Recent highlights and prospects on (n,γ) measurements at the CERN n_TOF facility

J. Lerendegui-Marco
on behalf of the n_TOF Collaboration

Outline

- **Motivation**
  - Relevance of neutron capture cross sections
  - Neutron capture measurements
- **Neutron measurements at CERN n_TOF**
  - Experimental areas & key features
  - Highlight measurements and limitations
- **Recent upgrades in the facility and detection systems**
- **Existing limitations and future perspectives**
  - TOF measurements on more unstable isotopes
  - NEAR: the new high flux activation station
- **Summary**

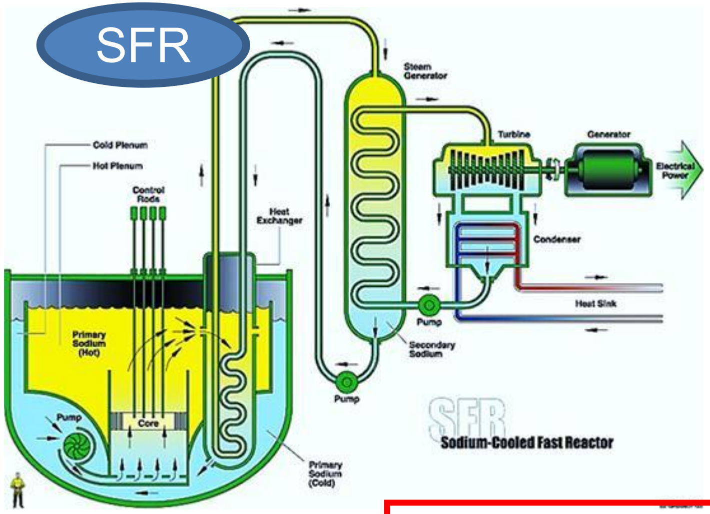
Motivation

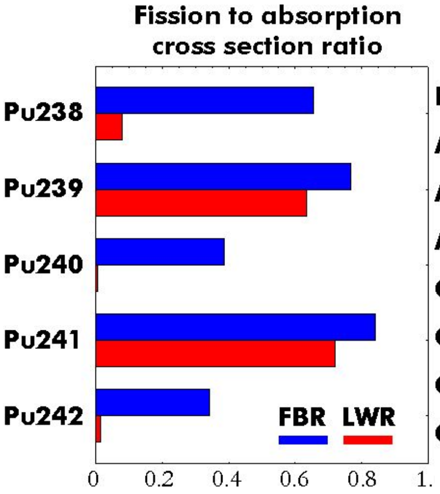
Nuclear technologies & (n,γ) cross sections

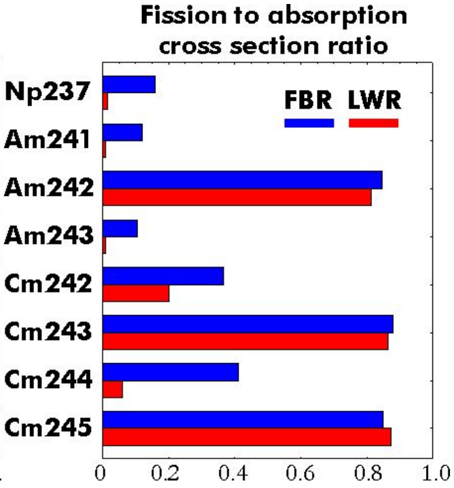
Innovative nuclear technologies

Accelerator-**D**riven **S**ystems

- Nuclear waste burners
- Sub-critical systems + neutron source
- Demonstrator: MYRRHA







IV Generation Fast Reactors

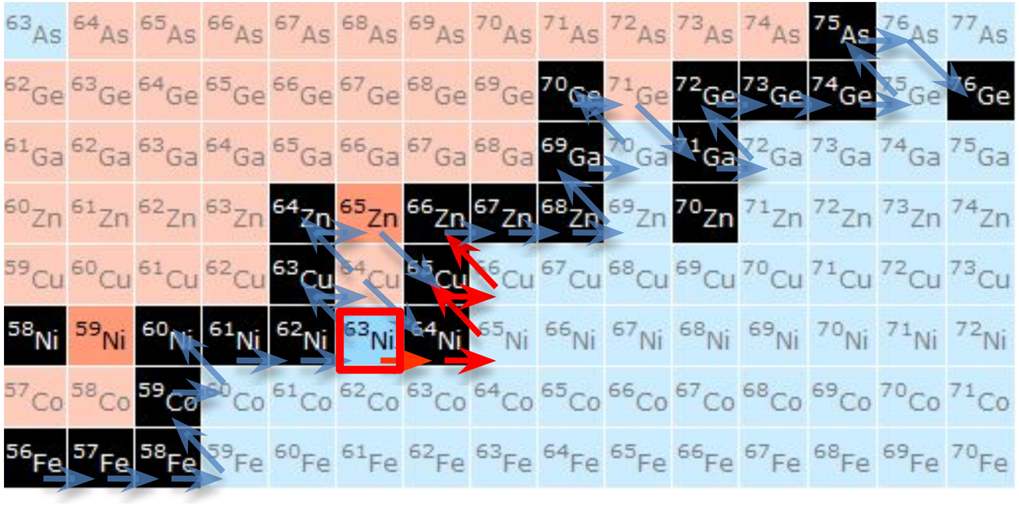
- Higher burn-up and reduced waste radio-toxicity in fast reactors (FBR) compared to thermal LWR
- Burns fuels composed by U, Pu, MA

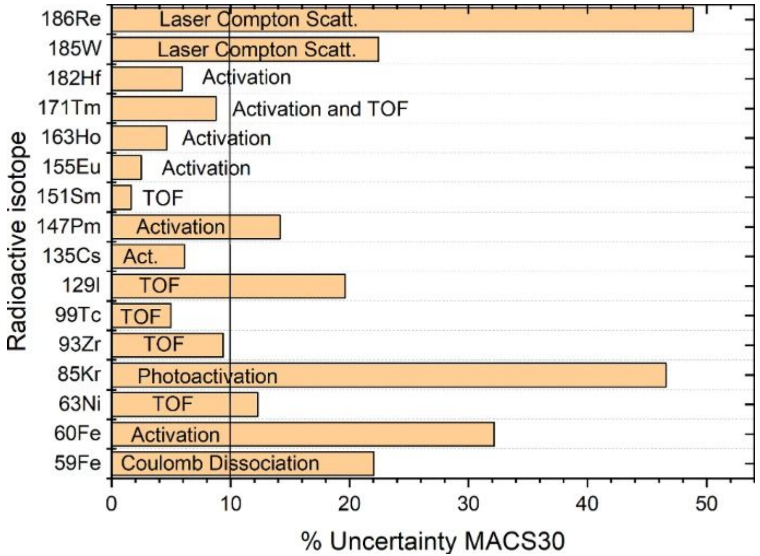
Fast reactors + new fuels : (n,γ) not known with the required accuracy

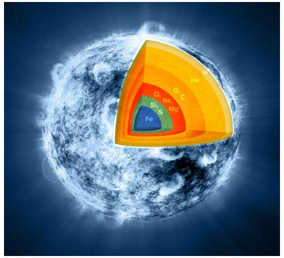
s-process of nucleosynthesis & (n,γ) cross sections

Astrophysics: s-process

I. Dillmann, *Eur. Phys. J. A* **59**, 105 (2023).







S-process:

- ~½ abundances A>56
- AGB & Massive stars

$T = 10^8 - 10^9$ K

$N_n = 10^6 - 10^{12}$ cm^{-3}

Key cases: branching points

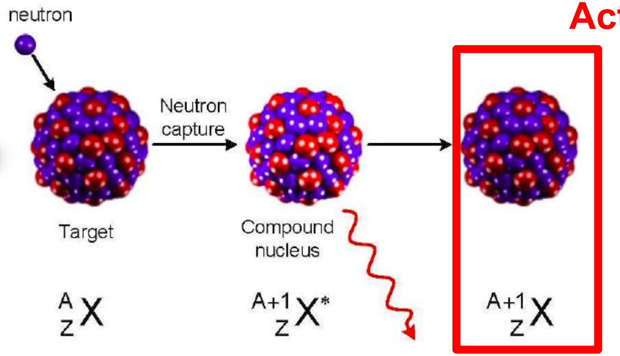
$^{A}Z(n,\gamma)$ competes with β decay

(n,γ) cross sections→ conditions stellar enviroment

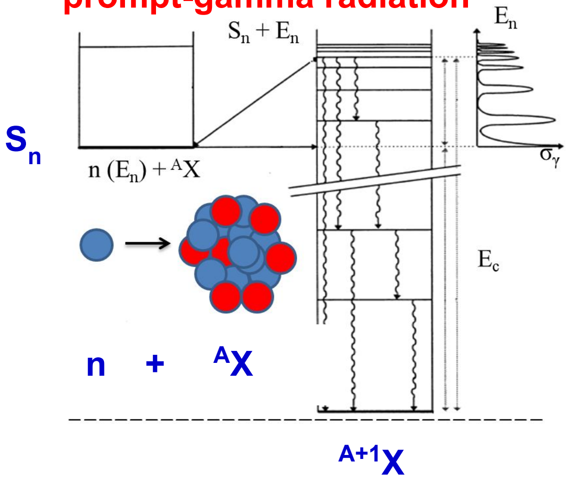
Challenging measurements: Radioactive isotopes, low masses

Neutron capture (n,γ) cross section measurements

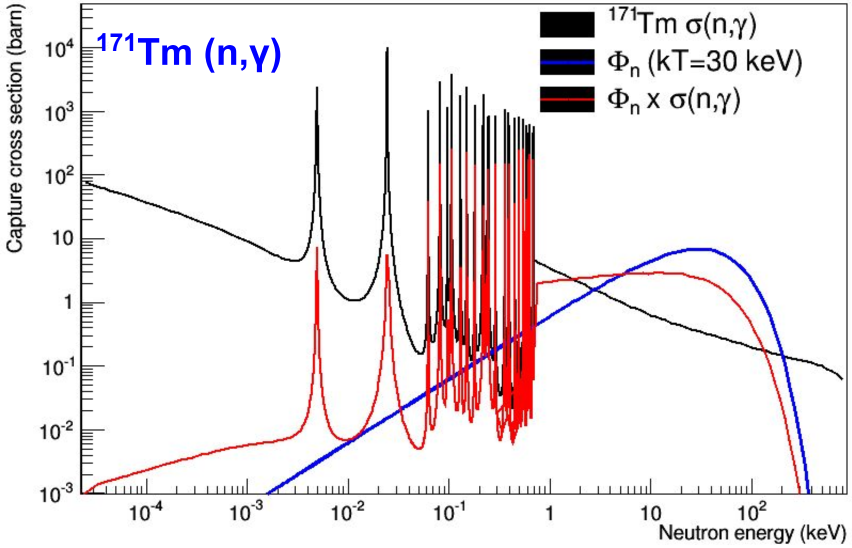
Activation



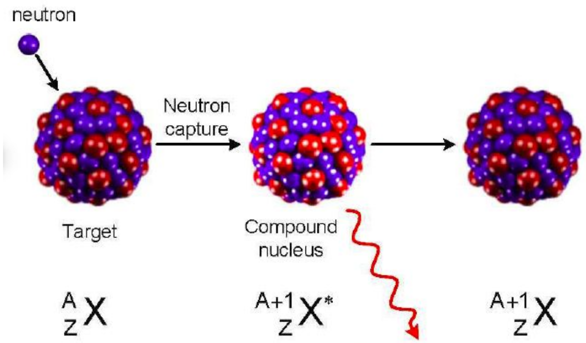
Neutron capture reaction:
Measured via **detection of the emitted prompt-gamma radiation**



Resonances



Neutron capture (n,ɣ) cross section measurements



Neutron capture reaction:
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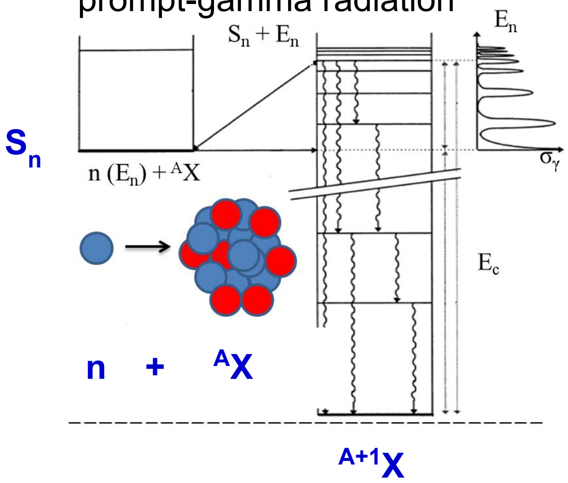
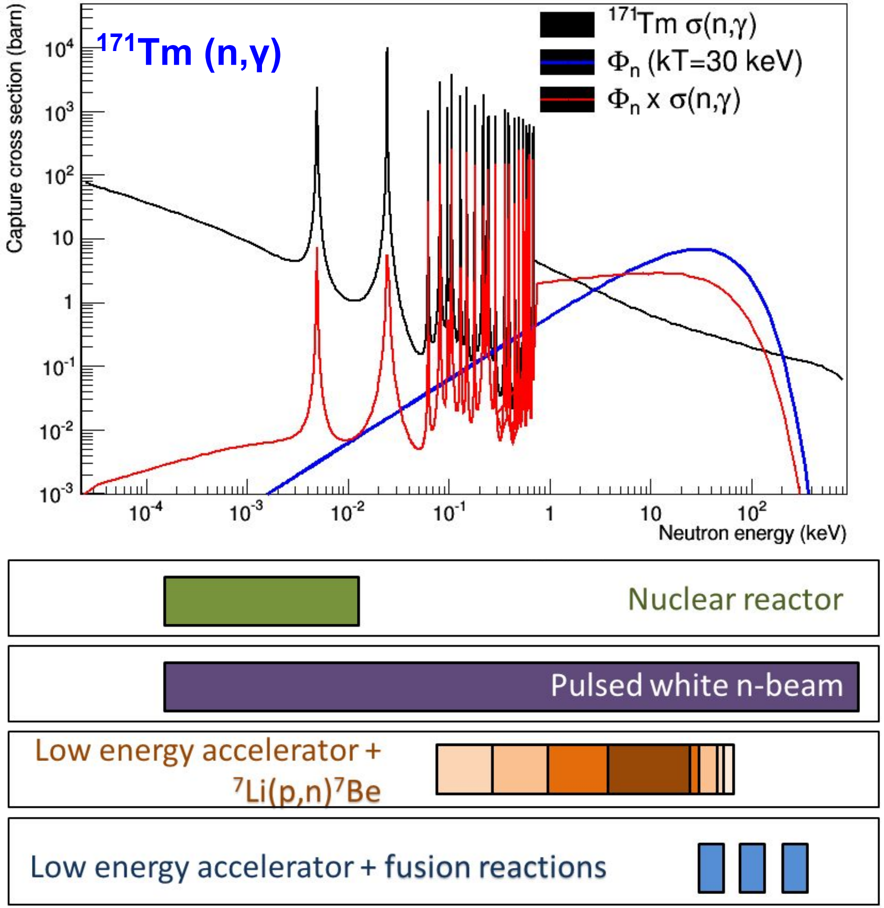


Resonances

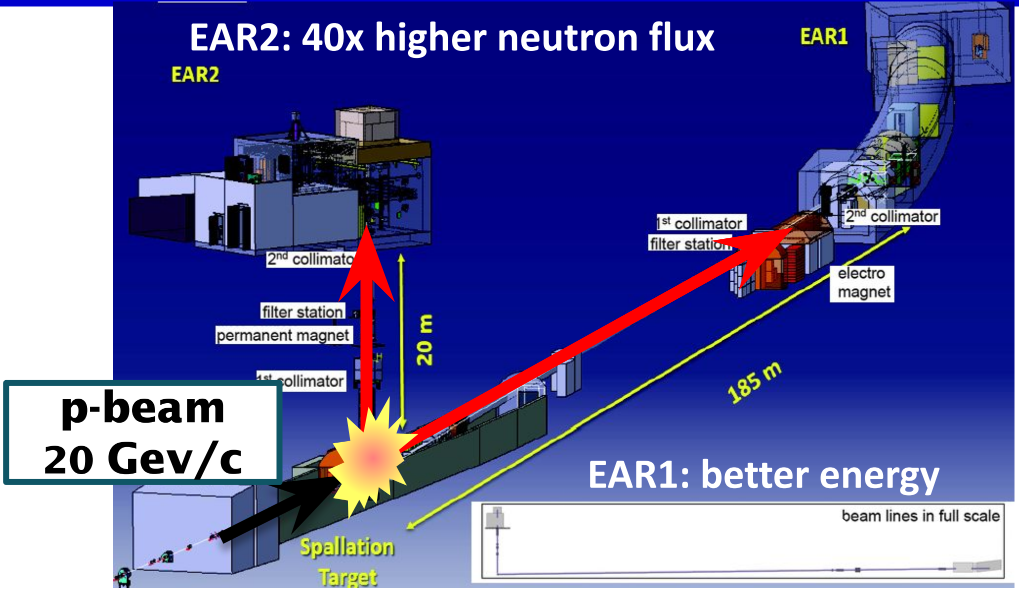
Time-of-flight Facility (e.g. CERN n_TOF)



Neutron capture measurements at n_TOF

The CERN n_TOF facility

Facility at CERN for high resolution neutron cross section measurements
C. Rubbia et al.
CERN/LHC/98-02(EET) 1998.



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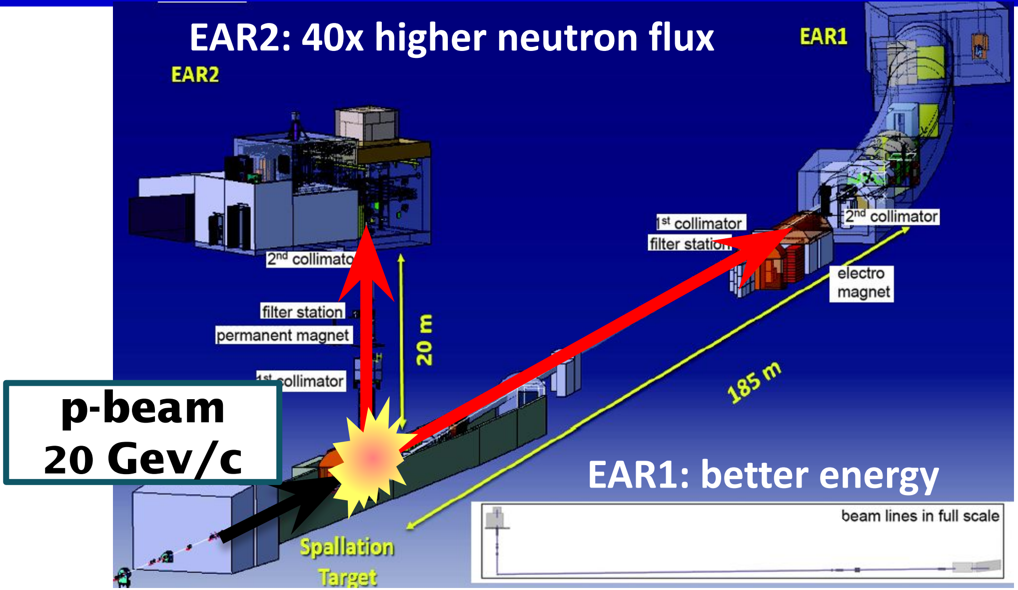
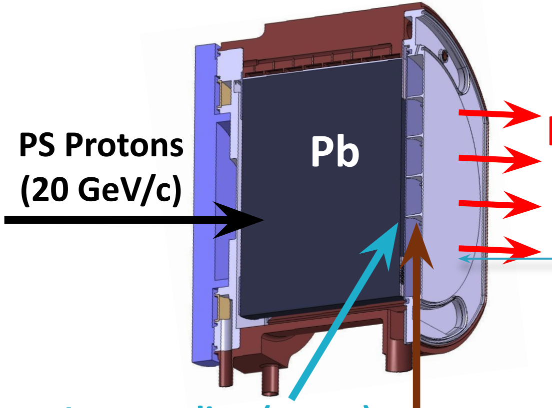
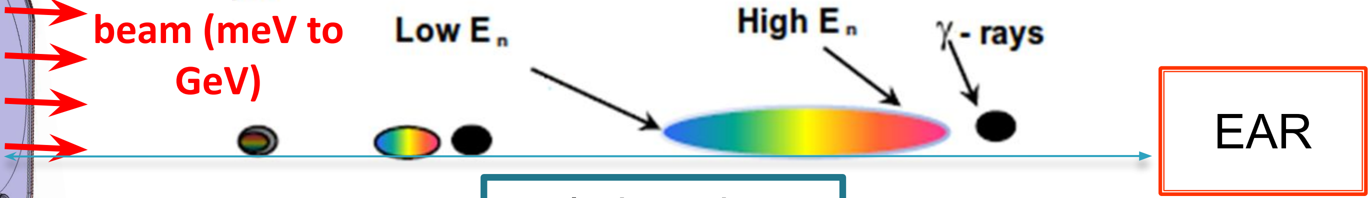


SPALLATION TARGET





Flightpath **L**

Time-of-flight technique

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

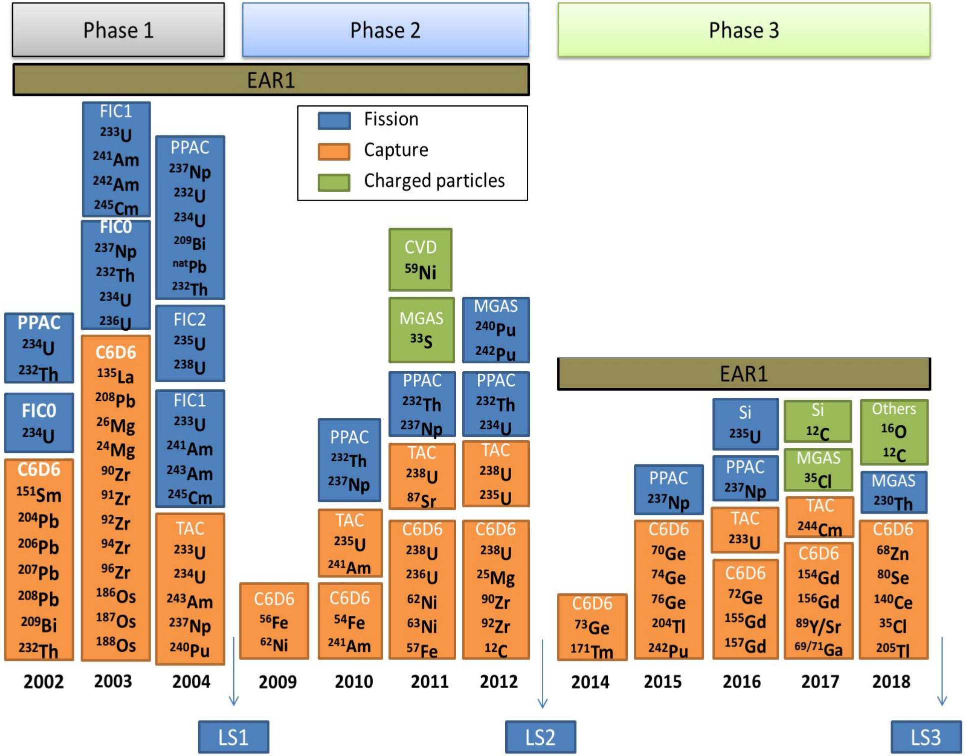
Measure arrival time **t**

n_TOF EAR1 (185 m, horizontal)

- Since 2001 → +50 (n,ɣ) measurements

Key features:

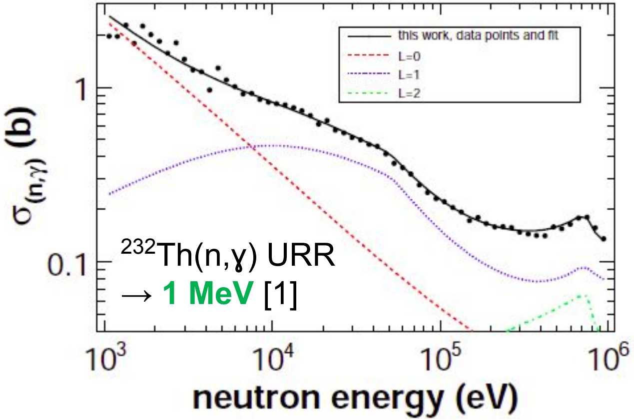
- Excellent energy resolution
- Energy range up to 1 MeV

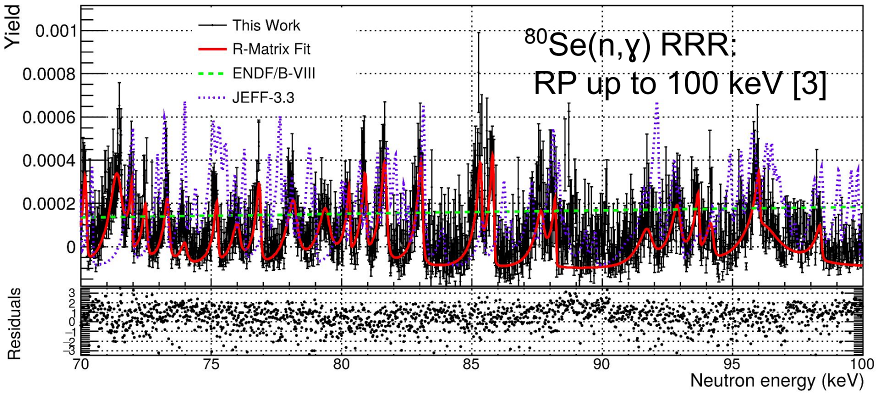


n_TOF-EAR1: key features for (n,g) & highlights

EAR1 (185m)

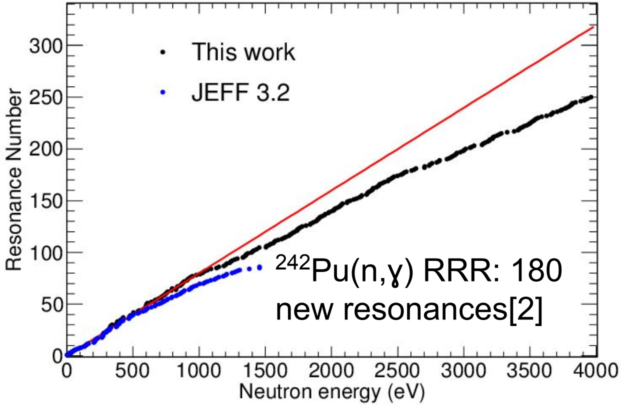
Key features: High neutron energy limit for (n,ɣ) + excellent energy resolution





E_n (eV)	$\Delta E_n/E_n$
1	3.2×10^{-4}
10	3.2×10^{-4}
10^2	4.3×10^{-4}
10^3	5.4×10^{-4}
10^4	1.1×10^{-3}
10^5	2.9×10^{-3}
10^6	5.3×10^{-3}

DeltaE / E= 10^{-4} - 10^{-3}



Common (n,g) measurements at n_TOF-EAR1:

- Stable nuclei (or very long $T_{1/2}$)
- Masses >=100 mg

[1] G. Aerts et al., Phys. Rev. C 73, 054610 (2006).
[2] J. Lerendegui-Marco et al., Phys. Rev. C 97, 024605 (2018)
[3] V. Babiano et al., EPJ Web of Conferences 284, 01001 (2023)

n_TOF-EAR1: key features for (n,g) & highlights

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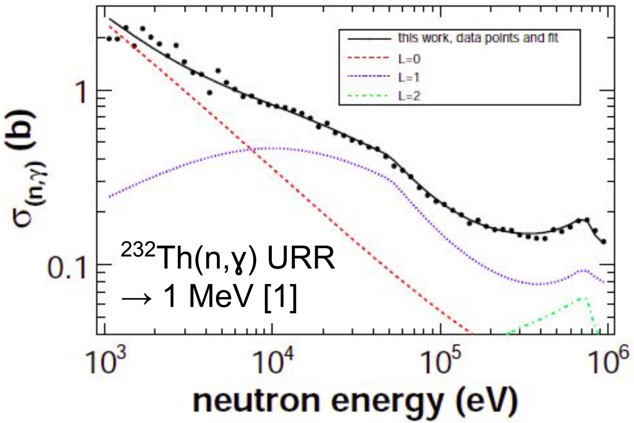

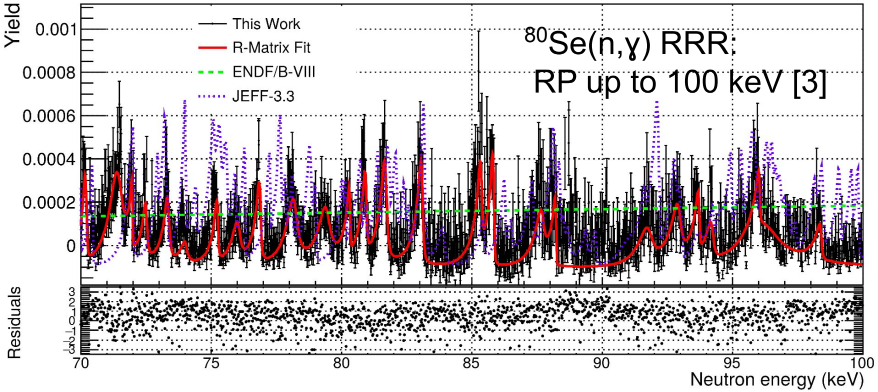

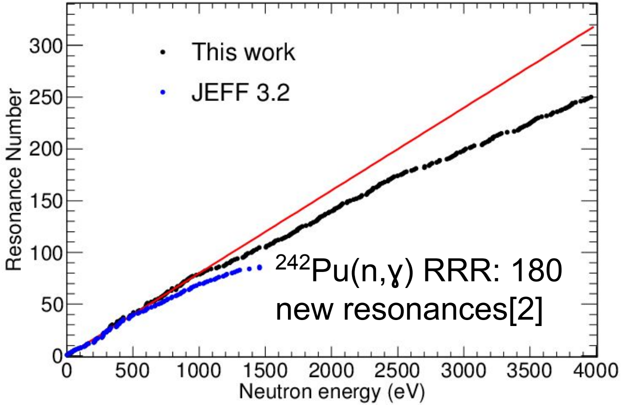

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Unstable isotopes?
(e.g. s-process branching points)

[1] G. Aerts et al., Phys. Rev. C 73, 054610 (2006).
[2] J. Lerendegui-Marco et al., Phys. Rev. C 97, 024605 (2018)
[3] V. Babiano et al., EPJ Web of Conferences 284, 01001 (2023)

(n,g) at EAR1: unstable s-process branchings

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

F. Kaeppeler et al.,
Rev. Mod. Phys 83, 157 (2011)

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	C. Lederer *et al.*, *Phys. Rev. Lett.* **110**, 022501 (2013)
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	U. Abbondanno *et al.*, *Phys. Rev. Lett.* **93**, 161103 (2004)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

Before 2015: only **2/21** of the key s-process isotopes measured by TOF
2015-2018: **New unstable isotopes** of astrophysical relevance
(**^{171}Tm & ^{204}Tl**) at **CERN n_TOF-EAR1**

n_TOF-EAR1: (n,g) on unstable isotopes

s-process branching points: radioactive isotopes

Tm-171(n,ɣ)
(PRL 2020)

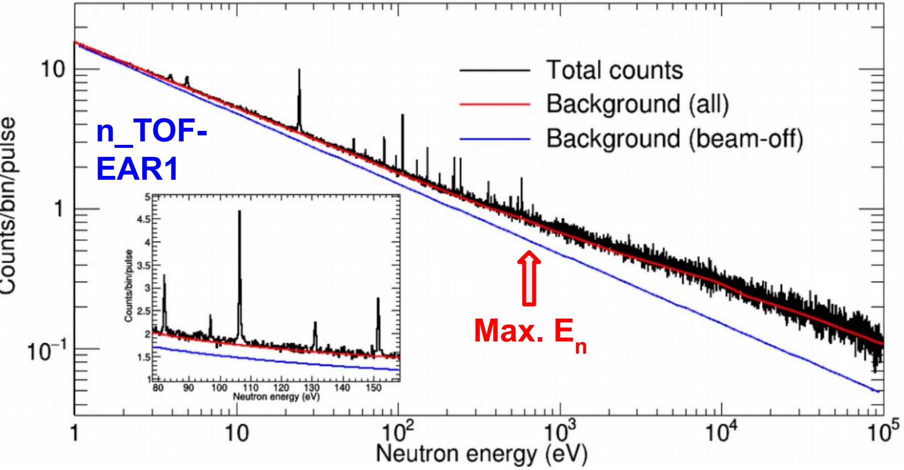
m = 3.1 mg
σ = 384(40) mb

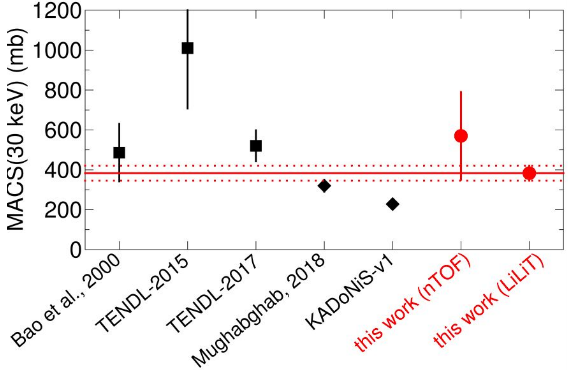
First measurement ever!
Combined TOF with activation @ LiLIT

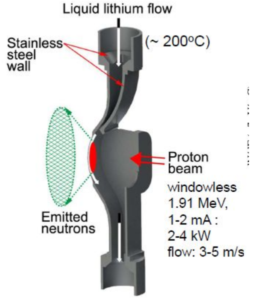
PHYSICAL REVIEW LETTERS

Neutron capture on the *s*-process branching point ^{171}Tm via time-of-flight and activation

C. Guerrero[1,2], J. Lerendegui-Marco[1], M. Paul[3], M. Tessler[4], S. Heinitz[5], C. Domingo-Pardo[6], S. Cristallo[7,8], R. Dressler[5], S. Halfon[4], N. Kivel[5], U. Köster[9], E. A. Maugeri[5], T. Palchan-Hazan[3], J. M. Quesada[1], D. Rochman[5], D. Schumann[5], L. Weissman[4], O. Aberle[10], S. Amaducci[26], J.







LiLIT

measurements are displayed in Fig. 2, with resonances showing up above the background up to 700 eV. It is remarkable that even though n_TOF is one of the facilities with the highest instantaneous neutron beam intensity worldwide, the dominant background in this region is still due to the activity of the sample.

Count rate dominated by activity of the sample!

Main limitation: Limited energy range due to due to the sample activity background →
higher flux facilities required

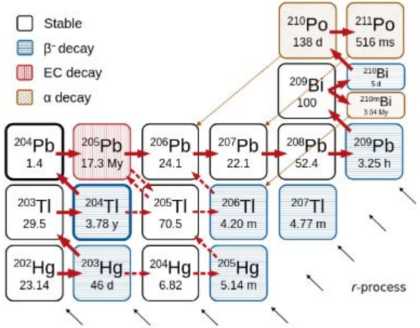
n_TOF-EAR1: (n,g) on unstable isotopes

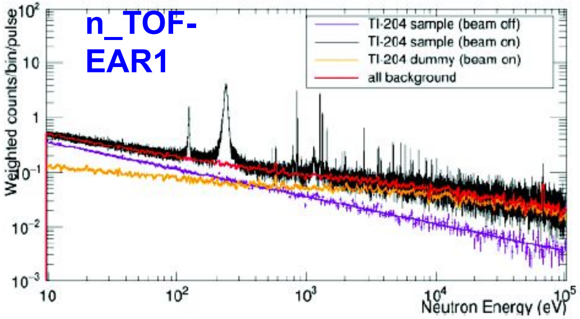
s-process branching points: radioactive isotopes

[1] A. Casanovas et al., Phys. Rev. Letters (2023, submitted)

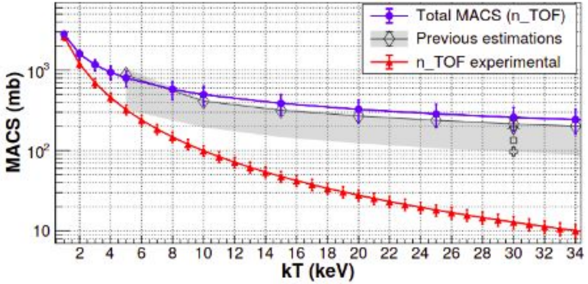
Tl-204(n,ɣ)

m = 9 mg
(+200 mg ^{203}Tl)
σ = 260(90) mb





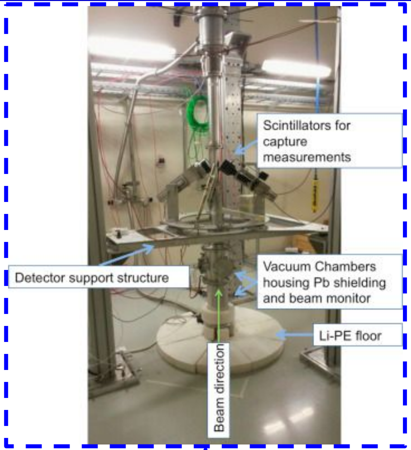
The neutron capture yield was measured by detecting the prompt de-excitation γ-rays emitted after each capture event, employing the standard setup at n_TOF of four C_6D_6 liquid scintillation detectors [42], which are optimized to minimize their neutron sensitivity [43]. Lead foils were placed on the detectors to reduce the impact of the γ-ray background arising from the ^{204}Tl decay. By

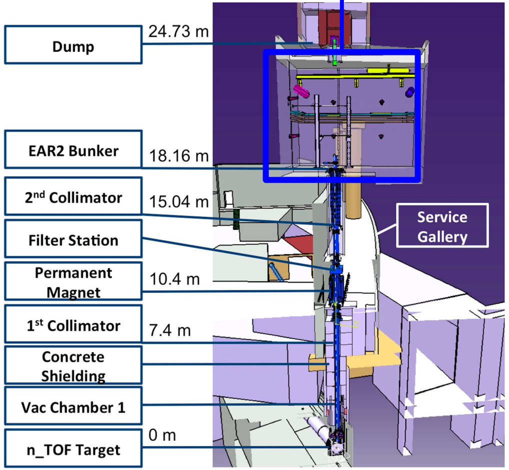


First measurement of this cross section!
n_TOF Only

Main limitations: Limited energy range due to mass, purity of the sample and background due to the sample activity →
Higher flux facilities and high purity samples are required

(n,g) @ the n_TOF facility: EAR2



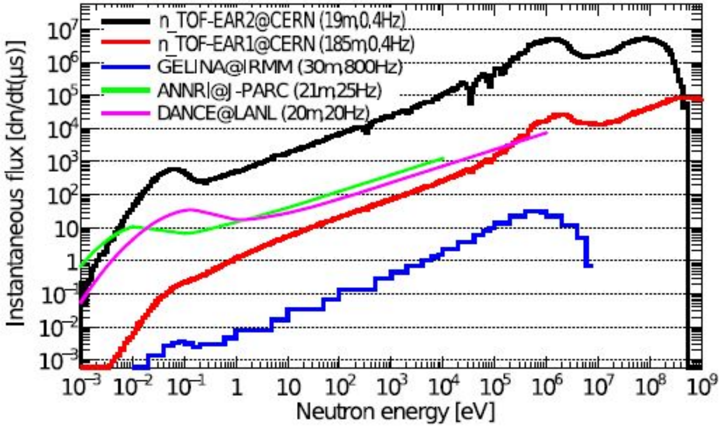


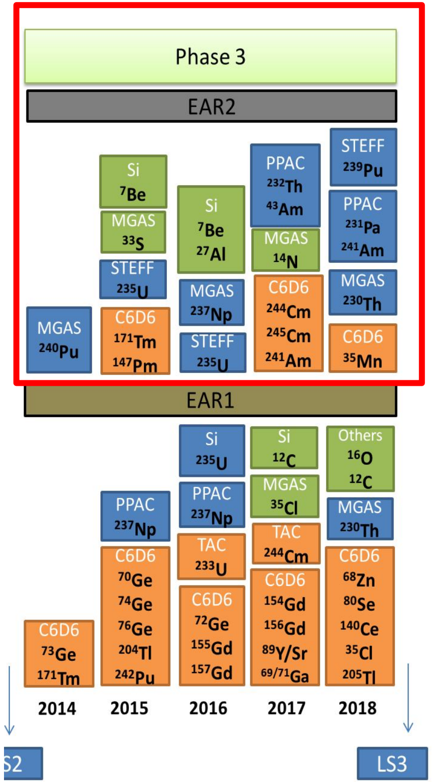
n_TOF EAR2 (20 m, vertical)

- 2014-2018 → 6 (n,γ) measurements

Key features:

- x300 higher instantaneous flux
- Low mass / radioactive samples





J. Lerendegui-Marco et al., Eur. Phys. J. A **52**, 100 (2016).

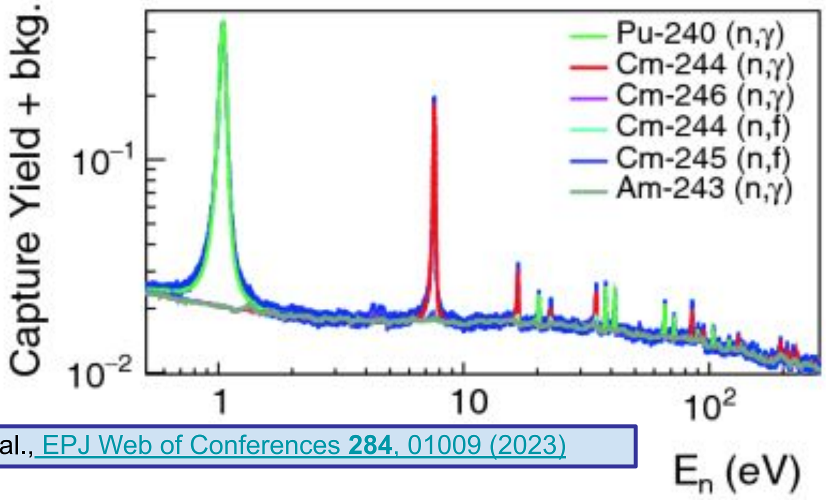
(n,g) highlights at n_TOF-EAR2

EAR2 (20 m)

Key features: Highest instantaneous flux → radioactive samples with lower masses

$^{244-246}$Cm(n,γ): **600 ug of CmO_2. (1.8 GBq)** [1]

Key feature: High n-flux/ activity ratio



[1] V. Alcayne et al., EPJ Web of Conferences **284**, 01009 (2023)

(n,g) highlights at n_TOF-EAR2

EAR2 (20 m)

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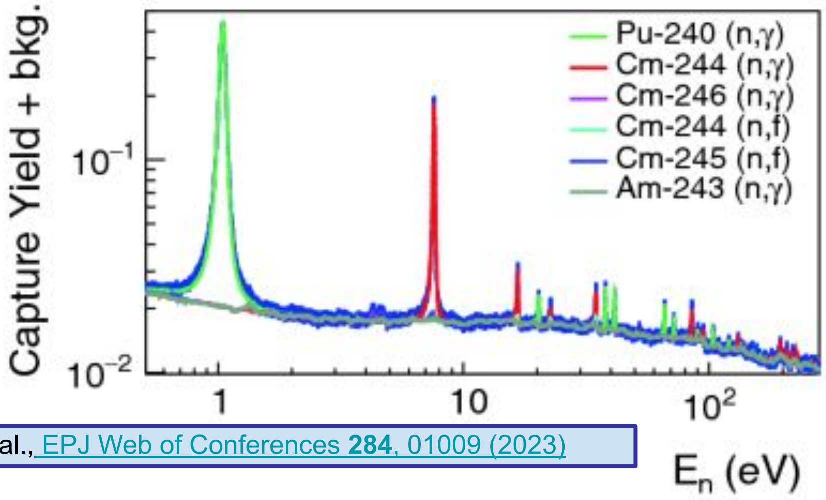
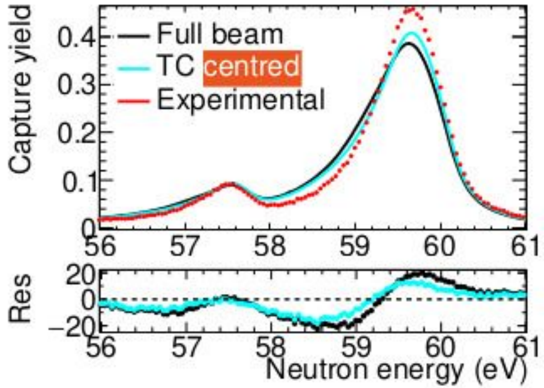


Key feature:
High n-flux/
activity ratio

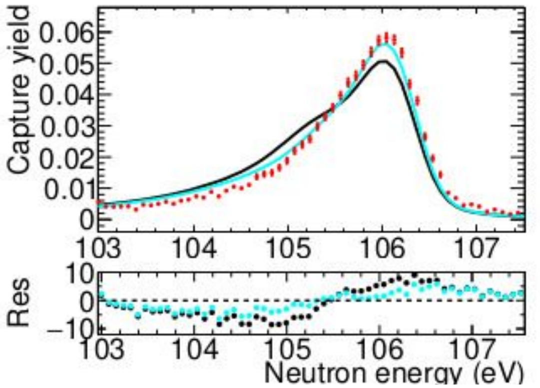
[1] V. Alcayne et al., EPJ Web of Conferences **284**, 01009 (2023)

Main limitations for (n,ɣ):

- Limited energy resolution
- Resolution vs En difficult to model with simulations
- Impact on RP accuracy



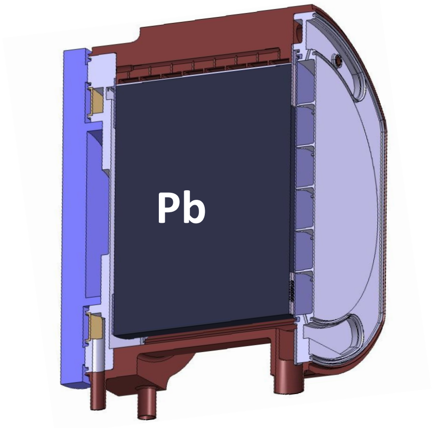
Au-197(n,g) @ 60 and 106 eV



Recent upgrades for (n,g) measurements

n_TOF target upgrade (2019-2021)

TARGET #2: Water cooled and water moderated lead block



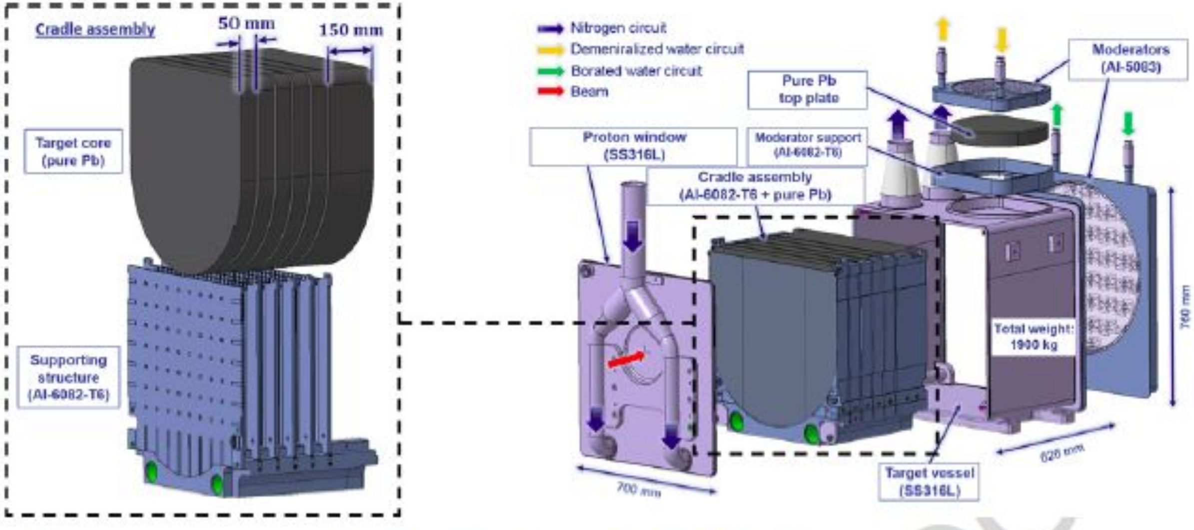
UPGRADED MECHANICAL PROPERTIES

- Avoid contamination
- Higher pulse intensity (+30%) and repetition rate

AIMED PHYSICS PERFORMANCE

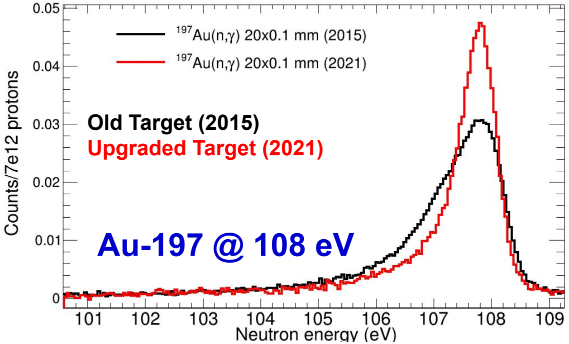
- EAR1: Still excellent resolution and similar/ higher flux
- EAR2: Improved RF + higher flux

TARGET #3: N-cooled and water moderated Pb target (cradle assembly)

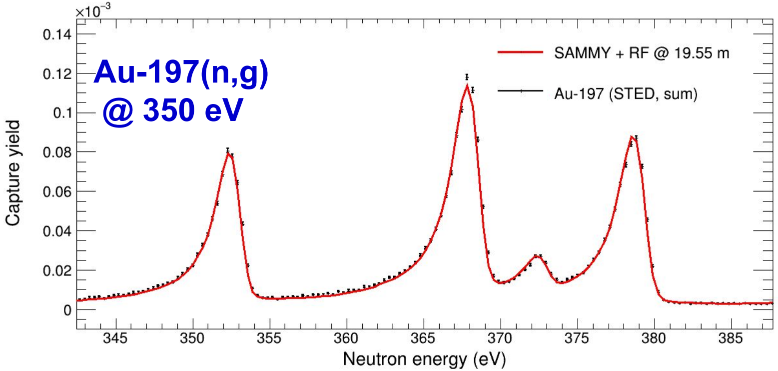


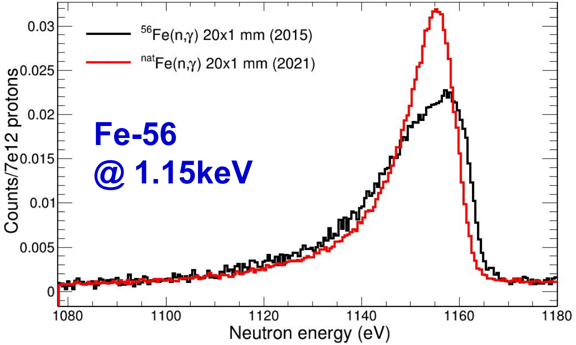
Target upgrade & (n,γ) measurements: E-resolution

Upgraded target→ n_TOF- EAR2:
Clear improvement of the energy resolution

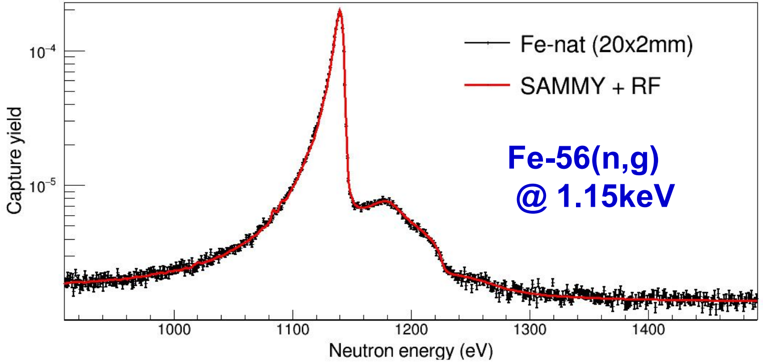


Improved E- resolution over the whole energy range





E-Resolution is **very well modelled with Simulations**



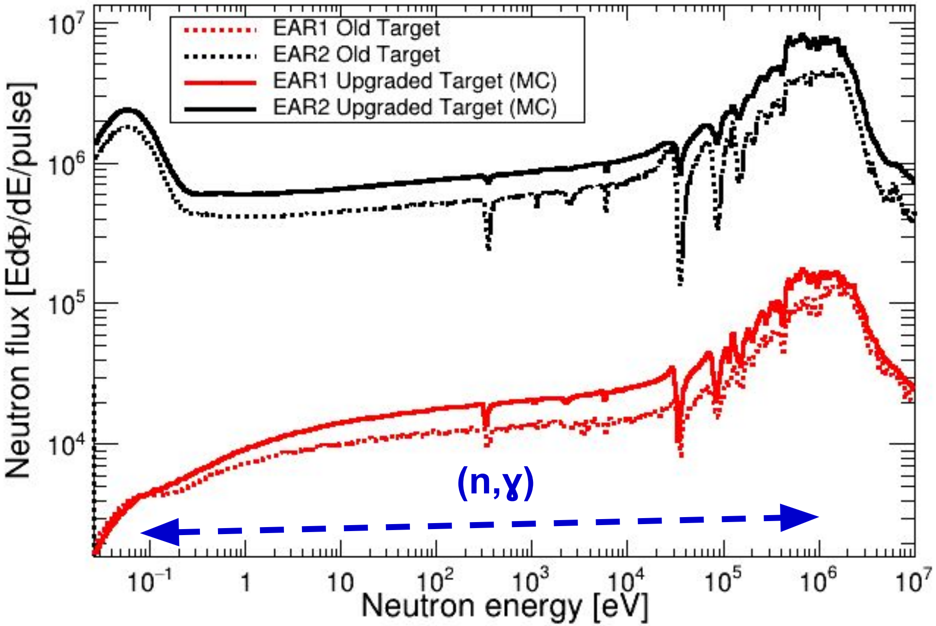
J. Lerendegui-Marco et al., EPJ Web of Conferences **284**, 01028 (2023)

Target upgrade & (n,ɣ) measurements: fluence

Before upgrade: EAR2 highest Instantaneous flux
(FOM for neutron-to-activity ratio)

Neutron fluence enhancement with upgraded target:

- MC: +30-50% for EAR1 & EAR2 in the En range for (n,ɣ)



J. Lerendegui-Marco et al., EPJ Web of Conferences **284**, 01028 (2023)

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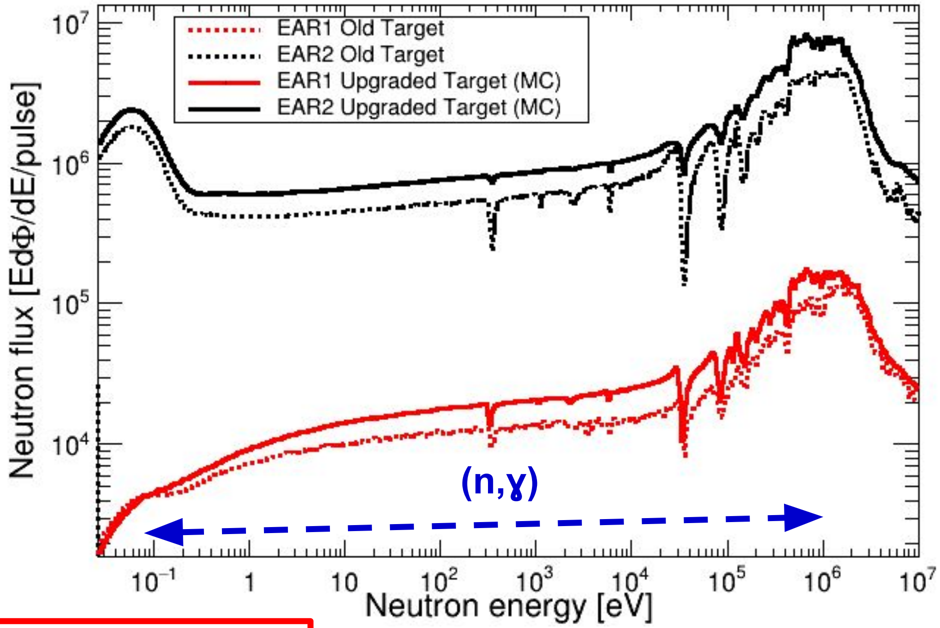
Neutron fluence enhancement with upgraded target:
- MC: +30-50% for EAR1 & EAR2 in the En range for (n,ɣ)



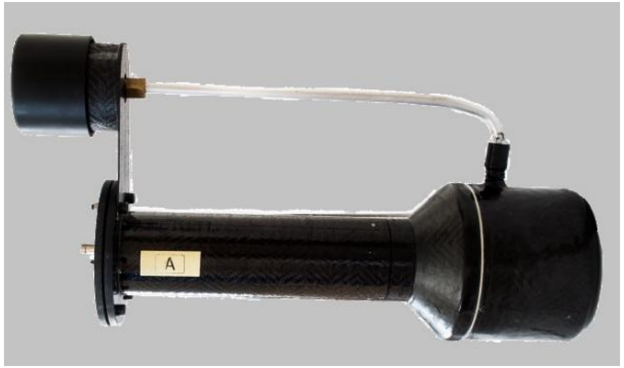
CHALLENGES
- Even Higher flux at EAR2 → Counting rate limit of detectors
- Neutron-induced background not solved with more flux
- Besides target upgrade →**New Detector concepts are required!**

J. Lerendegui-Marco et al., EPJ Web of Conferences **284**, 01028 (2023)

sTED: segmented (n,g) detectors at EAR2

State-of-the-art detectors:
Limited at the high-flux EAR2 by C. rates >=10MHz

State-of-the art C_6D_6 TED



0.6-1 L Liquid
Scintillator Cells

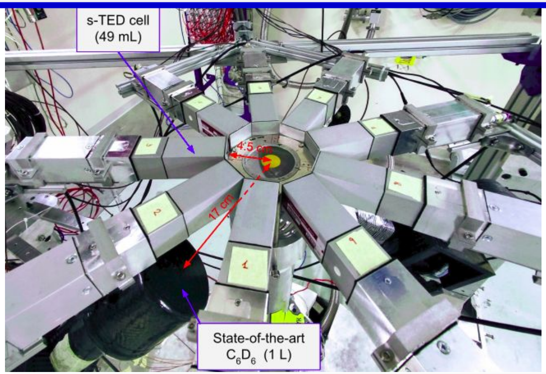
V. Alcayne , EPJ Web of Conferences **284**, 01043 (2023)

Solution:
Segmentation
of the volume

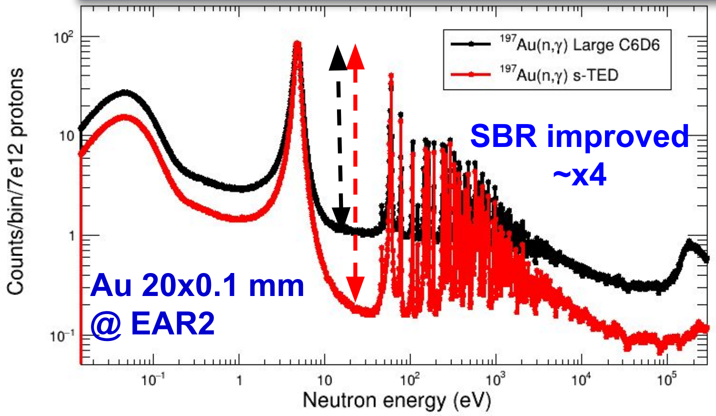
Segmented
(s)TED

9 cells of 0.05 L
(factor **15-20 reduction**)

s-TED cells in ring configuration
for optimized efficiency and SBR

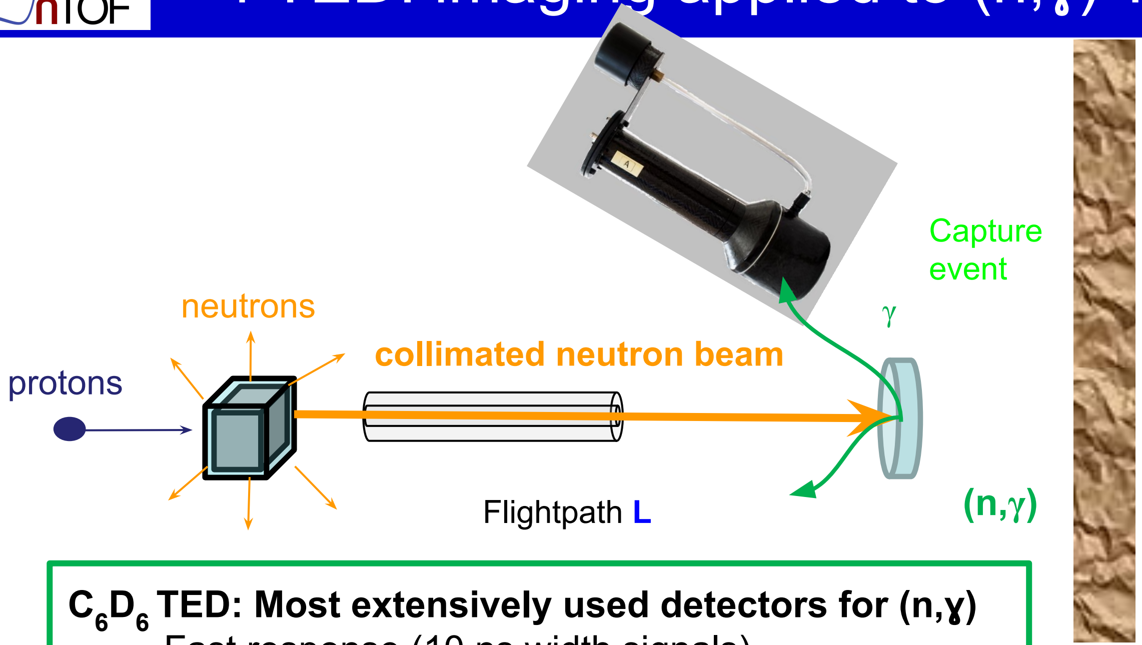


J. Balibrea, EPJ Web of Conferences **279**, 06004 (2023)



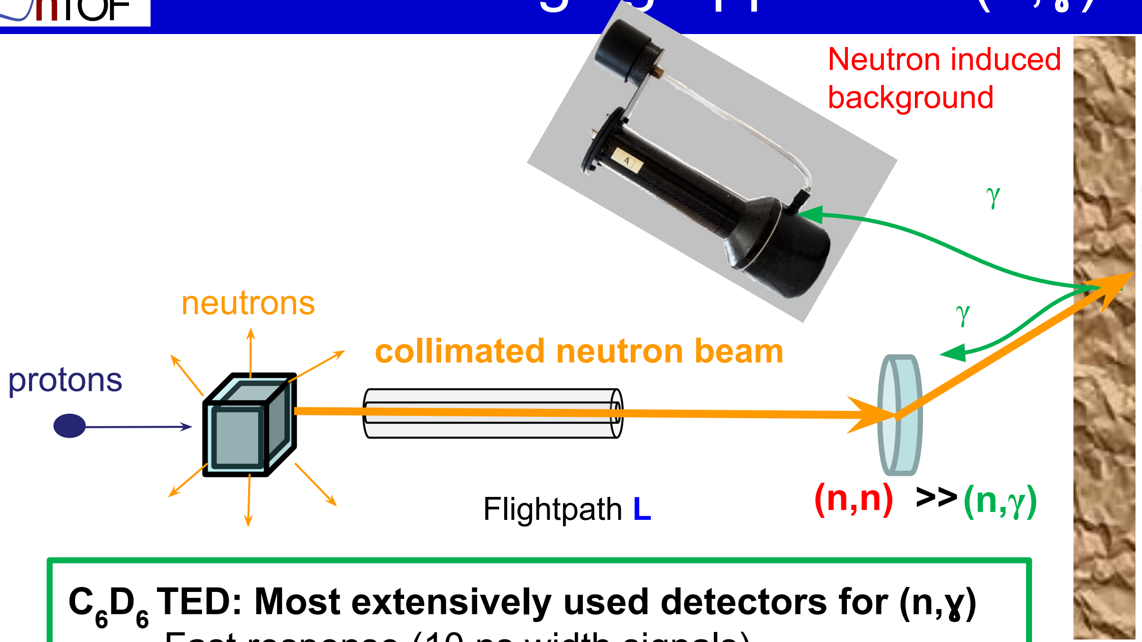
Gobierno de España
Ministerio de Ciencia e Innovación
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

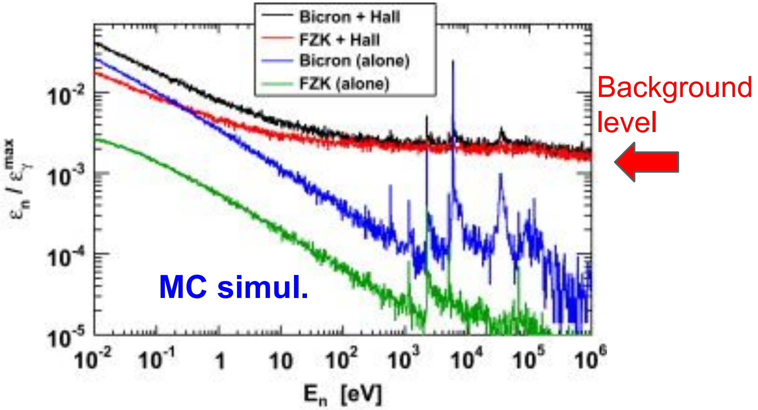
i-TED: imaging applied to (n,ɣ) TOF experiments



C_6D_6 TED: Most extensively used detectors for (n,ɣ)
- Fast response (10 ns width signals)
- Low neutron sensitivity

i-TED: imaging applied to (n,ɣ) TOF experiments

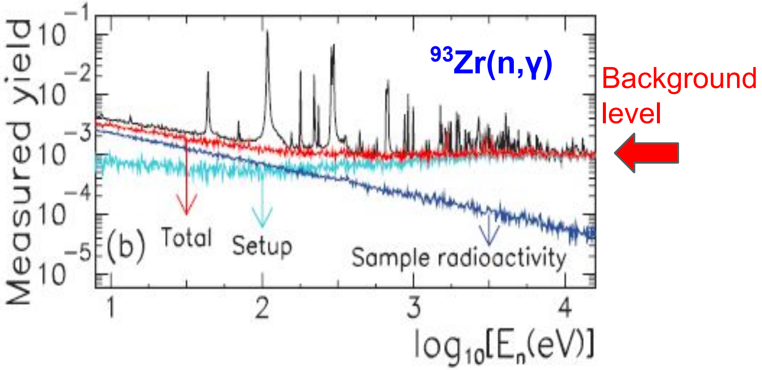




P. Zugec, et al., Nucl. Instrum. Methods A 760, 57 (2014);

PHYSICAL REVIEW C 87, 014622 (2013)

The ^{93}Zr(n, γ) reaction up to 8 keV neutron energy



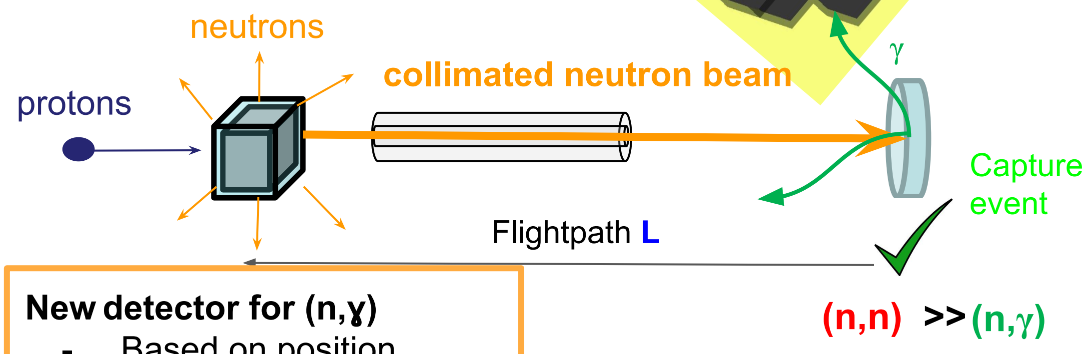
C_6D_6 TED: Most extensively used detectors for (n,ɣ)
- Fast response (10 ns width signals)
- Low neutron sensitivity

Limitation:

Poor background rejection capabilities.
In particular, background originated from neutron scattered in the sample

i-TED: imaging applied to (n,ɣ) TOF experiments


Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima
i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements
C. Domingo-Pardo
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain

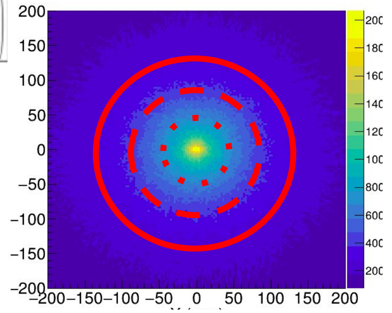


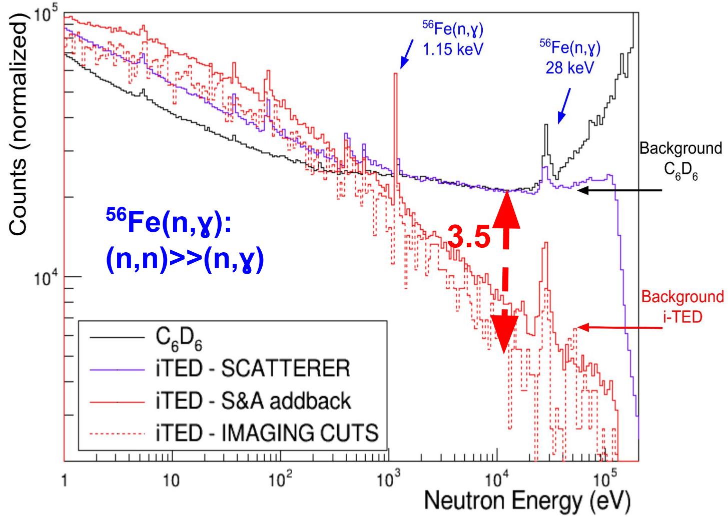
New detector for (n,ɣ)
- Based on position sensitive detectors
- Imaging capabilities

Solution: Exploit the Compton Imaging technique to reduce the neutron background and enhance the detection sensitivity

$$\theta = arcos\left[1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)\right]$$

COMPTON IMAGING





Babiano-Suárez, V., *et al.* Eur. Phys. J. A **57**, 197 (2021)

HYMNS nucleosynthesis & MS evolution

European Research Council

i-TED: imaging applied to (n,ɣ) TOF experiments

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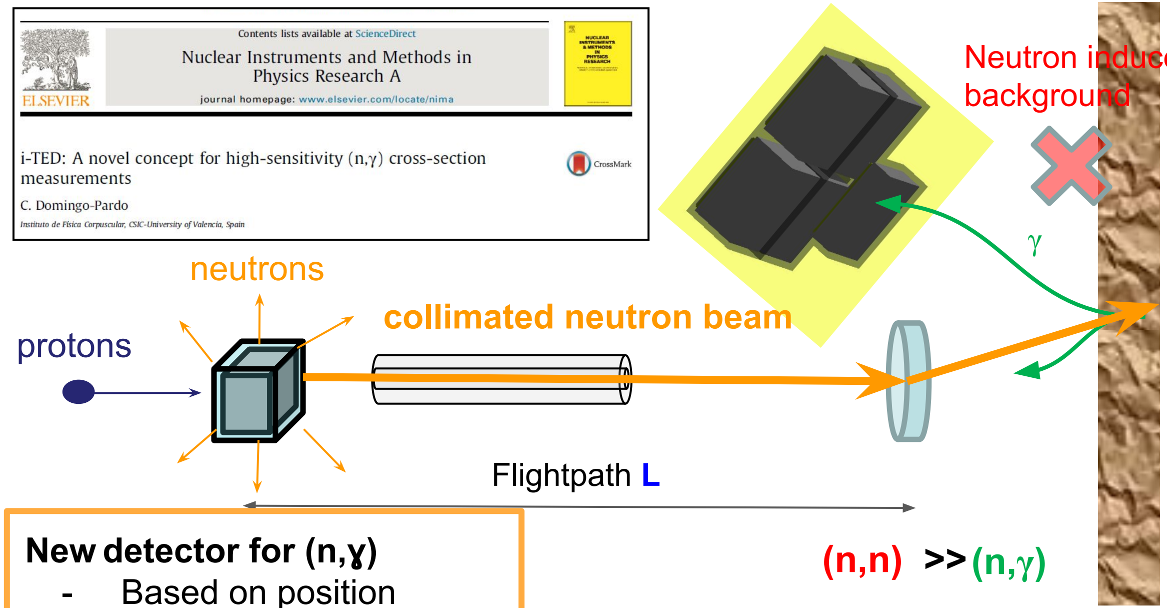

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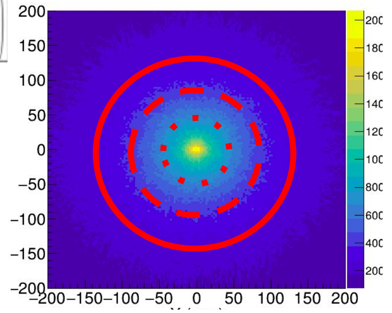
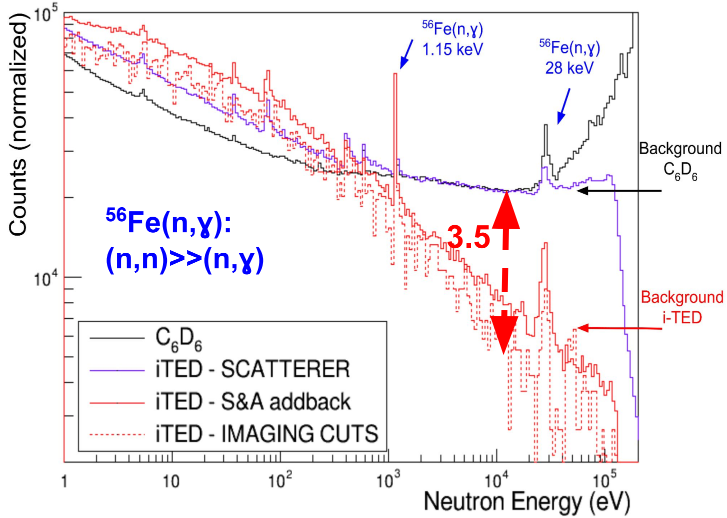




Babiano-Suárez, V., *et al.* Eur. Phys. J. A **57**, 197 (2021)

HYMNS nucleosynthesis & MS evolution

erc European Research Council

(n,γ) highlights after the latest upgrades

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

F. Kaeppeler et al.,
Rev. Mod. Phys 83, 157 (2011)

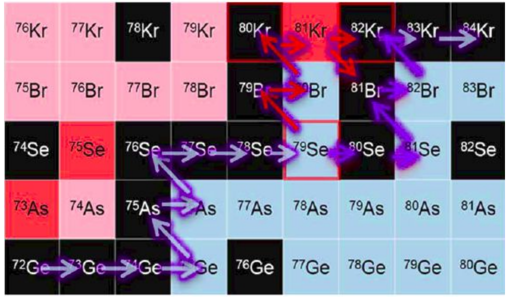
Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains s-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to s-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during s process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for s-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and s-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

After upgrades (2021-2022): **New unstable isotopes** of astrophysical relevance (**Se-79** & **Nb-94**) measured at **n-TOF-EAR2**

(n,γ) highlights after the latest upgrades

$^{79}Se(n,\gamma)$

m = 2.7 mg (+3g of PbSe)
σ = 263 mb

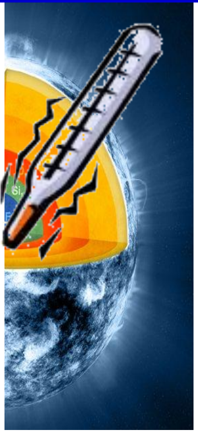


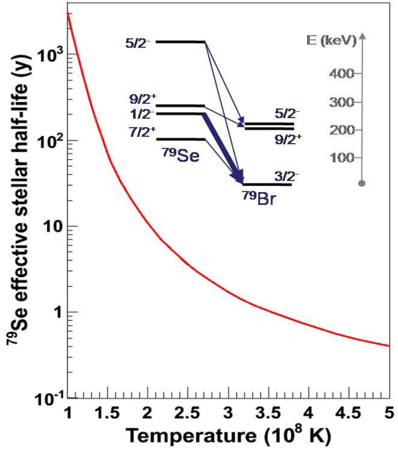
NEUTRONS FOR SCIENCE

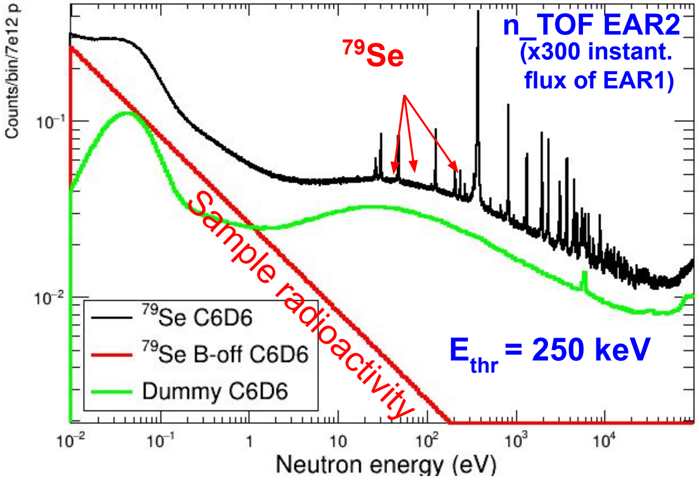
PAUL SCHERRER INSTITUT

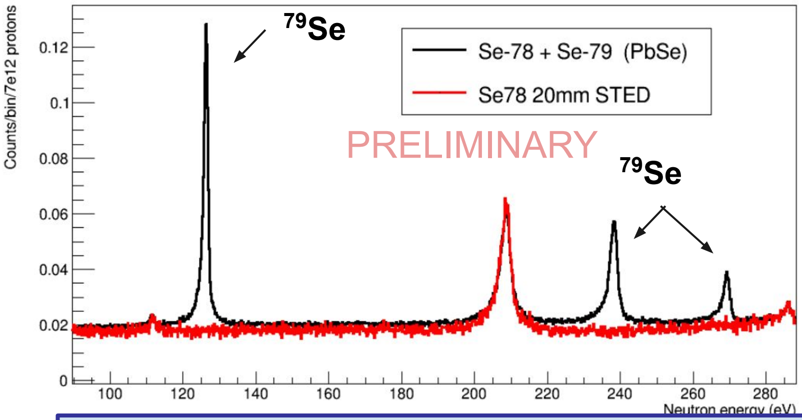
$^{79}Se(n,\gamma)$: suited for thermal conditions stellar medium→ strong thermal dependence of the beta decay rate

First measurement ever!









$^{79}Se(n,\gamma)$:
10-15 Resonances analyzed

Lerendegui-Marco, J. et al., EPJ Web Conf. 279, 13001 (2023).

Exiting limitations & future perspectives

TOF (n,g) on s-process branchings: future

Towards more unstable s-process branching point isotopes: radioactive → challenges

1. Difficult to produce in sizable quantities→ **Low capture/background ratio**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background that excludes current **standard measuring techniques and current neutron beam facilities.**

Pm-147(n,ɣ)
(PLB 2019)

Physics Letters B 797 (2019) 134809

n_TOF lowest mass record at that point!

m = 85 ug
σ = 826 mb

measurement features the smallest mass (85 μg) ever measured at the n_TOF facility. The mass was unexpectedly small due to the deviations in the assumed value for the thermal capture cross section of ^{146}Nd (seed irradiated at ILL). For this reason n_TOF-EAR2 was chosen over EAR1, featuring the highest instantaneous neutron flux among time-of-flight facilities worldwide [25]. The small mass just allowed to clearly measure the three largest resonances (see left panel of Figure 4) and identify ten

TOF measurement not fully successful due to limited mass

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TOF measurement not fully successful due to limited mass

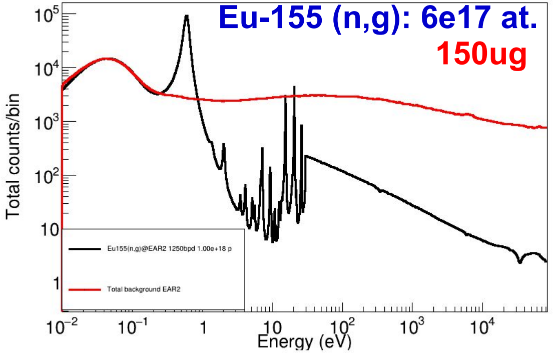
Very interesting unstable nuclei for the future: Eu-155, Ta-179, W-185

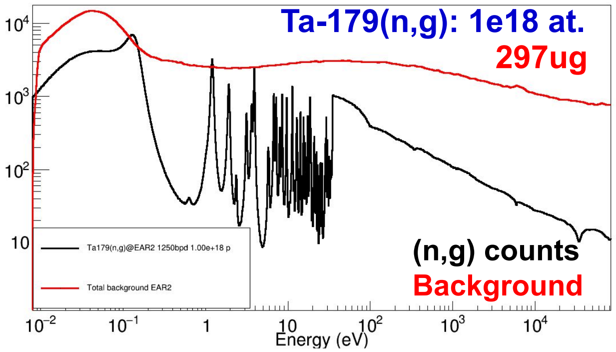
- First TOF measurement
- Low g-ray background
- **Activities ~ 4-100 GBq for masses as low as 1e18 atoms**

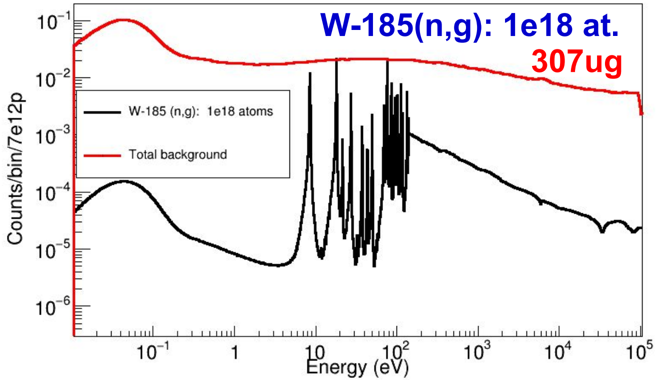
Isotope	Mass(ug)	Natoms	Activity (Gbq)	Decay / emitted g-rays
Eu-155	257.390	1.00E+18	4.70E+00	g<100keV, Qb<250keV
Ta-179	297.243	1.00E+18	1.21E+01	EC --> no gamma
W-185	307.207	1.00E+18	1.07E+02	g<125 keV(Ig = 0.02%), Qb:433 keV

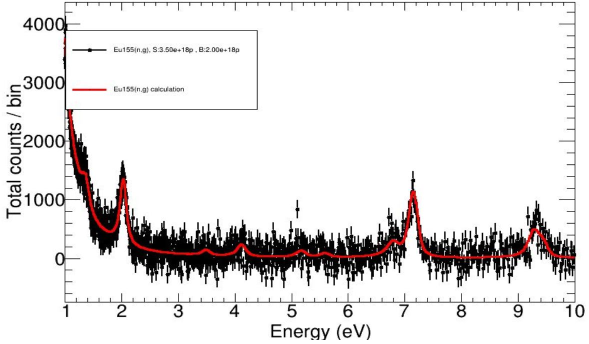
TOF (n,g) on s-process branchings: feasibility limit

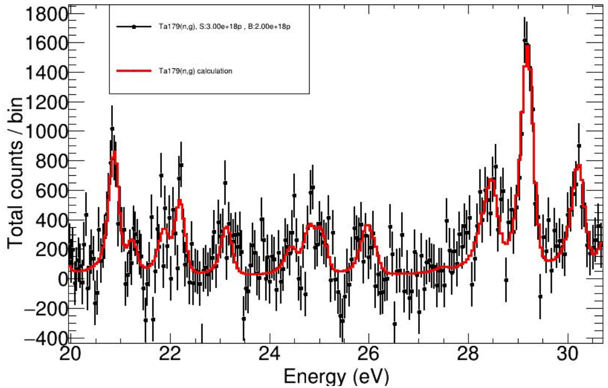
Estimated results in the upgraded **n_TOF-EAR2** with the **best sensitivity achieved so far with the STEDs**

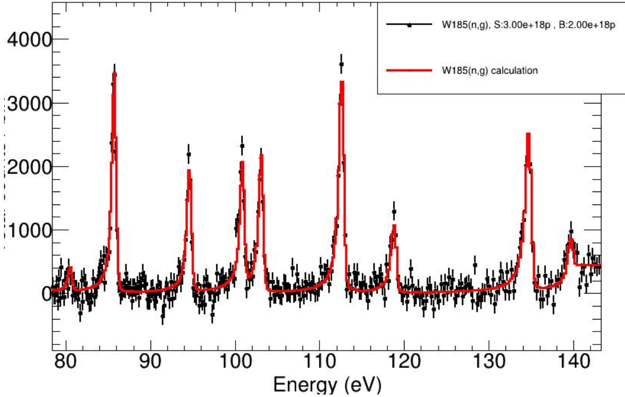










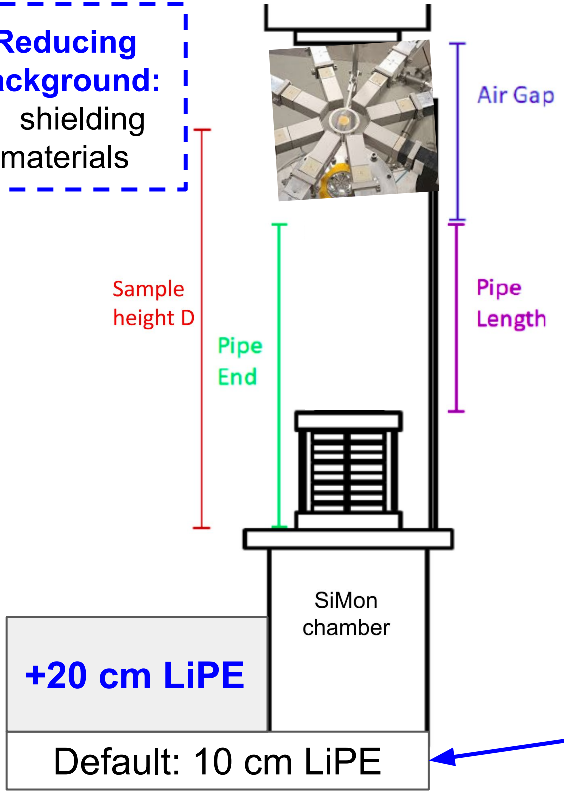


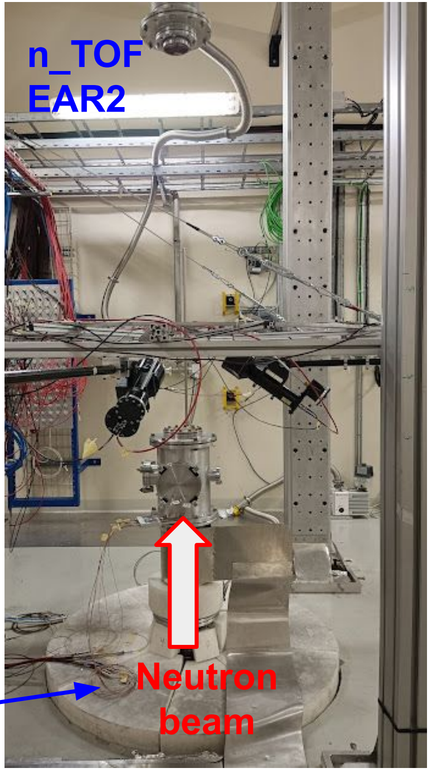
Limit: ~1e18 atoms (too high) currently required →We need **higher sensitivity** or **new techniques**!

Future: optimizing n_TOF-EAR2

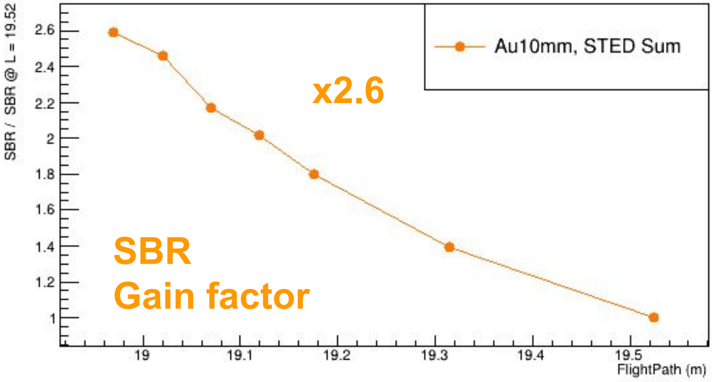
Short term: Optimization campaigns **at EAR2 & new ideas to improve the SBR for future experiments**

Reducing background:
+ shielding materials





SBR Gain of a factor >2
by lowering 60cm the setup!



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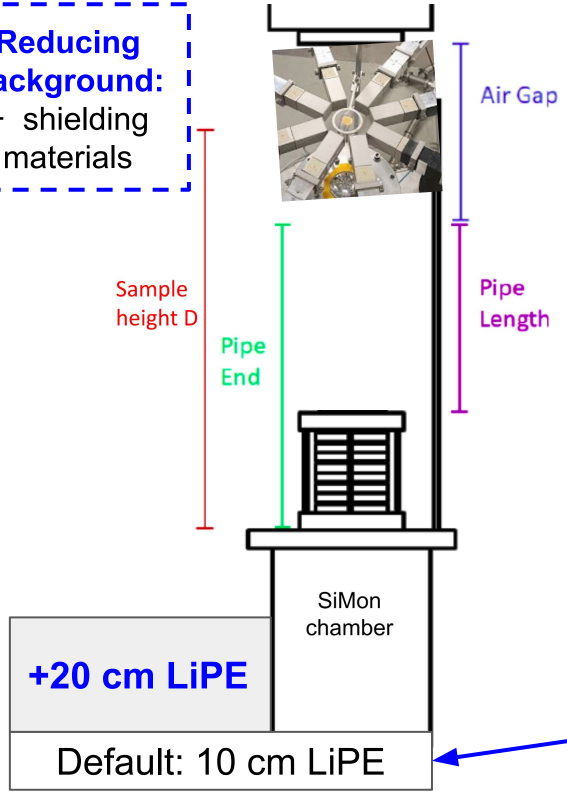

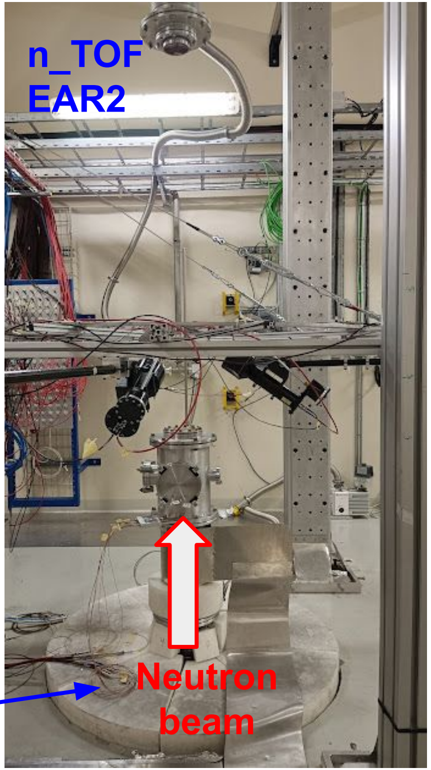

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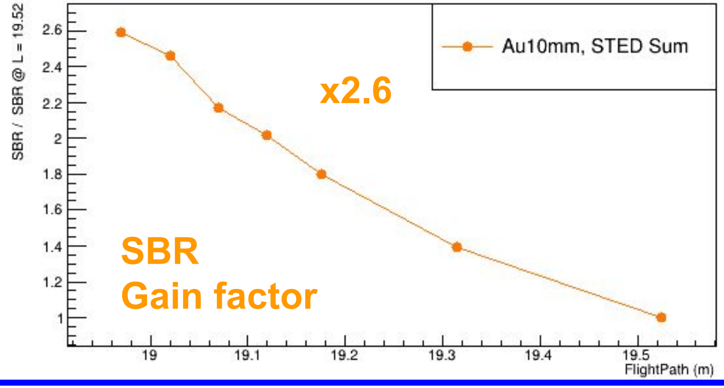
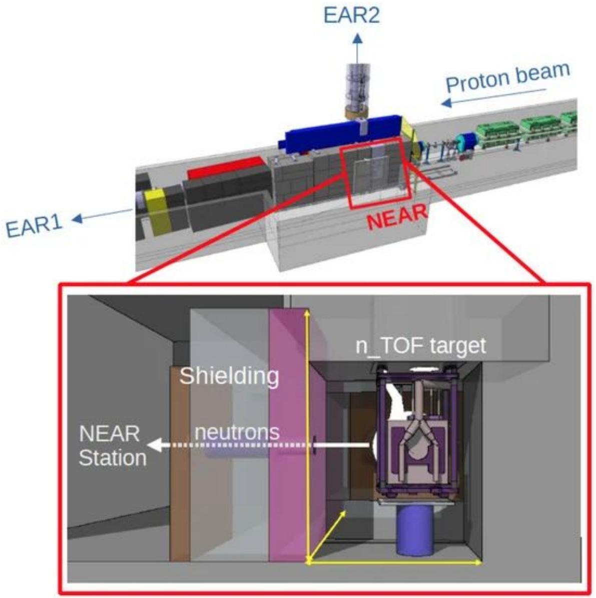


Long term:

- Change collimator design
- Upgraded experimental area (n-absorbers, enlarged: walls & floor further from beam)
- Avoid fastest neutrons: "look" only to moderator, new backwards TOF line

NEAR: the new high flux facility

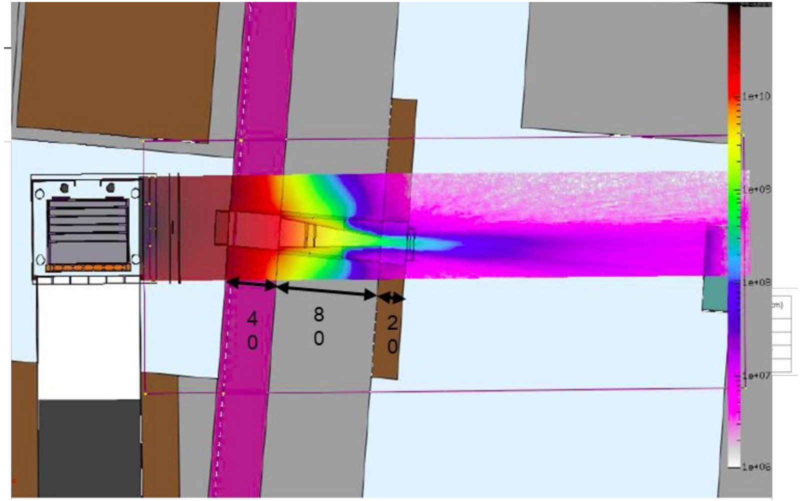


Physics at the NEAR: @ 3 m from spallation target

- High flux (x~100 EAR2 outside the collimator)
- Activation measurements
- Small mass
- Unstable isotopes

e.g. s-process branchings not accessible via TOF

Astrophysical (n,g) measurements @ NEAR



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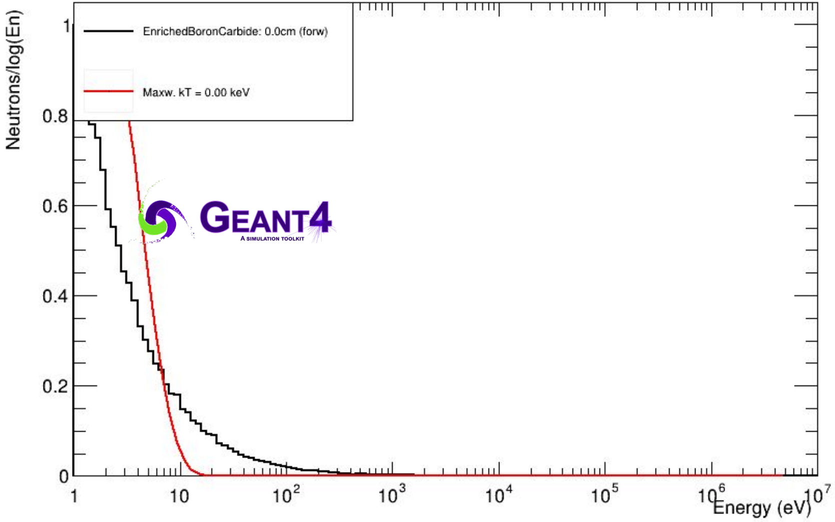
Neutron spectra + filter (^{10}B, $^{10}B_4C$, …) after the collimator exit:

- s-process: Measure SACS @ various stellar temperatures from 0.1 to few hundreds of keV.
- E. Stamati et al., CERN-INTC-2022-008; INTC-P-623 (2022): benchmark with long-lived (n,g) products



N. Patronis et al., arXiv (submitted to EPJ-C, 2023)

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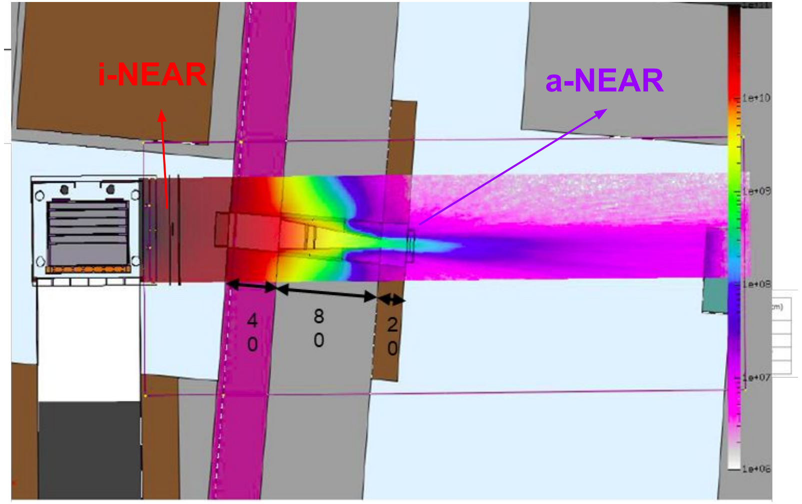

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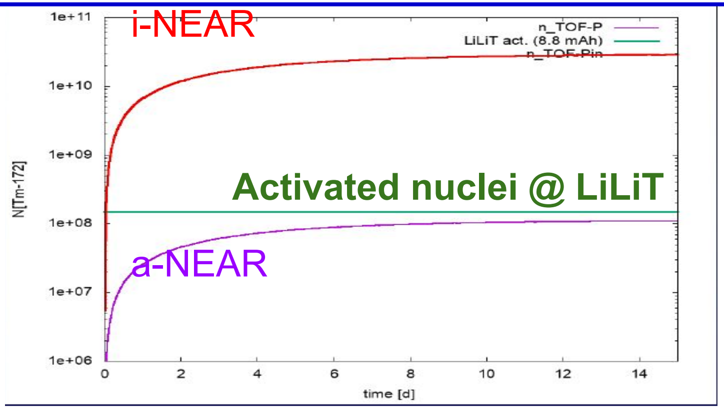

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^{171}Tm(n,g) example: state-of-the art LiLIT facility
NEAR could measure much smaller masses

Future: Cyclic activation station @ NEAR

Future:
CYCLING : CYCLIc activation for (N,G) measurements

- Allows: activation with short lived targets (s, min) (n,g) products

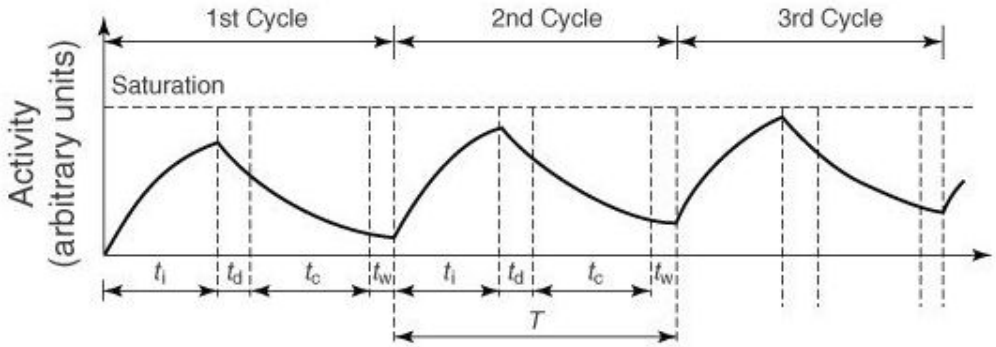
- Repetition of short irradiation **(ti)** + rapid transport to detector **(td)** + counting the decay **(tc)** and transport back to the irradiating beam **(tw)**

Requisites

- Beam period: Rep. rate of n_TOF (max 0.8 Hz) is well suited for short lived (seconds)

- Operate a high resolution g-ray detector (ideally HPGe) in **the harsh radiation environment in the NEAR bunker →** **characterization on-going [1]**

[1] http://cds.cern.ch/record/2809131



H. Beer, et al., Nucl. Inst. Meths. 337, 2–3 (1994)

Interesting cases for astrophysics:

- s-process/AGB: ^{107,109}Ag(n,γ), ^{26}Mg(n, γ), ^{50}Ti(n,γ), ^{19}F(n, γ), ^{60}Fe(n, γ)

- i-process: ^{137}Cs(n,γ), ^{132}Te(n,γ),...

C. Domingo-Pardo, et al., *Eur. Phys. J. A* **59**, 8 (2023)

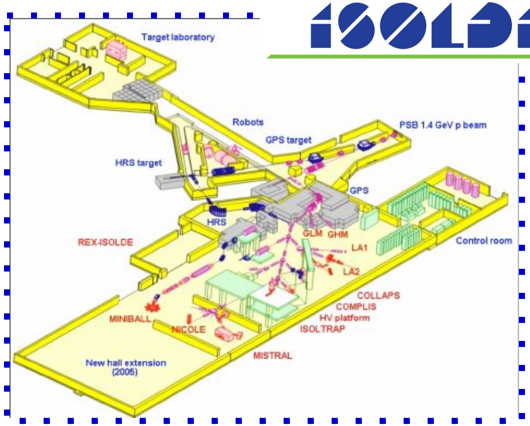
Future: ISOLDE-n_TOF-NEAR Synergy

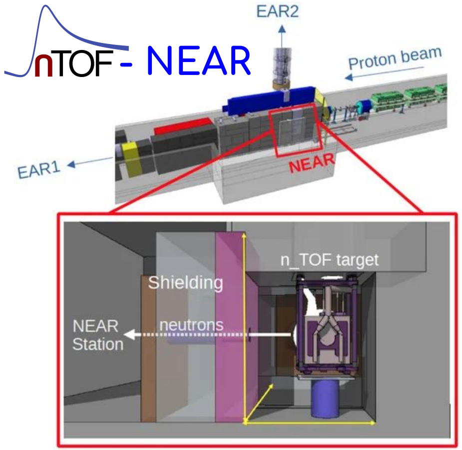
Goal:(n,g) on many unstable isotopes s and i- processes→ **(still) unfeasible via TOF**

Alternative: Produce samples of relevant unstable nuclei at **ISOLDE** & measure MACS at **NEAR**

- **ISOLDE + NEAR (w/ CYCLING) :** smaller production yields & shorter-lived isotopes would be accessible

- **Examples:** 59Fe, 134Cs, **135Cs**, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, and 181Hf (s-process), Cs-137, 66Ni, 72Zn (i-process)



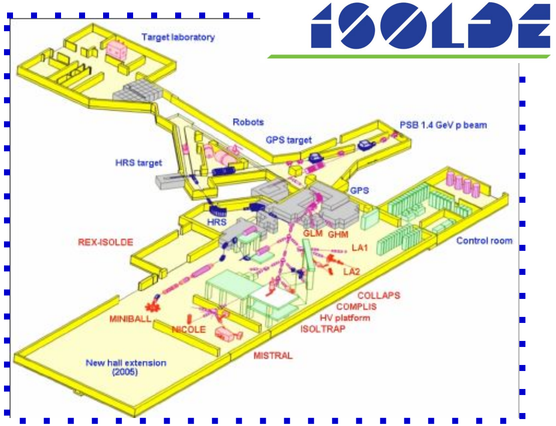


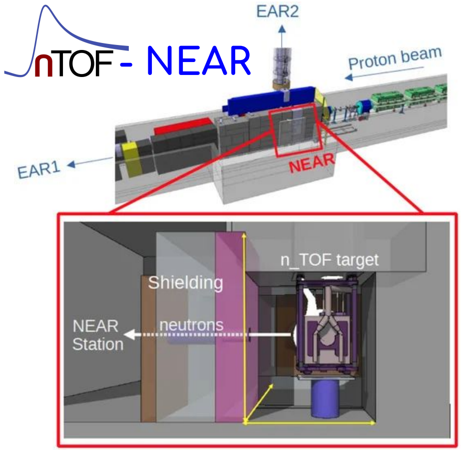
Future: ISOLDE-n_TOF-NEAR Synergy

Goal:(n,g) on many unstable isotopes s and i- processes→ **(still) unfeasible via TOF**

Alternative: Produce samples of relevant unstable nuclei at **ISOLDE** & measure MACS at **NEAR**

- **ISOLDE + NEAR (w/ CYCLING) :** smaller production yields & shorter-lived isotopes would be accessible
- **Examples:** 59Fe, 134Cs, **135Cs**, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, and 181Hf (s-process), Cs-137, 66Ni, 72Zn (i-process)





Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Production of a ^{135}Cs sample at ISOLDE for (n,γ) activation measurements at n_TOF-NEAR

https://cds.cern.ch/record/2834566

Min mass: 2e15 at

Molten La metal: 8.5e9 at/μC

^{135}Cs

→ Among the **21 key s-nuclei** listed in Kaeppeler, *Rev. Mod. Phys 83, 157 (2011)*

Summary

- **Accurate neutron capture CS** are key in various files such as **nuclear technologies or in the s-process of stellar nucleosynthesis,** for validating and constraining stellar nucleosynthesis models**.**

- **(n,g) measurements at CERN-n_TOF:**
  - **n_TOF EAR1**: Long standing facility, very high energy resolution and wide energy range (~MeV).
  - **Radioactive nuclei** (e.g. s-process branchings): dominant **background from radioactivity**.
  - **Solution:** Higher instantaneous flux facility → **n_TOF-EAR2**

- **Recent upgrades at n_TOF:**
  - n_TOF **neutron source upgrade**: More flux & improved E- resolution in EAR2
  - **New detection systems**:
    - **s-TED:** segmented volume & enhanced sensitivity for high flux facilities (n_TOF EAR2)
    - **i-TED:** imaging applied to suppress n-induced background .
  - Recent **highlight after upgrades: Unstable ^{79}Se(n,g)**, key s-process branching → stellar temperature

- **Existing limitations & future perspectives:**
  - **Towards + unstable isotopes (<=ug samples)** → **Current limit for TOF: signal-to-background ratio**
  - **Future:**
    - **Optimization of the** sensitivity in (n,g) **measurements at n_TOF EAR2**: setup, shieldings, collimator, …
    - **NEAR**: New high flux facility for MACS activation measurements + **CYCLING**: access short-lived.
    - **Synergy NEAR & ISOLDE**: Produce low mass samples of unstable isotopes + activation

HYMNS

European Research Council

High sensitivitY Measurements of key stellar Nucleo-Synthesis reactions

+ Info: https://hymnserc.ific.uv.es/public_documents

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AGENCIA ESTATAL DE INVESTIGACIÓN

Thank you for you attention!

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