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High-energy neutron-induced fission cross sections in ^{nat}Pb and ^{209}Bi

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on behalf of the n_TOF collaboration

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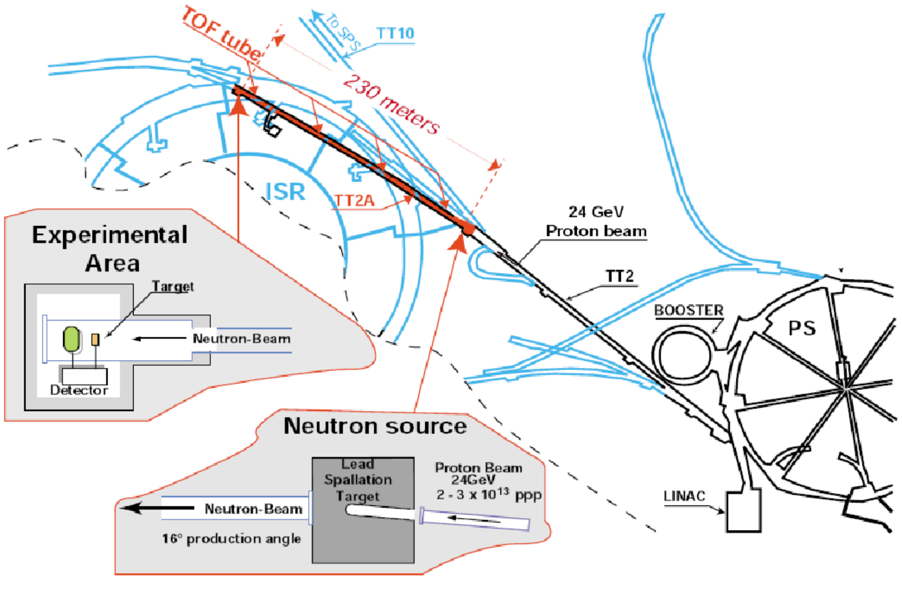
Motivation

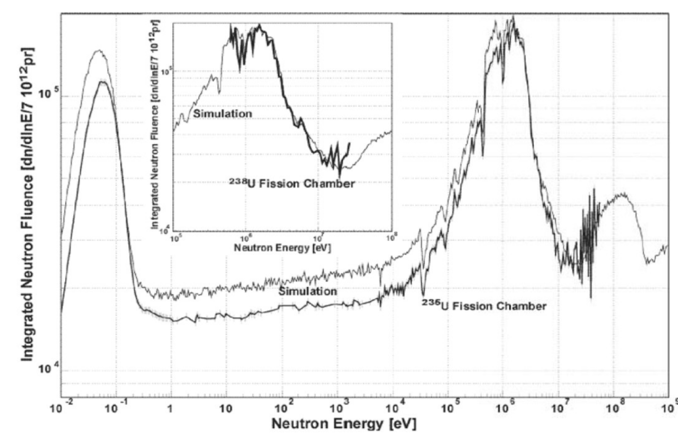
- Pb and Bi are neutron spallation sources in ADS systems.
  - Neutron spectrum.
  - Target heating and radioactivity.
- Bi-209 has been proposed [1] as a new standard for neutron-induced fission cross section above 50 MeV:
  - High fission threshold (~ 25 MeV) → insensitive to low-energy neutrons.
  - Monoisotopic and non-radiactive material.
- There are only a few experimental data with neutrons (only up to 200 MeV) → High uncertainties in Bi209(n,f) evaluations (~ 10% in ENDF/HE-VI; no evaluation for lead isotopes).
- **Int. Nuc. Data Com. (IAEA) pointed out the necessity of new and more precise measurements** [1]**.**
- Pb-nat(n,f) and Bi-209(n,f) cross sections have been measured **between threshold and up to 1 GeV** at CERN-n_TOF facility.

[1] A. D. Carlson, S. Chiba, F.-J. Hambsch, N. Olsson, A. N. Smirnov. IAEA Report INDC (NDS) 368, (1997)

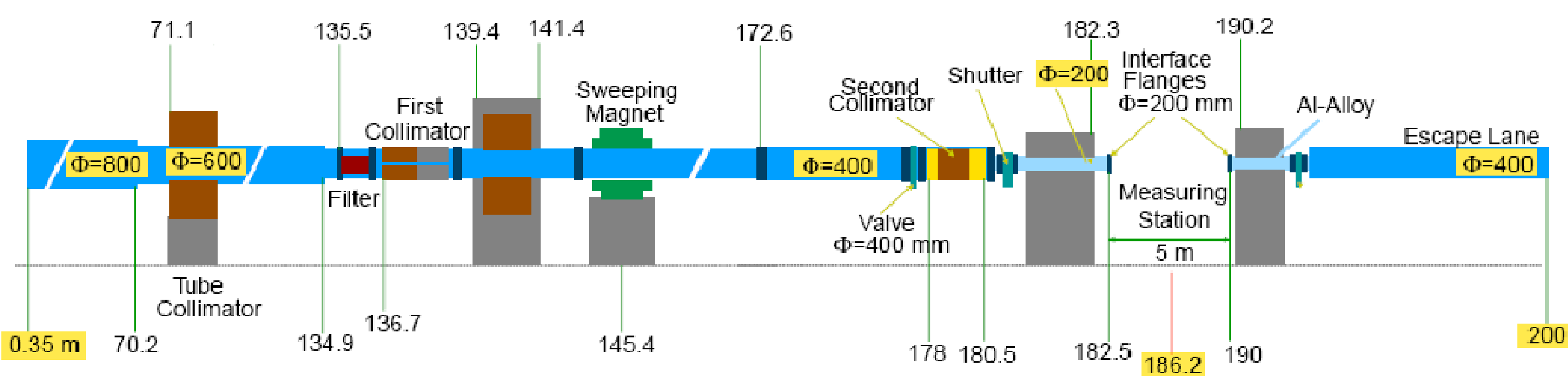
The n_TOF facility at CERN



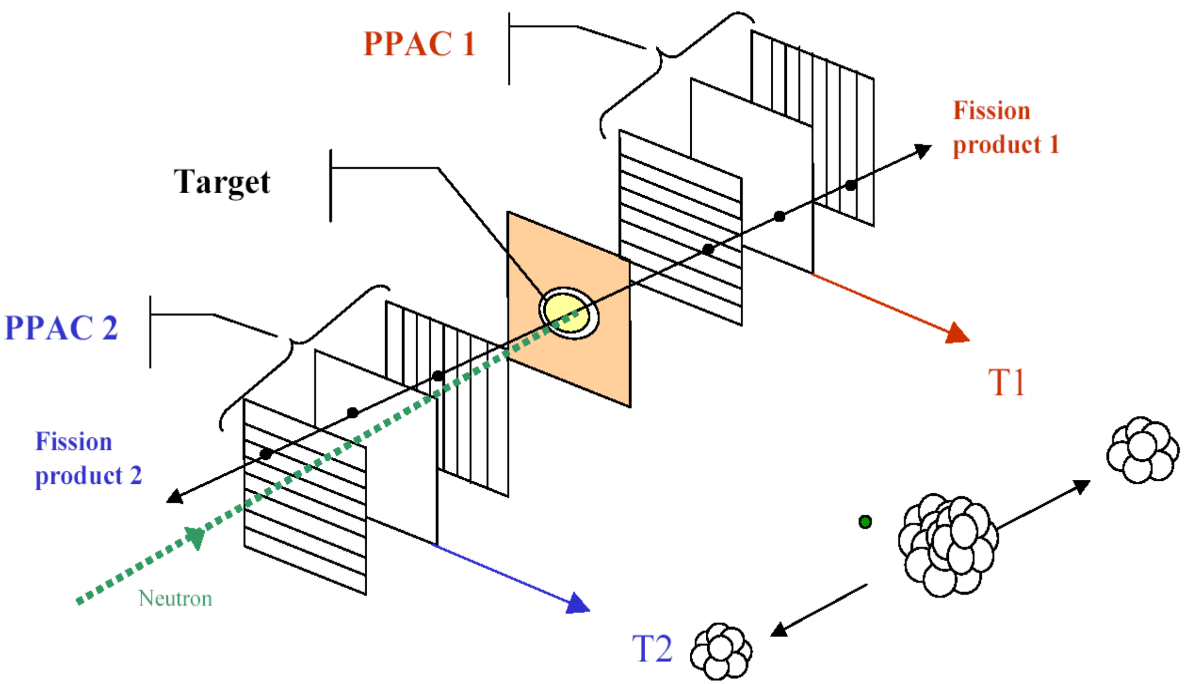
- n_TOF (Neutron Time-Of-Flight) is a facility dedicated to the study of neutron-induced reactions: fission and radiative capture.
- The neutron beam is produced by spallation reactions of 20 GeV/c protons from the PS (Proton Synchrotron) on a lead target.
- White spectrum neutron beam (0.02 eV – 1 GeV).

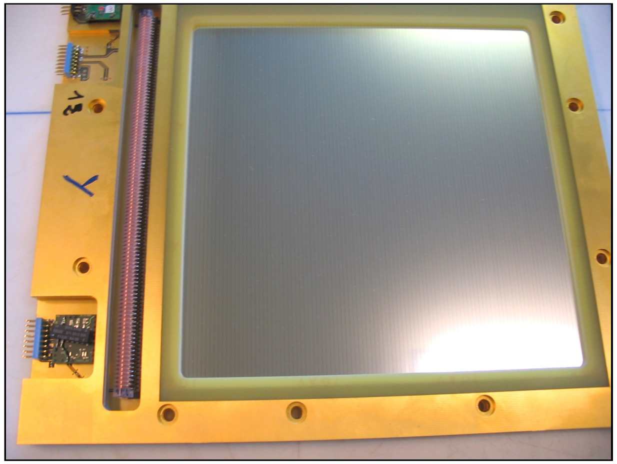


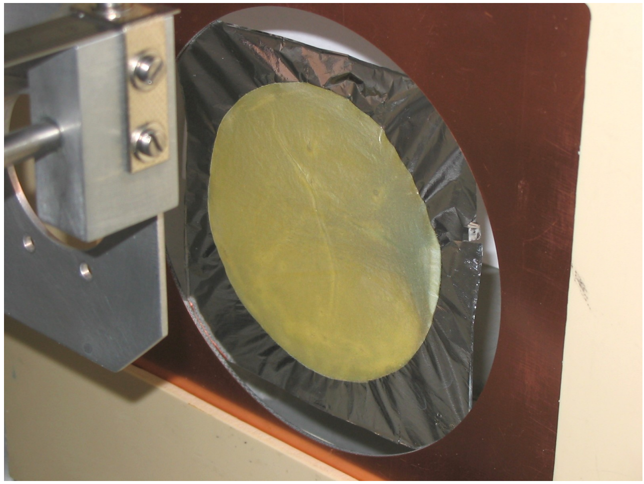
- Around $9.6 \cdot 10^5$ neutrons per proton bunch.
- Long-flight path (185 m) → high-accuracy resolution in neutron energy using its time of flight (0.01% at 1 eV; 6% at 1 GeV).



Experimental setup

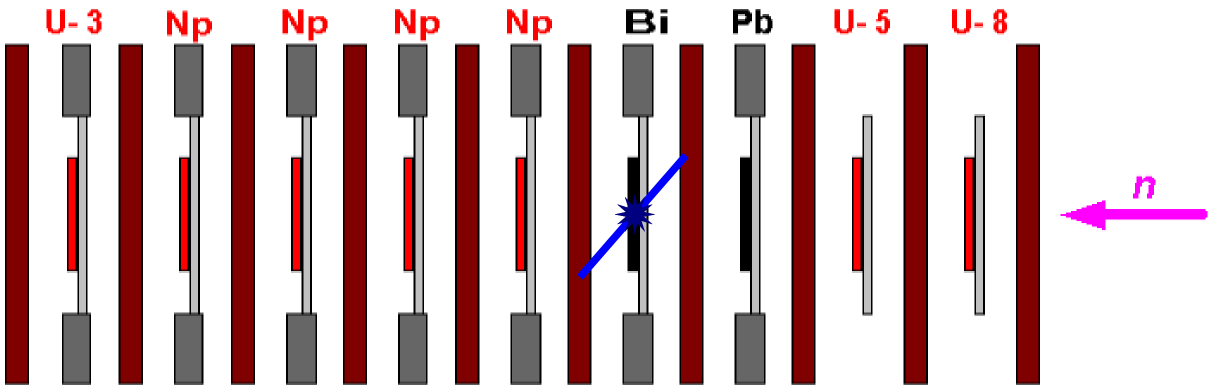






- Parallel Plate Avalanche Counter (PPAC) detectors.
- Central anode and two stripped cathodes.
  - Reconstruction of the trajectories of the fission fragments.
- **The fission fragments are detected in coincidence in two adjacent PPACs.**
  - Rejection of α-particles and light nuclei from other reactions.
- Samples of **Pb-nat** ant **Bi-209**, spread over a Mylar foil of 1.5 μm thickness.
- **U-235** and **U-238** deposited over 2.5 μm of Aluminium (8 cm diameter).

Fission cross section measurements



- 10 PPACs and 9 targets.
- Reference targets: ^{235}U and ^{238}U.
- Neutron flux attenuation lower than 1%.

- Number of detected fission events: $$C(E) = \Phi(E) \cdot N \cdot \sigma(E) \cdot \varepsilon(E)$$
- Relative cross sections:

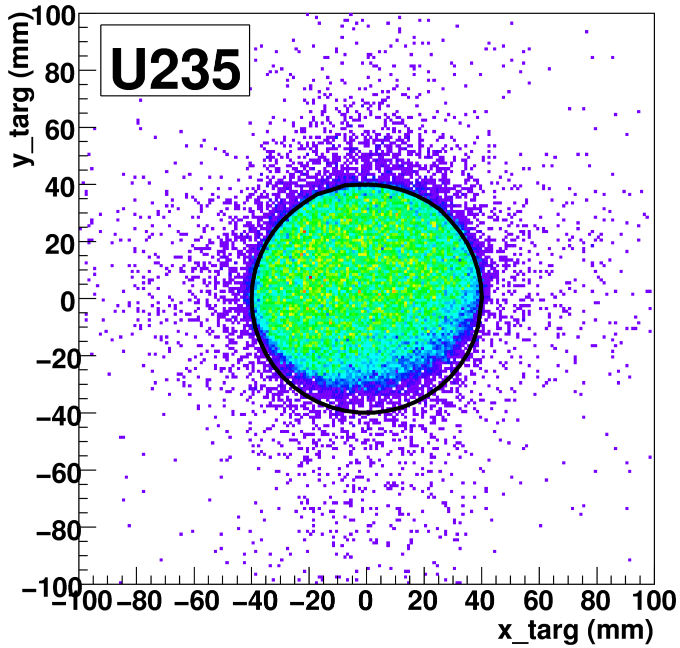
$$\frac{\sigma_i(E)}{\sigma_j(E)} = \frac{C_i(E)}{C_j(E)} \cdot \frac{\Phi_j(E)}{\Phi_i(E)} \cdot \frac{N_j}{N_i} \cdot \frac{\varepsilon_j(E)}{\varepsilon_i(E)}$$

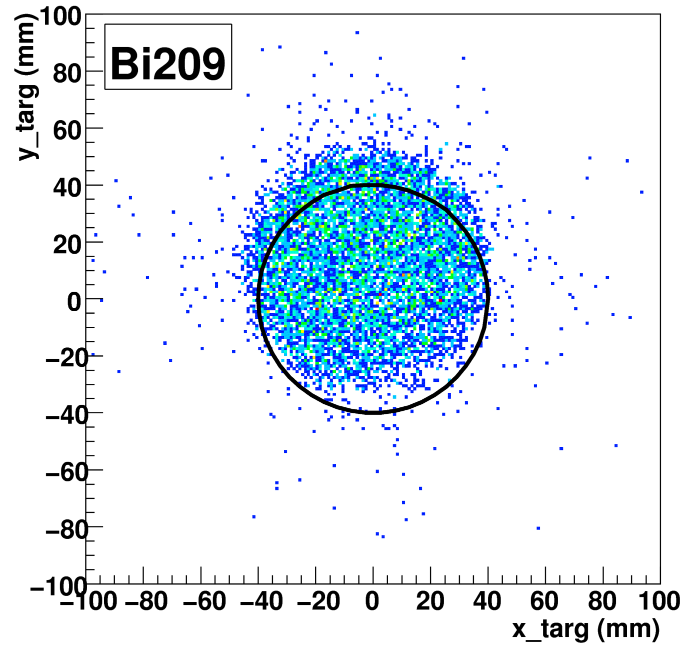
If the targets are **geometrically identical:**

$$\Phi_j(E) = \Phi_i(E)$$

Ratio of efficiencies:
- thickness of the samples and their backings
- angular distribution of the fission fragments

Beam spot correction



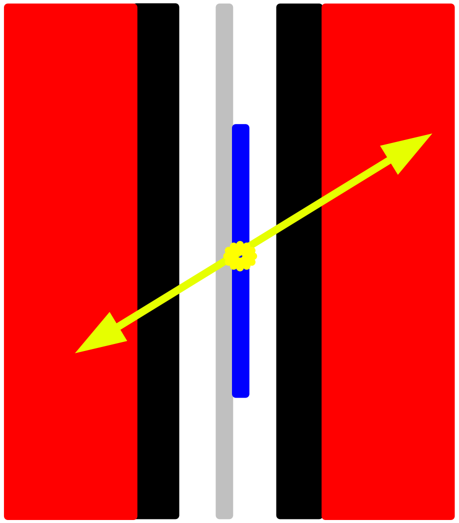


- Different size for subactinides and uranium samples.
- Beam was shifted upwards.
- It is needed to apply a correction on the counting rates.

$$F_{(Pb-nat,Bi-209)}/F_{(U-235,U-238)} = 0.81 \pm 0.03$$

Rejection of fission events outside the nominal beam.

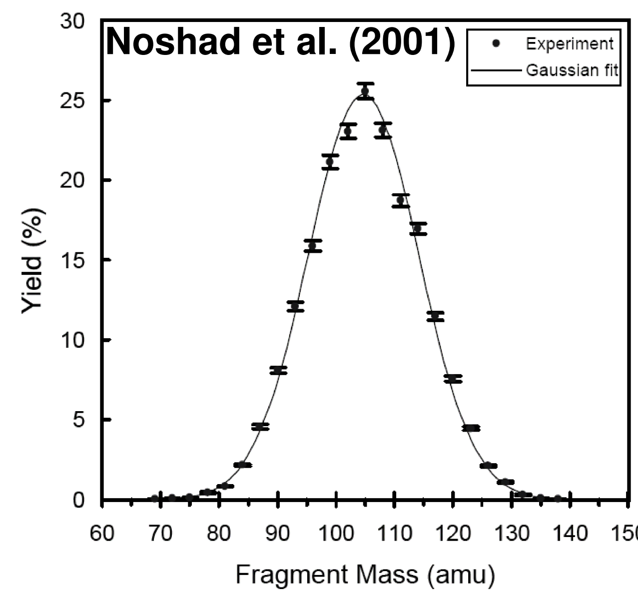
Efficiency detection



- The efficiency detection is given by the **maximum acceptance angle for the fission fragments (FF),** determined by its range (distribution on mass, charge and energy).
- Different backings: { 2.5 μm of Aluminum for U-235 and U-238. 1.5 μm of Mylar for Pb-nat and Bi-209.

A SIMULATION IS NEEDED!!!

- Calculation of the range for the different FF (Z, A, E),
- Experimental distribution of masses from Noshad [2] for Bi-209(p,f) at 30 MeV (and scaled, for U-235 and U-238).
- We assumed Z/A=const.
- Kinetic energy given by Viola's systematics [3].



$$\varepsilon_{(U-235)}/\varepsilon_{(Pb-nat,Bi-209)} = 0.85$$
$$\varepsilon_{(U-238)}/\varepsilon_{(Pb-nat,Bi-209)} = 0.88$$
$$\varepsilon_{(Bi-209)}/\varepsilon_{(Pb-nat)} = 1$$

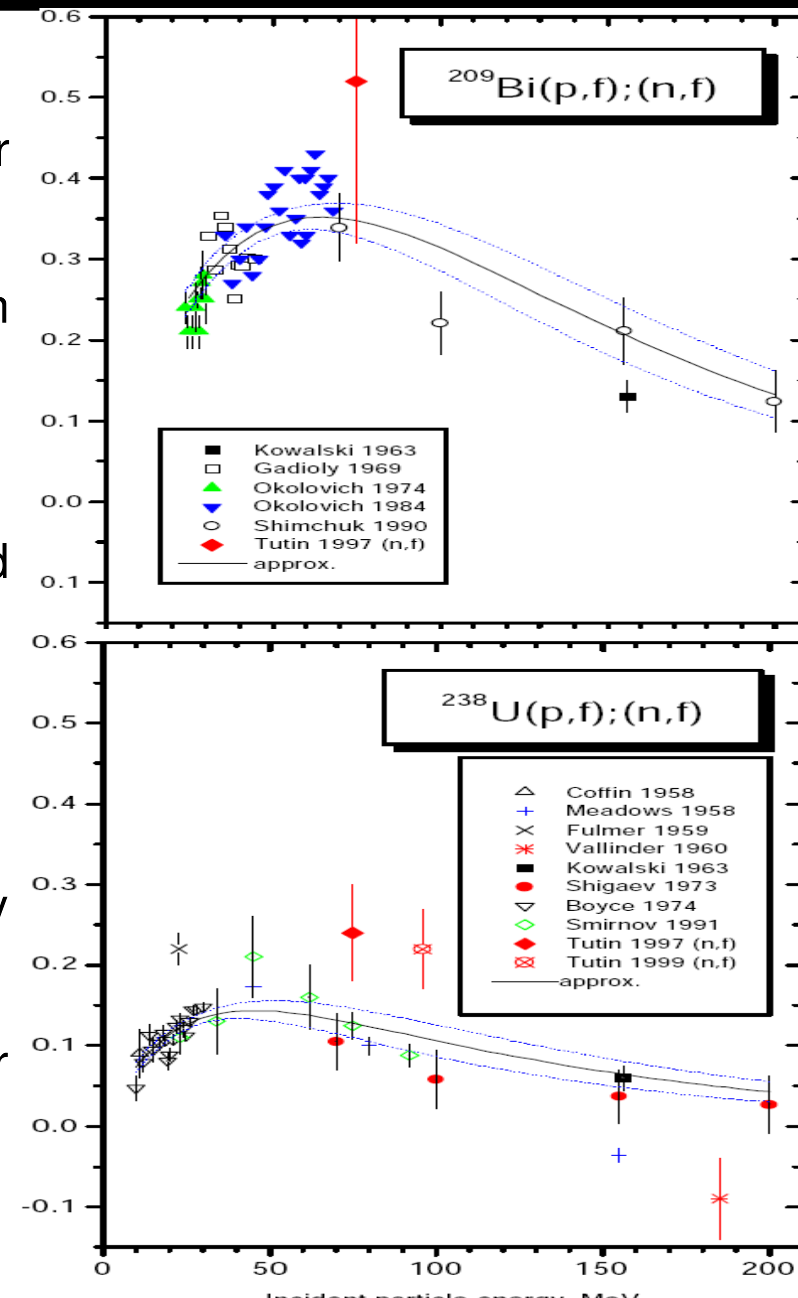
[2] H. Noshad et al., J. Nucl. Sci. Tech. 38, 901 (2001)
[3] V. E. Viola et al., Phys. Rev. C 31, 1550 (1985)

Angular distribution corrections

- Detection efficiency depends on the angular distribution.
- The actual setup allows us to measure the emission angle of the fission fragments, **BUT**:
  - Limited in angle: $0.5 \leq \cos\theta \leq 1.0$ ($0° \leq \theta \leq 60°$).
  - Poor statistics in $\cos\theta$ distributions for Pb-nat and Bi-209.

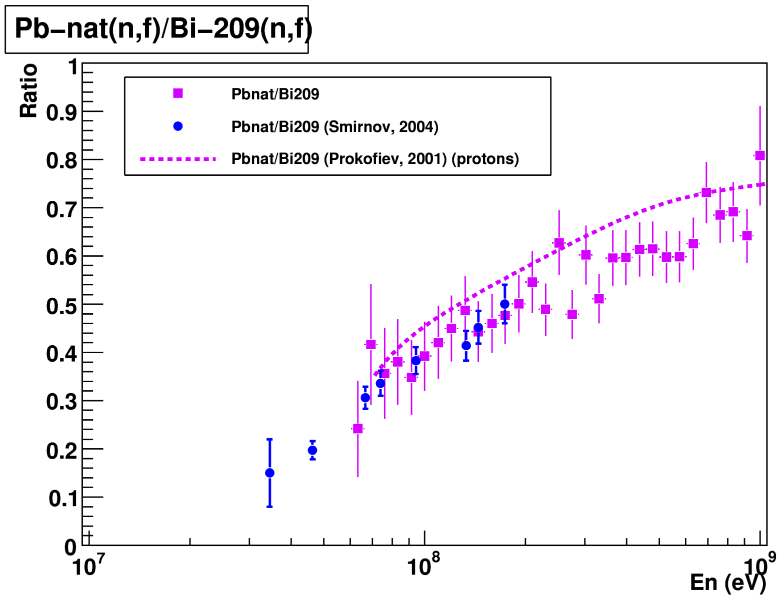
And, then:

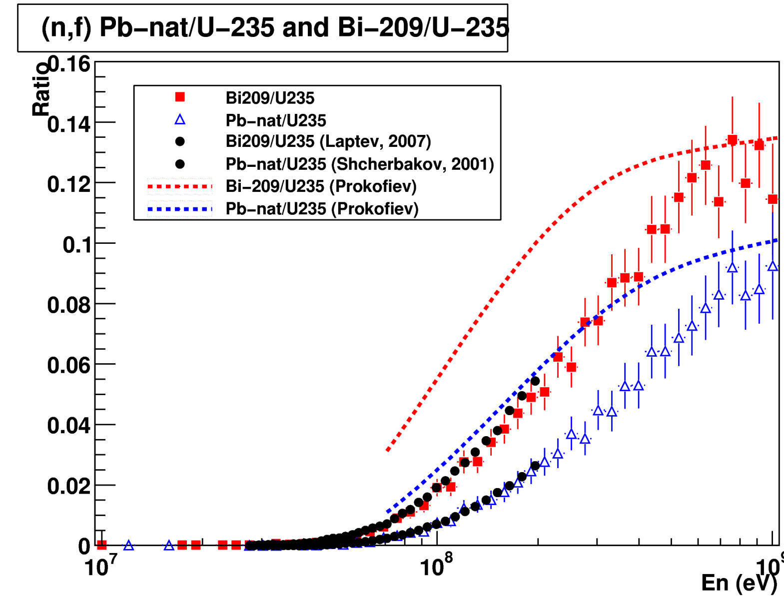
- We have used the parametrization for the anisotropy parameter W(0°)/W(90°)-1 given in Ref. [4].
- The correction factor in the ratio of efficiencies is lower than 6 % (value for Bi-209/U-238 around 40 MeV).

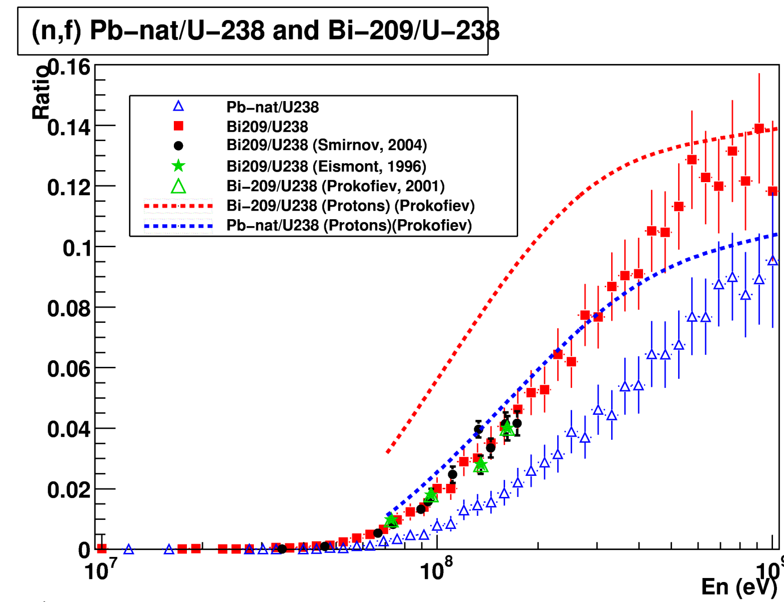


[4] V. P. Eismont, A. V. Prokofiev, I. V. Ryzhov et al. Proc. Of the 3rd Int. Conf. On Accelerator Driven Transmutation Technologies and Applications, Praha, Czech Republic (1999)

Ratios of cross sections



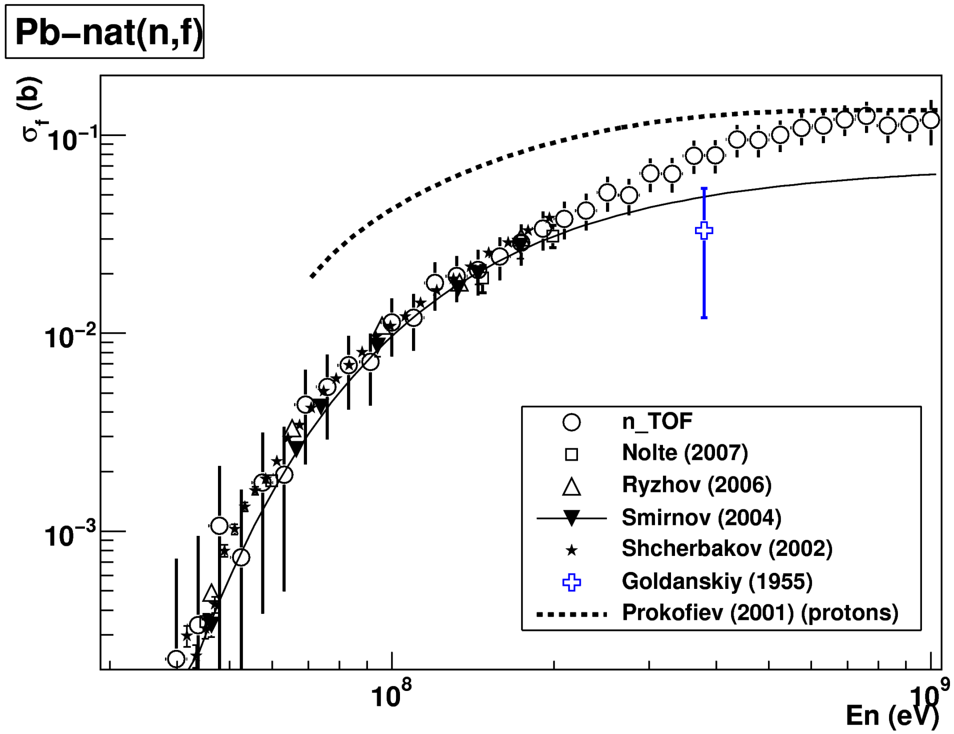


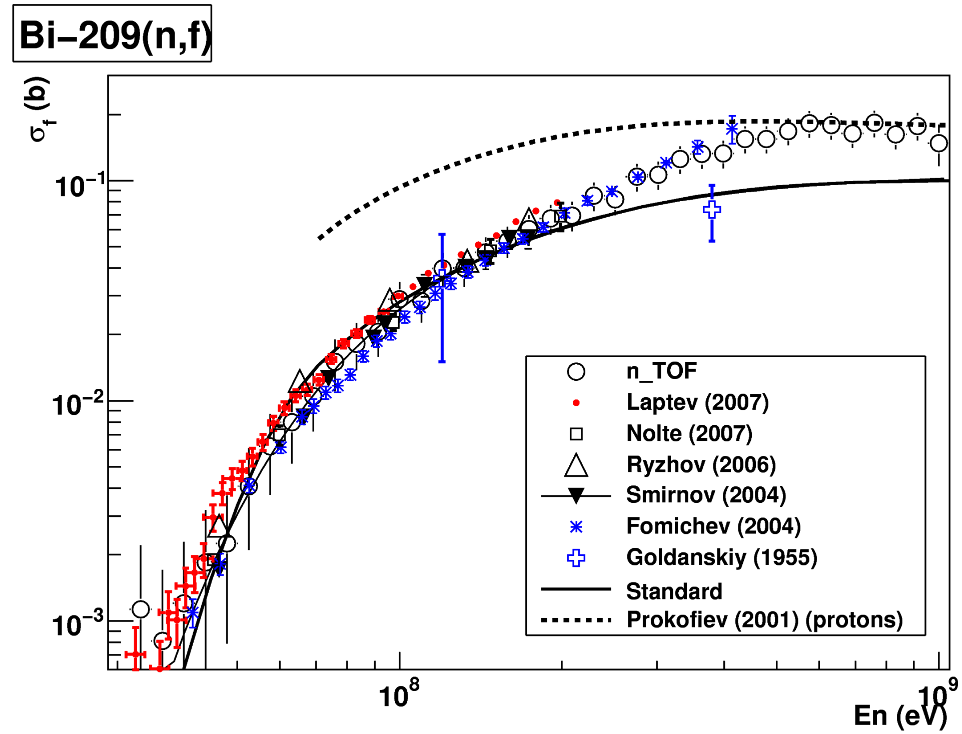


- First results up to 1 GeV-neutrons for subactinides.
- No normalization to previous results.
- Good agreement with earlier experimental values [5-9].
- Around 1 GeV, the results are close to Prokofiev systematics for $\sigma(p,f)$ [10].

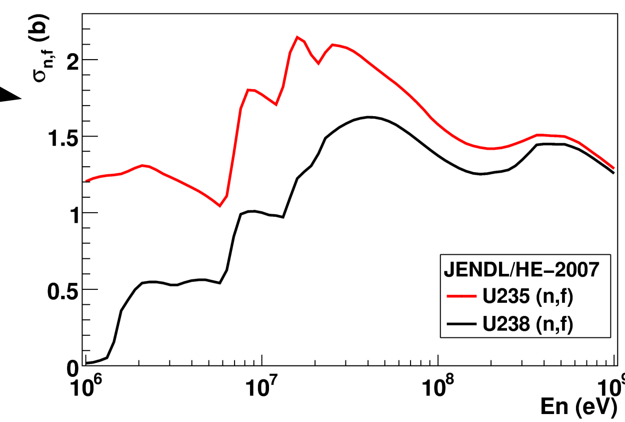
[5] Smirnov et al. PRC 70, 054603 (2004)
[6] Laptev et al. Conf. On Fission and Properties of Neutron-Rich Nuclei. Sanibel Island, Florida, USA (2007)
[7] O. Shcherbakov et al. Journ. Nucl. Sci. and Techn. Supp. 2, 230 (2002)
[8] V. P. Eismont et al. PRC 53, 2911 (1996)
[9] A. V. Prokofiev, PhD Thesis. Uppsala University (2001)
[10] A. V. Prokofiev, NIMA 463, 557 (2001)

Final cross sections σ(n,f)





- JENDL/HE-2007 evaluations for U-235 and U-238 to extract the final cross sections.



- Good agreement with previous results [5-7, 11-13]. Disagreement with Goldanskiy data at 380 MeV [14] and with the extension of previous evaluations beyond 200 MeV.

- **FIRST RESULTS FOR σ(n,f) IN SUBACTINIDES UP TO 1 GeV.**

[11] R. Nolte et al. Nuc. Sci. and Eng. Vol. 156, pp. 197-210 (2007)
[12] I. V. Ryzhov et al. NIMA 562, 439 (2006)
[13] A.V.Fomichev, V.N.Dushin, S.M.Soloviev, A.A.Fomichev, S.Mashnik. “Neutron Induced Fission Cross Sections For 240-Pu, 243-Am, 209-Bi, Nat-W Measured Relative to 235-U in the Energy Range 1-350 MeV” Khlopin Radiev. Inst., Leningrad Reports No.262 (2004). EXFOR Entry 41444004
[14] V. I. Goldanskiy et al. Doklady Academii Nauk 101, 1029 (1955). EXFOR Entry 41212001

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Conclusions

- First experimental results of Pb-nat(n,f) and Bi-209(n,f) cross sections up to 1 GeV.
- Comparison with previous experimental results:
  - Good agreement below 200 MeV.
  - Present parametrizations cannot be extended beyond 200 MeV
    - → They should be updated taking these new results into account.
- At 1 GeV, σ(n,f) cross sections are, approximately, equal to σ(p,f).

References

[1] A. D. Carlson, S. Chiba, F.-J. Hambsch, N. Olsson, A. N. Smirnov. IAEA Report INDC (NDS) 368, (1997)

[2] H. Noshad et al. J. Nucl. Sci. Tech. 38,901 (2001)

[3] V. E. Viola et al, Phys. Rev. C 31, 1550 (1985)

[4] V. P. Eismont, A. V. Prokofiev, I. V. Ryzhov et al. Proc. Of the 3rd Int. Conf. On Accelerator Driven Transmutation Technologies and Applications, Praha, Czech Republic (1999)

[5] Smirnov et al. PRC 70, 054603 (2004)

[6] Laptev et al. Conf. on Nucl. Data for Sci. and Techn., Santa Fe 2004 Vol.1, p.865 (2004)

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[12] I. V. Ryzhov et al. NIMA 562, 439 (2006)

[13] A.V.Fomichev, V.N.Dushin, S.M.Soloviev, A.A.Fomichev, S.Mashnik. "Neutron Induced Fission Cross Sections For 240-Pu, 243-Am, 209-Bi, Nat-W Measured Relative to 235-U in the Energy Range 1-350 MeV" Khlopin Radiev. Inst., Leningrad Reports No.262 (2004). EXFOR Entry 41444004

[14] I. Goldanskiy et al. Doklady Academii Nauk 101, 1029 (1955). EXFOR Entry 41212001