Neutron capture cross section measurements for nuclear astrophysics by the activation method at the n_TOF NEAR Station

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Neutron Capture @ NEAR

Neutron capture cross section measurements by the activation method
at the n_TOF NEAR Station

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Outline

1) Motivation and introduction

2) The activation technique and instrumentation

3) The filtering method

4) Conclusions and proton request

Motivation

Why are we interested in MACS measurements

- Measurements of Maxwellian Averaged Cross-Sections (MACS) are fundamental in nuclear astrophysics[1]
- Half the atomic nuclei heavier that iron are created through the s-process, a series of neutron capture reactions and β-decays[1]
- Accurate measurements of cross-sections are an essential input to calculate element abundances[2],[3]
- Typical temperatures for nucleosynthesis studies are in the range kT = 5-100 keV (60 – 1100 M Kelvin)

[1] Burbidge, E. M. et al (1957), Reviews of Modern Physics. 29 (4), 547–650
[2] N. Nishimura, et al (2017), Monthly Notices of the Royal Astronomical Society, Volume 469, Issue 2, August 2017, pages 1752–176
[3] G. Cescutti et al (2018), Monthly Notices of the Royal Astronomical Society, Volume 478, Issue 3, August 2018, pages 4101–4127

Motivation

Q: Can we perform MACS measurements at NEAR?

- At n_TOF, we usually measure the energy dependent cross-section so we can calculate MACS for various temperatures

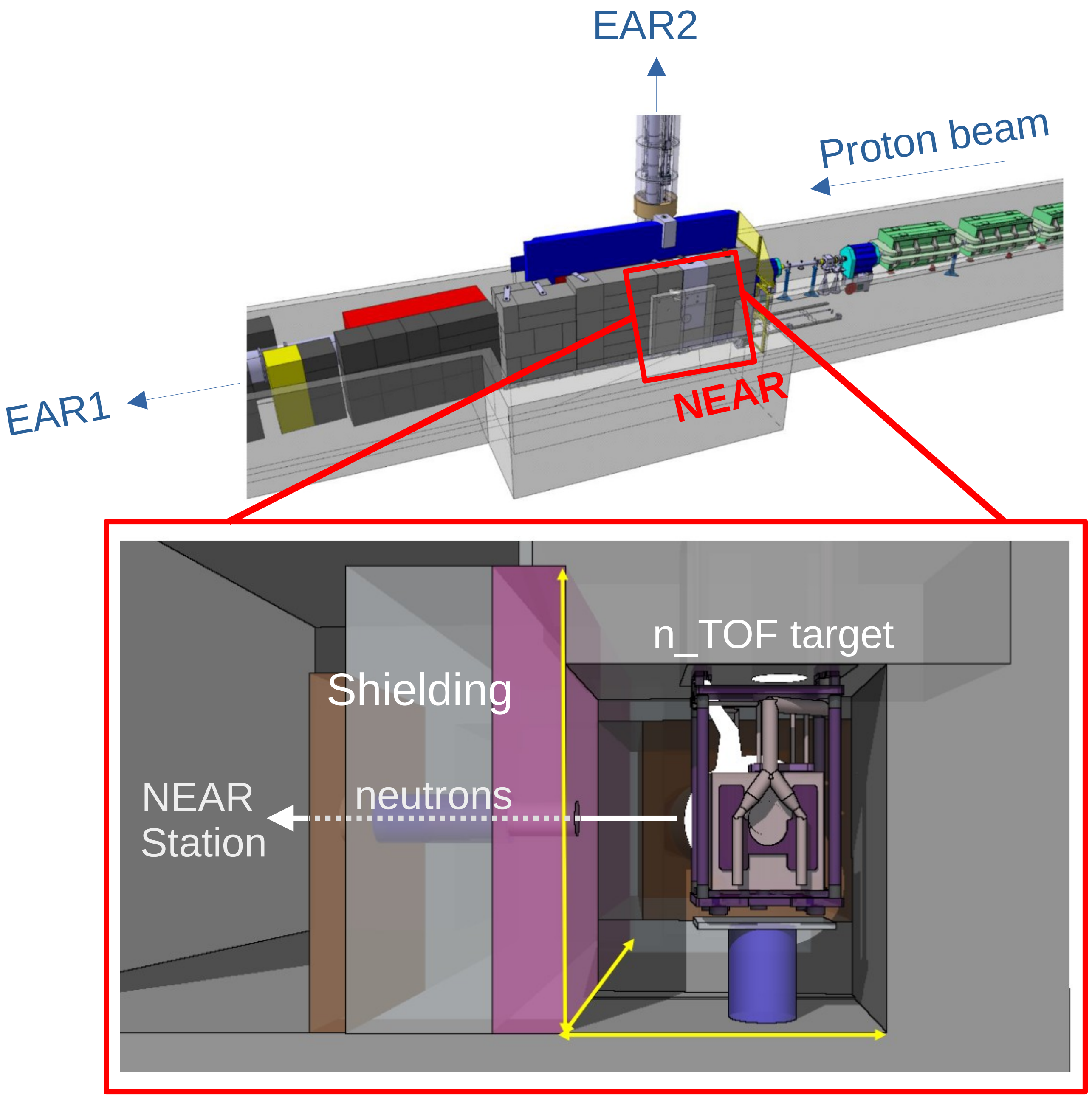
- However, not all physics cases are suitable to measure via the time-of-flight technique (e.g. low-mass samples)

- At NEAR we can perform integral measurements for those challenging cases that could not be measured via ToF

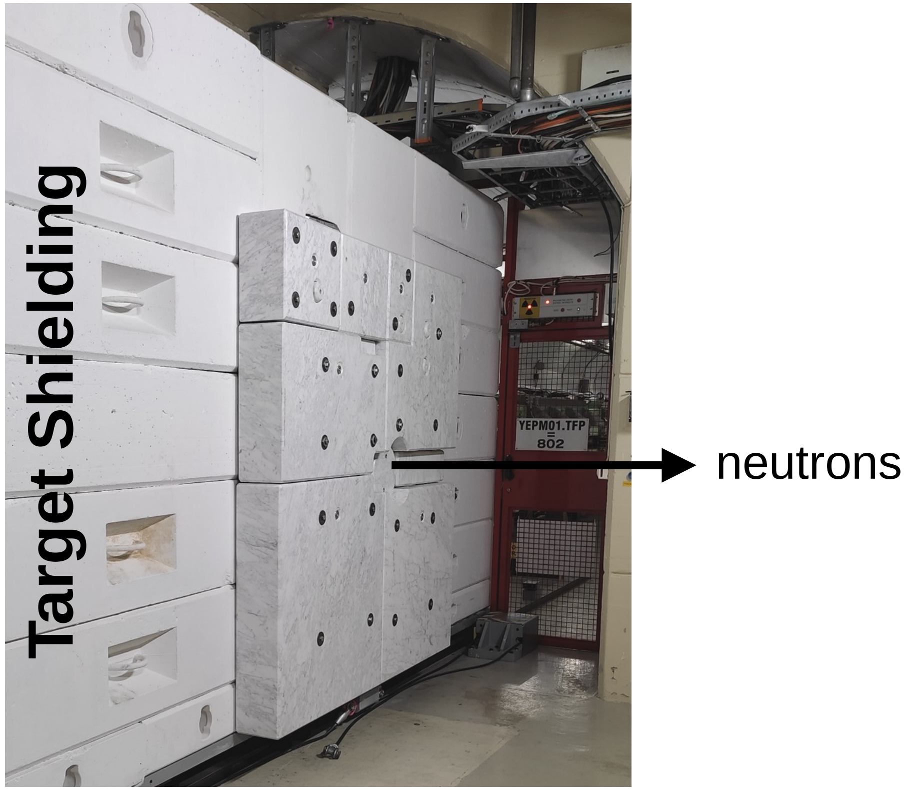
The Facility

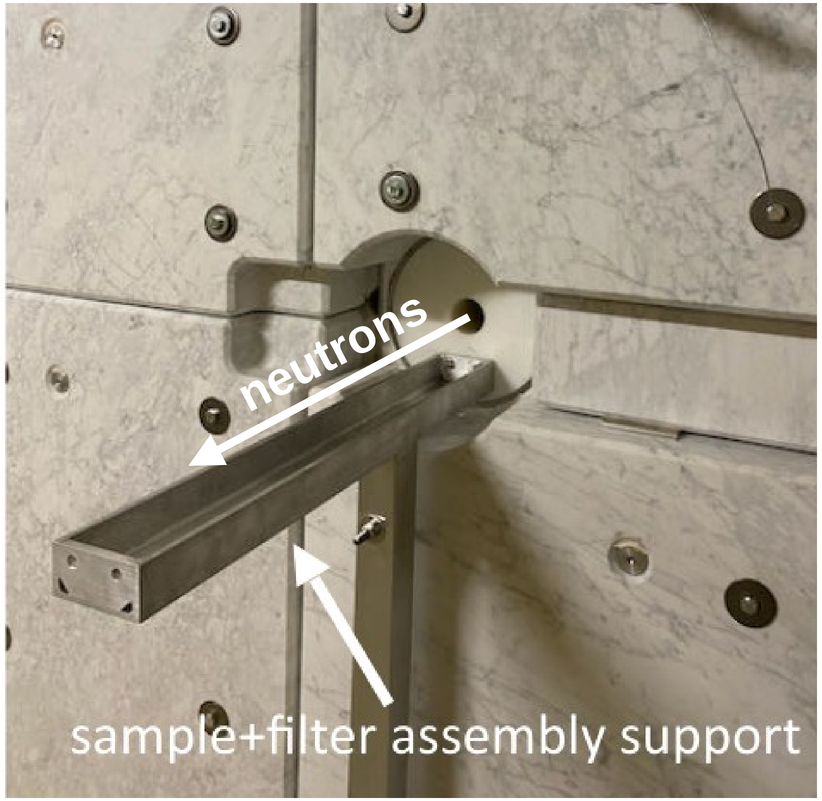
The NEAR Station is the n_TOF facility's new high-flux irradiation station.

It is located just outside the target bunker shielding, at only 3m distance from the target.



The Facility





NEAR: parasitic measurements without compromising other experiments @ EAR1 and EAR2

The Activation Technique

The activation technique is a well established method of determining cross-sections, thanks to the sensitivity and the selectivity that it provides. It consists of two steps

1) The irradiation of the sample
2) The measurement of the induced activity

It can only be applied to isotopes with suitable decay parameters[1] (decay mode, intensity, half-life, etc)

The formula[2] to calculate the cross-section is: $\sigma = \frac{counts}{\Phi \epsilon I N_T e^{-\lambda t_{wait}} (1 - e^{-\lambda t_{meas}}) f_B}$

- $Counts$: recorded counts in the experimental spectrum, corrected as needed
- Φ : total beam flux
- ε : detection efficiency
- I : γ-ray intensity
- N_T : Number of target nuclei
- t_{wait} : waiting time between the end of the irradiation and the beginning of the measurement
- t_{meas} : activity measurement time
- f_B : correction for the decay of product nuclei during the irradiation time

[1] Measurement and Detection Radiation, Nicholas Tsoulfanidis, Taylor & Francis (1798)
[2] G. Hevesy and H. Levi, Nature 137, 185 (1936)

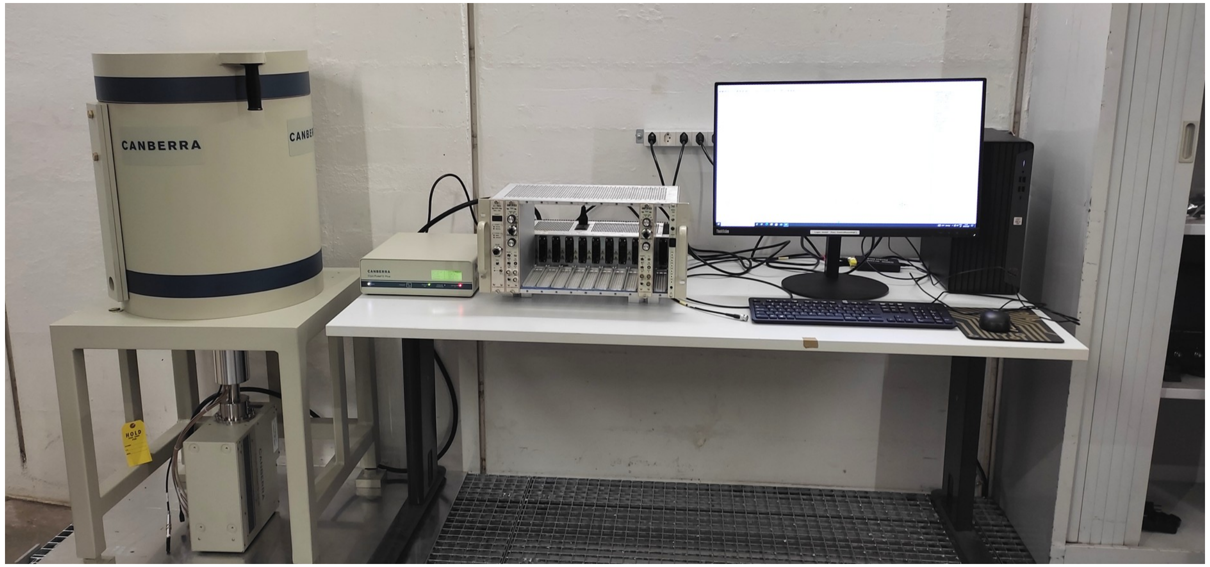
Instrumentation

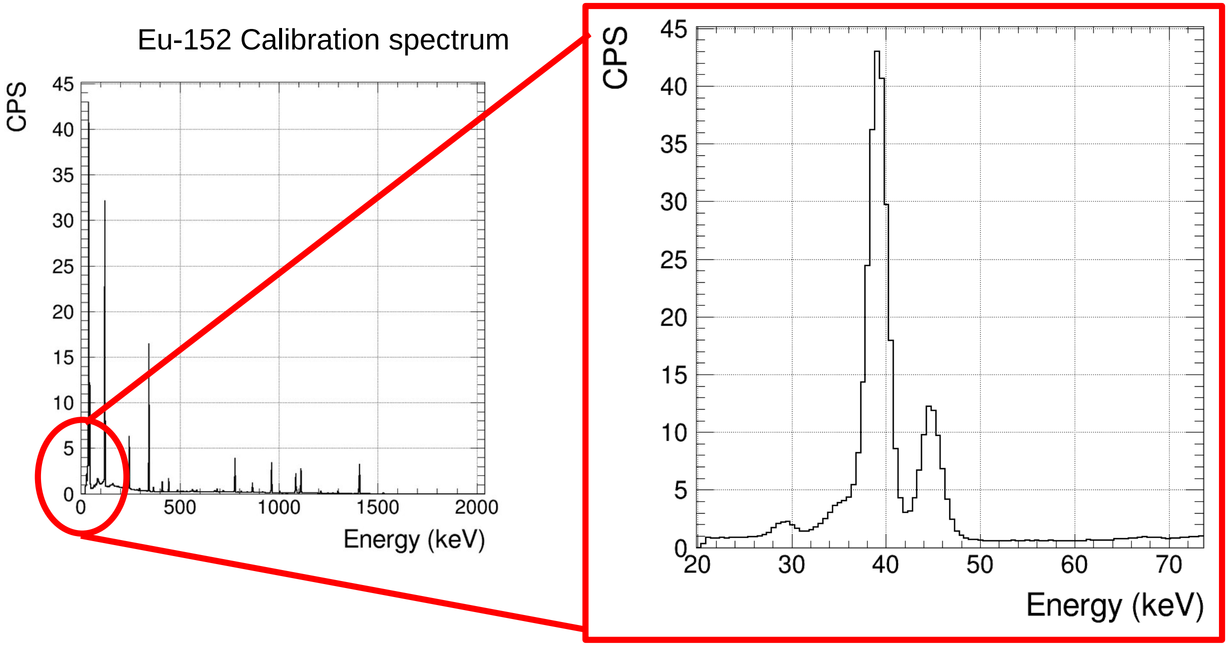
The measurement of the induced activity of the samples will be measured in the new Gamma-ray Spectroscopy Experimental Area (**GEAR**) of n_TOF with the use of a HPGe.

This HPGe

- Is of high relative efficiency (60%) ,
- Is shielded
- and has a window of Carbon epoxy,

allowing for high-accuracy measurements in a wide energy range





Neutrons @NEAR Station

Feasibility of MACS measurements at n_TOF/NEAR

MACS is needed in nuclear astrophysics for modeling neutron capture processes.

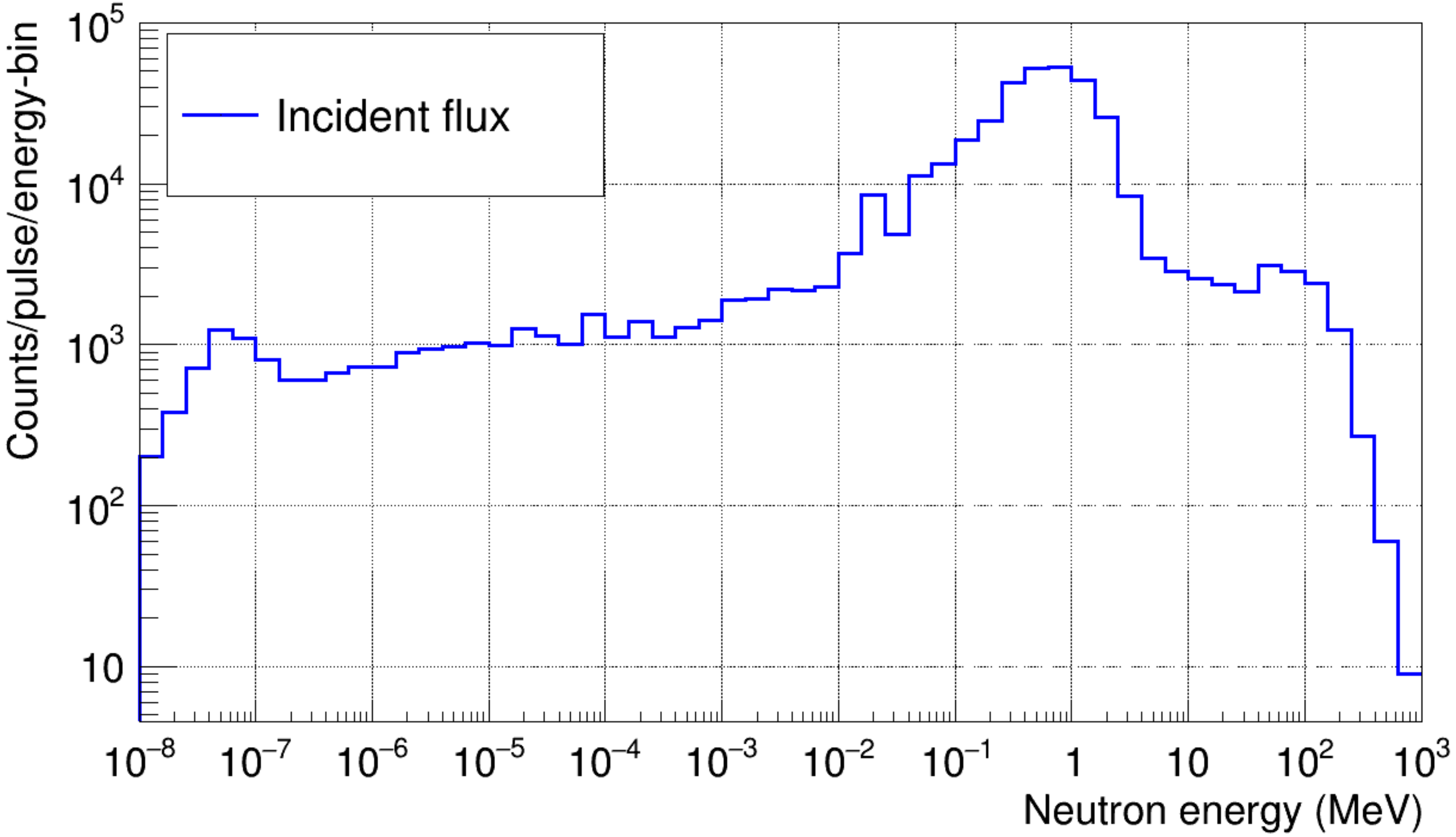
Typical temperatures for nucleosynthesis studies are in the range

kT = 5 to 100 keV

(Temperatures of 60 - 1100 MKelvin)

HOWEVER

the neutron spectrum at the NEAR Station is not at all Maxwellian



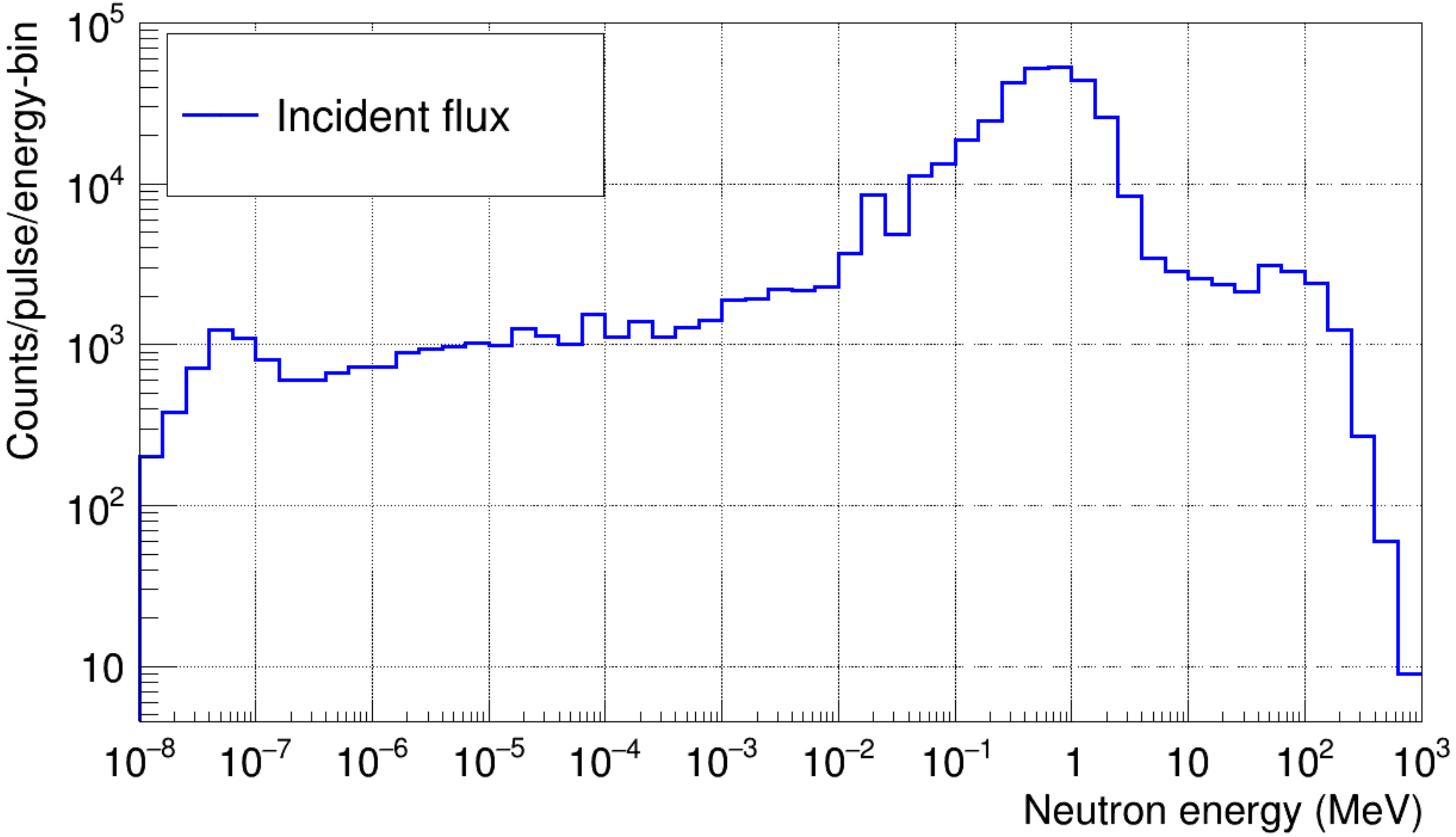
Neutrons @NEAR Station

Feasibility of MACS measurements at n_TOF/NEAR

With suitable filters:

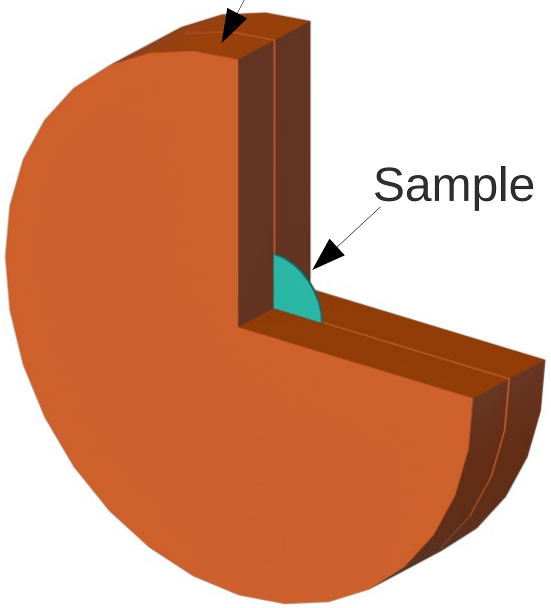
- the neutron flux can be shaped so that the Spectral Averaged Cross Section (SACS) is close (or as close as possible) to the MACS.

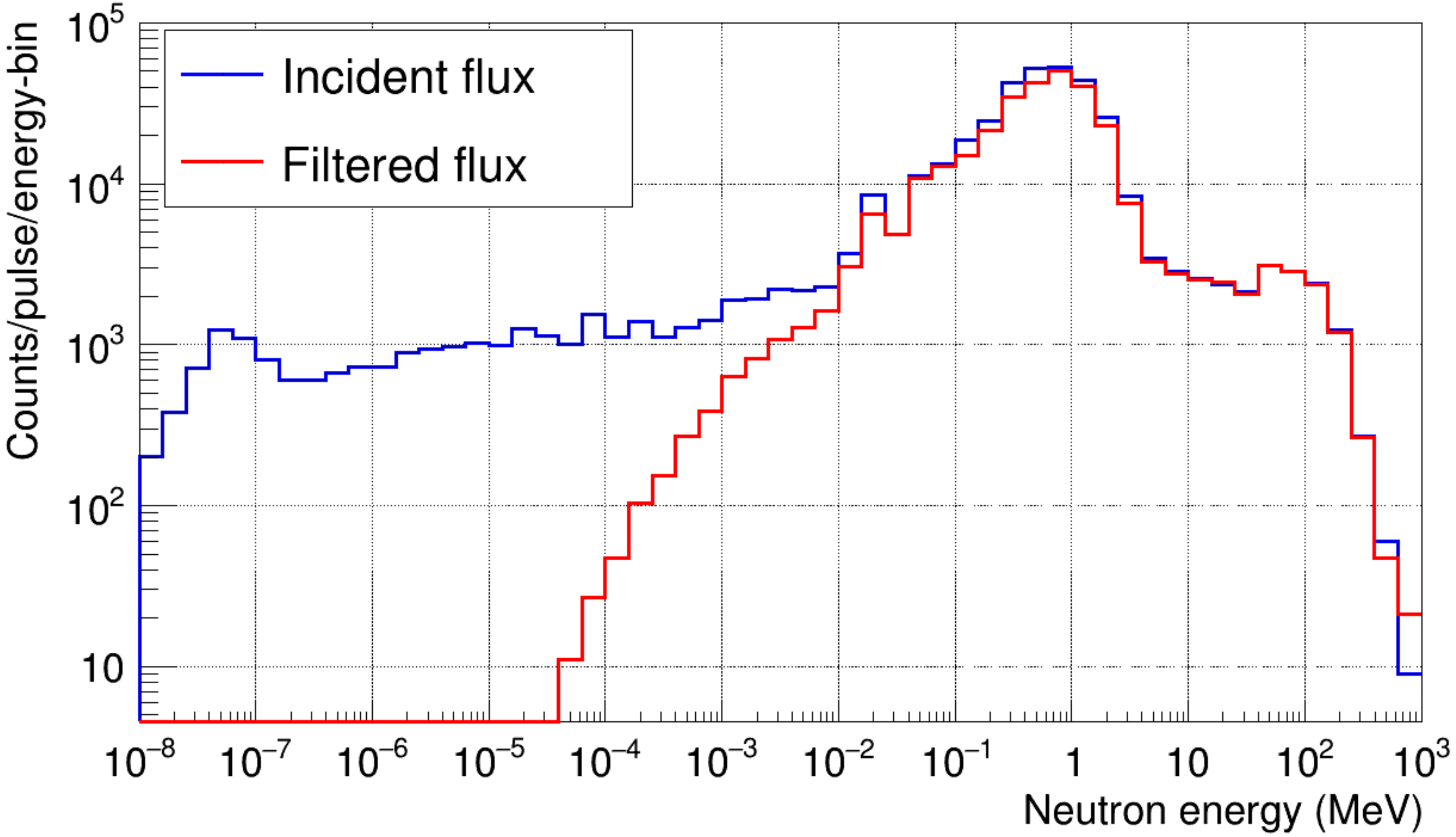
To investigate this possibility, we propose to measure the SACS



Filtered neutron flux

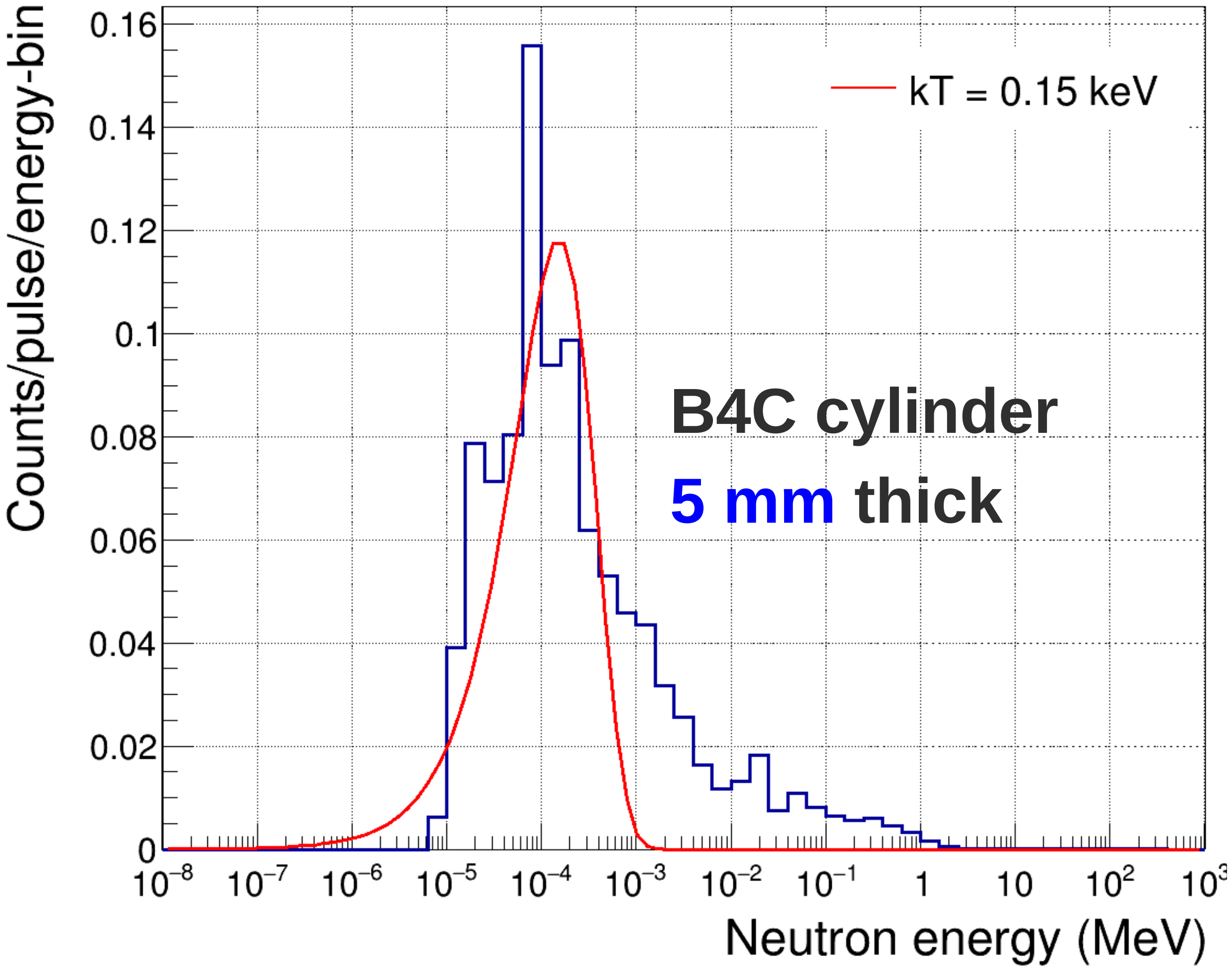
SACS measurements at n_TOF/NEAR





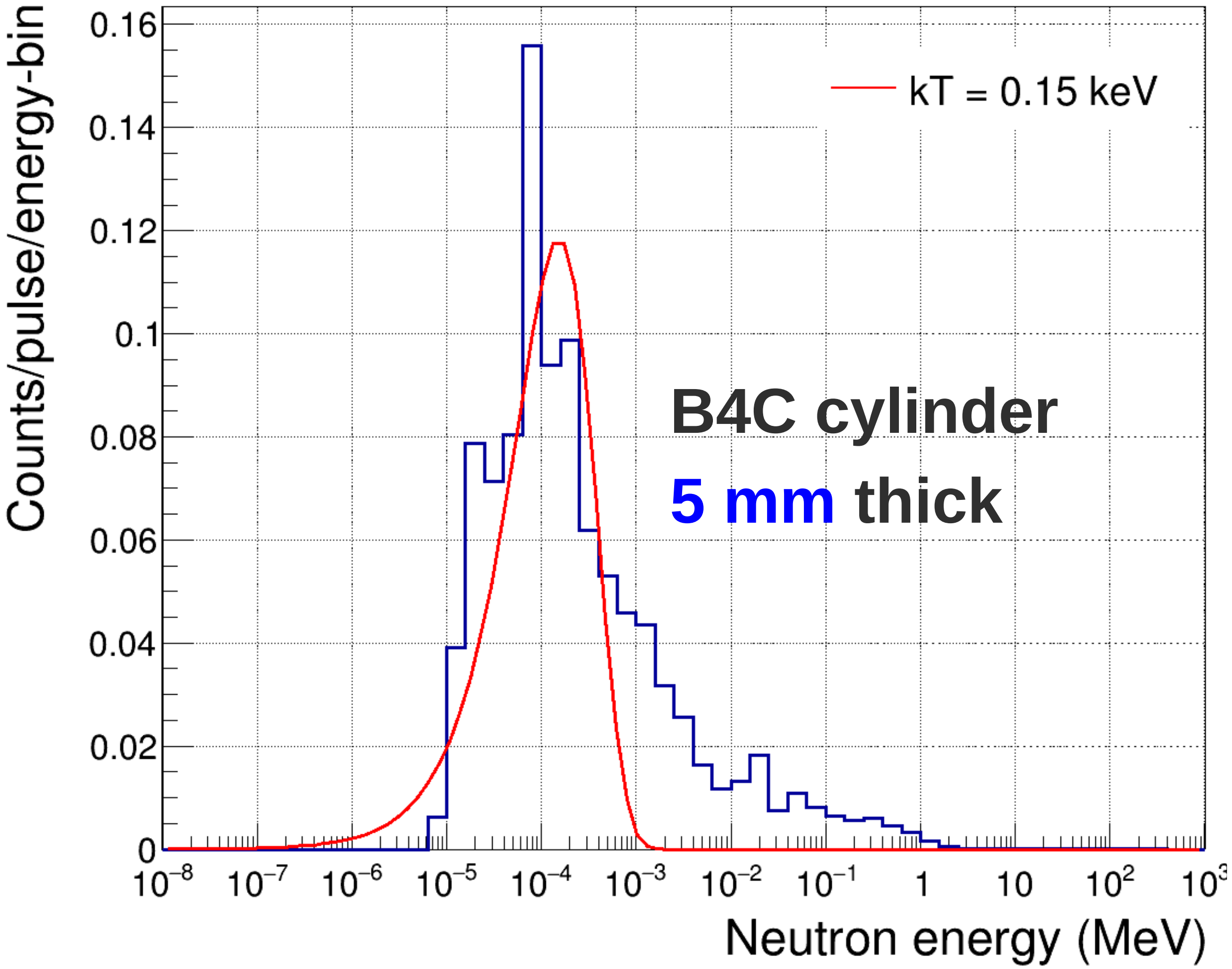
Filtered neutron flux

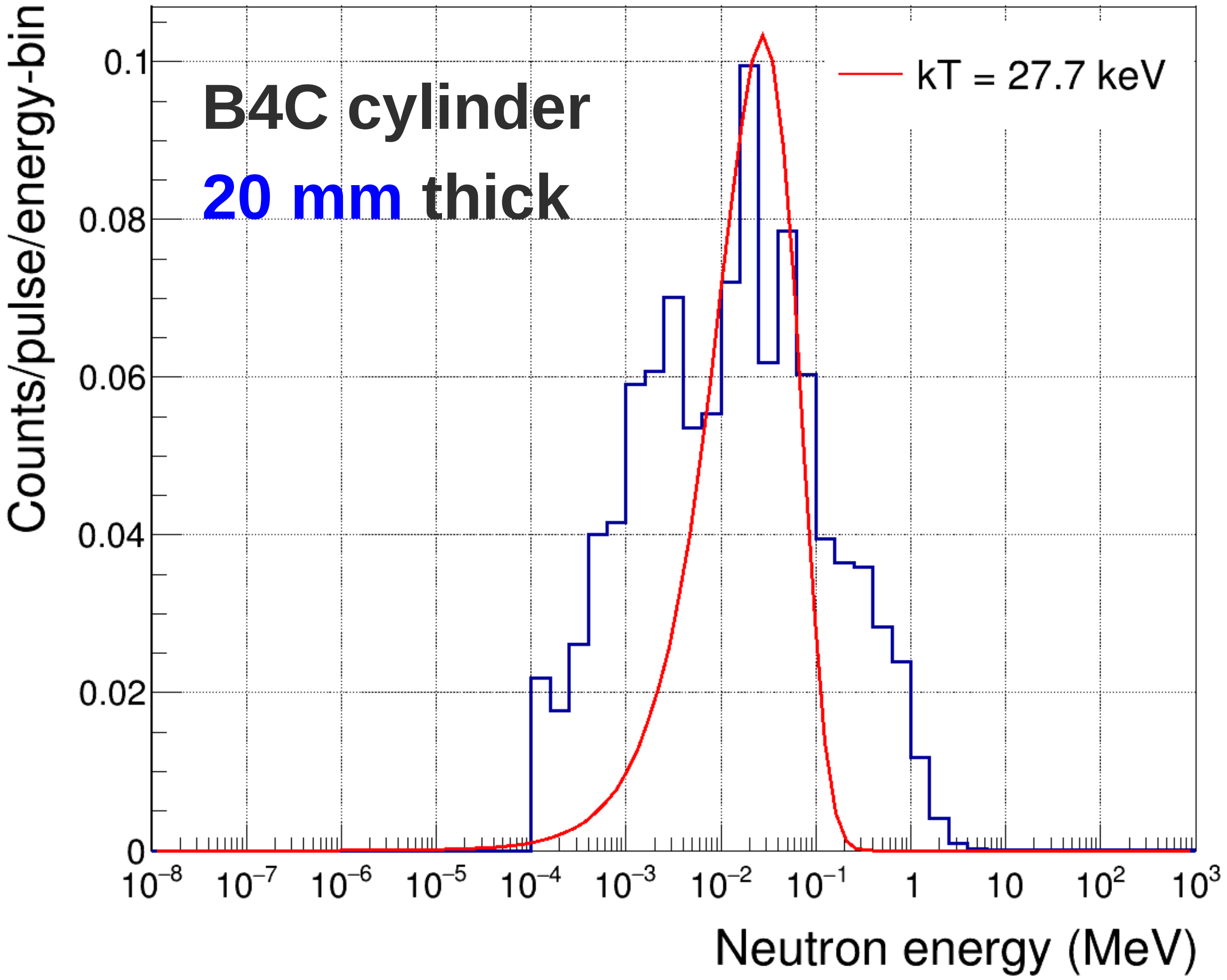
SACS measurements at n_TOF/NEAR



Filtered neutron flux

SACS measurements at n_TOF/NEAR

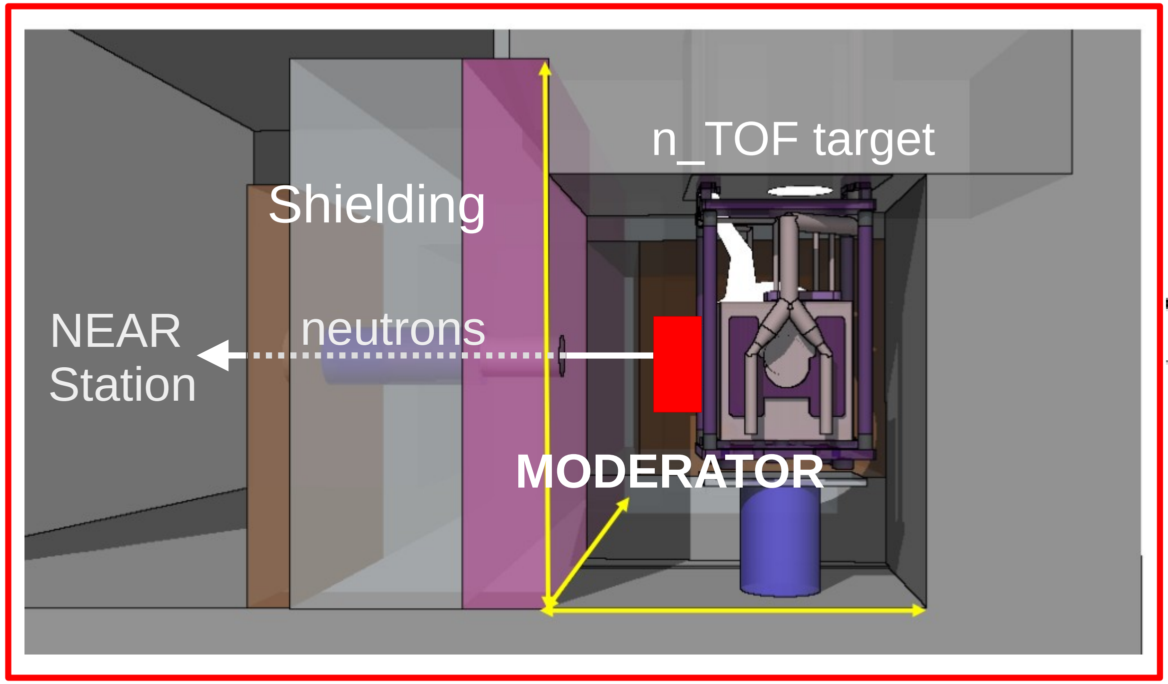


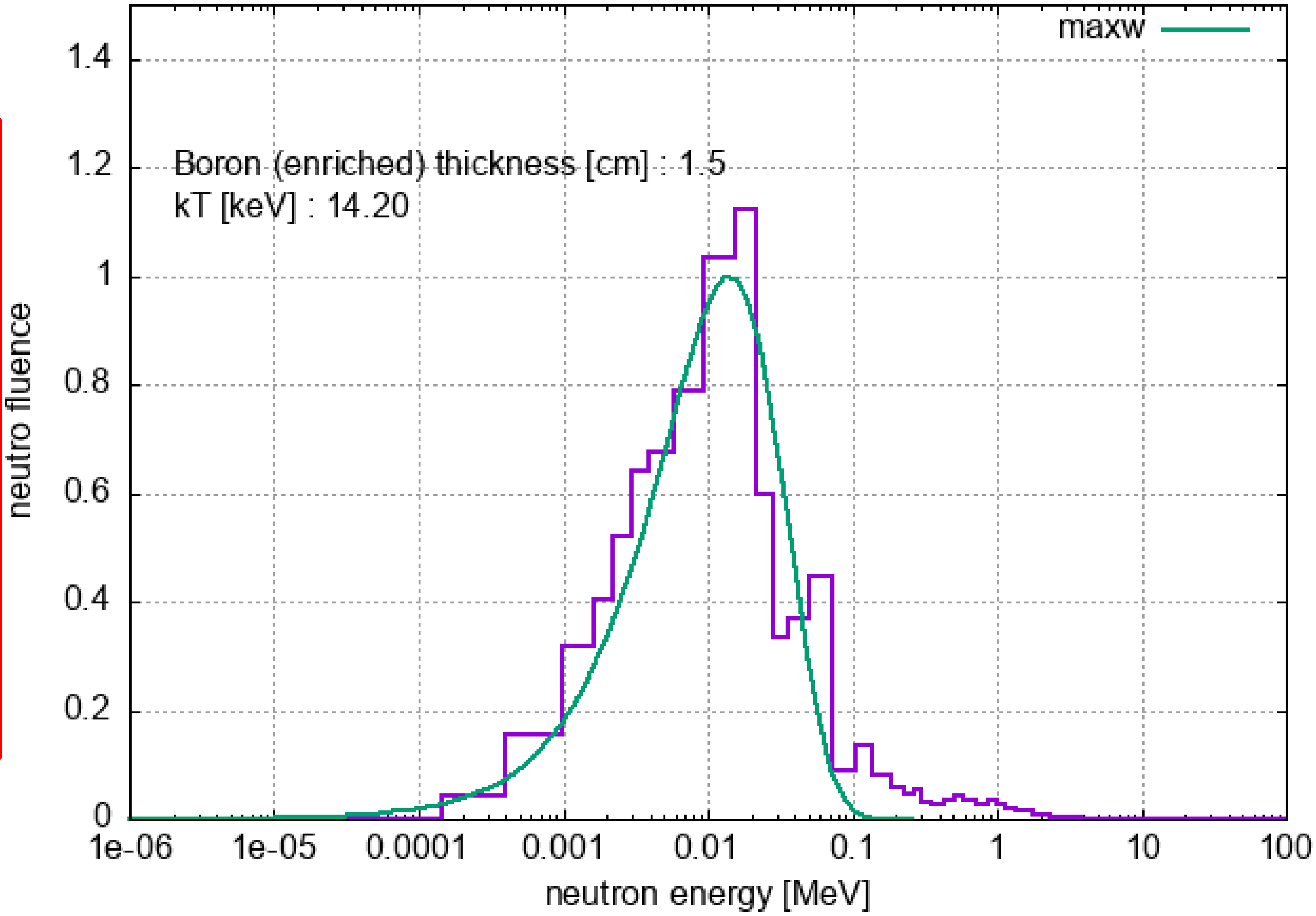


Filtered neutron flux

B-enriched filter
+
AlF3 Moderator (30 cm th)

SACS measurements at n_TOF/NEAR





Reactions chosen

cross-sections already measured in EAR1 and EAR2 allowing for the computation of any SACS

These reactions are the neutron capture of

- ^{197}Au

  "*^{197}Au(n,γ) cross section in the unresolved resonance region*" C. Lederer et al., Physical Review C 83, 034608 (2011)

  "*^{197}Au(n,γ) cross section in the resonance region*" C. Massimi et al., Physical Review C 81, 044616 (2010)

- ^{76}Ge

  "*Measurement of the 76 Ge(n,γ) cross section at the n_TOF facility at CERN*", A. Gawlik-Ramiega et al., Physical Review C 104, 7 (2021)

- ^{94}Zr

  "Neutron capture on 94 Zr: Resonance parameters and Maxwellian-averaged cross sections", G. Tagliente et al., Physical Review C 84, 015801 (2011)

- ^{140}Ce

  "First Results of the 140 Ce(n,γ) 141 Ce Cross-Section Measurement at n_TOF", S. Amaducci et al., Universe 7, 200 (2021); S. Amaducci et al., in preparation (2021)

- ^{89}Y

  G. Tagliente, P.M. Milazzo al., in preparation (2021)

Reactions chosen

1cm radius

Reaction	γ-ray energy [keV]	Product half-life	Mass (g)
^{197}Au(n,γ)	411.8	2.69 d	0.015
^{76}Ge(n,γ)	264.4	11.2 h	0.09
^{94}Zr(n,γ)	756.7	64 d	0.2
^{140}Ce(n,γ)	145.4	32.5 d	0.6
^{89}Y(n,γ)	(2186)	64 h	0.14

With: irradiation time of 14 days
(1.4x10 18 protons in parallel with EAR1 and EAR2 runs)
For: uncertainty of the measurement below 3%

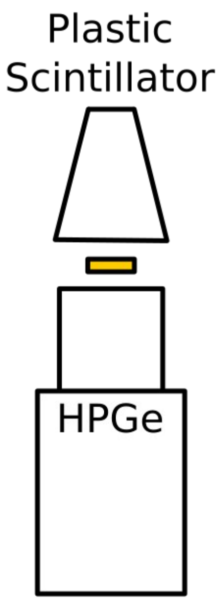
Reactions chosen

1cm radius

Reaction	Average β energy[keV]	γ-ray energy [keV]	Product half-life	Mass (g)
$^{89}Y(n,\gamma)$	932.4	(2186)	64 h	0.14

One of the samples that will be irradiated is the β-emitter ^{90}Y.

In this case, the HPGe will still be used, but in comparison with a plastic scintillator, in order to explore the feasibility of such an application.



Conclusions

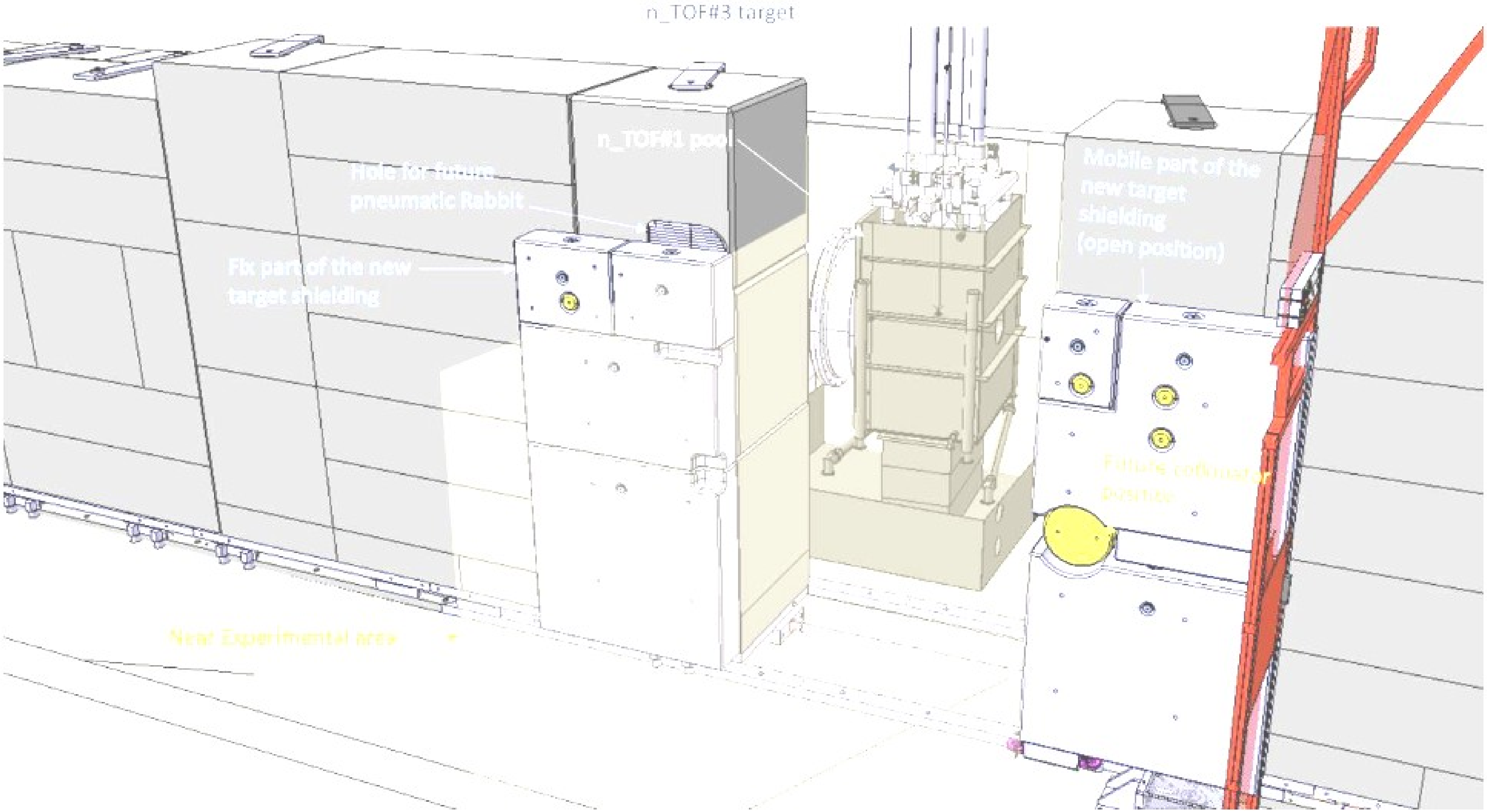
- The realisation of the proposed set of irradiations will be a fundamental benchmark for the future measurements at n_TOF's NEAR Station.

- A successful shaping of the neutron beam is going to pave the way for many MACS measurements that were too challenging to be performed with the ToF method.

The number of requested protons is: 0

as the irradiations will take place parasitically during normal operation, in parallel with measurements in the two experimental areas.

Thank you for your attention

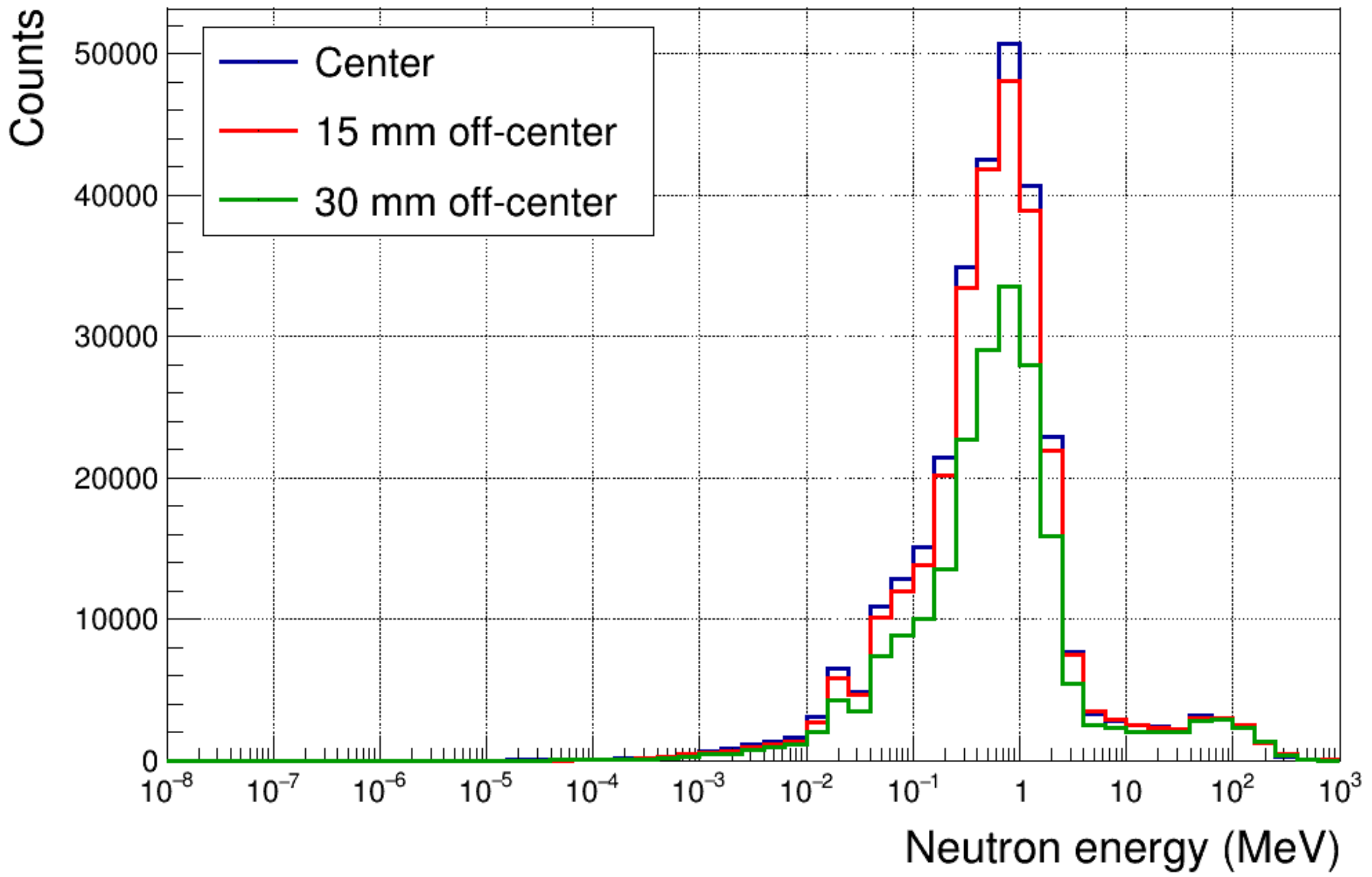


Extra Slides

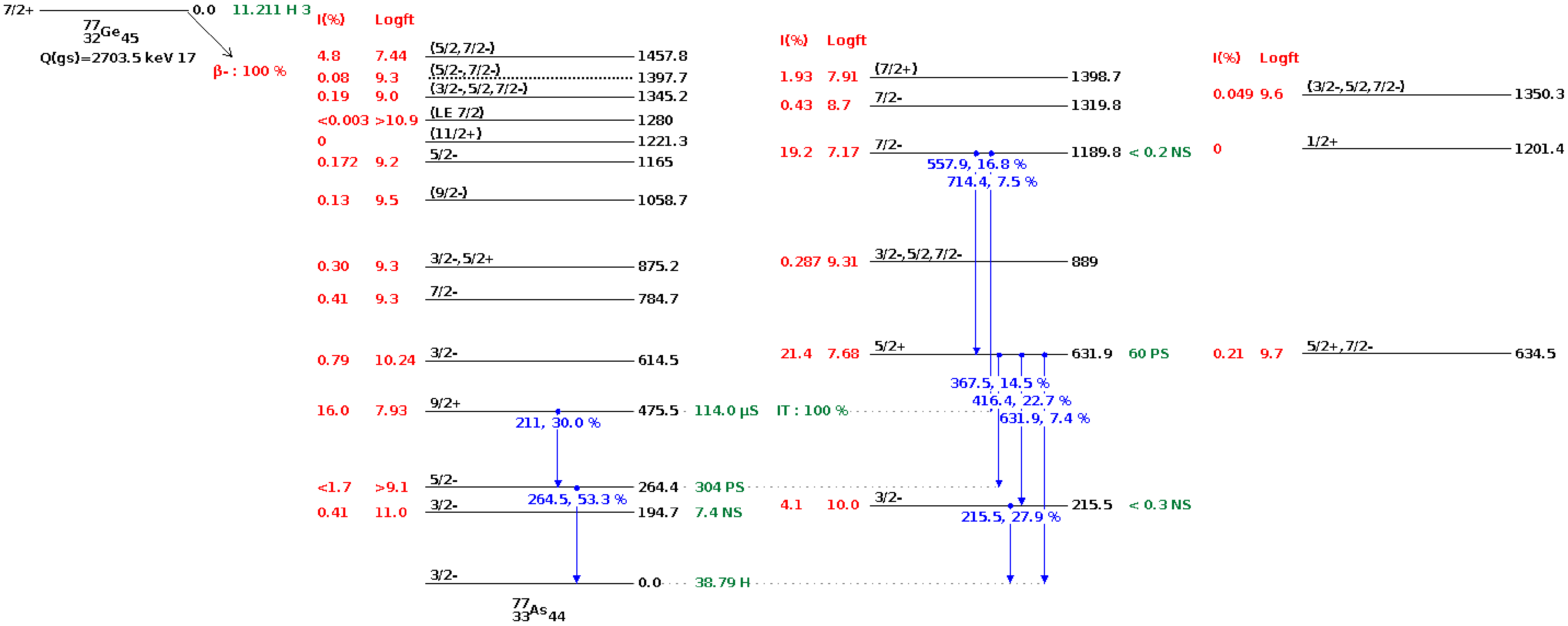
Neutron flux at different positions

SACS measurements at n_TOF/NEAR

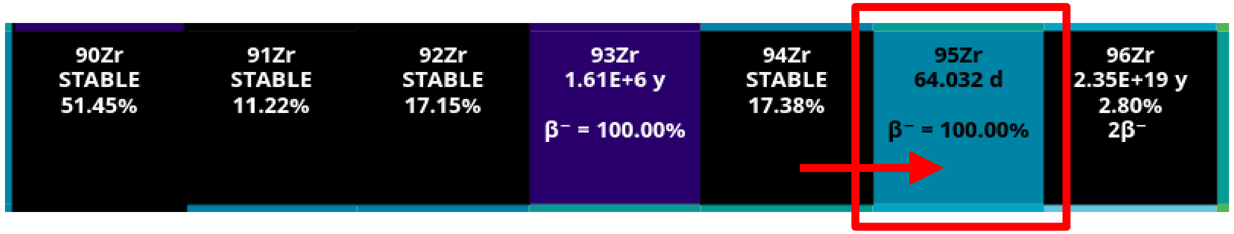
Variation of the neutron energy distribution as a function of the distance of the irradiated sample from the center of the B4C cylinder.

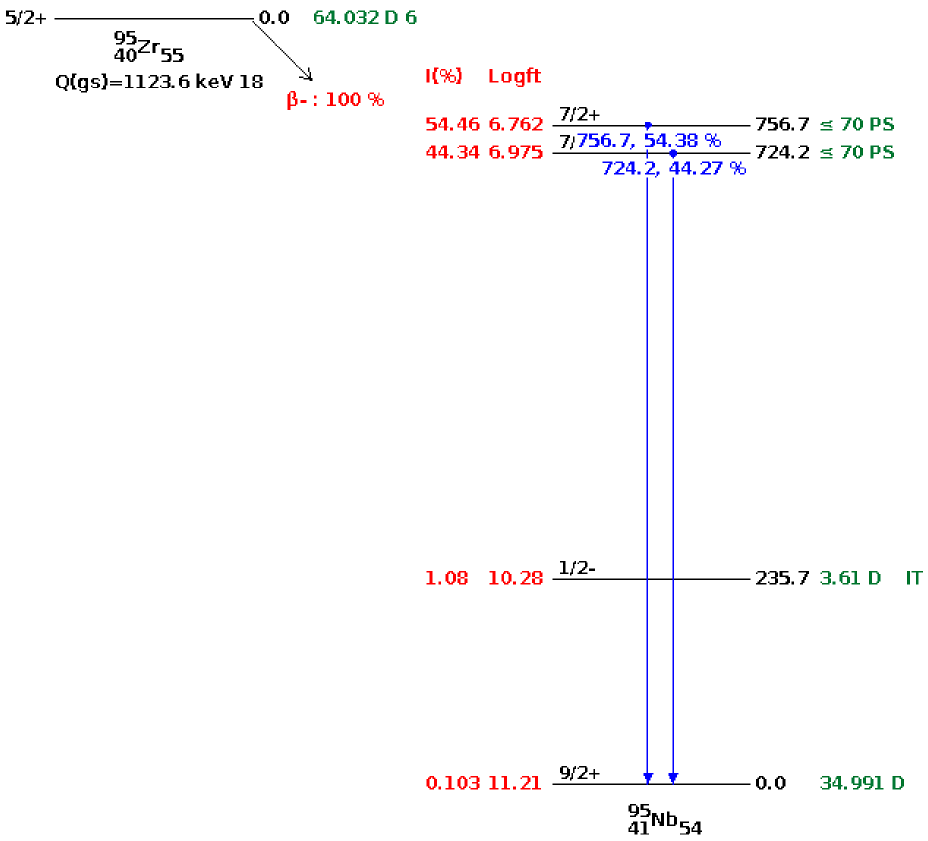


More details on the reactions: 76Ge(n,γ)

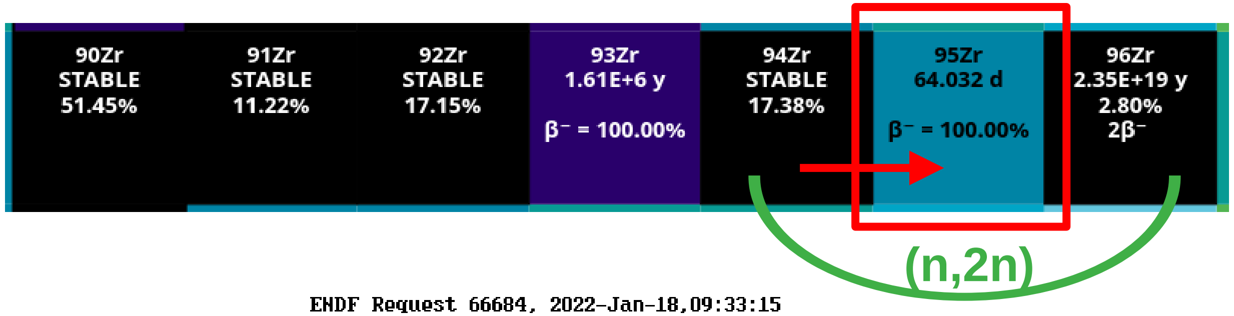


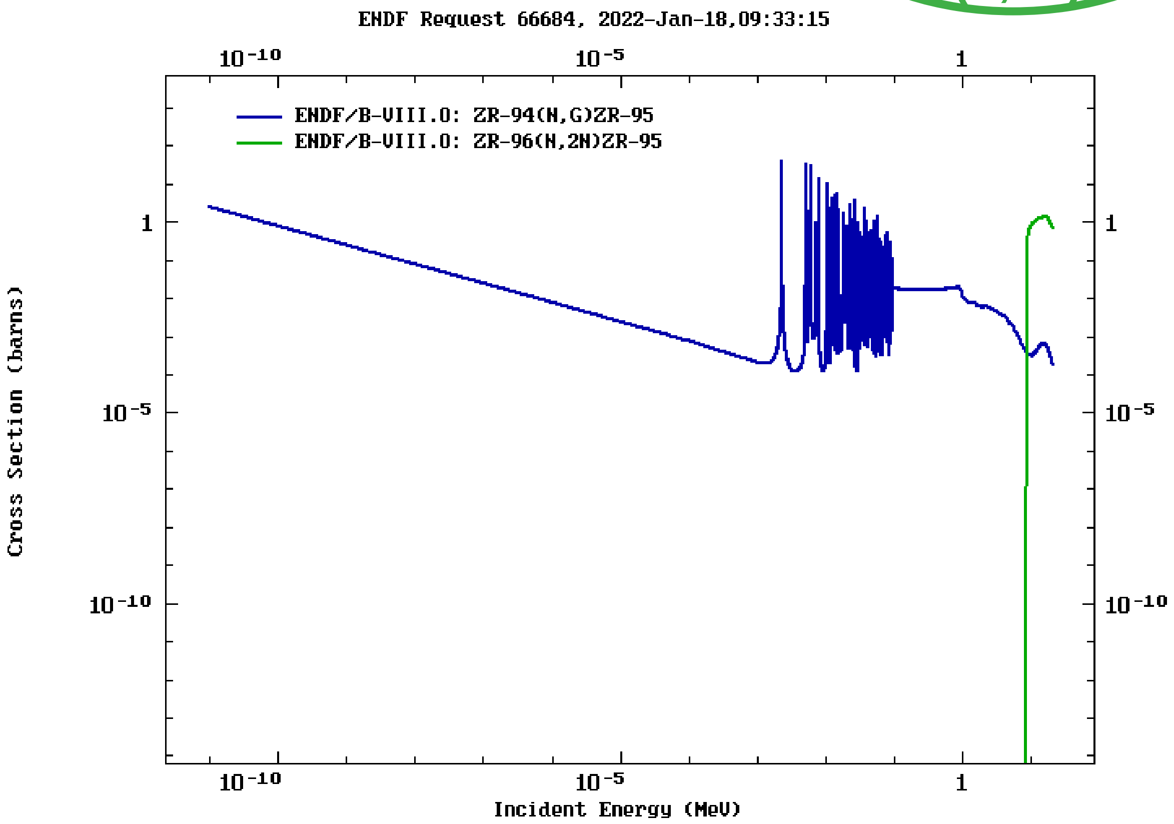
More details on the reactions: 94Zr(n,γ)





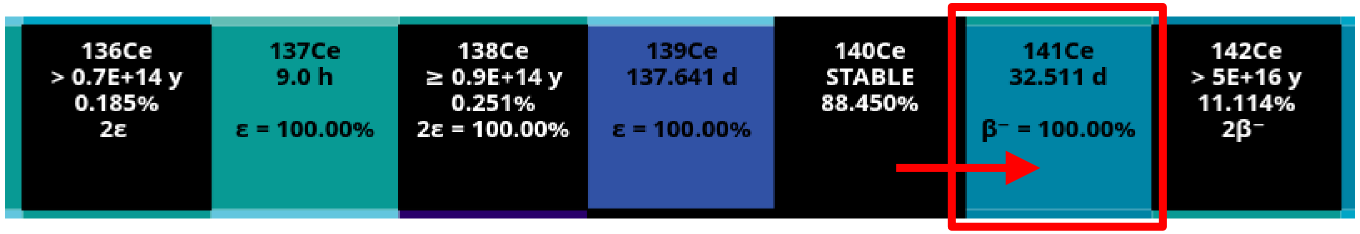
More details on the reactions: 94Zr(n,γ)

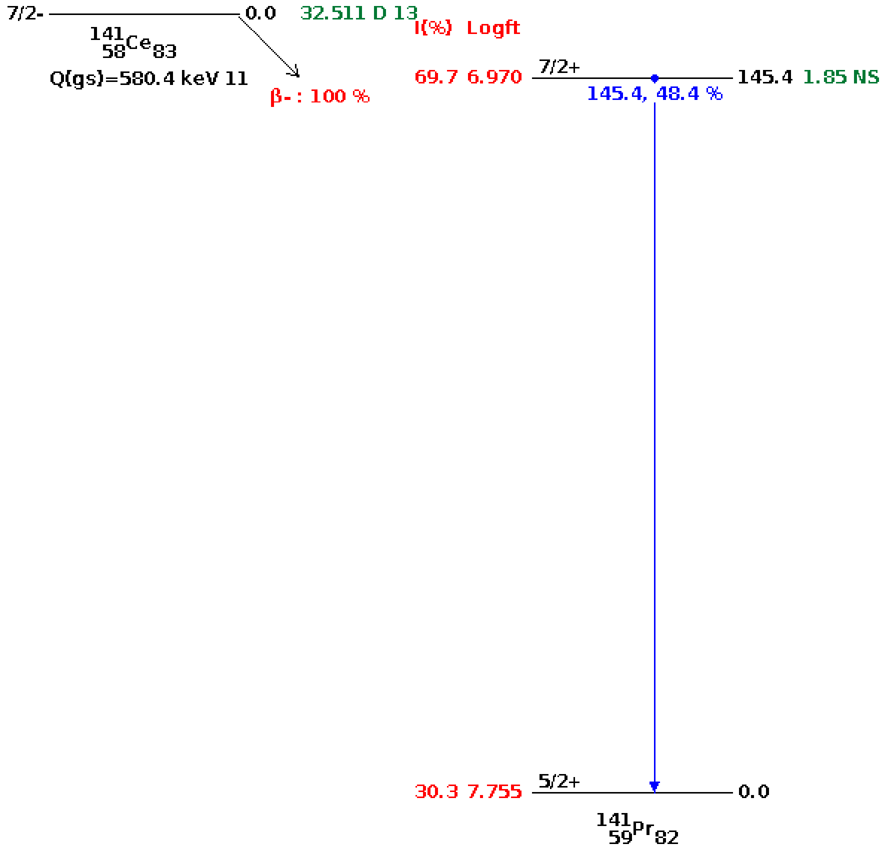




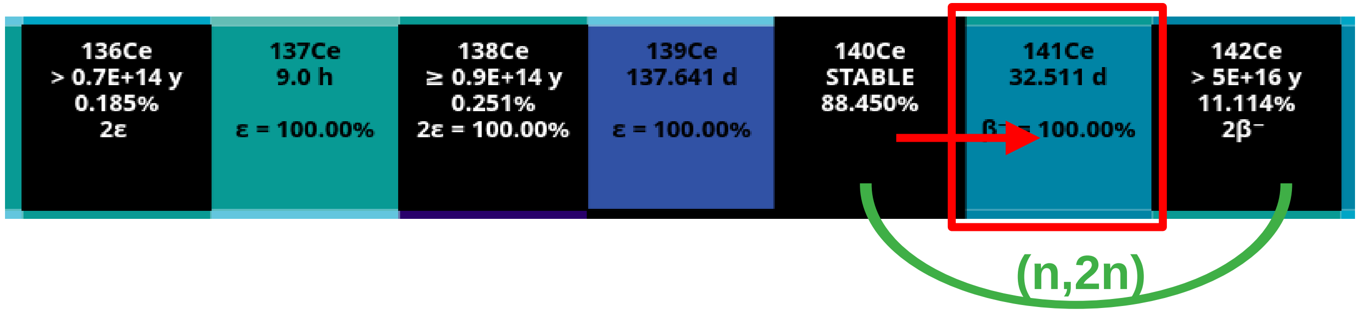
Small correction of the order of ~2% needed

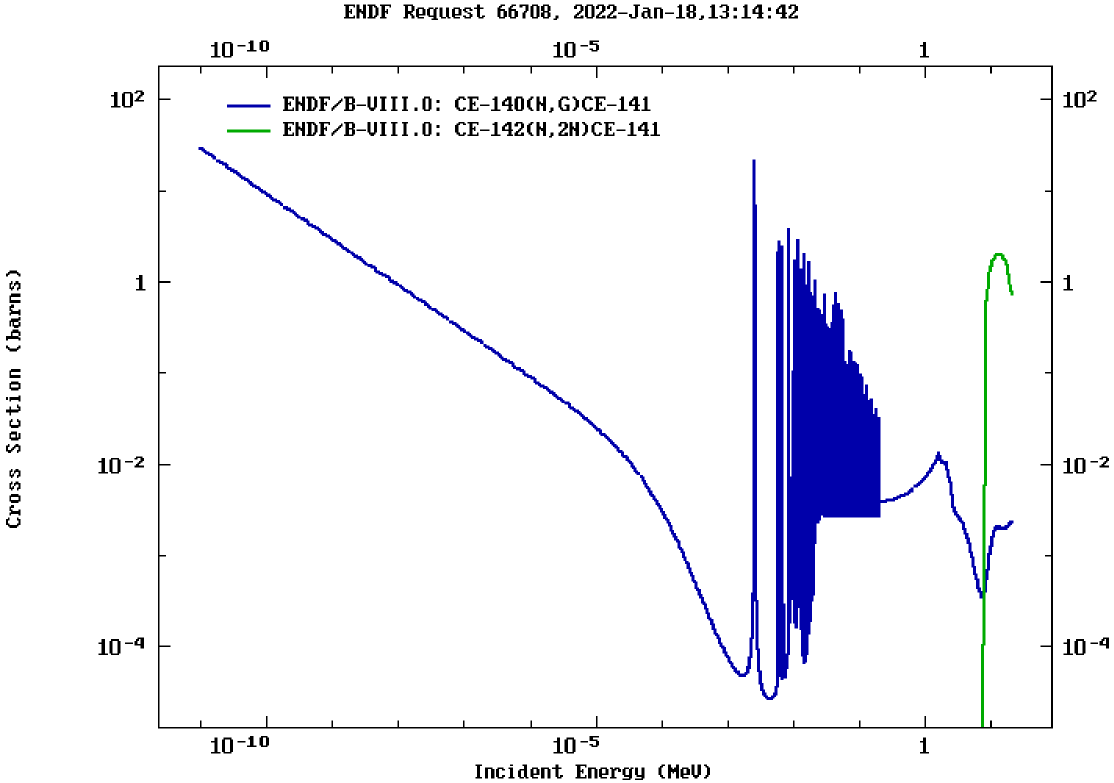
More details on the reactions: 140Ce(n,γ)





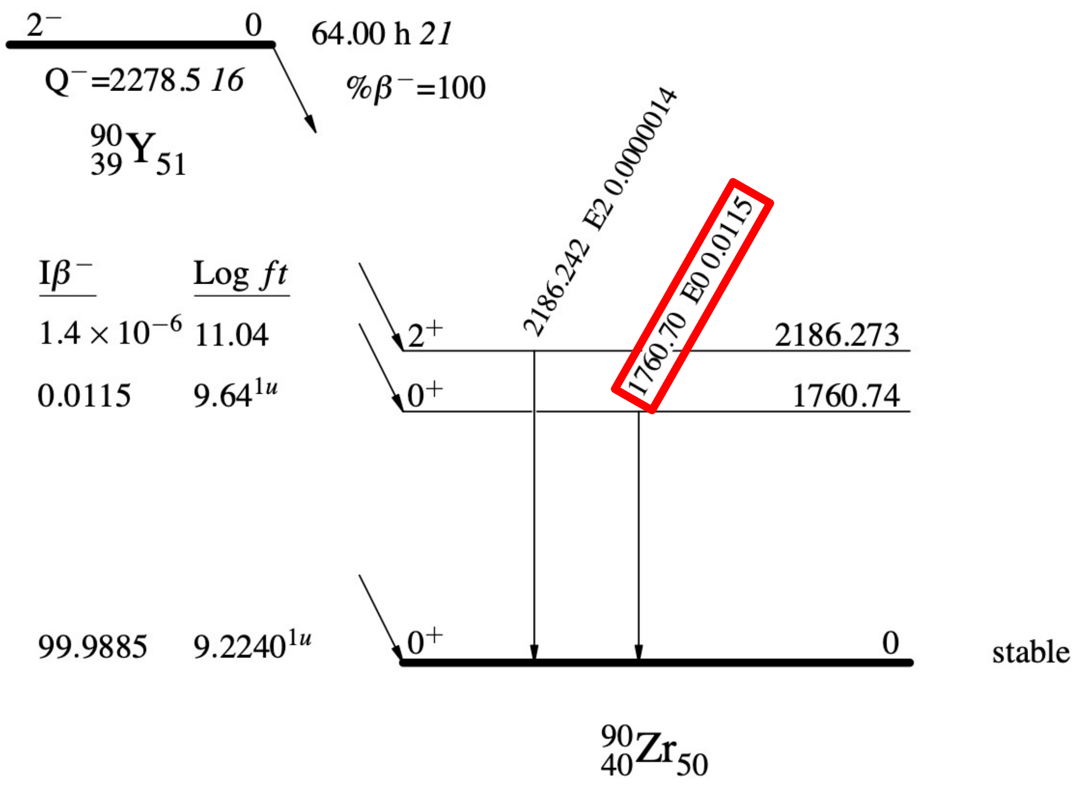
More details on the reactions: 140Ce(n,γ)

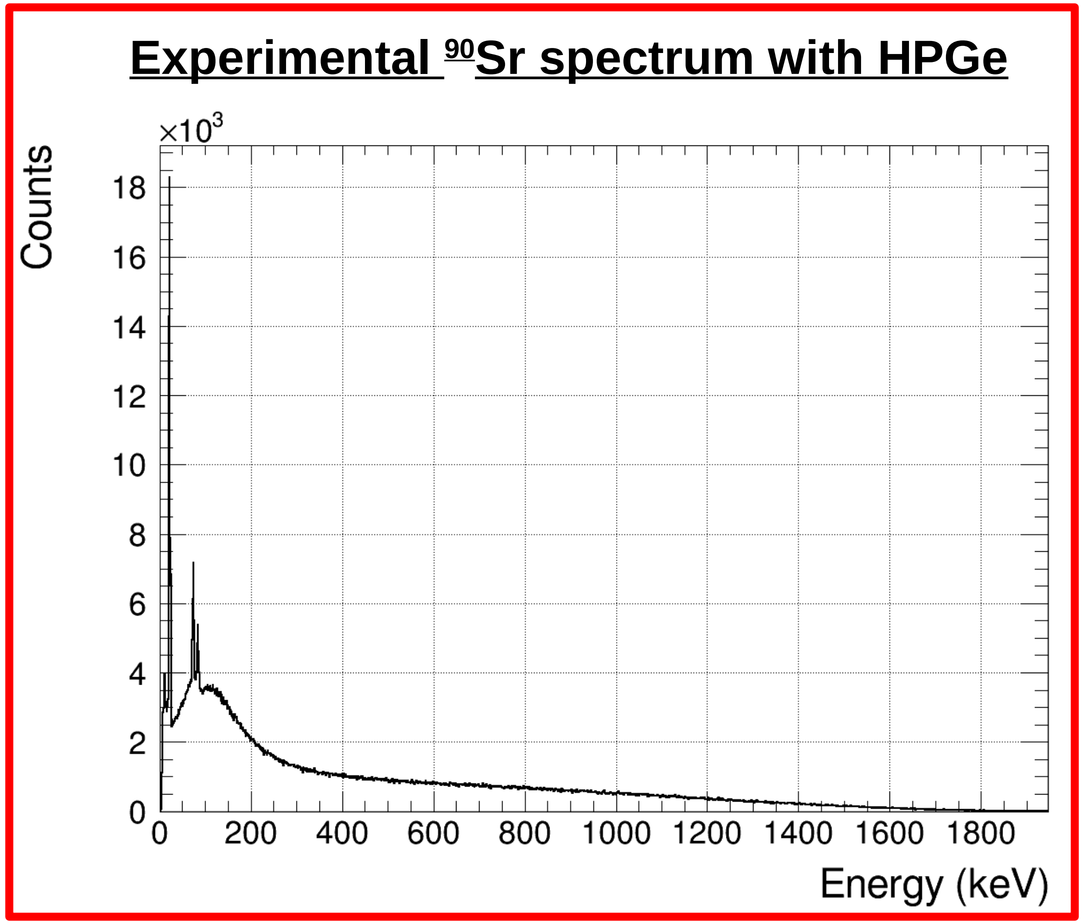




Expected correction of the order of ~20 - 30%

More details on the reactions: 89Y(n,γ)





Possible Contamination of The Spectra

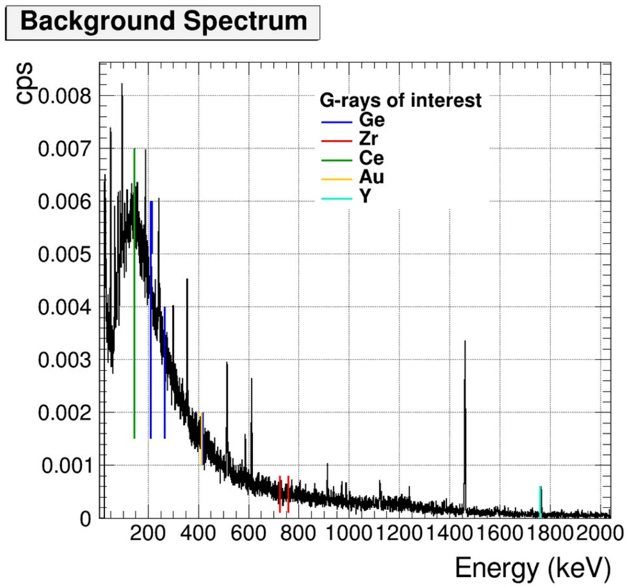
Reactions on other isotopes

Reaction of interest	Peak of interest (keV)	Interfering peak (keV)	Caused by reaction
^{76}Ge(n,γ)	264.5	264.6	^{74}Ge(n,γ)^{75}Ge ^{76}Ge(n,2n)^{75}Ge

Background

Reaction of interest	Peak of interest (keV)	Interfering peak (keV)	Caused by
^{89}Y(n,γ)	1760	1764	^{214}Bi

Furthermore:
Peaks originating from ^{228}Ac → Suppressed by the HPGe's lead shielding



Ratio between MACS and SACS