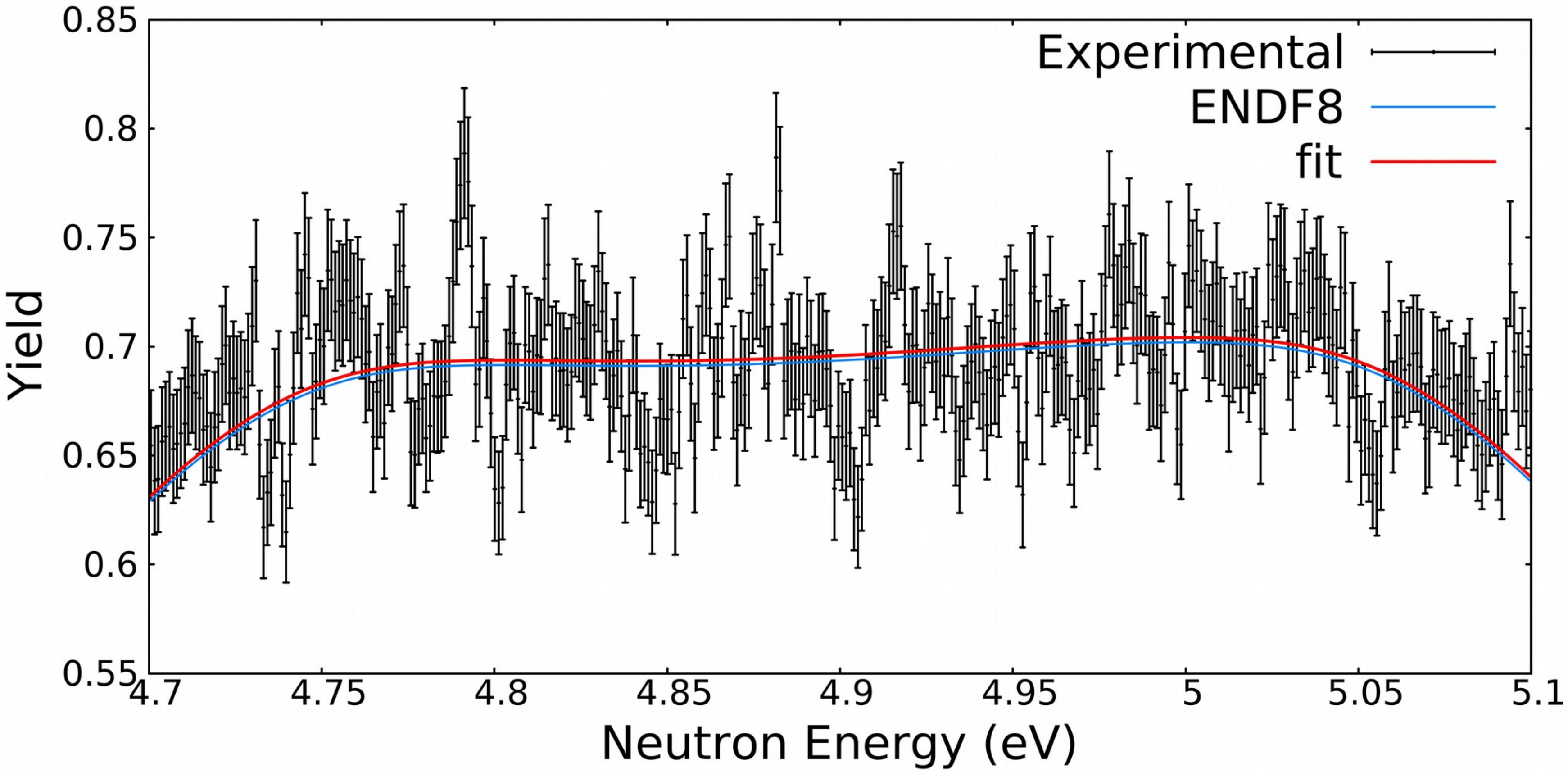


$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{tof^2 \cdot c^2}}} - 1 \right)$$



Normalization

Normalization constant computed fitting the gold yield between 4.7 and 5.1 eV
C = 0.7127 +- 0.0014
The value has been corrected for the sample diameter (19.5 mm vs the 20 mm of the gold sample).



Pulse Height Weight Technique

It is used to simplify the analysis **removing the dependence on the cascade decay path**. It requires the use of low efficiency γ detectors with efficiency proportional to the gamma energy. If is met the condition:

$$\varepsilon_{\gamma} = \alpha E_{\gamma}$$

the efficiency for detecting a neutron capture is proportional to the known cascade energy:

$$\varepsilon_{(n,\gamma)} = \sum_{j} \varepsilon_{\gamma_j} = \alpha E_{(n,\gamma)}$$

In our case the direct proportionality is obtained weighting the counts with a function computed via Monte Carlo simulation in GEANT4.