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Towards the adoption of $^{238}U(n,f)$ and $^{237}Np(n,f)$ as primary standards for fast neutron energies

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Why do we need still to study σ?

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1. Study of the fission process

2. Design of Gen-IV nuclear power plants

- Neutron energy spectra from 0.5MeV to 20MeV
- Highly enriched U to function
- Improved target accuracy

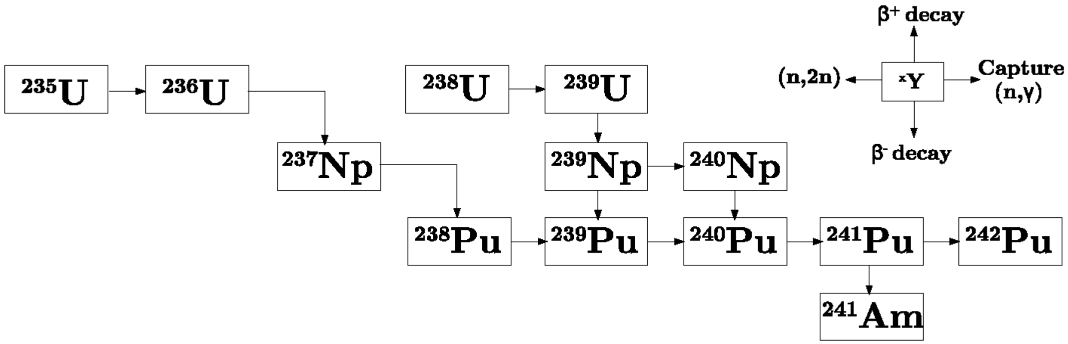

Table 32. Summary of Highest Priority Target Accuracies for Fast Reactors

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	σ_{inel}	6.07 ÷ 0.498 MeV	10 ÷ 20	2 ÷ 3
	σ_{capt}	24.8 ÷ 2.04 keV	3 ÷ 9	1.5 ÷ 2
Pu241	σ_{fiss}	1.35MeV ÷ 454 eV	8 ÷ 20	2 ÷ 3 (SFR,GFR, LFR) 5 ÷ 8 (ABTR, EFR)
Pu239	σ_{capt}	498 ÷ 2.04 keV	7 ÷ 15	4 ÷ 7
Pu240	σ_{fiss}	1.35 ÷ 0.498 MeV	6	1.5 ÷ 2
	ν	1.35 ÷ 0.498 MeV	4	1 ÷ 3
Pu242	σ_{fiss}	2.23 ÷ 0.498 MeV	19 ÷ 21	3 ÷ 5
Pu238	σ_{fiss}	1.35 ÷ 0.183 MeV	17	3 ÷ 5
Am242m	σ_{fiss}	1.35MeV ÷ 67.4keV	17	3 ÷ 4
Am241	σ_{fiss}	6.07 ÷ 2.23 MeV	12	3
Cm244	σ_{fiss}	1.35 ÷ 0.498 MeV	50	5
Cm245	σ_{fiss}	183 ÷ 67.4 keV	47	7
Fe56	σ_{inel}	2.23 ÷ 0.498 MeV	16 ÷ 25	3 ÷ 6
Na23	σ_{inel}	1.35 ÷ 0.498 MeV	28	4 ÷ 10
Pb206	σ_{inel}	2.23 ÷ 1.35 MeV	14	3
Pb207	σ_{inel}	1.35 ÷ 0.498 MeV	11	3
Si28	σ_{inel}	6.07 ÷ 1.35 MeV	14 ÷ 50	3 ÷ 6
	σ_{capt}	19.6 ÷ 6.07 MeV	53	6

NPL Van de Graaff accelerator

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NPL Van de Graaff accelerator

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Low-scatter area

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scatter of neutrons of 100-200keV lower energy than E_n

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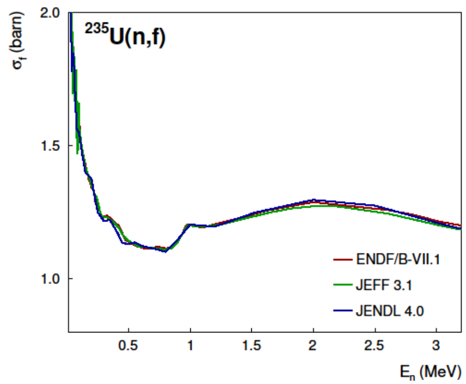
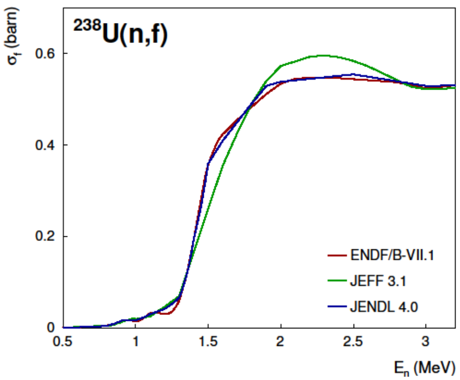
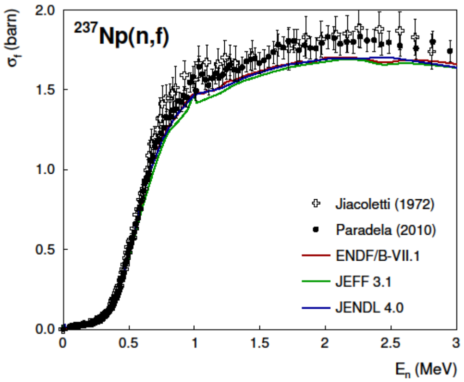
issue when using ^{235}U(n,f)

Need of secondary standards with fission threshold



→





Fluence measurement

(1) Fluence measurement with a Long counter
(2) Fluence meas. with shadow cone + Long counter

Fluence per unit beam charged

Fluence measurement

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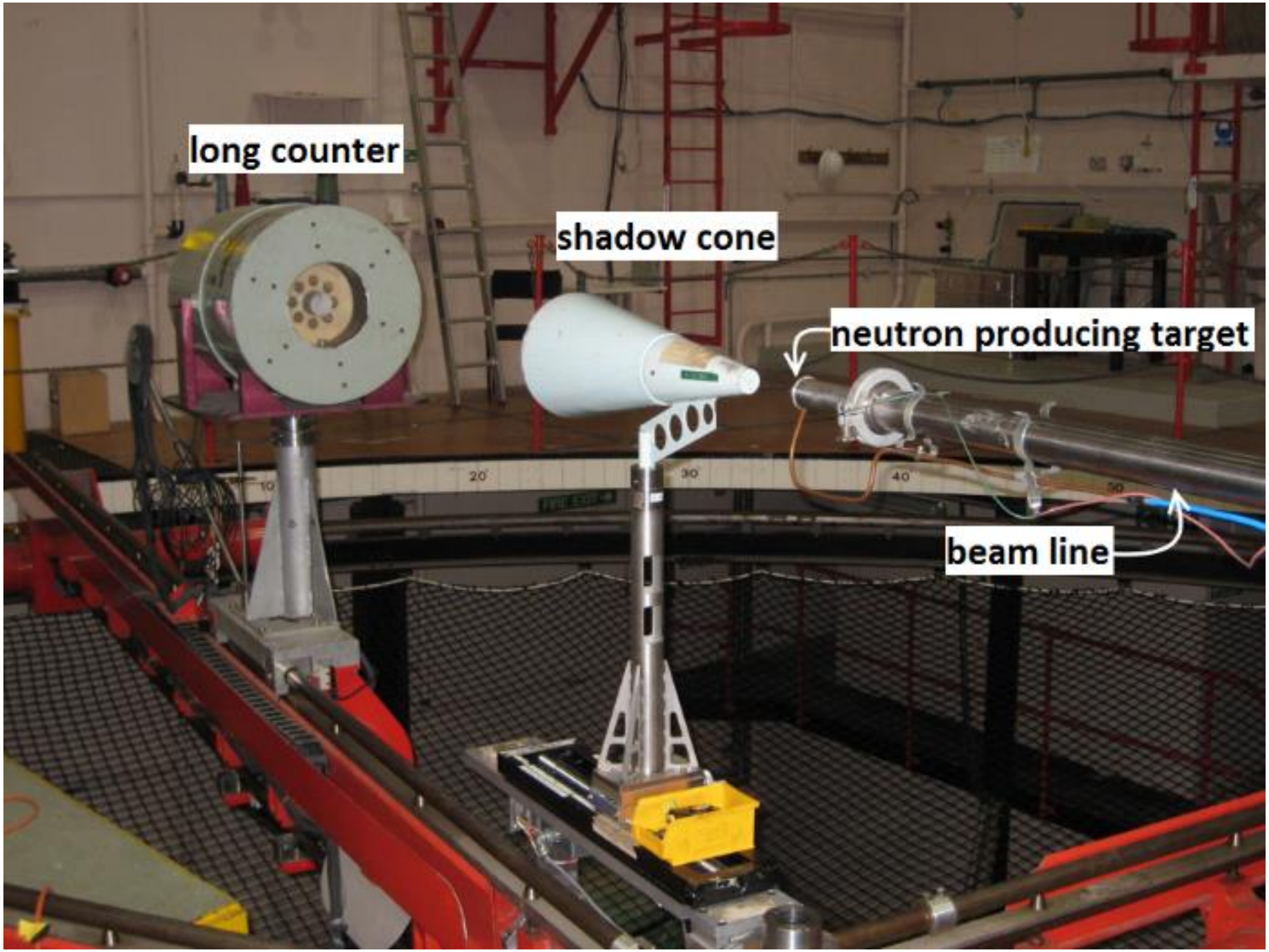
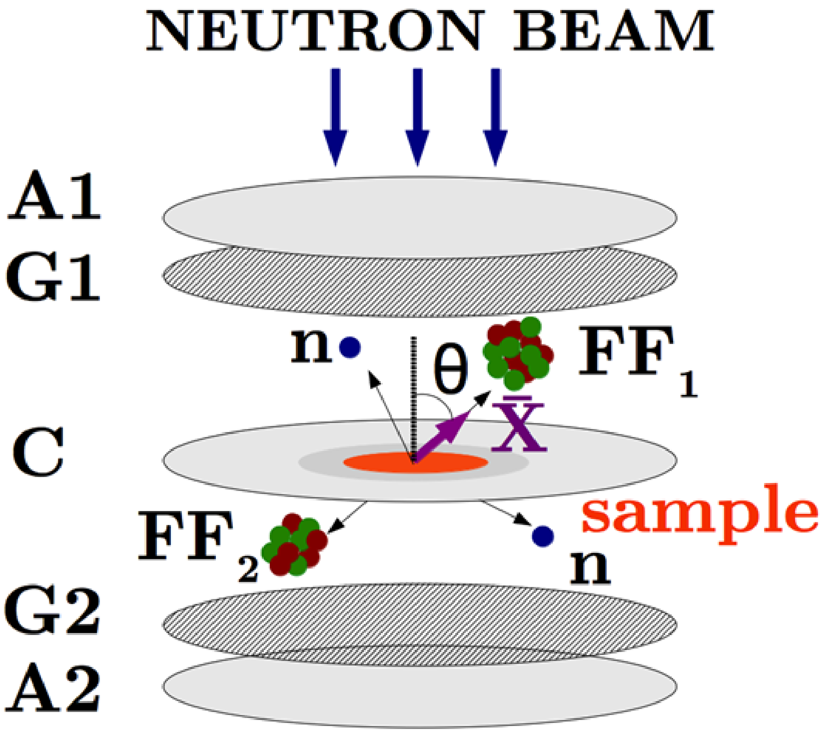
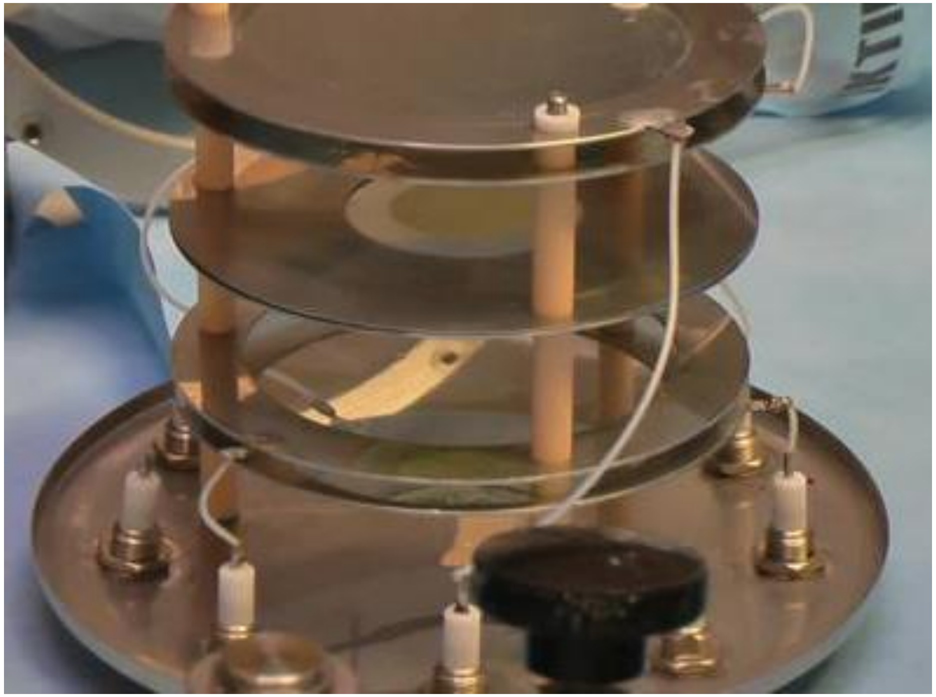
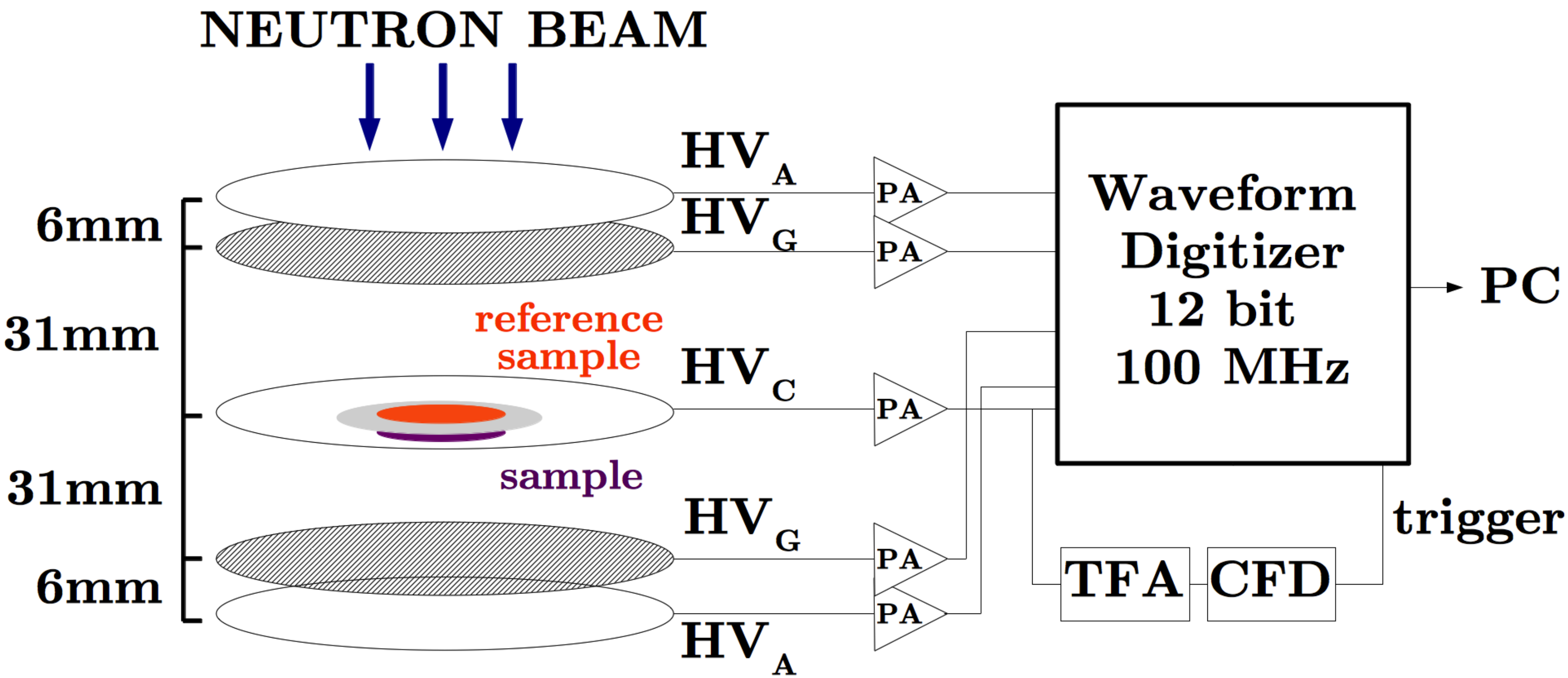


Twin Frisch-Grid Ionization Chamber



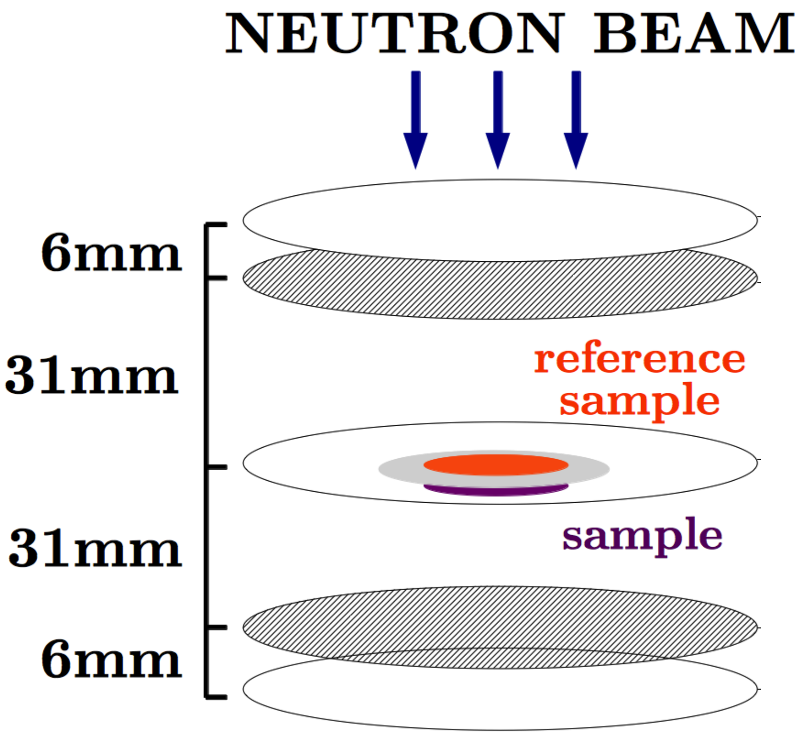


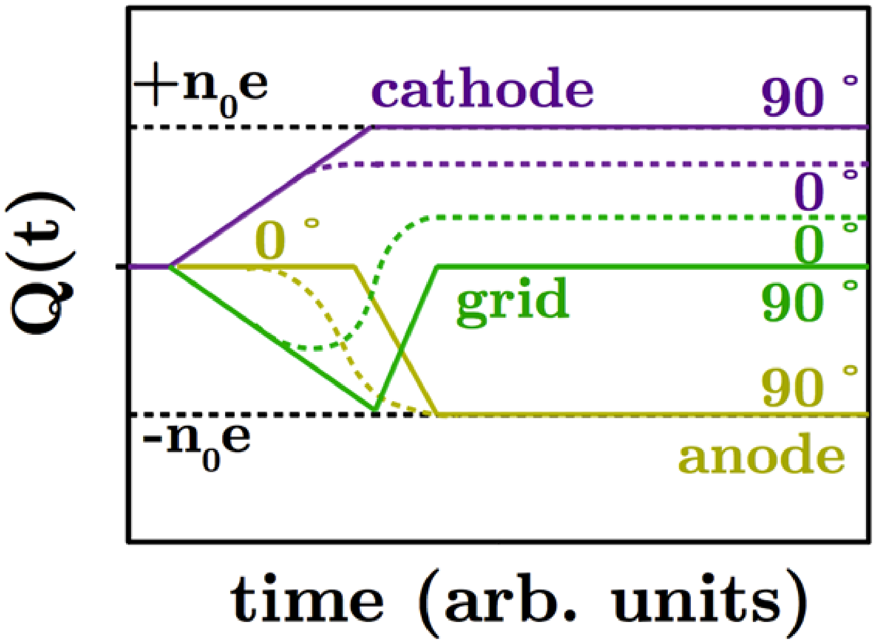
Twin Frisch-Grid Ionization Chamber



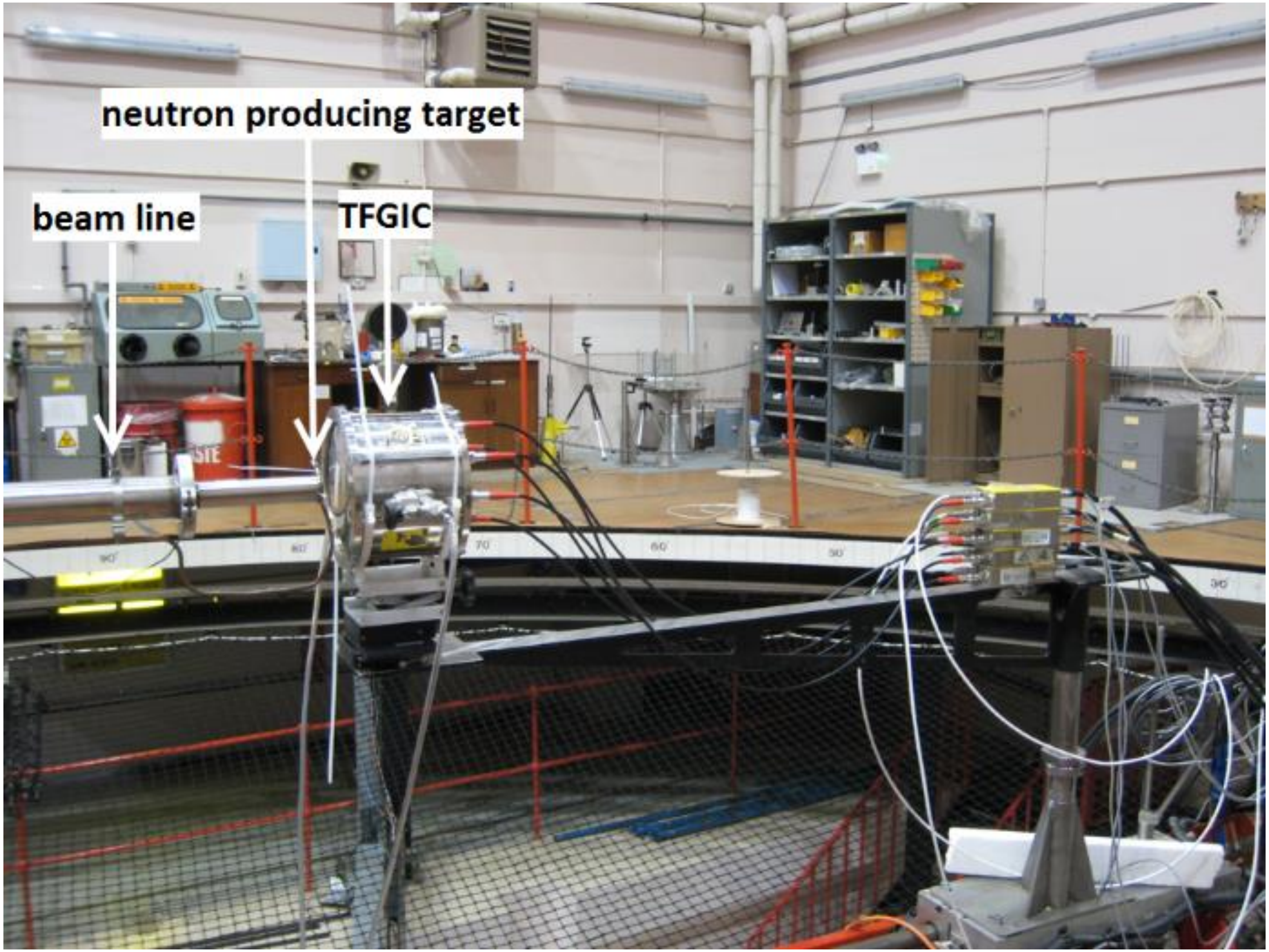
gas: CH_4
pressure: 1053 mbar
flow rate: 100 ml/min

Twin Frisch-Grid Ionization Chamber





Fission fragment measurement



Experimental campaigns

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Two campaigns under the CHANDA project: 2016 and 2017

Experimental campaigns

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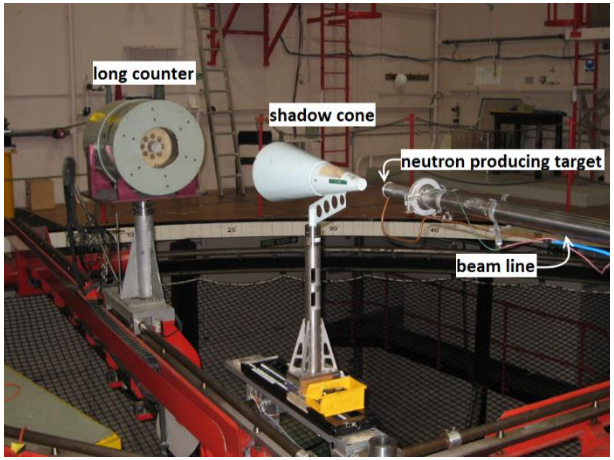
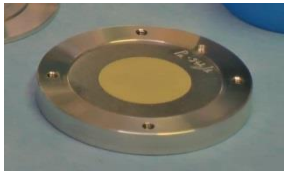
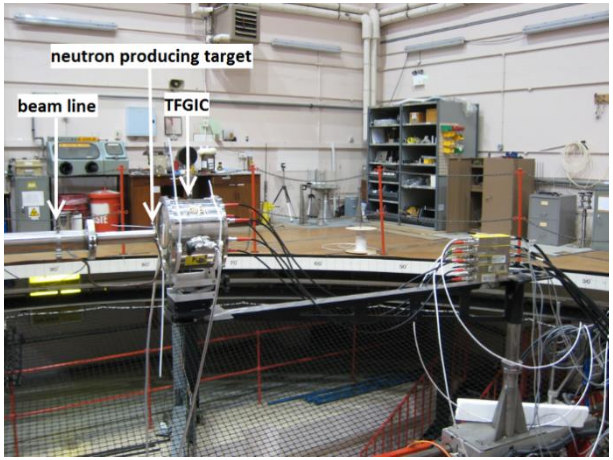
Two campaigns under the CHANDA project: 2016 and 2017







Samples	E_n(MeV)
$^{235}U/^{237}Np$	0.567, 1.2, 1.8, 2.0
$^{235}U/^{238}U$	1.8, 2.0, 2.4
$^{238}U/^{237}Np$	1.8, 2.0, 2.4
$^{235}U_{new}/^{235}U_{old}$	0.565, 1.2, 1.8, 2.4
$^{242}Pu/^{235}U_{new}$	0.565, 0.9, 1.0, 1.1,1.2, 1.8, 2.4
$^{242}Pu/^{237}Np$	1.0, 1.1, 1.2, 1.8, 2.4

Isotope	Mass (µg)	Purity
$^{235}U_{old}$	555 (22)	99.83%
$^{235}U_{new}$	701 (4)	99.93%
^{238}U	681 (18)	>99.99%
^{237}Np	489.5 (2.4)	>99.99%
^{242}Pu	671 (6)	99.97%

Experimental campaigns

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Two campaigns under the CHANDA project: 2016 and 2017

↓

correlated results

Similarities:

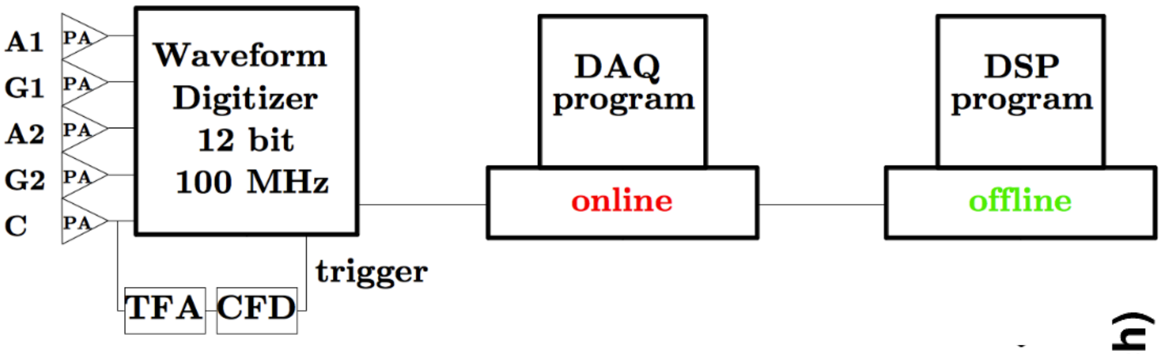
- NPL facility (fluence determination technique)
- Some of the samples ($^{235}U_{old}$, ^{237}Np)

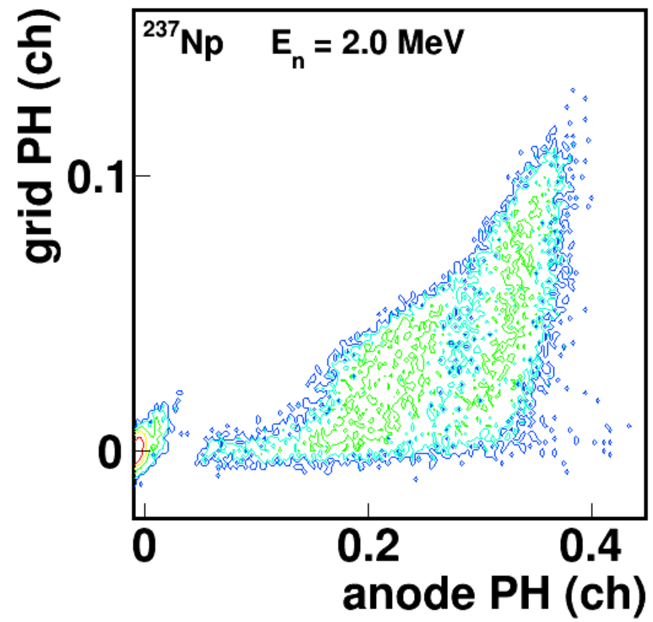
Differences:

- More control on:
  - proton beam spot shape and size
  - neutron producing target – TFGIC distance
- new built TFGIC in 2017
- different DAQ boards
- *New* ^{235}U sample in 2017

Data analysis

1. Fission fragment characterization





Data analysis

1. Fission fragment characterization

2. Absolute fluence determination

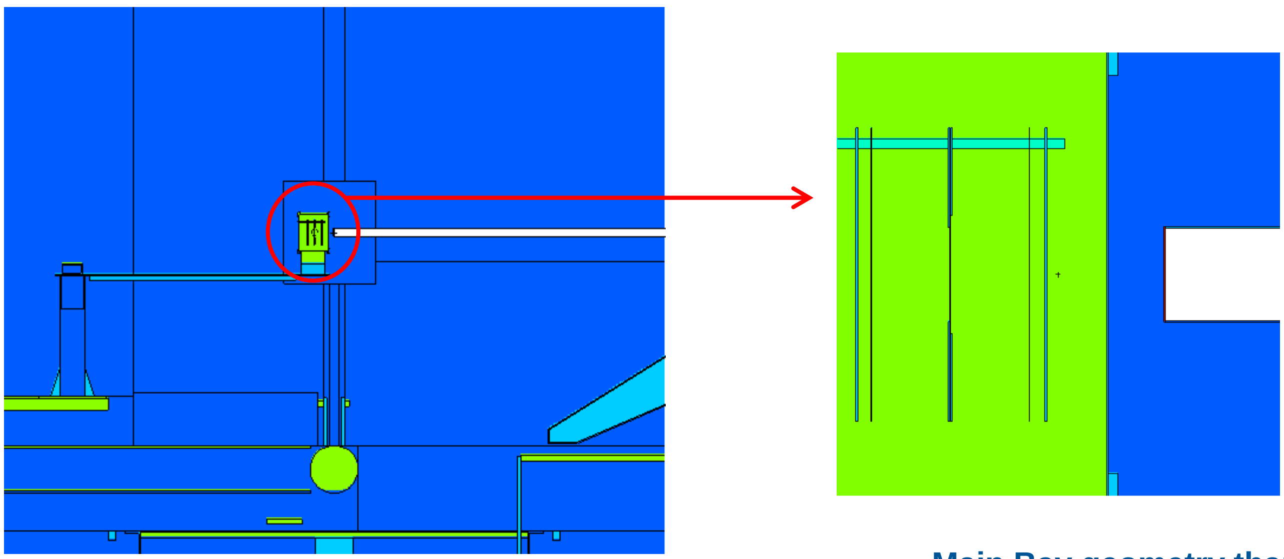
Flucal ⟶ fluence at the point of the samples from point source
MCNP6 ⟶ correction for disk sample and disk neutron source
MCNP6 ⟶ correction for target can scattering
MCNP6 ⟶ correction for attenuation on the front face TFGIC

Data analysis

1. Fission fragment characterization

2. Absolute fluence determination

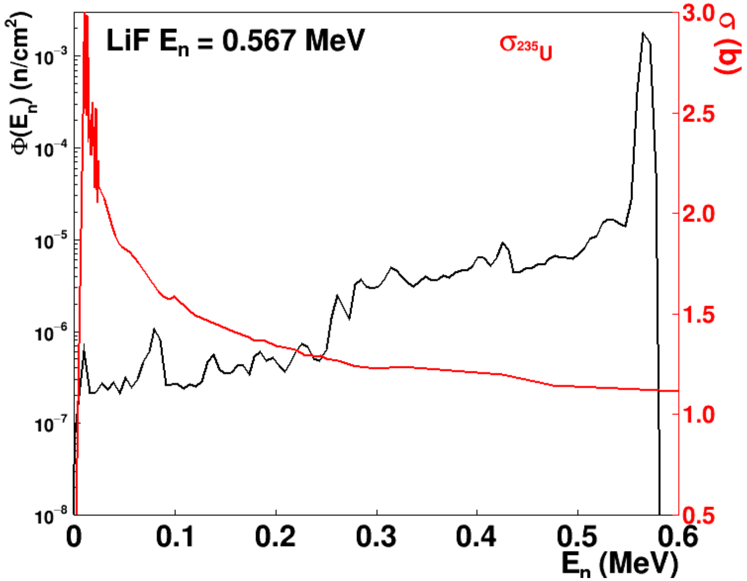
3. Neutron energy spectrum at the sample position

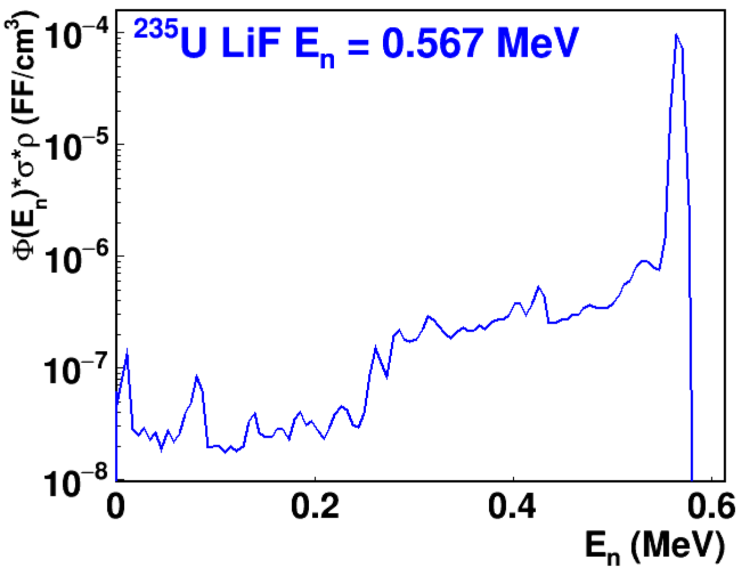


Main Bay geometry thanks to G. Taylor

Data analysis

1. Fission fragment characterization
2. Absolute fluence determination
3. Neutron energy spectrum at the sample position





Calculations (cross sections)

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$$\sigma(E_n) = \frac{C_{\text{corr}} \cdot k_{\text{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\text{PP-DD}} \cdot k_{\text{TS}} \cdot k_{\text{AttFC}}}$$

Calculations (cross sections)

NPL National Physical Laboratory

$$\sigma(E_n) = \frac{C_{\text{corr}} \cdot k_{\text{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\text{PP-DD}} \cdot k_{\text{TS}} \cdot k_{\text{AttFC}}}$$

Corrected counts below electronic threshold (2-5%)

+

Spontaneous fission (^{242}Pu only)

Calculations (cross sections)

NPL National Physical Laboratory

$$\sigma(E_n) = \frac{C_{\mathrm{corr}} \cdot k_{\mathrm{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\mathrm{PP\text{-}DD}} \cdot k_{\mathrm{TS}} \cdot k_{\mathrm{AttFC}}}$$

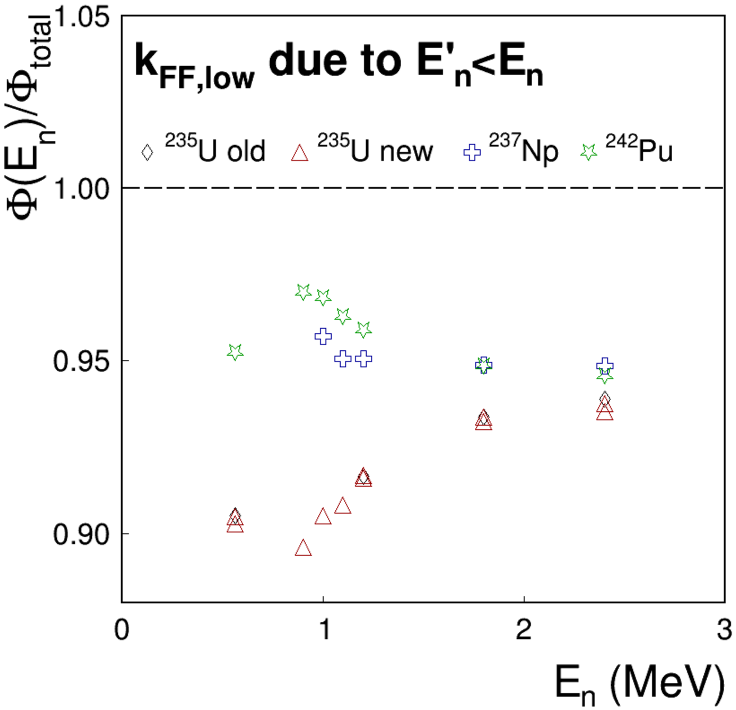
Corrected counts below electronic threshold (2-5%)

\+

Spontaneous fission (^{242}Pu only)

Reaction rate due to $E'_n < E_n$

(4-10%)



Calculations (cross sections)

NPL National Physical Laboratory

$$\sigma(E_n) = \frac{C_{\text{corr}} \cdot k_{\text{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\text{PP-DD}} \cdot k_{\text{TS}} \cdot k_{\text{AttFC}}}$$

Corrected counts below electronic threshold (2-5%)
+
Spontaneous fission (^{242}Pu only)

Point-to-point to disk-to-disk correction (2-4%)

Reaction rate due to $E'_n < E_n$ (4-10%)

Calculations (cross sections)

$$\sigma(E_n) = \frac{C_{\text{corr}} \cdot k_{\text{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\text{PP-DD}} \cdot k_{\text{TS}} \cdot k_{\text{AttFC}}}$$

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Reaction rate due to $E'_n < E_n$ (4-10%)

Target can scatter correction (2-3%)

Calculations (cross sections)

NPL National Physical Laboratory

$$\sigma(E_n) = \frac{C_{\mathrm{corr}} \cdot k_{\mathrm{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\mathrm{PP\text{-}DD}} \cdot k_{\mathrm{TS}} \cdot k_{\mathrm{AttFC}}}$$

Corrected counts below electronic threshold (2-5%)
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Point-to-point to disk-to-disk correction (2-4%)

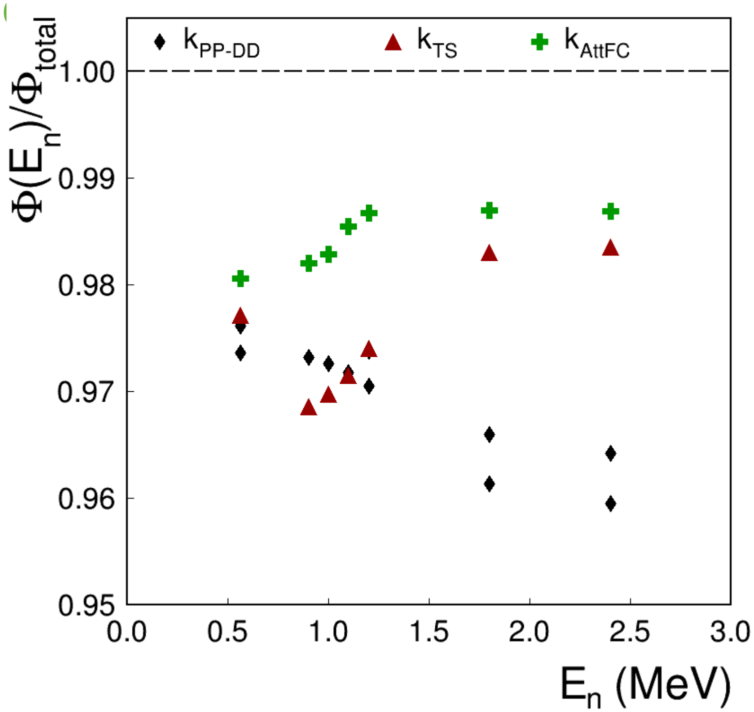
Reaction rate due to $E'_n < E_n$ (4-10%)

Target can scatter correction (2-3%)

Attenuation of neutrons in the front face TFGIC (1.5-2%)

Calculations (cross sections)

$$\sigma(E_n) = \frac{C_{\text{corr}} \cdot k_{\text{FF,low}}}{\epsilon} \frac{A}{m \cdot N_A} \frac{1}{\Phi_n(E_n) \cdot k_{\text{PP-DD}} \cdot k_{\text{TS}} \cdot k_{\text{AttFC}}}$$



hold (2-5%)

ly)

Point-to-point to disk-to-disk correction (2-4%)

$_n < E_n$

Target can scatter correction (2-3%)

ttenuation of neutrons in the front face TFGIC (1.5-2%)

Calculations (spontaneous fission ^{242}Pu)

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$$T_{1/2,SF} = \frac{\%^{242}\mathrm{Pu}}{A_{242}} \frac{1}{\left(\frac{C_{SF}}{t \cdot \ln 2 \cdot m_{242} \cdot N_A} - \sum_{i}^{n} \frac{\%^{i}\mathrm{Pu}}{A_i \cdot T_{1/2,SF}(i)} \right)}$$

	$T_{1/2,SF}$ (y)
Holden (2000) – Literature average	6.77×10^{10} (1.0%)
Chechev (2009) – Literature average	6.79×10^{10} (1.4%)
Salvador-Castiñeira (2013)	6.74×10^{10} (1.3%)
This experiment	6.76×10^{10} (1.3%)

→ Based on 5 measurements > 25000 events/each

Uncertainty evaluation

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E_n (MeV)	u_{total} (%)	u_m (%)	u_C (%)	u_ε (%)	$u_{c<thr}$ (%)	u_{SF} (%)	u_Φ (%)	$u_{FF,low}$ (%)	u_{PP-DD} (%)	u_{TS} (%)	u_{AttFC} (%)
0.565	**3.8-9.1**	0.5-2	1.4-5.9	1	20	1.3	3.2	<1	3.2	27	1-1.4
0.9	**4.0-9.4**	0.5-2	1.8-6.1	1	20	1.3	3.2	0.6-1.6	2.0	30	5.8-6.1
1.0	**4.4-9.2**	0.5-2	1.5-5.7	1	20	1.3	3.9	0.7-2.7	4.6	30	<1
1.1	**4.0-7.3**	0.5-2	1.8-4.4	1	20	1.3	3.3	0-2.3	1.9	31	6.6-7.1
1.2	**4.0-7.1**	0.5-2	1.8-4.2	1	20	1.3	3.3	<0.5	2.2	31	6.4-6.8
1.8	**3.7-5.6**	0.5-2	1.5-2.8	1	20	1.3	3.2	1.2-3	2.5	32	2.2-2.7
2.4	**3.7-5.3**	0.5-2	1.3-2.7	1	20	1.3	3.2	0.3-3.2	0.9	33	1.3-1.8

* Data from 2017, similar values for 2016

Uncertainty evaluation

National Physical Laboratory

E_n (MeV)	u_{total} (%)	u_m (%)	u_C (%)	u_ε (%)	$u_{c<thr}$ (%)	u_{SF} (%)	u_Φ (%)	$u_{FF,low}$ (%)	u_{PP-DD} (%)	u_{TS} (%)	u_{AttFC} (%)
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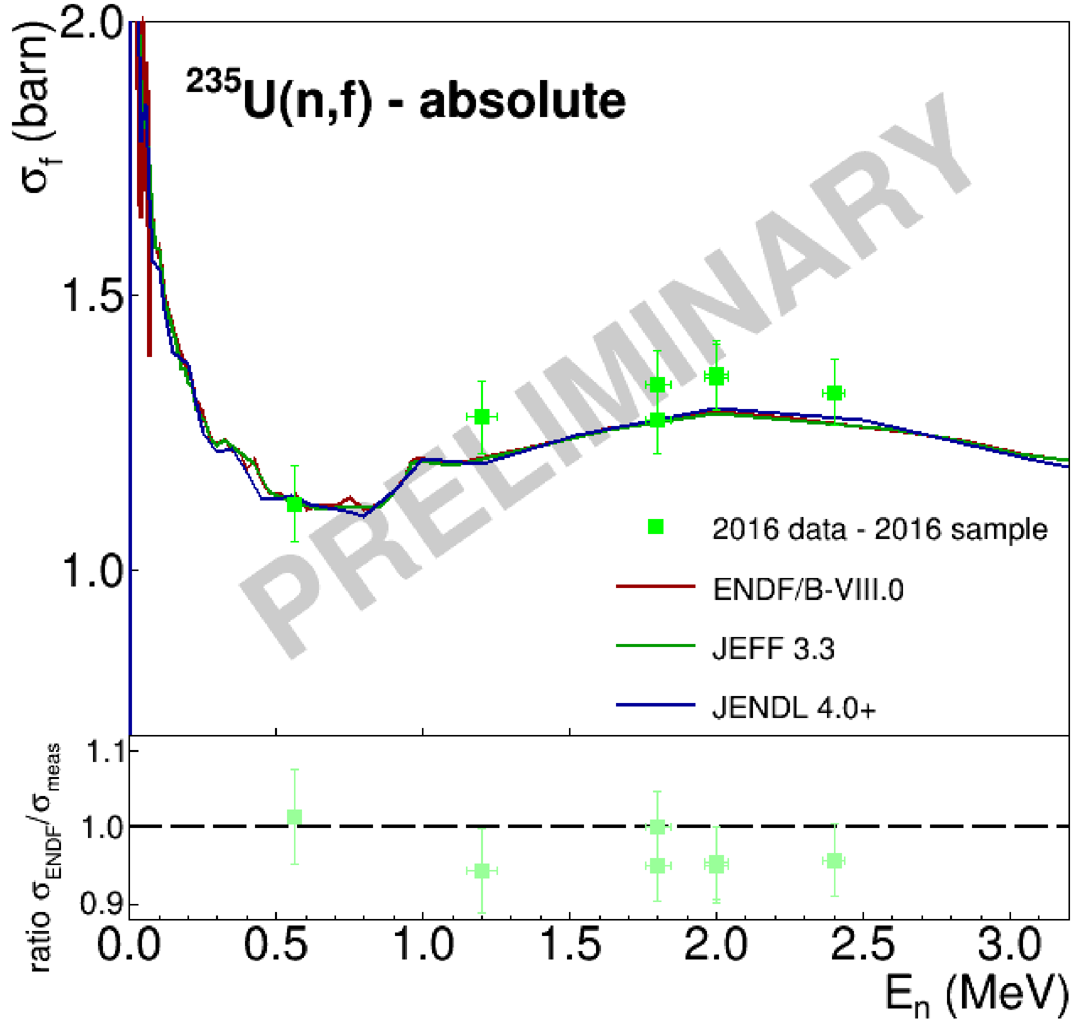
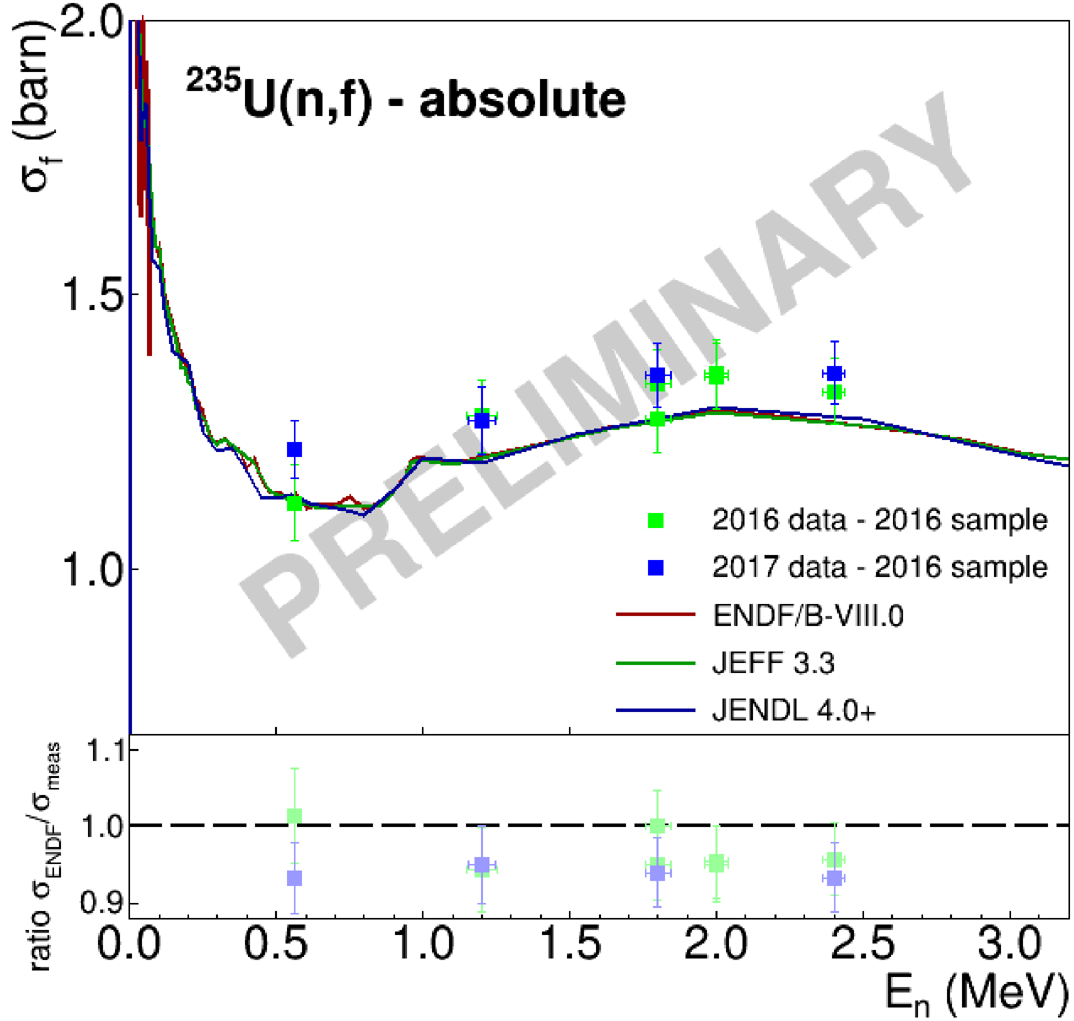
0.9	**4.0-9.4**	0.5-2	1.8-6.1	1	20	1.3	3.2	0.6-1.6	2.0	30	5.8-6.1
1.0	**4.4-9.2**	0.5-2	1.5-5.7	1	20	1.3	3.9	0.7-2.7	4.6	30	<1
1.1	**4.0-7.3**	0.5-2	1.8-4.4	1	20	1.3	3.3	0-2.3	1.9	31	6.6-7.1
1.2	**4.0-7.1**	0.5-2	1.8-4.2	1	20	1.3	3.3	<0.5	2.2	31	6.4-6.8
1.8	**3.7-5.6**	0.5-2	1.5-2.8	1	20	1.3	3.2	1.2-3	2.5	32	2.2-2.7
2.4	**3.7-5.3**	0.5-2	1.3-2.7	1	20	1.3	3.2	0.3-3.2	0.9	33	1.3-1.8

* Data from 2017, similar values for 2016

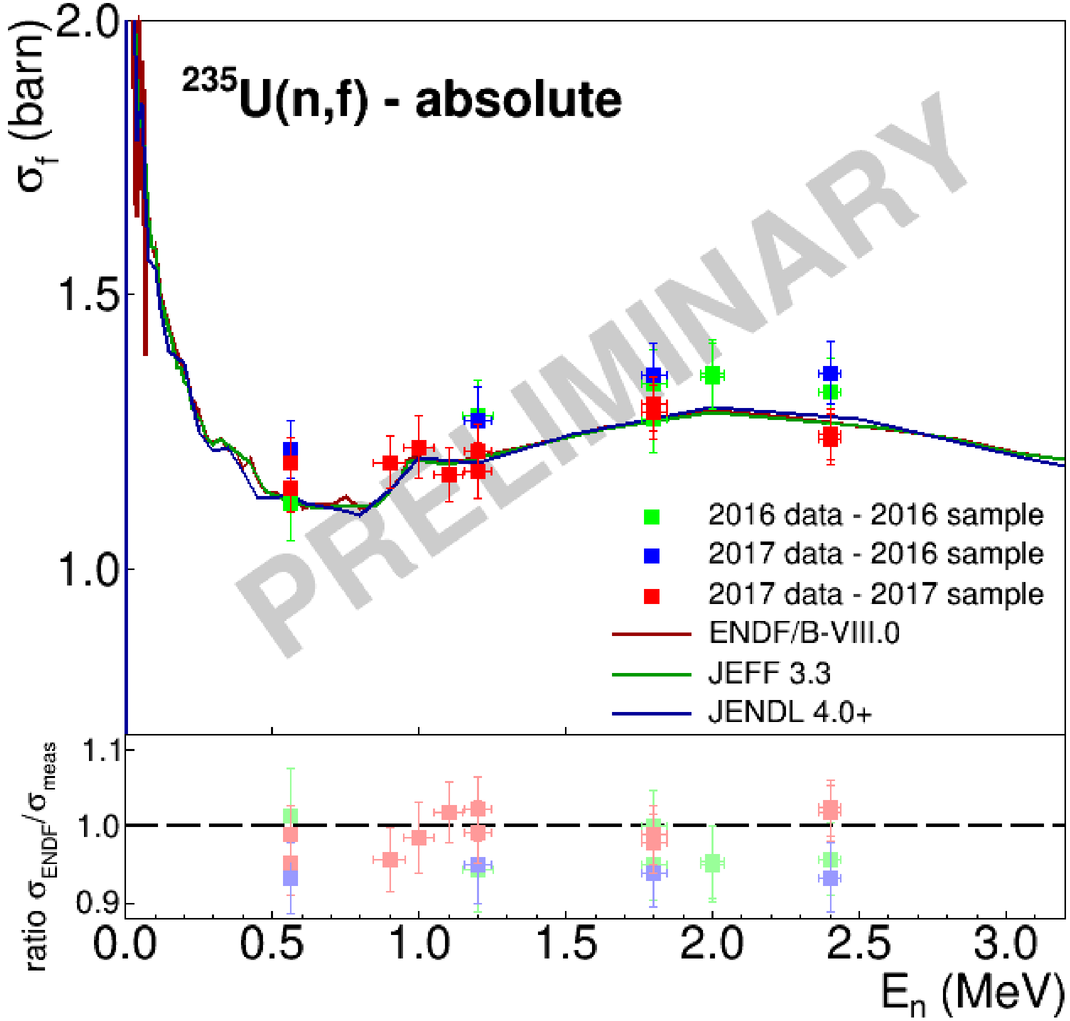
Preliminary ^{235}U results



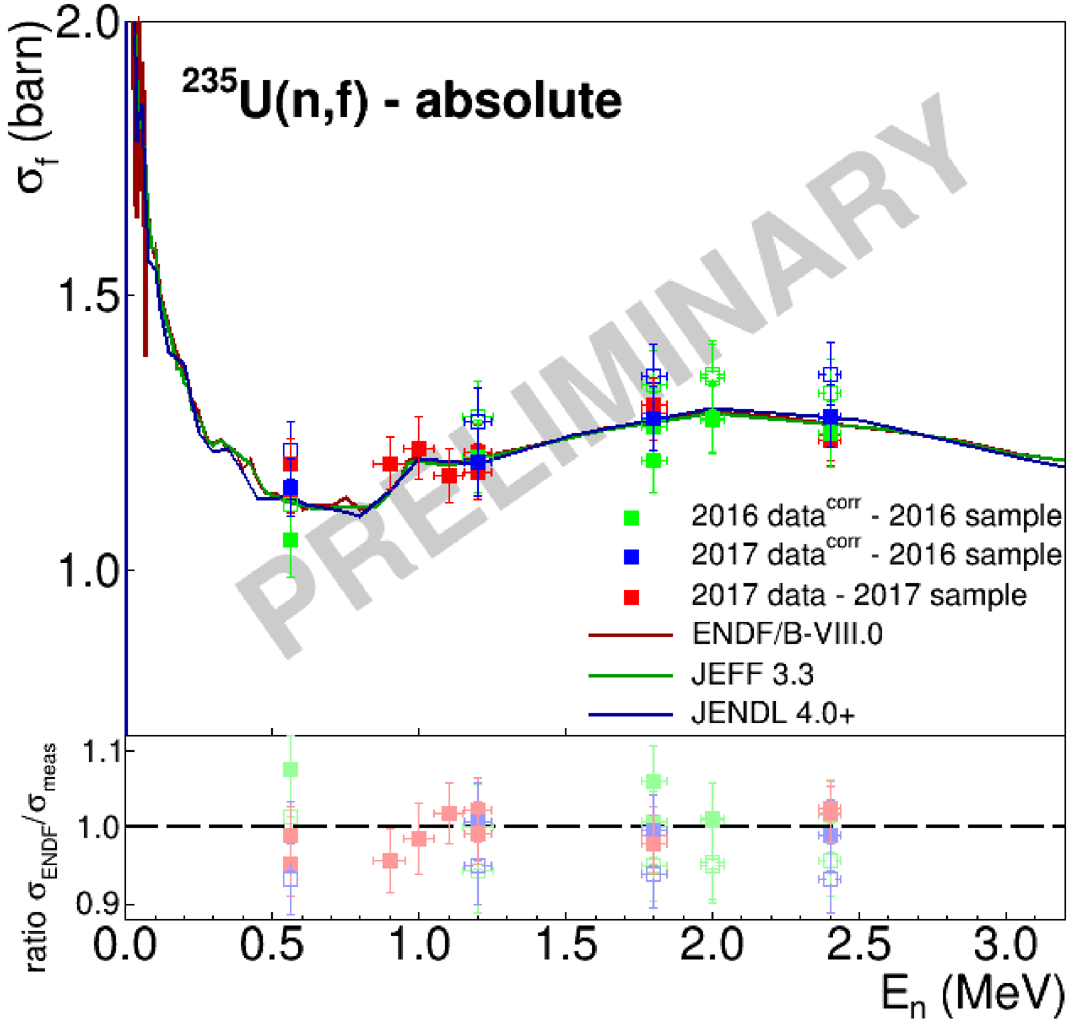
Preliminary ^{235}U results



Preliminary ^{235}U results



Preliminary ^{235}U results



Correction factor from 2017 data using $^{235}U_{new}$ sample:

0.943

Preliminary ^{238}U results

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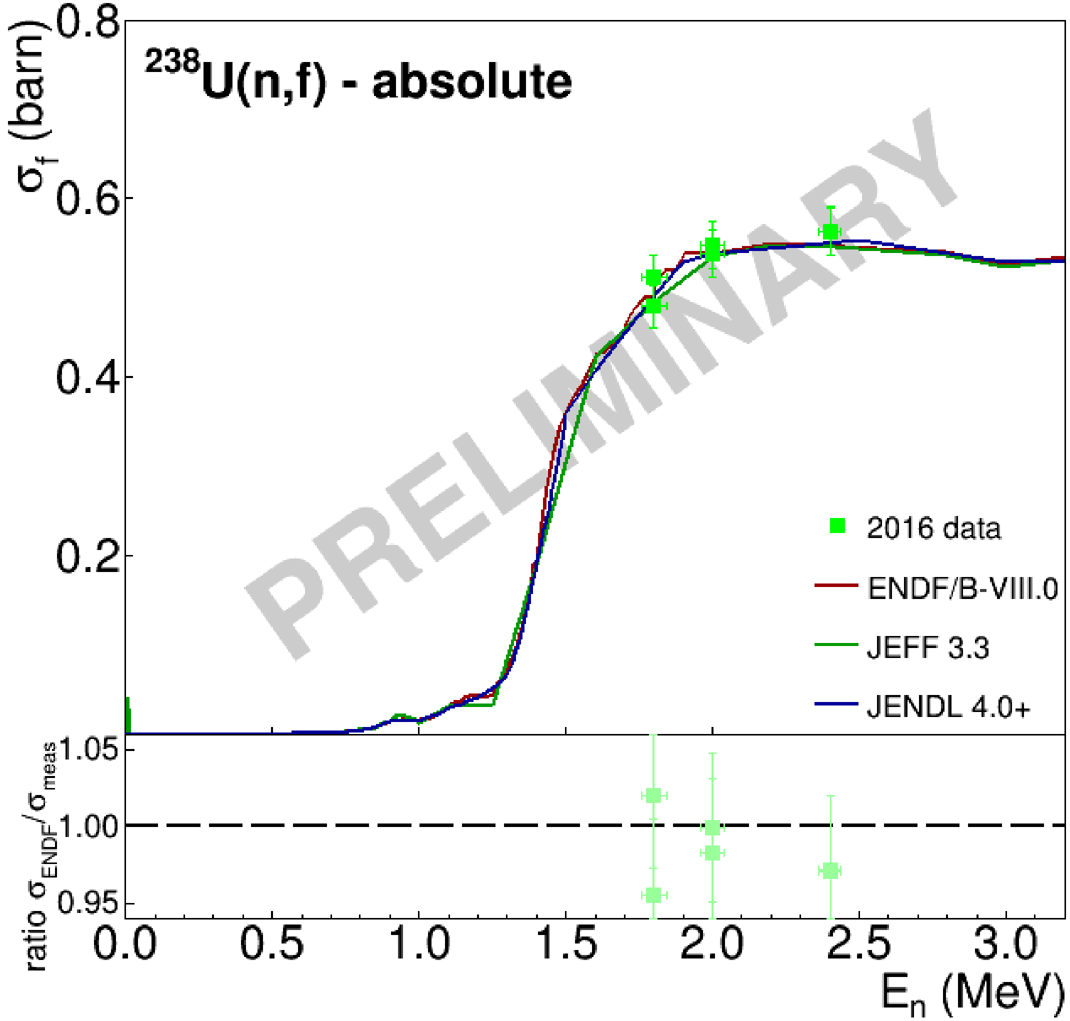
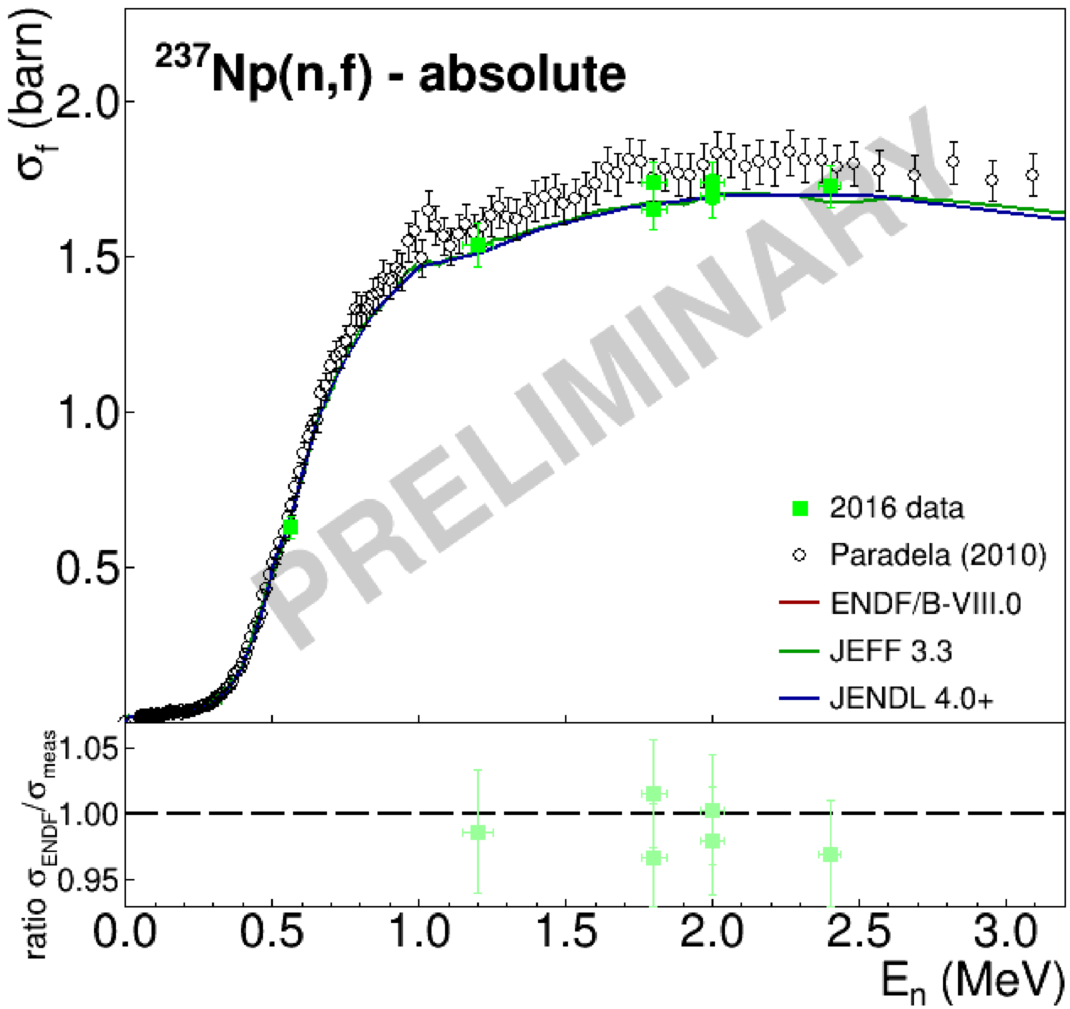
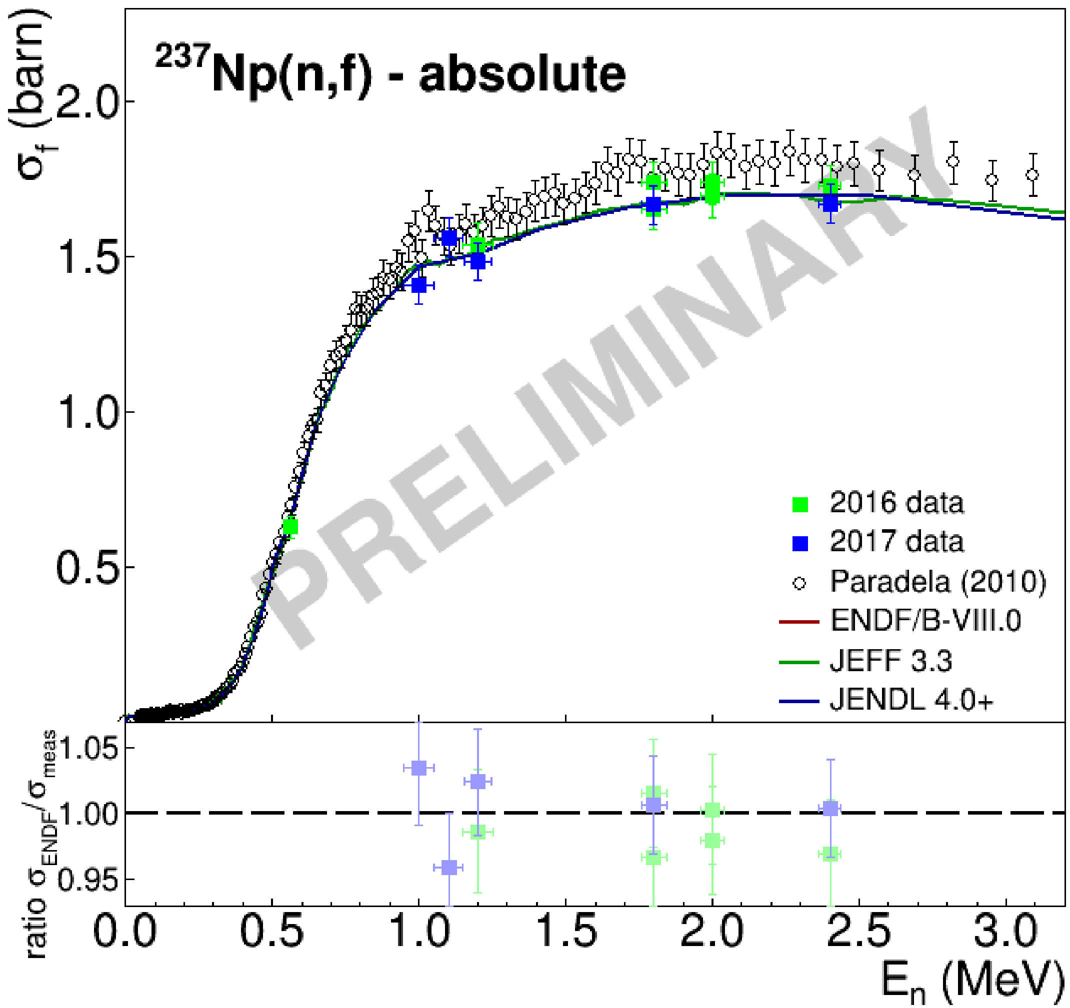


Preliminary ^{237}Np results

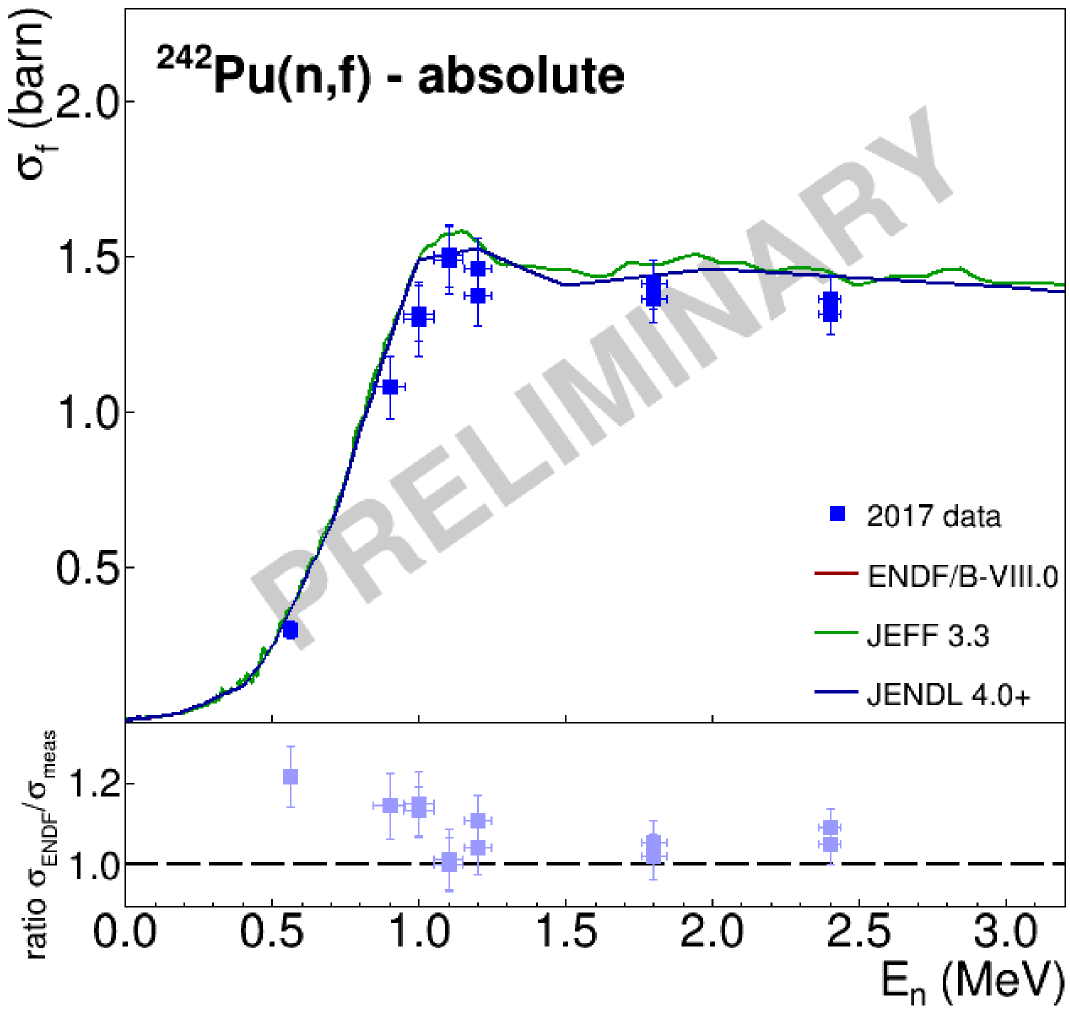


Preliminary ^{237}Np results

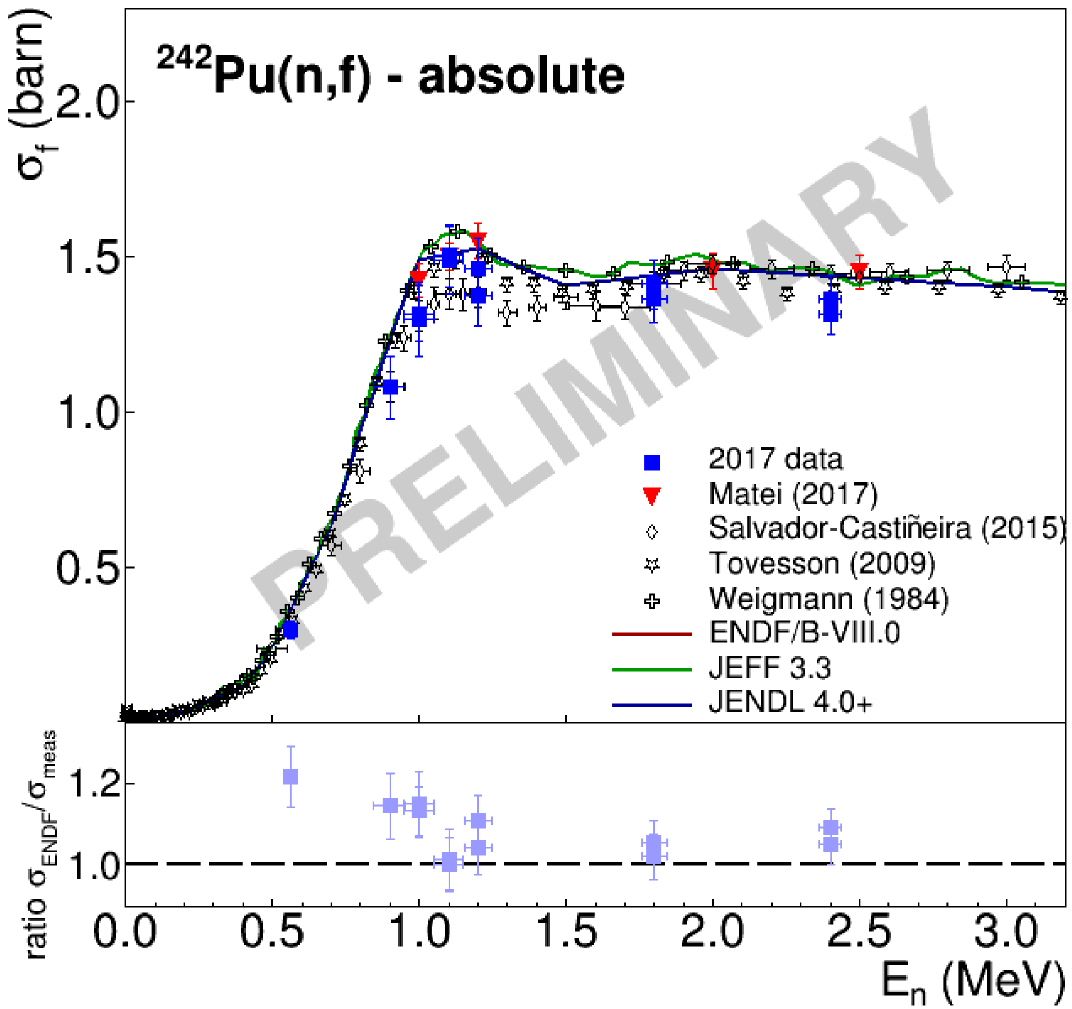
National Physical Laboratory



Preliminary ^{242}Pu results



Preliminary ^{242}Pu results



Other mmts not yet in EXFOR:

- **Tsinganis, nTOF, 2012**
- **Marini, CENBG + CEA, 2013**
- **Kögler, nELBE, 2014**

Preliminary ^{242}Pu results (threshold)

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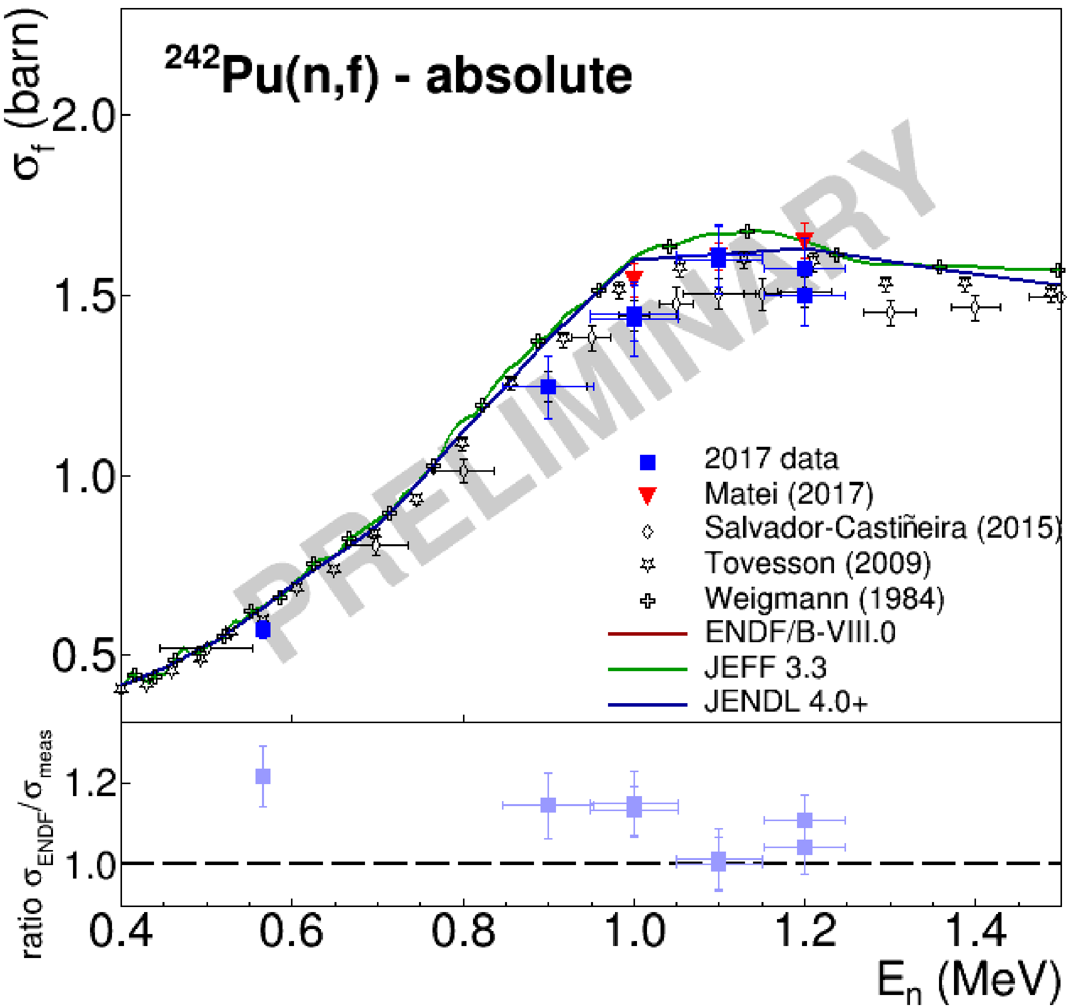

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- **Tsinganis, nTOF, 2012**
- **Marini, CENBG + CEA, 2013**
- **Kögler, nELBE, 2014**

Summary

- Cross sections key element on reactor design → improved accuracies
- VdG environments require new reference cross sections
- Two experiments performed for $^{235,238}U(n,f)$, $^{237}Np(n,f)$ and $^{242}Pu(n,f)$
- Uncertainties driven by counting statistics and distance between neutron producing target and detector

↓

Reaching uncertainties <5% requires new methodologies or increased accelerator output

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Department for Business, Energy & Industrial Strategy

FUNDED BY BEIS

CHANDA SOLVING CHALLENGES IN NUCLEAR DATA FOR THE SAFETY OF EUROPEAN NUCLEAR FACILITIES

SEVENTH FRAMEWORK PROGRAMME

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