Measurement of the neutron-induced fission cross section of ^{236}U at n_TOF

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and the n_TOF Collaboration

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Motivation

- High- accuracy cross section data for neutron-induced reactions are needed over a wide energy range for the **design, feasibility and sensitivity studies on advanced nuclear systems**

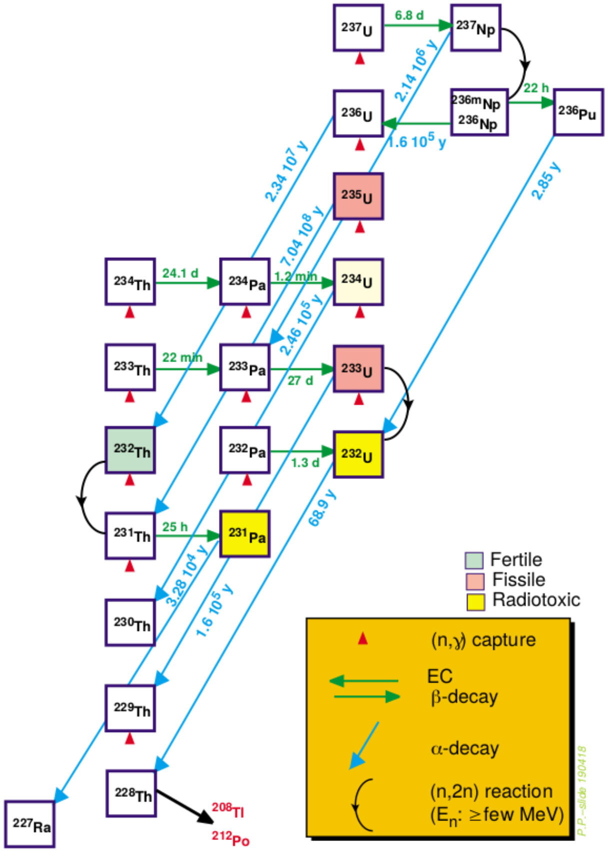
- The ^{236}U isotope ($T_{1/2}$= 2.342x10^{7} years) has the **longest half-live** compared to any other fission product or actinide produced in nuclear reactors

- Due to its specific activity (2.4 MBq/gr) which is 190 times higher than the one of ^{238}U, it significantly contributes to the radioactivity of reprocessed uranium

- In current reactors based on U/Pu fuel, ^{236}U is produced by (n,γ) on ^{235}U→considerably **affects the neutron balance in the reactor core as well as the fuel composition**

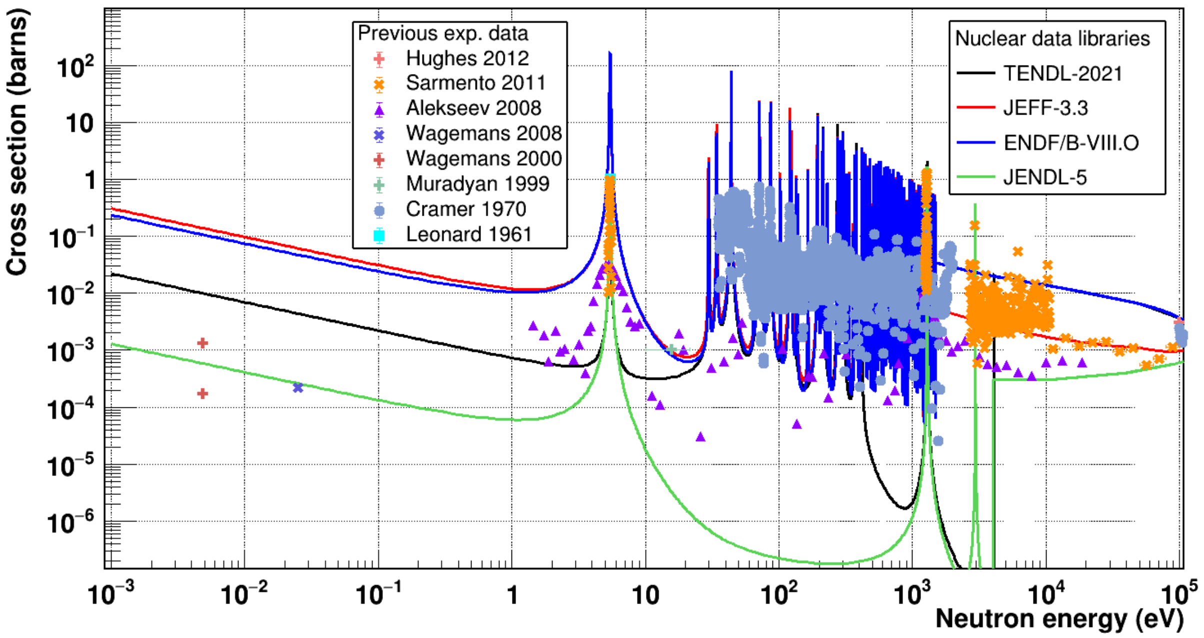
- Moreover, ^{236}U builds up in the equilibrium state in the Th/U fuel cycle

- For the development of fast nuclear reactors and accelerator-driven systems (ADS) the knowledge of its fission cross section is required within 5% accuracy



Existing experimental data from EXFOR in the low energy region

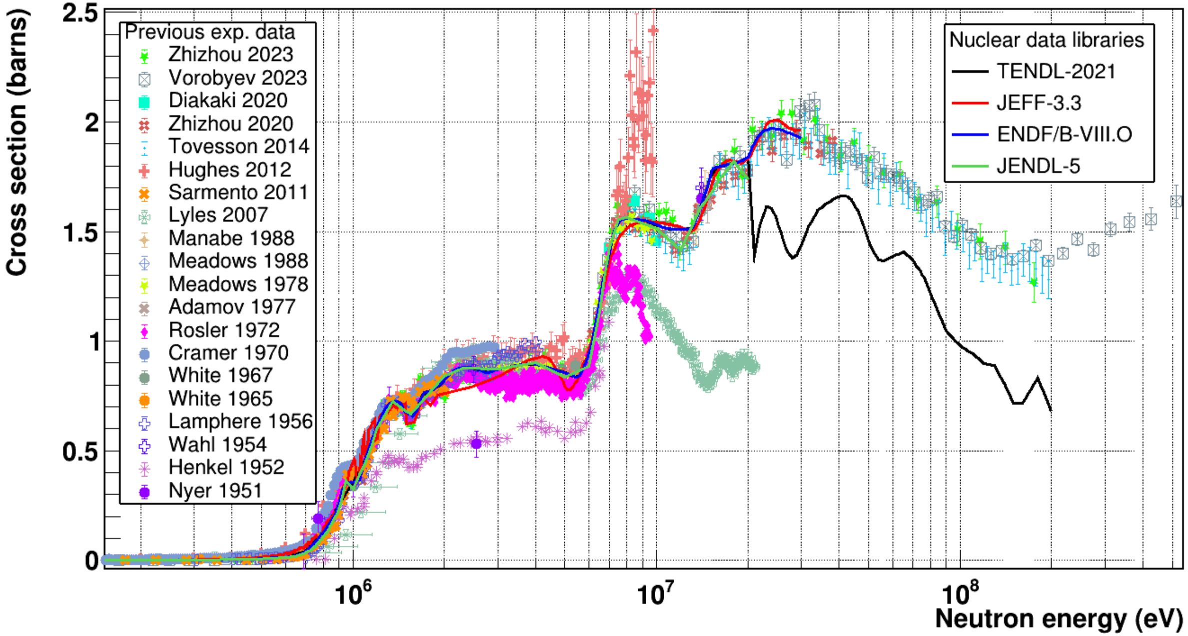
Scarce and discrepant experimental data



*The error bars of the experimental data are omitted in this plot

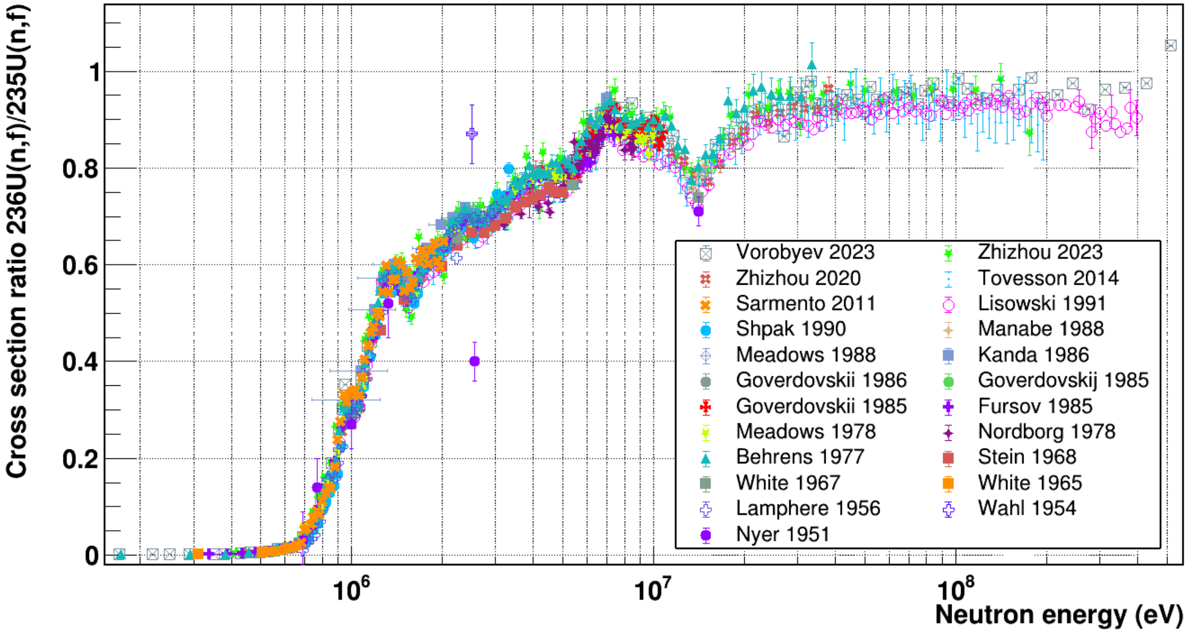
- In the **thermal region**, evaluated libraries, in particular, JENDL-5, JEFF-3.3, ENDF/B-VIII-0 and TENDL-2021, **exhibit major discrepancies of up to 2 orders of magnitude**
- Only JENDL-5 seems to fairly reproduce the only 2 data points in the thermal region by Wagemans et al.
- There are only 2 data-sets covering the first resonance of ^{236}U @5.45 eV
- Data from Sarmento et al. with the highest resolution in this region, reveal that **current evaluations need revision** since they overestimate the height of the resonance by ~150 times
- In the region between 30 eV and 1 keV, resonance structures reported by Cramer and Berger have been adopted by some evaluations but are not confirmed by later measurements

Existing experimental data from EXFOR in the high energy region



- Above 500 keV the situation of the experimental data is better since there are a lot of measurements that have lead to the improvement of the knowledge of the cross section in the high energy region
- Nonetheless, **discrepancies of up to ~15% are observed among recent data-sets** especially for the region of interest for the fast nuclear reactors (0.5 - 10 MeV)
- Moreover, above 40 MeV, which exceeds the upper limit of most evaluations, only 3 data-sets are available
- The experimental information in this region is of particular importance to **constrain the theoretical models of the fission process**

Existing experimental data from EXFOR in the high energy region



- Systematic discrepancies among different data-sets above 100 keV are better demonstrated by the **fission cross section ratio of ^{236}U/^{235}U**
- Above 2 MeV, discrepancies of up to 15% are observed among EXFOR data-sets

Previous measurement at n_TOF

- A previous measurement was already performed at n_TOF in 2003 (EAR-1) during Phase I
- The fission yield of the ^{236}U(n,f) reaction was affected by the contribution of α- particles from the ^{236}U decay but most importantly from the **0.05% impurity of ^{235}U** present in the samples
- After the subtraction of the ^{235}U contamination, the analysis revealed resonance structures attributed to **^{236}U @5.45 eV and @1.25 keV** in the form of a triple resonance
- Unfortunately, above the fission threshold, **data were limited up to 2 MeV**

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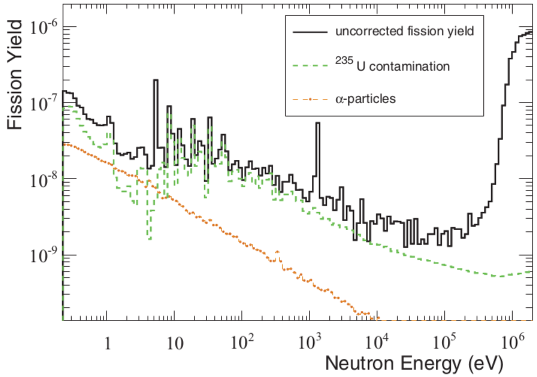


FIG. 4. (Color online) Fission yield measured with samples (black histogram), ^{235}U(n,f) yield normalized to the ^{235}U impurity (green dashed histogram), and the residual α-particle background (orange circles). The contribution of the ^{235}U contamination to the ^{236}U signal is evident in the region above the ^{236}U resonance at 5.45 eV.

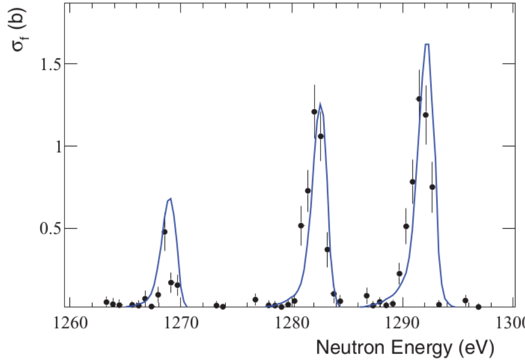


FIG. 6. (Color online) Resonance triplet at 1.25 keV was resolved at n_TOF with high resolution. The n_TOF data (black points, vertical error bars corresponding to statistical uncertainties) were fit with SAMMY (blue line).

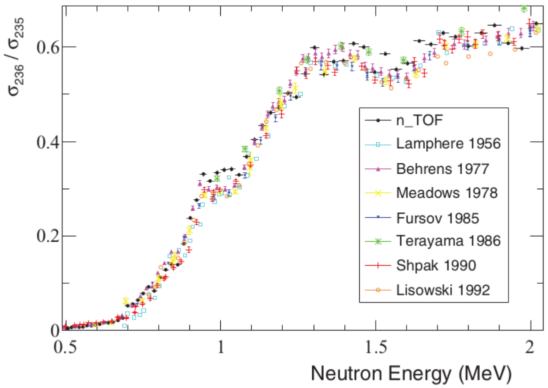
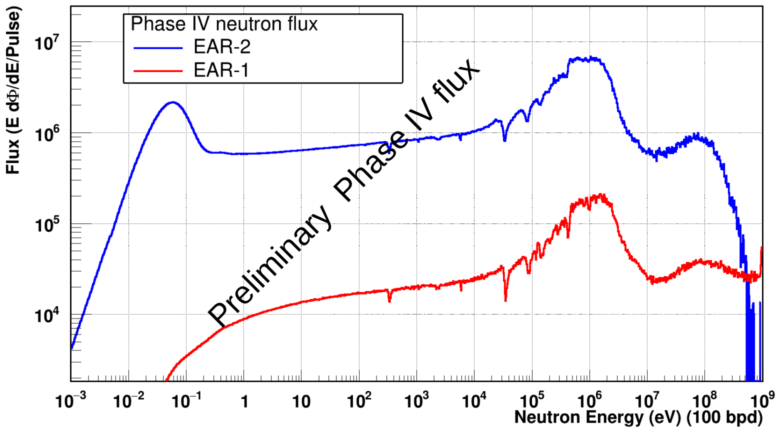
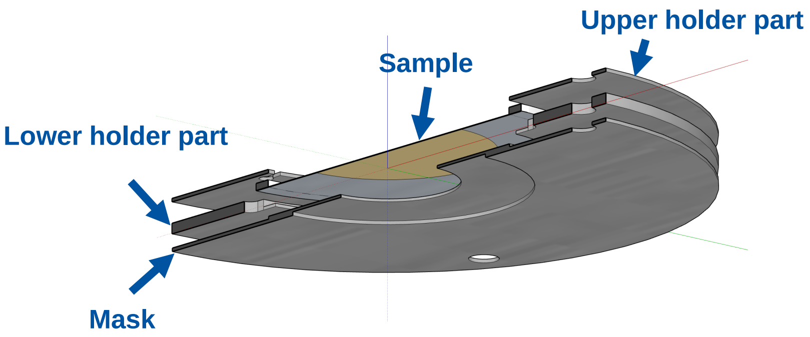


FIG. 9. (Color online) Fission cross-section ratio of ^{236}U and ^{235}U above threshold. The n_TOF results are plotted together with experimental data available from the EXFOR database [9,14,15,21–24].

Plan of the measurement

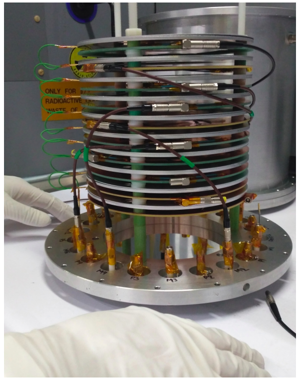
- We aim at producing, for the first time, a single accurate data-set covering the energy range from thermal up to ~ 0.5 GeV neutron energy
- Fission collimators in both areas to profit from increased statistics (8 cm diameter in EAR-1 and 6 cm diameter in EAR-2)
- **6E18 protons in EAR-1** to cover the fission threshold up to ~0.5 GeV
- **3E18 protons in EAR-2** to collect data in the thermal and resonance region up to ~700 keV
- Use the same high-purity ^{236}U samples used by Wagemans et al. for the determination of the cross section at the thermal points
- Use aluminum “masks” in all samples (236U and references), so as to achieve the same effective diameter of 4 cm → important step in order to perform a relative fission cross section measurement since the same “Beam Interception Factor” (BIF) for all samples will lead to reduced systematic uncertainties in the analysis

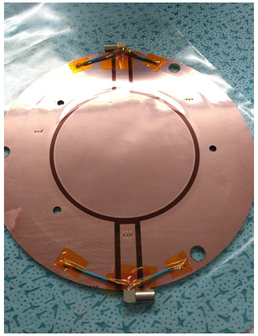




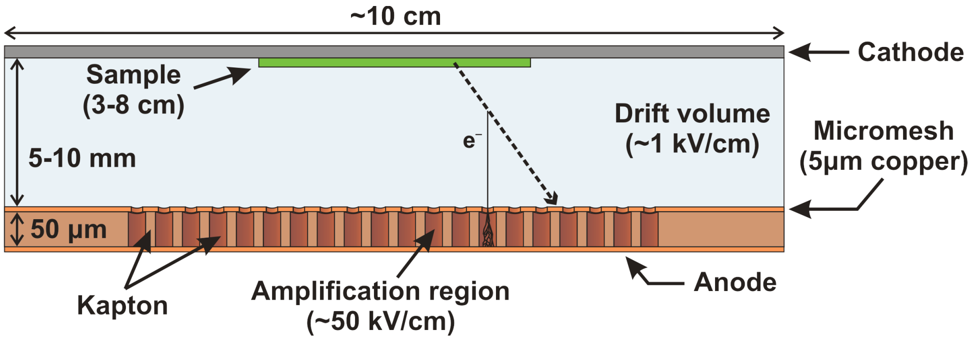
Micromegas detectors

- Micromegas (**MICRO- Mesh Gaseous Structure**) detectors offering ~100% efficiency
- Parallel plate avalanche gaseous detectors consisting of two regions: the conversion and the narrow amplification region
- Each detector is coupled with a sample, therefore creating a stack of sample-detector modules (2 x ^{236}U samples, 6 x reference samples, 1 x empty)
- All the sample-detector modules, will be housed in an aluminum chamber
- The fission chamber will be filled with a constantly circulating gas mixture @ 1 atm
  EAR-1: $Ar:CF_4:isoC_4H_{10}$ (88:10:2) and for
  EAR-2: $Ar:CF_4$ (90:10) → minimize the elastic interactions with the hydrogen inside the drift region of the detector → better γ-flash tail
- Employ a gas regulation system → to ensure stable gain conditions for the detectors





Mesh

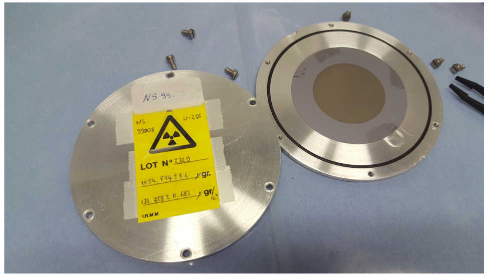


Anode

236U samples from JRC-Geel

- **2 x ^{236}U samples of high purity**

- **Mass isotopic composition**
  234U: <0.00001%
  235U: 0.0043%
  236U: 99.9732%
  238U: 0.0225%



	236U samples	
Target ID:	NS0010	NS99008
Description:	236U oxide layer (lot number. 2329)	
Preparation method:	Electrolysis	
Diameter of deposit (mm):	50	40
Backing:	20 um Al	0.5 mm Si
Areal Density (ugr/cm2):	210.442 +/- 1.365	131.758 +/- 0.466
Total Activity of 236U (kBq):	**9.9**	**4.0**
***Effective Activity (kBq):**	**6.3**	**4.0**
***Effective Mass (mgr):**	**2.64**	**1.66**

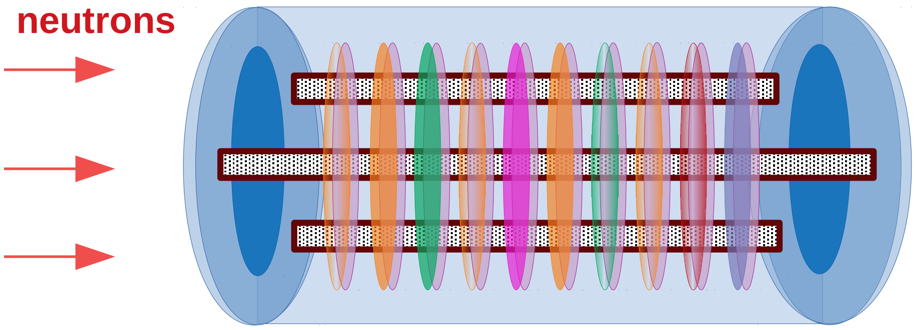
* Refers to the unmasked part of the target

- For the **neutron flux determination** we will use the already existing reference samples (^{10}B, ^{235}U and ^{238}U samples with 6 cm diameter) **from the ^{243}Am(n,f) campaign which are well optimized for both experimental areas**

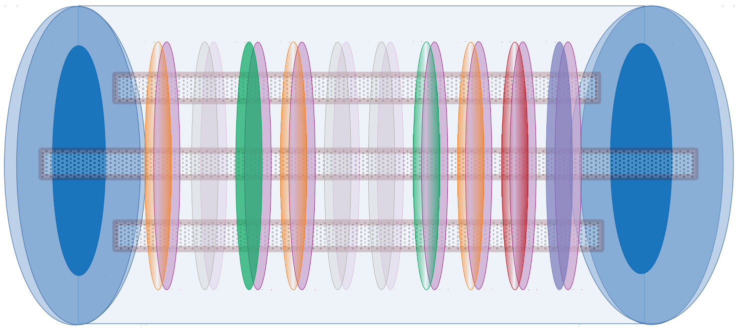
Proposed set-up inside the fission chamber

- In order to take full advantage of the characteristics of the two experimental areas we will use a common set-up of samples inside the fission chamber

- The set-up is **simultaneously** optimized for both EARs by employing samples with various thicknesses



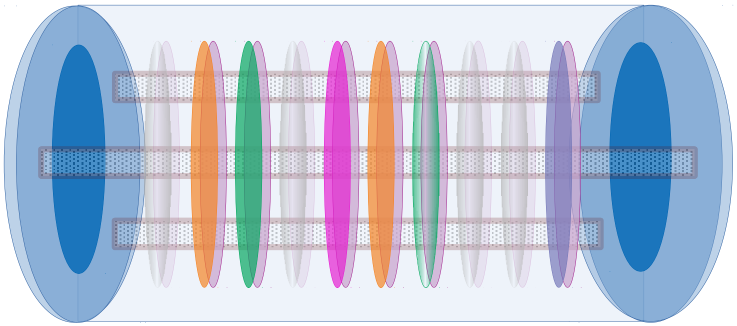
Optimization for EAR-2
(higher neutron flux, thin samples)



Empty
238 U
10 B
235 U
236 U

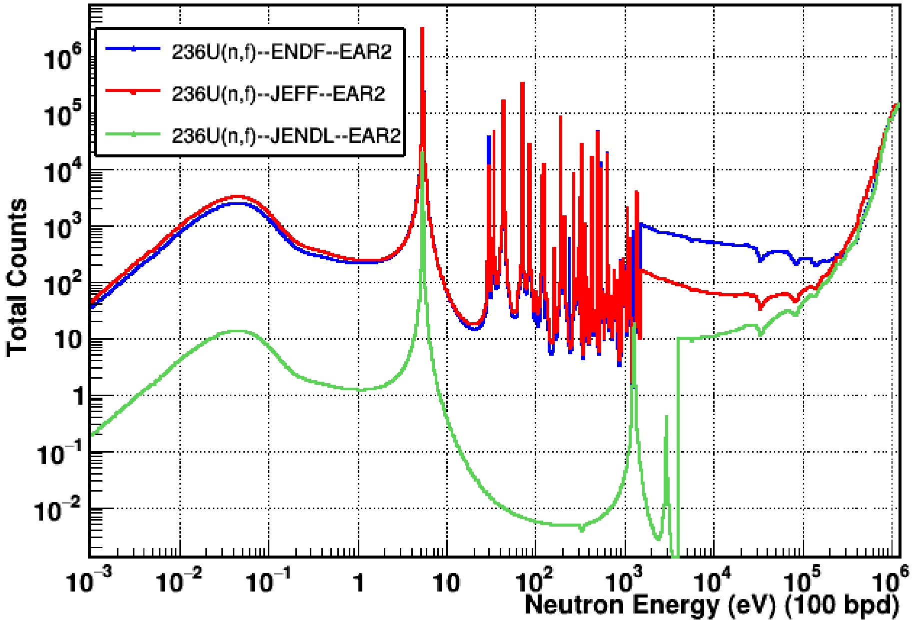
Thick samples
Thin samples

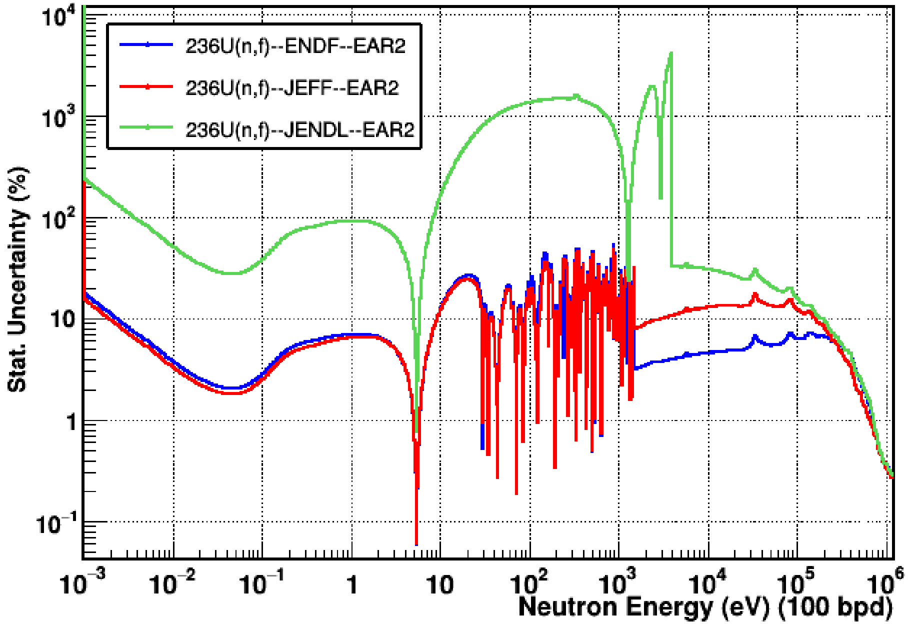
Optimization for EAR-1
(thick samples)



EAR-2: Reaction Rate @100 bpd

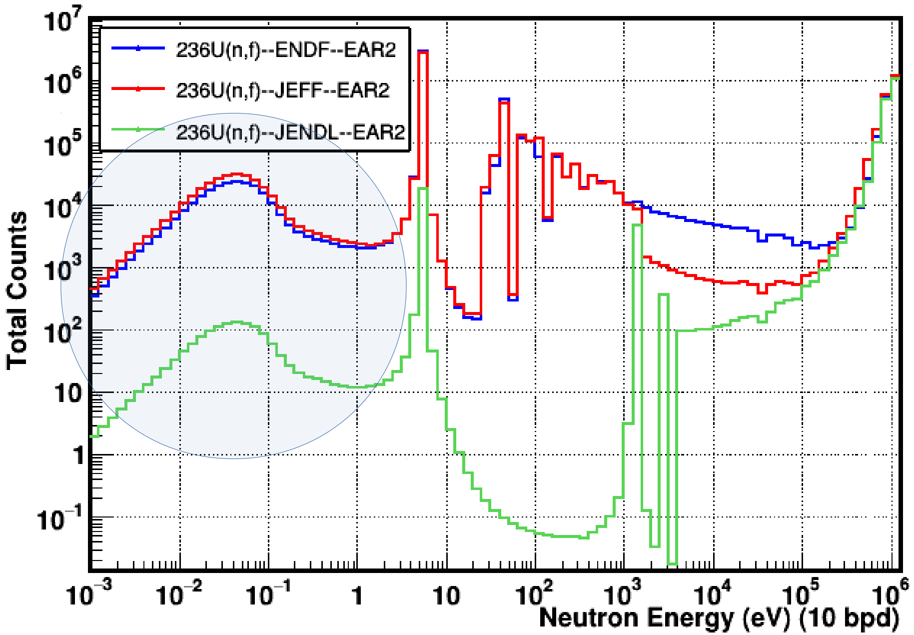
- Upper and lower limit for the reaction rate and stat. uncertainty estimates in EAR-2 from the thermal region up to 1 MeV
- **Beam request: 3E18 protons**

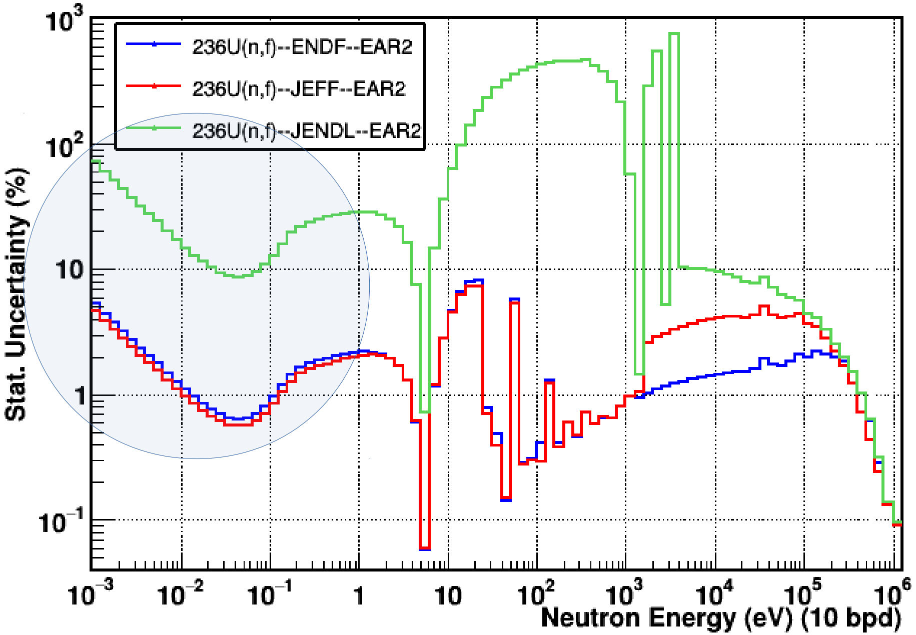




EAR-2: Reaction Rate @10 bpd

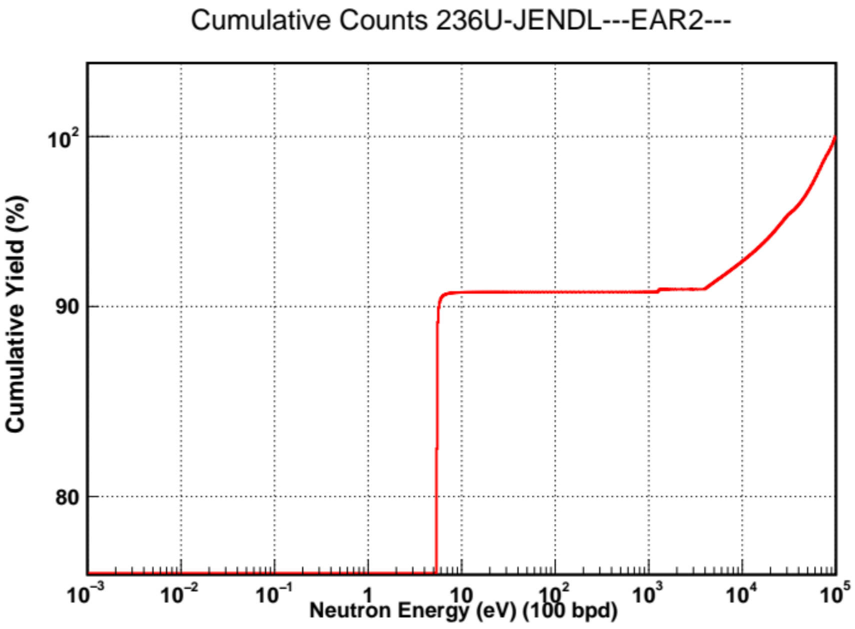
- By adopting a coarser energy bin (e.g 10 bpd) in the thermal region we can further reduce the stat. uncertainties
- In the end, we can use a coarser energy binning for the thermal region and around 5.45 eV we can provide a better mapping of the resonance that dominates the fission cross section below the threshold





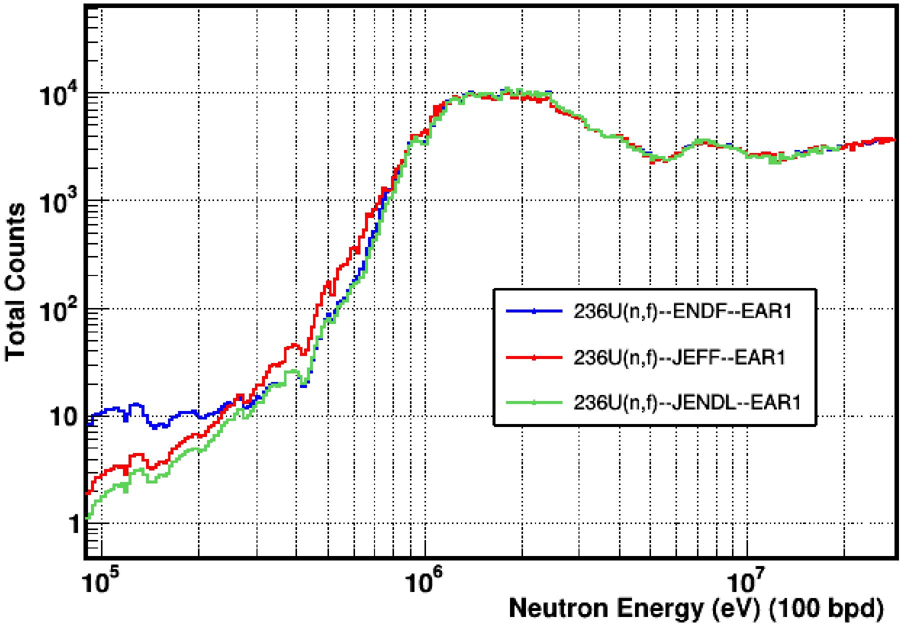
EAR-2: Cumulative fission yield

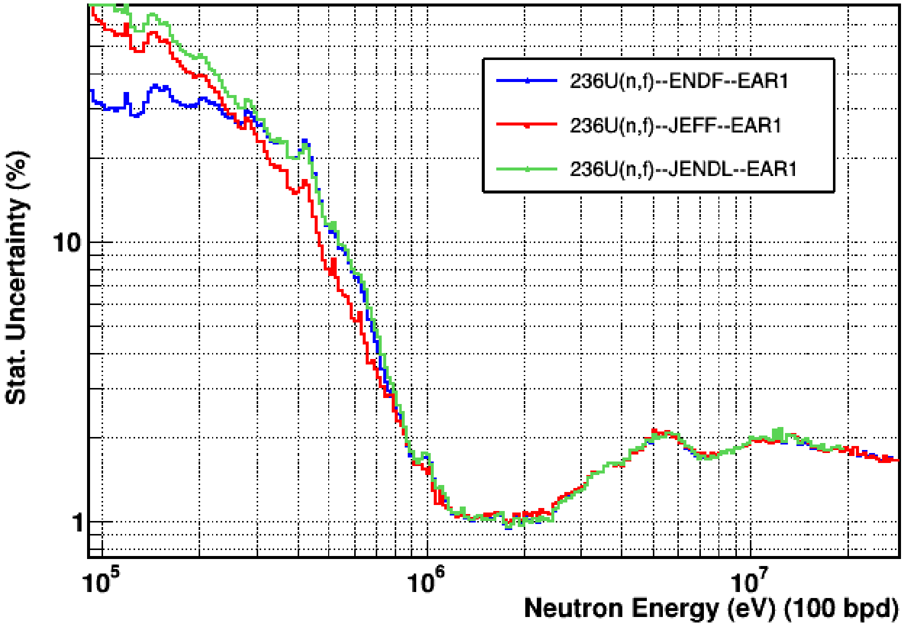
- Even if our experiment confirms the JENDL-5 evaluation, limiting in this way the measurement in the thermal part, the **contribution of the first resonance** of ^{236}U @5.45 eV will be important because it **accounts for almost 90%** of the total fission yield up to 100 keV and 99% up to 1 keV



EAR-1: Reaction Rate @100 bpd

- Reaction rates and stat. uncertainty estimates in EAR-1 from the threshold of the reaction (~300 keV) up to 30 MeV
- **Beam request: 6E18 protons**
- We can provide fission cross section data above 1 MeV with a **stat. uncertainty below 2%** even at 100 bpd





Summary

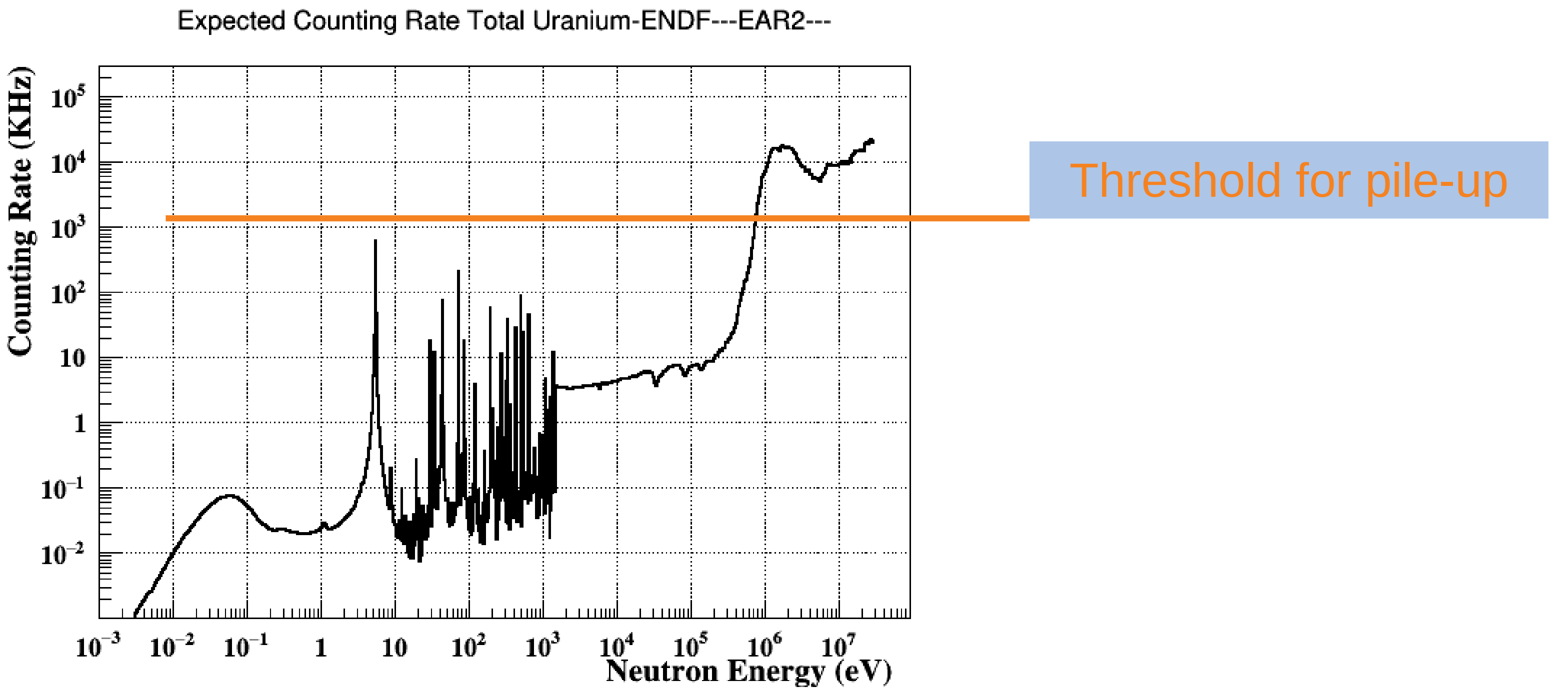
- We propose the measurement of the neutron-induced fission cross section of ^{236}U for an extended energy region, from thermal energies up to ~0.5 GeV by exploiting the specific characteristics of both n_TOF areas
- The use of **high-purity** ^{236}U samples provided by JRC-Geel will allow for the collection of data with notably reduced ^{235}U impurities, compared to other TOF data-sets
- In **EAR-2**, given the higher instantaneous neutron flux and the improved signal-to-background ratio, useful data will become available for the first time, in a unique data-set spanning from the **thermal region and covering the resonances up to a few hundreds of keV**
- Data collected from **EAR-1** measurement will cover the energy region from the **fission threshold up to several hundreds of MeV**
- We aim to improve significantly the accuracy of current data and resolve long standing discrepancies of evaluations and different data-sets in the low energy region
- Summary of requested protons: **6E18 protons in EAR-1** and **3E18 protons in EAR-2**

Thank you for your attention!!

Back up slides

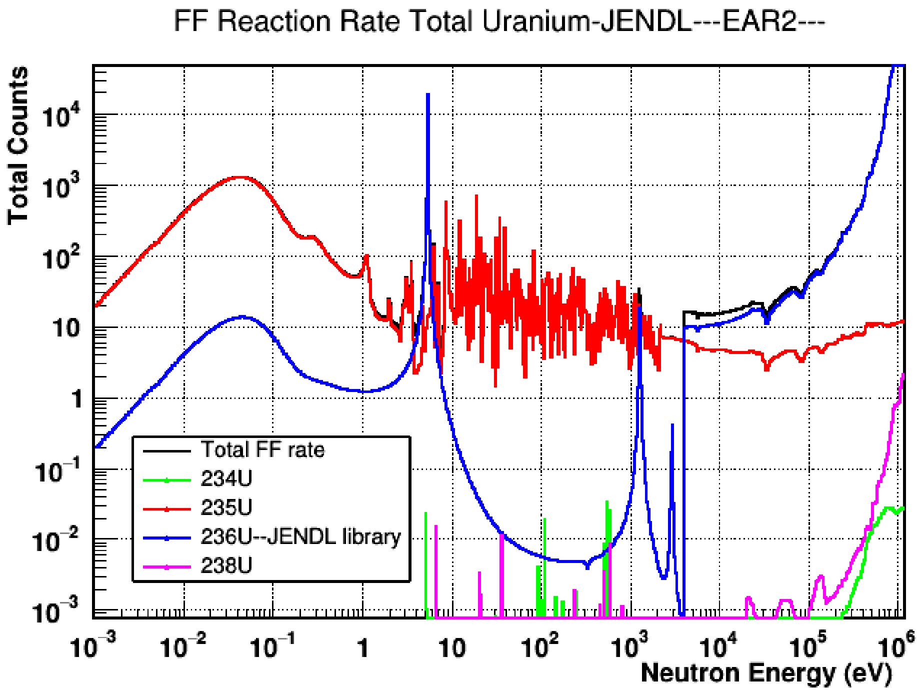
Counting rate estimation in EAR-2

- Counting rate estimation taking into account the thickest ^{236}U sample (210 ugr/cm2) and using ENDF/B-VIII.0 library → We can extend the measurement up to 700 keV where the CR< 1 MHz and therefore we will not suffer from pile-up in the analysis

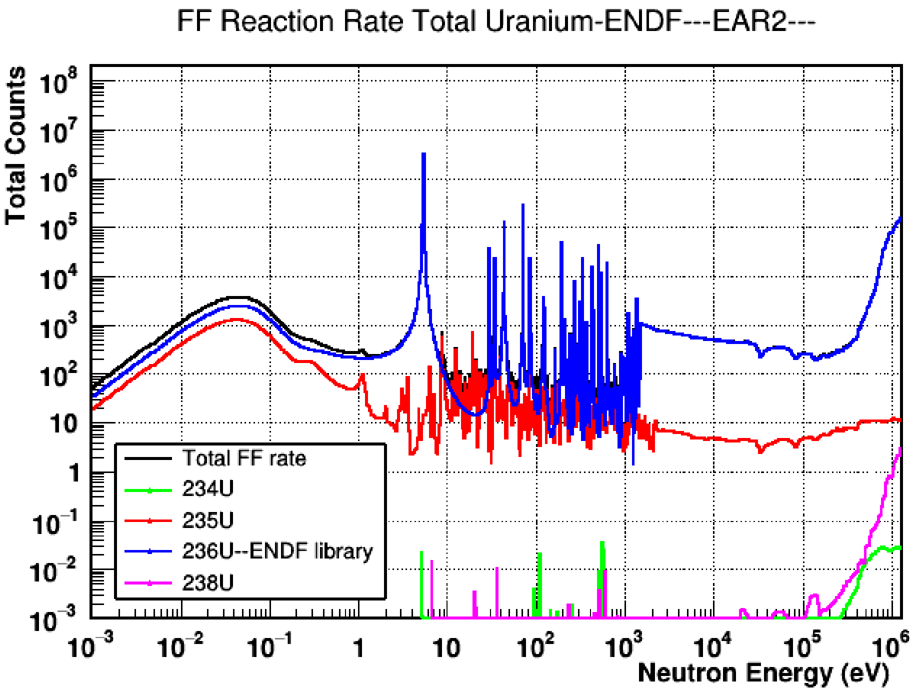


Expected reaction rate according to mass composition

Scenario A: cross section of ^{236}U close to **JENDL-5**



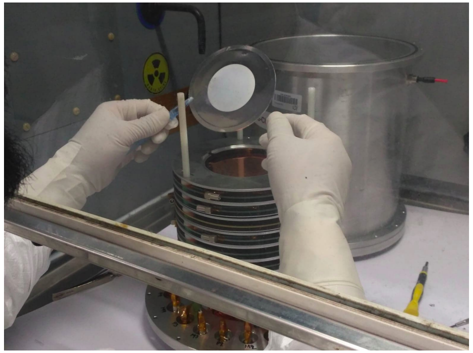
Scenario B: cross section of ^{236}U close to **ENDF/B-VIII.0**



Reference samples from JRC-Geel

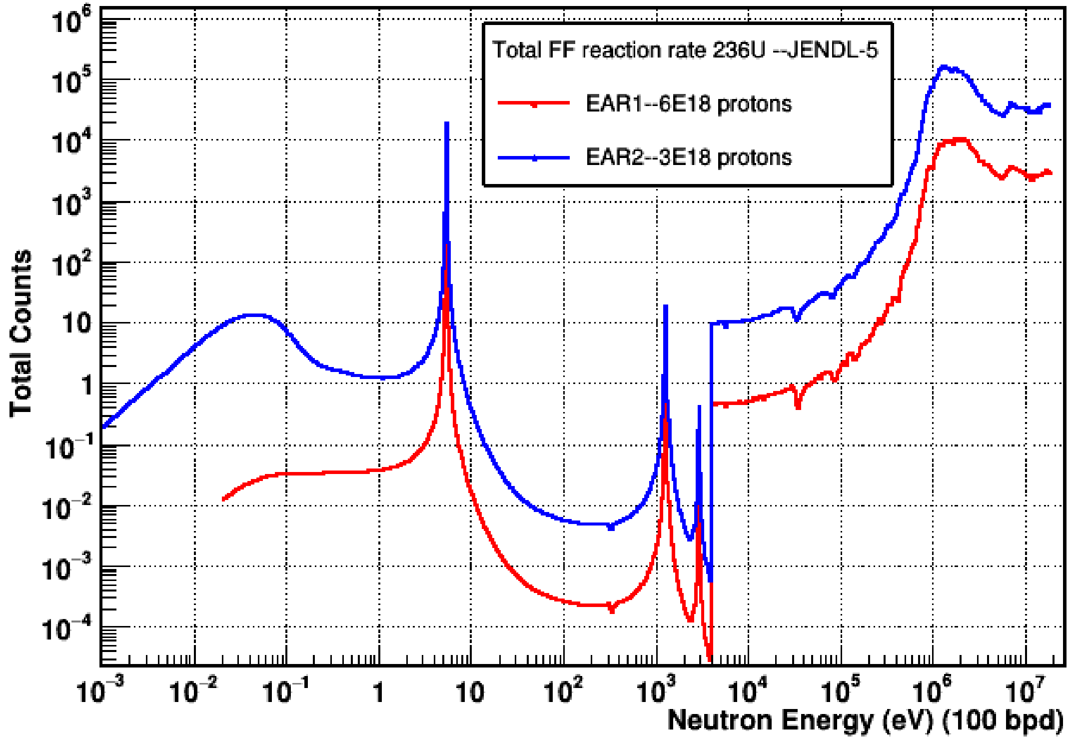
- For the neutron flux determination we will use the already existing reference samples from the ^{243}Am(n,f) campaign which are well optimized for both experimental areas
- ^{10}B, ^{235}U and ^{238}U samples with 6 cm diameter

	Sample ID	Areal density (ugr/cm^2)
10B (EAR-2)	TP2020-011-02	0.3
235U (EAR-2)	TP2020-009-04	4.3
	TP2020-009-06	3.5
235U (EAR-1)	TP2020-009-02	74
	TP2020-010-04	76
238U (EAR-1)	TP2020-010-04	226



Many thanks to the Target Preparation Laboratory team of JRC-Geel for the sample production
(A. Moens, G. Sibbens, D. Vanleeuw)

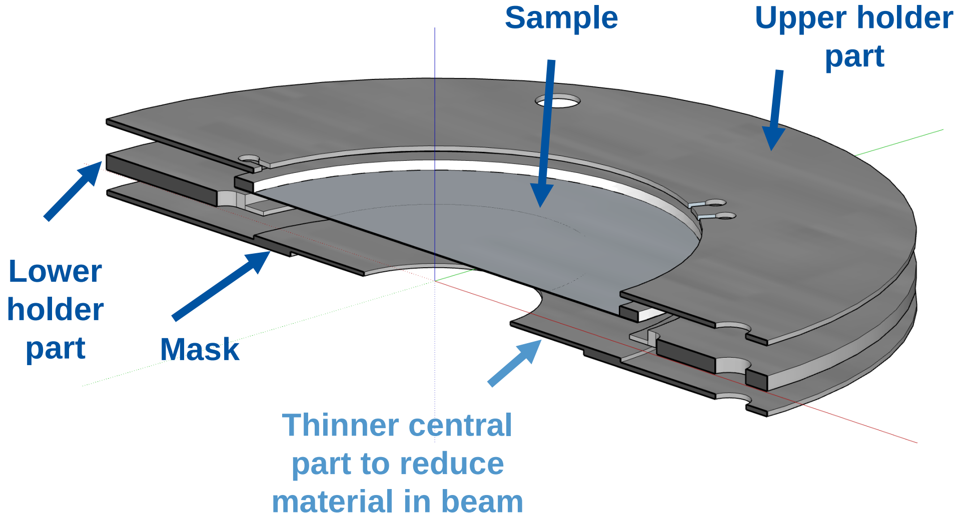
Expected FF reaction rate of 236U according to JENDL-5 in both EARs



Sample holders with masks

- Not all samples have the same dimensions
- In order to reduce the systematic uncertainties in the analysis the same "Beam Interception Factor" (BIF) should be applied to all the samples
- To achieve that, we plan to use aluminum "masks" with a diameter of 40 mm, so that all the samples will end up with the same exposed "effective" surface to the neutron beam

- **Top view**



- **Bottom view**