Direct neutron capture experiments on stable and unstable isotopes (for the s- and i-processes)

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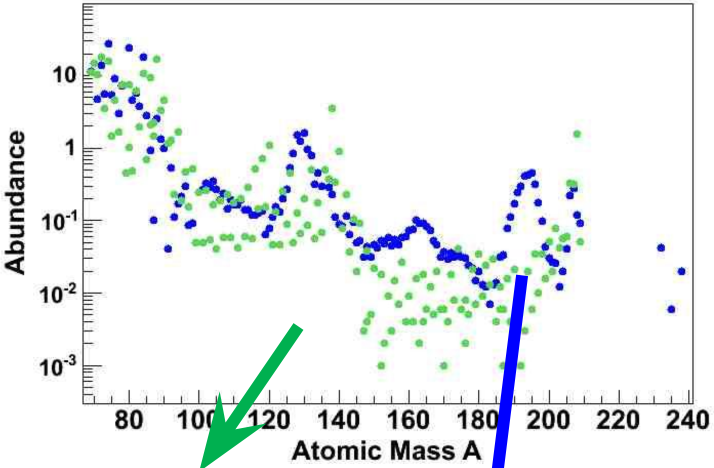
Instituto de Física Corpuscular (Valencia, Spain)
n_TOF Collaboration (CERN)

Outline

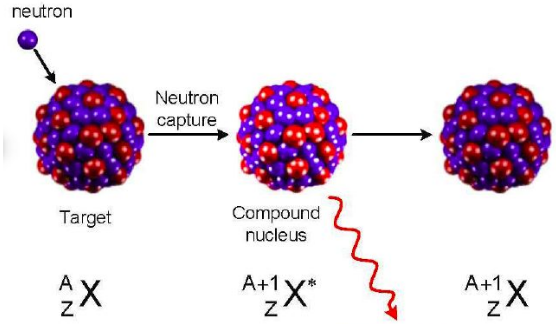
- The synthesis of (heavy) elements in the universe
- Nucleosynthesis & neutron capture: data needs for unstable and stable nuclei
- Direct neutron capture reactions: from stars to the lab
- State-of-the art & future of direct neutron capture reactions

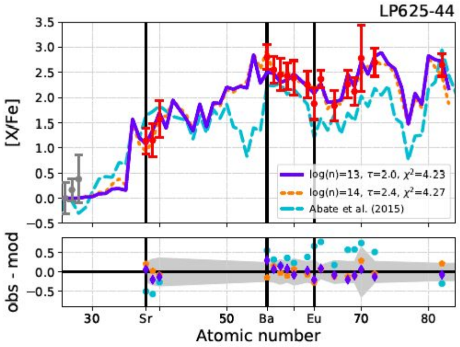
The synthesis of heavy nuclei in stars

Neutrons capture (n,g) reactions play a key role in the synthesis of heavy elements



s + i + r EN



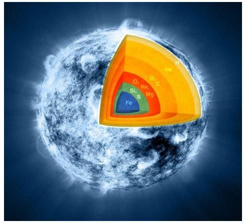


i-process: abundance pattern in CEMP stars

s-process

T =10^8 -10^9 K

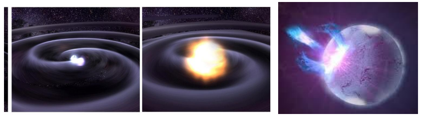
N_n = 10^6-10^{12} cm^{-3}



r-process

T = 10^8-10^{10} K

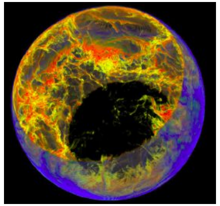
N_n = 10^{20}-10^{27} cm^{-3}



i-process

T > 10^8 K

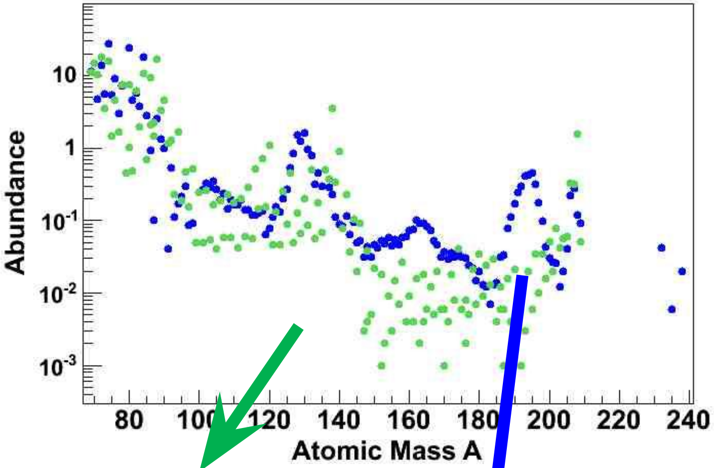
N_n = 10^{13} - 10^{16} cm^{-3}

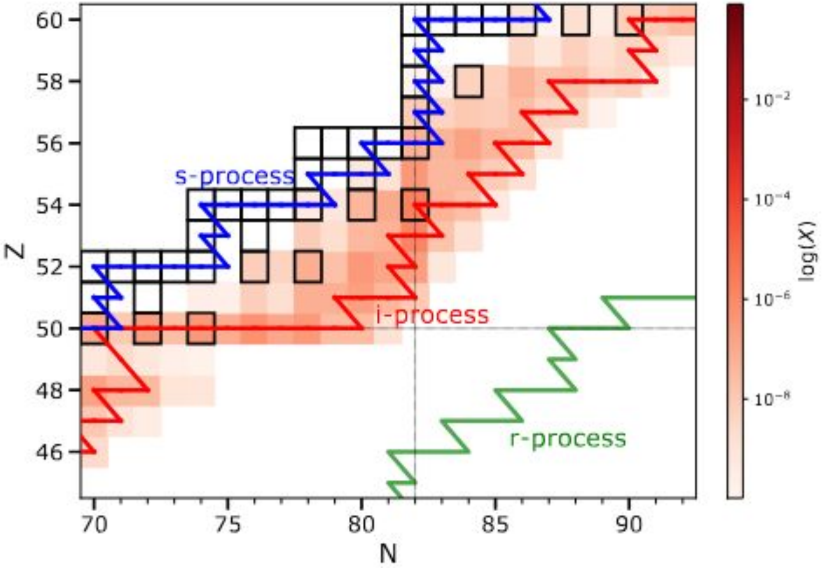


Falk Herwig et al 2011 ApJ 727 89
Melanie Hampel et al 2019 ApJ 887 11

The synthesis of **heavy** nuclei in stars

Neutrons capture (n,g) reactions play a key role in the synthesis of heavy elements



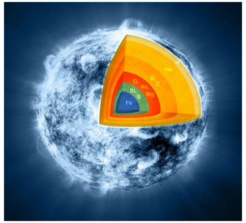


A. Choplin, EPJ Web of Conferences 279, 07001 (2023)

s-process

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

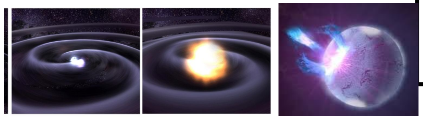
$N_n = 10^6 - 10^{12}$ cm^{-3}



r-process

$T = 10^8 - 10^{10}$ K

$N_n = 10^{20} - 10^{27}$ cm^{-3}



i-process

$T > 10^8$ K

$N_n = 10^{13} - 10^{16}$ cm^{-3}

s-process: stable or long-lived unstable → **Direct (n,g)**

i-process: few units from stability → shorter-lived → **Direct (n,g) in future**

r-process: n-rich (veeery short lived) → ~~**Direct (n,g)**~~

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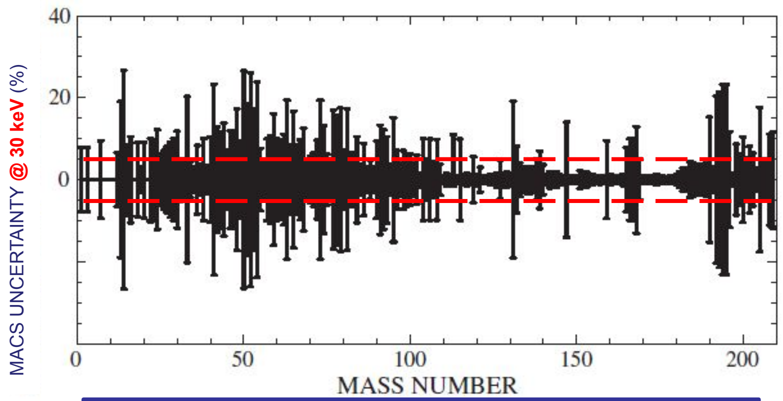
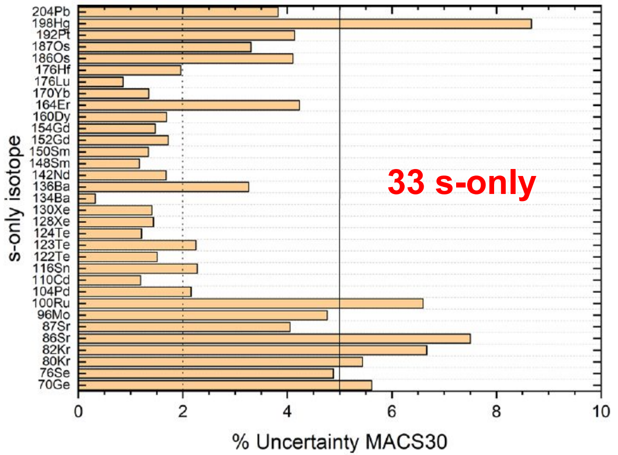
s-process: data needs on stable isotopes



F. Käppeler et al. Rev. Mod. Phys. (2011)

s-only isotopes:
Benchmark for s-process and galactic-chemical evolution (GCE) models,

Aim:Accuracy MACS down to 2% unc.



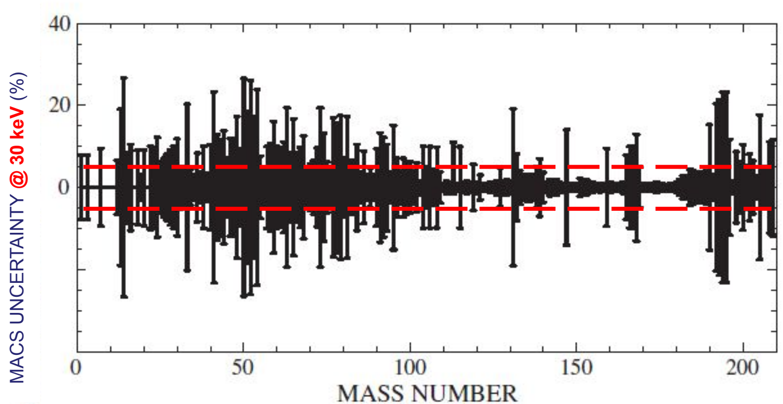
I. Dillmann et al., *Eur. Phys. J. A* **59**, 105 (2023).

MC Sensitivity studies:

AGB: G. Cescutti et al., MNRAS, 478, 4101(2018).

Massive: Nishimura et al.,, *MNRAS*, 469, 1752 (2017)

s-process: data needs on stable isotopes



5%

F. Käppeler et al. Rev. Mod. Phys. (2011)

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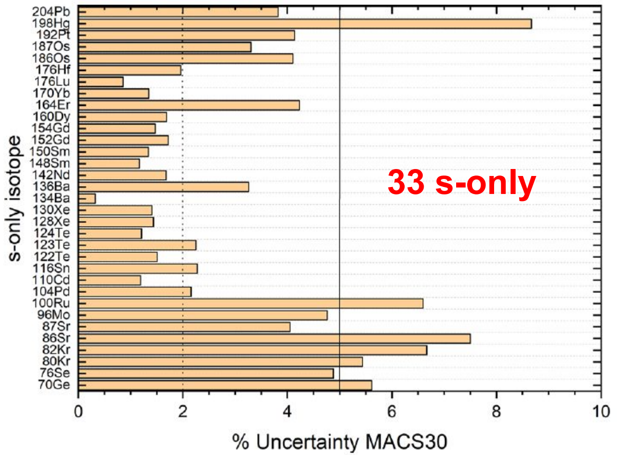
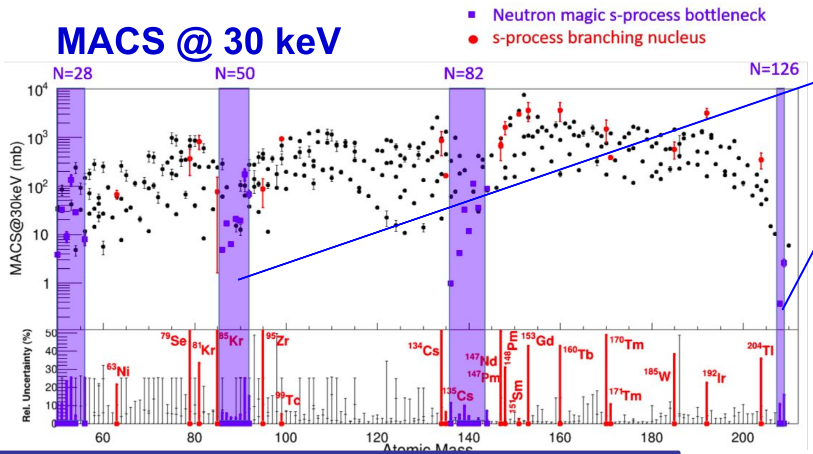


33 s-only

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

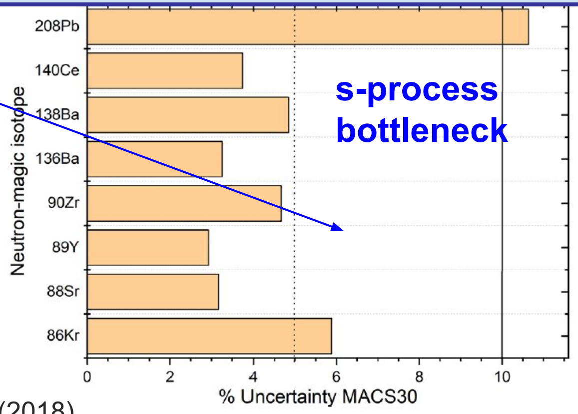
MACS @ 30 keV



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

n-magic nuclei:
s-process bottlenecks

Very small (n,g) XS



s-process bottleneck

High accuracy (n,g) data on stable nuclei still needed!

MC Sensitivity studies:
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Massive: Nishimura et al.,, *MNRAS*, 469, 1752 (2017)

s-process: the relevance of unstable isotopes

Key unstable cases: branching points

$^{A}Z(n,\gamma)$ competes with β decay: (n,γ) cross sections→ conditions stellar environment

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

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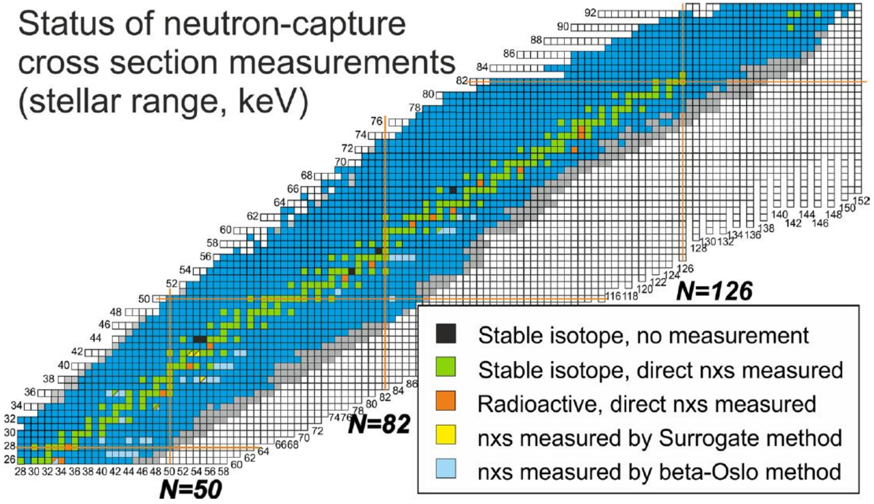

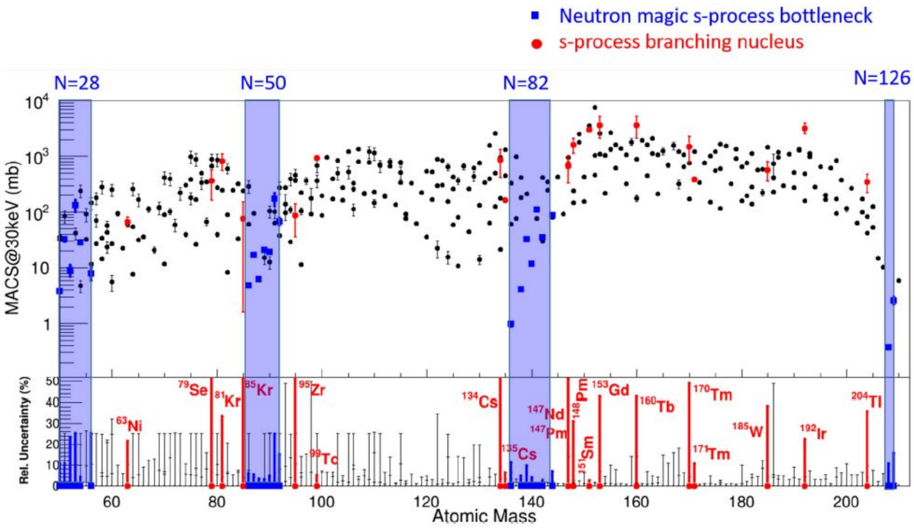

Status Unstable isotopes:

Very little direct (n,g) data,

Very large uncertainties

Incomplete neutron energy range

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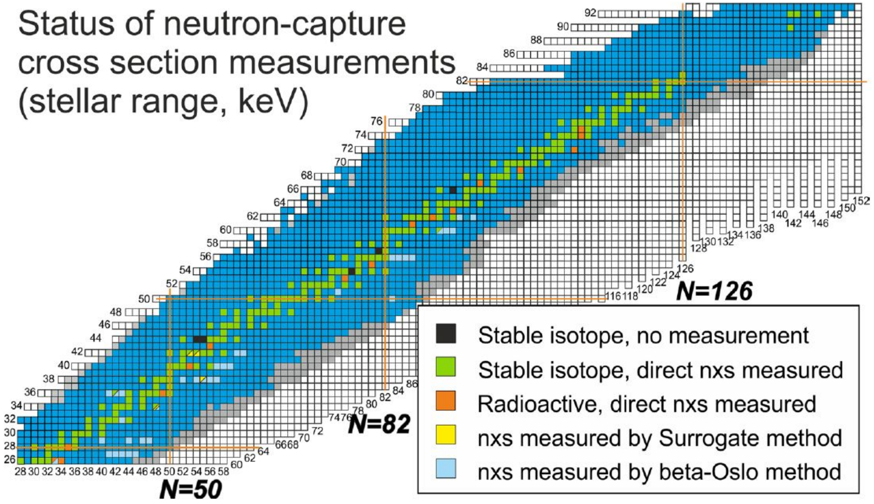
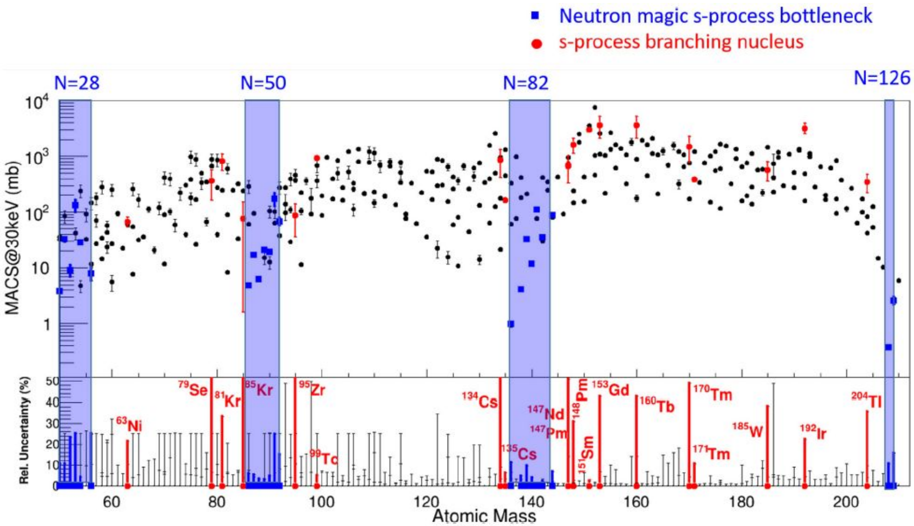




Status Unstable isotopes:
Very little direct (n,g) data,
Very large uncertainties
Incomplete neutron energy range

WHY? Challenging measurements:
Radioactive isotopes, low masses

i-process: more neutron-rich (short-lived) nuclei

The impact of (n,γ) reaction rate uncertainties on the predicted abundances of i-process elements with $32 \leq Z \leq 48$ in the metal-poor star HD94028

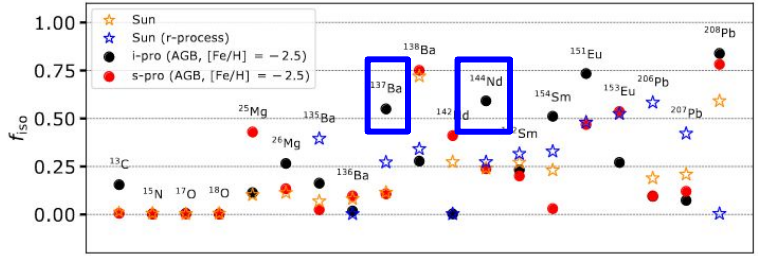
John E. McKay,[1,2]† Pavel A. Denissenkov,[1,3]★† Falk Herwig,[1,3]★† Georgios Perdikakis[3,4,5] and Hendrik Schatz[3,5,6]†

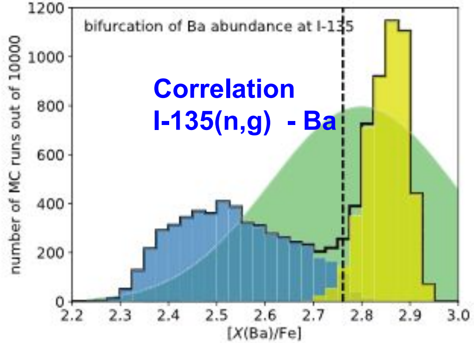
The impact of (n,γ) reaction rate uncertainties of unstable isotopes on the *i*-process nucleosynthesis of the elements from Ba to W

Pavel A. Denissenkov,[1,2,3]★† Falk Herwig,[1,2]★† Georgios Perdikakis[2,4,5] and Hendrik Schatz[2,5,6]†

Signatures of i-process: Ba-137, Nd-144:
^{137}Cs(**30 y**)(n,γ) , ^{144}Ce(**285 d**) (n,γ) compete with production

Very high impact (n,g) in i-process abundances:
^{66}Ni(**55h**)(n,γ),^{72}Zn(**46.5h**)(n,γ),^{75}Ga(**2.10m**)(n,γ),
^{135}I(**6.6h**)(n,γ), ^{141}Ba(**18.3 m**)(n,γ), ^{141}La (**3.92h**)(n,γ)





Reaction		Element
^{66}Ni	54.6 h	Zn
		Ge
		As
^{72}Zn	46.5 h	Ge
^{75}Ga	2.10 m	As

Element	Reaction	
Ba	^{135}I	6.6 h

(n,g) for i-process: involves n-rich nuclei → even more challenging than s-process

1. **Half-life is in general too short (minutes-hours)** to allow a (days/weeks-long) measurement.
2. To be produced in **exotic beam facilities**
3. **Requires: new neutron facilities** & **experimental techniques**

Currently: indirect (n,g) (A. Spyrou)

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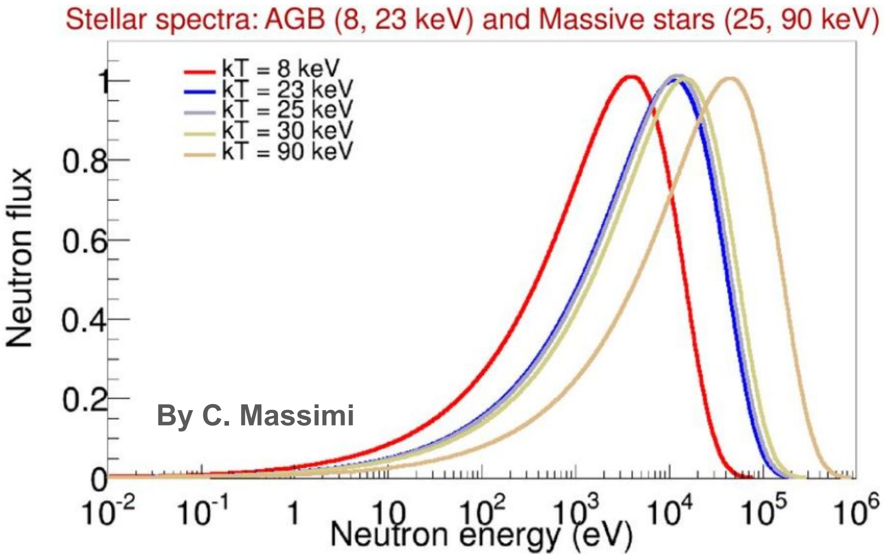
(n,ɣ) reaction rates in stars: MACS



Maxwellian stellar spectra

$$\phi_{MB}(v)dv = \phi_{MB}(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

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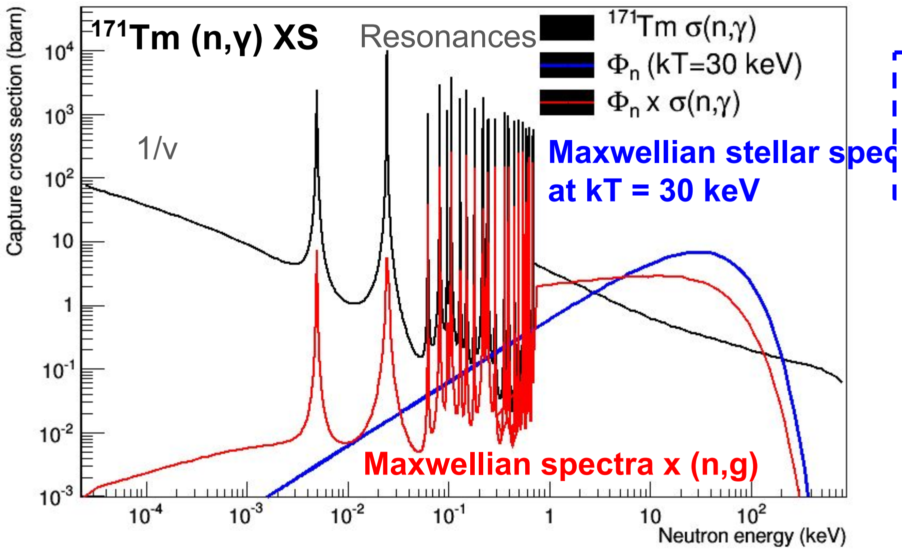

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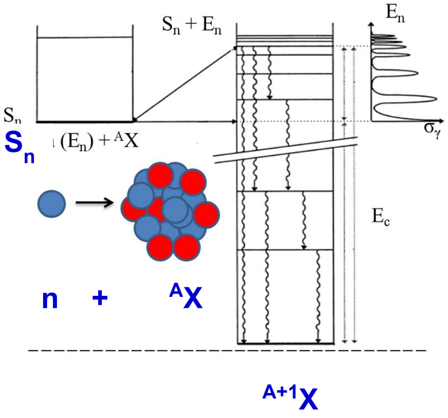
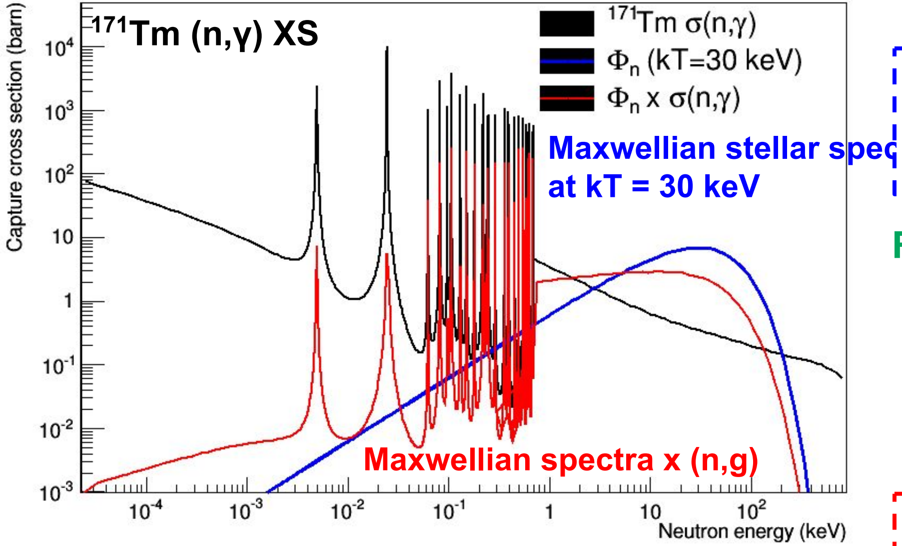
Resonances <-> Compound nucleus



(n,γ) reaction rates in stars: MACS



Maxwellian stellar spectra

$$\phi_{MB}(v)dv = \phi_{MB}(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

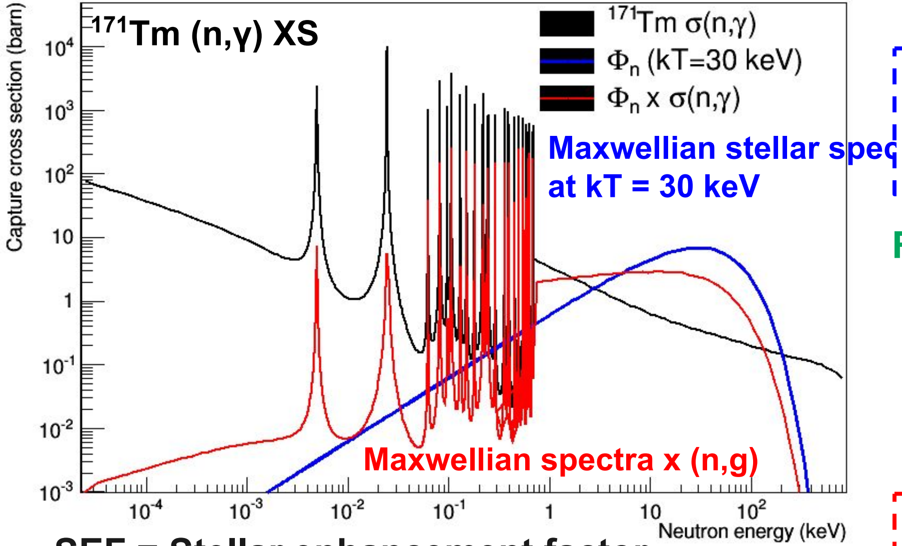
Reaction rate per particle pair

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

MACS = Maxwellian Averaged Cross Section

$$\text{MACS} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

(n,γ) reaction rates in stars: MACS



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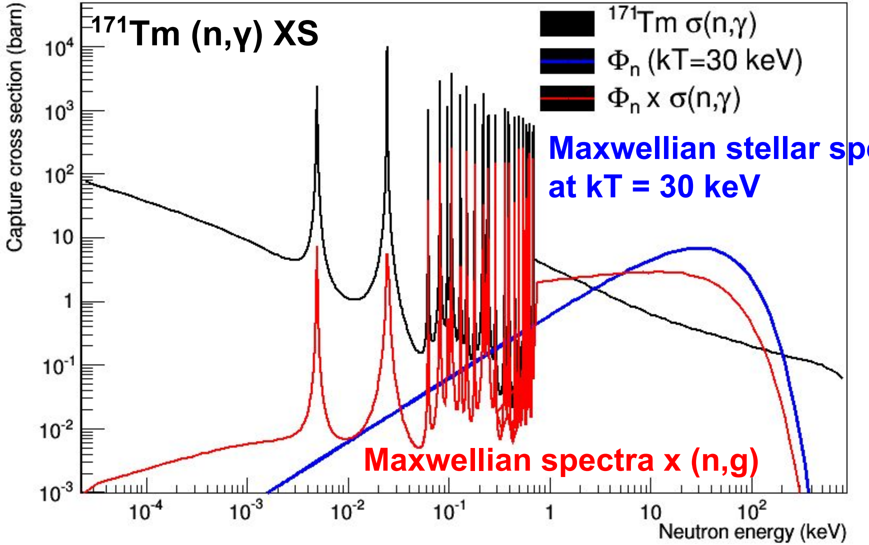
SEF = Stellar enhancement factor

For some isotopes:

$$SEF(T) = \frac{\langle\sigma\rangle^{\text{star}}}{\langle\sigma\rangle_{kT}},$$

(n,γ) reaction rates in stars: MACS



Maxwellian stellar spectra at kT = 30 keV

Maxwellian stellar spectra

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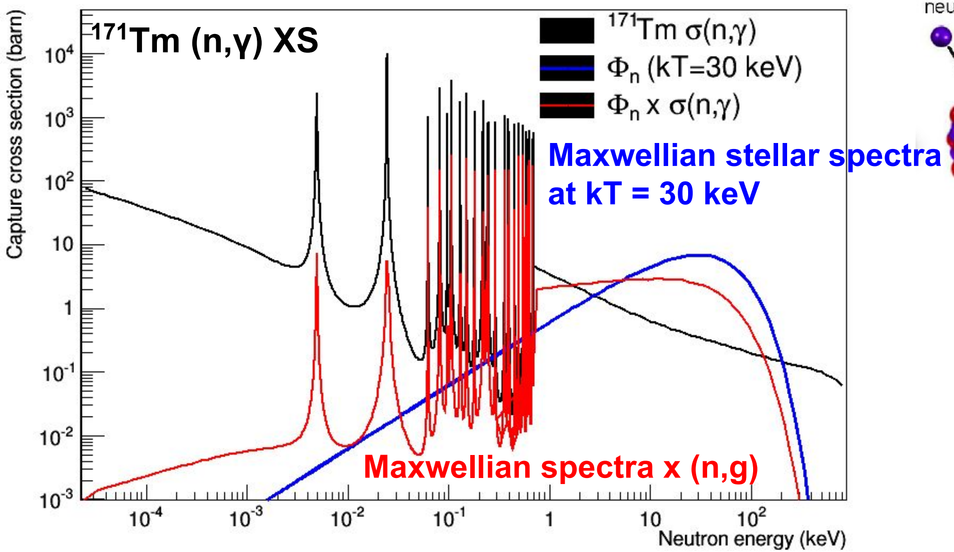
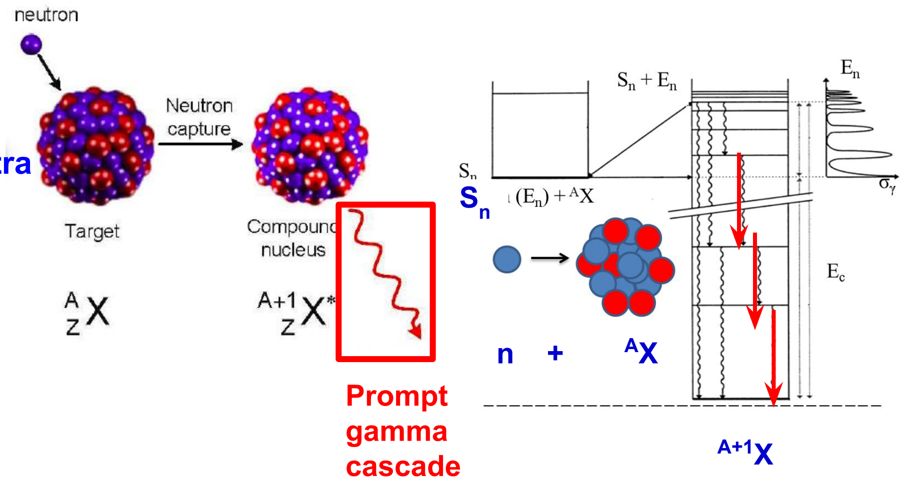
Is it possible to replicate a **Maxwellian neutron spectra in the lab**?
How do we measure **energy-dependent cross sections**?

Stellar (n,ɣ) cross sections: beams & techniques

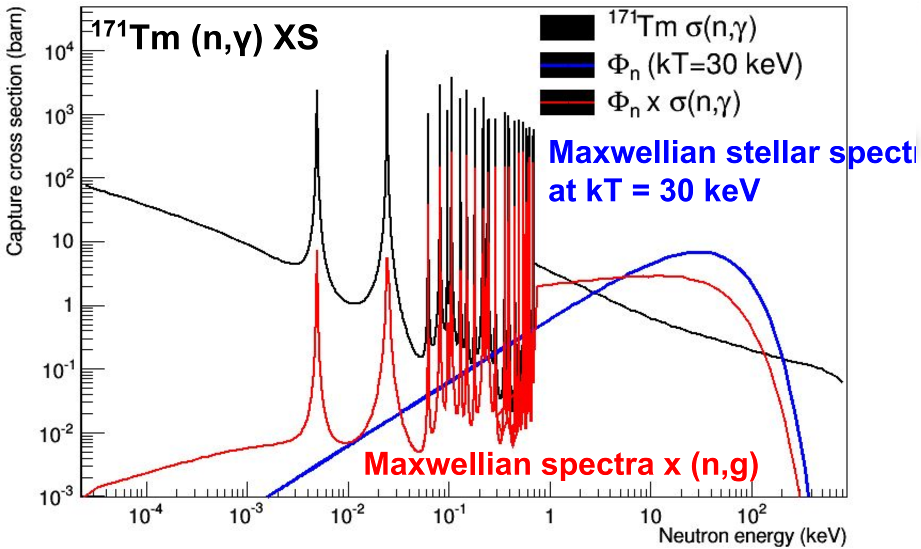


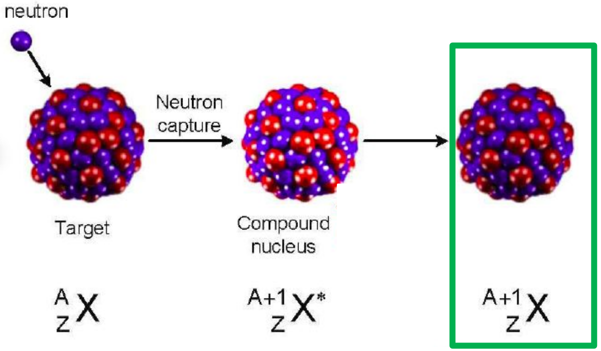


OPTION 1:

Beam: Pulsed white neutron beam + Time-of-flight technique
Technique: Measure (n,g) prompt g-ray yield vs neutron energy
Outcome: Cross section vs neutron energy → **MACS different kT**

Stellar (n,γ) cross sections: beams & techniques

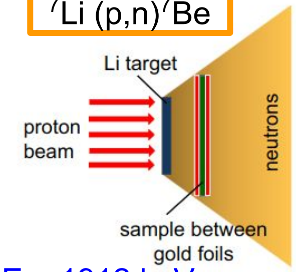




Activation: count product nuclei

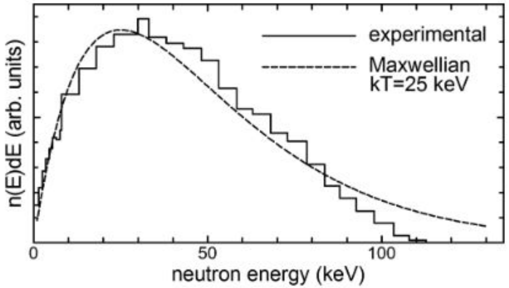
Low energy accelerator + ^{7}Li(p,n)^{7}Be

^{7}Li (p,n)^{7}Be



Ep=1912 keV

Quasi-maxwellian @ 25 keV



A. Wallner, Phys. Rev. C 93, 045803 (2016)

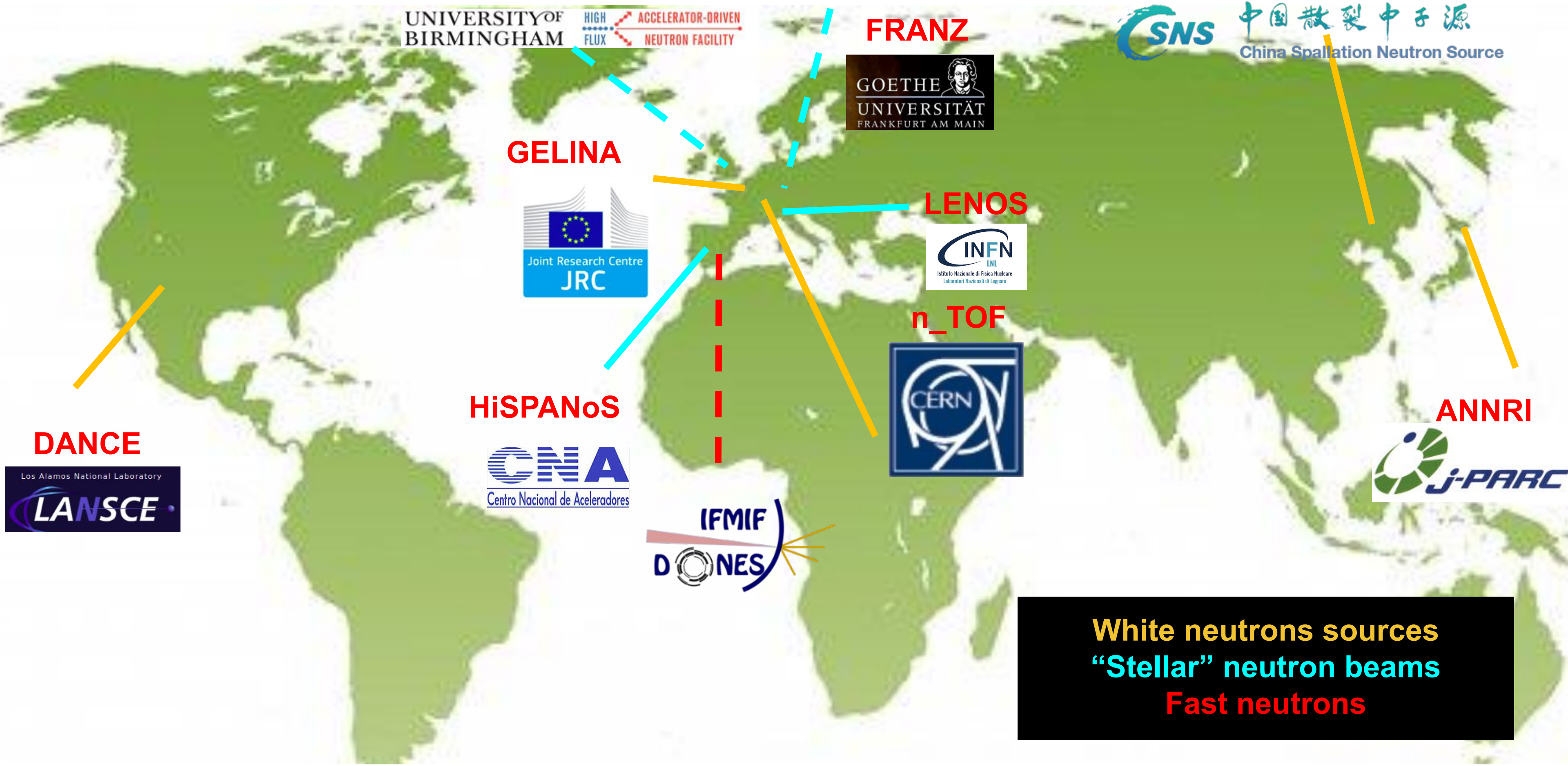
OPTION 2:

Beam: Quasi-maxwellian spectra
Technique: Count (n,g) product nuclei (activation)
Outcome: Integral XS (SACS) → **MACS at kT = 25 keV**

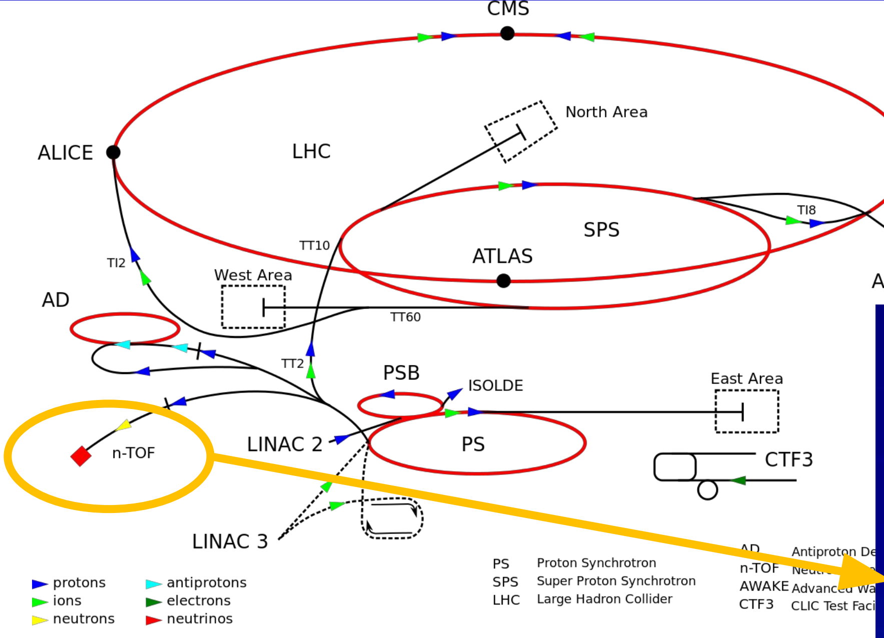
nTOF

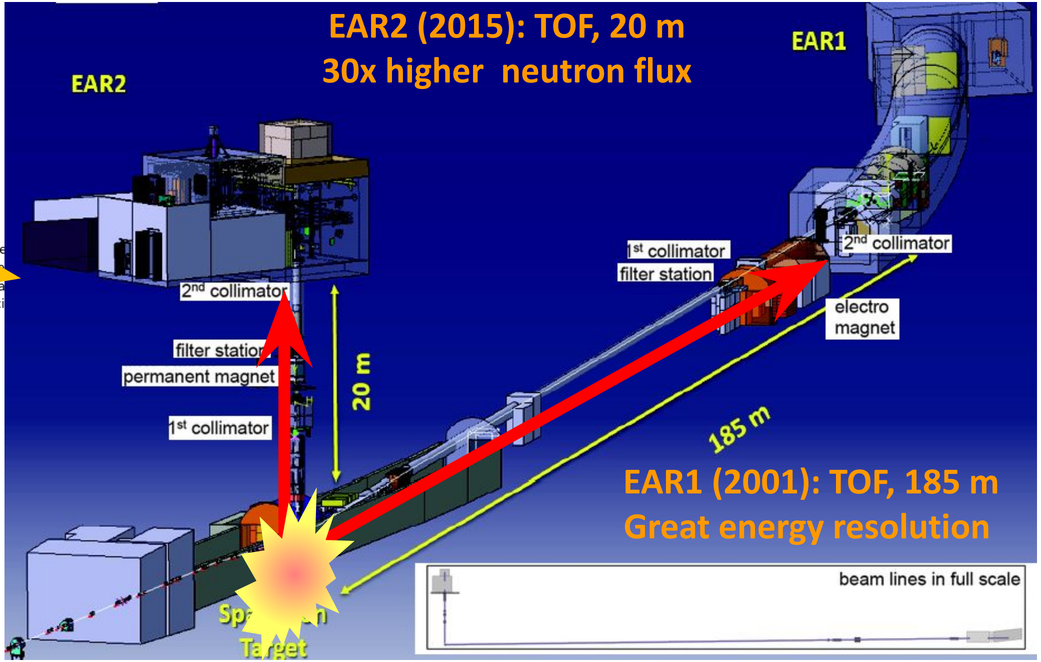
Neutron beams facilities (for astrophysics)

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

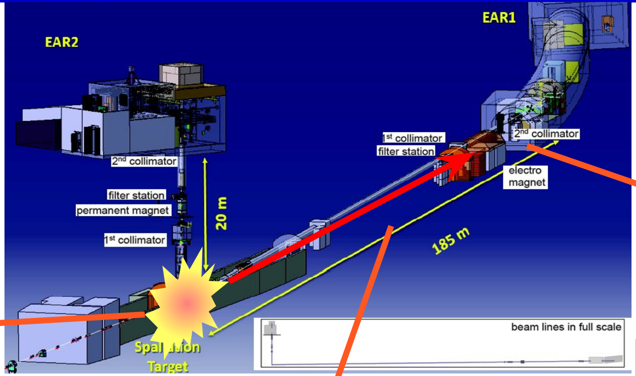


Time-of-flight facilities





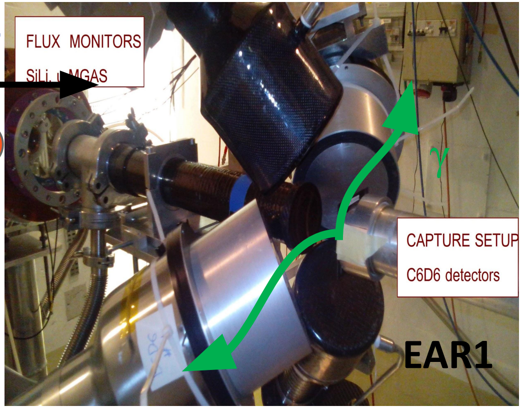
The Time-of-flight (TOF) technique



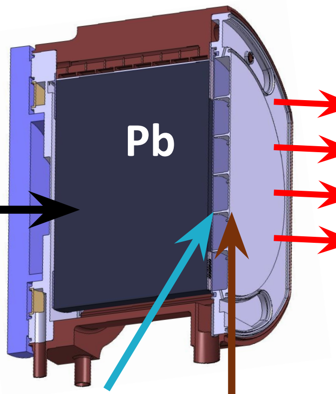
EXPERIMENTAL AREA

SPALLATION TARGET

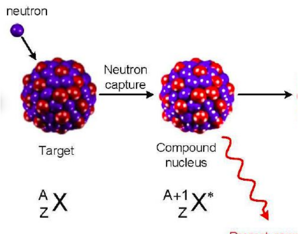
Flightpath (L=185 m)



PS Protons (20 GeV/c)



Neutron energies (meV to GeV)



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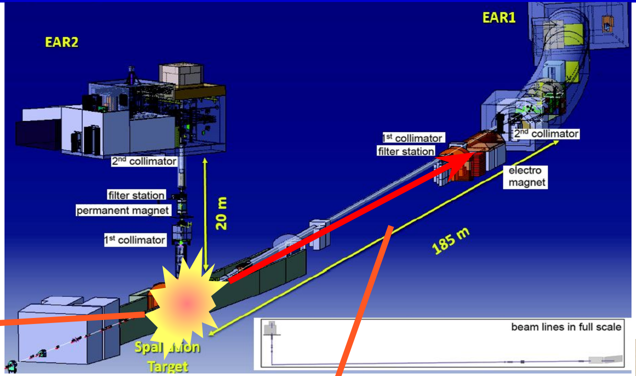

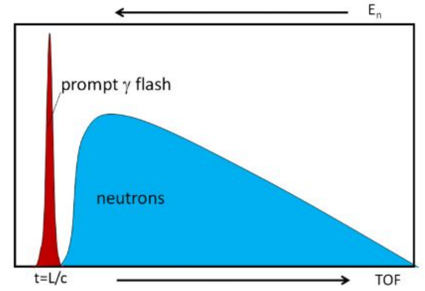

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Flightpath (L=185 m)

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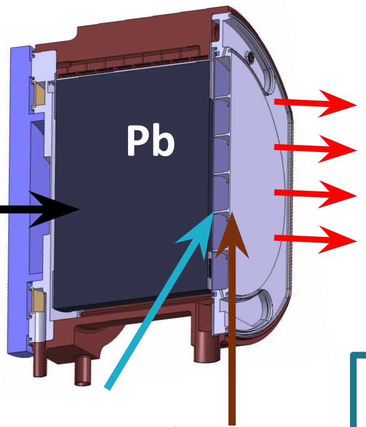
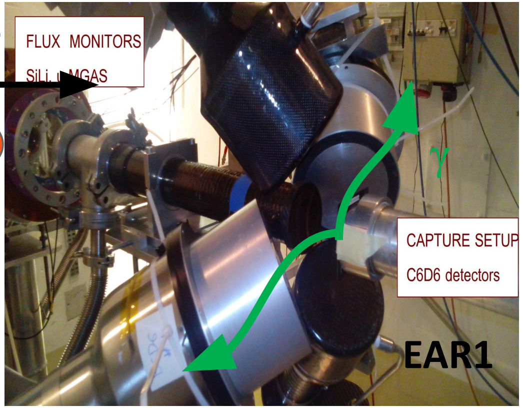




Neutron energies (meV to GeV)

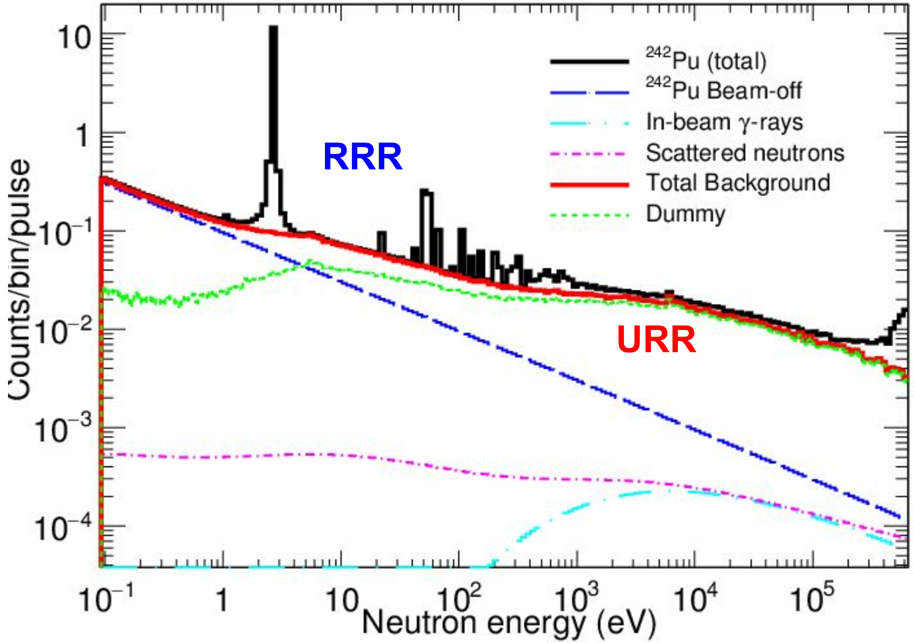
Time to energy conversion	Neutron time-of-flight
$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$	$t = t_m - (t_\gamma - L/c)$

Time reference: t_γ
Arrival of prompt γ-rays

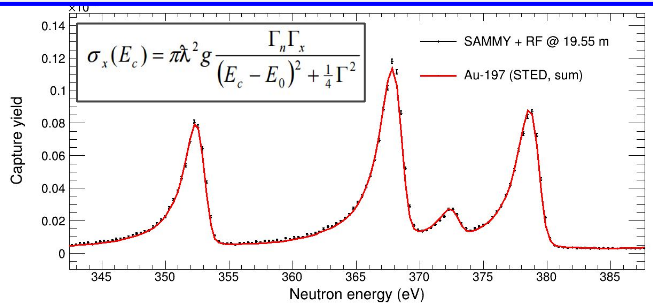
Neutron capture via TOF technique

$$Y(E_n) = F^{thr}_{norm} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n) \cdot \varepsilon_c}$$

Capture yield:
Many points + experimental effects

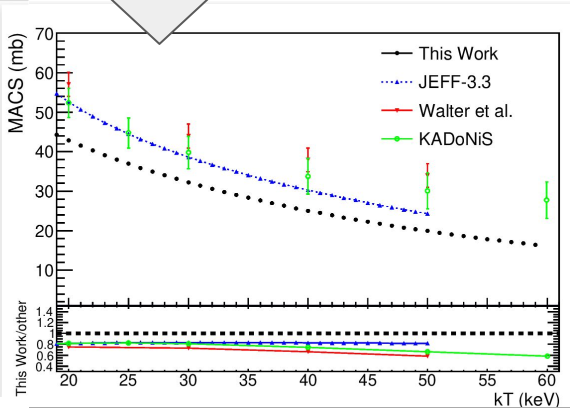


Cross-section: R-Matrix Analysis
Fit yield & extract cross section with Few parameters per resonance (E, Jp, Γ)



MACS from:

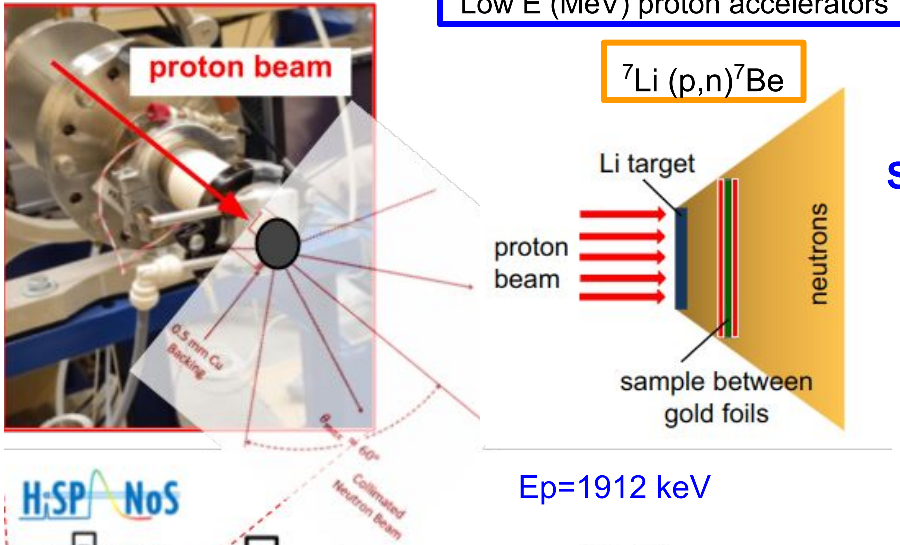
- Resonance (**RRR**)
- XS vs En (**URR**)



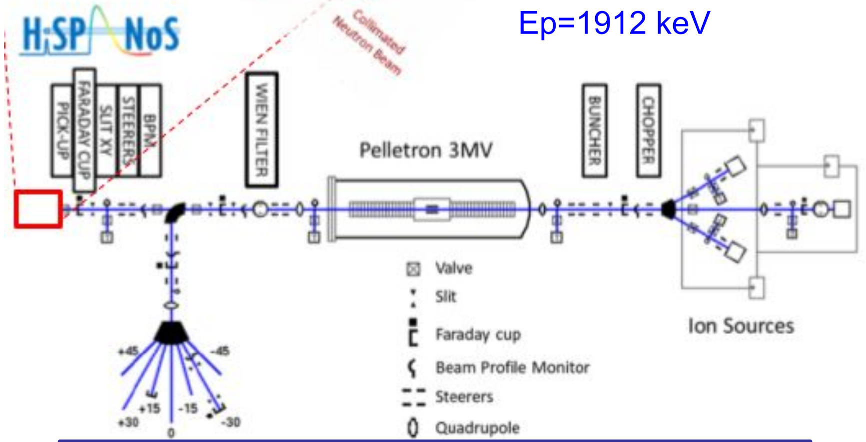
Activation in stellar beam facilities

Low E (MeV) proton accelerators

$^{7}Li\ (p,n)^{7}Be$



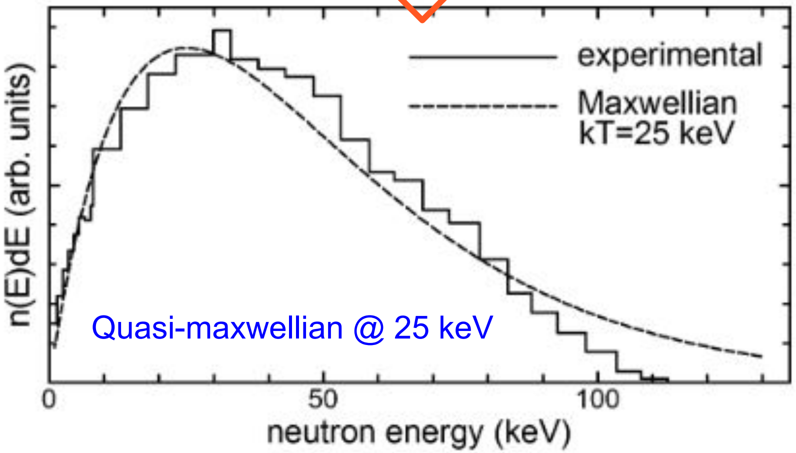
Ep=1912 keV



Adapted from P. Pérez-Matoto, PhD Thesis (U. Sevilla, 2024)

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)

STANDARD METHOD



Quasi-maxwellian @ 25 keV

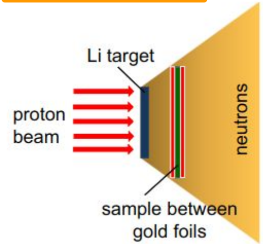
A. Wallner, Phys. Rev. C 93, 045803 (2016)

HiSPANoS · LENOS Legnaro Neutron Source · Goethe Universität Frankfurt am Main · High Flux Accelerator-Driven Neutron Facility

Activation in stellar beam facilities

Low E (MeV) proton accelerators

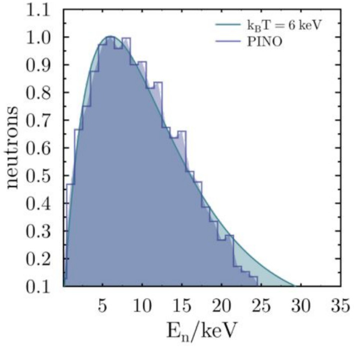
$^{7}Li\ (p,n)^{7}Be$



+ RECENT: STELLAR ENERGIES

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)

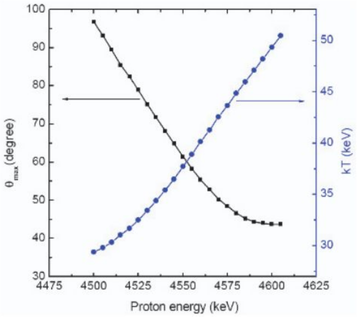
Lower s-process temperatures with ring-shaped samples

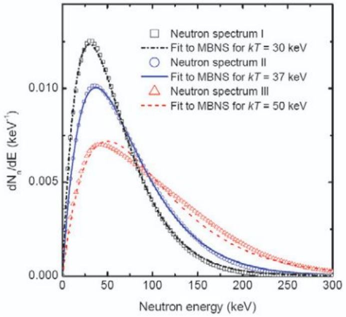


T. Heftrich, EPJ Web of Conferences 279, 06011 (2023)

Legnaro Neutron Source

Tuning the kT with the angle at higher proton energies

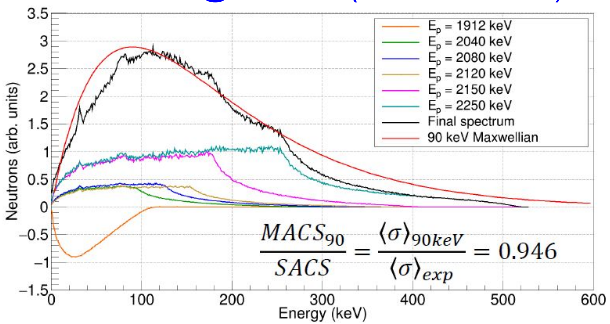




P. Mastinu, Physics Procedia 26, p.261-273 (2012)

HiSPANoS

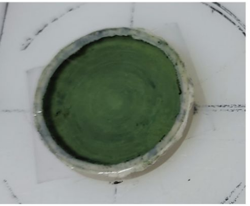
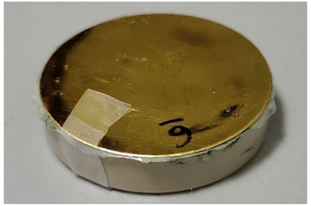
Different Ep combined → MACS @ 90 keV (massive stars)

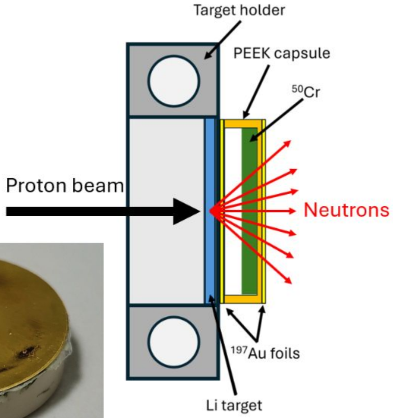


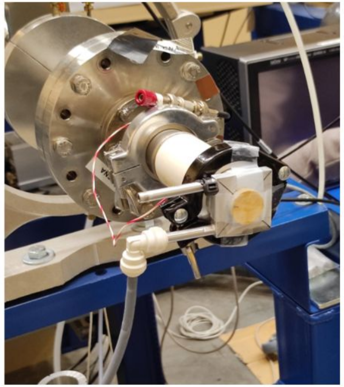
P. Pérez-Maroto, EPJ Web of Conferences 294, 01004 (2024)

Stellar (n,g) activations: Method

2) Irradiation in the neutron beam

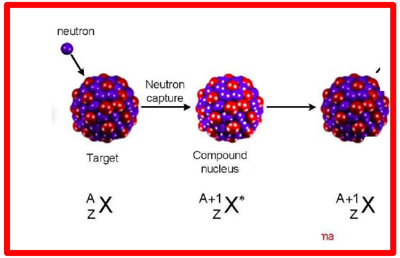







1) Main sample + reference/normalization samples

P. Pérez-Maroto, [PhD Thesis (U. Sevilla, 2024)]

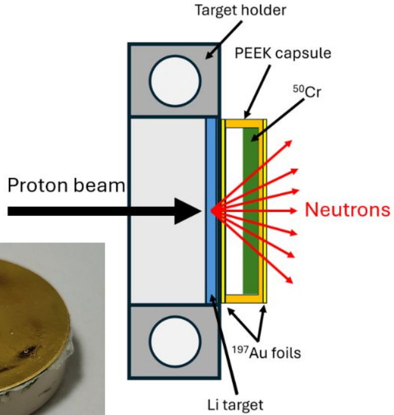


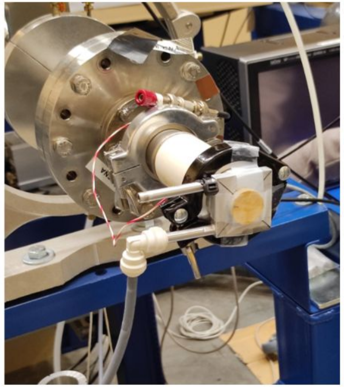
Activation:

1) Irradiation in neutron beam →$^{A}X(n,g)^{A+1}X$

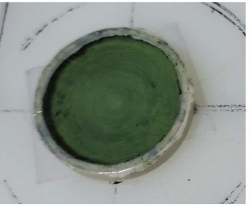
Stellar (n,g) activations: Method

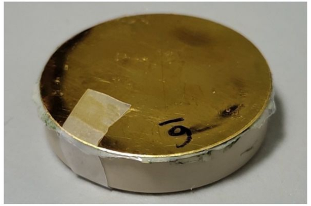
2) Irradiation in the neutron beam





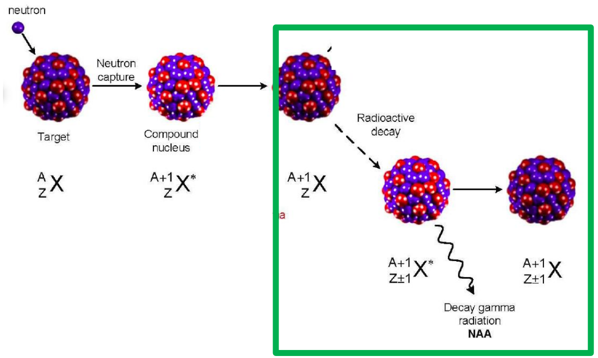
3) Decay measurement at:
High resolution station (HPGe, LaBr3)





1) Main sample and reference/normalization samples sample

P. Pérez-Maroto, [PhD Thesis (U. Sevilla, 2024)]



Only applies for unstable ^{A+1}X!

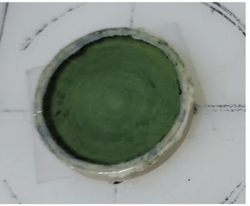
Activation:

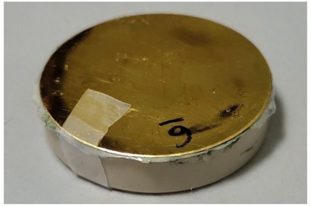
1) Irradiation in neutron beam → $^{A}X(n,g)^{A+1}X$

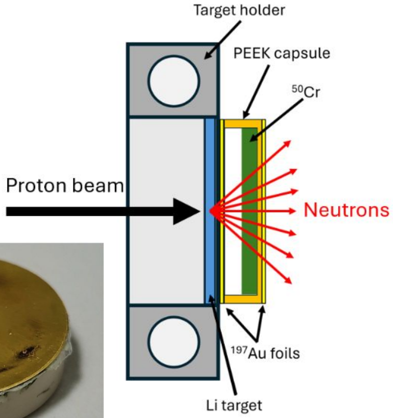
2) Count number of (n,g) reactions from the decay of ^{A+1}X

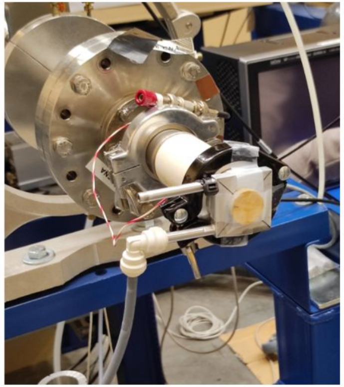
Stellar (n,g) activations: Method

2) Irradiation in the neutron beam



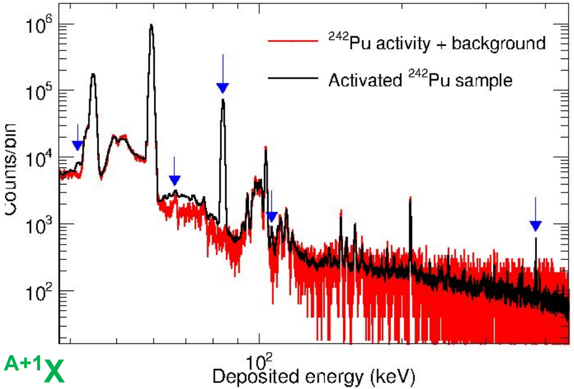






1) Main sample and reference samples (Au-197)

P. Pérez-Maroto, [PhD Thesis (U. Sevilla, 2024)]



3) Decay measurement at: resolution station (HPGe, LaBr3)

4) MACS derived from number of decays
(relative to reference MACS, e.g. Au-197)

Activation:

1) Irradiation in neutron beam → $^{A}X(n,g)^{A+1}X$

2) Count number of (n,g) reactions from the decay of ^{A+1}X

Outline

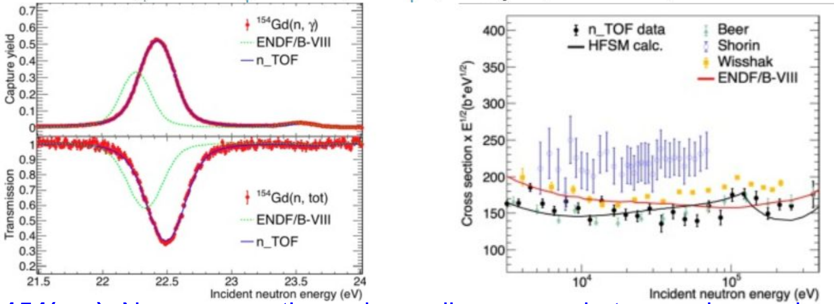
- The synthesis of (heavy) elements in the universe
- Nucleosynthesis & neutron capture: data needs for unstable and stable nuclei
- Direct neutron capture reactions: from stars to the lab
- State-of-the art & future of direct neutron capture reactions

s-only isotopes: Benchmark for s-process models

Physics Letters B 804 (2020) 135405

Measurement of the ^{154}Gd(n,γ) cross section and its astrophysical implications

A. Mazzone [a,b], S. Cristallo [c,d], O. Aberle [e], G. Alaerts [f], V. Alcayne [g], S. Amaducci [h,i],



Gd-154(n,g): New ross section reduces discrepancy between observed and calculated solar s-only abundances

(Some) recent (n,g) on key stable s-process isotop.

CSIC
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s-only isotopes: Benchmark for s-process models

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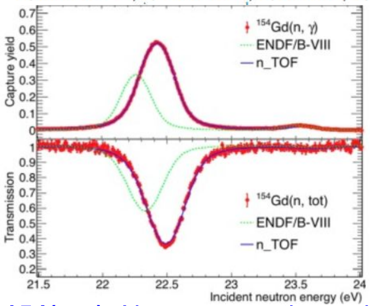
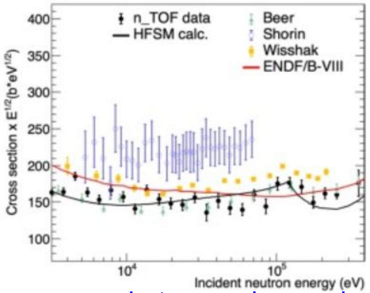
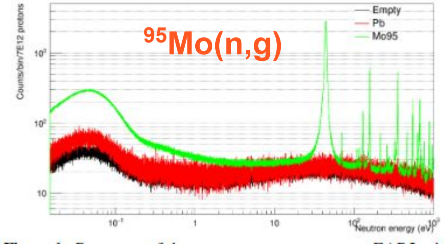
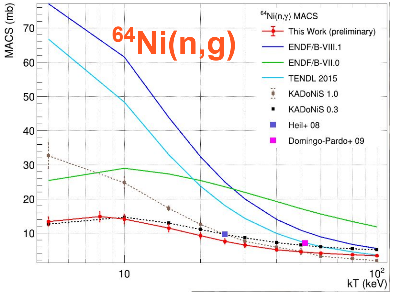




Gd-154(n,g): New ross section reduces discrepancy between observed and calculated solar s-only abundances

Ni, and Mo-isotopic anomalies in presolar SiC grains





+ Details: Talks by M. Spelta & R. Mucciola

(Some) recent (n,g) on key stable s-process isotop.

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s-only isotopes: Benchmark for s-process models

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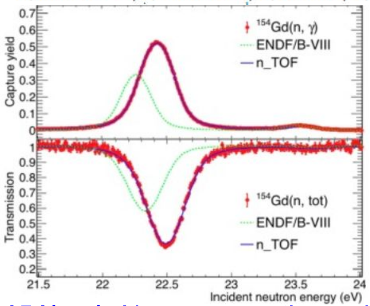
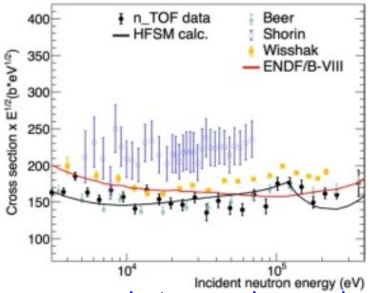




Gd-154(n,g): New ross section reduces discrepancy between observed and calculated solar s-only abundances

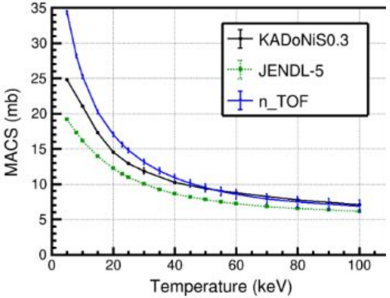
n-magic nuclei: s-process bottlenecks, very small (n,g) XS

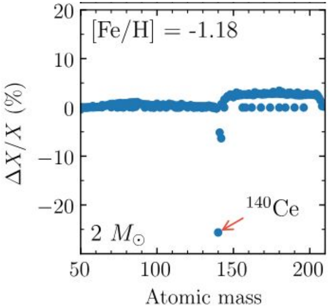
PHYSICAL REVIEW LETTERS 132, 122701 (2024)

Editors' Suggestion Featured in Physics

Measurement of the ^{140}Ce(n,γ) Cross Section at n_TOF and Its Astrophysical Implications for the Chemical Evolution of the Universe

S. Amaducci,[1] N. Colonna,[2] L. Cosentino,[1] S. Cristallo,[3,4] P. Finocchiaro,[1] M. Krtička,[5] C. Massimi,[6,7]

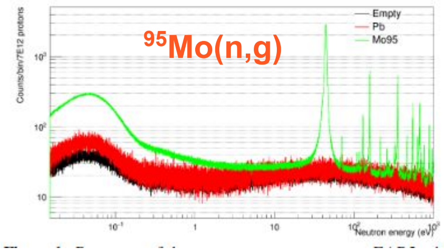


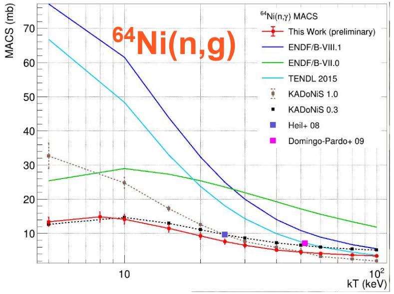


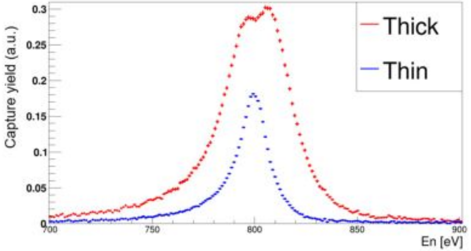
MACS (30 keV) 13.15 mb

Ce-140(n,g): The new XS leads to an even smaller Ce-abundance

Ni, and Mo-isotopic anomalies in presolar SiC grains







One of the lowest MACS (25 keV) 2.89 mb!

Bi-209(n,g): repeat w/ high precision less in-beam g-rays (EAR2) and thinner sample (MS) and higher sensitivity setup (sTED)

+ Details: Talks by M. Spelta & R. Mucciola

unstable (n,g) branching-points: 10y ago

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REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 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

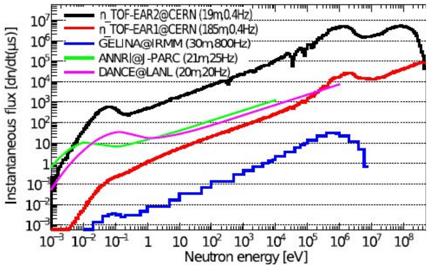
F. Kaeppeler et al., Rev. Mod. Phys 83, 157 (2011)

Challenging measurements: Radioactive isotopes, low masses

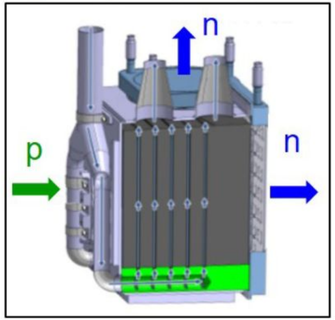
Before 2015: only **2/21** of the key s-process isotopes measured **by TOF**

unstable branching-points: recent advances

Upgrade I: instantaneous neutron flux → **n_TOF EAR2 (+ Target upgrade)**



Target#3 (2021-present)



n-TOF EAR2: highest Instantaneous flux **(FOM for neutron-to-activity ratio)**

x300 instantaneous flux of n_TOF-EAR1!

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

J.A. Pavón-Rodríguez et al., Eur. Phys. J. *A (arxiv) (2025)*

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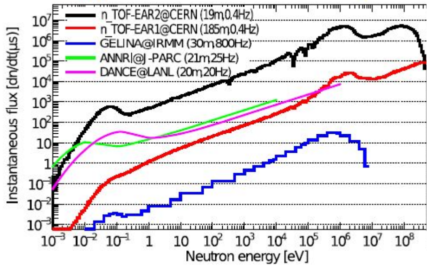

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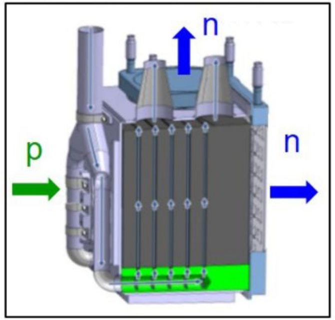

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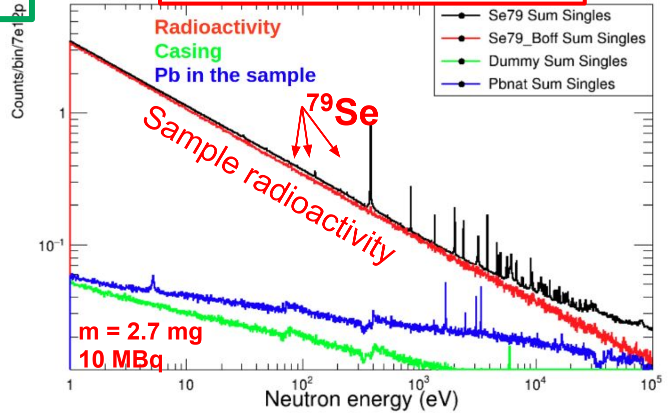
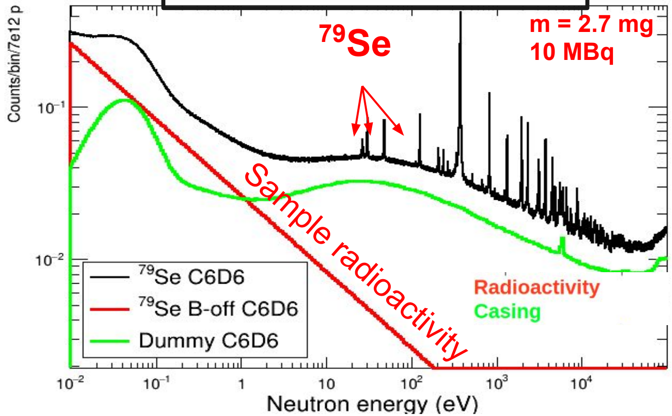
J.A. Pavón-Rodríguez et al., Eur. Phys. J. A (arxiv) (2025)

$^{79}Se(n,\gamma)$ @ n_TOF EAR1

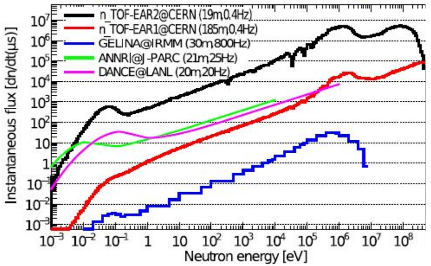


$^{79}Se(n,\gamma)$ @ n_TOF EAR2



unstable branching-points: recent advances

Upgrade I: instantaneous neutron flux → **n_TOF EAR2 (+ Target upgrade)**



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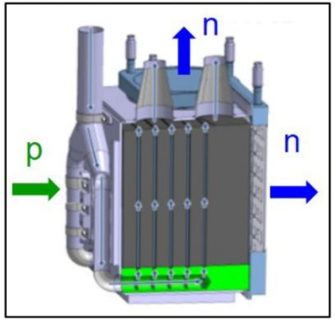


n-TOF EAR2: highest Instantaneous flux **(FOM for neutron-to-activity ratio)**

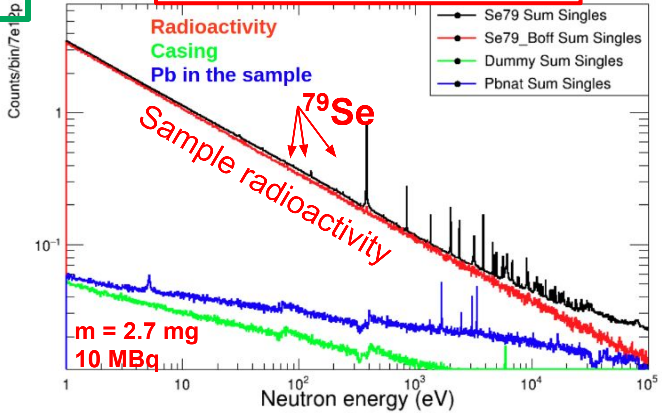
x300 instantaneous flux of n_TOF-EAR1!

New generation of detectors

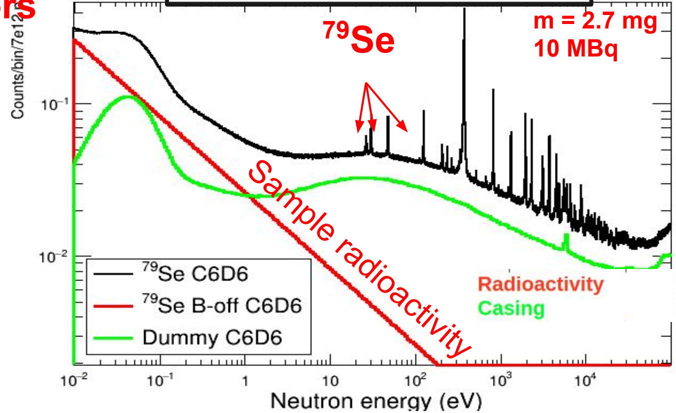
J. Lerendegui-Marco et al., Eur. Phys. J. A **52**, 100 (2016).

J.A. Pavón-Rodríguez et al., Eur. Phys. J. A (arxiv) (2025)

^{79}Se(n,γ) @ n_TOF EAR1

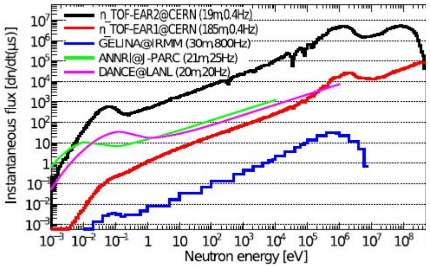


^{79}Se(n,γ) @ n_TOF EAR2

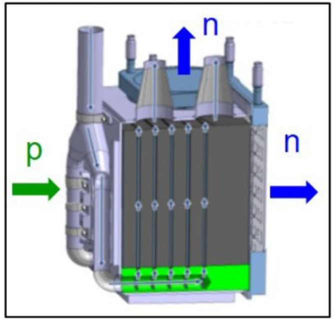


unstable branching-points: recent advances

Upgrade I: instantaneous neutron flux → **n_TOF EAR2 (+ Target upgrade)**



Target#3 (2021-present)



n-TOF EAR2: highest Instantaneous flux **(FOM for neutron-to-activity ratio)**

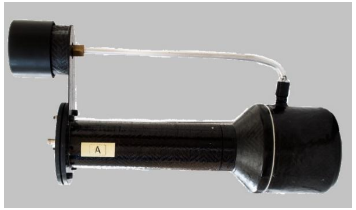
x300 instantaneous flux of n_TOF-EAR1!

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

J.A. Pavón-Rodríguez et al., *Eur. Phys. J. A (arxiv) (2025)*

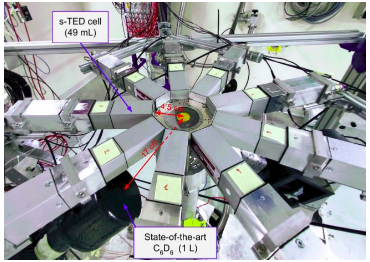
New generation of detectors

Upgrade II: detectors for high C. rates (+ enhanced signal-to-bckg)



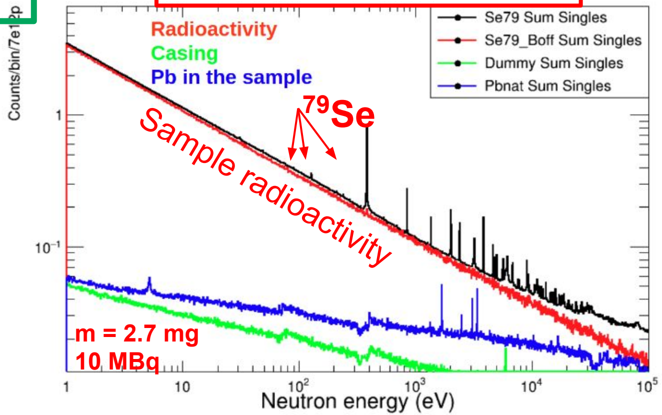
Large TED (~1L)
C.R. max ~ 20 MHz

s-TED (~50mL)
C.R. max ~1 MHz

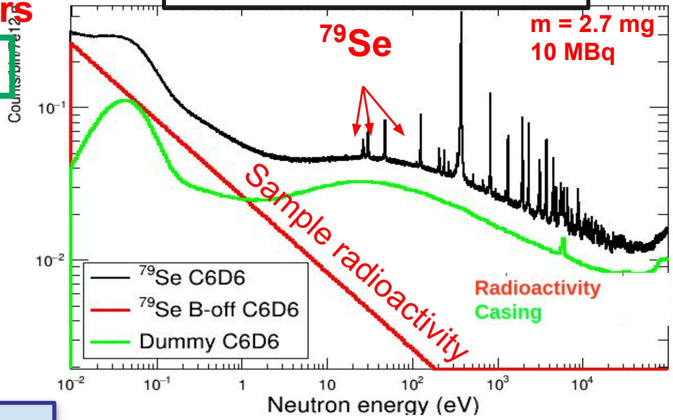


V. Alcayne , EPJ Web of Conferences **284**, 01043 (2023)

^{79}Se(n,γ) @ n_TOF EAR1



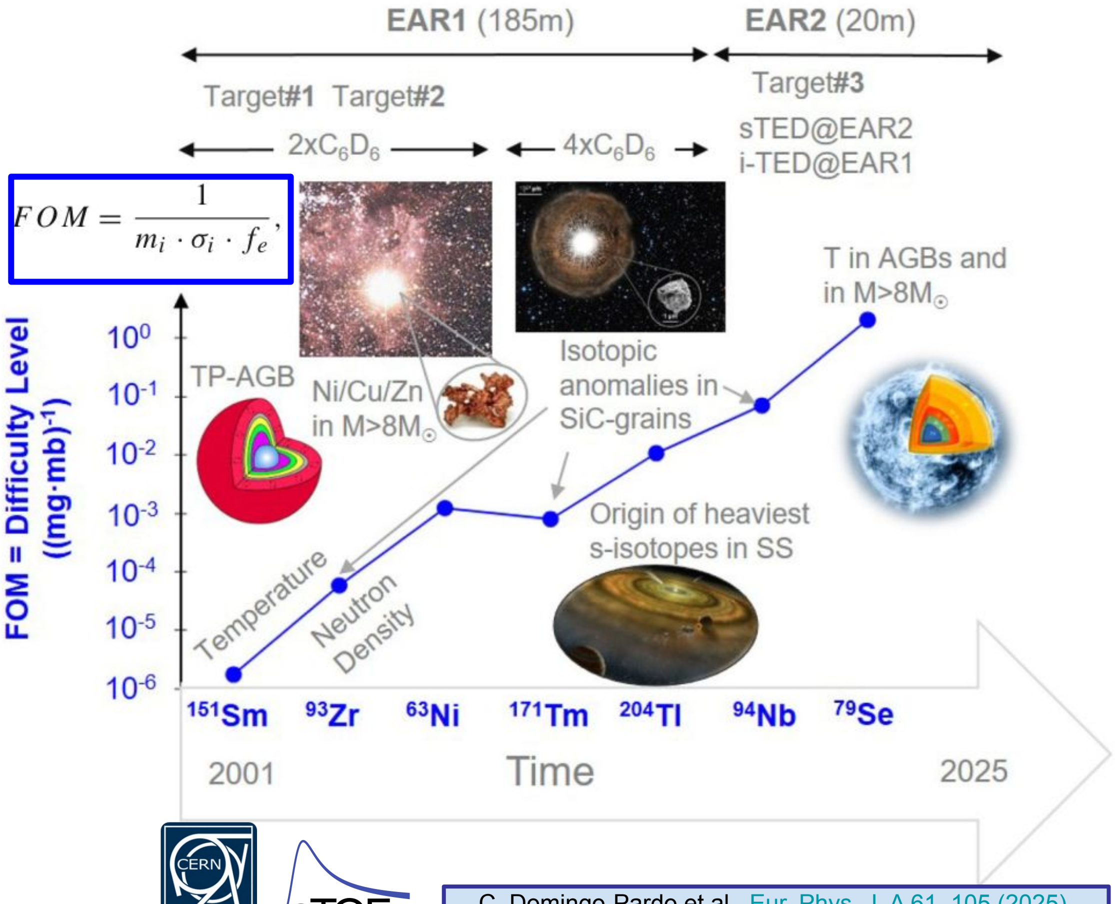
^{79}Se(n,γ) @ n_TOF EAR2



unstable branching-point isotopes: state-of-the-art

Facility upgrades
(EAR2, new spallation target, …)
+
Advanced detectors
=
ENHANCED DIFFICULTY LEVEL

$$FOM = \frac{1}{m_i \cdot \sigma_i \cdot f_e},$$



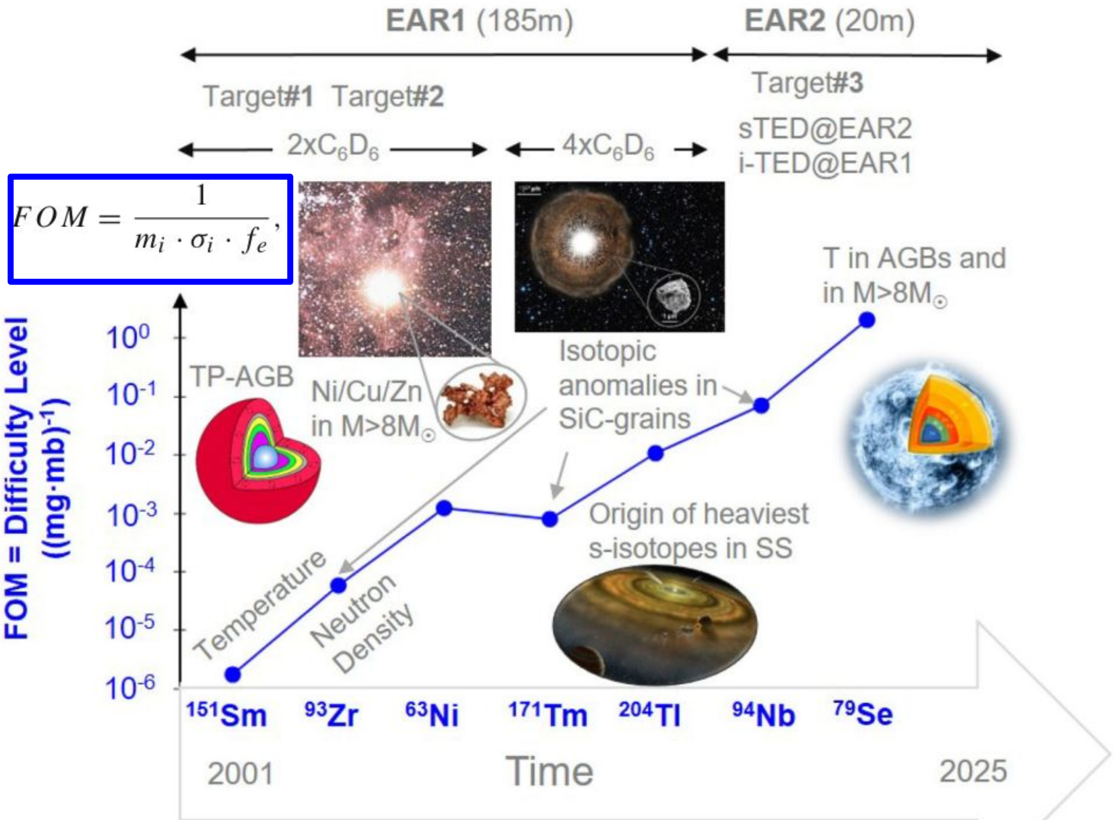
C. Domingo-Pardo et al., Eur. Phys. J. A 61, 105 (2025).

unstable branching-point isotopes: state-of-the-art

Facility upgrades
(EAR2, new spallation target, …)
+
Advanced detectors
=
ENHANCED DIFFICULTY LEVEL

Before 2015: only **few** key s-process branchings measured **by TOF:**
^{151}Sm, ^{93}Zr, ^{63}Ni
2015-2018: **^{171}Tm (TOF & Act), ^{204}Tl (TOF) , ^{147}Pm (Act)**
Very recent progresses: **^{79}Se, ^{94}Nb**

$$FOM = \frac{1}{m_i \cdot \sigma_i \cdot f_e},$$



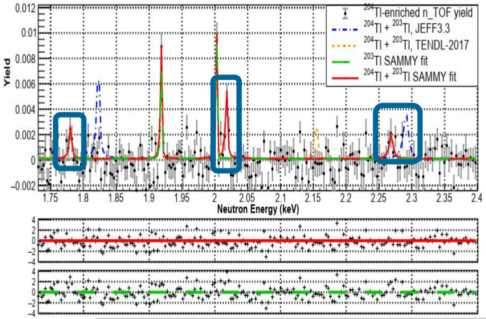
C. Domingo-Pardo et al., Eur. Phys. J. A 61, 105 (2025).

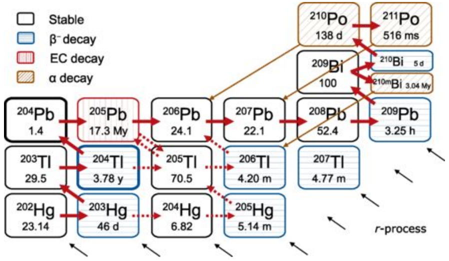
unstable branching-point isotopes: state-of-the-art

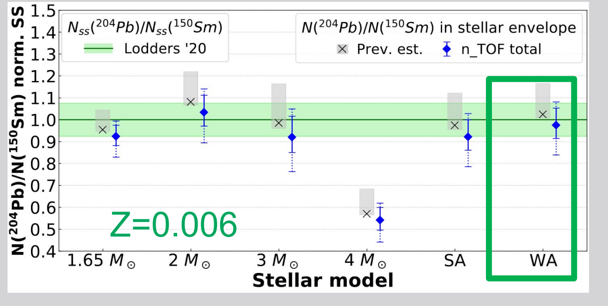
Tl-204(n,ɣ)

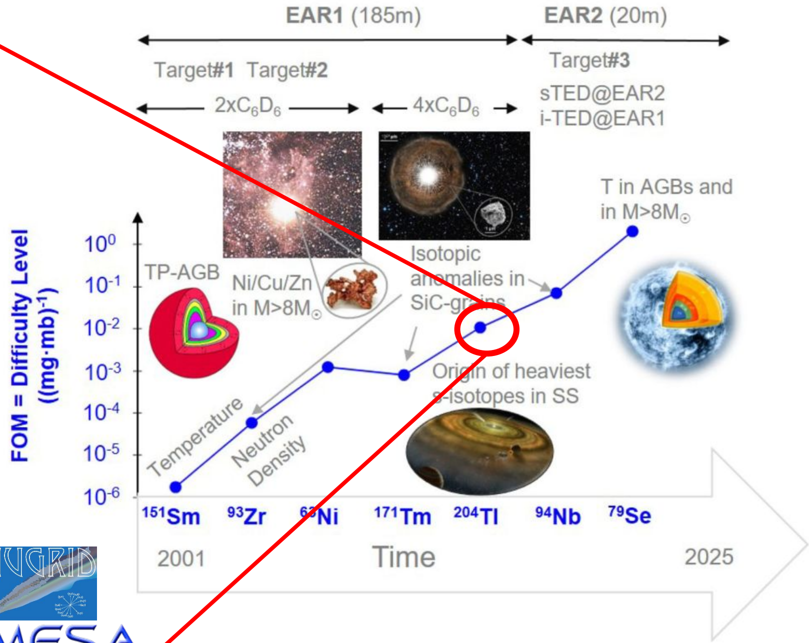
First measurement ever
TOF-unique case

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









Uncertainty in the abundance of the heaviest s-only 204Pb has been reduced from ~30% down to +8%/−6%

A. Casanovas, *Phys. Rev. Letters* ***133***, *052702 (2024).*

unstable branching-point isotopes: state-of-the-art

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

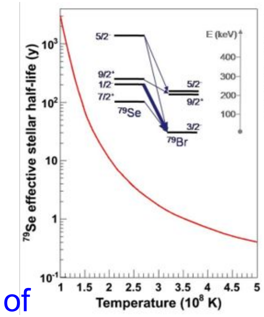
Se-79(n,γ)

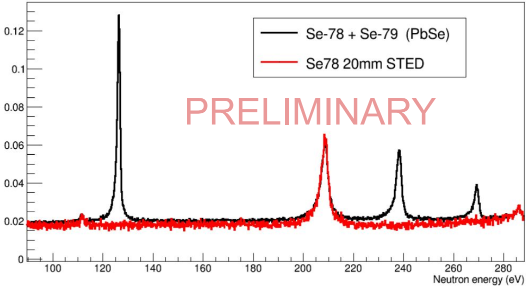
First measurement ever
TOF-unique case

m = 2.6 mg
(+3 g ^{208}Pb^{78}Se)
σ = 263(43) mb

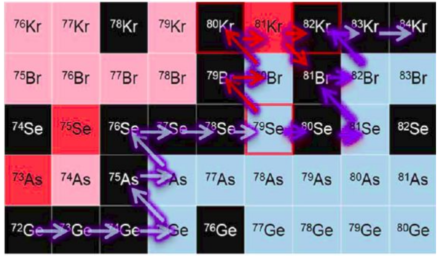
PAUL SCHERRER INSTITUT
PSI

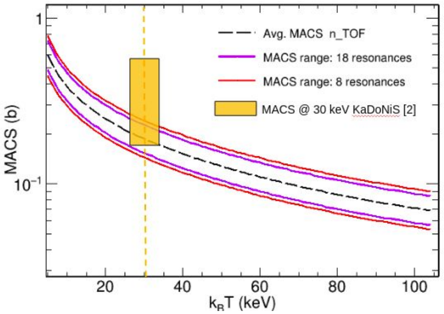
NEUTRONS FOR SOCIETY

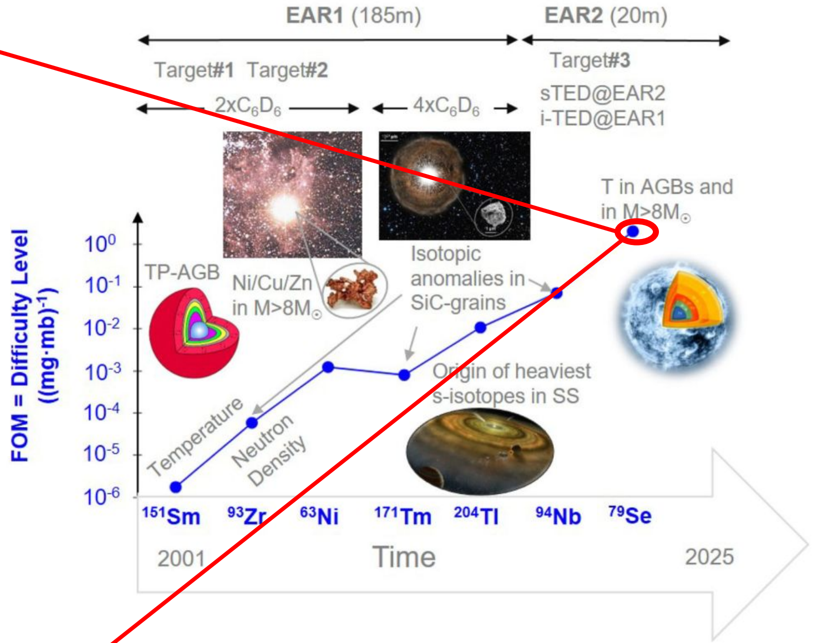




Thermal conditions of weak s-process







Expected: 10-15 Resonances → experimental constraint of MACS down to~30%

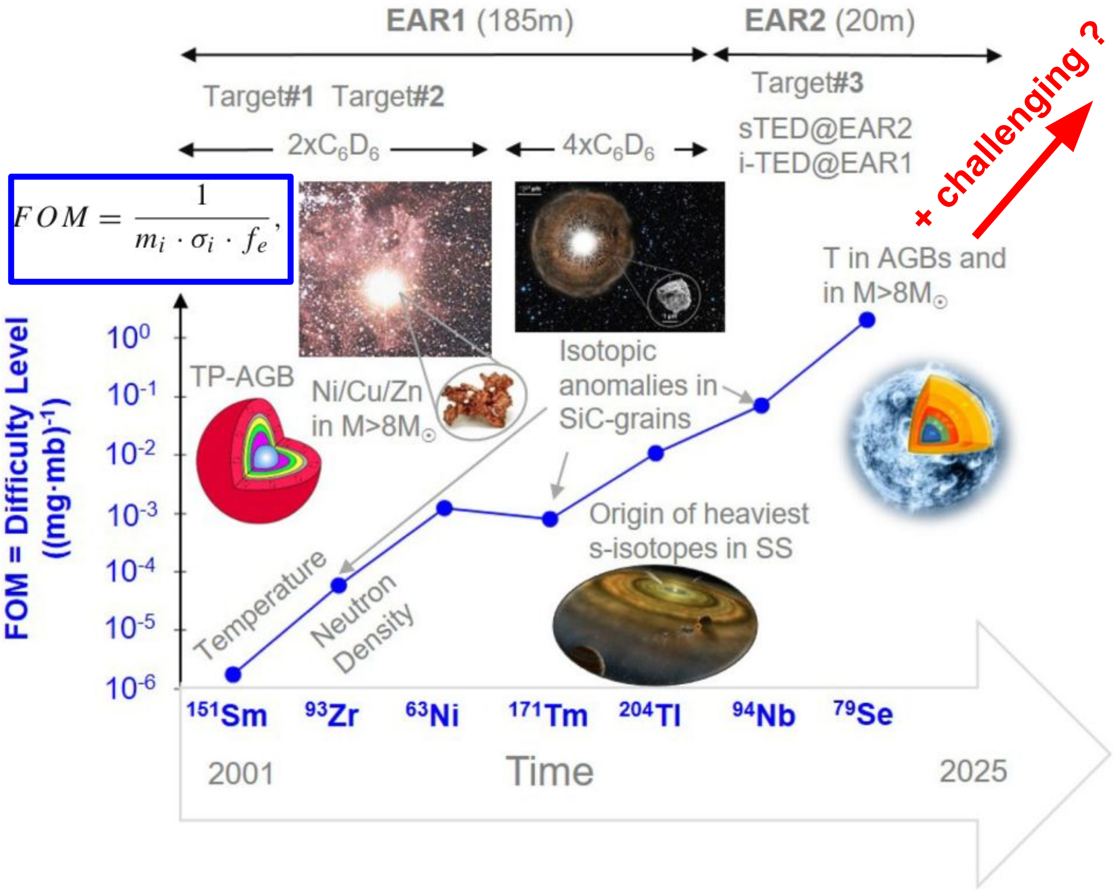
Lerendegui-Marco, J. et al., EPJ Web Conf. 279, 13001 (2023).

unstable branching-point isotopes: state-of-the-art

Challenges unstable s-process branching points:

1. TOF requires mass >= 5×10^{17}-10^{18} atoms (EAR2)
2. Mass/Activity: **radiation hazard & activity background**

→Many (n,g) reactions still not accessible via TOF



unstable branching-point isotopes: state-of-the-art

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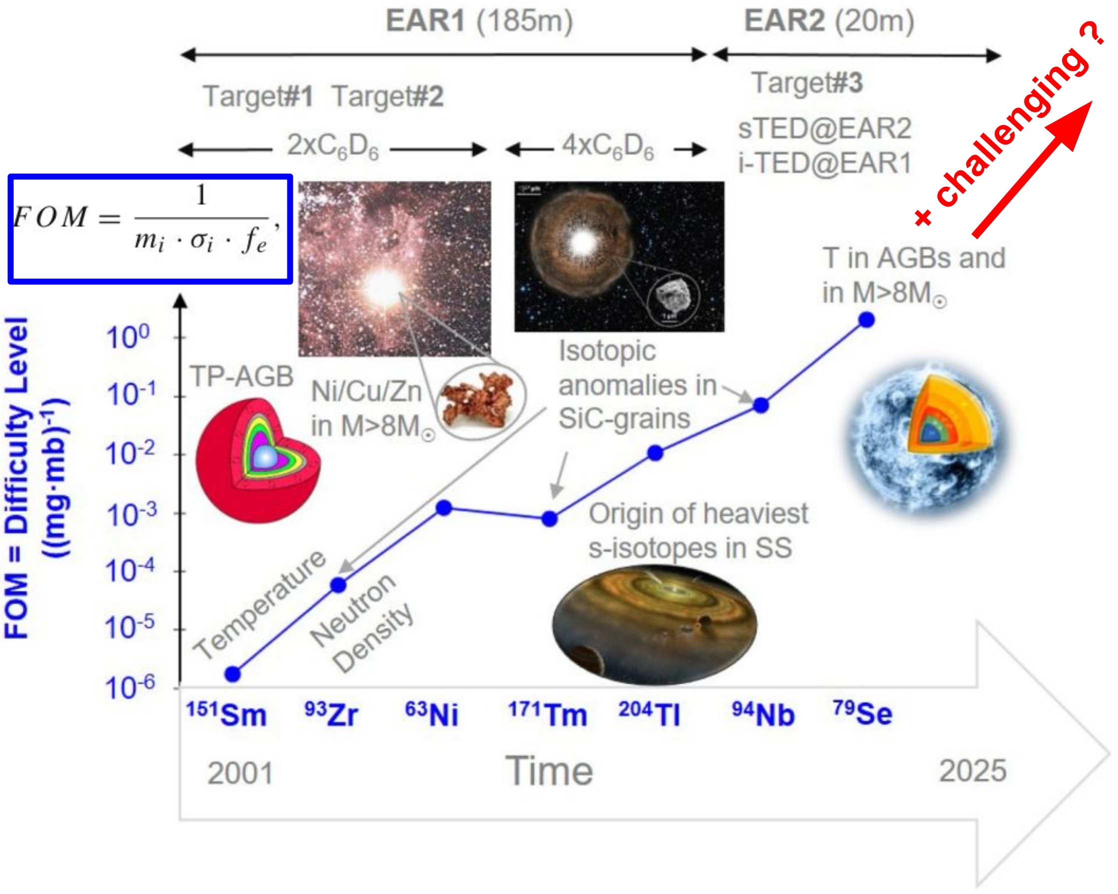
1. TOF requires mass >= 5×10^{17}-10^{18} atoms (EAR2)
2. Mass/Activity: **radiation hazard & activity background**

→Many (n,g) reactions still not accessible via TOF

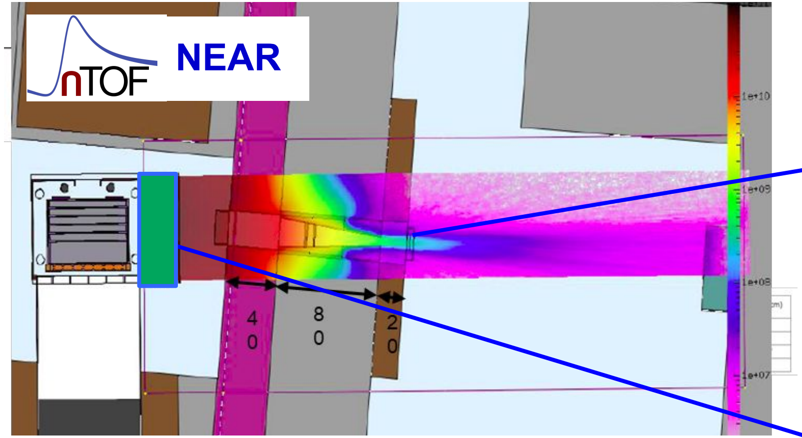
SOLUTION:
Activation in high flux facilities
(HIGHER SENSITIVITY → LOWER MASS REQUIRED)

$$FOM = \frac{1}{m_i \cdot \sigma_i \cdot f_e},$$

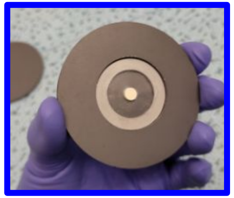


Short-term future of (n,g) on unstable isotopes

n_TOF NEAR: (n,g) activations with very high flux (x~100 EAR2): small masses, unstable isotopes

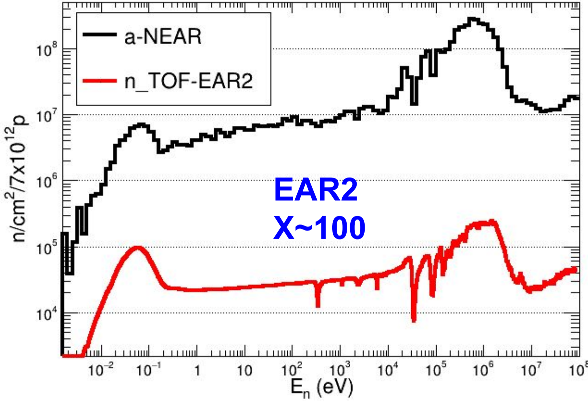


9x10^{8} n/cm2/pulse → **Mass limit ~ 10^{15} atoms**

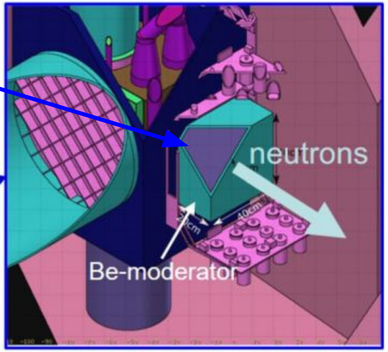


$^{10}B_4C$ Filters

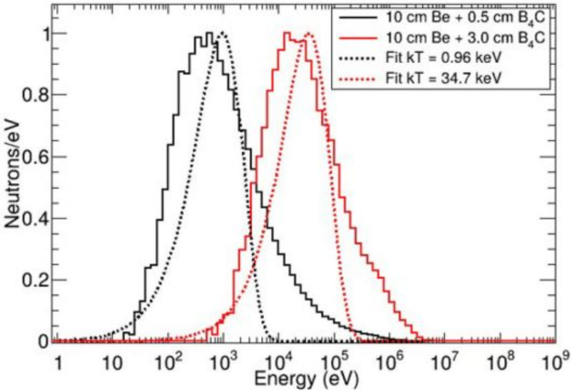
Different Stellar temperatures kT:0.1~500 keV



White neutron beam moderated + filtered →"quasi-Stellar"



Be / Al203 moderator

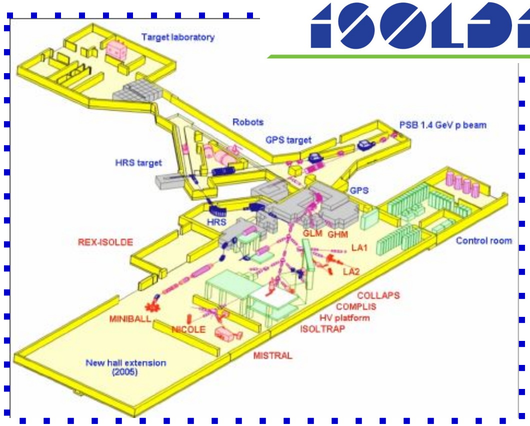


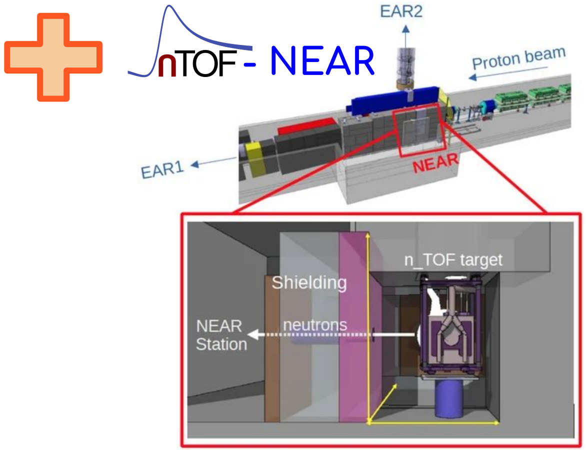
N. Patronis et al., arXiv (submitted to EPJ-A, 2025)

Short-term future of (n,g) on unstable isotopes

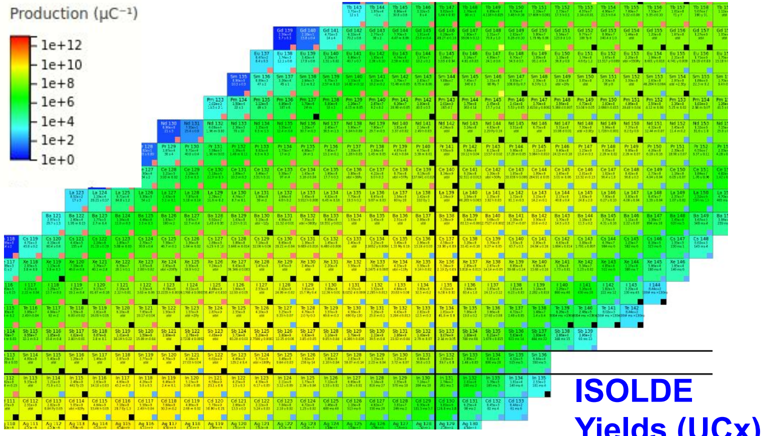
Synergy RIB-neutron facilities

Goal: Produce samples of relevant unstable nuclei at **RIB** & measure MACS at **high-flux facility**





- **Example at CERN: ISOLDE + n_TOF-NEAR**
- **High flux + proximity**: Smaller masses & shorter-lived isotopes would be accessible
- **Examples:**
  - 59Fe, 134Cs, 135Cs, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, and 181Hf (s-process),
  - Cs-137, Ce-144, 66Ni, 72Zn (i-process)



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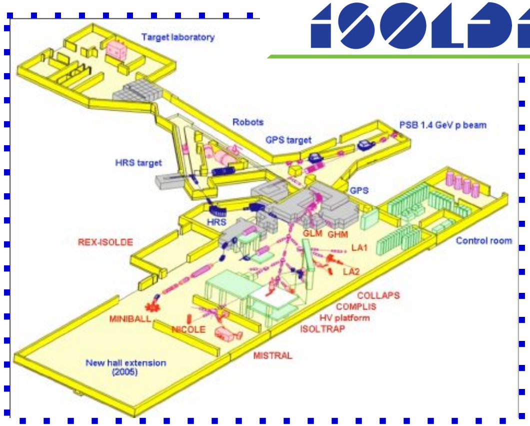

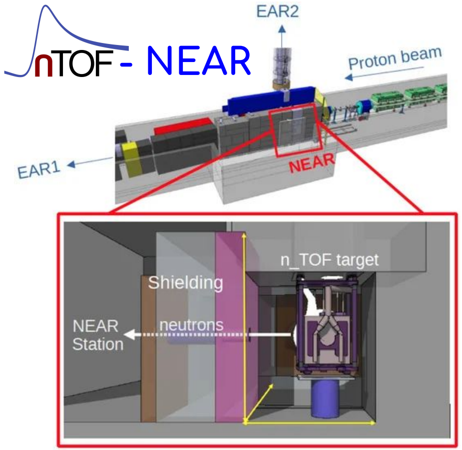

- **Example at CERN: ISOLDE + n_TOF-NEAR**
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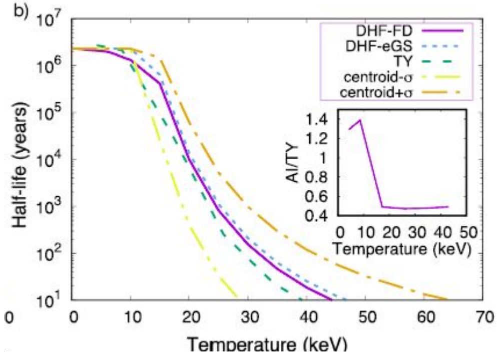
J. Lerendegui, S. Carollo et al., CERN-INTC-2022-040; INTC-P-641



Cs-135: branching s-process, New stellar beta decay rates (Taioli)

Long-term future: bright neutron flux facilities

TOF facility in astro-range: FRANZ (?)

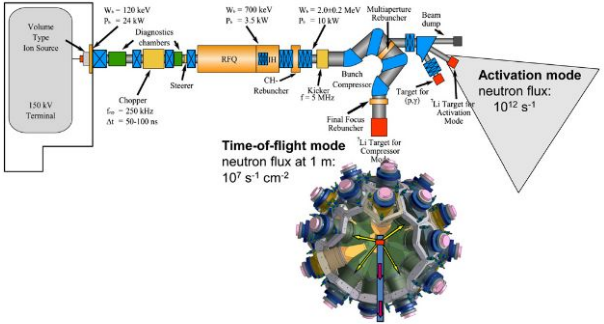
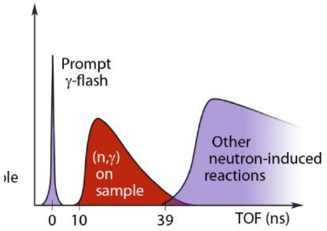


Figure 10. Sketch of the neutron facility FRANZ, currently under construction at Goethe University Frankfurt/Germany.

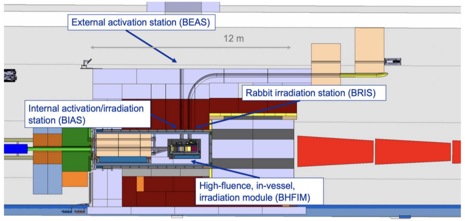


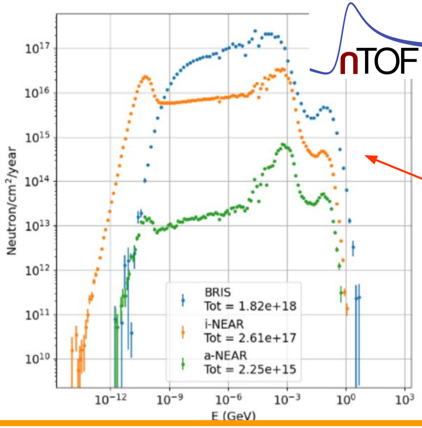
TOF (L=1m):
~1e7 n/cm2/s

50 mA p-beam + high repetition rate →
Integrated flux **~x5 (n_TOF-EAR2)**

R Reifarth *et al J. Phys.: Conf. Ser.* **940** 012024 (2018)

Activation facility nAct @ BDF/SHIP (SPS,CERN) (>2030)





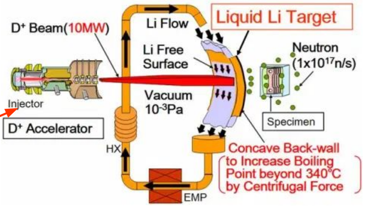
NEAR-like spectrum shaping

Flux (**a-NEAR x1000**) + fast rabbit
(T1/2>=min-h)

C. Lederer et al. (n_TOF collaboration)
, CERN-SPSC-2024-027 ; SPSC-EOI-023 (2024)

(n,g) at IFMIF-DONES? (>2033)

10 MW 40 MeV d-beam:
(10^{13}n/cm²/s) @ 14 MeV
:UNIQUE FACILITY



Ancillary science:
quasi-stellar flux
~1e9 - 4e9 n/cm2/s
(x~100 **a-NEAR**,
x~200 **HISPANoS**)

White Book on the Complementary Scientific Programme at IFMIF-DONES

Towards short-lived unstable: Future concepts

DIRECT (N,G) IN INVERSE KINEMATICS

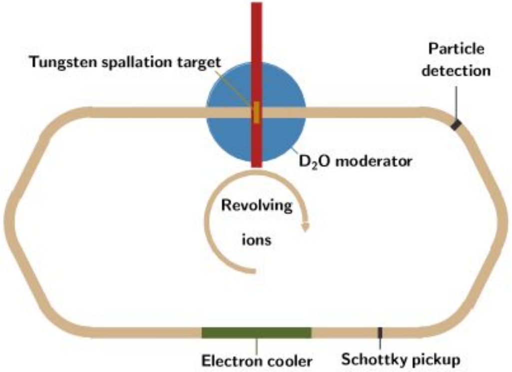
Aim: short-lived (s- and i-process)

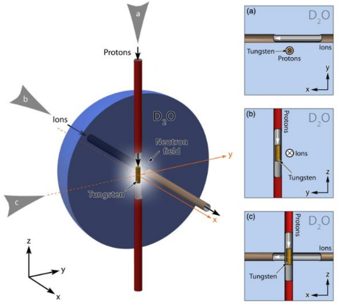
- s-process: ^{134}Cs ($t_{1/2}$ = 2.06 y), ^{147}Nd ($t_{1/2}$ = 11 d), ^{148}Pm ($t_{1/2}$ = 5.37 d), ^{153}Gd ($t_{1/2}$ = 240.4 d), ^{160}Tb ($t_{1/2}$ = 72.3 d), ^{170}Tm ($t_{1/2}$ = 128.6 d), and ^{204}Tl ($t_{1/2}$ = 3.78 y).
- i-process: ^{66}Ni ($t_{1/2}$ = 54.6 h), ^{75}Ga ($t_{1/2}$ = 126 s), ^{135}I ($t_{1/2}$ = 6.58 h), ^{141}Ba ($t_{1/2}$ = 18.27 m), and ^{141}La ($t_{1/2}$ = 3.92 h).

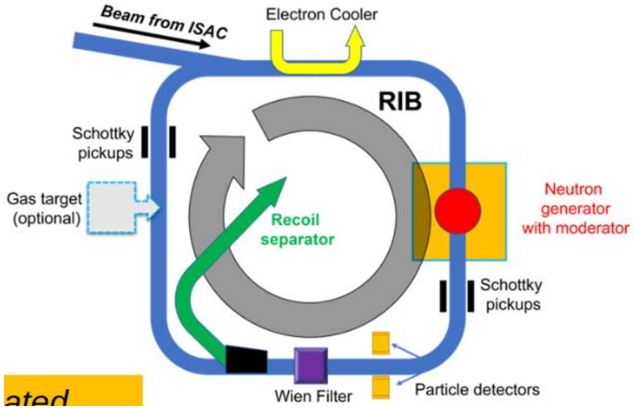
PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 044701 (2017)

Spallation-based neutron target for direct studies of neutron-induced reactions in inverse kinematics

René Reifarth,* Kathrin Göbel, Tanja Heftrich, and Mario Weigand







Neutron target facility @ LANL

800 MeV p, 100 mA + spallation target + moderation
n density= 8*10^9 n/cm2

TRISR @ ARIEL-TRIUMF

Compact high-flux neutron generator:
10^8 n/s/cm2

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

Summary

- **Accurate neutron capture cross sections** are key **the s- and i-process of stellar nucleosynthesis,** for validating and constraining stellar nucleosynthesis models**.**

- **Data needs for nucleosynthesis studies:**
    - Stable nuclei: s-only, s-process bottlenecks
    - Unstable nuclei: s-process branching points & i-process

- **Beams & techniques for direct neutron capture measurements**
    - TOF in a white neutron beam: En-dependent cross section in a wide range
    - Activation in quasi-stellar beam: MACS @ 25 keV

- **State-of-the-art**
    - Improving accuracies of key stable isotopes
    - Many first-time (n,g) on unstable s-process branchings in the last decade due to upgrades in facilities and detectors
    - Towards more unstable isotopes (s-process, i-process) → Current limit for TOF: signal-to-background

- **Future**
    - Higher sensitivity: High flux facilities for activation (e.g. n_TOF NEAR)
    - Faster/closer sample production: Synergy between neutron beam and RIB facilities (e.g. NEAR & ISOLDE)
    - Future very bright neutron sources: FRANZ, nACT @ BDF, IFMIF-DONES
    - Towards very short-lived (i-process): Direct (n,g) in inverse kinematics: neutron target + exotic ion storage ring

Thank you!

Any questions?

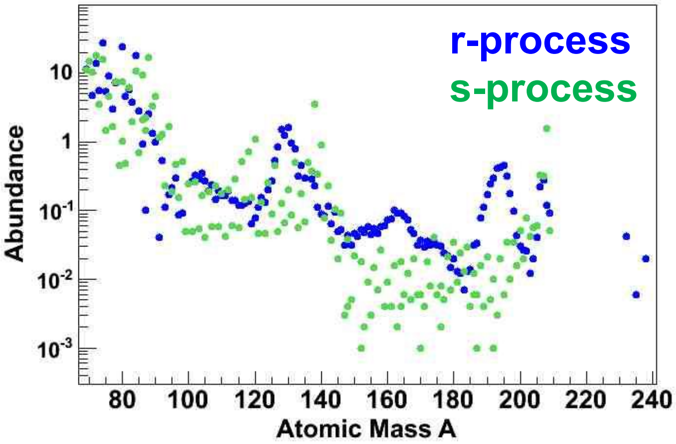
J. Lerendegui-Marco,

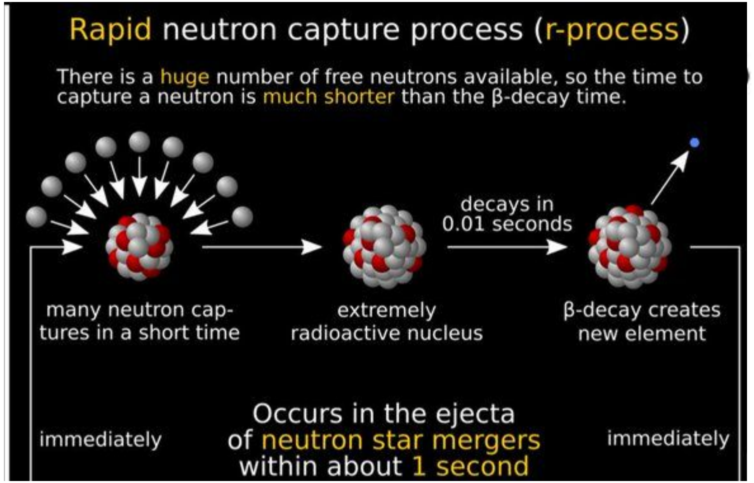
Instituto de Física Corpuscular (Valencia, Spain) / n_TOF Collaboration (CERN)
jorge.lerendegui@ific.uv.es

BACK-UP

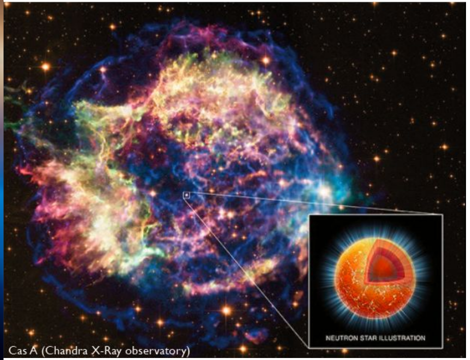
s- / i-process

The synthesis of heavy nuclei in stars





high neutron fluxes , short time scales, very n-rich nuclei



SN,N-Star Mergers, etc ?

[r-process path (gif)]

rapid (r)-process

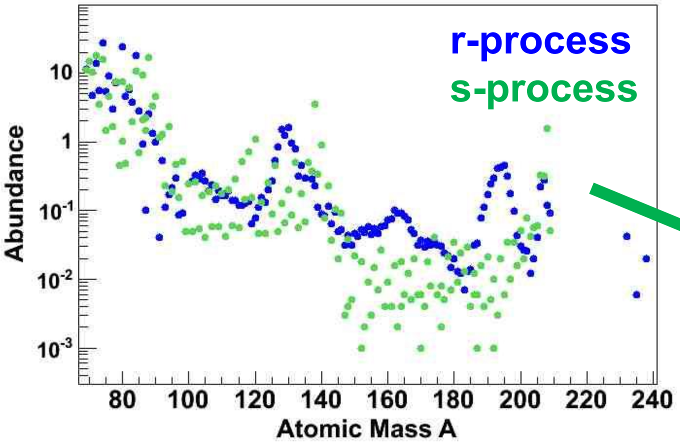
$T = 10^{8}$-10^{10} K

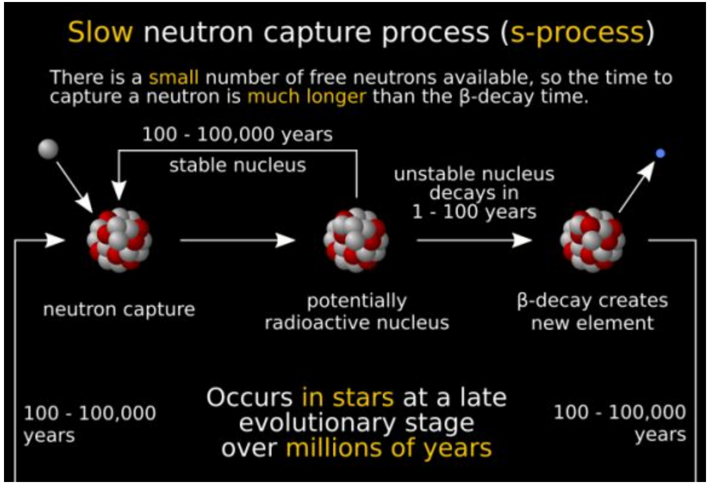
$N_n = 10^{20}$-10^{27} cm^{-3}

r-process : extremely short-lived nuclei ➜

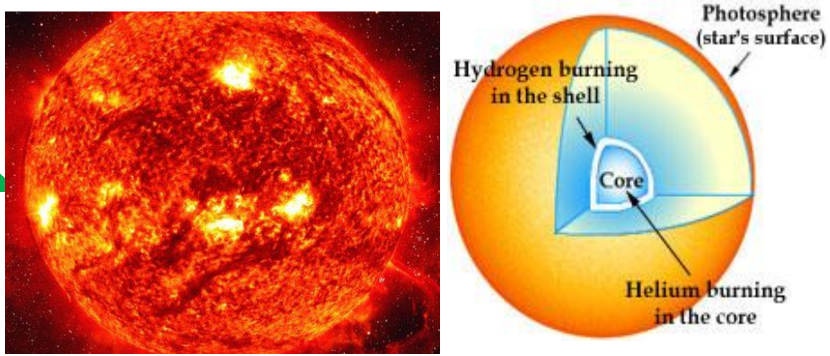
Neutron capture cannot be <u>directly</u> studied.

The synthesis of heavy nuclei in stars





**Low neutron fluxes , very long time scales,
Stable or long-lived unstable nuclei**



AGB (red giant) stars, massive stars

slow (s)-process

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

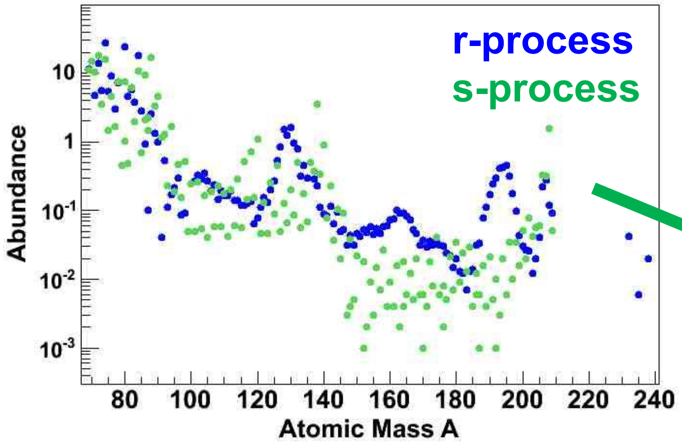
$N_n = 10^6 - 10^{12}$ cm^{-3}

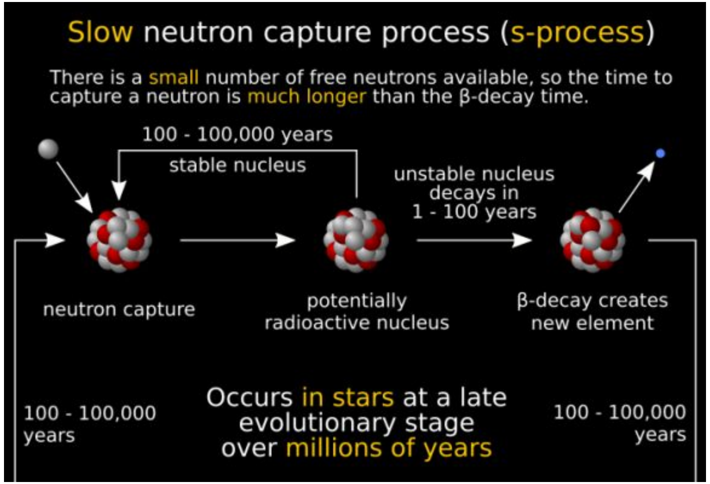
NEUTRON SOURCES (AGB)

$^{22}Ne(\alpha,n)$: 10^{12} n/cm³, kT ~30 keV

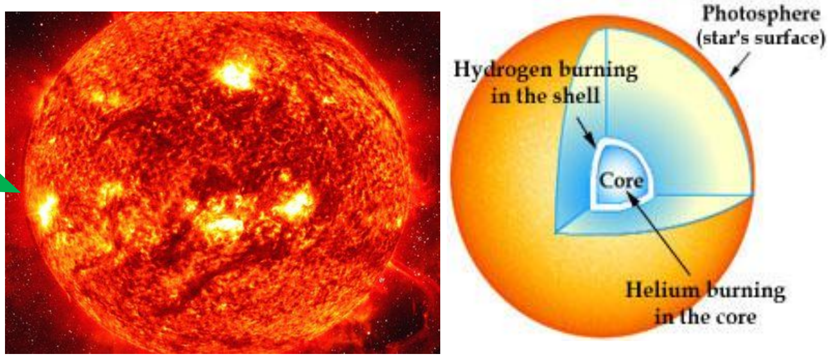
$^{13}C(\alpha,n)$: 10^7 n/cm³, kT ~5 keV

The synthesis of heavy nuclei in stars





Low neutron fluxes , very long time scales, Stable or long-lived unstable nuclei



AGB (red giant) stars, massive stars

slow (s)-process

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

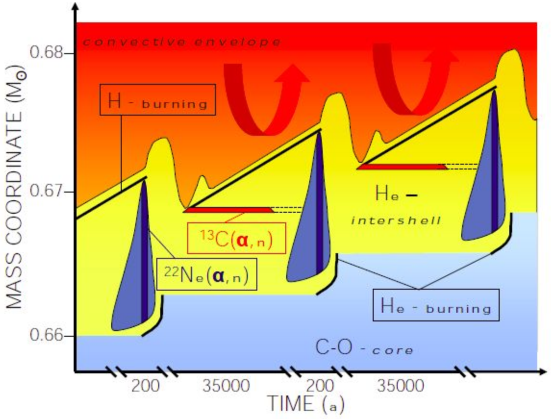
$N_n = 10^6 - 10^{12}$ cm^{-3}

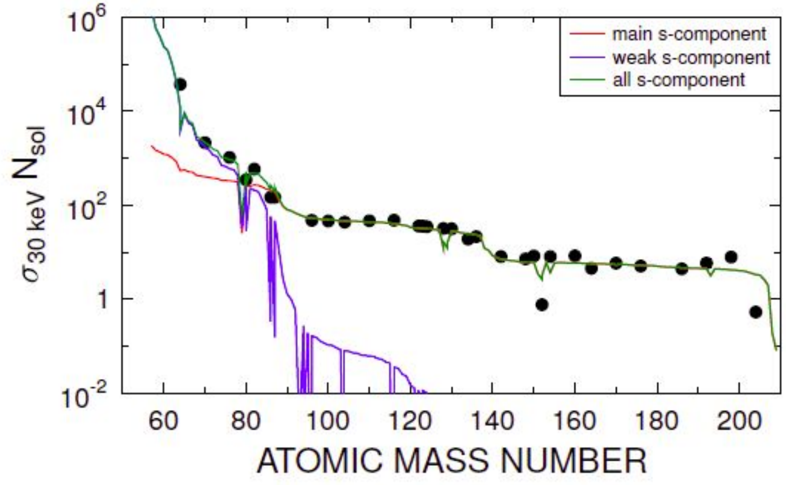
s-process: along stability valley→

Direct neutron capture reactions in existing neutron beams

s-process: stellar sites, temperatures & neutron sources

Thermally pulsing low-mass AGB stars





S-PROCESS COMPONENTS

MAIN S-PROCESS:

He shell burning phase in AGB STARS

^{22}Ne(α,n): 10^{12} n/cm³, kT ~30 keV

^{13}C(α,n): 10^7 n/cm³, kT ~5 keV

90<A<209

WEAK S-PROCESS:

Massive stars

^{22}Ne(α,n)

He core burning: 10^6n/cm³, kT ~25 keV

C-shell burning: 10^{12}n/cm³, kT ~90 keV

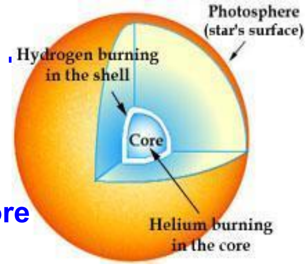
56<A<90

Energy - Temperature

90 keV ~ 1 GK

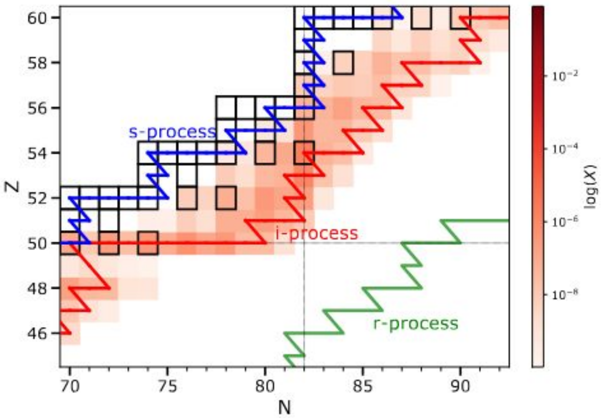
He-burning core

Massive star

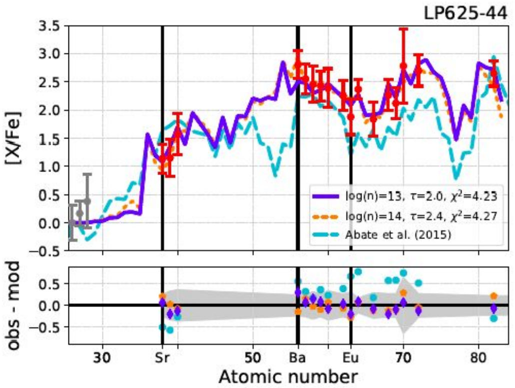


The synthesis of **heavy** nuclei in stars

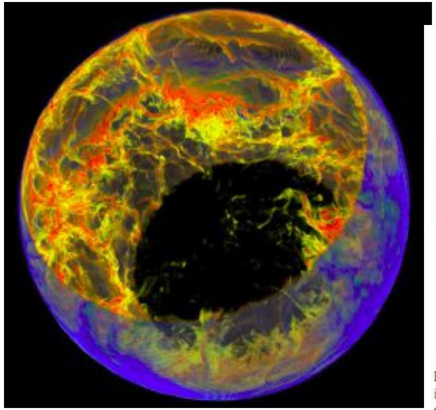
i-process



Required to reproduce experimental abundance pattern in CEMP stars



Intermediate neutron fluxes and time scales, short(er)-lived unstable nuclei (hours-days)



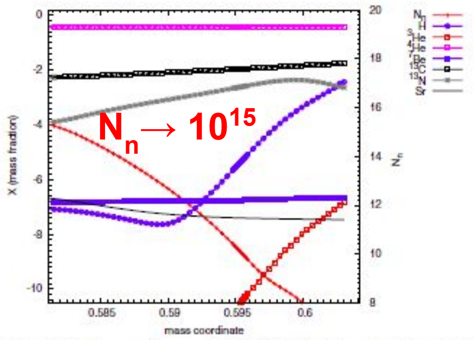


Figure 7. Abundance profiles snapshot (RUN103), just before the mixing split is imposed, demonstrates the simultaneous action of nucleosynthesis and mixing on similar timescales.

Low metallicity, low mass AGB

Intermediate (i)-process

$T > 10^8$ K

$N_n = 10^{13} - 10^{16}$ cm^{-3}

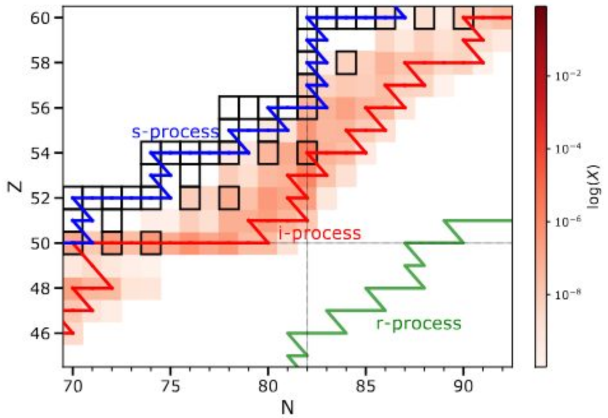
NEUTRON SOURCE

12C(p,γ)13N → 13C→ 13C(α, n)16O

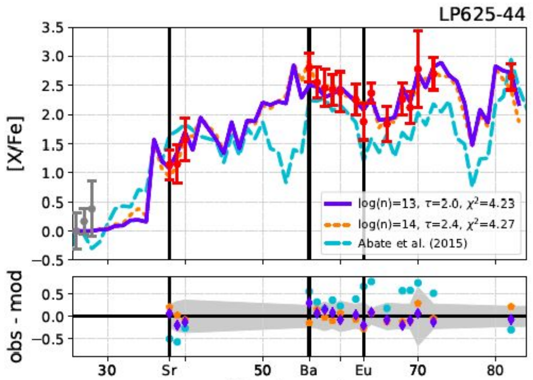
Falk Herwig et al 2011 ApJ 727 89
Choplin, EPJ Web of Conferences 279, 07001 (2023)
Melanie Hampel et al 2019 ApJ 887 11

The synthesis of **heavy** nuclei in stars

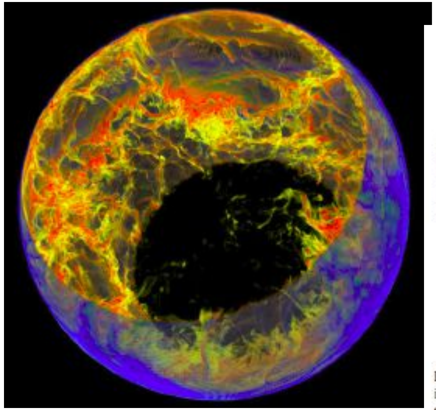
i-process



Required to reproduce experimental abundance pattern in CEMP stars



Intermediate neutron fluxes and time scales, short(er)-lived unstable nuclei (hours-days)



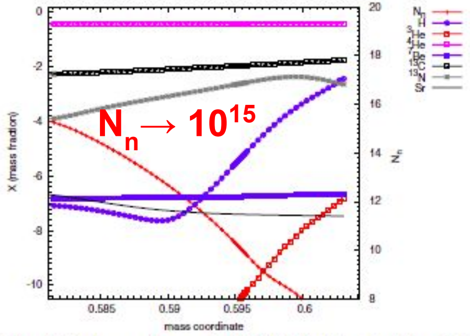


Figure 7. Abundance profiles snapshot (RUN103), just before the mixing split is imposed, demonstrates the simultaneous action of nucleosynthesis and mixing on similar timescales.

Low metallicity, low mass AGB

Intermediate (i)-process

$T > 10^8$ K

$N_n = 10^{13} - 10^{16}$ cm^{-3}

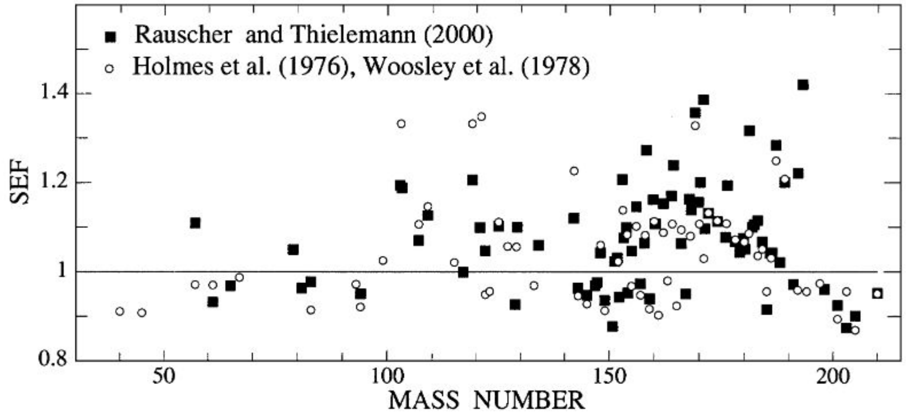
i-process: few units away from stability →

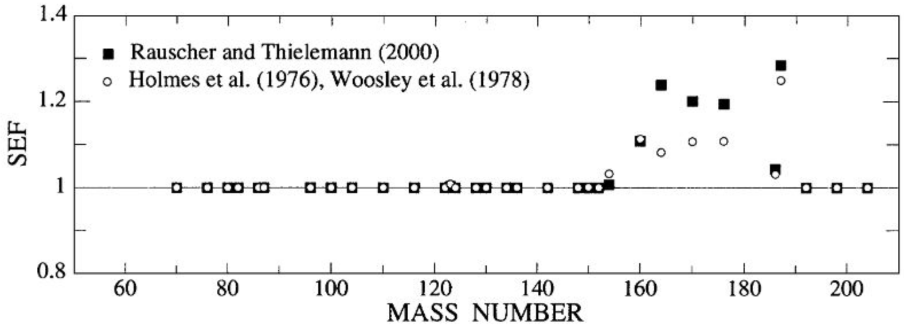
Direct neutron capture is challenging → Future neutron beams & techniques

i- process nucleosynthesis: stellar site

1) Early AGB phase of metal-poor low-mass stars, in which the entropy barrier between the hydrogen- and helium-rich zones can be surmounted by the energy released by a thermal pulse (Fujimoto et al. 2000; Chieffi et al. 2001; Siess et al. 2002; Iwamoto et al. 2004; Cristallo et al. 2009, 2016; Suda & Fujimoto 2010). The penetration of the helium driven convection zone in the hydrogen-rich layers is favored in metal-poor stars as a result of the absence of heavy elements.
2) Core helium flash of very low-metallicity low-mass stars (Fujimoto et al. 1990, 2000; Schlattl et al. 2001; Suda & Fujimoto 2010; Campbell et al. 2010; Cruz et al. 2013). A
3) Very late thermal pulses of post-AGB stars (Herwig et al. 2011).
4) Rapidly accreting carbon-oxygen (C-O) or oxygen-neon (O-Ne) white dwarfs (RAWDs) in close binary systems could also host *i*-process nucleosynthesis (Denissenkov et al. 2017, 2019). In this scenario, the helium shell formed by the combustion of the accreted hydrogen material becomes thermally unstable. As a consquence of convection, protons from the accreted hydrogen-rich envelope may reach the helium-burning shell and lead to the production of an intense neutron burst.
5) Super-AGB stars ($7\ M_{\odot} \lesssim M_{ini} \lesssim 10\ M_{\odot}$). Jones et al. (2016) show that at low metallicity ($Z \leq 10^{-3}$), a $7\ M_{\odot}$ model can experience a proton ingestion episode during the thermally pulsing super-AGB phase leading to *i*-process nucleosynthesis.
6) Helium shell of very low- or zero-metallicity massive stars ($M_{ini} > 10\ M_{\odot}$). These stars can experience a proton ingestion.

SEF



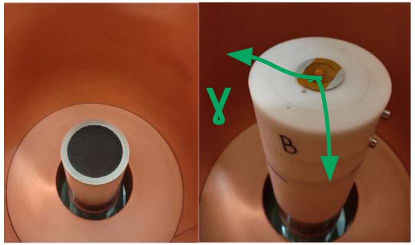


- 25% of all isotopes involved in the s process show SEF corrections of more than 2%.
- Significant corrections are to be expected for odd and/or deformed nuclei with excited states well below 100 keV.
- s-only isotopes little affected, except for the mass region 160 < A <190

Intro techniques & recent upgrades

J. Lerendegui-Marco, sirEN Conference, 12/06/2025

Stellar (n,g) activations: Analysis

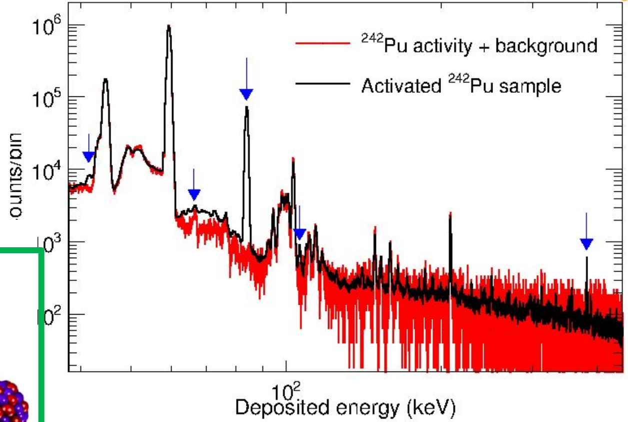


Sample inside the HPGe shielding

Peak Fit area

$$N_0 = \frac{R_j(t_d=0)}{F_{geom}\ F_{abs}\ \varepsilon_j\ I_j}$$

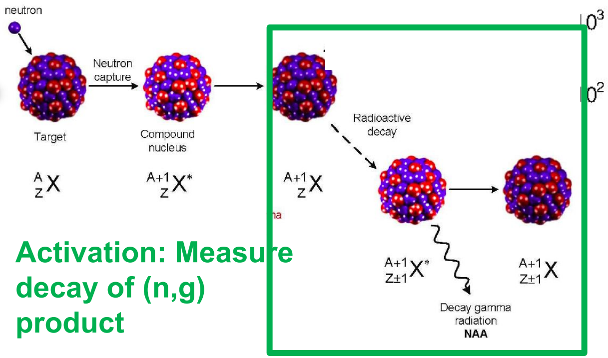
Number of (n,g) reactions



g-ray spectrum from the decay

$$\frac{MACS_{Pu,\ kT}}{MACS_{Au,\ kT}} = \frac{F_c^{242Pu}}{F_c^{197Au}} \frac{N_0^{243Pu}}{N_0^{198Au}} \frac{n_{197Au}}{n_{242Pu}}$$

MACS relative to **reference (Au-197)**



Activation: Measure decay of (n,g) product

(n,γ) TOF measurements @ n_TOF: Capture yield

$$Y(E_n) = (1 - e^{-n_C \sigma_{tot}(E_n)}) \frac{\sigma_\gamma(E_n)}{\sigma_{tot}(E_n)} + Y_{MS}(E_n),$$

Theory

Capture yield = Probability for an incident neutron to undergo a capture reaction

$$Y(E_n) = F^{thr}_{norm} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n) \cdot \varepsilon_c}$$

Experimental

(n,ɣ) TOF measurements @ n_TOF: Capture yield

TOF to neutron energy: TOF - E_n
Taking into account RF
(MC simulations)

Dead time:
correction vs. TOF

Capture yield = Probability for an incident neutron to undergo a capture reaction

Background subtraction:
Direct + n/g scattering (MC)

$$Y(E_n) = F^{thr}_{norm} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n)\,\varepsilon_c}$$

Efficiency: TED
$\varepsilon_C \rightarrow E_C = S_n + E_n$

Flux: measured with different setups, unc. within 1-5%

$$F^{thr}_{norm} = \frac{\langle W^{thr} \rangle}{f^{thr}_{SRM}} \frac{F^{thr}_{c,Pu}}{F^{thr}_{c,Au}}$$

Efficiency correction factors :
low energy g-rays, EC
(cascade modelling + MC)

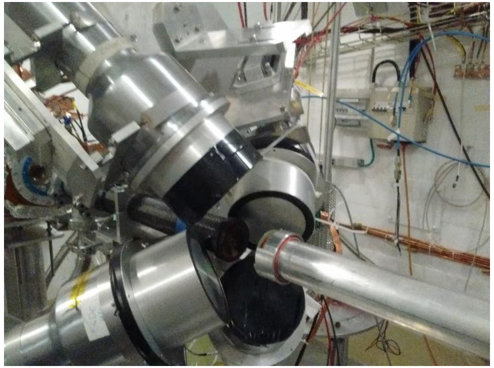
Normalization:
Saturated Resonance Method (^{197}Au)

(n,ɣ) measurements @ n_TOF

	TAC	C_6D_6 TED
Advantages	Good background rejection High efficiency High resolution	Low neutron sensitivity Simple set-up Fast detectors
Drawbacks	Neutron sensitive Slow detectors: pile-up problems Complex detector (42 crystals)	Poor background rejection Low efficiency Software manipulation (PHWT) needed

Not able to measure in the keV range of astrophysical interest (dead time)

Usual setup for stellar (n,ɣ) measurements

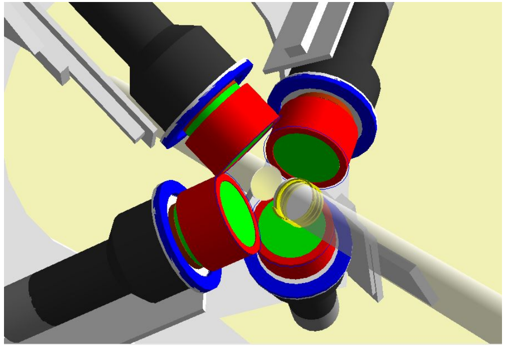


State-of-the art for measurements in the astrophysical range of interest (1 - 100 keV):

- Fast response (10 ns width signals)
- Low neutron sensitivity

C_6D_6 TED

+ PHWT



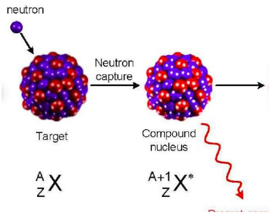
Limitations:

- Background in the keV range due to dominant neutron scattering
- Limited by maximum count rate in high flux facilities such as n_TOF-EAR2

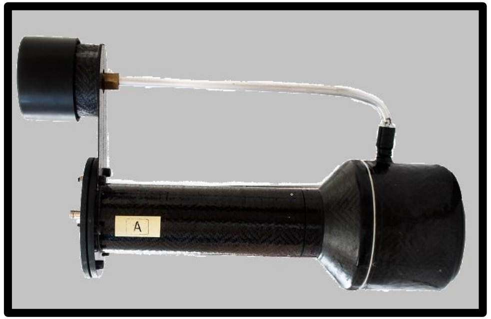
Solutions:
Recent progresses!

Neutron capture via TOF technique

$$n + {}^{A}Z \rightarrow {}^{A+1}Z^{*} \rightarrow {}^{A+1}Z + \gamma\text{'s}$$



Most extensively used for stellar(n,ɣ): able to cover the keV neutron energy range range of interest

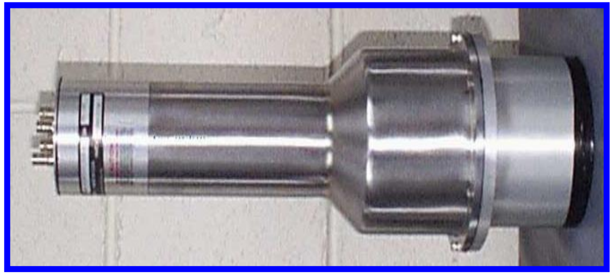


TOF technique

Detect the γ-ray cascades vs TOF (neutron energy)

TOTAL ENERGY DETECTORS

Detect at-least/only ONE γ-ray



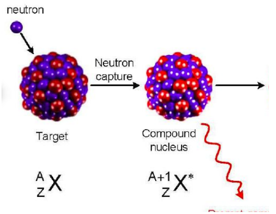
4 x D-benzene detectors (organic scintillator) → Low neutron sensitivity, fast detectors, simple setup

TOTAL ABSORPTION

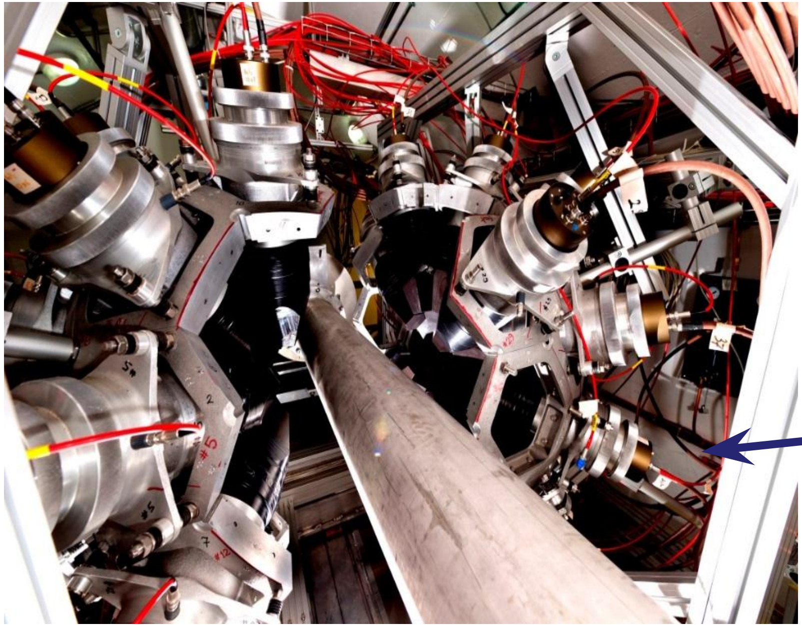
Detect ALL the γ-rays

Neutron capture via TOF technique

$$n + {}^{A}Z \rightarrow {}^{A+1}Z^{*} \rightarrow {}^{A+1}Z + \boxed{\gamma\text{'s}}$$



The n_TOF Total Absorption Calorimeter (TAC)



40 BaF_2 scintillator crystals → 95% solid angle

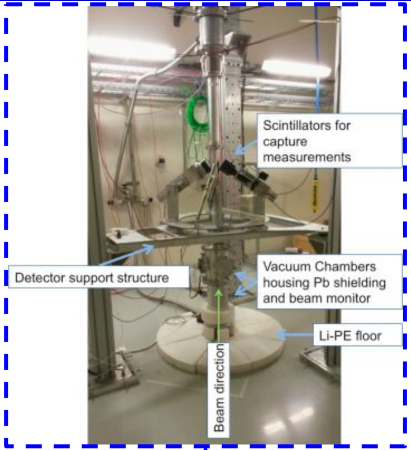
At n_TOF

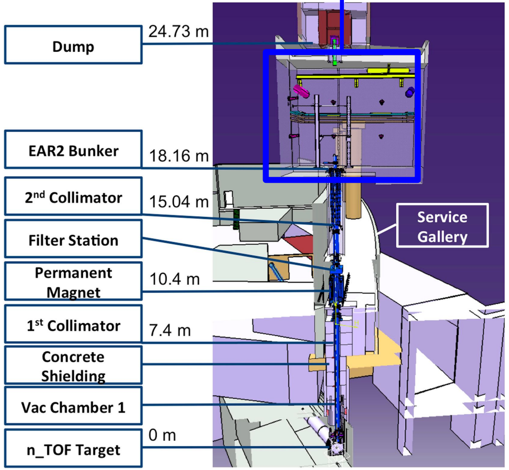
Detect the γ-ray cascades vs TOF (neutron energy)

TOTAL ABSORPTION

Detect ALL the γ-rays

Latest facility upgrades



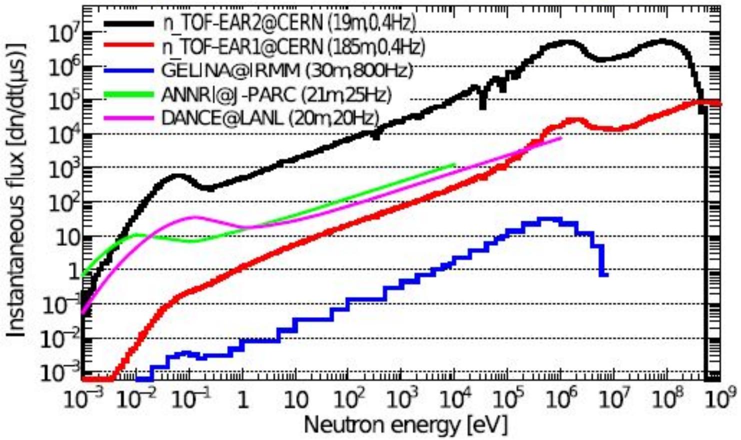


n_TOF EAR2 (20 m, vertical)

- Since **2015**: ~15 (n,ɣ) measurements

Key features:

- **x300** higher **instantaneous flux**
- Low mass / **radioactive samples**

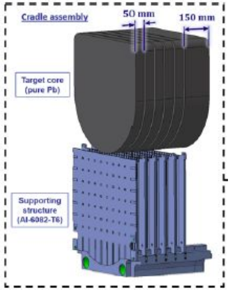


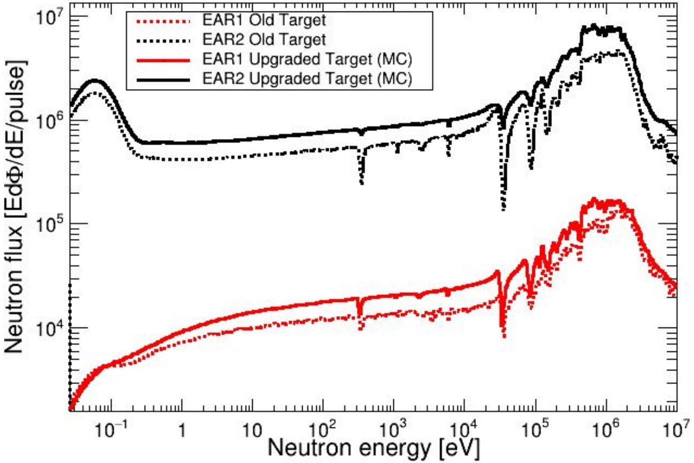
New spallation target

- Replaced in 2021

Key features:

- EAR2: 30-50% higher flux & improved energy resolution

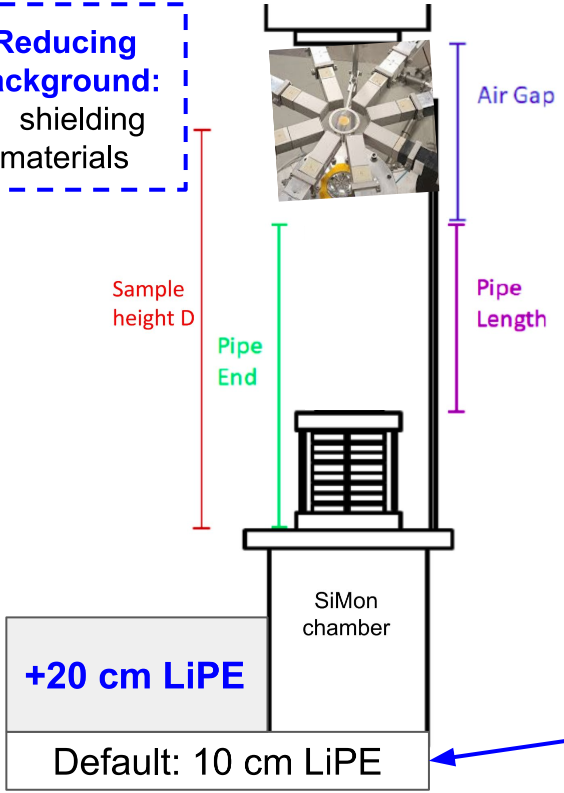


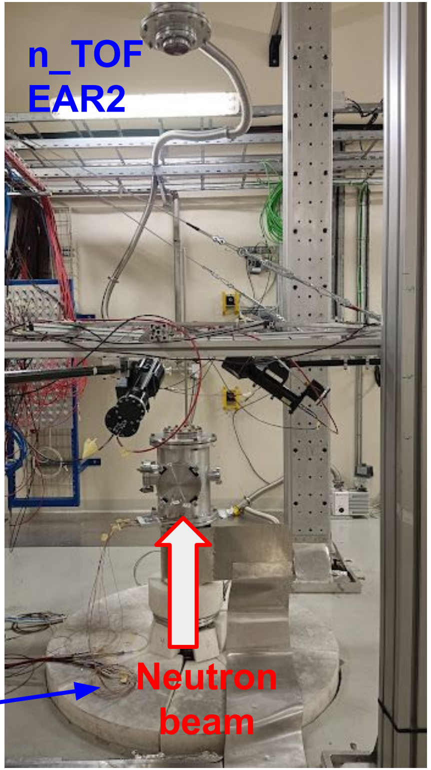


Future: optimizing n_TOF-EAR2

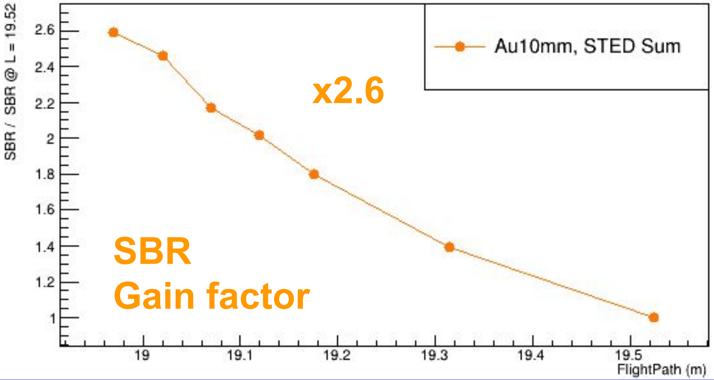
Short term: Optimization campaigns **at EAR2 & new ideas to improve the SBR for future experiments**

Reducing background:
\+ shielding materials





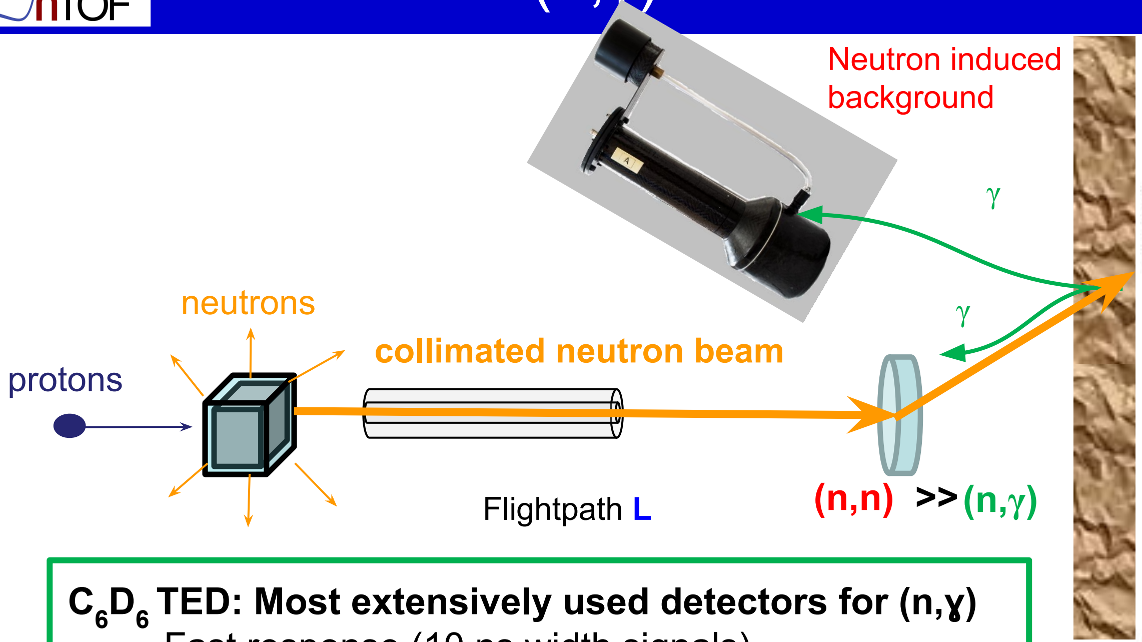
SBR Gain of a factor >2
by lowering 60cm the setup!

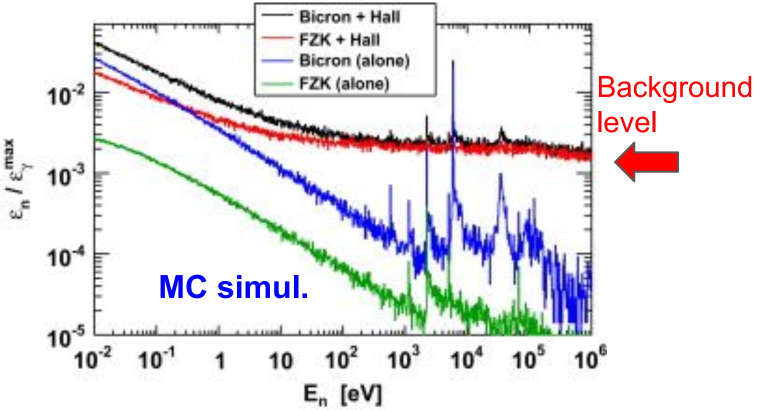


Long term:

- 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

Stellar (n,γ) TOF measurements: challenges

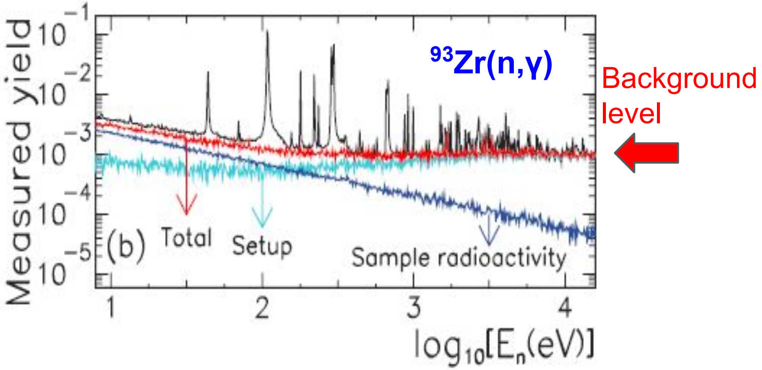




P. Zugec, et al., [Nucl. Instrum. Methods A 760, 57 (2014)]();

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,γ)

- Fast response (10 ns width signals)
- Low neutron sensitivity

Limitation:

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

Stellar (n,γ) TOF measurements: solutions

Contents lists available at ScienceDirect

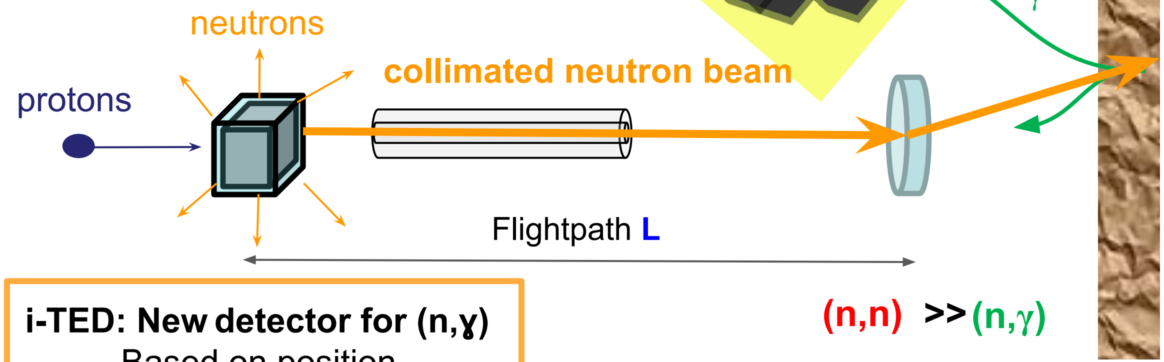
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements

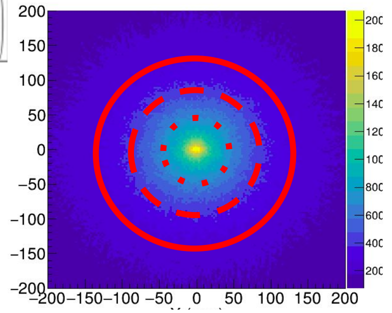
C. Domingo-Pardo

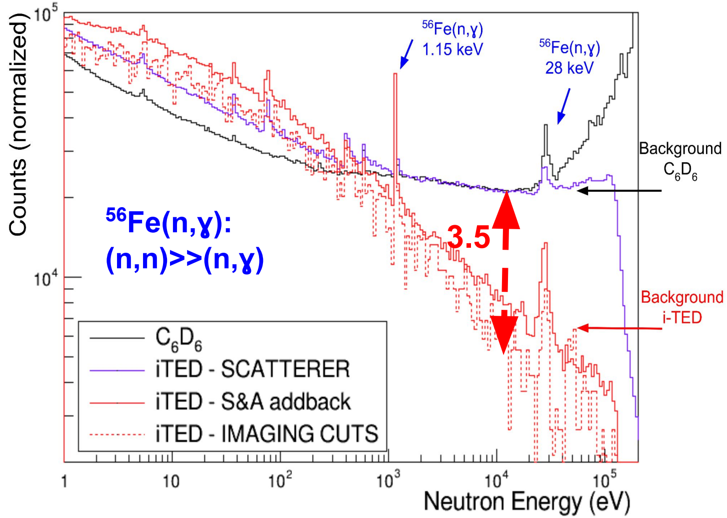
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain



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

COMPTON IMAGING





i-TED: New detector for (n,γ)
- Based on position sensitive detectors
- Imaging capabilities

Solution: i-TED → Compton Imaging technique to reduce the neutron background and enhance the detection sensitivity

HYMNS nucleosynthesis & MS evolution

European Research Council

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

s-process branchings: + examples

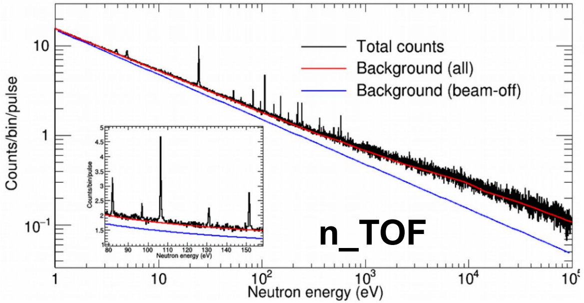
J. Lerendegui-Marco, sirEN Conference, 12/06/2025

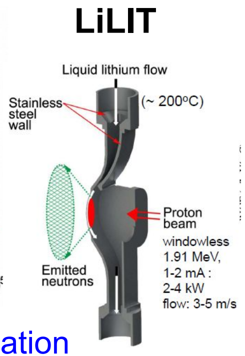
unstable branching-point isotopes: state-of-the-art

Tm-171(n,γ)

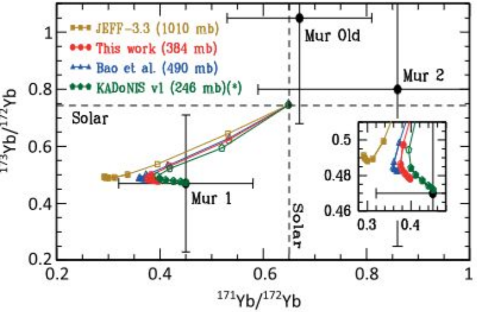
First measurement ever!
TOF @ n_TOF + activation @ LiLIT

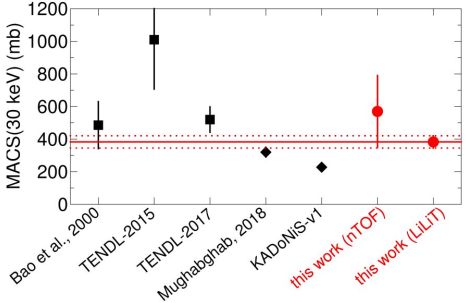
m = 3.1 mg
97.9% pure
σ = 384(40) mb

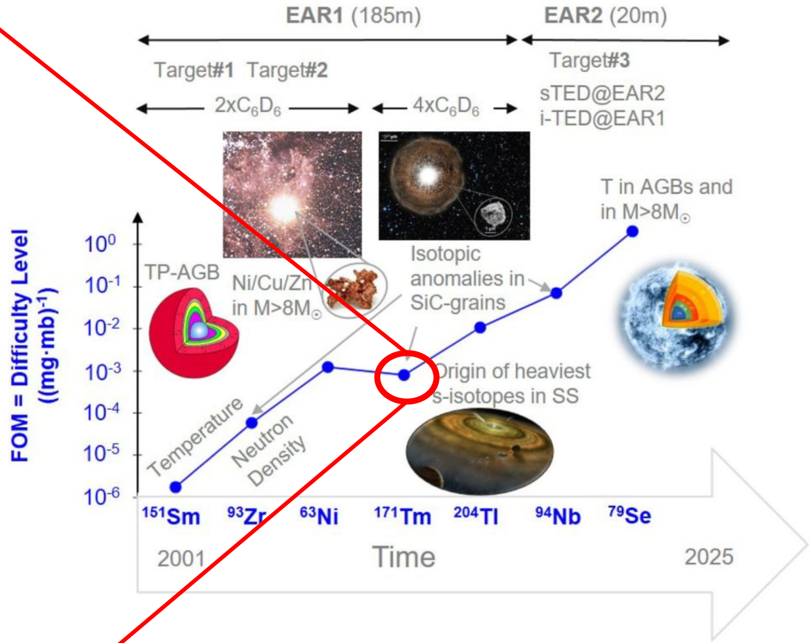




Consistent TOF & activation



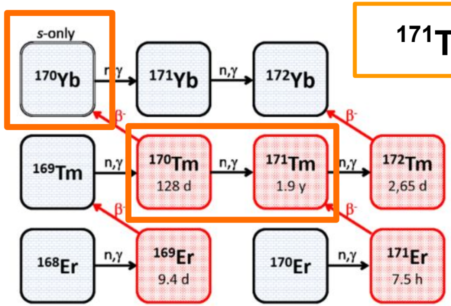




Yb-ratios SiC grains: Improved agreement vs JEFF-3.3

C. Guerrero et al., *Phys. Rev. Letters* **125**, 142701 (2020)

(n,g) on unstable branching-point isotopes



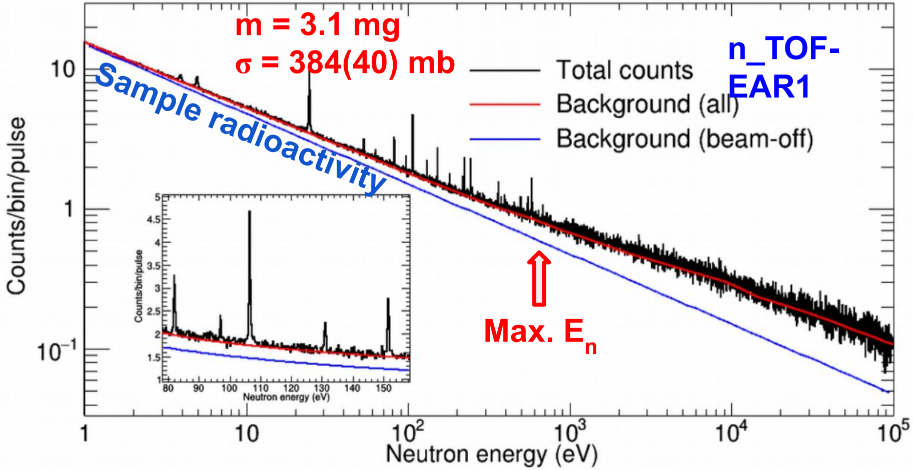
^{171}Tm(n,g)

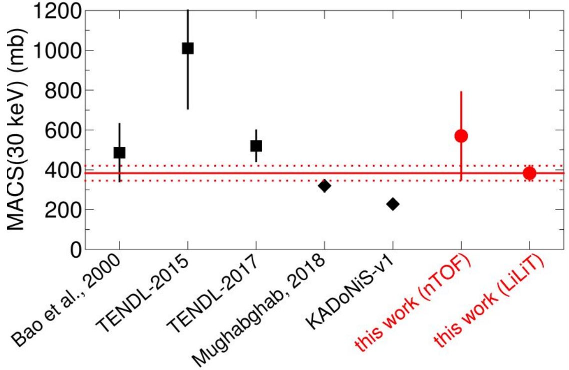
PHYSICAL REVIEW LETTERS

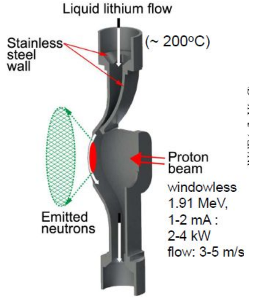
Neutron capture on the *s*-process branching point ^{171}Tm via time-of-flight and activation

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.

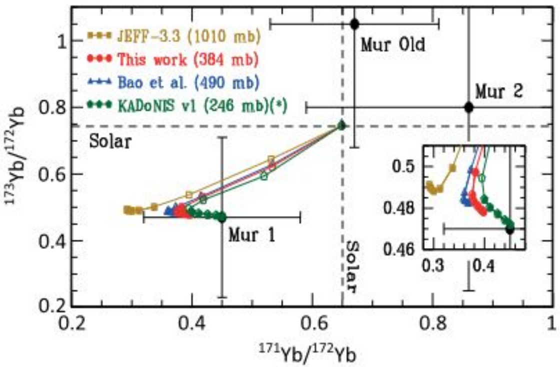
First TOF measurement ever! Combined TOF with activation MACS @ LiLIT







LiLIT



Yb-ratios from SiC grains: JEFF-3.3 large discrepancies (2Mo, Z=0.01)

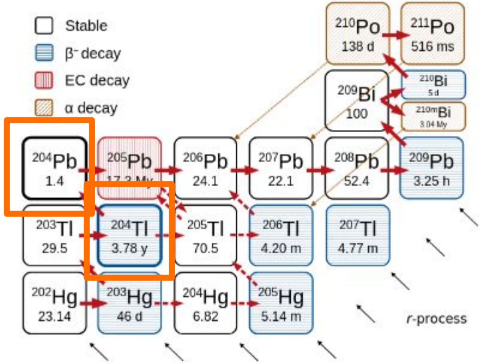
s-process branchings: highlights & limitations

Tl-204(n,γ)

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

NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT PSI



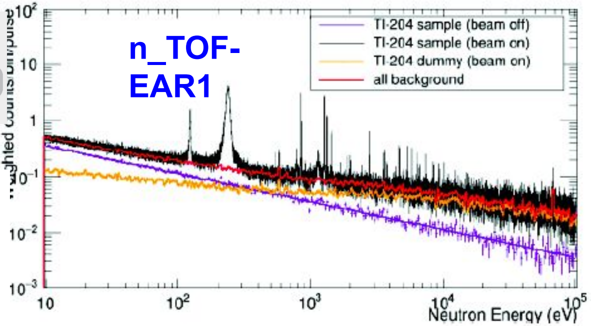
First measurement of this cross section!
n_TOF Only

PHYSICAL REVIEW LETTERS **133,** 052702 (2024)

Shedding Light on the Origin of ^{204}Pb, the Heaviest *s*-Process–Only Isotope in the Solar System

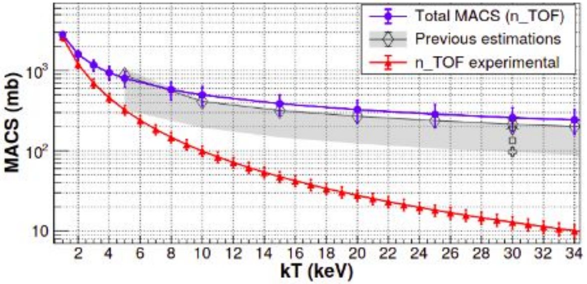
A. Casanovas-Hoste,[1,2,3,*] C. Domingo-Pardo,[2] J. Lerendegui-Marco,[4] C. Guerrero,[4] A. Tarifeño-Saldivia,[2] M. Krtička,[5]

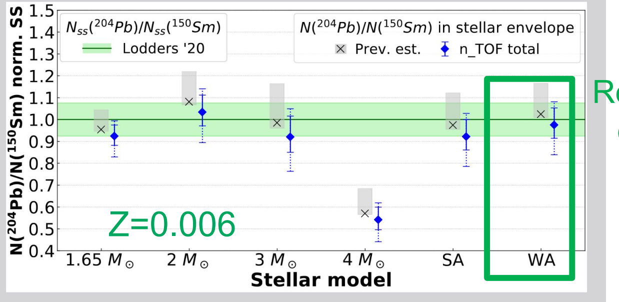
n_TOF-EAR1



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

Relevant for the abundance of the heaviest s-only ^{204}Pb





Reproduces experim. abund.

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

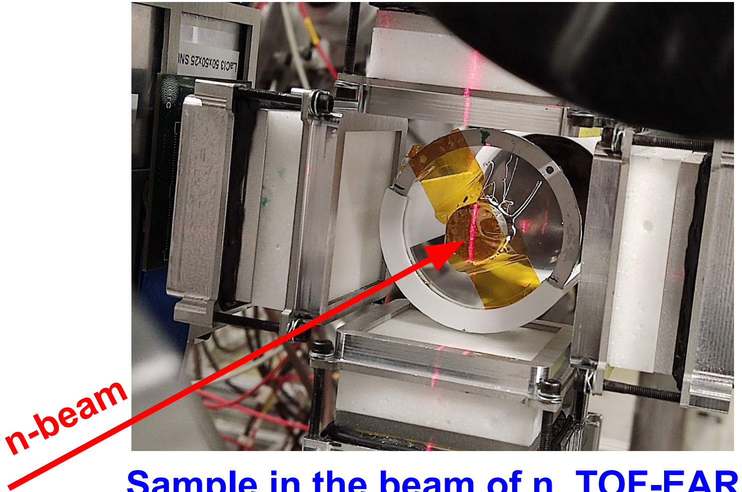
^{79}Se sample: a collaborative effort

~15x4mm

PSI: ^{208}Pb^{78}Se alloy to avoid low melting point

CERN: Encapsulated in e-welded 6N Al+

~17x6mm



Sample in the beam of n_TOF-EAR1

ILL: ~3 mg of ^{79}Se via ^{78}Se(n,γ)

Isotope	Mass (g)
Se-78	1.064
Se-79	0.003
Pb-208	2.838
Al-27	1.0244

PSI: Characterized active contaminants

Isotope	Activity (Mbq)
Se-79	4.33E-01
Se-75	5.66E+00
Ag-110m	2.04E-01
Zn-65	2.33E-01
Co-60	1.40E+00

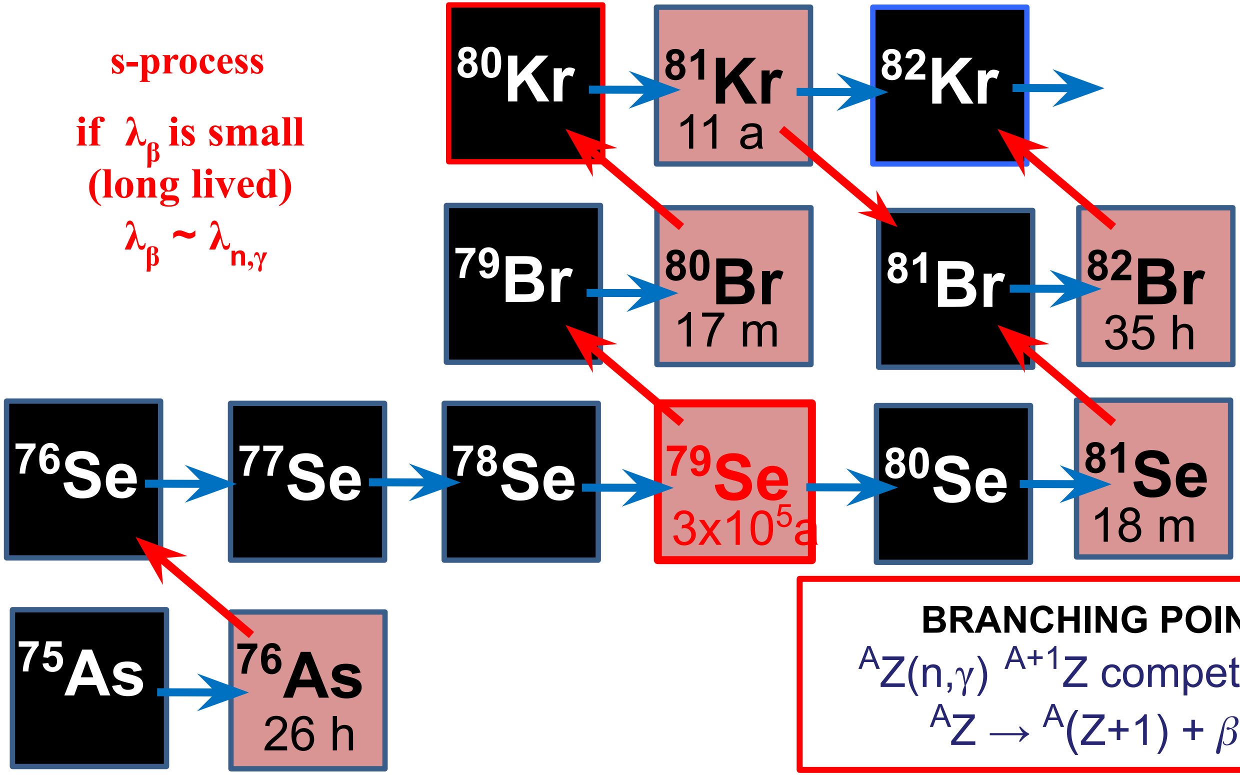
gamma emmiters

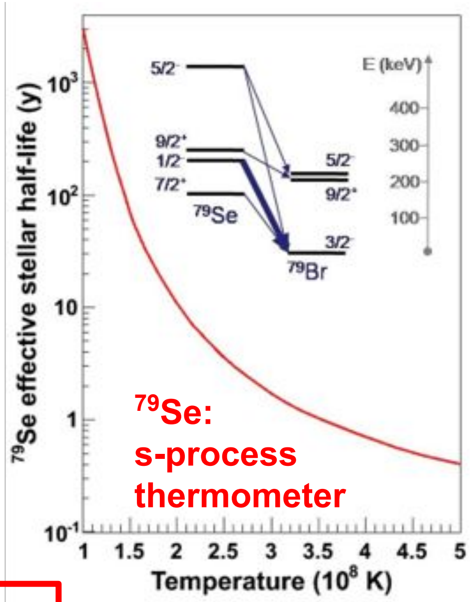
s-process: the relevance of unstable isotopes

s-process

if λ_β is small (long lived)

$\lambda_\beta \sim \lambda_{n,\gamma}$

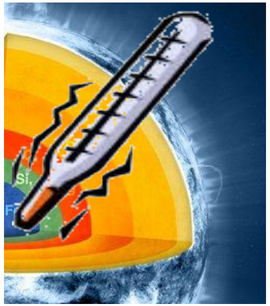




BRANCHING POINTS:

$^{A}Z(n,\gamma)\ ^{A+1}Z$ competes with

$^{A}Z \rightarrow {}^{A}(Z+1) + \beta + \nu$



s-process: chain **n-capture** + **beta decays**

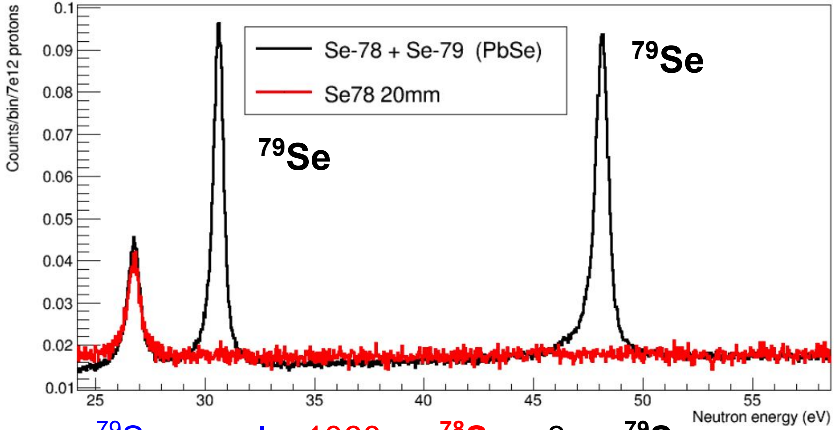
Heavier elements along stability valley

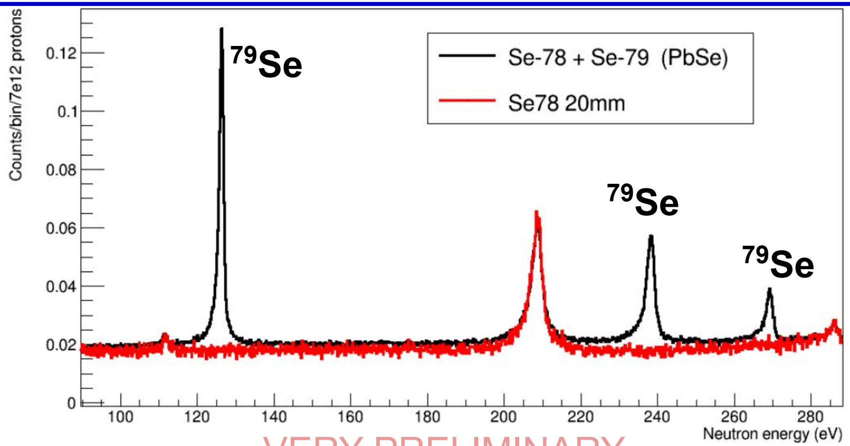
(n,γ) measurements + isotopic ratios provide tight constraints to stellar conditions (T, n-dens)

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

10-15 Resonances of Se-79 **First ever measured!**

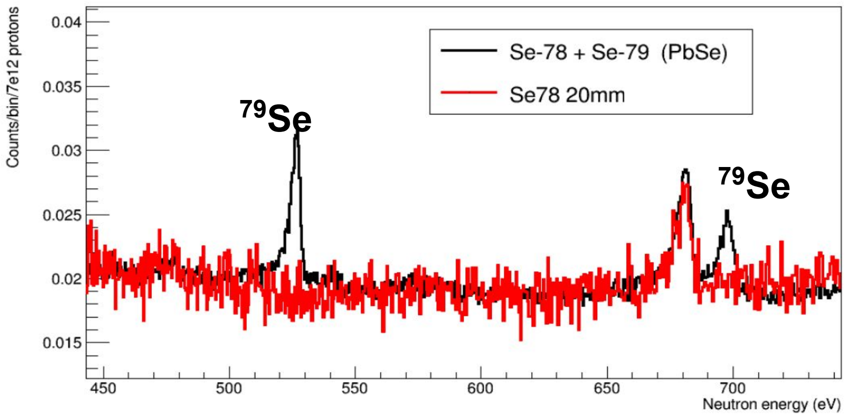
- **Se-79+Se-78 sample** vs **Se-78 sample**

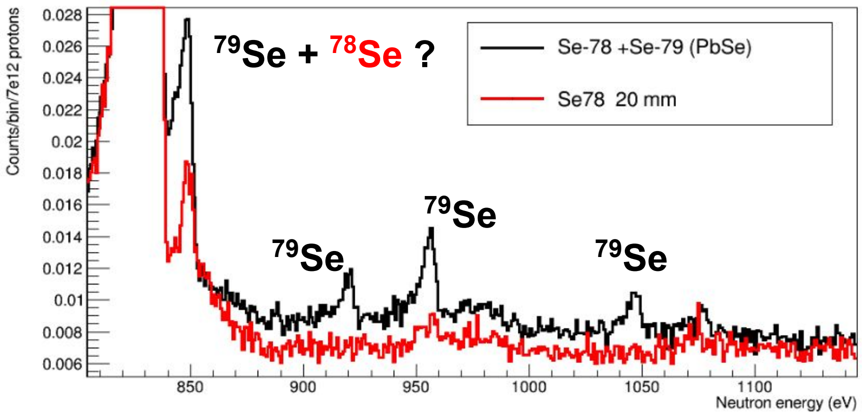




^{79}Se sample: 1060mg ^{78}**Se** + 3mg ^{79}**Se**

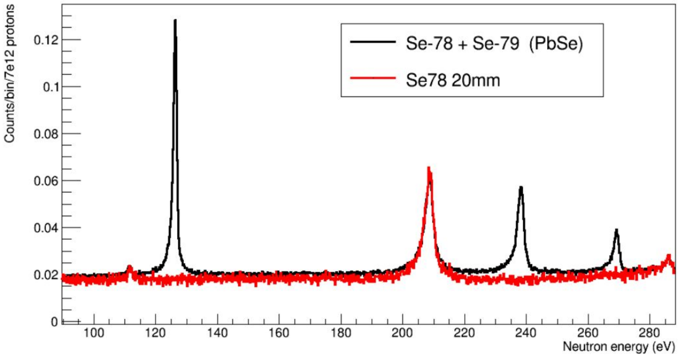
VERY PRELIMINARY





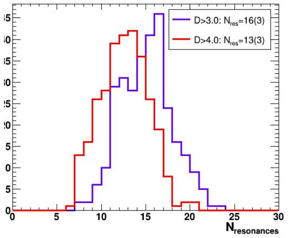
^{79}Se(n,γ): expected results

Experimental RRR: (s-wave Avg. Par.)



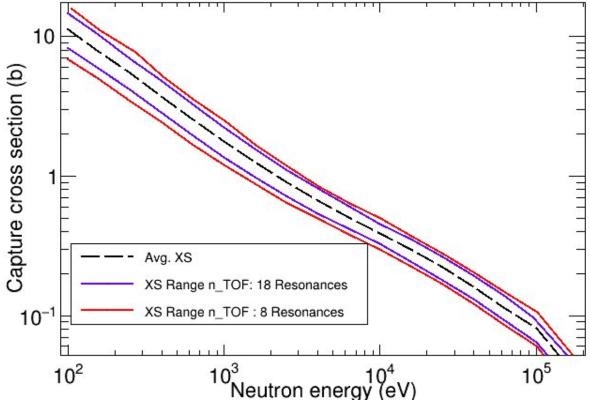
R-Matrix

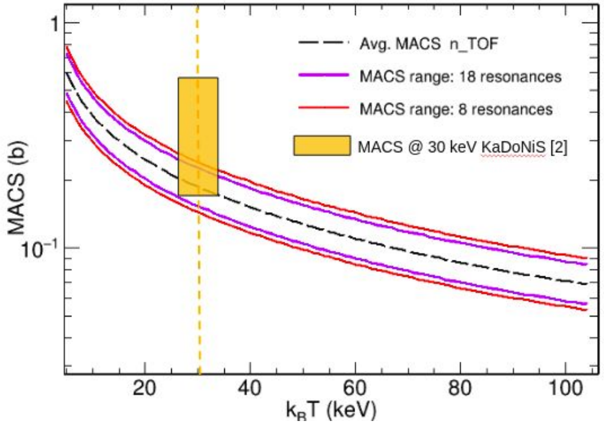
Measured: 10-15 resonances



Uncertainty D_0, S_0 ~ sqrt(N_{res})

Hauser-Feshbach (FITACS): CS in the URR





- MACS @30 keV: 20-26% unc (from avg. par. only)
- Stellar enhancement Factor = 1 at 8, 30 keV
- **Direct stringent constraint for the thermal conditions of AGB and MSs**

MACS @ different kT: Constrain **theor. calculations in KaDoNiS** (@ 30 keV)

Same method for ^{171}Tm(n,γ): C. Guerrero, J. Lerendegui-Marco et al., **Phys. Rev. Letters 125**, 142701 (2020).

(n,g) on s-process branchings: current status

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 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	Lerendegui-Marco, J. et al., EPJ Web Conf. 279, 13001 (2023).
^{81}Kr	2.29×10^5	EC, 0.322	
^{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	C.Guerrero *et al.*, Phys. Letters B, 797, 134809 (2019)
^{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	C. Guerrero, J. Lerendegui-Marco et al., *Phys. Rev. Letters* **125**, 142701 (2020)
^{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	A. Casanovas, C. Domingo et al., *Phys. Rev. Letters (submitted)*

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

Significant progress in the last decade but still many measurements not feasible, in particular (n,g) via TOF →**WHY?**

Before 2015: only **2/21** of the key s-process isotopes measured by TOF

2015-2018: **^{171}Tm, ^{204}Tl , ^{147}Pm** at **CERN n_TOF and/or LiLIT (activation)**

Very recent progresses: **^{79}Se, ^{94}Nb**

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

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

1. Difficult to produce in sizable quantities→ **Low capture/background ratio in TOF measurements**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background for **standard measuring techniques.**

Example: ^{147}Pm(n,ɣ)

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

m = 85 ug
σ = 826 mb

n_TOF lowest mass record at that point!

Current Limit TOF (n,g): 5e17-1e18 atoms

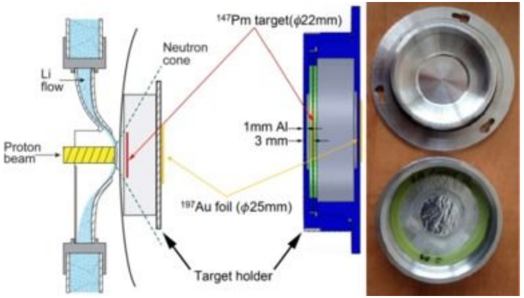
TOF measurement not fully successful due to limited mass

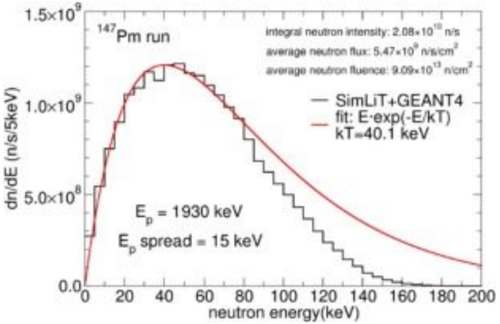
Only MACS via activation with a stellar spectra at LiLiT was feasible

C.Guerrero, M. Tessler, M. Paul, J. Lerendegui., Phys. Letters B, 797, 134809 (2019)

MACS @ 30 keV

	$\langle\sigma(^{147\to148g}\mathrm{Pm})\rangle_{30\ \mathrm{keV}}$	$\langle\sigma(^{147\to148m}\mathrm{Pm})\rangle_{30\ \mathrm{keV}}$
This work	469(50) mb	357(27) mb
Reifarth et al.+	332(64) mb	419(58) mb



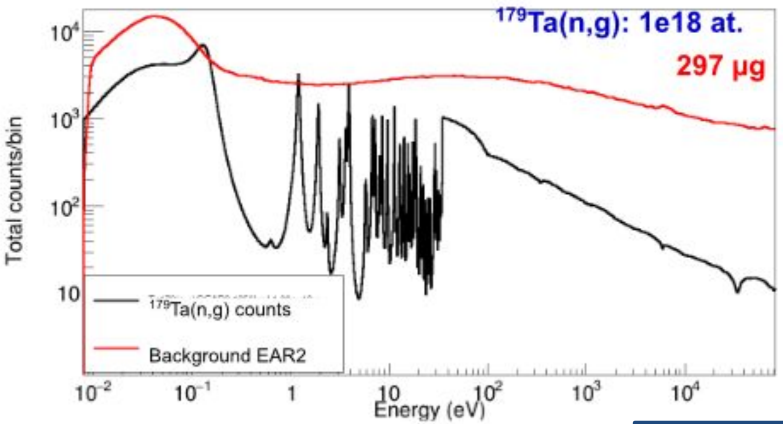


(n,g) on s-process branchings: current limits of TOF

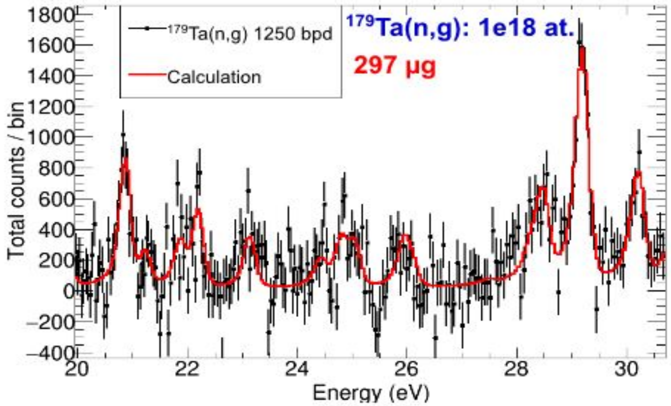
Towards more unstable s-process branching point isotopes: radioactive → challenges

1. Difficult to produce in sizable quantities→ **Low capture/background ratio in TOF measurements**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background for **standard measuring techniques.**

(n,g) vs background



Expected (n,g) yield with ~45 days of measurement



Current Limit TOF (n,g): 5e17-1e18 atoms

J. Lerendegui-Marco et al., EPJ-WOC (2023)
arXiv:2310.15714

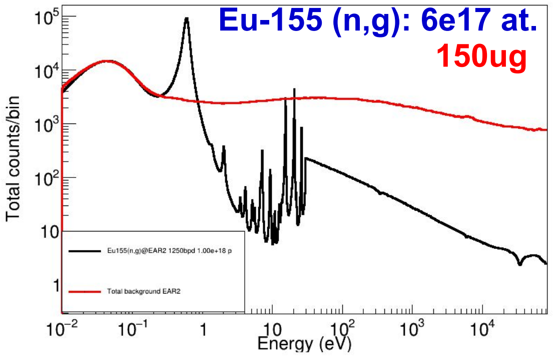
"First-time" key s-process branching that could be feasible:

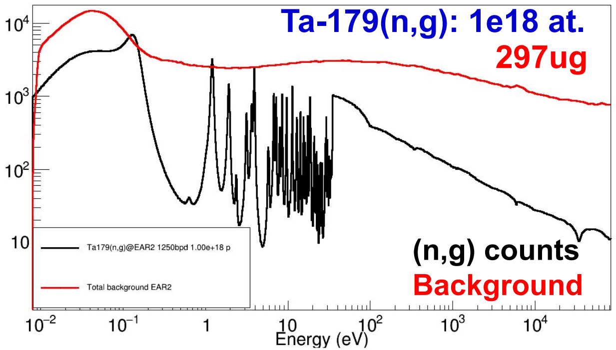
- Eu-155, Ta-179, W-185 (low g-ray background)
- **Mass required for TOF → Activity 5 - 100 GBq!**

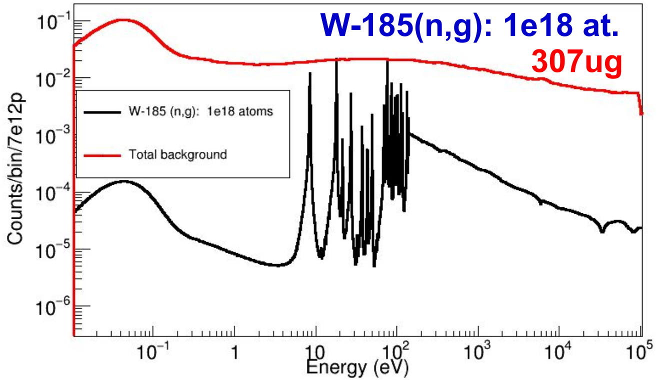
Isotope	Mass(ug)	Natoms	Activity (Gbq)
Eu-155	257.390	1.00E+18	4.70E+00
Ta-179	297.243	1.00E+18	1.21E+01
W-185	307.207	1.00E+18	1.07E+02

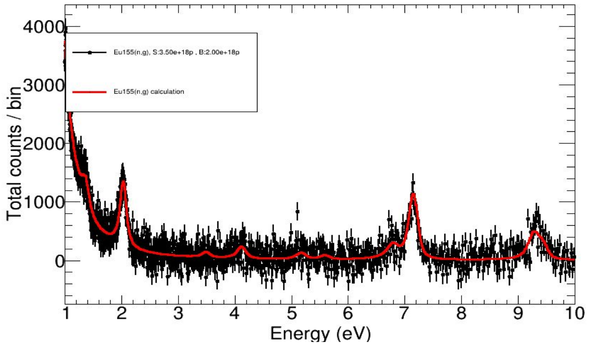
TOF (n,g) on s-process branchings: feasibility limit

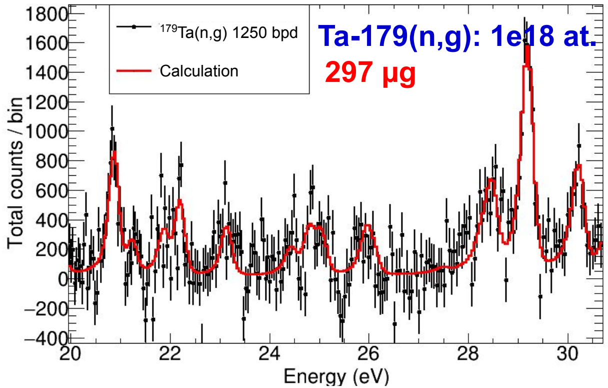
Estimated results in the upgraded **n_TOF-EAR2** with the **best sensitivity achieved so far with the STEDs**

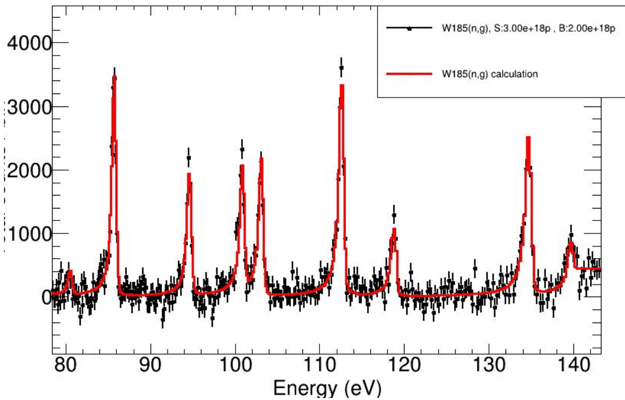












Limit: ~1e18 atoms (too high) currently required →We need **complementary techniques** → **ACTIVATION**!

s-process branchings: more details

J. Lerendegui-Marco, sirEN Conference, 12/06/2025

Temperature and $T_{1/2}$ of ^{79}Se

PHYSICAL REVIEW C VOLUME 38, NUMBER 1 JULY 1988

β-decay rate of ^{79m}Se and its consequences for the *s*-process temperature

N. Klay and F. Käppeler

Institut für Kernphysik III, Kernforschungszentrum Karlsruhe, D-7500 Karlsruhe, Federal Republic of Germany

(Received 21 December 1987)

The branching ratio between internal electromagnetic transitions and β^- decays of the isomer ^{79m}Se was determined experimentally. Extremely clean samples of ^{78}Se were activated with thermal neutrons at a high-flux reactor. A mini-orange-Si (Li) detection system was used to measure β^- particles and conversion electrons immediately after neutron irradiation. For the β^- decay we obtain $\log ft = 4.70^{+0.10}_{-0.09}$. Our present result was used to recalculate the temperature dependence of the effective β^- half-life of ^{79}Se in the stellar interior. In combination with the half-life deduced from a quantitative branching analysis, we obtain a possible temperature range between 182 and 295 million degrees for the weak component of the *s* process.

Nevertheless, the effective stellar half-life at temperatures above 200 million degrees is not changed by the assumed lower limit for the ground state half-life. This leads to the rather strange consequence that, at present, we know the stellar life time of ^{79}Se at a fixed temperature much better than its terrestrial one.

weak *s*-process component to range between 182 and 295 million degrees. **Need of improved cross sections**

The related uncertainty is mainly due to the uncertainty for the effective stellar half-life deduced from the σN systematics which can only be reduced by improved cross section measurements. The present experimental uncer-

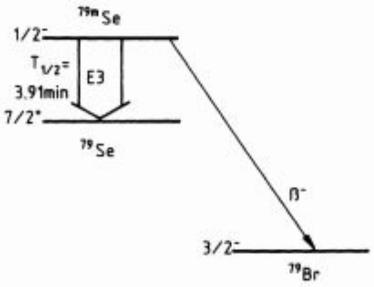


FIG. 1. Decay scheme of ^{79m}Se.

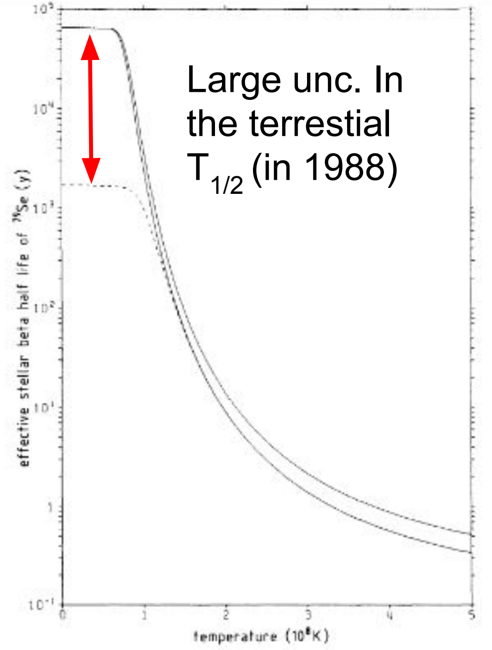


FIG. 7. Stellar half-life of ^{79}Se as a function of temperature. The error band reflects the uncertainty of our measurement. The dashed line refers to $\log ft = 8.5$ for the ground state decay.

Experimental measurement of the logft of the beta decay of the ^{79m}Se state at 96 keV, thermally populated at stellar temperatures

Branching at ^{79}Se: Kr abundances

Published: 22 November 1990

Meteoritic silicon carbide: pristine material from carbon stars

Roy S. Lewis, Sachiko Amari & Edward Anders

All five noble gases in interstellar silicon carbide grains have grossly non-solar isotopic and elemental abundances that vary with grain size but are strikingly similar to calculated values for the helium-burning shell of low-mass carbon stars. Apparently these grains formed in carbon-star envelopes, and were impregnated with noble gas ions from a stellar wind. Meteoritic SiC provides a detailed record of nuclear and chemical processes in carbon stars.

AGB Stars

The Kr isotopic ratios have been measured in bulk SiC acid residues providing details on AGB stars evolved prior to the formation of the Solar System.

Presolar grain measurements give the **most precise data** currently available on s-process nucleosynthesis (at least one order of magnitude better than spectroscopic observations)

ELSEVIER

Geochimica et Cosmochimica Acta

Volume 58, Issue 1, January 1994, Pages 471-494

Interstellar grains in meteorites: II. SiC and its noble gases

Roy S Lewis, Sachiko Amari *, Edward Anders †

interstellar SiC, isolated from the Murchison C2 chondrite. All are mixtures of a highly anomalous component bearing the isotopic signature of the astrophysical s-process and a more normal component, generally solar-like but with anomalies of up to 30% in the heavy isotopes. As these two components strikingly resemble predictions for the He-burning shells and envelopes of red giant carbon stars, it appears that the SiC grains are pristine circumstellar condensates from such stars. A number of elemental and isotopic ratios (such as $K^{80}K^{82}$ and $K^{86}Kr^{82}$) vary with grain size, suggesting that the SiC comes from carbon stars representing a range of masses, metallicities, temperatures, and neutron densities.

European Research Council

Branching at ^{79}Se: Kr abundances

nTOF

Published: 22 November 1990

Meteoritic silicon carbide: pristine material from carbon stars

Roy S. Lewis, Sachiko Amari & Edward Anders

AGB Stars

release temperature of the gas on heating or combustion[7,8]. The variations of ^{80}Kr and ^{86}Kr reflect branching of the s-process at their radioactive progenitors, ^{79}Se and ^{85}Kr (ref. 7). These branchings depend sensitively on neutron density and temperature in the s-process region[7,12], and thus can provide clues about the stars in which the Kr was formed. What we would

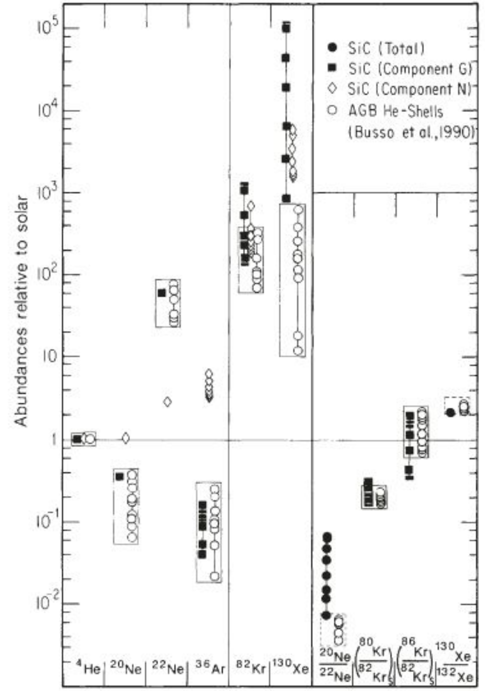


FIG. 3 Right, isotope ratios of SiC and AGB-star He shells, normalized to

TABLE 1 Noble gases in SiC size fractions from Murchison chondrite

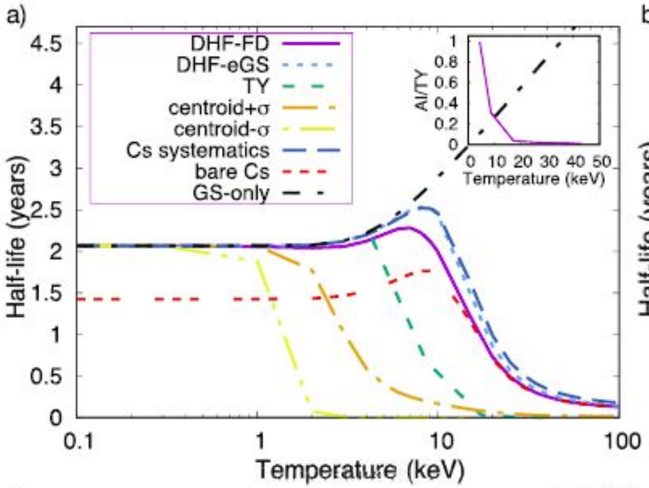
Sample	Size (μm)	^{3}He/^{4}He ×10^{-4}	^{20}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{84}Kr/^{82}Kr	^{130}Xe/^{132}Xe	(^{80}Kr/^{82}Kr)$_s$	(^{86}Kr/^{82}Kr)$_s$
KJA	0.05–0.1	1.32 (18)	0.9075 (10)	0.1927 (5)	3.702 (24)	0.3532 (10)	0.0597 (67)	0.621 (44)
KJB	0.1–0.2	2.00 (10)	0.8933 (3)	0.1919 (1)	3.603 (6)	0.3602 (4)	0.0586 (16)	0.695 (24)
KJC	0.2–0.3	1.48 (7)	0.6345 (3)	0.1907 (2)	3.693 (10)	0.3604 (6)	0.0526 (27)	1.145 (19)
KJD	0.3–0.5	1.16 (6)	0.4582 (5)	0.1935 (1)	3.769 (8)	0.3558 (5)	0.0490 (25)	1.733 (23)
KJE	0.5–0.8	0.81 (4)	0.2977 (5)	0.2051 (2)	3.756 (11)	0.3465 (10)	0.0451 (21)	2.363 (34)
KJF	0.8–1.5	0.56 (3)	0.2001 (2)	0.2210 (5)	3.776 (21)	0.3291 (22)	0.0365 (37)	2.710 (71)
KJG	1.5–3	0.53 (5)	0.1556 (2)	0.2313 (6)	3.915 (21)	0.2716 (28)	0.0336 (72)	2.872 (62)
KJH	3–5		0.0979 (19)	0.2090 (23)	4.500 (87)	0.1606 (52)	0.055 (58)	
Solar[21]		1.42	13.7	0.188	4.988	0.1643		
He-Shell, Range*			0.05–0.084	0.57–1.25	2.2–2.6	0.39–0.44		
He-Shell, Typical		0	0.0808	0.74	2.55	0.485†		

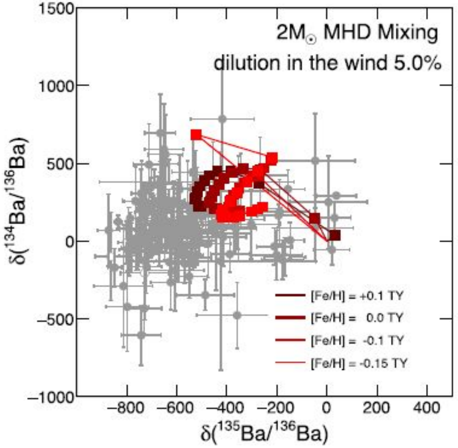
Very accurate 80Kr/82Kr abundances ratios

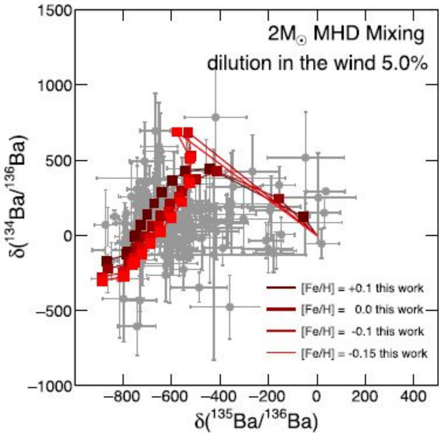
^{134}Cs, ^{135}Cs: T-dependence β-decay

Theoretical Estimate of the Half-life for the Radioactive ^{134}Cs and ^{135}Cs in Astrophysical Scenarios

Simone Taioli[1,2], Diego Vescovi[3], Maurizio Busso[4,5], Sara Palmerini[4,5,10], Sergio Cristallo[5,6], Alberto Mengoni[7,8], and Stefano Simonucci[5,9]







Agreement with the data improves with New beta decay rates of both ^{134,135}Cs

^{134}Cs, ^{135}Cs: Relevance s-process

Presolar Grain Isotopic Ratios as Constraints to Nuclear and Stellar Parameters of Asymptotic Giant Branch Star Nucleosynthesis

Sara Palmerini[1,2], Maurizio Busso[1,2], Diego Vescovi[2,3], Eugenia Naselli[4], Angelo Pidatella[4], Riccardo Mucciola[1,2], Sergio Cristallo[2,5], David Mascali[4], Alberto Mengoni[6,7], Stefano Simonucci[2,8], and Simone Taioli[9,10,11]

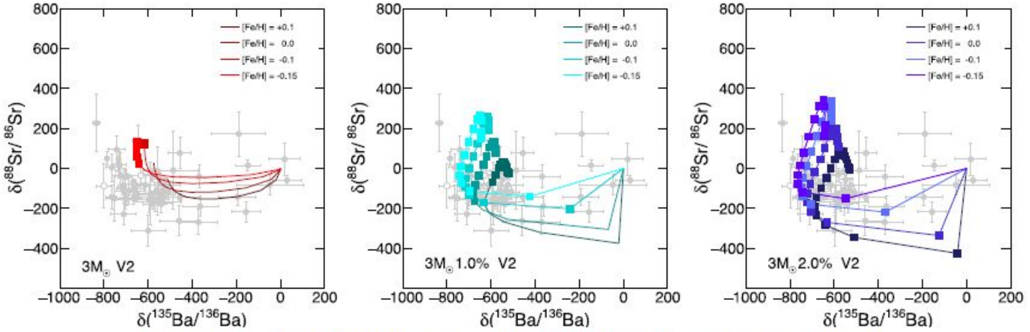


Figure 13. Same as Figure 12, but for the test models V2, with tentatively modified nuclear inputs (see Section 3).

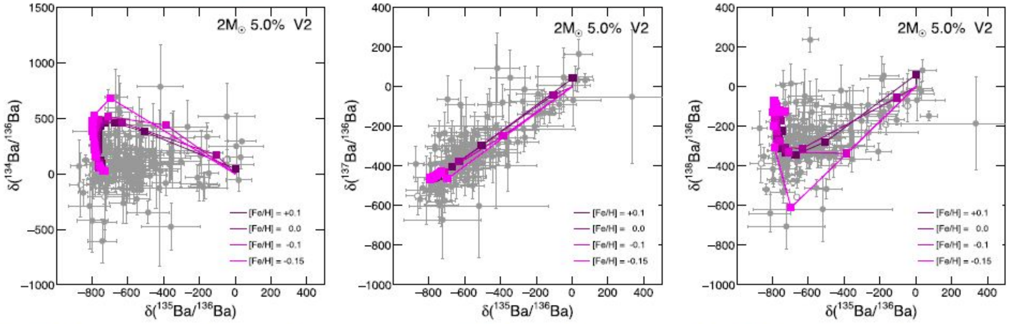


Figure 19. A comparison of model predictions from a representative case of 2 $M_\odot$ models (full lines with heavy dots) with SiC data for various Ba isotopes and with the the choice V2 for nuclear parameters, including revisions for the ^{134}Cs decay, as illustrated in Section 4. The meaning of the symbols is the same as in previous figures. The three panels represent the composition of winds with 5% of He-shell material added.

Sr/Ba ratios:
A longer half-live of 135Cs at 30 keV or **variations in the ^{135}Cs(n,g)cross section** will improve the agreement with the data

Ba-ratios separately:
Revision of the capture cross sections of Cs-isotopes would improve the agreement

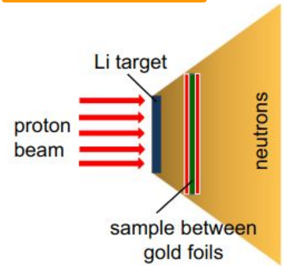
On-going & future developments

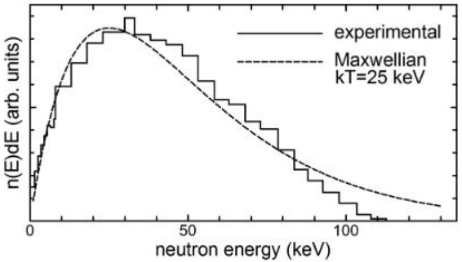
NEAR: "stellar" activations at n_TOF

Low E (MeV) proton accelerators

$^{7}Li\,(p,n)^{7}Be$

Quasi-maxwellian @ 25 keV

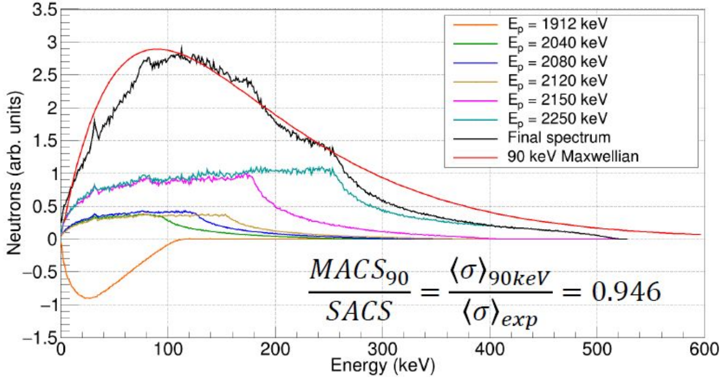




Ep=1912 keV PHYSICAL REVIEW C **93**, 045803 (2016)

STANDARD METHOD

Different Ep combined → MACS @ Higher kTs

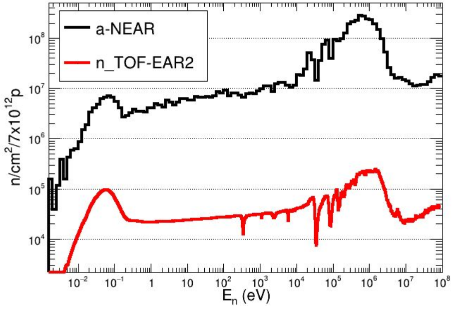


$$\frac{MACS_{90}}{SACS} = \frac{\langle\sigma\rangle_{90keV}}{\langle\sigma\rangle_{exp}} = 0.946$$

Med/High energy accelerator (~10MeV - ~GeV)

Target + moderator

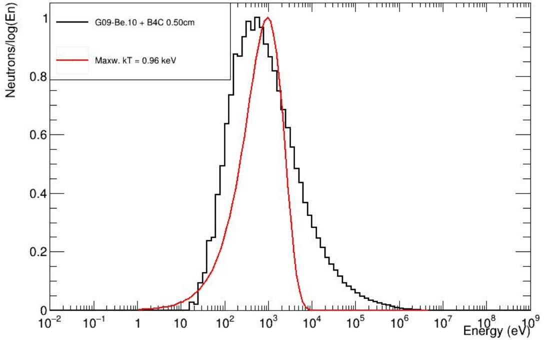
White neutron beam



n_TOF-NEAR APPROACH

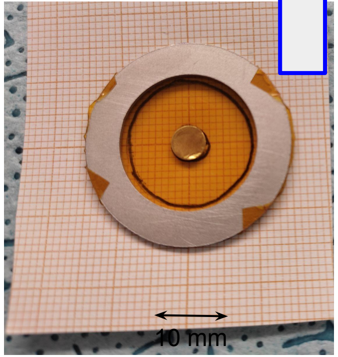
Moderating + Filtering assembly

Neutron energy shaping → MACS @ different kTs



Stellar (n,g) activations at NEAR: Present

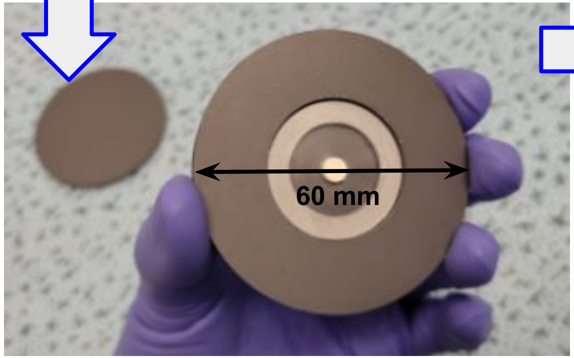
MACS measuring capability benchmark:
E. Stamati et al.,
CERN-INTC-2022-008;
INTC-P-623 (2022)



1) Sample preparation:
5 mm sample
on 30mm diam Al ring

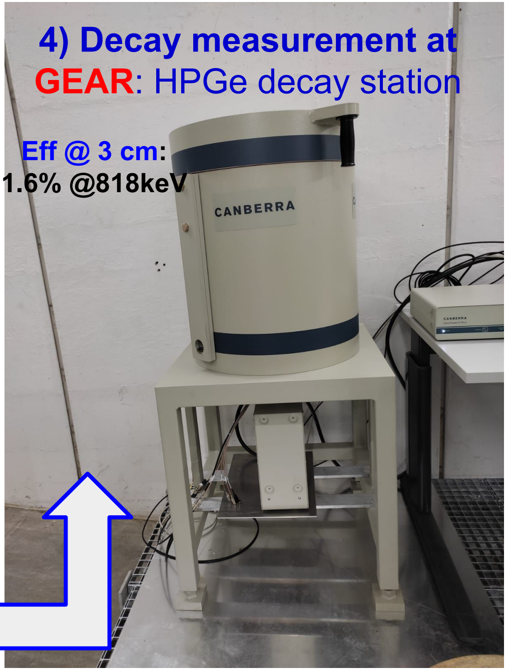
2) Irradiation at NEAR:
One long irradiation (~1 week)

3) Access to NEAR (6h) + manual transport to decay station (~h)



4) Decay measurement at GEAR: HPGe decay station

Eff @ 3 cm:
1.6% @818keV

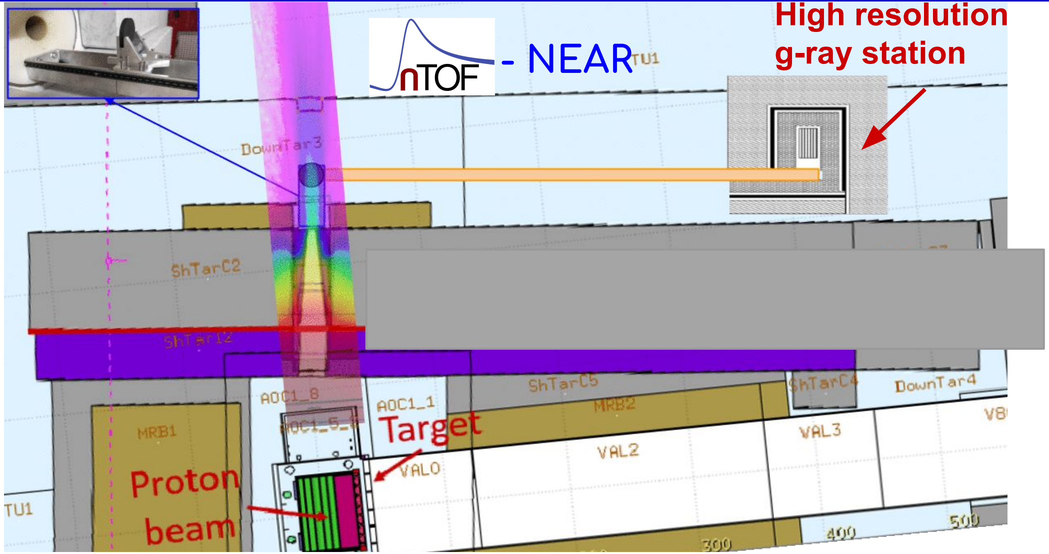


Main limitations:
- Not able to measure activation with short lived (s, min) (n,g) products
- Impossible to activate short lived (hours-days) targets

Stellar (n,g) activations at NEAR: Future

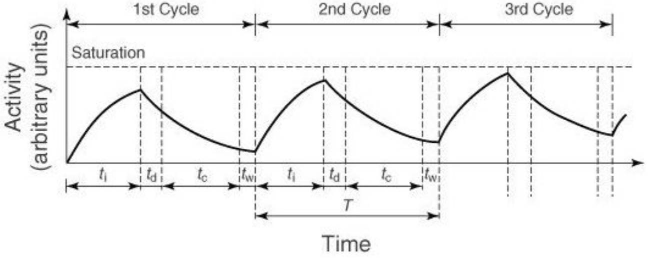
CYCLING @ NEAR: CYCLIc activation for (N,G) measurements

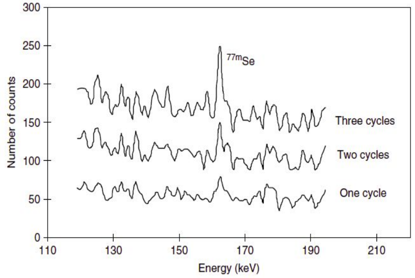
- Allows: activation with short lived (s, min) (n,g) products
- Especially interesting for unstable isotopes.
- Well suited to the rep. Rate (>0.8Hz) of n_TOF



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), ^{144}Ce(n,γ), ^{132}Te(n,γ),...





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

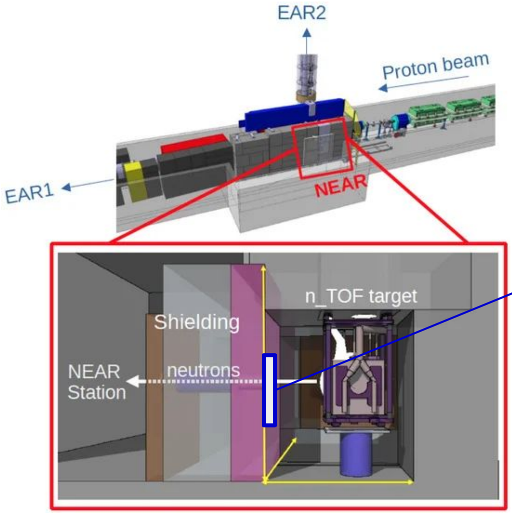
J. Lerendegui, M. Bacak *CERN-INTC-2022-018 ; INTC-I-241*.

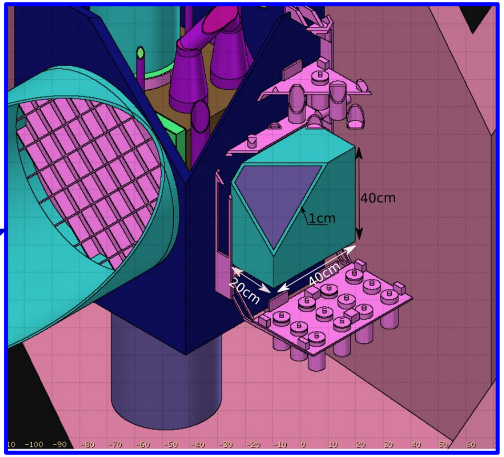
H. Beer, et al., Nucl. Inst. Meths. 337, 2–3 (1994)

Stellar (n,g) activations at NEAR: Future

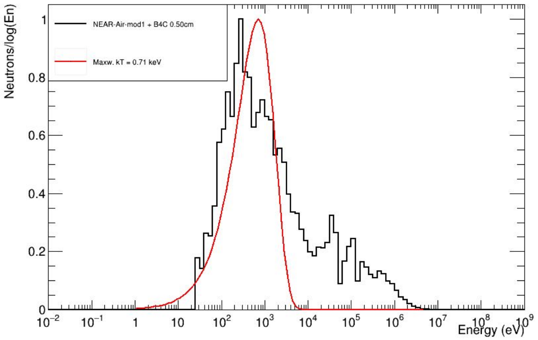
Solution:

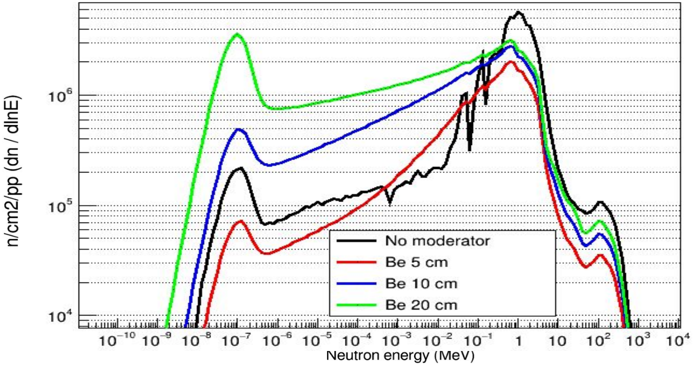
- Include a moderator in the target to improve the match between spectra and a Maxwellian spectra



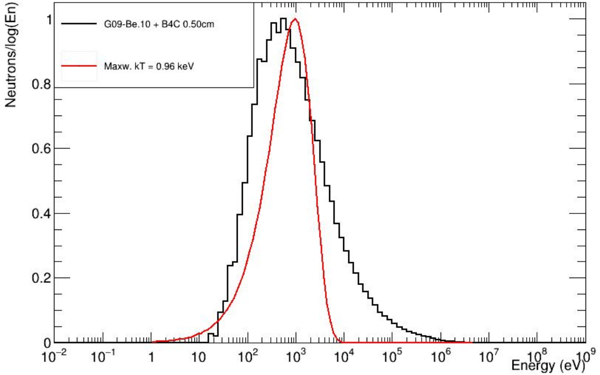


Current: No moderator



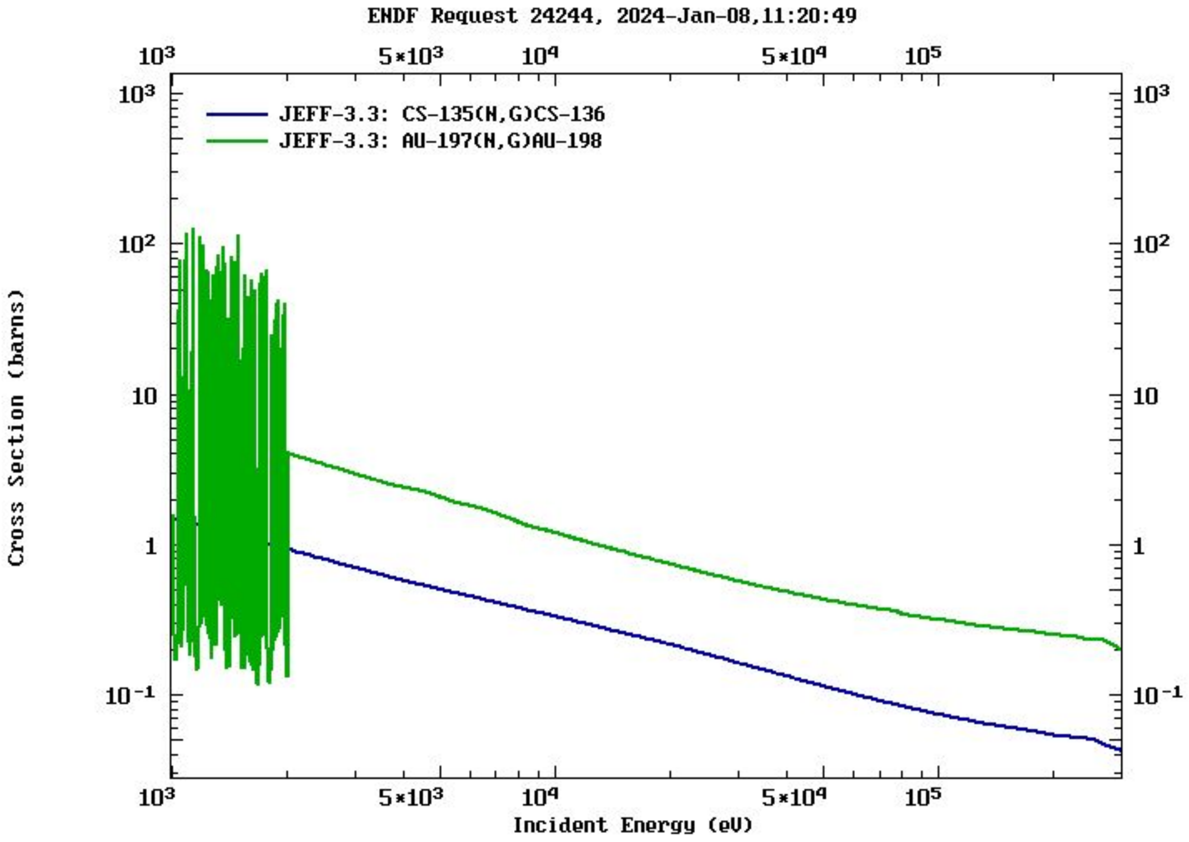


10 cm Be moderator



SACS to MACS: Au-197

- Very similar shape of the cross section
- No large resonances in any of the isotopes
- MACS/SACS expected to be not very different.
- Shape of the cross sections can be used to improve the accuracy



Stellar (n,γ): future projects/ideas @ n_TOF

nTOF

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

GENERAL AIM: Enhancing the capabilities for new physics
Focusing on (n,g) measurements on unstable nuclei relevant for astrophysics:

TOF Measurements on lower mass unstable (s-process):

- Improve CR capability, efficiency & sensitivity (higher segmentation, larger arrays, solid scintillators, …)
- Improve signal-to-background: New shieldings and collimator for EAR2 or modification of EAR2 with walls and ceiling further from setup.
- High purity samples (RITU project, PSI)
- Beamline looking to moderator and/or new beamlines (backwards): less background from high energy neutrons
- Higher intensity per pulse & higher rep. rate with similar t-resolution.

Current spallation target

Before LS3 (-2026)

Beyond LS3 (2028-)

New spallation target

NEAR: activations on short-lived isotopes (s/i-process)

- Installation of NEAR moderator (target) → Improve SACS/MACS
- Cycling: Rabbit system NEAR-ISR and (if feasible) decay station at NEAR.
- Activations inside the target shielding (factor x100 flux) → Rabbit system.
- Strengthen Synergy ISOLDE-NEAR for sample production and combined direct - surrogate reactions.
- Average intensity x10 higher with worse t-resol (suitable only for NEAR).

Towards short-lived unstable: Future concepts

DIRECT (N,G) IN INVERSE KINEMATICS

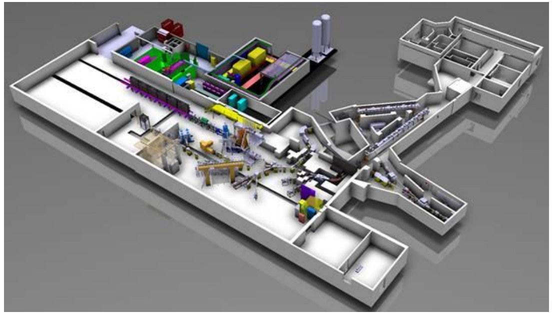
Aim: short-lived (s- and i-process)

Short-lived nuclei → Storage Ring → Neutrons → Measure reaction product

- *s*-process: ^{134}Cs ($t_{1/2}$ = 2.06 y), ^{147}Nd ($t_{1/2}$ = 11 d), ^{148}Pm ($t_{1/2}$ = 5.37 d), ^{153}Gd ($t_{1/2}$ = 240.4 d), ^{160}Tb ($t_{1/2}$ = 72.3 d), ^{170}Tm ($t_{1/2}$ = 128.6 d), and ^{204}Tl ($t_{1/2}$ = 3.78 y).
- *i*-process: ^{66}Ni ($t_{1/2}$ = 54.6 h), ^{75}Ga ($t_{1/2}$ = 126 s), ^{135}I ($t_{1/2}$ =6.58 h), ^{141}Ba ($t_{1/2}$ = 18.27 m), and ^{141}La ($t_{1/2}$ = 3.92 h).

- Posible at CERN n_TOF beam & ISOLDE?

CERN ISOLDE + nTOF + RING?



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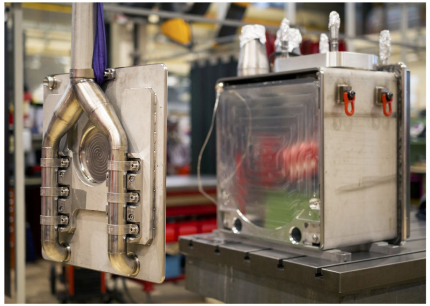

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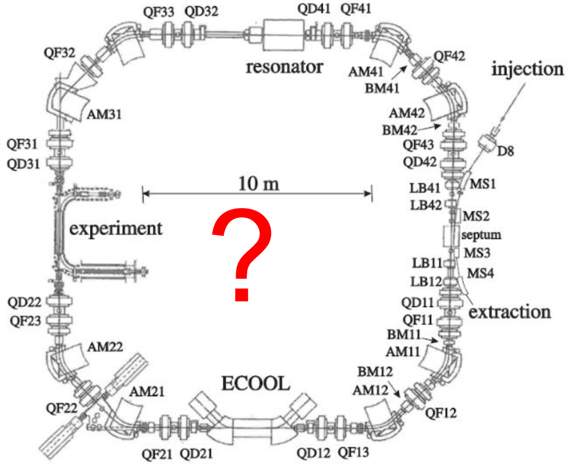
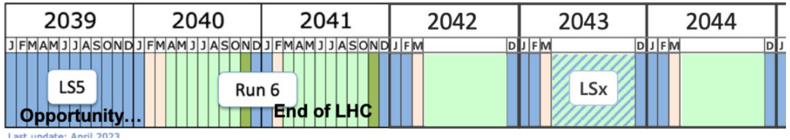




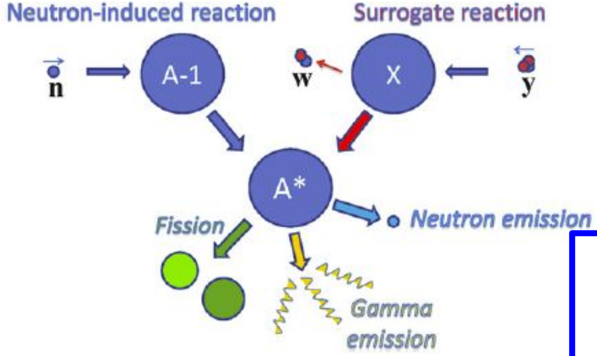
Project: Storage ring at HIE-ISOLDE

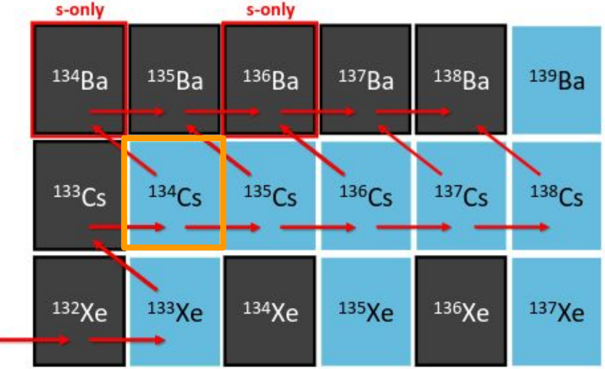
M. Grieser et al., Eur. Phys. J Spec. Top. 207, 1 (2012)

Other reaction channels / methods

Future of stellar (n,γ) beyond n_TOF

SURROGATE REACTIONS





Temperature-sensitive s-branching
No TOF (High activity) + No activation

PHYSICAL REVIEW LETTERS **122,** 052502 (2019)

Towards Neutron Capture on Exotic Nuclei: Demonstrating $(d,p\gamma)$ as a Surrogate Reaction for (n,γ)

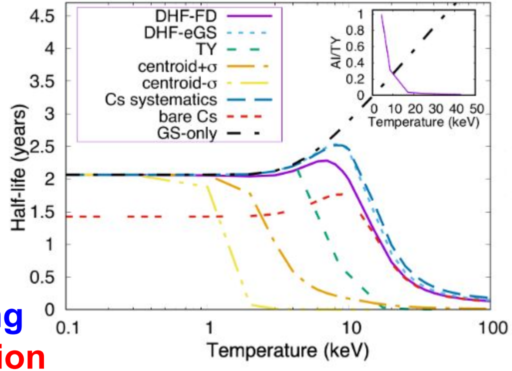
A. Ratkiewicz,[1,2,*] J. A. Cizewski,[2] J. E. Escher,[1] G. Potel,[3,4] J. T. Harke,[1] R. J. Casperson,[1]

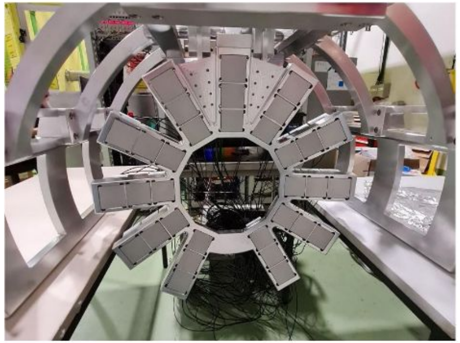
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of neutron capture cross section on ^{134}Cs through surrogate reaction (d,pγ) at ISS

January 10, 2024





Surrogate reaction Inverse kinematics
^{134}Cs beam @ ISOLDE + CD_2 target
ISOLDE Solenoid

Future idea: complement (n,g) at NEAR (low En) + (d,pg) at ISS-ISOLDE

Neutrons and nuclear astrophysics @ n_TOF

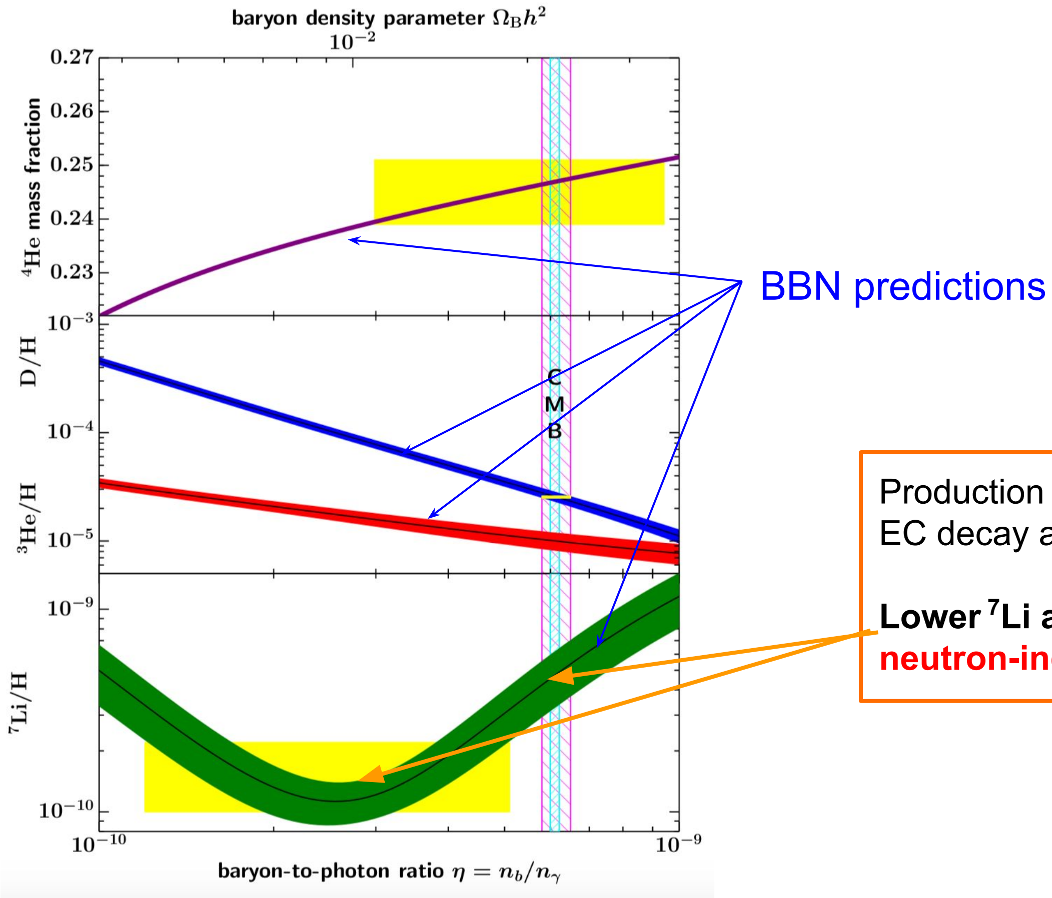
s-process: production of the majority of elements heavier than Fe.

BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

Neutron-induced reactions in Nuclear Astrophysics

Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.

Neutrons and nuclear astrophysics @ n_TOF



BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

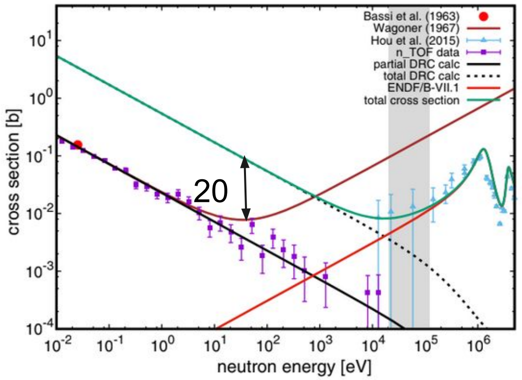
Production of ^{7}Li: dominated by the ^{7}Be EC decay after the BBN.

Lower ^{7}Li abundance? A higher rate for **neutron-induced** reactions on 7Be?

Neutrons and nuclear astrophysics @ n_TOF

PRL 117, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

^{7}Be$(n,\alpha)^{4}$He Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN



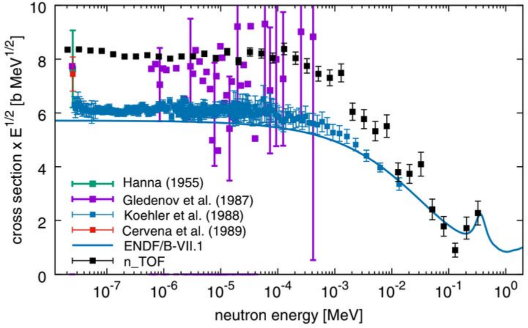
BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

PHYSICAL REVIEW LETTERS 121, 042701 (2018)

^{7}Be$(n,p)^{7}$Li Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

^{7}Be$(n,p)^{7}$Li rate	η_{10}	Li/H yield
Cyburt (2004) rate [22]	6.09	5.46
This work [Eq. (3)]	6.09	5.26 ± 0.40
	5.8–6.6	4.73–6.23
Observations [1]		1.6 ± 0.3

- Be-7(n,a): x20 vs calculations of BBN below 100 eV
- Be-7(n,p): +40% vs previous at low En



Neutrons and nuclear astrophysics @ n_TOF

PRL **117**, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

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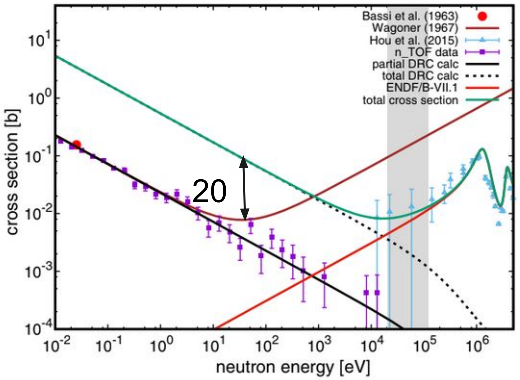

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PHYSICAL REVIEW LETTERS **121**, 042701 (2018)

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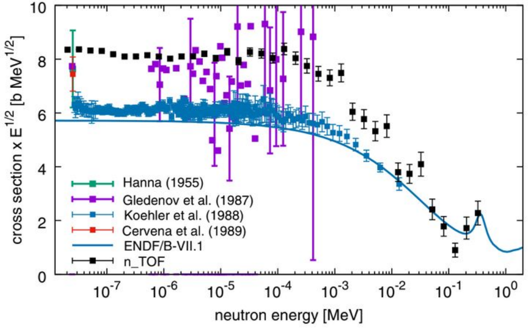


Neutrons are not enough to solve the CLiP → Alternative physics or astromical scenarios

Neutrons and nuclear astrophysics @ n_TOF

CSIC
Consejo Superior de Investigaciones Científicas

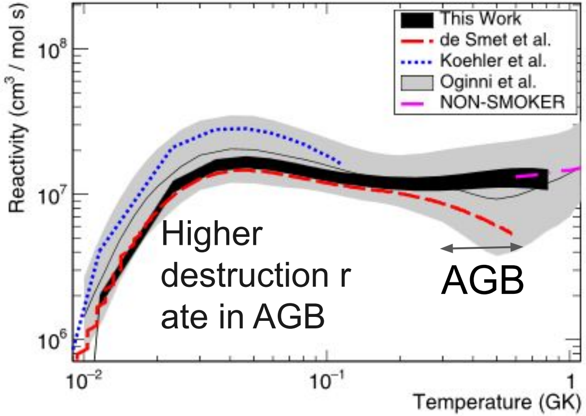
Neutron-induced destruction of the cosmic-ray emitter Al-26 (T1/2 = 0.7 Myr)

PHYSICAL REVIEW C **104**, L032803 (2021)

Letter

Destruction of the cosmic γ-ray emitter ^{26}Al in massive stars: Study of the key ^{26}Al(n, α) reaction

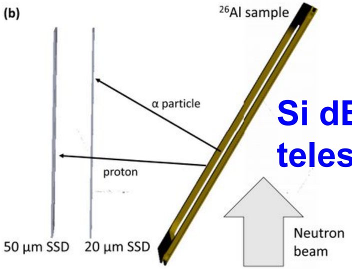
C. Lederer-Woods,[1,*] P. J. Woods,[1] T. Davinson,[1] A. Estrade,[1,†] J. Heyse,[2] D. Kahl,[1,‡] S. J. Lonsdale,[1] C. Paradela,[2]



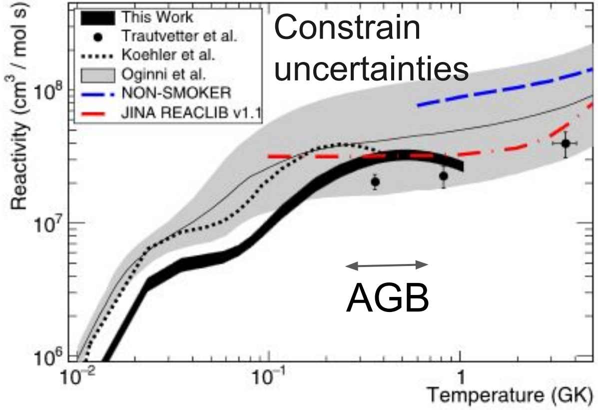
PHYSICAL REVIEW C **104**, L022803 (2021)

Letter

Destruction of the cosmic γ-ray emitter ^{26}Al in massive stars: Study of the key ^{26}Al(n, p) reaction



Si dE/E telescope



- Significant discrepancies in the Al-26 destruction rates.
- Impact in the Al-26 production in supernovae and AGB origin of our early solar system

Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.

Next: extend>1 GK (Massive stars)

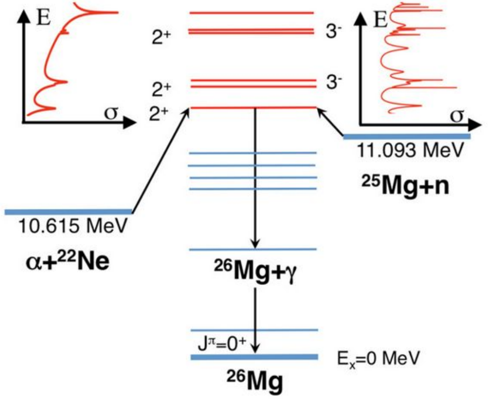
Neutrons and nuclear astrophysics @ n_TOF

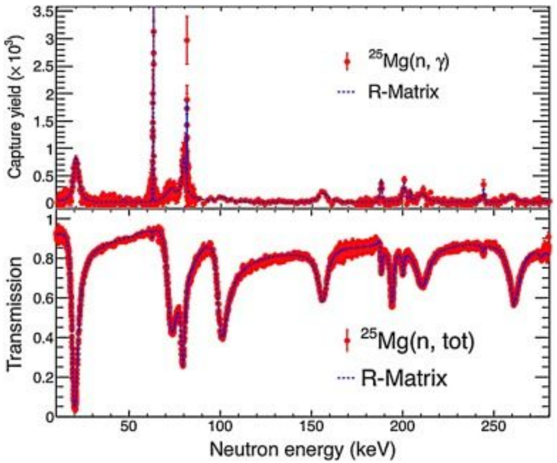
Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source $^{22}Ne(\alpha,n)^{25}$Mg

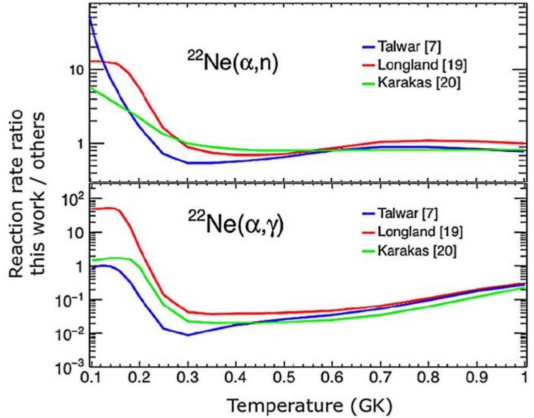
CrossMark

C. Massimi[a,b,*], S. Altstadt[c], J. Andrzejewski[d], L. Audouin[e], M. Barbagallo[f], V. Bécares[g],

Neutron-spectroscopy to experimentally constrain the neutron source reaction 22Ne(α,n)25Mg







- R-matrix on (n,g) → parity assignment of the excited states in 26Mg
- 22Ne(a,n) rates enhanced at low temperature.
- Large impact in the AGB s-process abundances (2-5 M).

Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.