Measurement of the $^{35}Cl(n, p)^{35}S$ cross section

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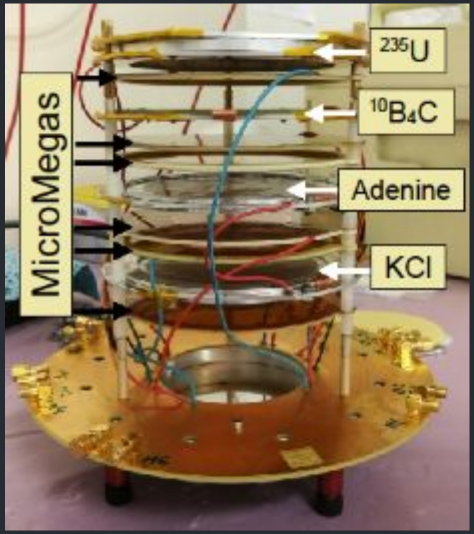
(22-23 November 2023, n_TOF Collaboration Meeting, Valencia (Spain))

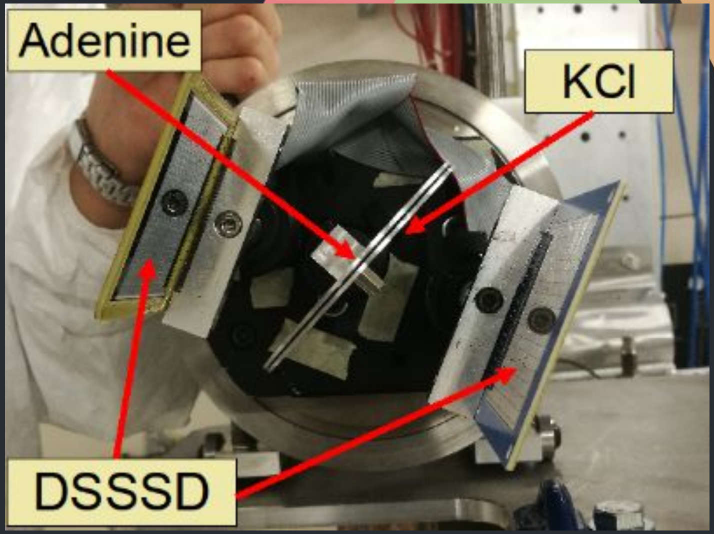
Measurement performed at EAR-2

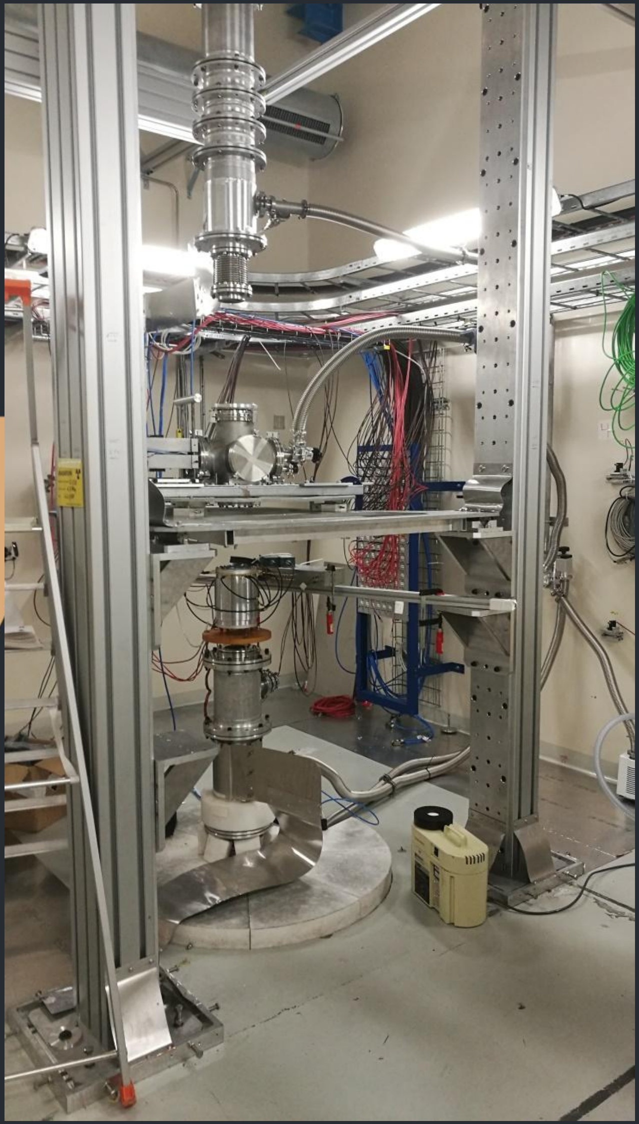
Data taking in September - October 2017.

- Joint measurement $^{14}N(n,p)$ and $^{35}Cl(n,p)$

Two parallel setups:
1 Stack of Micromegas (upstream)
1 DSSSD (downstream)







C ≡ «Clean» counts (atoms/s).
E_n ≡ Neutron energy (MeV).
n ≡ Target surface density (atoms/cm^2).
Φ ≡ Flux (neutrons/s).
ε ≡ Efficiency (-).
σ ≡ Cross section (atoms/cm^2).

T ≡ Transmition factor (-).
P_M ≡ Molecular weight (g/molecule).
ρ ≡ Density (g/cm^3).
e ≡ Thickness (cm).

1.-Introduction:

Starting equation:

$$C(E_n)=n \cdot \Phi(E_n) \cdot \varepsilon(E_n) \cdot \sigma(E_n)$$

$$C_{35Cl}(E_n) = n_{35Cl} \cdot \Phi_{35Cl}(E_n) \cdot \varepsilon_{35Cl}(E_n) \cdot \sigma_{35Cl}(E_n)$$

$$C_{10B}(E_n) = n_{10B} \cdot \Phi_{10B}(E_n) \cdot \varepsilon_{10B}(E_n) \cdot \sigma_{10B}(E_n)$$

$$\Phi_Z = \Phi \cdot T_Z$$

$$n_Z = P_{M,Z} \cdot \rho_Z \cdot e_Z$$

We equate each term independently with its corrections and associated uncertainties.

$$\sigma_{35Cl}(E_n) = \frac{P_{M,10B} \cdot \rho_{10B}}{P_{M,35Cl} \cdot \rho_{35Cl}} \cdot \frac{e_{10B}}{e_{35Cl}} \cdot \frac{T_{10B}}{T_{35Cl}} \cdot \frac{C_{35Cl}}{C_{10B}} \cdot \frac{\varepsilon_{10B}}{\varepsilon_{35Cl}} \cdot \sigma_{10B}$$

Terms: *(A)* *(B)* *(C)* *(D)*

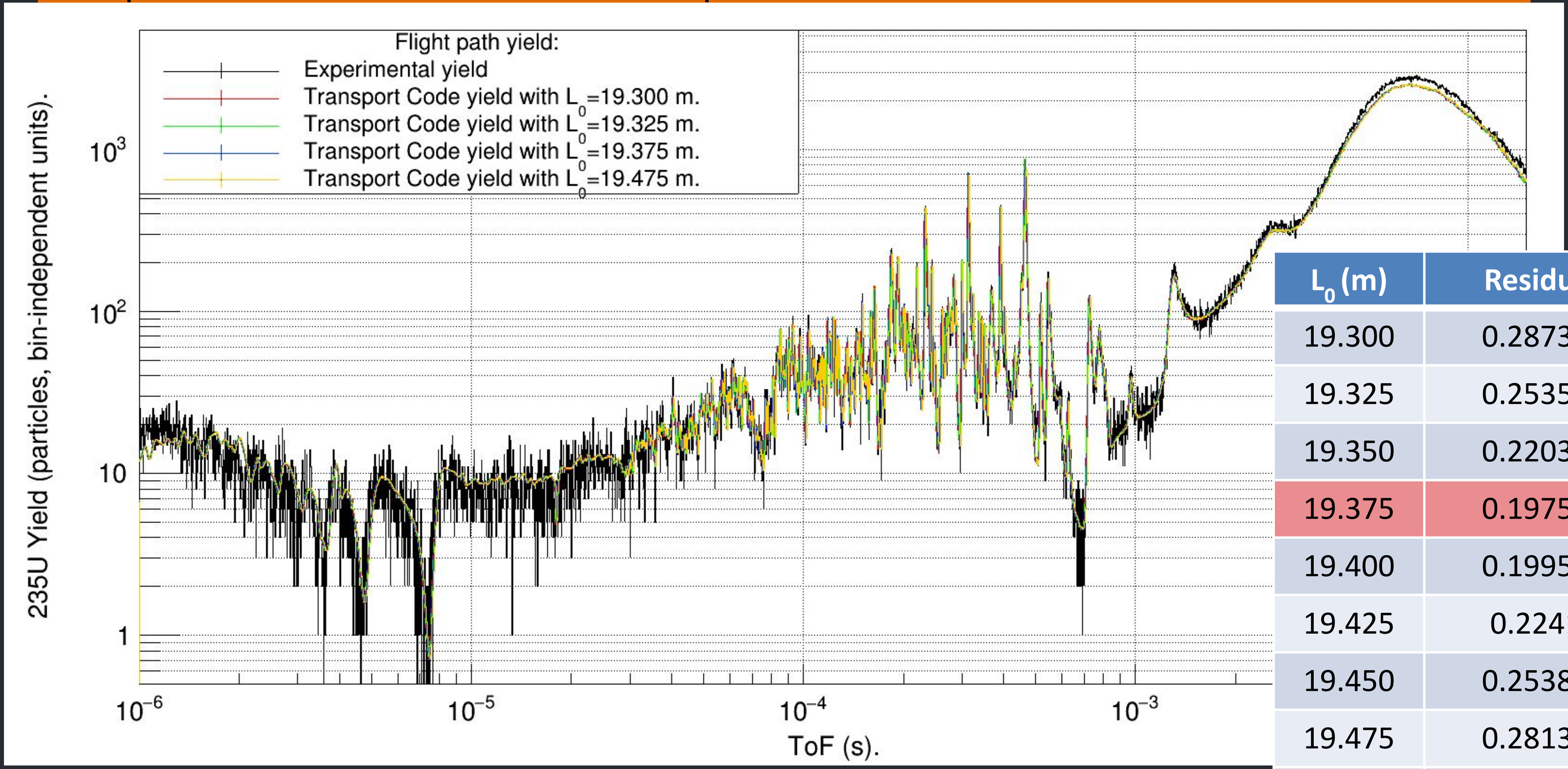
L_0 ≡ Flight path(m).
c ≡ Speed of light in vacuum (m/s).
m_n ≡ Neutron's rest mass (MeV/c^2).
E_n ≡ Neutron energy (MeV).
ToF ≡ Time of Flight (s).

1.-Corrections:

*0: Flight path determination.

E_n ↔ ToF: $E_n = \frac{1}{2} \cdot m_n \cdot \left(\frac{L_0}{ToF}\right)^2$, we need to know the flight path.

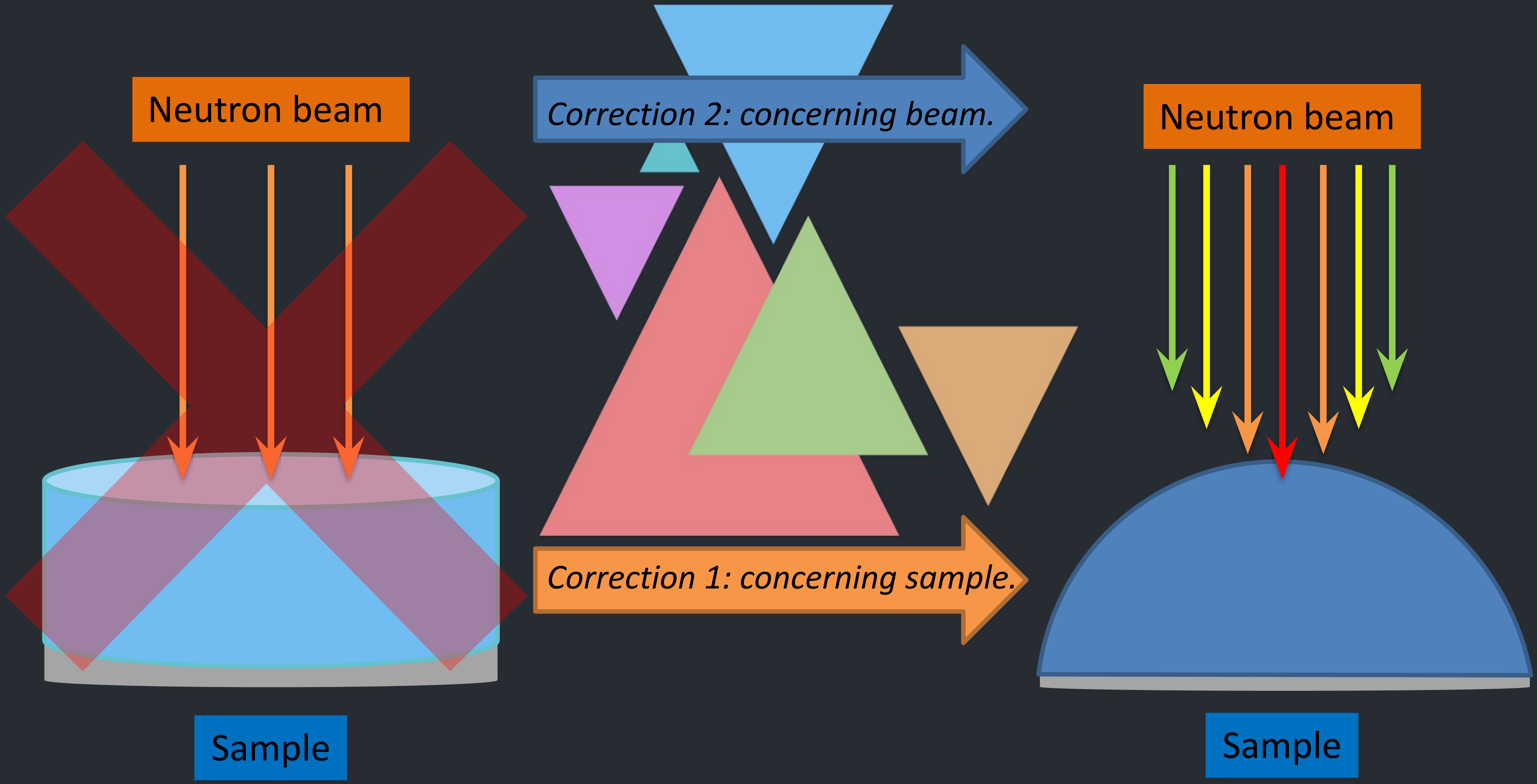
In order to obtain it, comparison between experimental data of the 235U reference sample and the results from the Transport Code were made.



L_0 (m)	Residues
19.300	0.287322
19.325	0.253554
19.350	0.220393
19.375	0.197531
19.400	0.199509
19.425	0.22411
19.450	0.253882
19.475	0.281313
19.500	0.305845

1.-Corrections:

*(A): Mass determination and correction.



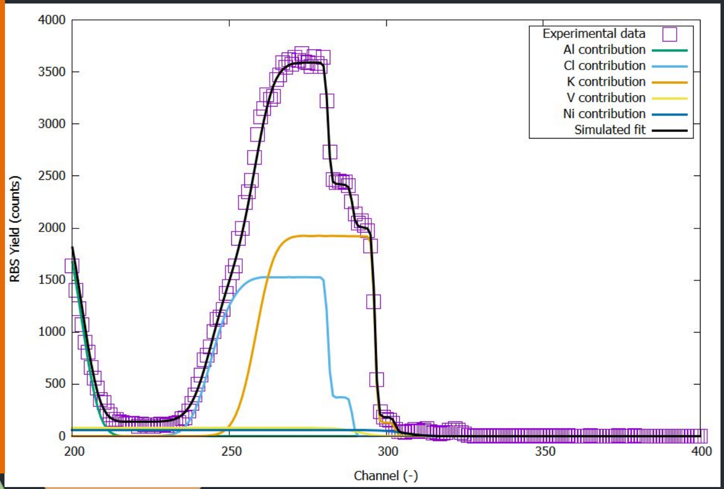
e ≡ Thickness (cm).
x, y ≡ Coordinates.
Δe ≡ Incremental hickness (1/cm).
e_0 ≡ Thickness at centre (cm).
r ≡ Distance from the centre (cm).

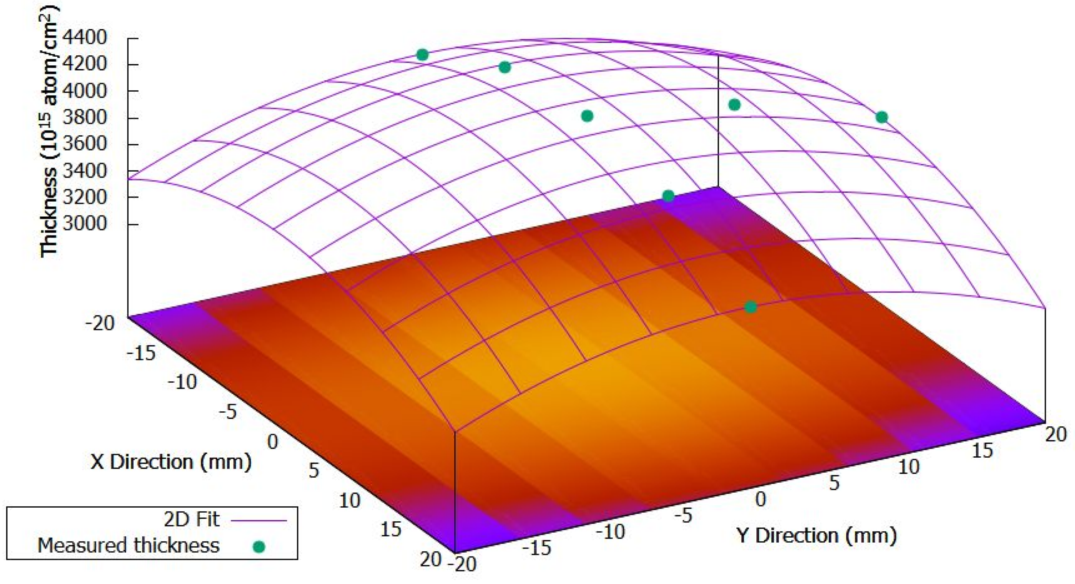
1.-Corrections:

*(A): Mass determination.

1 - Experimental technique: **R**utherford **B**ack-**S**cattering (RBS) at different positions of the sample.
Performed at Centro Nacional de Aceleradores (CNA), Sevilla.

2 - Analysis of experimental data.
2.1–Calibration with the aluminium backing.
2.2–Centering of the sample and experimental grid.
2.3–Estimation of parameters e_0 and Δe.





Sample:

$$e(x,y)=a\cdot((x-x_0)^2 + (y-y_0)^2)+b$$

↓

$$(x_0, y_0)$$

↓

$$e(r)=e_0-\Delta e\cdot r^2$$

e ≡ Thickness (cm).
Δe ≡ Incremental hickness (1/cm).
e_0 ≡ Thickness at centre (cm).
r ≡ Distance from the centre (cm).
m_T ≡ Total mass (g).

1.-Corrections:

*(A): Mass determination.

1 - Experimental technique: **R**utherford **B**ack-**S**cattering (RBS).

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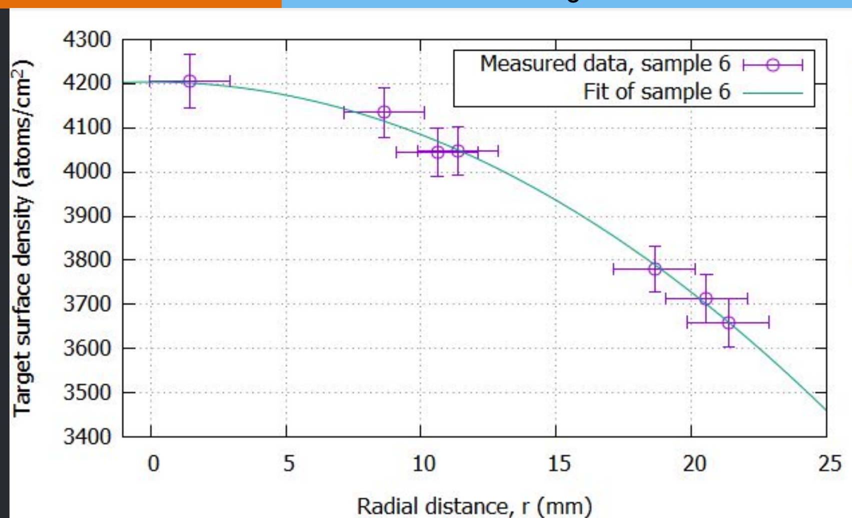
Sample:

$$e(r)=e_0-\Delta e\cdot r^2$$



Composition of Al backing:	
Al	98.5% (atomic)
V	1% (atomic)
Ni	0.5% (atomic)

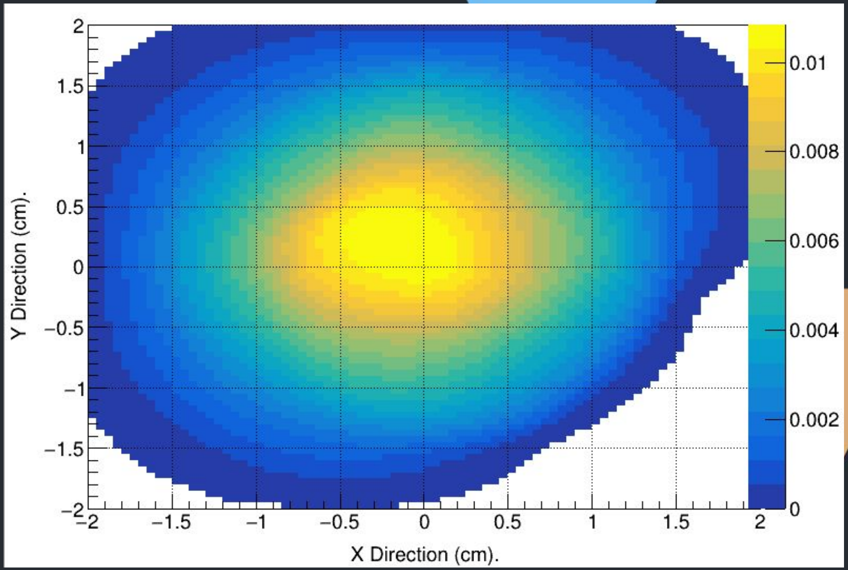
Sample	e_0 (cm)	Δe (1/cm)
MGAS 5	(1.105 ± 0.008)E-4	(1.966 ± 0.014)E-8
MGAS 6	(0.999 ± 0.014)E-4	(2.00 ± 0.03)E-8
DSSSD	(1.314 ± 0.013)E-4	(3.72 ± 0.04)E-8

e' ≡ Effective thickness (cm).
S ≡ Surface intersected of sample by beam.
x, y ≡ Coordinates.
e ≡ Thickness (1/cm).
P ≡ 2D Profile of neutrons across surface (-).
Δ_{rel} ≡ Relative difference (-).

1.-Corrections:

*(A): Mass correction.

Neutron beam not homogeneous: 2D-profile obtained from Transport Code.



We equate an «effective thickness», e', such that a cylindrical sample with that thickness would produce the same amount of reactions as the curved one:

$e(x, y)=e_0-\Delta e\cdot(x^2 + y^2)$

$$e' = \frac{\int\int_S P(x,y)\cdot e(x,y)\cdot dxdy}{\int\int_S P(x,y)\cdot dxdy}$$

Corrected masses:

Sample	e_0 (cm)	e' (cm)	Δ_{rel}
10B	1.8E-6	1.7999…E-6	4.55E-13 %
#5 Cl	1.105E-4	1.10458E-4	0.020%
#6 Cl	0.999E-4	0.998271E-4	0.023%

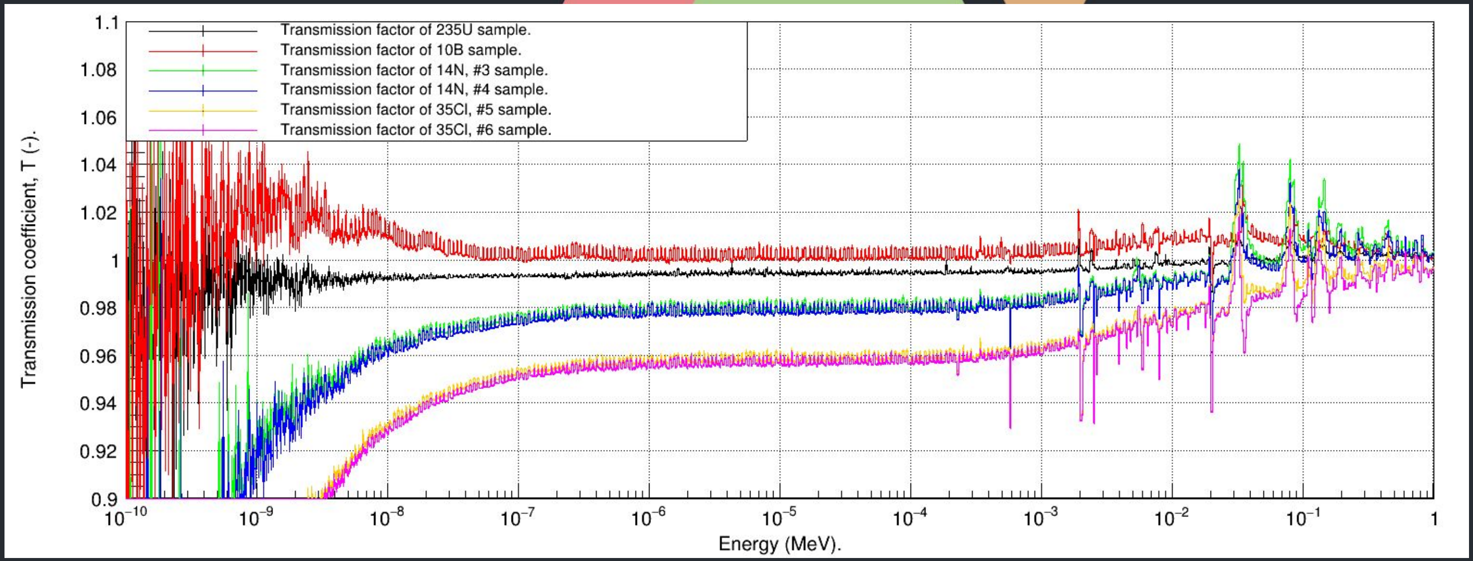
E_n ≡ Neutron energy (MeV).
Φ ≡ Flux (neutrons/s).
T ≡ Transmition factor (-).

1.-Corrections:
*(B): Transmission correction.

Samples at different distances from the neutron source and behind different layers of materials receive different amounts of neutrons as function of their kinetic energy!

$\Phi_Z(E_n) = \Phi(E_n) \cdot T_Z(E_n)$

We simulate the microMGAS set-up and ensemble with MCNP and use the same energy profile of neutrons at n_TOF, obtained from the Transport Code.



C_M ≡ Measured counts (counts).
C_C ≡ Cut counts (counts).
C_{DT} ≡ Dead-time corrected counts (counts).
ΔDT ≡ Dead –time (ns).
Δt ≡ Time period in which C_M is measured (ns).
C_R ≡ Real counts (counts).
C ≡ Clean counts (counts).
f ≡ Energy cuts correction factor (-).

1.-Corrections:

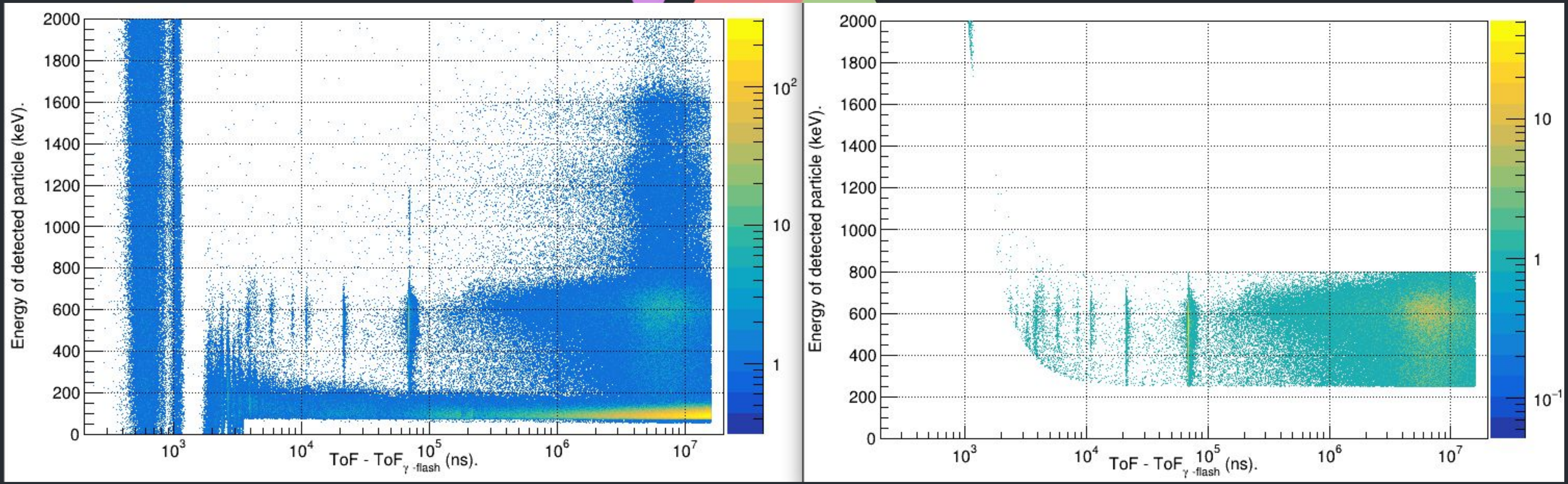
*(C): Counts corrections.

$C_M \rightarrow C_C$ by cutting counts either too high or low in energy.

$C_C \rightarrow C_{DT}$ by applying non-paralyzable model: $C_{DT} = \frac{C_C}{1-\Delta DT \cdot C_C/\Delta t}$.

$C_{DT} \rightarrow C_R$ by substracting background, which is corrected by previous corrections too.

$C_R \rightarrow C$ by applying $C = C_R \cdot f(ToF)$.



We discard all counts beyond certain energy limits, knowing that the proton from the [35Cl + n ⟶ 35S + p] reaction has around 613keV (at thermal energy).

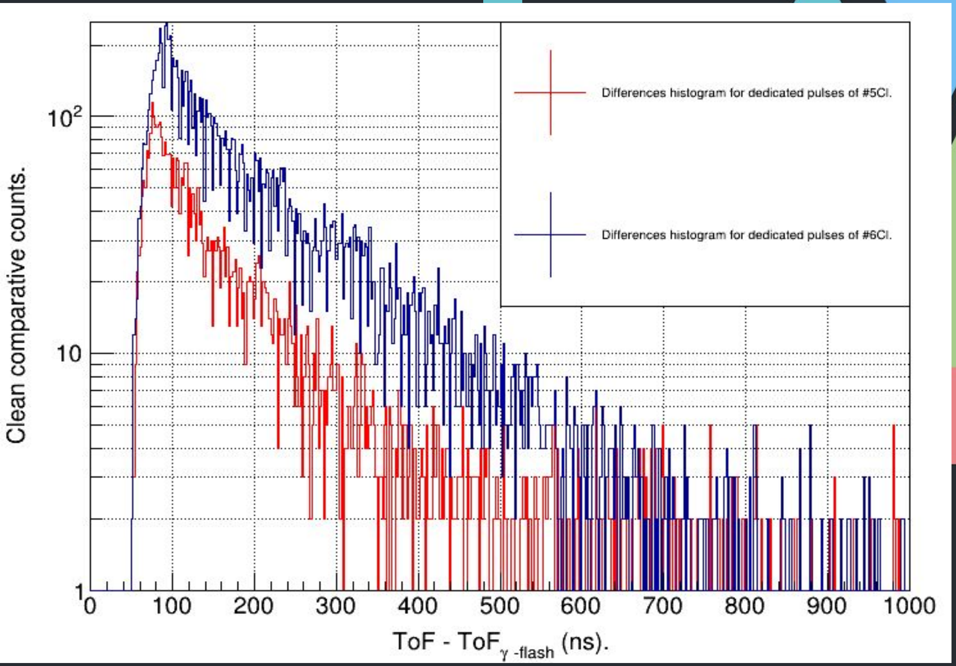
ToF ≡ Time of Flight (ns).
$ToF_{\gamma\text{-flash}}$ ≡ Time of Flight of γ-Flash (ns).

1.-Corrections:

*(C): Counts corrections: dead-time.

Dead-time (period after a particle detection during which the detector cannot resolve a new detection) calculation following ToF difference of consecutive detections.

Time difference of consecutive detections.



Sample	Dedicated	Parasitic
#1, 235U	78.76 ns	79.00 ns
#2, 10B	57.61 ns	57.18 ns
#5, 35Cl	57.55 ns	59.40 ns
#6, 35Cl	58.73 ns	60.40 ns

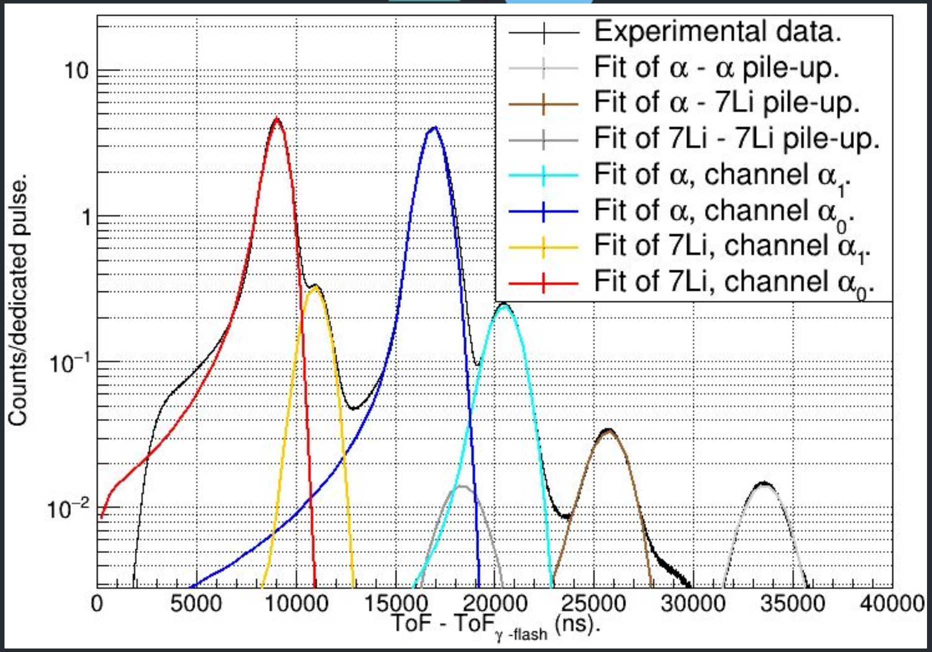
E_n ≡ Neutron energy (MeV).
Φ ≡ Flux (neutrons/s).
T ≡ Transmition factor (-).

1.-Corrections:

*(C): Counts corrections: dead-time.

Dead-times obtained is verified with a validation method:

Coincidence between pile-up counts and the increase in counts predicted by non-paralyzable model.



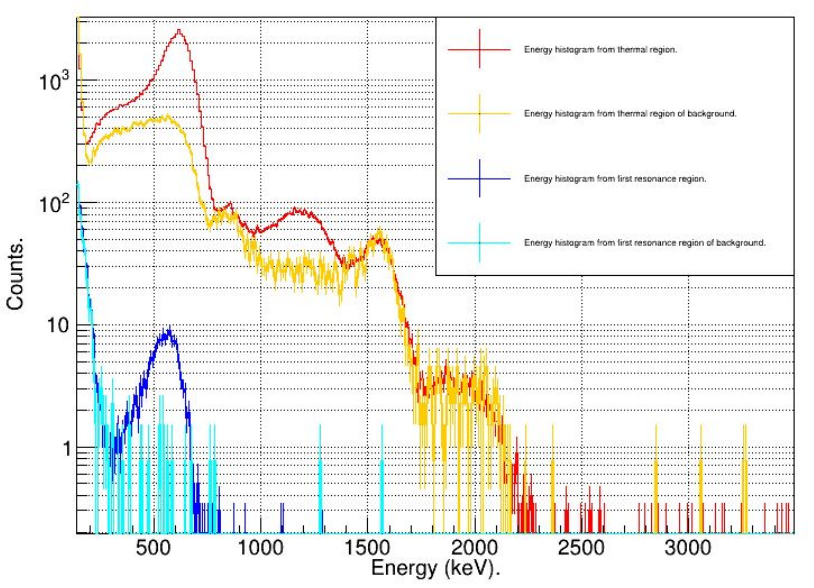
Counts in all pile-ups: 17.6835.
Increase in counts after correction: 17.3850.

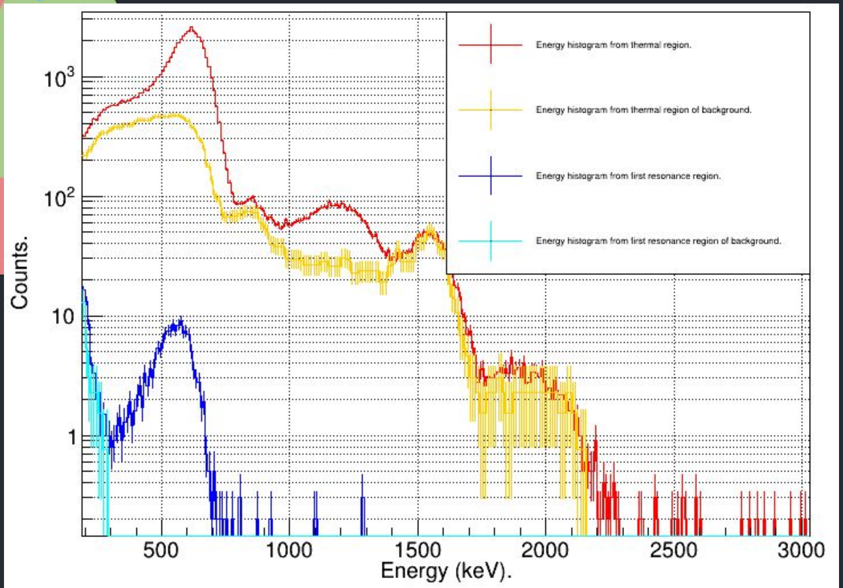
1.-Corrections:

*(C): Counts corrections: background.

Background obtained by doing the same procedure and corrections to measurements performed in the detectors at positions #5 and #6 with the KCl samples and with a dummy samples (Al backing).

(If necessary, background is smoothed by substituting the original measured value of each bin for the statistic median of its surroundings, in order to avoid negative cross sections in low-statistics areas.)



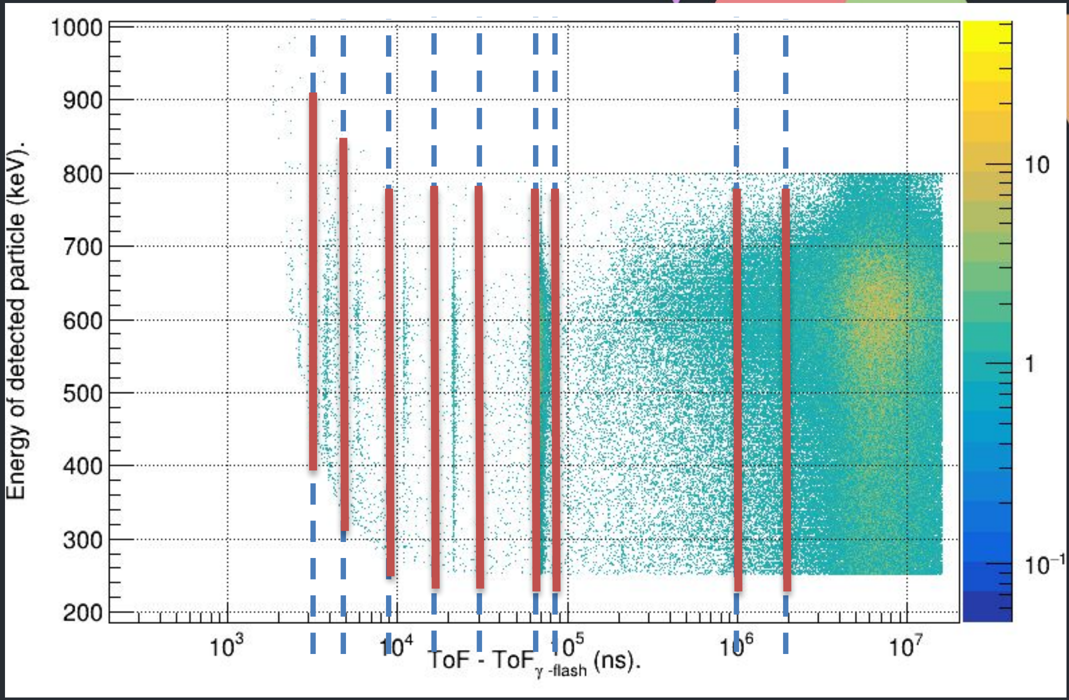


1.-Corrections:

*(C): Counts corrections: energy cuts.

Once the background has been substracted and dead-time corrected, we have to account for the real detections discarded due to selection cuts. We fit the detected particles to a convolution of a Gaussian and an inverse Landau distribution to estimate how many counts were left behind.

Several fits are made at different ToF bins and true corrections are obtained by extrapolation.



1.-Corrections:

*(D): Counts corrections: efficiency correction.

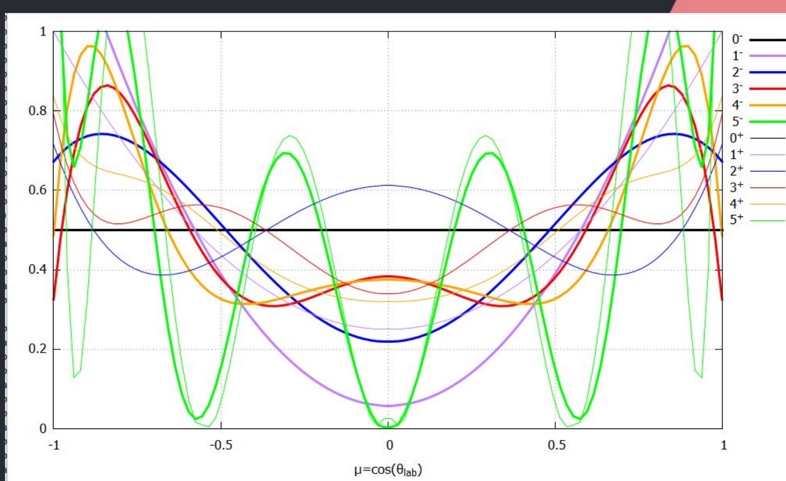
Angular distribution of emitted protons is theoretically calculated as a function of their inducing neutron energy in the CM system and for possible J^{π} combinations and simulated in MCNP.

The Angular Distribution of Scattering and Reaction Cross Sections

John M. Blatt and L. C. Biedenharn

Rev. Mod. Phys. **24**, 258 – Published 1 October 1952

$$R_L(\alpha' s'; \alpha s) \equiv \frac{(-)^{s'-s}}{4[(E-E_0)^2+(\frac{1}{2}\Gamma)^2]} \sum_{l_1=|J_0-s|}^{J_0+s} \sum_{l_2=|J_0-s|}^{J_0+s} \sum_{l_1'=|J_0-s'|}^{J_0+s'} \sum_{l_2'=|J_0-s'|}^{J_0+s'}$$
$$\times Z(l_1 J_0 l_2 J_0, sL) Z(l_1' J_0 l_2' J_0, s'L) g_{\alpha s l_1} g_{\alpha s l_2} g_{\alpha' s' l_1'} g_{\alpha' s' l_2'} \cos[\xi_{\alpha l_1} - \xi_{\alpha l_2} + \xi_{\alpha' l_1'} - \xi_{\alpha' l_2'}] \quad (\text{for } \alpha, s \neq \alpha', s').$$



Simulations of the actual efficiency using these angular distributions are ongoing.

DSSSD will help discriminate the correct angular distribution.

2.-(Very) preliminary results:

Cross section at thermal energy (25.3 meV):

Vs. recent evaluations

Sample	Dedicated	Parasitics
#5, 35Cl	0.5259 b	0.5397 b
#6, 35Cl	0.4465 b	0.4908 b

Evaluations	Value:
ENDF/B-VII.0	0.480534 b
JEFF-3.1.2	0.480534 b
JENDL-4.0	0.489299 b
TENDL-2021	0.48959 b

3.-Pending tasks:

To be done:

-Simulation of geometrical efficiencies.
- Improve fits and selection cuts in the resonance region.
- Extend the high energy range above 100 keV.

-Include and properly propagate all uncertainties:

*Mass: error from RBS + correction.
*Reference cross-section (^{10}B) uncertainty.
*Selection cuts and efficiency uncertainty.
*Statistical uncertainty.

-Fit cross section with SAMMY.

-Start DSSSD analysis.

Thank you for your attention

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