MACS measurements for nuclear astrophysics at n_TOF/NEAR: Feasibility study and first results

M.E. Stamati, A. Manna, N. Patronis, A. Mengoni, C. Massimi, R. Mucciola, N. Colonna, A.-P. Bernardes, G. Gervino, P. Vaz, R. Vlastou
07.09.2022

Outline of the talk

MACS

- Why are MACS measurements important?

The n_TOF facility

- Quick overview of the n_TOF facility
- The “NEAR” Station
- MACS measurements at n_TOF

MACS @ NEAR

- Can we perform MACS measurements at NEAR?
- Validation method and Experimental set-up

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Why MACS?

Relevance of MACS results

- Nucleosynthesis of elements heavier than iron: largely based on neutron capture.
- s-process: series of neutron captures followed by beta decays, responsible for producing ~half the heavy nuclei. Takes place mainly in AGB stars where
    1. neutron fluxes are not particularly high
    2. The gas of the star is in thermodynamic equilibrium → Maxwell-Boltzmann velocity distribution
- Even though the s-process is one of the most well-known astrophysics processes, reaction rate inputs are still missing and are very important for astrophysical models (for example to calculate elemental abundances).

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Quick reminders!
For details, see "Neutron induced cross section measurements" given by C. Massimi on Monday 10h30

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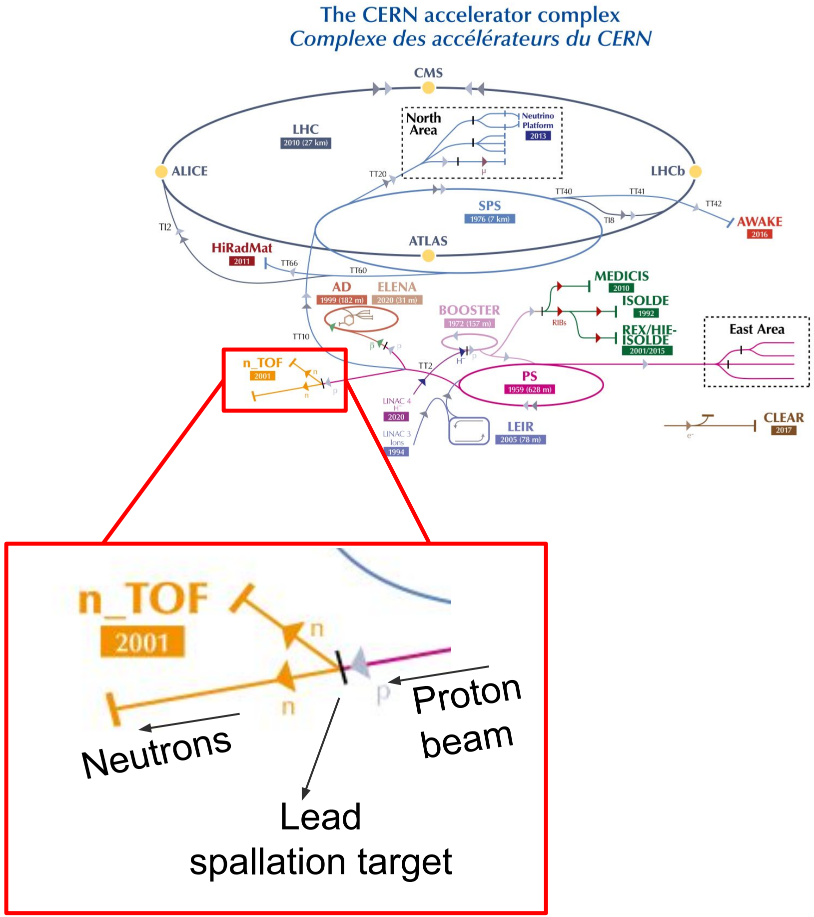
The n_TOF facility overview

The n_TOF facility

- CERN's pulsed neutron source
- Neutron production: Proton beam of 20GeV/c impinging on lead spallation target



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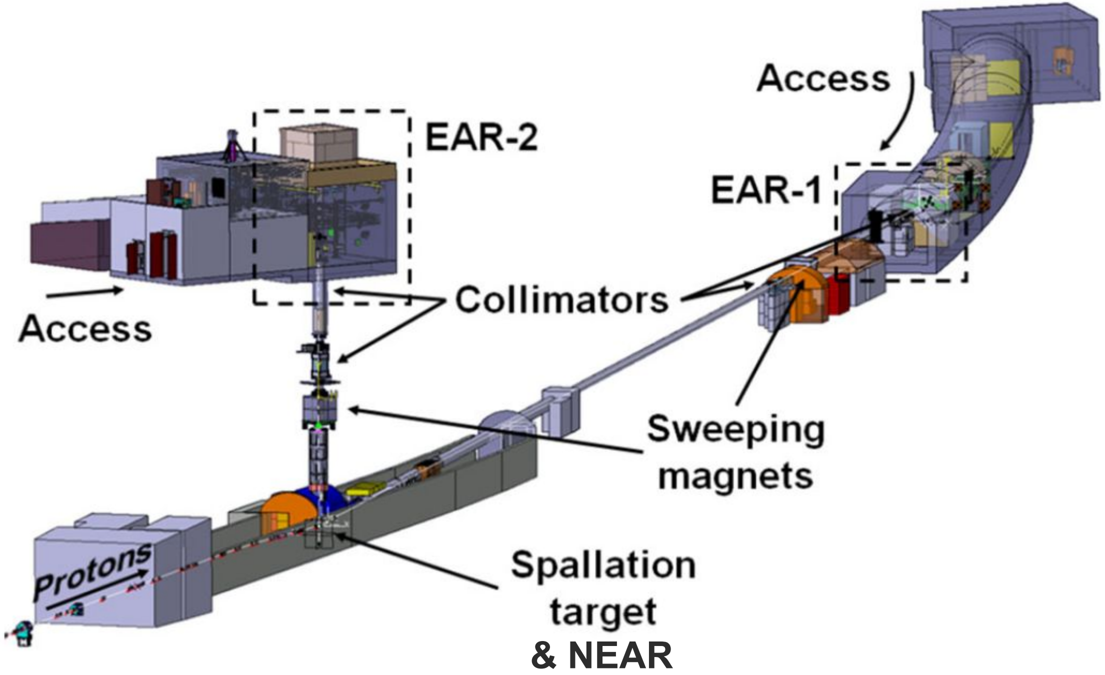

The n_TOF facility overview

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- CERN's pulsed neutron source
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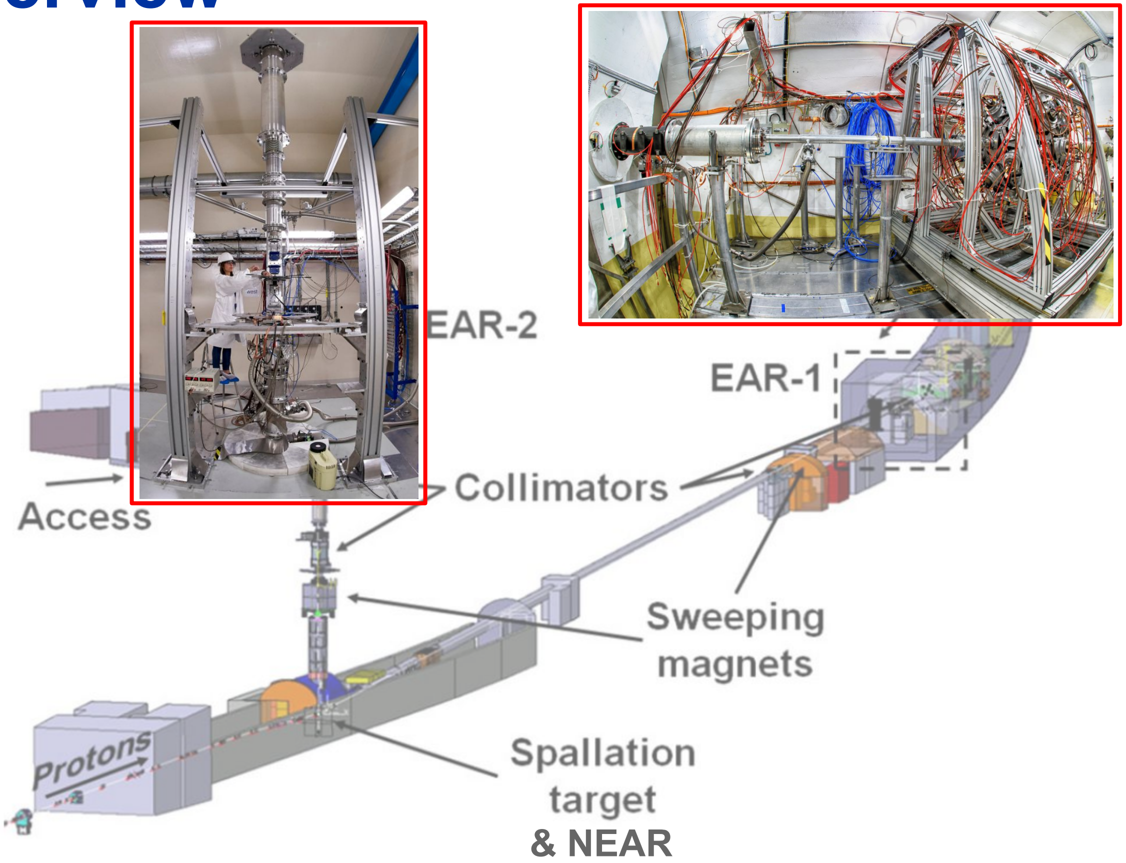
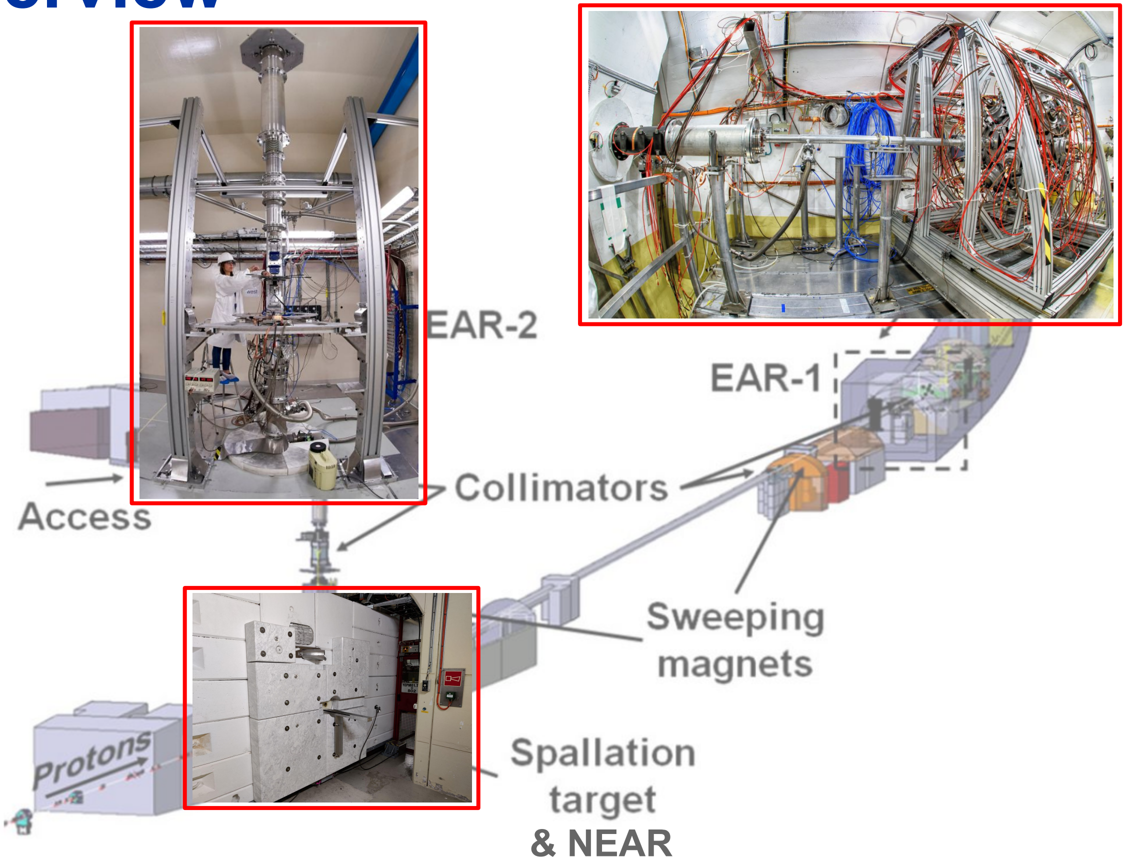
- 2 flight paths of 185m and 20m length



The n_TOF facility overview

The n_TOF facility

- CERN's pulsed neutron source
- Neutron production: Proton beam of 20GeV/c impinging on lead spallation target
- 2 flight paths of 185m and 20m length
- Irradiation and activation station near the target ("NEAR" Station)

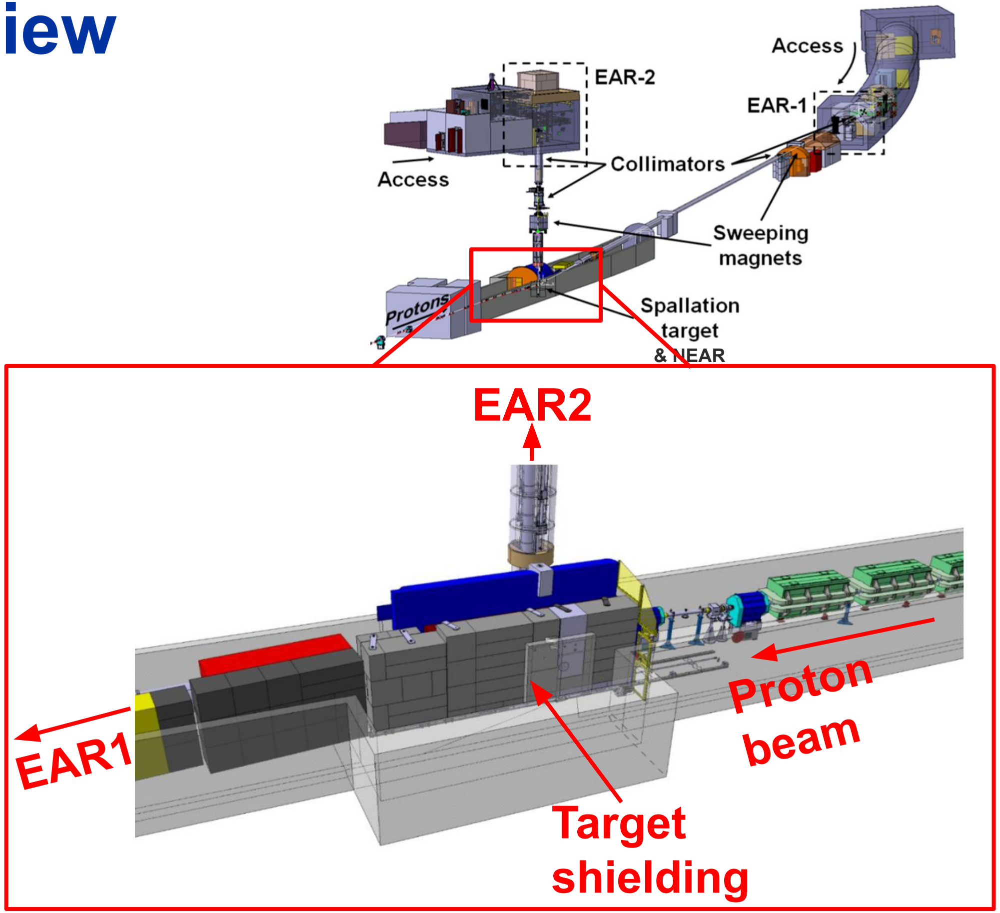


The n_TOF facility overview

The NEAR Station

- Activation station right outside the target bunker shielding
- Distance from target ~3m => high instantaneous flux
  → much higher than the EARs, can measure much smaller masses

- Beam is directed to a-NEAR through a hole in the shielding
- Collimating system: Stainless steel + Borated PE



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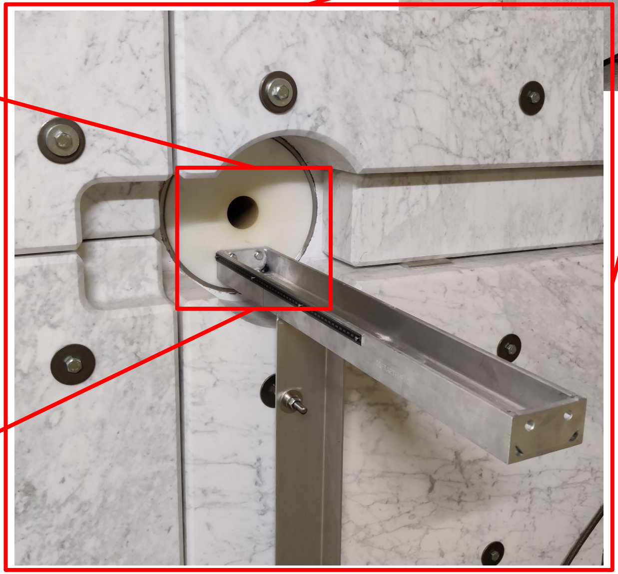

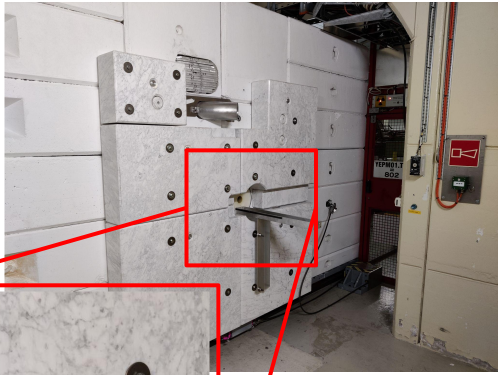

MACS @ n_TOF

MACS measurements at n_TOF

- Two ways of measuring MACS at n_TOF:
    1. Measuring the σ(E) via time-of-flight at the EARs
    2. Integral measurements at NEAR?

See "Neutron induced cross section measurements" given by C. Massimi on Monday 10h30

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  1. **Measuring the σ(E) via time-of-flight at the EARs**
  2. Integral measurements at NEAR?

See "First measurement of the 94Nb neutron capture cross-section at the CERN n_TOF facility" by J. Balibrea on Wednesday 9h30

See "New detection systems for an enhanced sensitivity in key stellar (n,γ) measurements" by J. Lerendegui on Thursday 11h00

See "Measurement of the 140Ce(n,γ) cross section at n_TOF and astrophysical implications" by S. Amaducci on Thursday 11h30

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MACS @ n_TOF

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- Two ways of measuring MACS at n_TOF:
  1. Measuring the σ(E) via time-of-flight at the EARs
  2. **Integral measurements at NEAR?**

  Why?
  →Some physics cases are not suitable for measurement with the tof technique (e.g. signal-to-background limitations)

  Thanks to the high flux of NEAR → Measure very small masses, even radioactive samples!

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MACS @ NEAR?

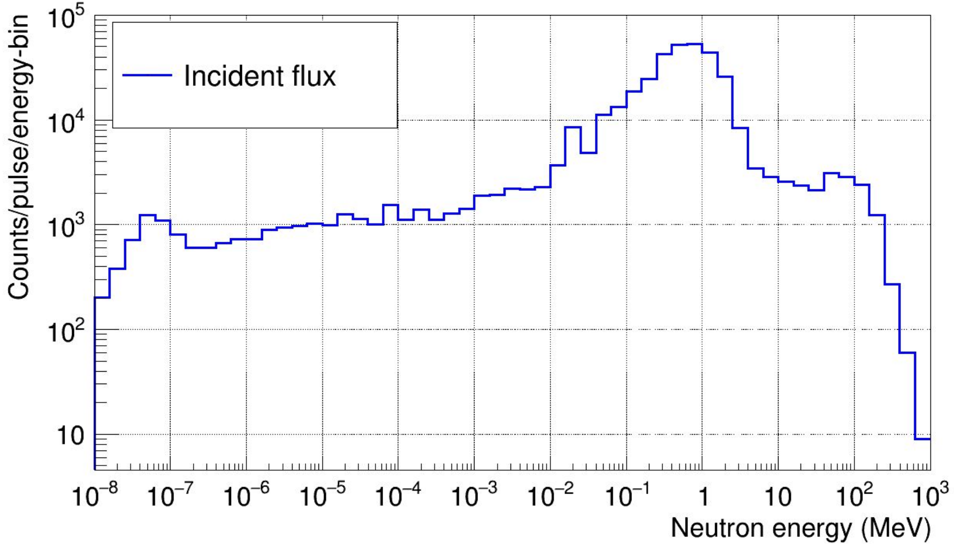
MACS measurements at NEAR?

- To perform an integral measurement of a MACS we need neutrons with a Maxwellian energy distribution

MACS @ NEAR?

MACS measurements at NEAR?

- To perform an integral measurement of a MACS we need neutrons with a Maxwellian energy distribution
  But the NEAR flux is **not** Maxwellian



MACS @ NEAR?

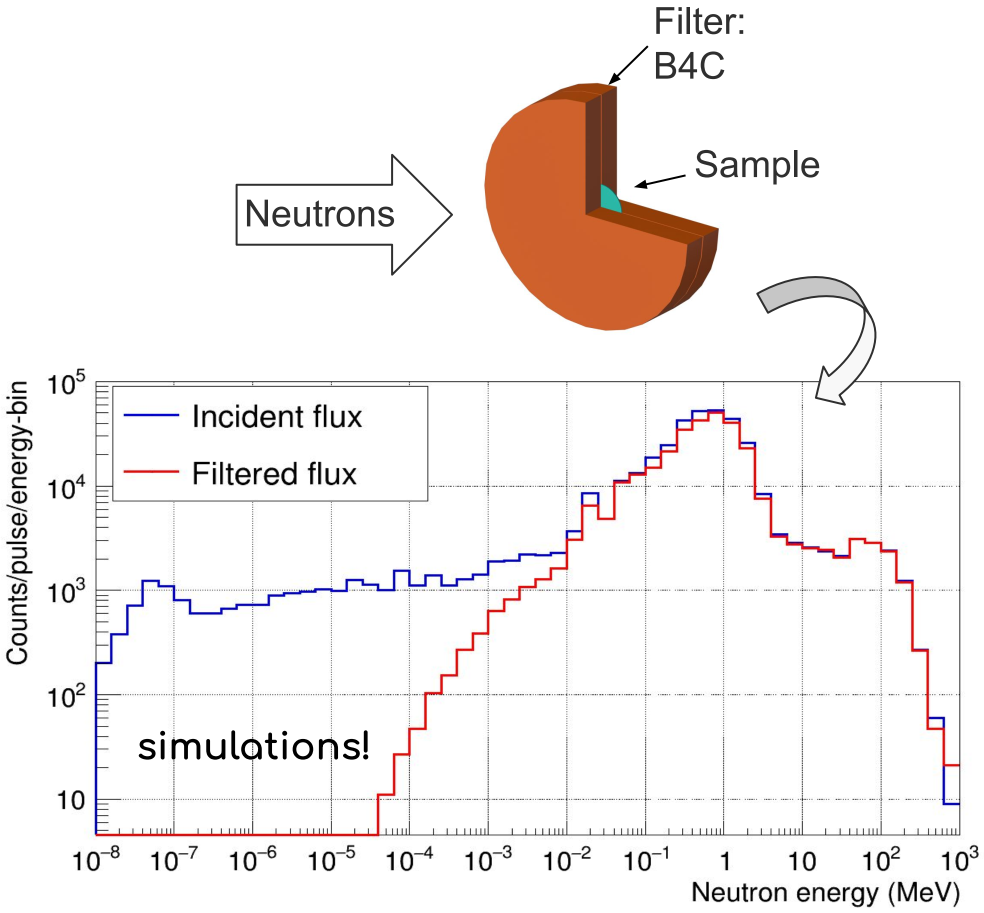
MACS measurements at NEAR?

- To perform an integral measurement of a MACS we need neutrons with a Maxwellian energy distribution
  But the NEAR flux is **not** Maxwellian
- Can we shape it into a Maxwellian?

MACS @ NEAR?

MACS measurements at NEAR?

- To perform an integral measurement of a MACS we need neutrons with a Maxwellian energy distribution
  But the NEAR flux is **not** Maxwellian
- Can we shape it into a Maxwellian?
  We can use a filtering material with high neutron capture cross-section to filter out low energy neutrons and a moderating material to alter the energy distribution



Validation method and experimental set-up

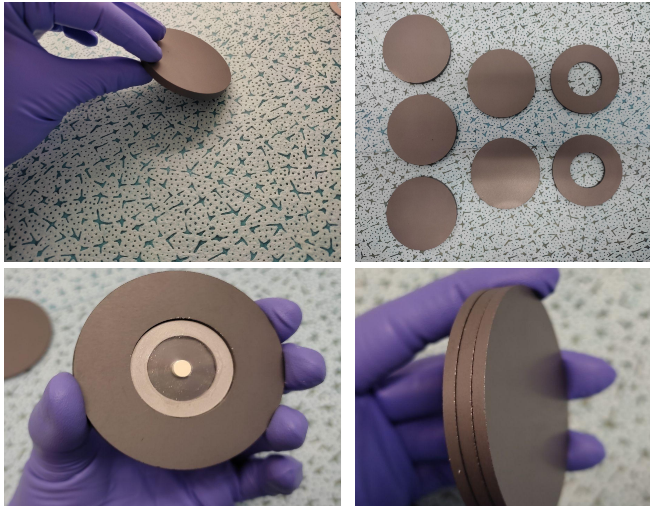
Validation method

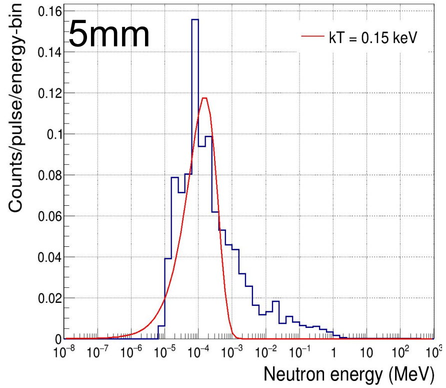
- To validate whether the shaping of the beam is possible with a filtering material, we are performing a series of integral cross-section measurements on materials with σ(E) measured already in the EARs
- In this way, we can compare the SACS obtained experimentally with the MACS of interest

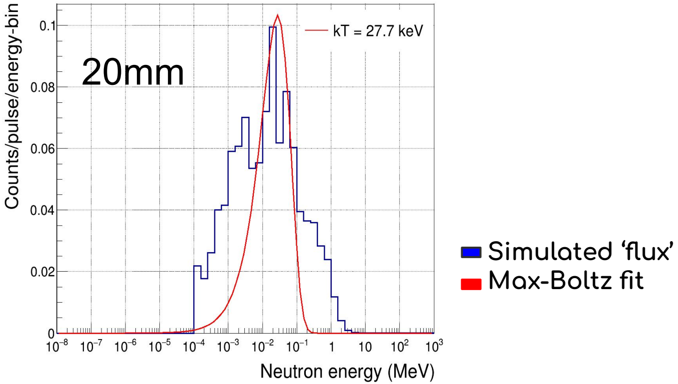
Validation method and experimental set-up

Experimental set-up: Filter part

- Filtering material used: B_4C of different thicknesses → filtered flux resembling Maxwellian distributions centered around key stellar temperatures







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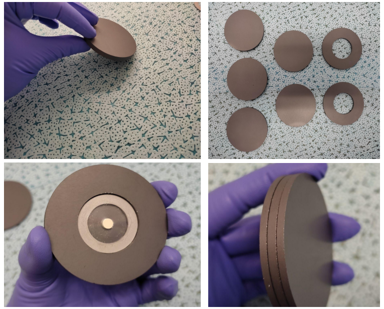
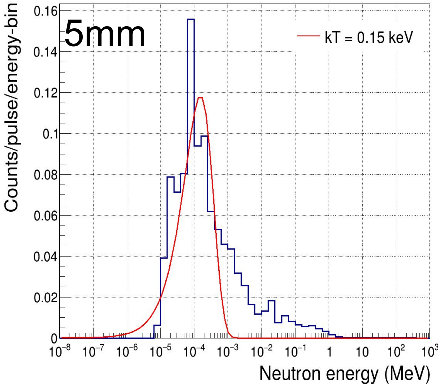
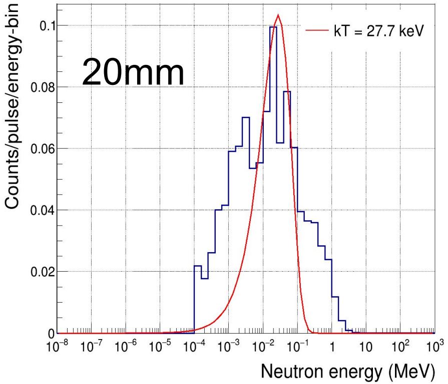




<u>Advantage:</u>
Using different thicknesses of the filter can give not only one but many Max-Boltz distributions matching different temperatures!

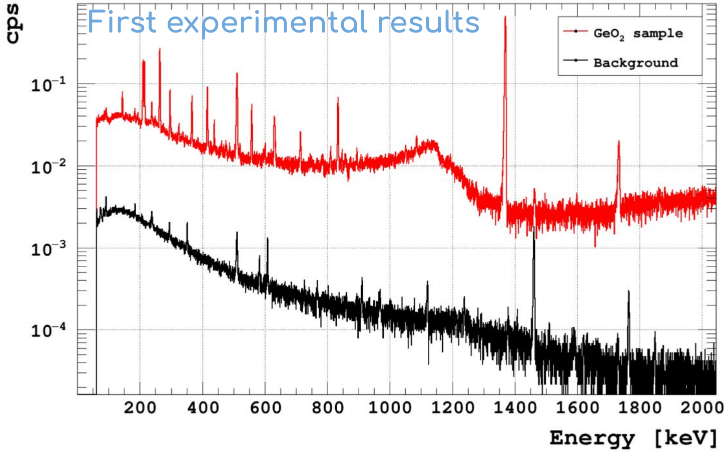


Simulated ‘flux’
Max-Boltz fit

Validation method and experimental set-up

Experimental set-up: Filter part

- Measurements via the activation method
  → Irradiation @ NEAR and measurement with HPGe equipped with Pb shielding and carbon window



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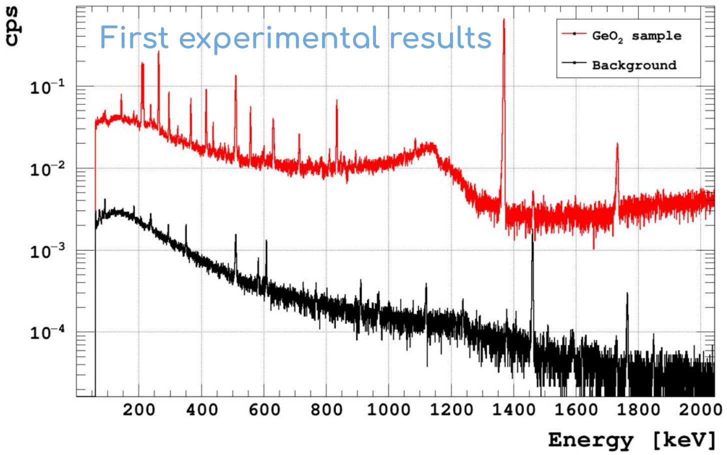

$$counts = \epsilon I N_{act} e^{-\lambda t_{wait}} (1 - e^{-\lambda t_{meas}})$$

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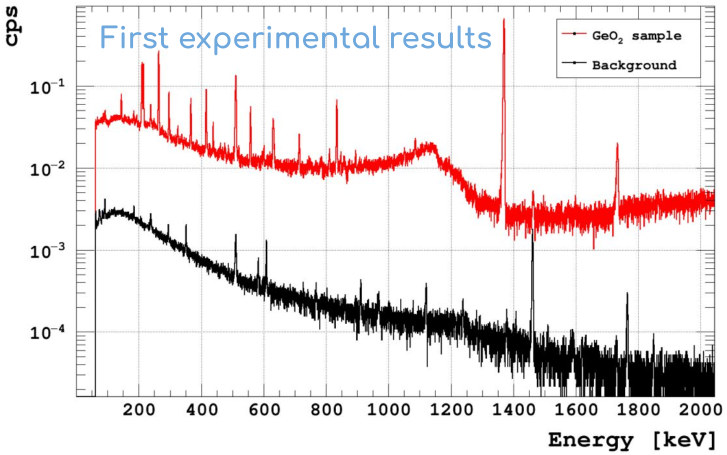

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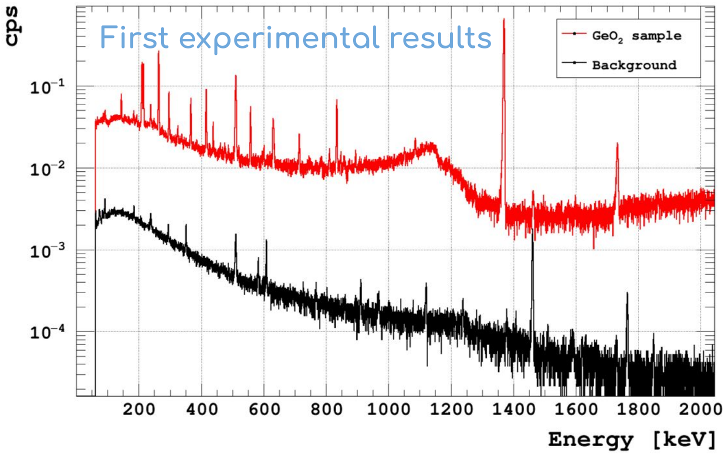

$$counts = \epsilon I N_{act} e^{-\lambda t_{wait}} (1 - e^{-\lambda t_{meas}})$$

$$N_{act} = \sigma N_T \Phi f_B$$

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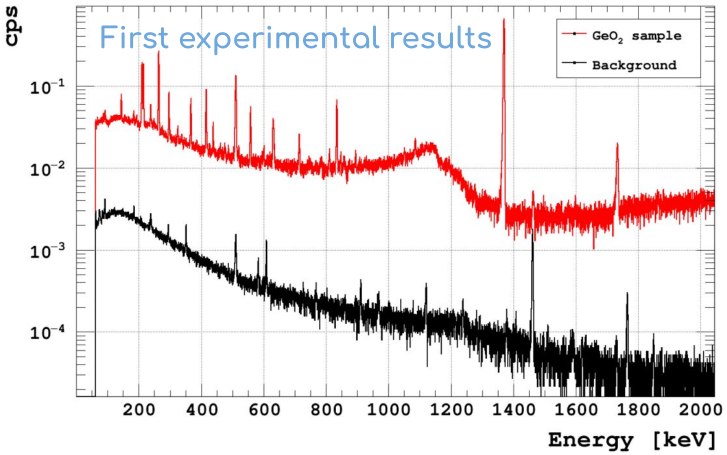


$$counts = \epsilon I N_{act} e^{-\lambda t_{wait}} (1 - e^{-\lambda t_{meas}})$$

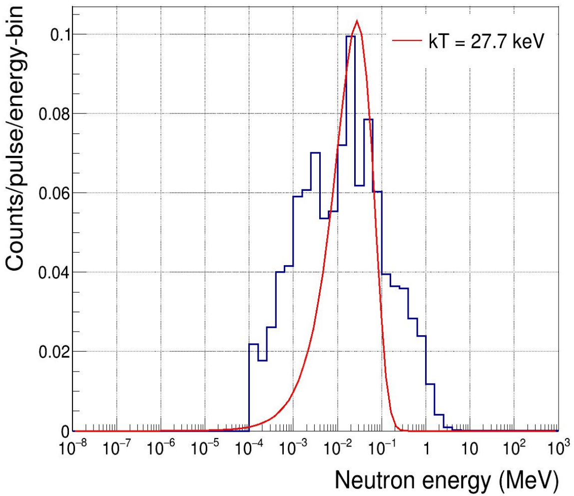
$$N_{act} = \sigma N_T \Phi f_B$$

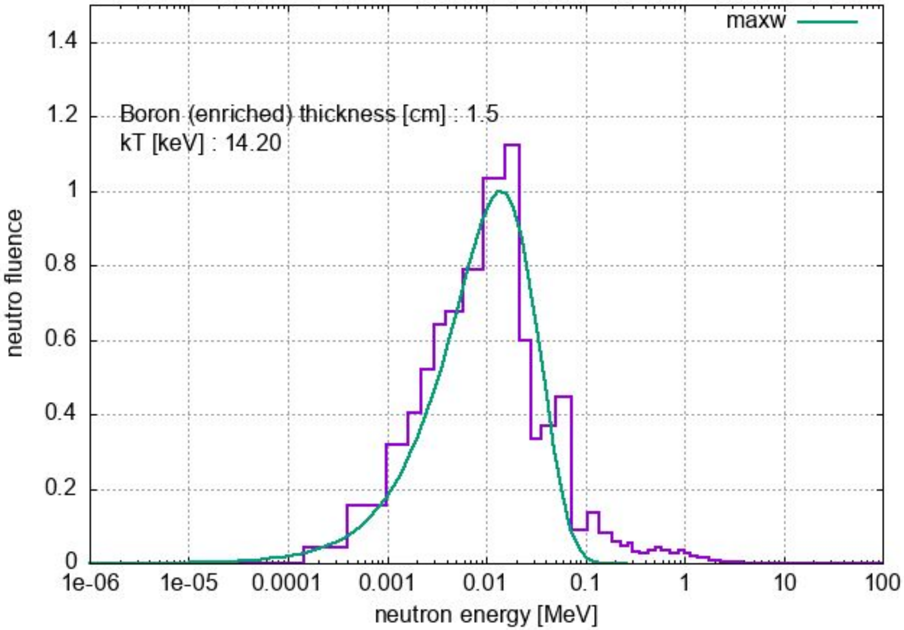
→ Determine the spectral average cross-section

Validation method and experimental set-up

Experimental set-up: Moderator part

- Next step: Add moderator to refine high energy part





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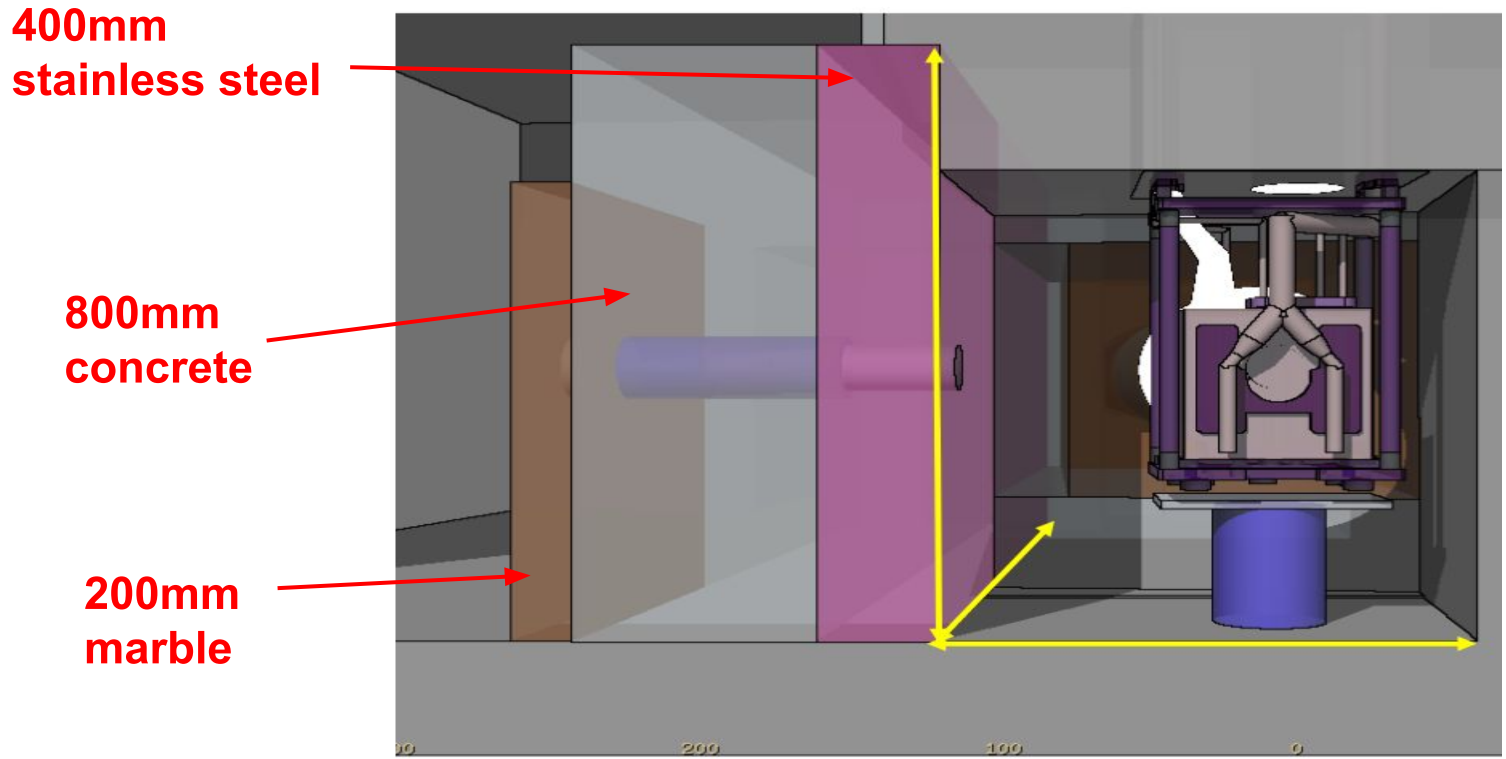
- MACS are an important input in nuclear astrophysics
- At n_TOF we already extract MACS by measuring neutron capture cross-sections via time-of-flight technique (see dedicated talks)
- For cases that are too challenging to measure via tof → Integral measurements @ NEAR
- Feasibility study for shaping the NEAR flux into a Maxwellian ongoing
- Method: Use B_4C as filter to filter out thermal neutrons
- Validation: Measure known elements and compare SACS with simulations and MACS of interest

Thank you

Backup slides

Backup: NEAR

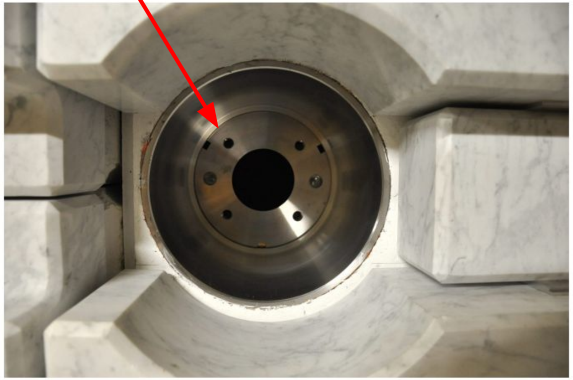


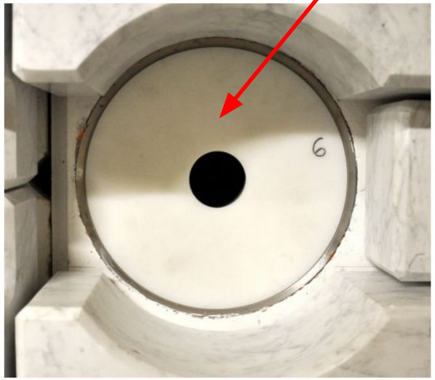
From:
https://arxiv.org/abs/2202.12809
M. Ferrari et al., Design development and implementation of the near area and its neutron irradiation station at the n_TOF facility at cern (2022).

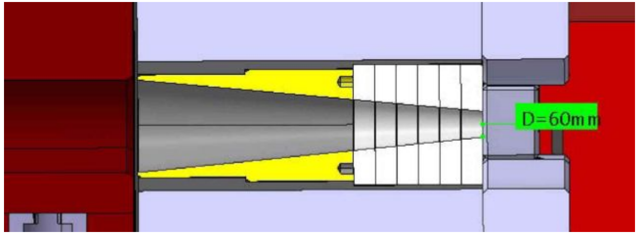
Backup: NEAR

500mm stainless steel

300mm (5%) B-PE







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Backup: Activation Technique

- ***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

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:

$$\sigma = \frac{counts}{\Phi \epsilon I N_T e^{-\lambda t_{wait}} (1 - e^{-\lambda t_{meas}}) f_B}$$

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

Backup: Reactions

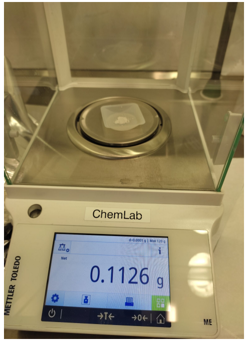
cross-sections already measured in EAR1 and EAR2 allowing for the computation of any SACS

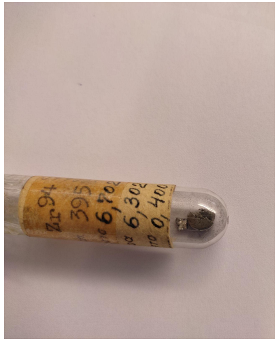
Neutron capture of

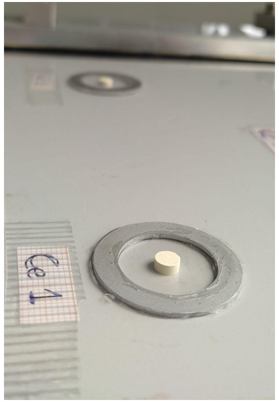
- ^{197}Au
  - "*^{197}Au(n,γ) cross section in the unresolved resonance region*" C. Lederer et al., Physical Review C 83, 034608 (2011)
  - *"^{197}Au(n,γ) cross section in the resonance region"* C. Massimi et al., Physical Review C 81, 044616 (2010)
- ^{76}Ge
  - "*Measurement of the 76 Ge(n,γ) cross 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

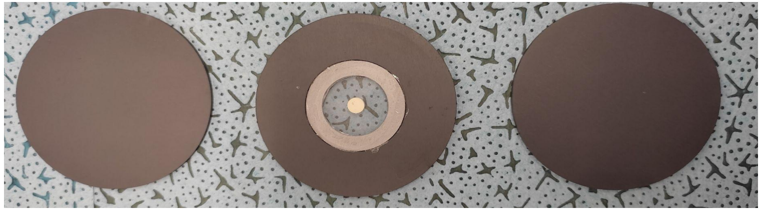
  G. Tagliente, P.M. Milazzo al., in preparation (2021)

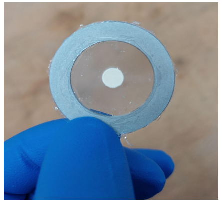
Backup: Details on experimental set-up

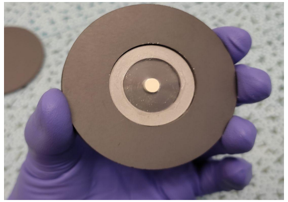


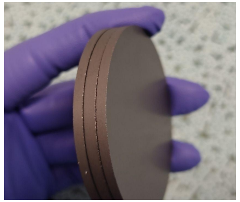


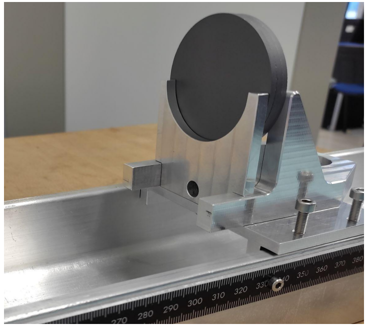


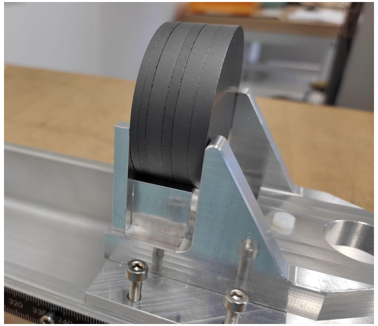




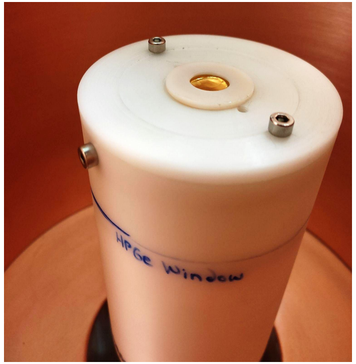


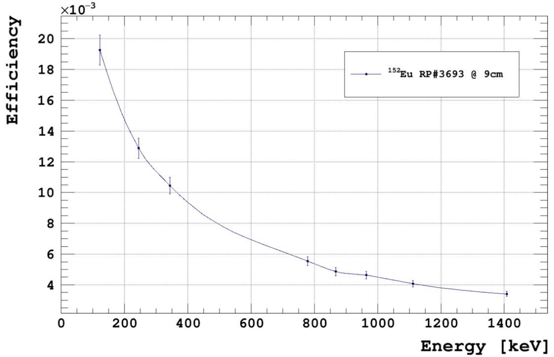


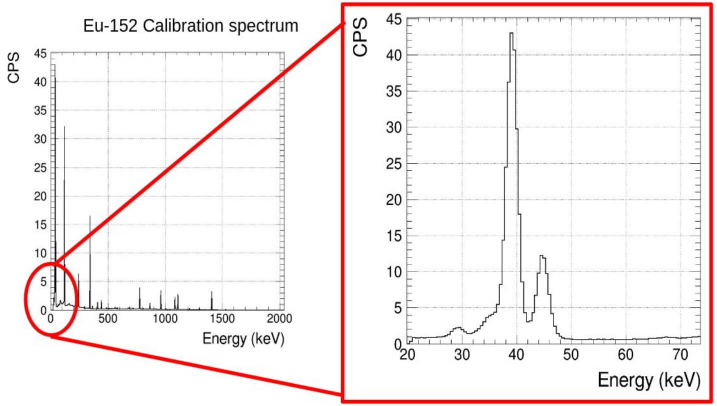


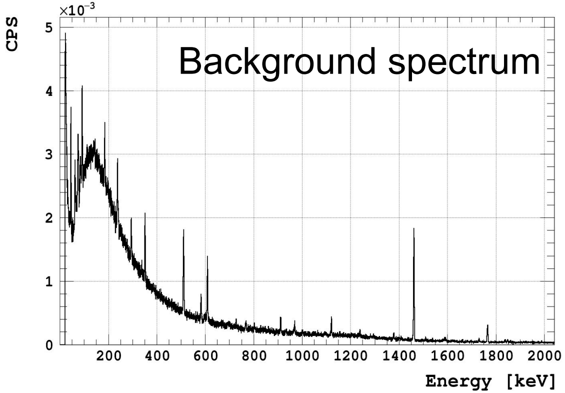


Backup: Details on HPGe



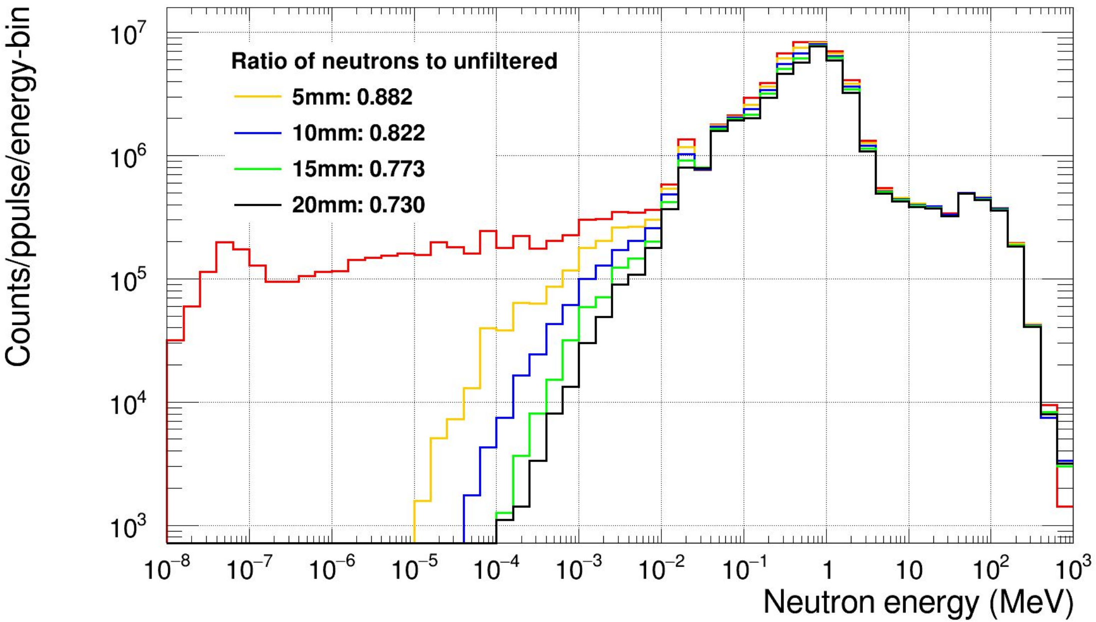




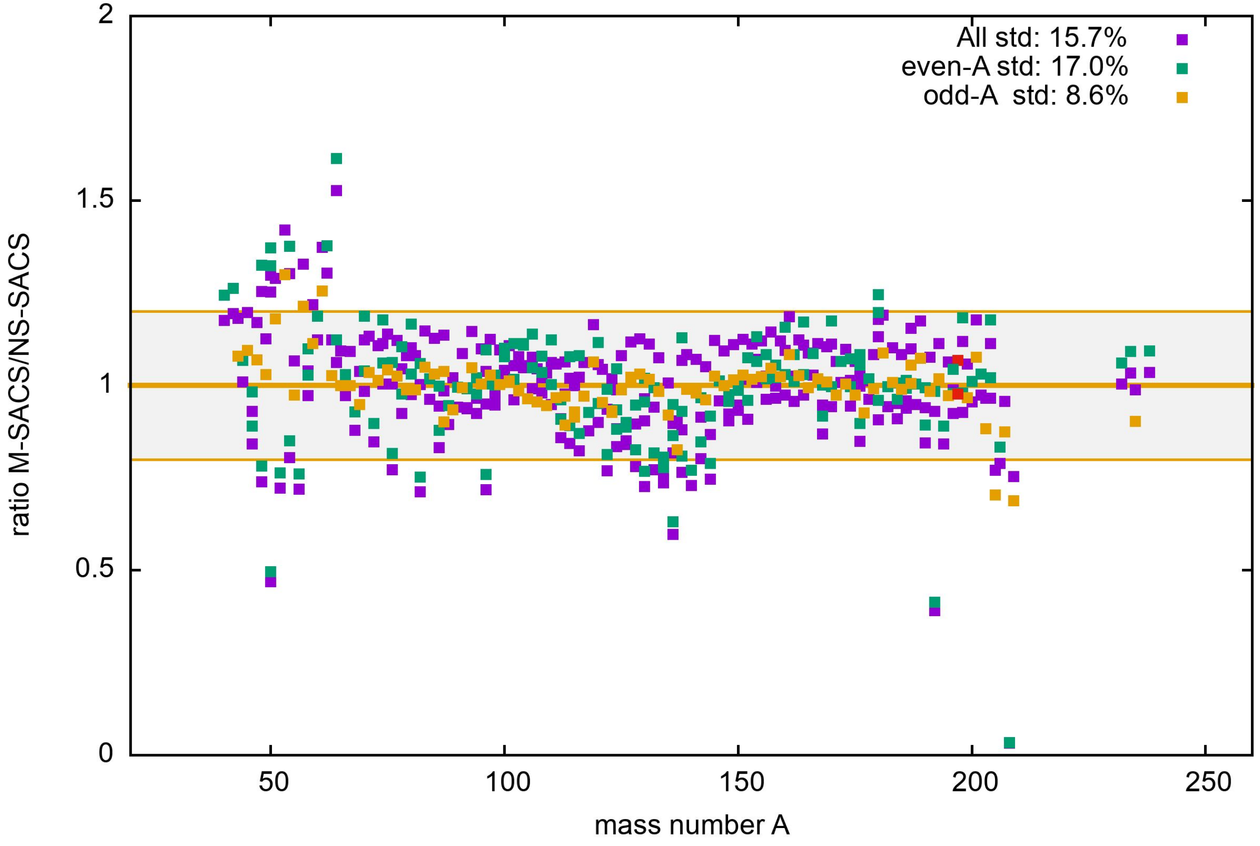


Backup: Flux simulations

4 filter thicknesses thicknesses → shape and percentage of filtered neutrons



Backup: SACS vs MACS



Backup: Coming in the future!

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Direct measurement of the n_TOF NEAR neutron fluence with diamond detectors

May 2, 2022

M. Diakaki[1], M. Bacak[2], C. Weiss[3,4], E. Griesmayer[3,4], C. Guerrero[5], E. Jericha[3], M. Kokkoris[1], A. Mengoni[6,8], N. Patronis[7], E. Stamati[2,7], R. Vlastou[1] and the n_TOF Collaboration[9]

[1]*National Technical University of Athens, Greece*
[2]*European Organization for Nuclear Research (CERN), Switzerland*
[3]*TU Wien, Atominstitut, Stadionallee 2, 1020 Wien, Austria*
[4]*www.cividec.at*
[5]*Universidad de Sevilla, Spain*
[6]*ENEA Bologna, Italy*
[7]*University of Ioannina, Greece*
[8]*INFN, Sezione di Bologna, Italy*
[9]*www.cern.ch/n_TOF*

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the radiation background at the n_TOF NEAR facility to study the feasibility of cyclic activation experiments

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J. Lerendegui-Marco[1], M. Bacak[2], V. Alcayne[3], D. Cano-Ott[3], A. Casanovas[4], G. Cortés[4], C. Domingo-Pardo[1], C. Guerrero[5], C. Massimi[6,7], E. Mendoza[3], A. Mengoni[8], A. Musumarra[6], N. Patronis[9], A. Tarifeno-Saldivia[1], and the n_TOF Collaboration[10]

[1]*Instituto de Física Corpuscular, CSIC - Universidad de Valencia, Spain*
[2]*European Organization for Nuclear Research (CERN), Switzerland*
[3]*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain*
[4]*Universitat Politècnica de Catalunya, Spain*
[5]*Universidad de Sevilla, Spain*
[6]*Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy*
[7]*Dipartimento di Fisica e Astronomia, Università di Bologna, Italy*
[8]*Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy*
[9]*University of Ioannina, Greece*
[1]*0www.cern.ch/n_TOF*