High precision ^{209}Bi(n, γ) cross section measurement at nTOF EAR2

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and nTOF collaboration.

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[2] Universidad de Valencia
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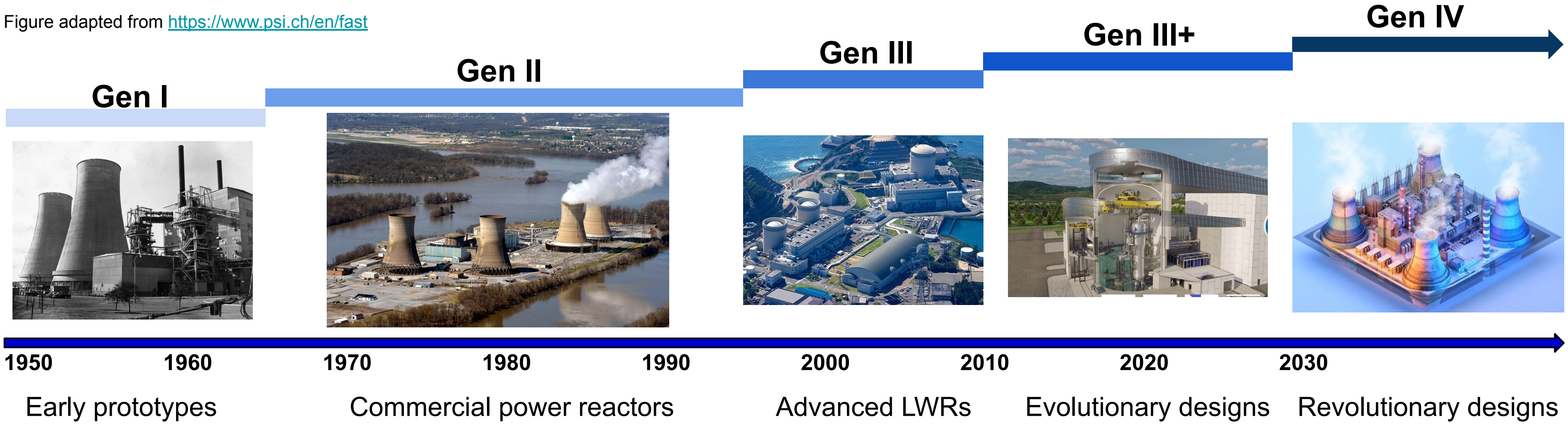
[6] University of Manchester, United Kingdom

EURO-LABS 3rd annual meeting: 27-30 October 2024

Gen-IV & ADS nuclear systems

Figure adapted from https://www.psi.ch/en/fast



New generation of advanced nuclear power plants (**GenIV**) and **ADS** is under design and development aiming to:

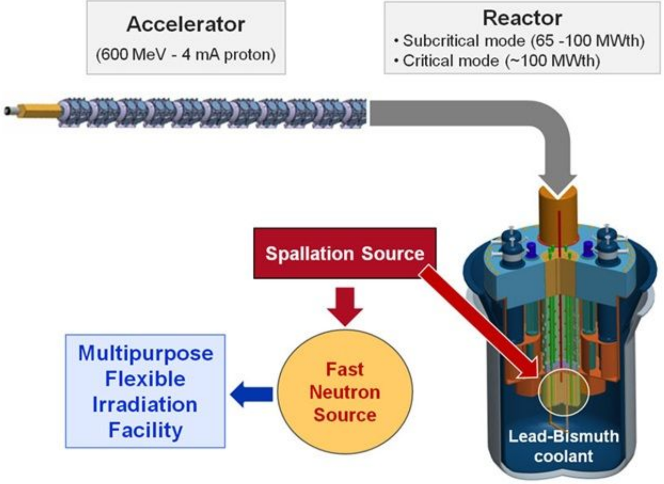
- Excel **safety** and **reliability** during operation.
- **Sustainability** energy generation and minimization of nuclear waste in long-term.
- Comply with **Non proliferation** agreements.

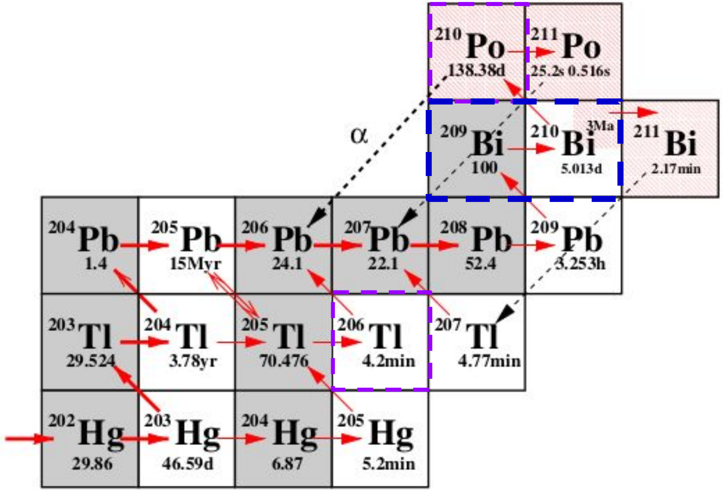
Development on nuclear technology requires **improvement** on **nuclear data** accuracy:

- **Delayed neutron emission** probabilities.
- **Neutron** induced **cross sections.**

MYRRHA and ^{210}Po production

Figure adapted from https://www.sckcen.be/en/expertises-0





MYRRHA is a multipurpose Accelerator Driven System (ADS) nuclear reactor able to operate in subcritical and critical mode. It is made of:

- **600 MeV** Proton **accelerator**.
- Spallation target.
- A core with MOX fuel **cooled** by liquid **lead-bismuth** (Pb-Bi).

Radiological Burden associated with the use of Pb-Bi coolant is because of **^{209}Bi(n,ɣ)** populating ^{210}Bi and ^{210m}Bi:

^{210}Po ($t_{1/2}$~5 days)/^{206}Tl ($t_{1/2}$~3My)

Calculations for **^{210}Po** concentration for **MYHRRA** in one irradiation **ranges** from **5** to **20%** depending on the **evaluation**.

MINISTERIO DE CIENCIA E INNOVACIÓN
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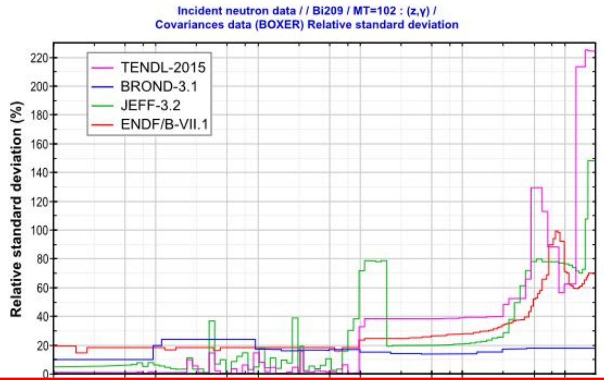
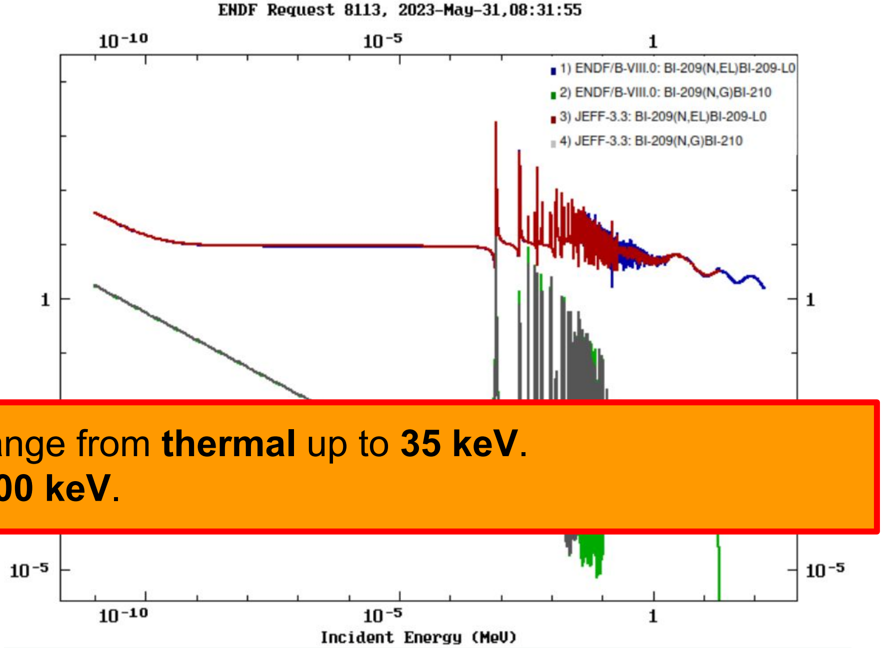
^{209}Bi(n,ɣ) XS and challenges

Figure adapted from L. Fiorito *et al.* EPJ Nuclear Sci. Technol. (2018) **4**, 48





- **5-10% accuracy** in RRR covering **neutron energies** range from **thermal** up to **35 keV**.
- **<15% accuracy** in the neutron energy range from **35-100 keV**.

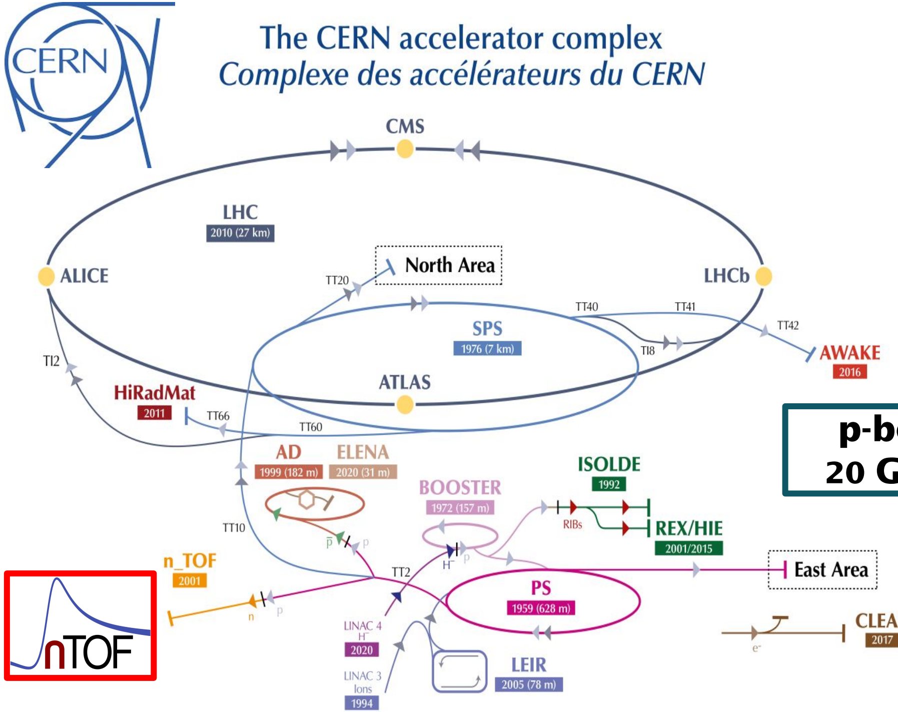
Relative **Bi(n,ɣ) uncertainty** for **different evaluated libraries** are in between **20%** and **40%** for **neutron resonances.**

Need for new accurate **^{209}Bi(n,ɣ)** and ^{209m}Bi(n,ɣ)/^{209}Bi(n,ɣ) data as requested in the High Priority request list.

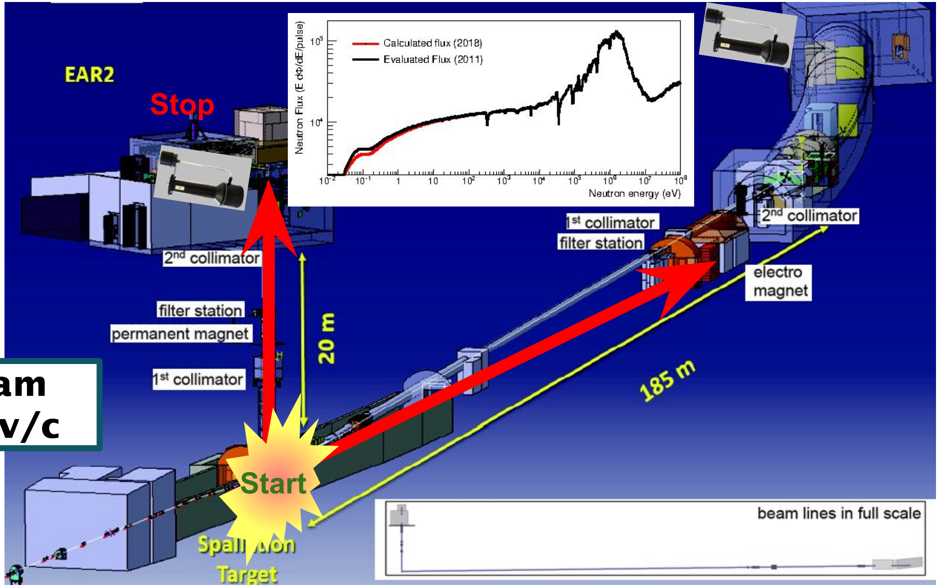
Measurement of **^{209}Bi(n,ɣ) cross section** is very challenging because of:

- **Small (n,ɣ)** cross section.
- **(n,ɣ)/(n,el)<<1**.

The nTOF facility @ CERN


The CERN accelerator complex
Complexe des accélérateurs du CERN

p-beam
20 Gev/c



C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

CERN n_TOF Collaboration: 150 scientists, 41 institutions worldwide

n_TOF + ISOLDE = 75% of PS proton Budget (!)

Time to energy conversion

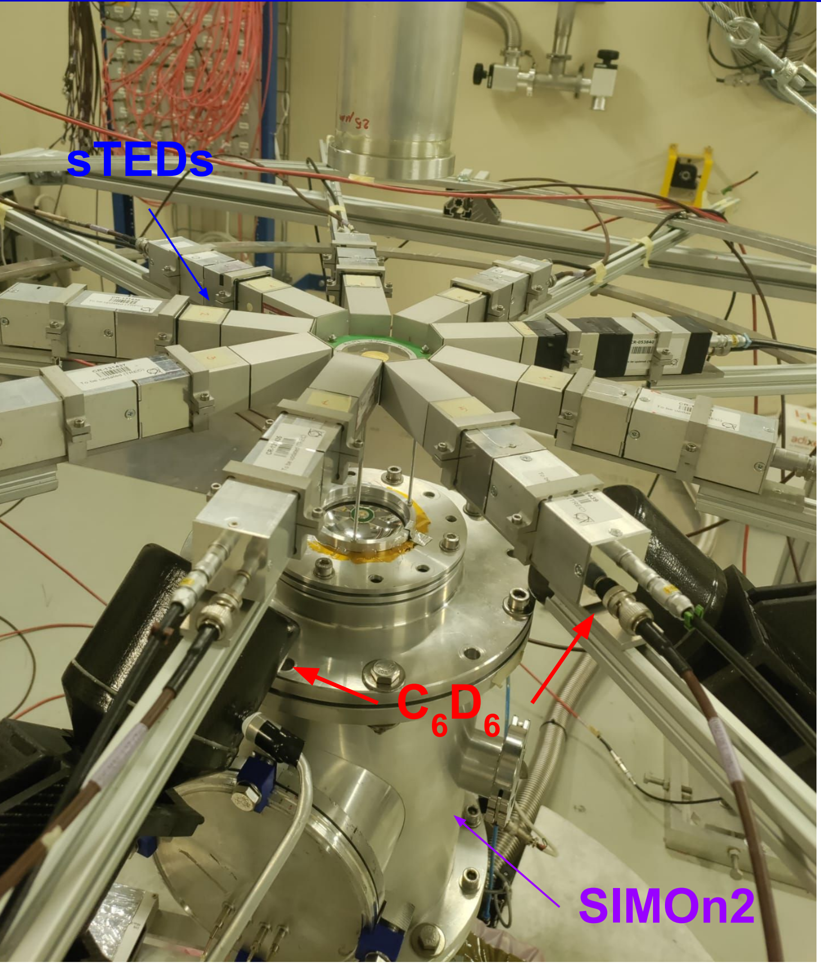
$$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$$

Neutron time-of-flight

$$t = t_m - (t_\gamma - L/c)$$

Start: p-beam time impact **Stop: (n,ɣ)** time detection

Experimental setup @ nTOF EAR2



The experiment took place in **April 2024** at the **nTOF EAR2** using the **state-of-the-art (n,ɣ)** experimental setup:

- **Lightweight sample holder** design to minimize dead material around the target under study.
    - Reduce background from scattered neutrons
- **9 sTEDs** in compact configuration **@90º** and **4.5 cm** from the target position:
    - High sensitivity (n,ɣ) detection setup.
- **2 C_6D_6** detectors **@135º** and **17 cm** and **20 cm** from target:
    - Angular anisotropies + other possible systematics.
- **SiMOn2** : neutron beam monitoring/rel. normalization.

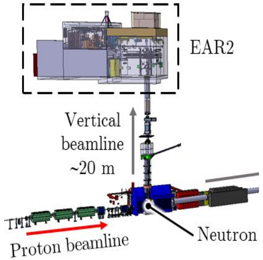
Experimental setup especially **well suited** for **small (n,ɣ) cross sections** and/or **high radioactive targets**

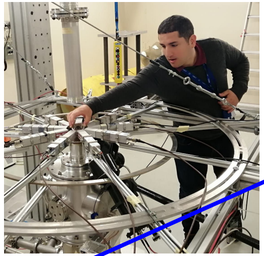
High precision measurement

The reaction yield is calculated experimentally as:

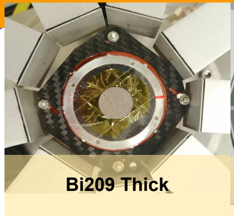
$$Y(E_n) = \frac{C(E_n) - B(E_n)}{B_{if} \times \phi(E_n) \times \varepsilon_\gamma(E_n)}$$

Improve ^{209}Bi(n,ɣ) signal



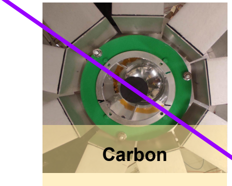


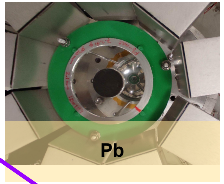
Well controlled geometry, high purity, targets with different thicknesses

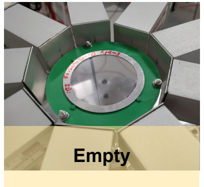

Bi209 Thick


Bi209 Thin

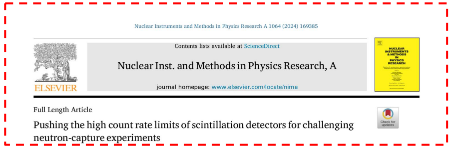
Dedicated bkg. measurements


Carbon


Pb


Empty

Develop new methodologies



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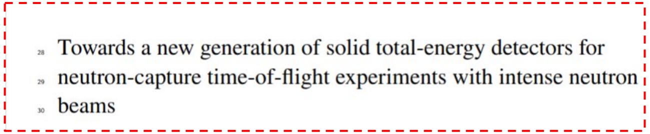
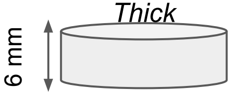
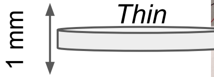
Full Length Article

Pushing the high count rate limits of scintillation detectors for challenging neutron-capture experiments

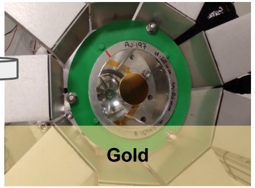


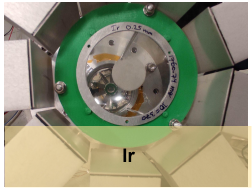
Towards a new generation of solid total-energy detectors for neutron-capture time-of-flight experiments with intense neutron beams

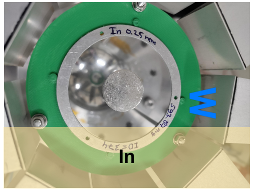




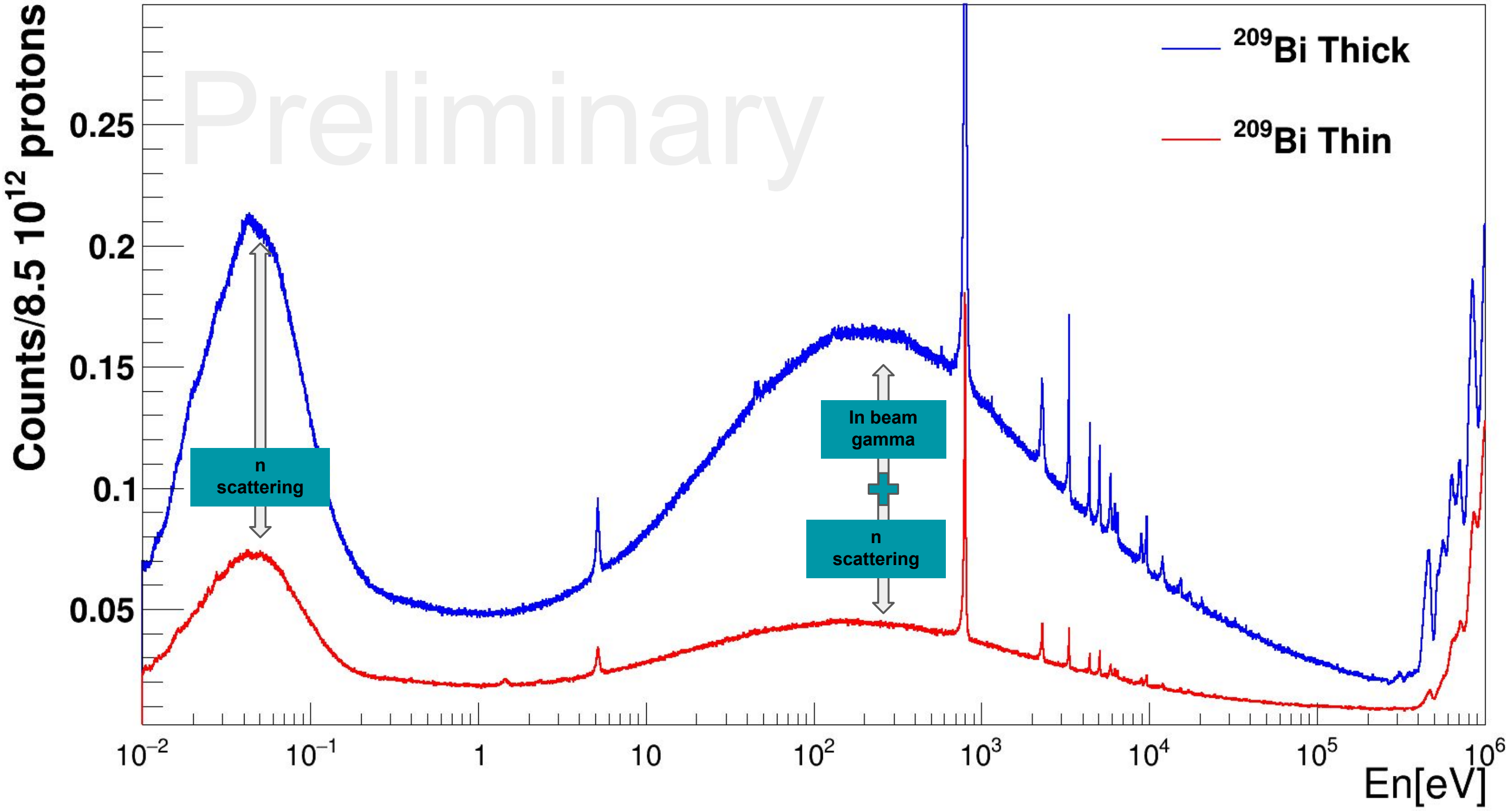
Several normalizations


Gold


Ir

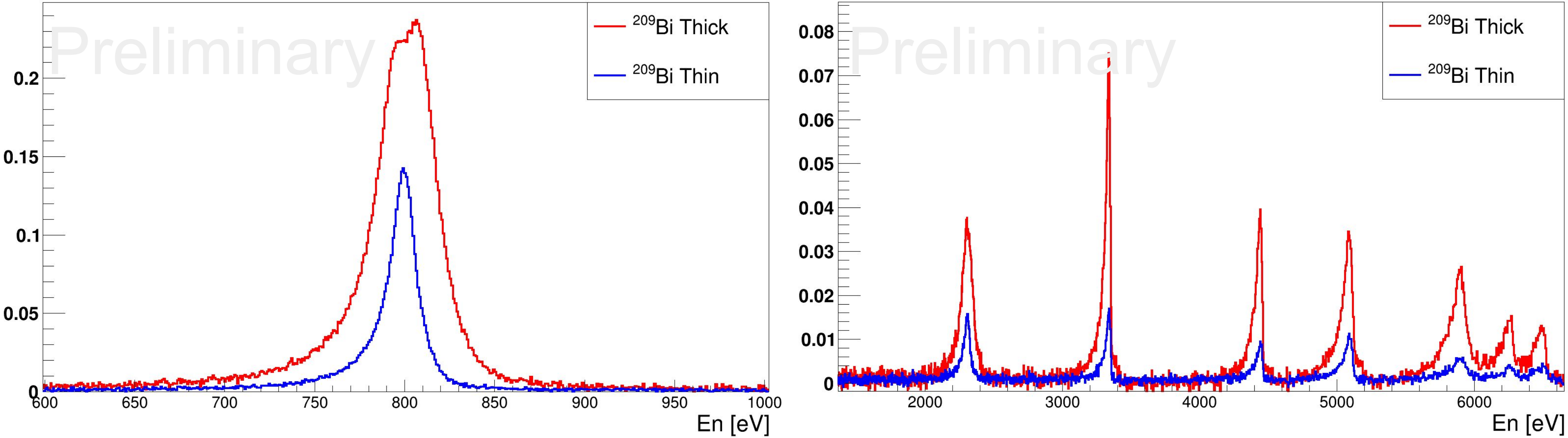

In

Preliminary ^{209}Bi(n,γ) data



The **thin** and **thick** targets are of **capital** importance for **MS contributions**, cover the goal **neutron energy range** and control other **systematics**

Preliminary ^{209}Bi(n,ɣ) data



After a very **preliminar background subtraction**:

- Different neutron resonance shape between **thin** and **thick** target data
  - We can account for MS and other systematics thanks to both datasets!
- Expected useful **thin** and **thick** datasets up to **E_n~30 keV**
- For **E_n>30 keV**, **only** the **thick** target will be of use.

Summary & conclusions

- ^{209}**Bi(n,ɣ)** cross section is important for both, nuclear energy applications and nuclear astrophysics:
  - Critical to assess the **radiological burden** associated to ^{210}Po for **GenIV** and **ADS** systems cooled by **Bi/Pb** mixtures.
  - ^{209}**Bi(n,ɣ)** is **important** for **s-process** and for **U/Th clocks.**

- Measurement very **challenging** because:
  - **Small (n,ɣ).**
  - **(n,ɣ)/(n,el)<<1.**

- Present high precision ^{209}Bi(n,ɣ) cross section measurement **goals**:
  - **5-10% uncertainty** in RRR **En<35 keV.**
  - **<15% uncertainty** in NRR **35 keV<En< 100 keV.**

Experiment design to overcome previous measurements.

- It took place in **April 2024** at the high luminosity **nTOF EAR2**:
  - **Experimental setup** design to enhance sensitivity
  - Several efforts over background estimation and normalization
  - **2 targets** with different **thicknesses** to control MS and Self-Shielding

- Very promising preliminary results from both thin and thick targets:
  - **Analysis just started!**

G. de la Fuente phD candidate

Thank you very much for your attention!

Outline

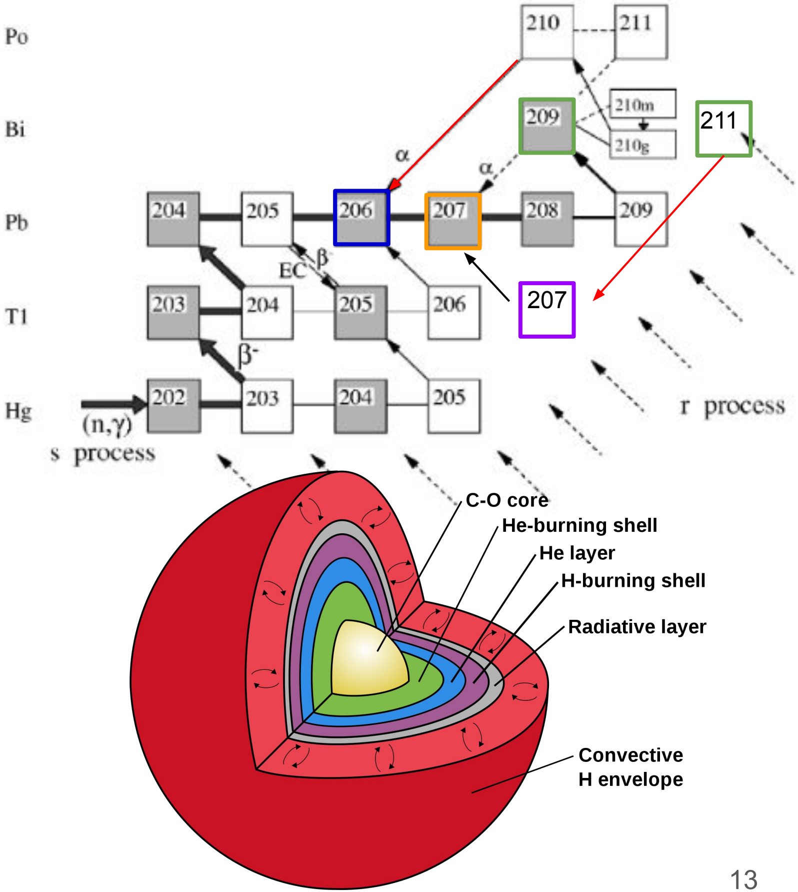
- Introduction
- The nTOF facility and the experimental setup
- Very preliminary results
- Summary & conclusions

s-process & Th/U cosmic clocks

From the **astrophysical** point of view, ^{209}Bi(n,ɣ) is **important** for understanding the chemical evolution of the Universe via **s-process** and for **U/Th** cosmic **clocks**:

- ^{209}Bi is the **last stable** s-process **nucleus** before the α-unstable region feeding to the region above ^{206}**Pb** recycling heavy material.
- ^{209}Bi(n,ɣ) also **contribute** to ^{207}**Tl** **branching** point towards production of ^{207}**Pb**.
- **Th/U ratio**s, used as **cosmic clocks** for stars, needs **accurate data** on ^{209}Bi(n,ɣ) to disentangle **radiogenic** contributions from **Th** and **U α-chain** decays.

Figure adapted from U. Ratzel et al Phys. Rev. C 70 065803 (2004)



XS & neutron reaction yield

There is a catch: the microscopic $\sigma_\gamma(En)$ cross-section is not an experimental observable; the reaction yield $Y_\gamma(En)$ is:

$$Y(E_n) = Y_0(E_n) + Y_1(E_n) + Y_2(E_n) + \mathcal{O}(\Sigma^4)$$

Y_0= capture
Y_1= scattering+capture
Y_2=scattering+scattering+capture

$\sigma_T \cong \sigma_\gamma + \sigma_n$

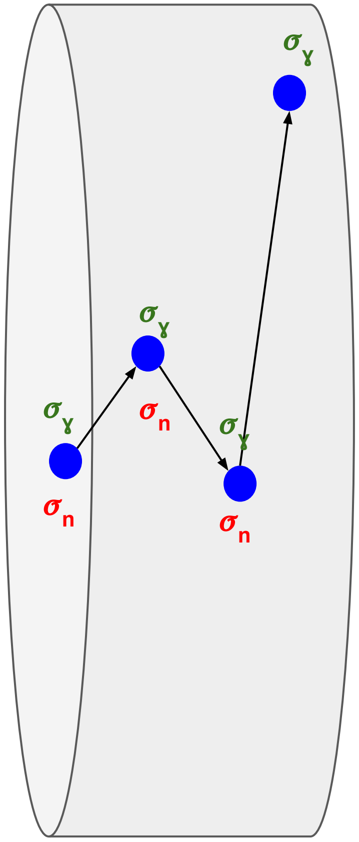
$$Y_n(E_n) = \prod_{i=0}^{n-1}\left[\int_0^{l_{max,i}} \Sigma e^{-\Sigma\sigma_T(E_{n,i})l_i}\, dl_i \int \frac{d\sigma_{nn}(E_n)}{d\Omega}\, d\Omega_i\right] \int_0^{l_{max,n}} \Sigma\sigma_\gamma(E_{n,n})\, e^{-\Sigma\sigma_T(E_{n,n})l_n}\, dl_n$$

Is this important?

Yes, for measurements with the following characteristics:

- Small $\sigma_\gamma(E_n)$
- $\sigma_\gamma(E_n)/\sigma_n(E_n) << 1$
- Thick targets

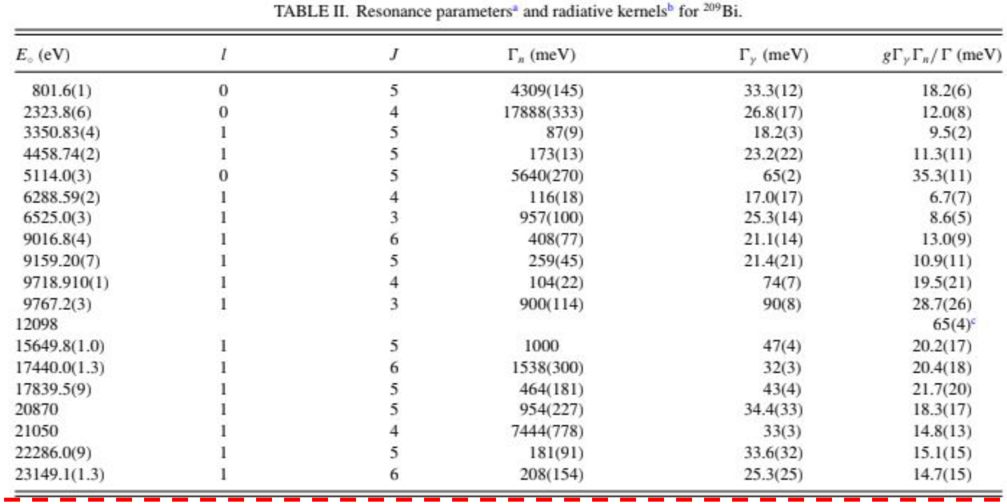
^{209}Bi(n,γ)



Target

Prev. ^{209}Bi(n,ɣ) and present goals

^{209}Bi(n,ɣ) **nTOF** using **C_6D_6** detectors @ **EAR1** in **2006**



C. Doming et al. Phys. Rev. C 74 025807 (2006)

TABLE II. Resonance parameters[a] and radiative kernels[b] for ^{209}Bi.

$E_\circ$ (eV)	l	J	Γ_n (meV)	Γ_γ (meV)	$g\Gamma_\gamma\Gamma_n/\Gamma$ (meV)
801.6(1)	0	5	4309(145)	33.3(12)	18.2(6)
2323.8(6)	0	4	17888(333)	26.8(17)	12.0(8)
3350.83(4)	1	5	87(9)	18.2(3)	9.5(2)
4458.74(2)	1	5	173(13)	23.2(22)	11.3(11)
5114.0(3)	0	5	5640(270)	65(2)	35.3(11)
6288.59(2)	1	4	116(18)	17.0(17)	6.7(7)
6525.0(3)	1	3	957(100)	25.3(14)	8.6(5)
9016.8(4)	1	6	408(77)	21.1(14)	13.0(9)
9159.20(7)	1	5	259(45)	21.4(21)	10.9(11)
9718.910(1)	1	4	104(22)	74(7)	19.5(21)
9767.2(3)	1	3	900(114)	90(8)	28.7(26)
12098					65(4)[c]
15649.8(1.0)	1	5	1000	47(4)	20.2(17)
17440.0(1.3)	1	6	1538(300)	32(3)	20.4(18)
17839.5(9)	1	5	464(181)	43(4)	21.7(20)
20870	1	5	954(227)	34.4(33)	18.3(17)
21050	1	4	7444(778)	33(3)	14.8(13)
22286.0(9)	1	5	181(91)	33.6(32)	15.1(15)
23149.1(1.3)	1	6	208(154)	25.3(25)	14.7(15)

Resonance detection **limited** by
background conditions and EAR1 **neutron flux**.

^{209}Bi(n,ɣ) **ORNL** using **C_6F_6** detectors in **1976**

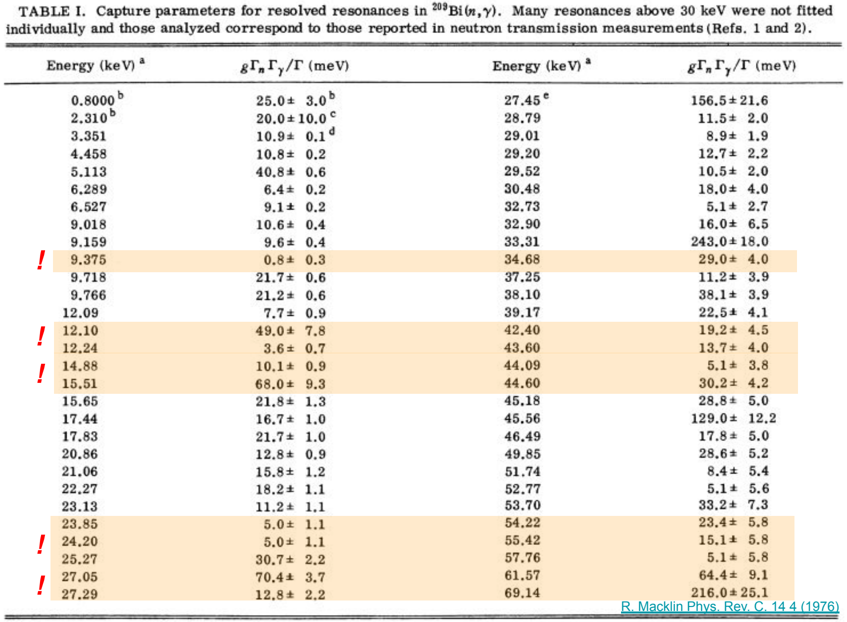


TABLE I. Capture parameters for resolved resonances in ^{209}Bi(n,γ). Many resonances above 30 keV were not fitted individually and those analyzed correspond to those reported in neutron transmission measurements (Refs. 1 and 2).

	Energy (keV)[a]	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Energy (keV)[a]	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)
	0.8000[b]	25.0 ± 3.0[b]	27.45[e]	156.5 ± 21.6
	2.310[b]	20.0 ± 10.0[c]	28.79	11.5 ± 2.0
	3.351	10.9 ± 0.1[d]	29.01	8.9 ± 1.9
	4.458	10.8 ± 0.2	29.20	12.7 ± 2.2
	5.113	40.8 ± 0.6	29.52	10.5 ± 2.0
	6.289	6.4 ± 0.2	30.48	18.0 ± 4.0
	6.527	9.1 ± 0.2	32.73	5.1 ± 2.7
	9.018	10.6 ± 0.4	32.90	16.0 ± 6.5
	9.159	9.6 ± 0.4	33.31	243.0 ± 18.0
!	9.375	0.8 ± 0.3	34.68	29.0 ± 4.0
	9.718	21.7 ± 0.6	37.25	11.2 ± 3.9
	9.766	21.2 ± 0.6	38.10	38.1 ± 3.9
	12.09	7.7 ± 0.9	39.17	22.5 ± 4.1
!	12.10	49.0 ± 7.8	42.40	19.2 ± 4.5
	12.24	3.6 ± 0.7	43.60	13.7 ± 4.0
!	14.88	10.1 ± 0.9	44.09	5.1 ± 3.8
	15.51	68.0 ± 9.3	44.60	30.2 ± 4.2
	15.65	21.8 ± 1.3	45.18	28.8 ± 5.0
	17.44	16.7 ± 1.0	45.56	129.0 ± 12.2
	17.83	21.7 ± 1.0	46.49	17.8 ± 5.0
	20.86	12.8 ± 0.9	49.85	28.6 ± 5.2
	21.06	15.8 ± 1.2	51.74	8.4 ± 5.4
	22.27	18.2 ± 1.1	52.77	5.1 ± 5.6
	23.13	11.2 ± 1.1	53.70	33.2 ± 7.3
	23.85	5.0 ± 1.1	54.22	23.4 ± 5.8
!	24.20	5.0 ± 1.1	55.42	15.1 ± 5.8
	25.27	30.7 ± 2.2	57.76	5.1 ± 5.8
!	27.05	70.4 ± 3.7	61.57	64.4 ± 9.1
	27.29	12.8 ± 2.2	69.14	216.0 ± 25.1

R. Macklin Phys. Rev. C. 14 4 (1976)

Might be affected by **systematics** associated with
experimental **W.F.** and **n-sensitivity (C_6F_6)**

Goals of the present ^{209}Bi(n,ɣ) measurement:

- **5-10% accuracy** in RRR covering **neutron energies** range from **thermal** up to **35 keV**.
- **<15% accuracy** in the neutron energy range from **35-100 keV**.