First measurement of the ^{94}Nb(n,γ) cross-section at the CERN n_TOF facility

V. Babiano, J. Balibrea-Correa, L. Caballero, F. Calviño, A. Casanovas, S. Cristallo,
C. Domingo-Pardo, R. Dressler, C. Guerrero, S. Heinitz, U. Köster, I. Ladarescu,
J. Lerendegui-Marco, E. A. Maugeri, A. Mengoni, I. Mönch, *D. Schumann,*
A. Tarifeño-Saldivia , E. González , D. Cano-Ott , E. Mendoza, N. Colonna,
C.Lederer-Woods, N. Sosnin ,T. Rauscher

and the n_TOF collaboration

erc European Research Council

Vniversitat de València

CSIC
Consejo Superior de Investigaciones Científicas

nTOF

Nuclear Physics in Astrophysics X: 05-09 September 2022

Outline

- **Introduction**
- **Challenges of ^{94}Nb(n,γ) & experimental details**
- **Preliminary ^{94}Nb(n,ɣ) experimental yield with s-TED**
- **Summary, conclusions & outlook**

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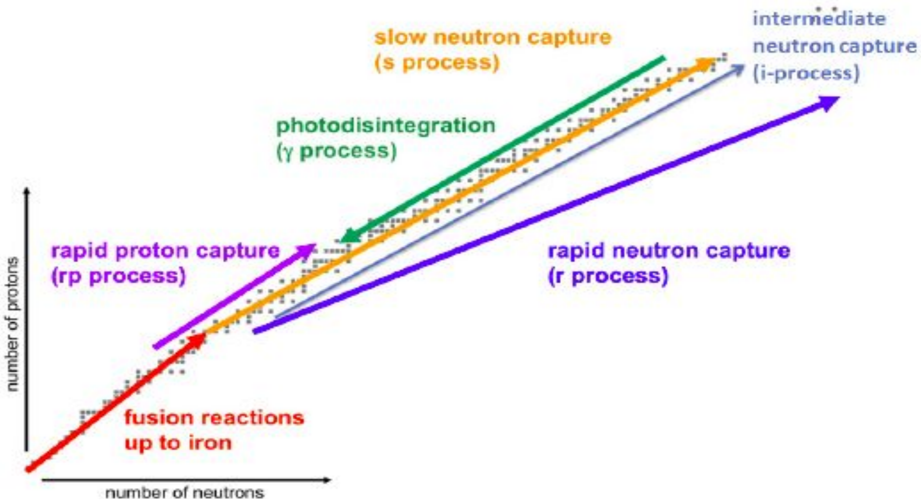
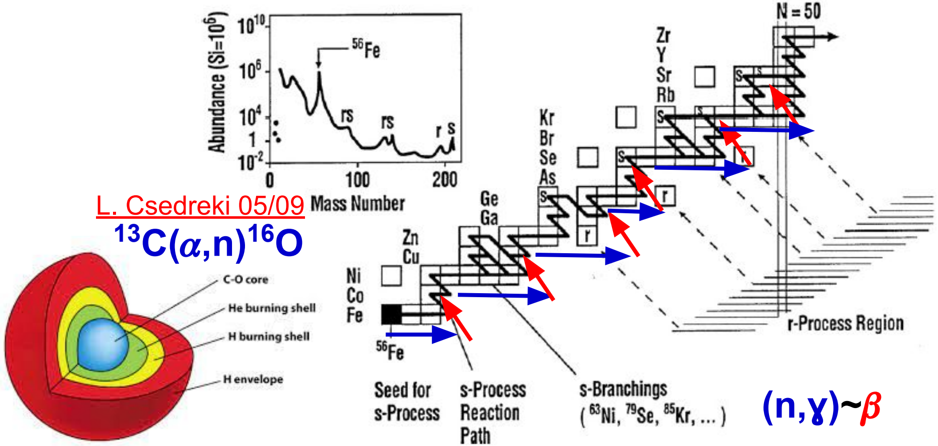
Introduction: neutrons & s-process



Neutron induced reactions **produce ~75%** of all **known** chemical **elements**.

Depending on the **stellar conditions**, different neutron fluxes are produced and thus **several mechanism** (s- r- i-..) are activated.

The **s-process**: **(n,γ)** + **β** decay close to stability valley



L. Csedreki 05/09

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

$(n,\gamma)\sim\beta$

It takes place in AGB stars during He-flashes:

$T\sim10^8$-10^9 K

$N_n\sim10^6$-10^{12} cm^{-3} ←Small/Moderate neutron flux

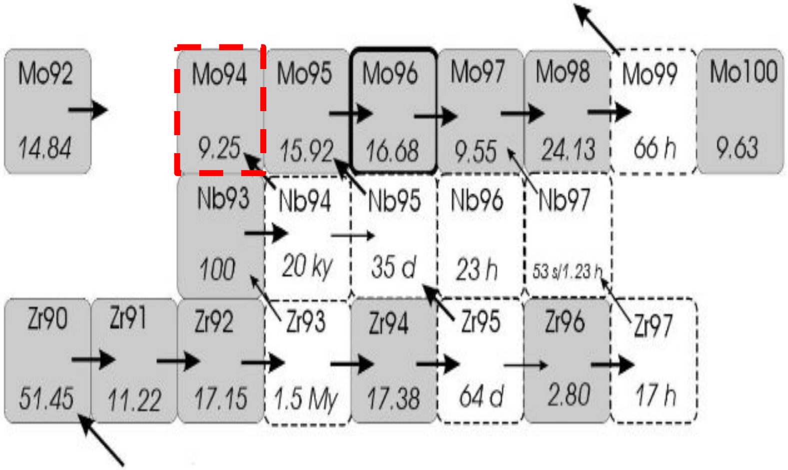
s-process is responsible of **~½** of **chemical abundances** for **A>56** up to **Pb**.

Some are key branching: ^{79}Se J. Lerendegui 08/09

The s-process & presolar SiC grains

Anomalies in isotopic composition of presolar SiC grains:

- The solar-system ^{94}**Mo abundance** represents yet a **challenge** for **s-process** models.
- **Predicted** s-process abundance of ^{94}Mo is at most **1%**.
- Analysis of molybdenum in **presolar SiC grains** (Murchison meteorite) indicate an **abundance five times larger.**



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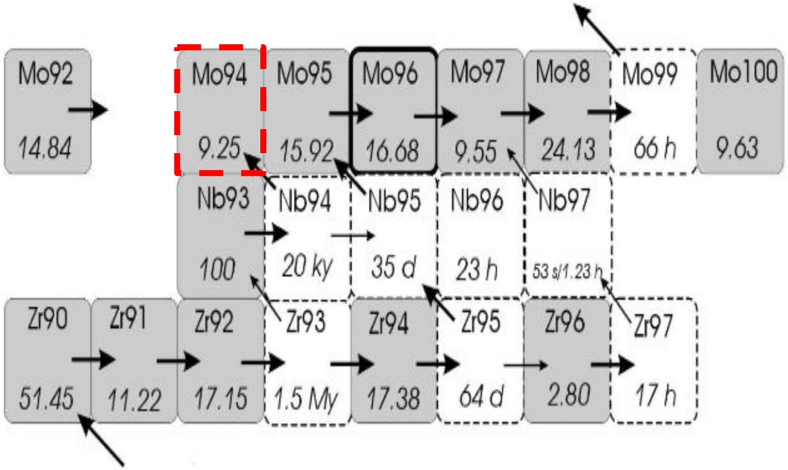

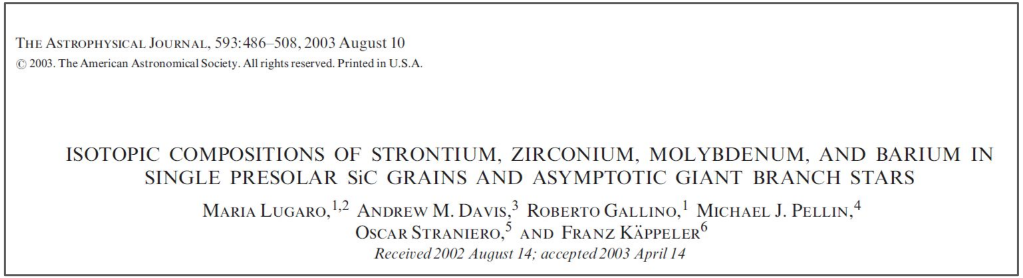
The Astrophysical Journal, 593:486–508, 2003 August 10

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ISOTOPIC COMPOSITIONS OF STRONTIUM, ZIRCONIUM, MOLYBDENUM, AND BARIUM IN SINGLE PRESOLAR SiC GRAINS AND ASYMPTOTIC GIANT BRANCH STARS

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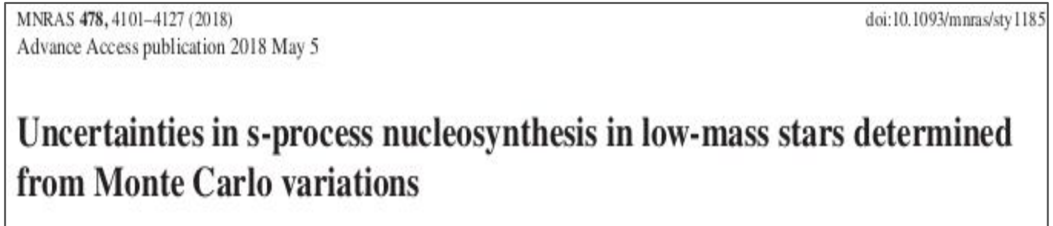
Received 2002 August 14; accepted 2003 April 14


MNRAS **478**, 4101–4127 (2018) doi:10.1093/mnras/sty1185

Advance Access publication 2018 May 5

Uncertainties in s-process nucleosynthesis in low-mass stars determined from Monte Carlo variations

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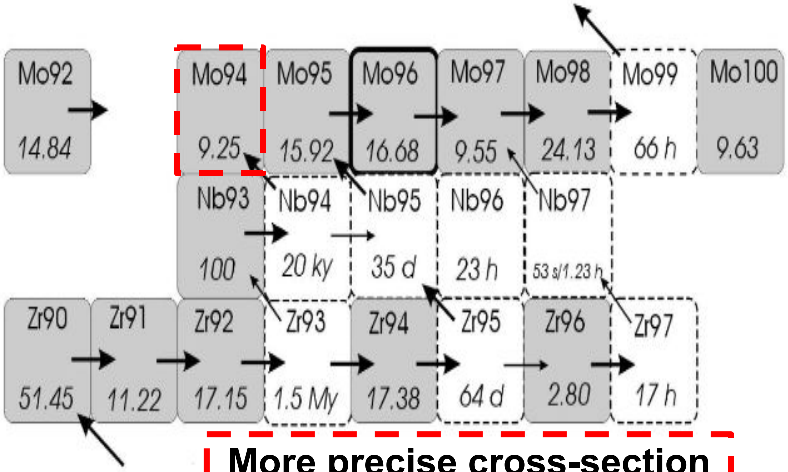
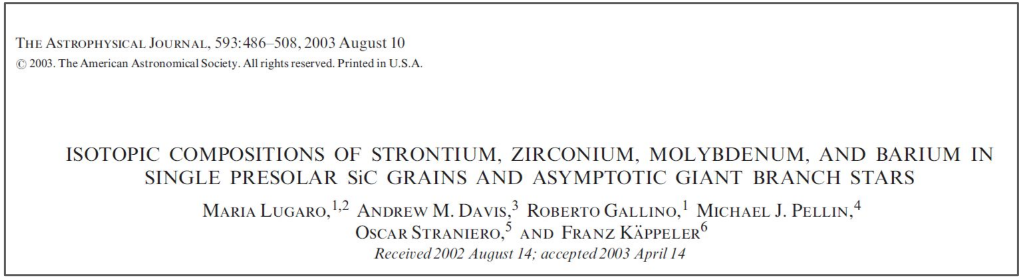


More precise cross-section determinations



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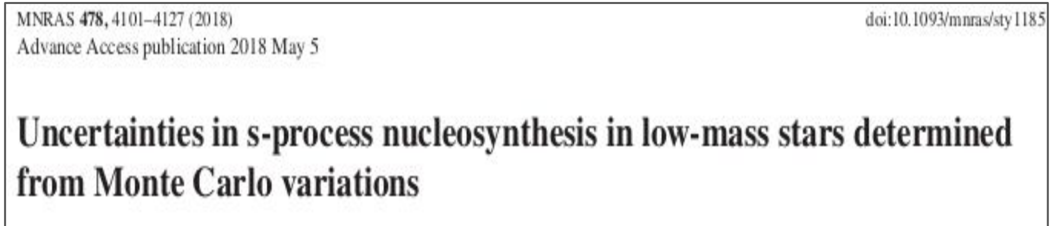

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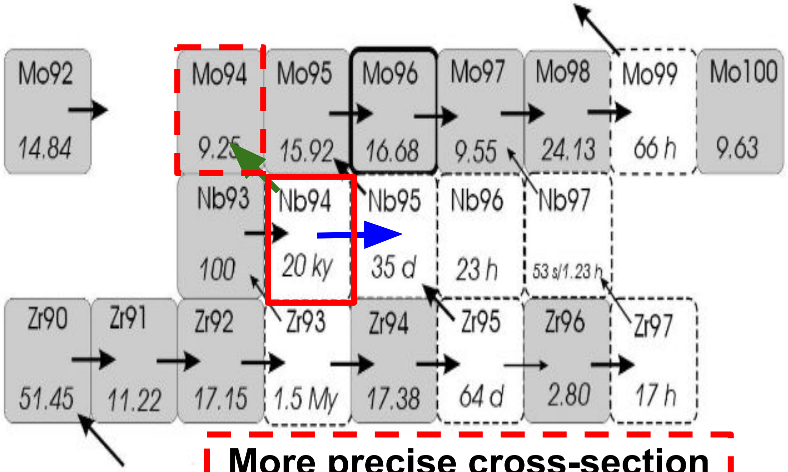

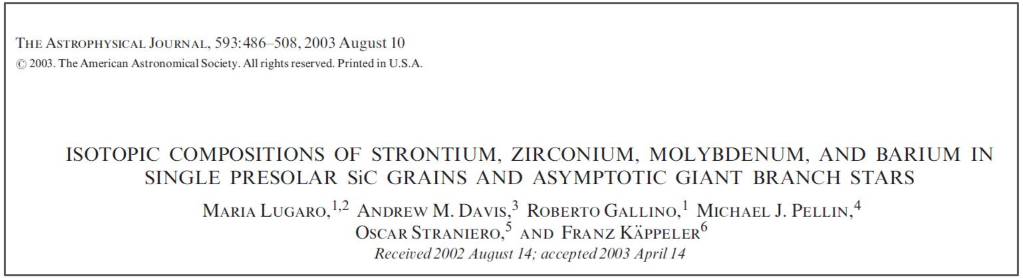
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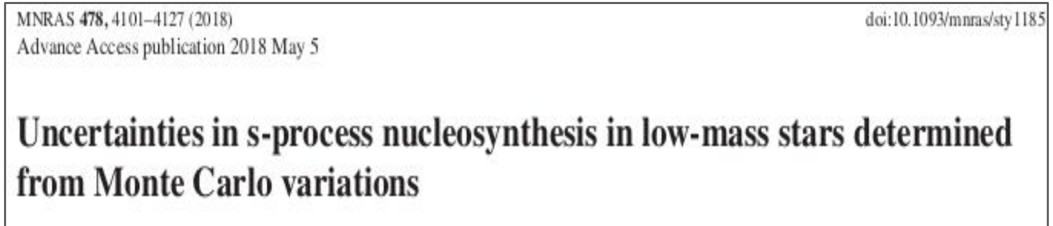
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MACS
^{94}Nb(n,γ)↓↓

^{94}Nb(n,γ) would be critical to disentangle and constrain **^{94}Mo abundances** in AGB stars and **presolar SiC grains predicted** by stellar models

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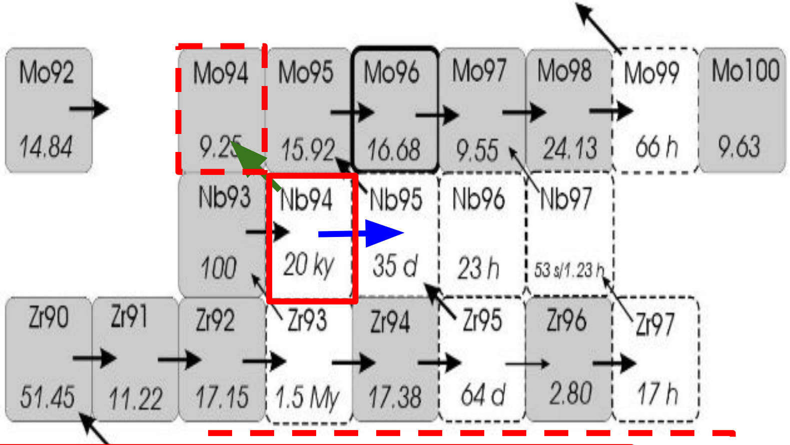

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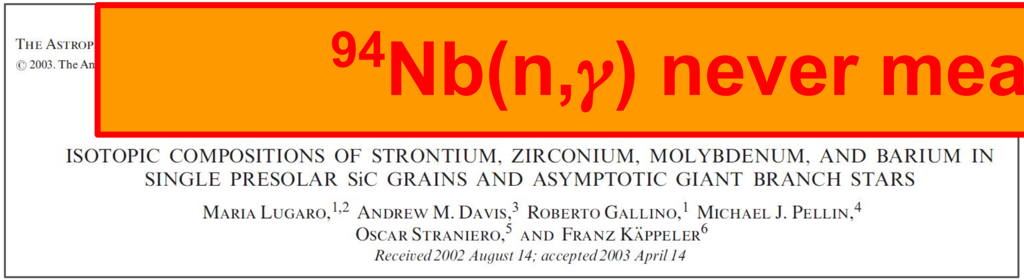
^{94}Nb(n,γ) never measured before!



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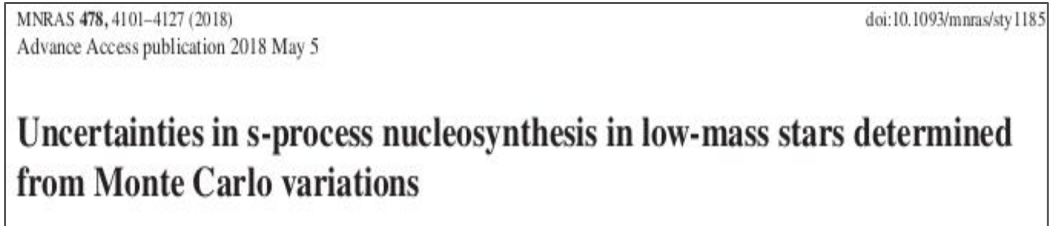

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Challenges of ^{94}Nb(n,γ) measurement

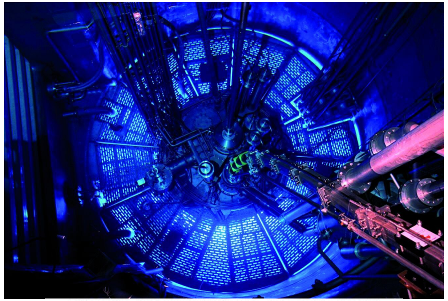
What are the challenges in this particular measurement?

^{94}Nb **target production**:

- It is not present in nature! (**$T_{1/2}$=2.03 10^4 y**) →It needs to be produced by an **irradiation** in a nuclear reactor (51 days **@ ILL**)
- Hyper-pure material → **Hyperpure ^{93}Nb** (<1 ppm Ta) sample originally produced at the Solid State and Materials Research of Dresden.

Jens Ingolf Moench et al. Material Transactions JIM Vol. 41 67 (2000)

- Sample **characterization** & target **production** (**@ PSI**):
  - **304 mg** hyper-pure **^{93}Nb+^{94}Nb** material (47+45 mm **wires**).
  - **^{94}Nb/^{93}Nb ~ 1%** (9.24×10^{18} ^{94}Nb atoms).



“Disk”

Radiation hardness

E. Maugeri 09/09

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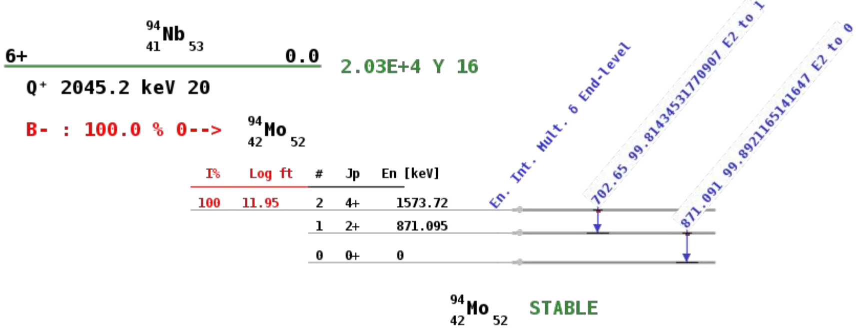

^{94}Nb(n,γ) **experimental setup**:

- Low mass & high radioactive sample!
  - Only **1%** of target is **^{94}Nb** atoms
  - **10.1 MBq** (only ^{94}Nb) (**e$^-$** (200 keV) + **γ**(702+871) keV)

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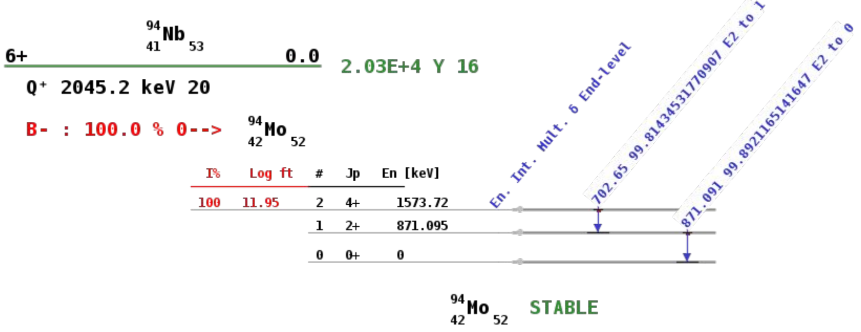

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High luminosity facility & next generation of neutron capture cross-section detectors

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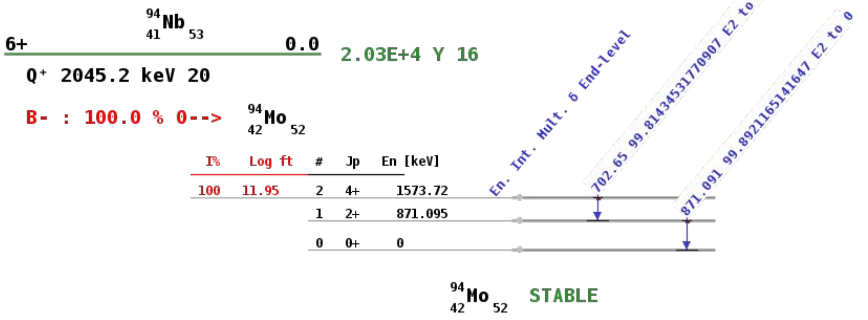

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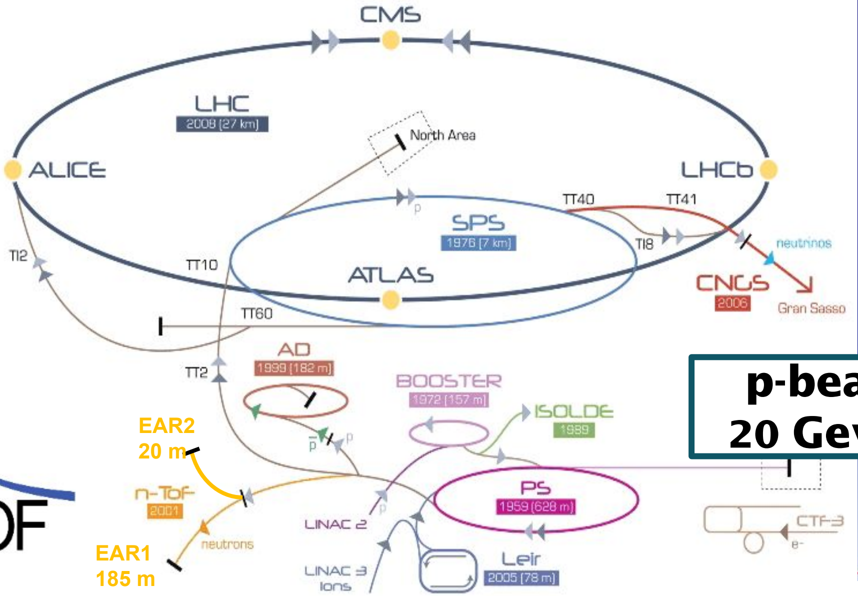
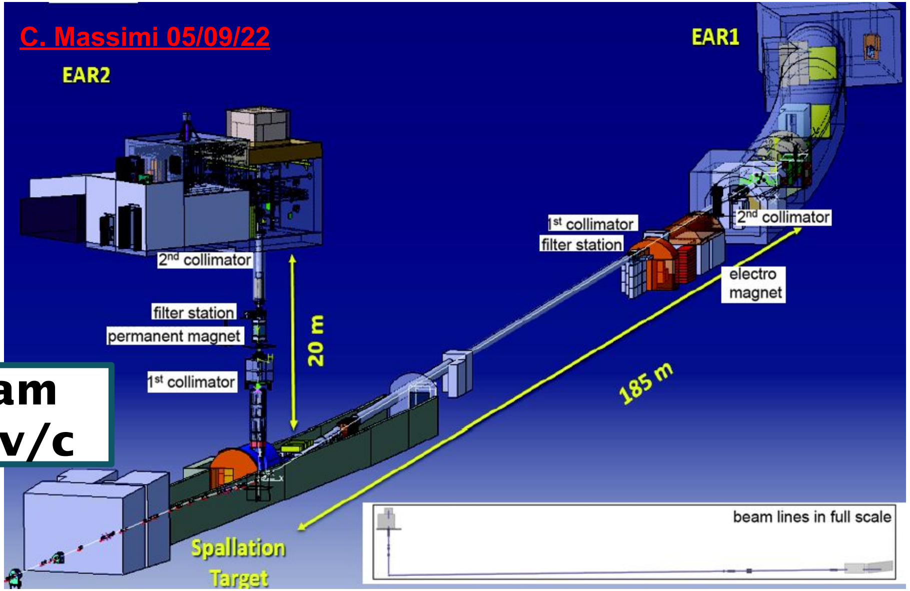
High luminosity facility & next generation of neutron capture cross-section detectors

nTOF + **EAR2**

The n_TOF facility @ CERN



p-beam
20 Gev/c



C. Massimi 05/09/22

C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.
CERN n_TOF Collaboration: 150 scientists, 41 institutions worldwide
n_TOF + ISOLDE = 75% of PS proton Budget (!)

More details about EAR2 & ToF technique in backup slides!

Nowadays at n_TOF there are 3 experimental areas:

- EAR1 @ 185 m → High E_n resolution
- EAR2 @ 20 m → High luminosity
- NEAR→MACS & activations E. Stamati 07/09/22

Challenges of ^{94}Nb(n,γ) measurement

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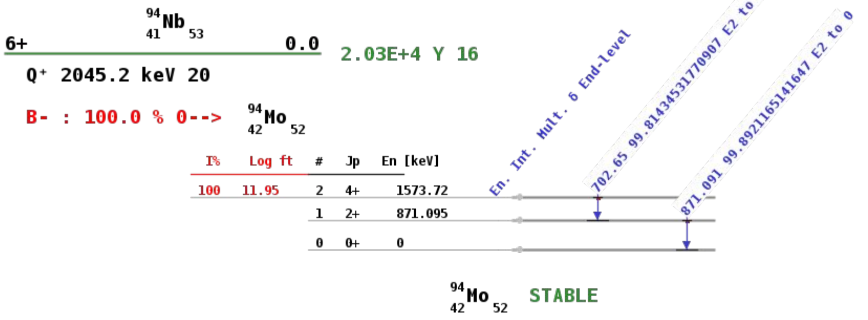

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High luminosity facility & next generation of neutron capture cross-section detectors

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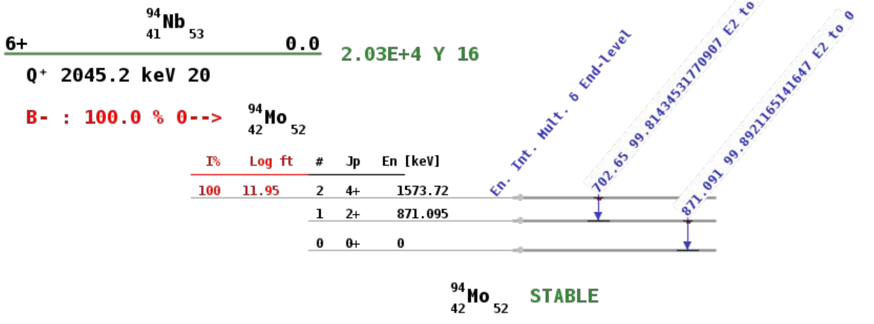

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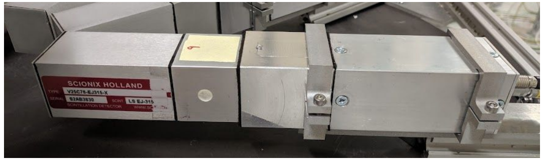
High luminosity facility & next generation of neutron capture cross-section detectors

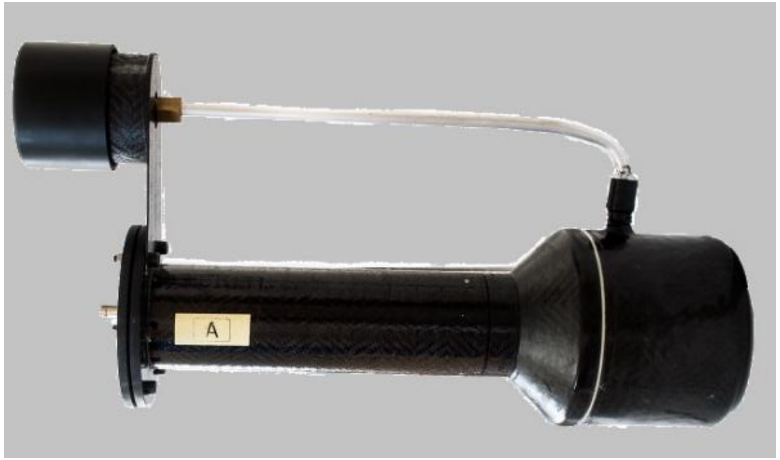
s-TED detectors



EAR2

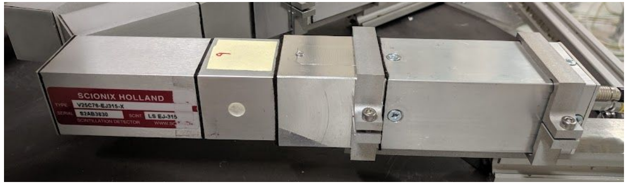
New developments for (n,γ) detectors

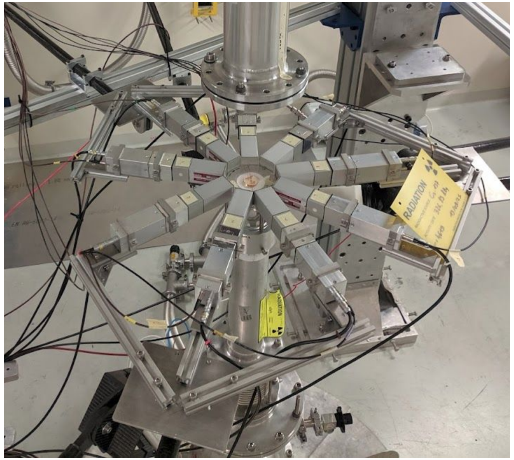
State-of-the art for (n,γ):
C_6D_6 TED detectors



Limitations @ EAR2:
High C. rates + effect of the G-flash in the PMT
- Limitations in max En
- Large dead-time corrections.

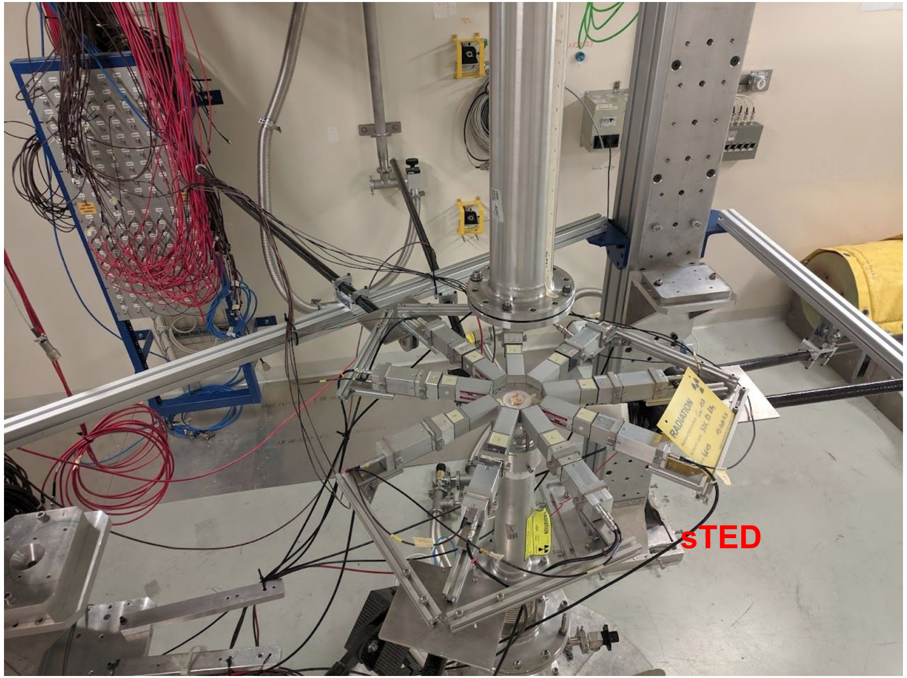
sTED detectors (~1/9 L C_6D_6) + New PMTs

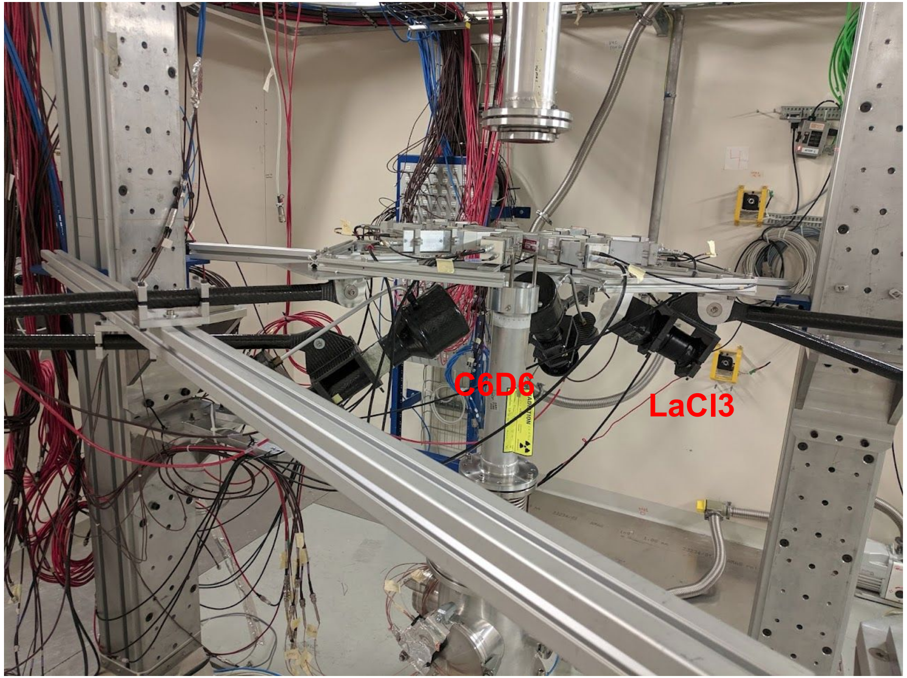




Minimized G-flash effects:
→**Max En in A. range**
Low C. rates
→**Low dead-time**
Geom. optimization for (n,γ)
→**Large sensitivity**

Experimental setup for ^{94}Nb(n,γ)



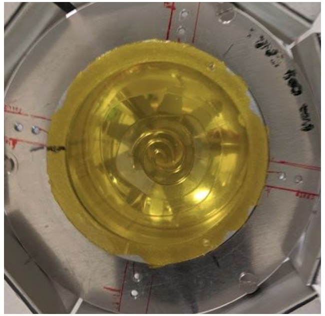


Full experimental setup for ^{94}Nb(n,ɣ) campaign:

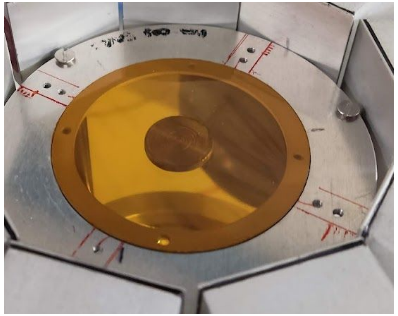
- **9 sTEDs** @ **4.5 cm** (ring-configuration) → Main detectors for (n,ɣ) (~1 L6D6).
- **1 LaCl3** @ **9 cm** with thick **PE(6Li)** → Spectroscopic inf. & angular distribution
- **2 L6D6** @ **17.5 cm** with the **new PMT+VD** → Validation.
- **SiMOn2** → Beam monitoring/normalization/neutron flux shape.

Summary of the experiment

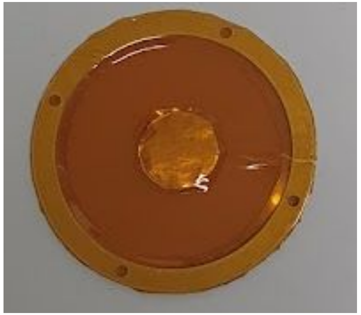
^{94}Nb
(Main configuration)



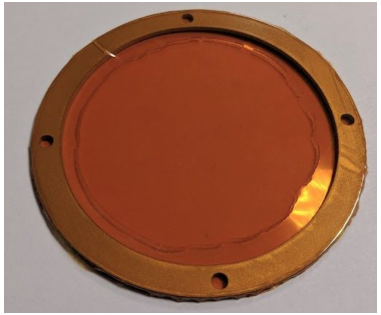
^{93}Nb spiral
(^{93}Nb bkg)



^{93}Nb disk
(Normalization)



^{197}Au disk
(Normalization)



Empty +Ancillary
(bkg)

^{94}Nb+^{93}Nb yield

Normalization

Background

The **experiment** was performed along **March and April** of **2022**:

- **Two main** configurations for **^{94}Nb** and **^{93}Nb resonances.**
- **^{93}Nb** and **^{197}Au disks** for absolute **normalization** to Gold saturated resonance.
- Several **Ancillary configurations** were measured to account for **all possible** backgrounds **contributions**:
  - **Empty** →Background induced by samples frames.
  - **C** → neutron scattering in the sample.
  - **Pb** →In-beam gamma-rays scattering.

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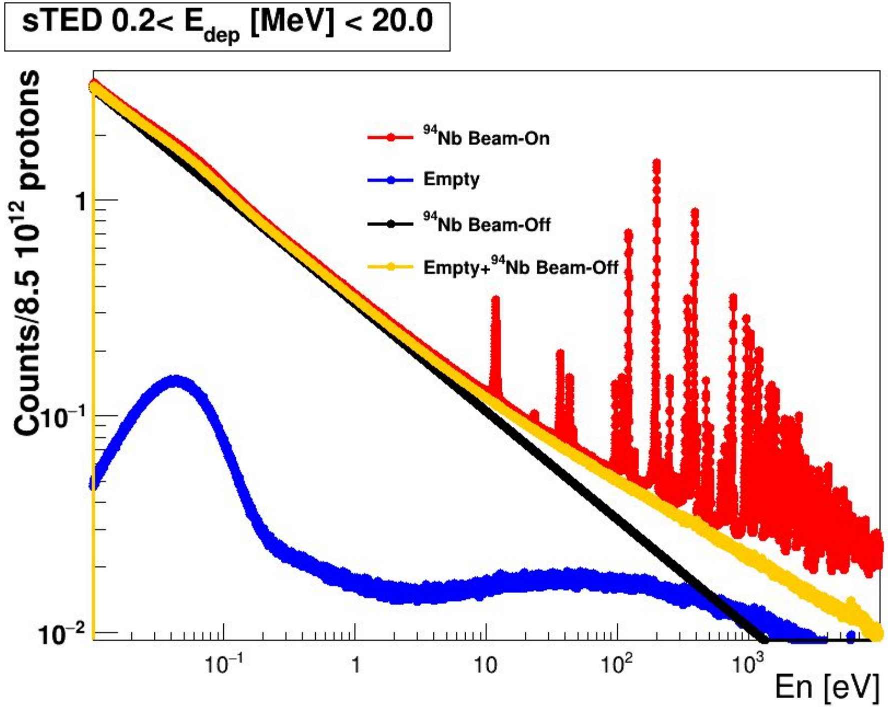
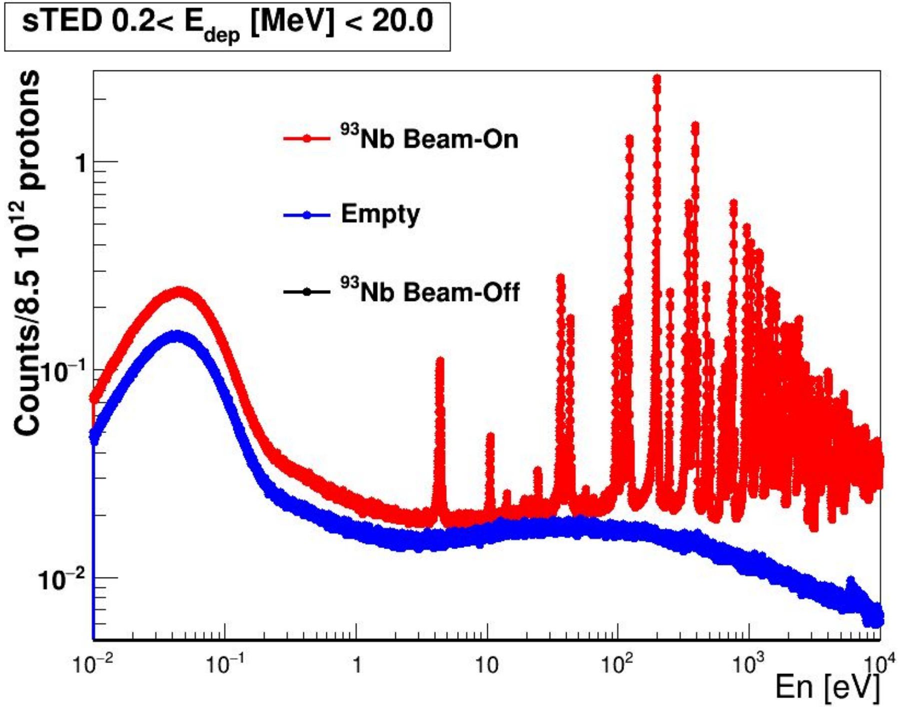
Preliminary experimental yield for s-TED

^{94}Nb target in place



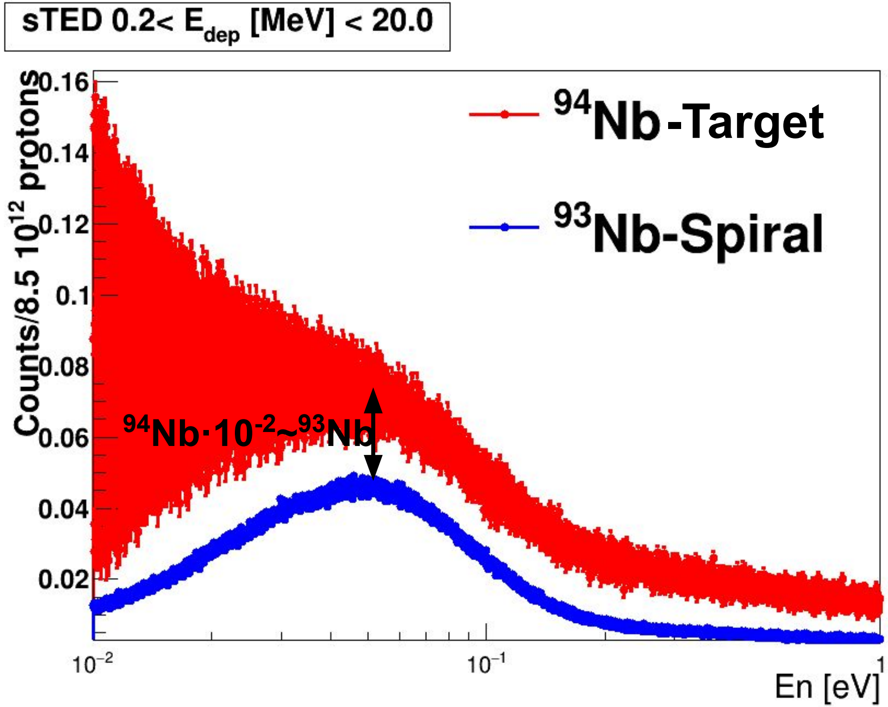
^{93}Nb-spiral target in place



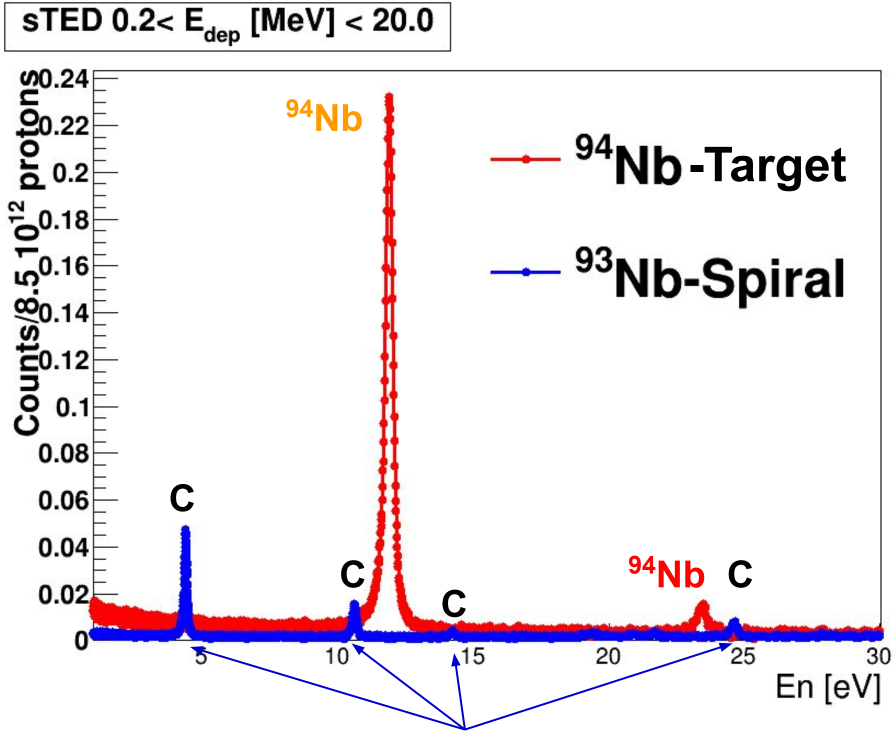
Experimental yields registered by the s-TEDs for the two main configurations

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



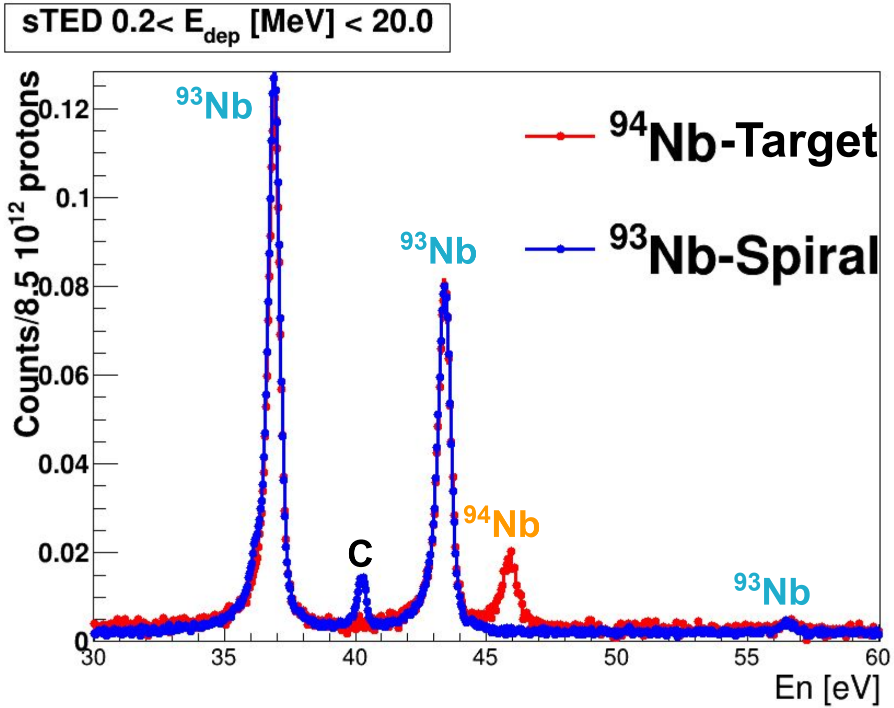
Expected large ^{94}Nb(n,γ) thermal cross-section!

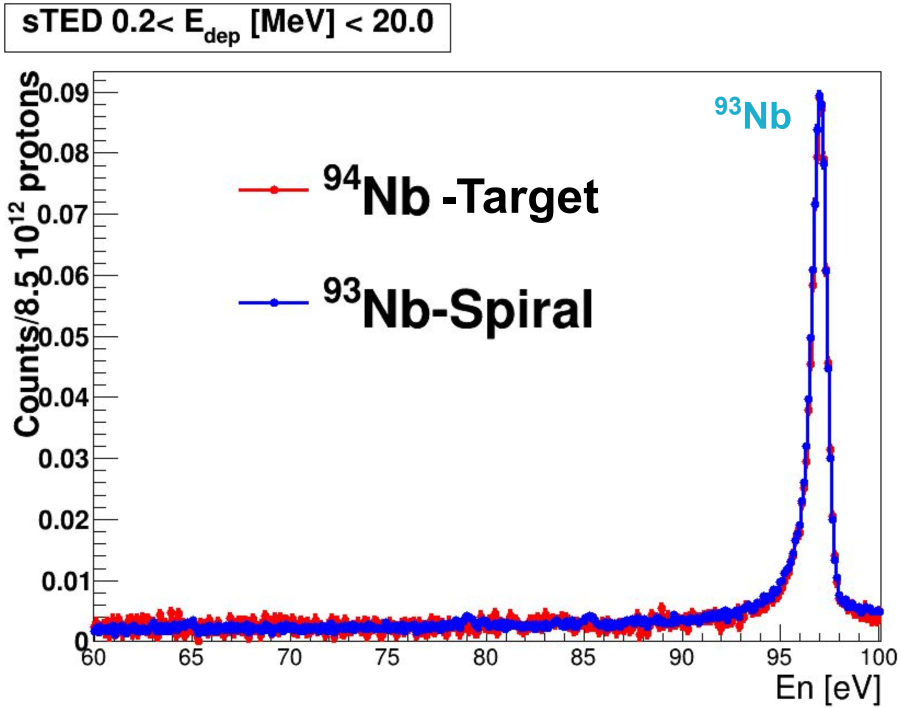


Contaminant resonances in ^{93}Nb-Spiral

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



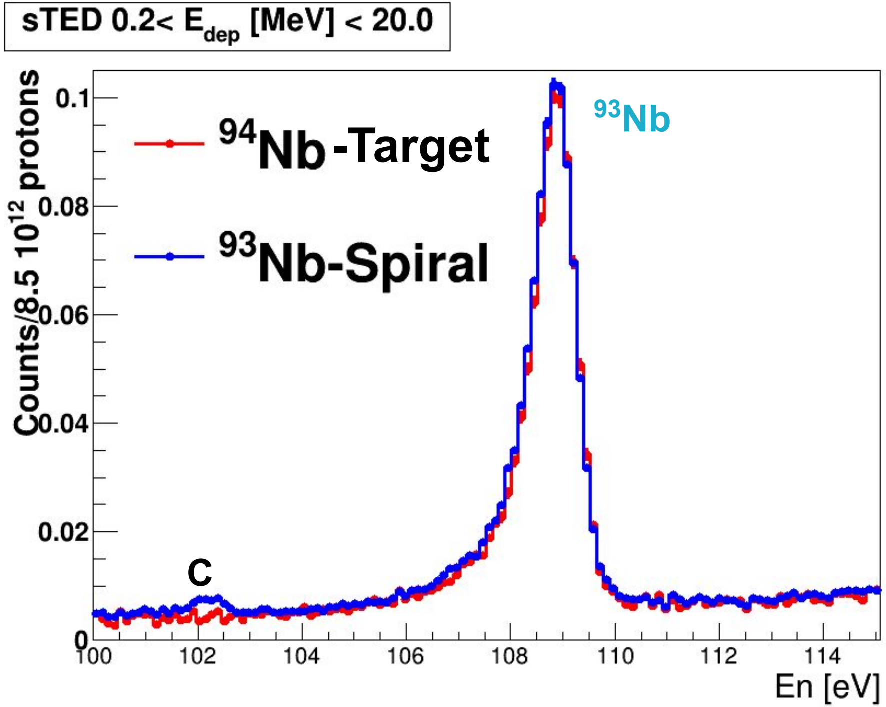


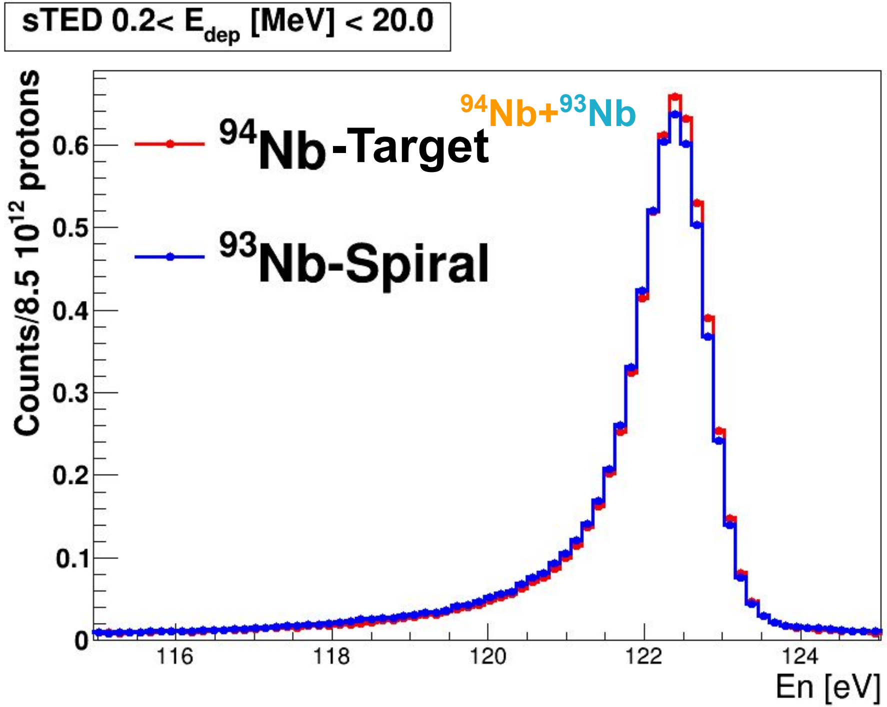
Cumulative number of ^{93}Nb resonances detected:4
Cumulative number of ^{94}Nb resonances detected:3
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: **0**

E_n<100 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



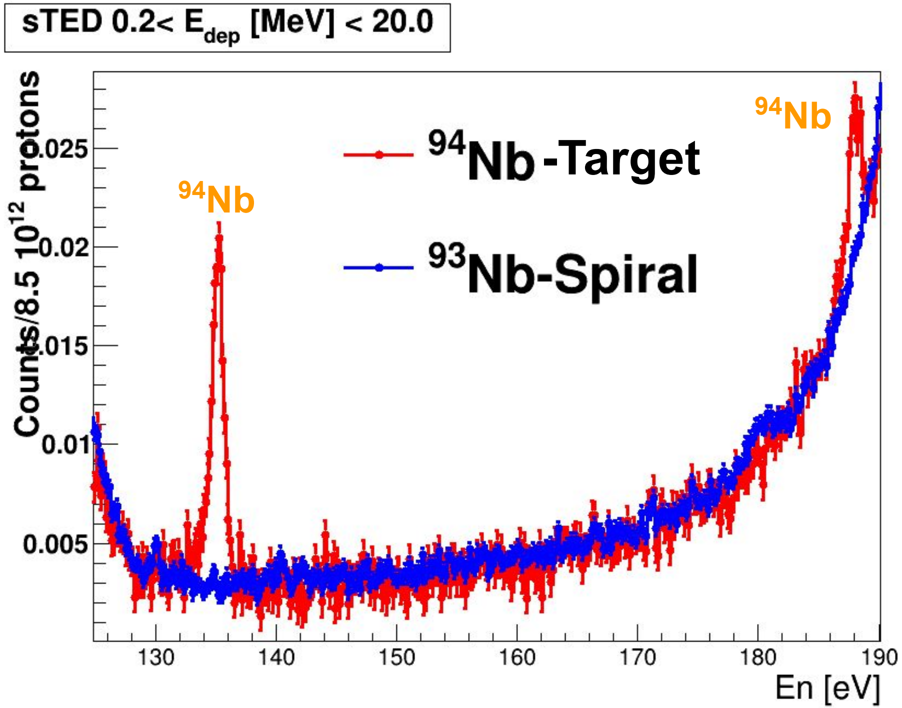


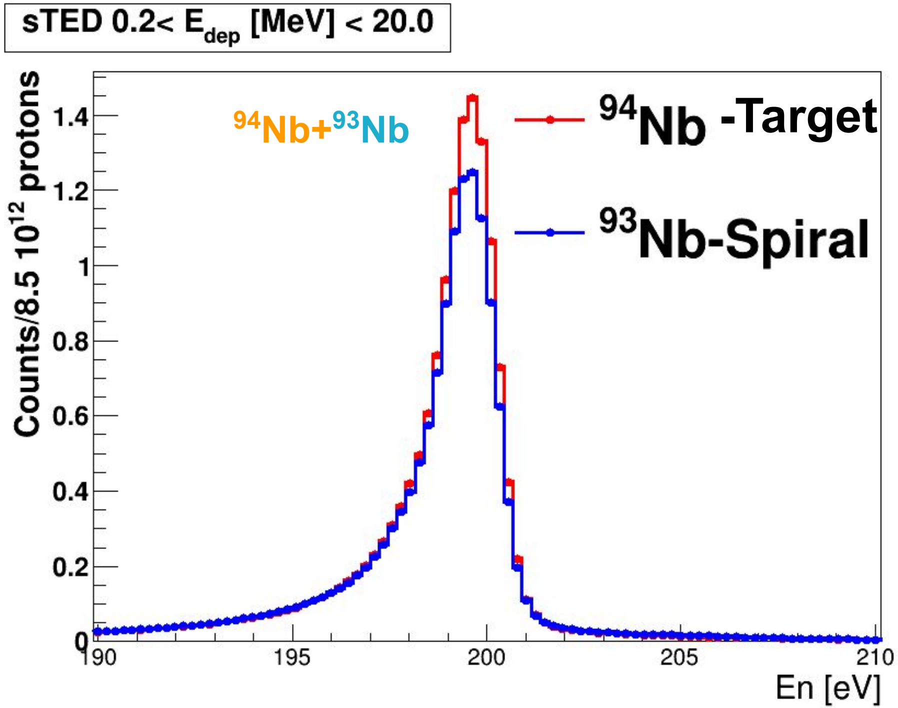
Cumulative number of ^{93}Nb resonances detected:5
Cumulative number of ^{94}Nb resonances detected:3
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 1

E_n<125 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



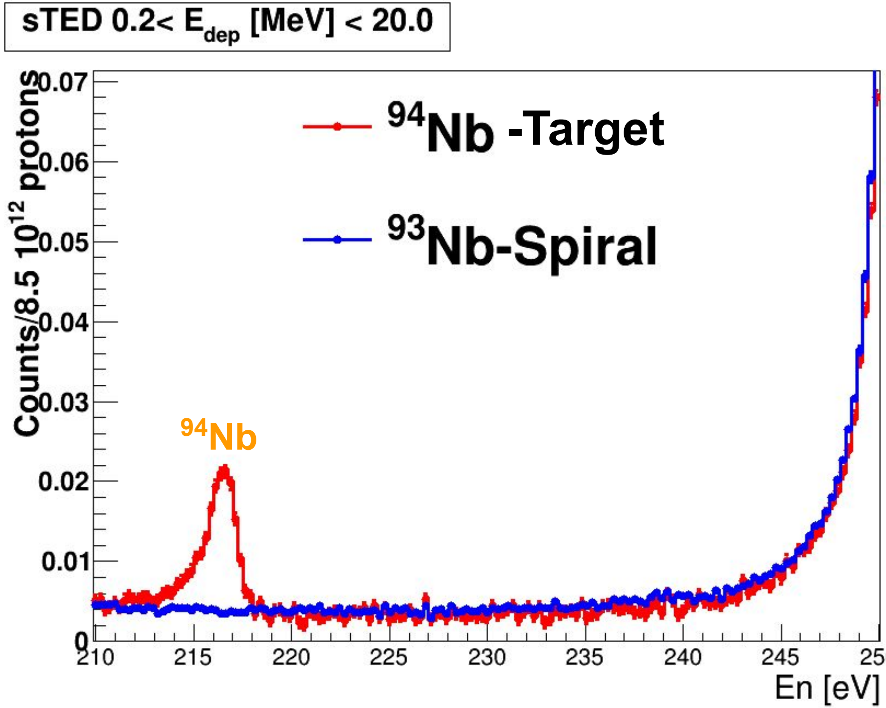


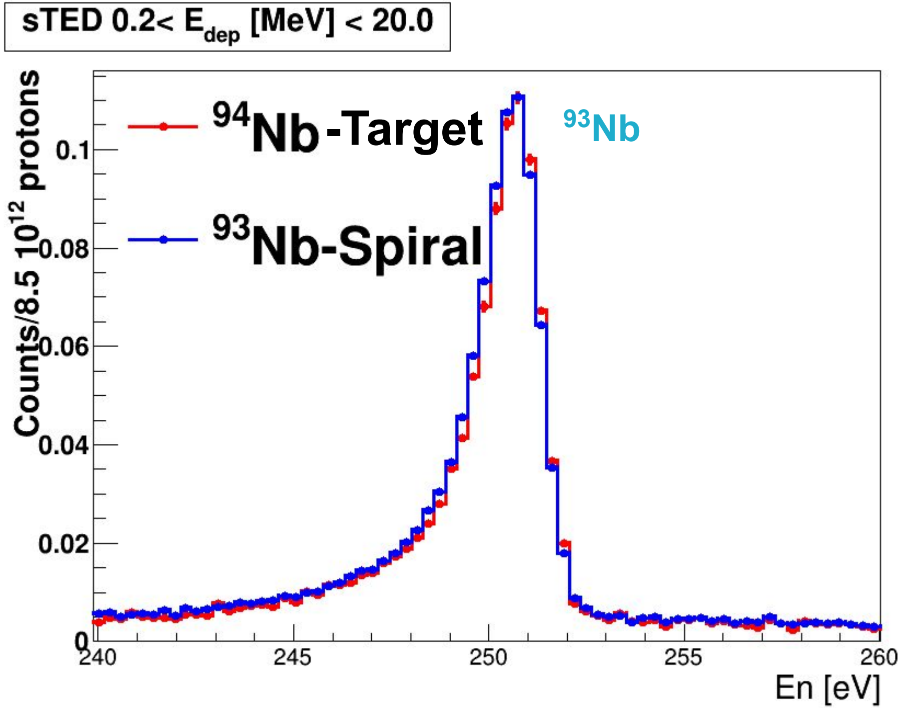
Cumulative number of ^{93}Nb resonances detected:5
Cumulative number of ^{94}Nb resonances detected:5
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 2

E_n<210 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



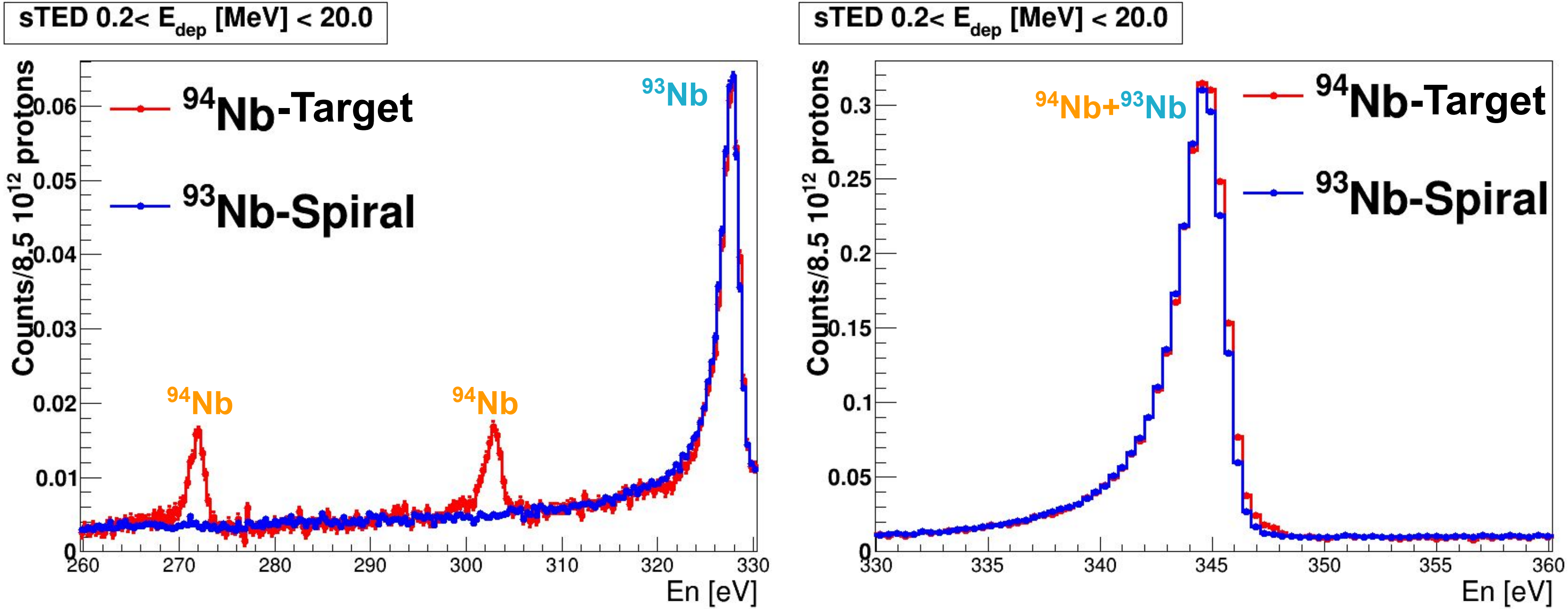


Cumulative number of ^{93}Nb resonances detected:6
Cumulative number of ^{94}Nb resonances detected:6
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 2

E_n<260 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction

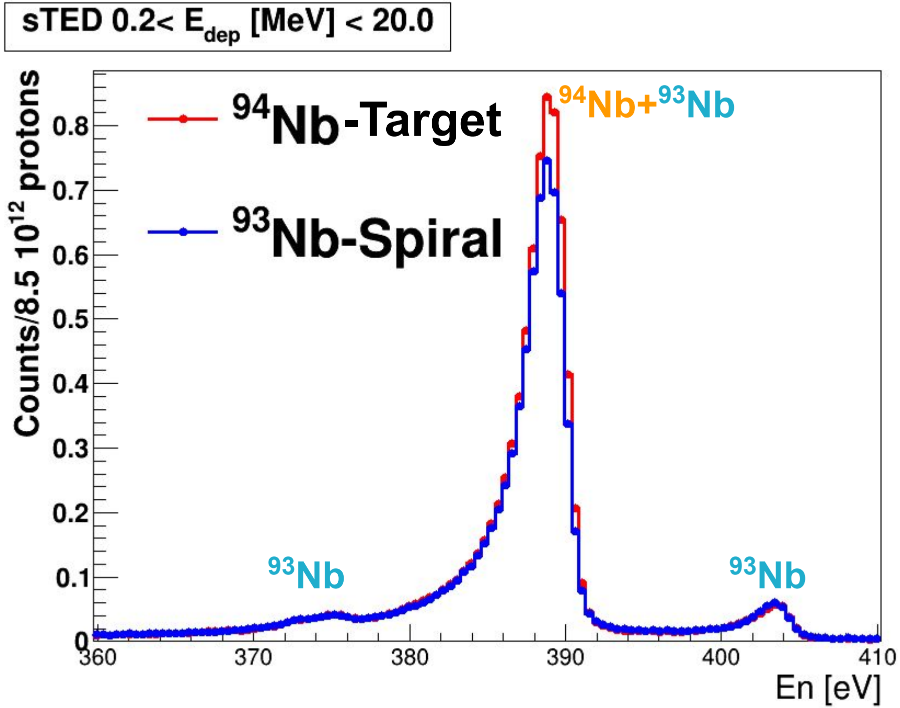


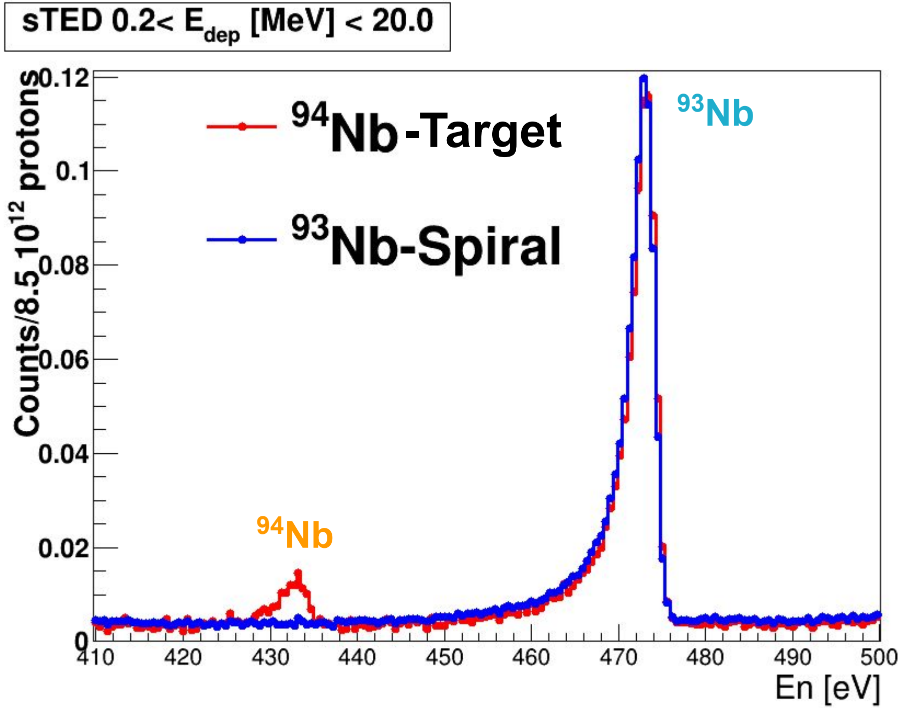
Cumulative number of ^{93}Nb resonances detected:7
Cumulative number of ^{94}Nb resonances detected:8
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 3

E_n<360 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction





Cumulative number of ^{93}Nb resonances detected:11

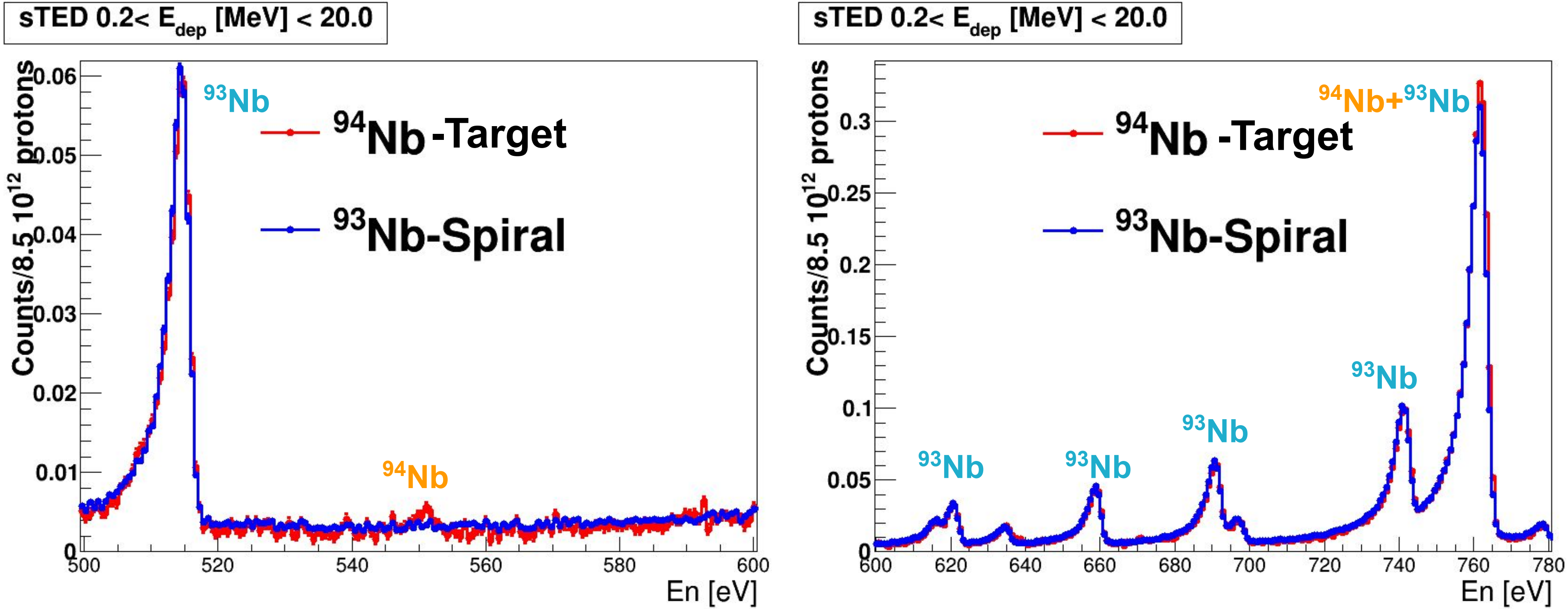
Cumulative number of ^{94}Nb resonances detected:9

Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 4

E_n<500 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction

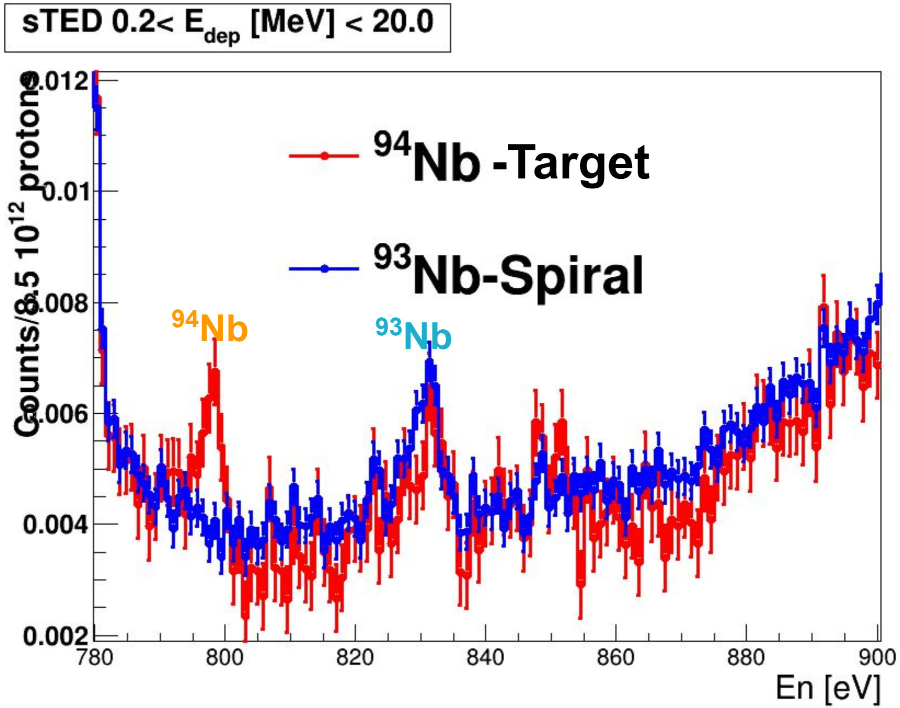


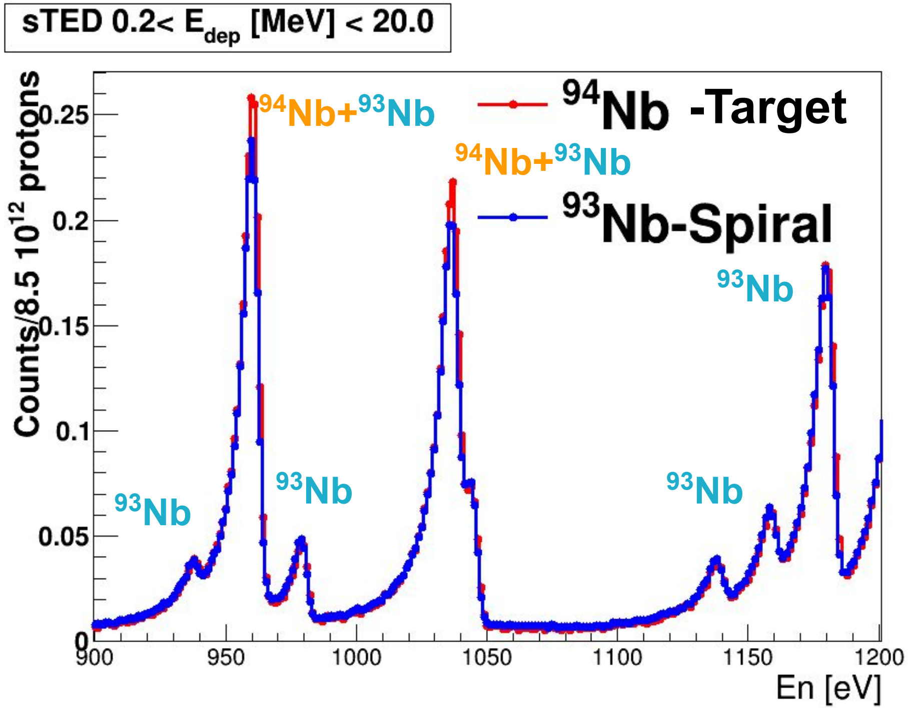
Cumulative number of ^{93}Nb resonances detected:20
Cumulative number of ^{94}Nb resonances detected:10
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 5

E_n<780 eV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction





Cumulative number of ^{93}Nb resonances detected:27

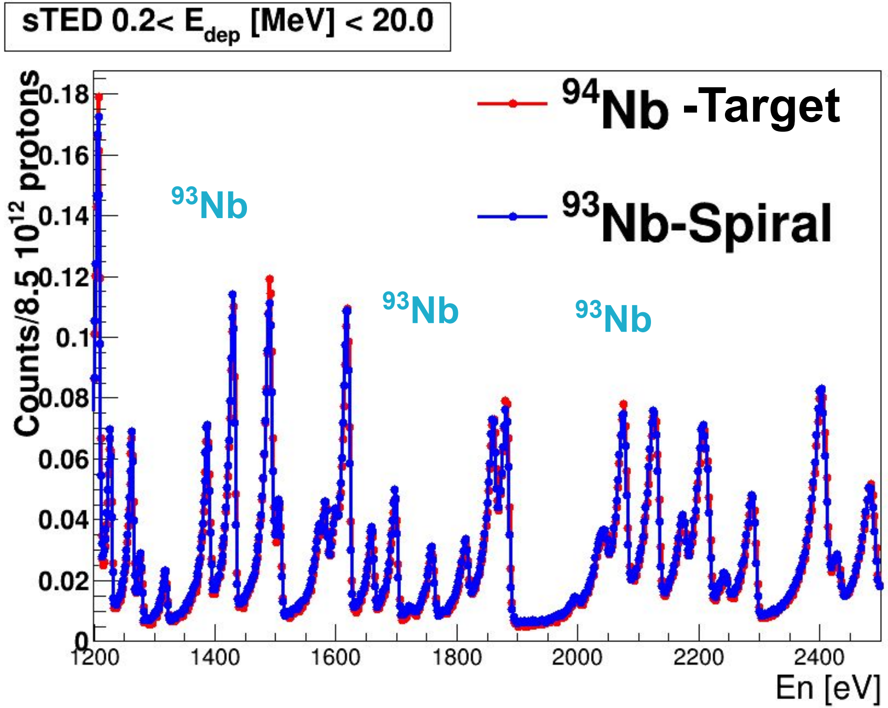
Cumulative number of ^{94}Nb resonances detected:11

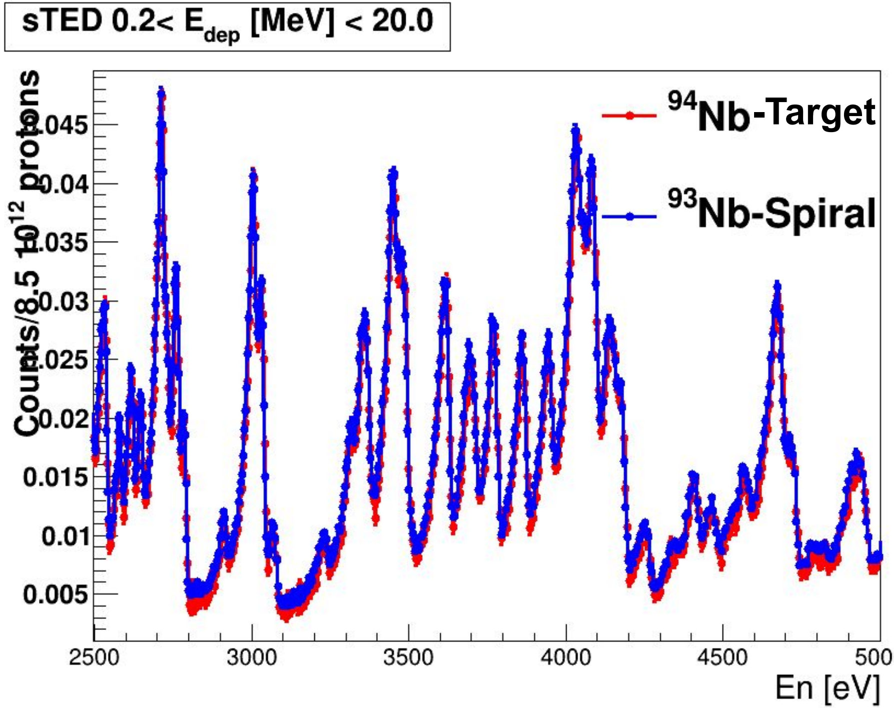
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 7

E_n<1.2 keV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



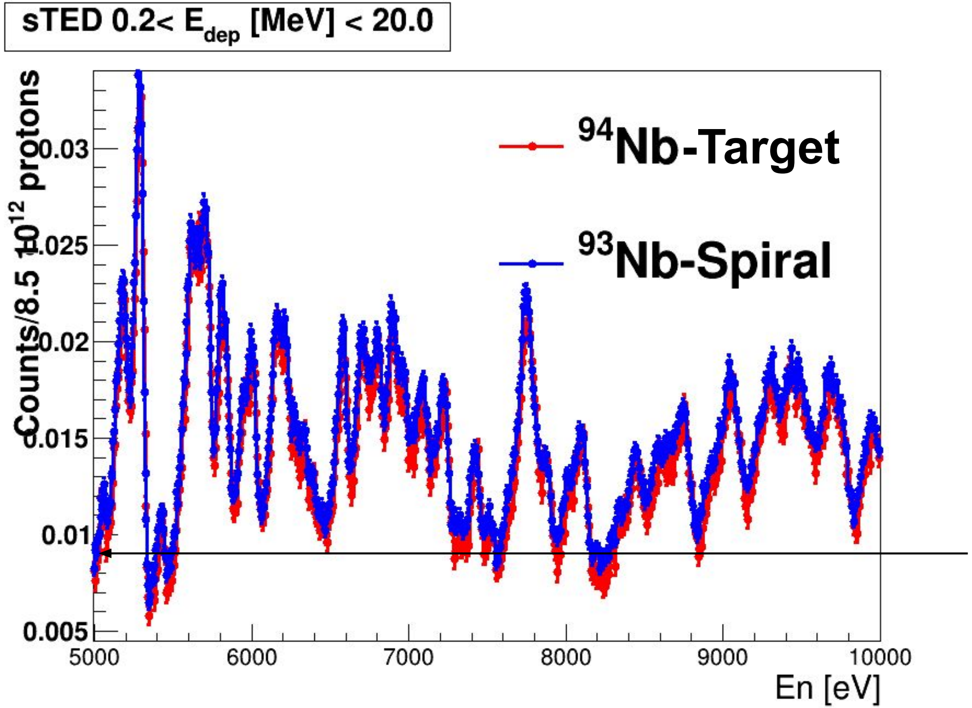


Cumulative number of ^{93}Nb resonances detected:>50
Cumulative number of ^{94}Nb resonances detected:11
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 7

E_n<5 keV

Preliminary yield background subtracted

Experimental ^{94}Nb-target (^{94}Nb/^{93}Nb~1%) and ^{93}Nb-Spiral (^{93}Nb) after background subtraction



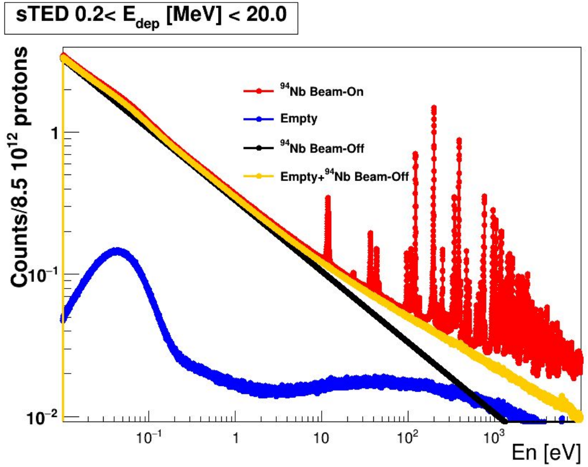
Non-Resolved Resonance Region

Background level needs to be studied

Cumulative number of ^{93}Nb resonances detected:>70
Cumulative number of ^{94}Nb resonances detected:11
Cumulative number of ^{93}Nb+^{94}Nb overlaping resonances detected: 7

E_n<10 keV

^{94}Nb(n,ɣ) capture yield (overview)



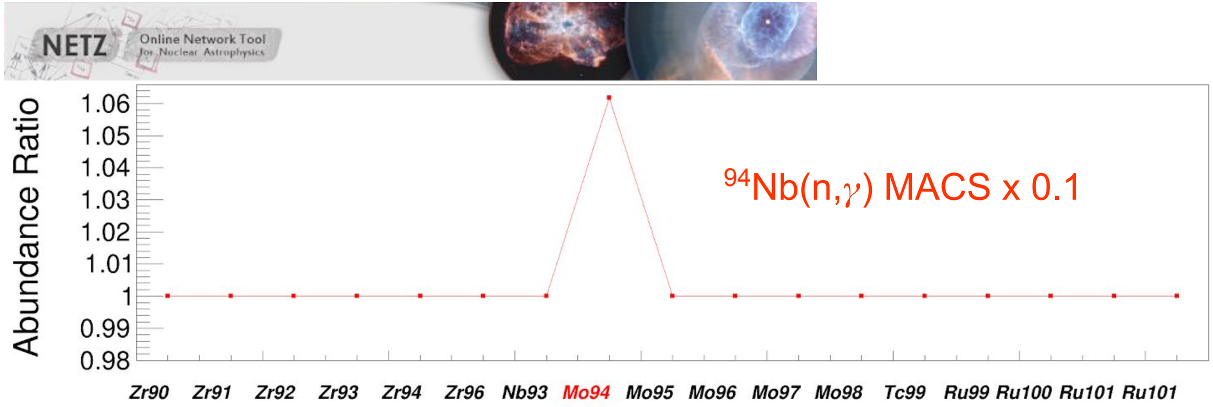
In summary:

→ About 18 capture resonances (first ever!) in the energy range between 1eV and 10 keV

→ Systematic effects under control: PHWT, angular distribution effects, neutron sensitivity, aiming at 2-3% systematic error bar

→Fast analysis on the scope: Expect final results within less than one year

→ Next steps: astrophysical interpretation



^{94}Nb(n,γ) MACS x 0.1

Summary & conclusions

Summary:

- **s-process** is **responsible** about ½ of **abundances** above **A>56**
- Understand **Mo anomalies** in **SiC presolar** grains **requires new** accurate **(n,γ) cross-section** data
  - **No ^{94}Nb(n,γ)** cross-section data in **RRR & NRR up to now**!
- **High challenging** cross-section **measurement**:
  - **Target production→Hyper-purity** required, **Irradiation**, **Radiation** hardness
  - **Challenging experiment→Highly radioactive** sample,**Low ^{94}Nb/^{93}Nb atoms** in target!
- A **successful ^{94}Nb(n,γ)** cross-section **experiment** has been carried **@ n_TOF EAR2 this year**:
  - **High neutron flux**+Good neutron energy resolution after n_TOF target upgrading.
  - **Development** of optimized **experimental setup @ EAR2.**
- **Very preliminary ^{94}Nb(n,γ) yield** in the RRR for the first time:
  - **18 isolated or overlapping** ^{94}Nb detected **resonances** up to **1 keV**.
  - The measurement will analyzed up to ~100 keV in the non-resolved resonance region.

Very preliminary conclusion:

- The requirement of **10 times smaller ^{94}Nb(n,γ) MACS** to produce **5-6% higher ^{94}Mo** seems **not the case**, due to the **large number of levels observed** in accordance with predictions, **of course to be confirmed** after the **detailed analysis** of the Cross section and astrophysical calculations.

Outlook:

- We are **pushing hard** to “start finishing” the analysis by the **^{94}Nb(n,γ) cross-section** measurement.
- **^{94}Nb(n,γ) &^{93}Nb(n,γ) cross-section** will be distributed to **EXFOR & astrophysical community**

Thank you very much for your attention!

We acknowledge funding from ERC-CoG HYMNS Grant Agreement Nr. 681740
https://hymnserc.ific.uv.es

Backup

EAR2 & ToF technique

The experiment was carried out at the EAR2:

Advantages:

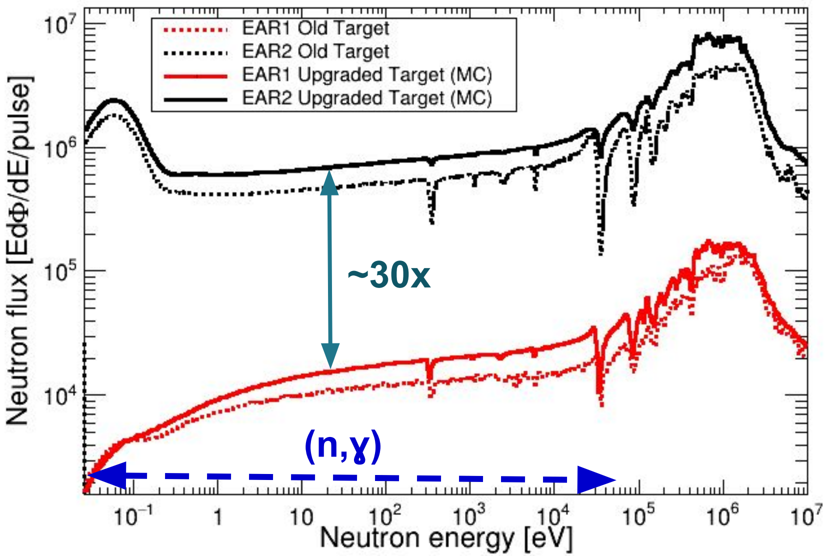
- **High Luminosity**
- **Short ToF window**

Maximize s/bkg for low mass & radioactive samples

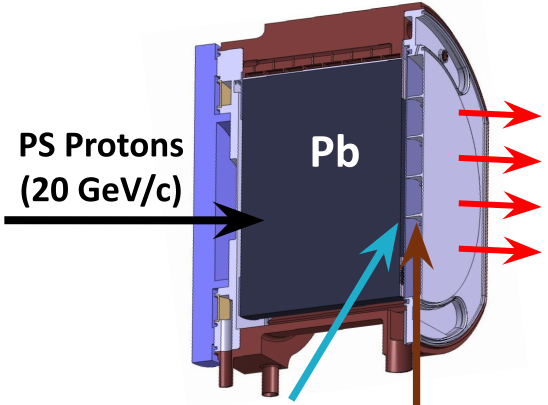
Drawbacks:

- **Strong G-Flash**
- **High counting rates**

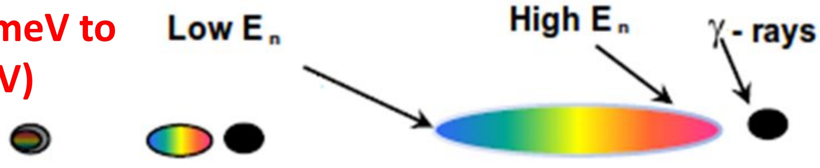
Require dev. of (n,γ) detectors' generation



SPALLATION TARGET



Pulsed n beam (meV to GeV)



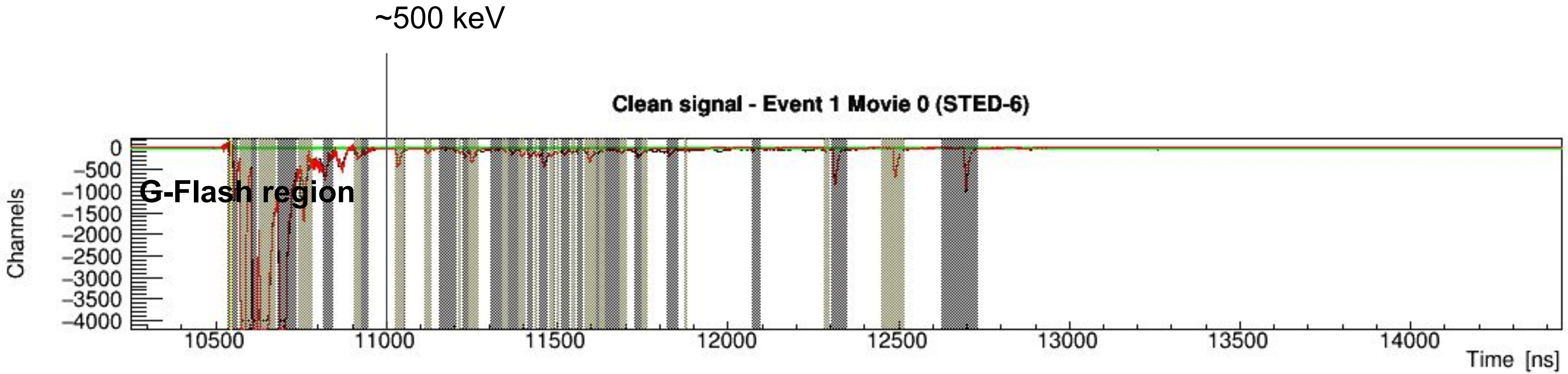
EAR2

Time-of-flight technique

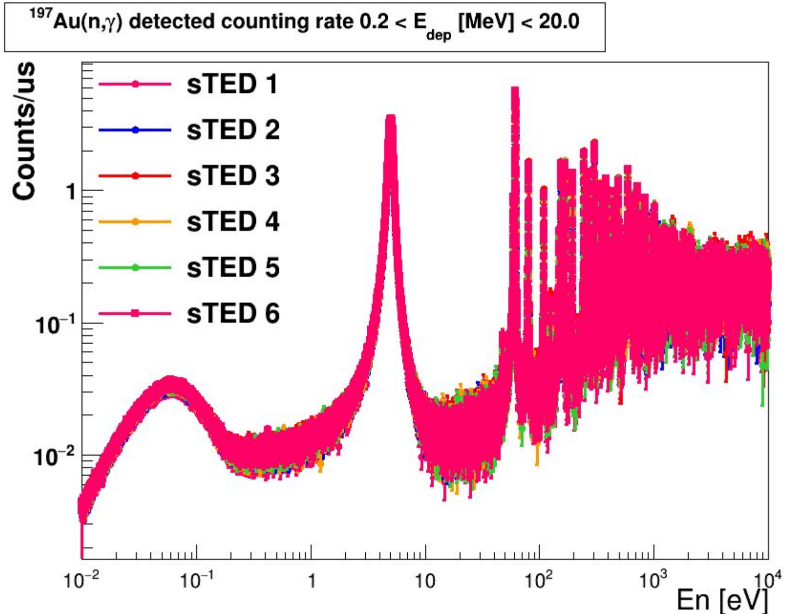
Flightpath **L**

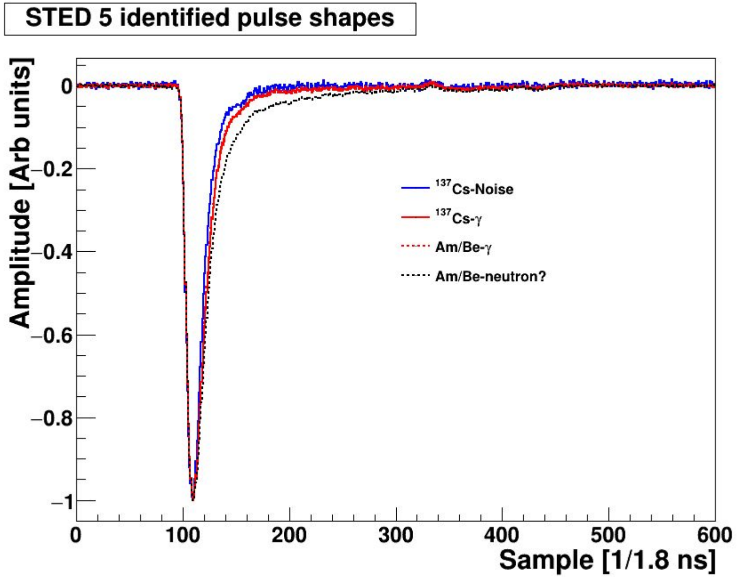
$$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$$

Measure arrival time **t**


~500 keV

Clean signal - Event 1 Movie 0 (STED-6)


^{197}Au(n,γ) detected counting rate 0.2 < E_{dep} [MeV] < 20.0


STED 5 identified pulse shapes