Fast neutron inelastic scattering from ^{7}Li & neutron transmission results

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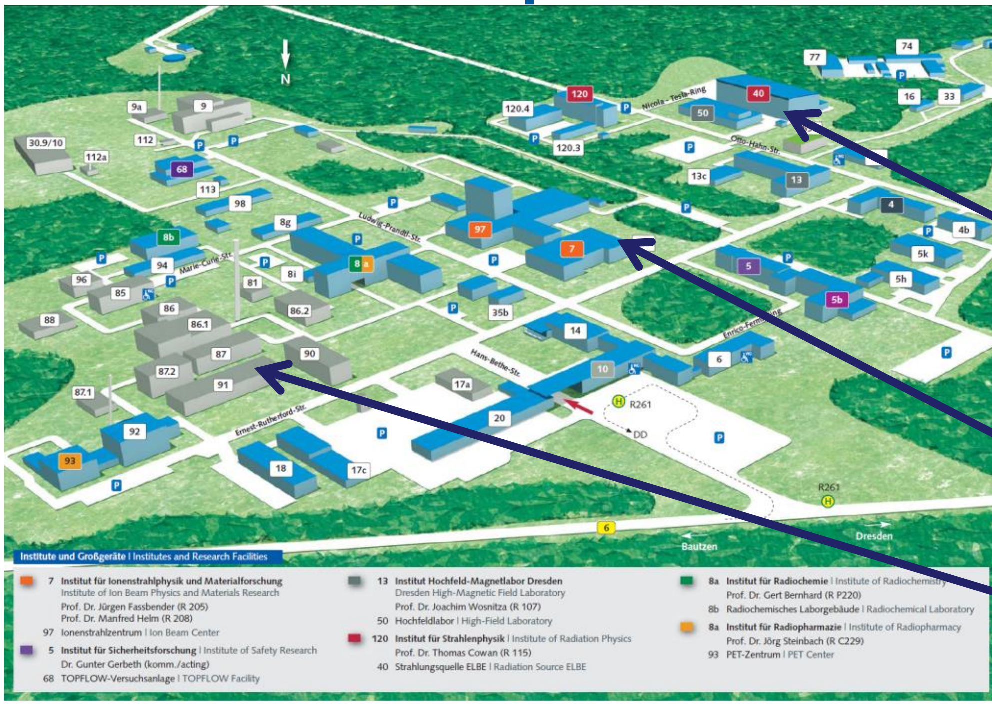
- The nELBE neutron time-of-flight facility at HZDR
- Inelastic neutron scattering on ^{7}Li
- Neutron transmission of Fe, Zr, N, Ar

HZDR Main Campus and Research Facilities



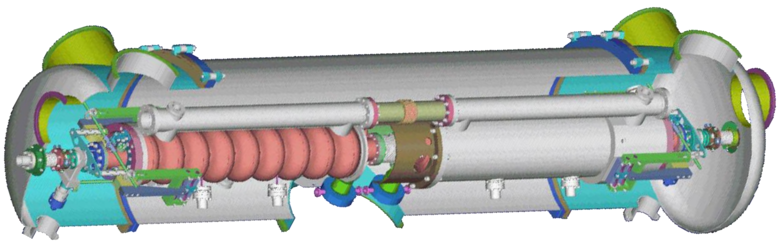
User facilities

- **SC Electron LINAC ELBE**
  40 MeV, 1.6 mA
- **High-Power Lasers**
  150 TW (1 PW)
- High magnetic field lab.
  90+ T
- Ion beam center
  incl. 6 MV Tandetron
- PET center (cyclotrons)
- TOPFLOW
  thermo-hydraulics lab.
- HIBEF beam-line / XFEL

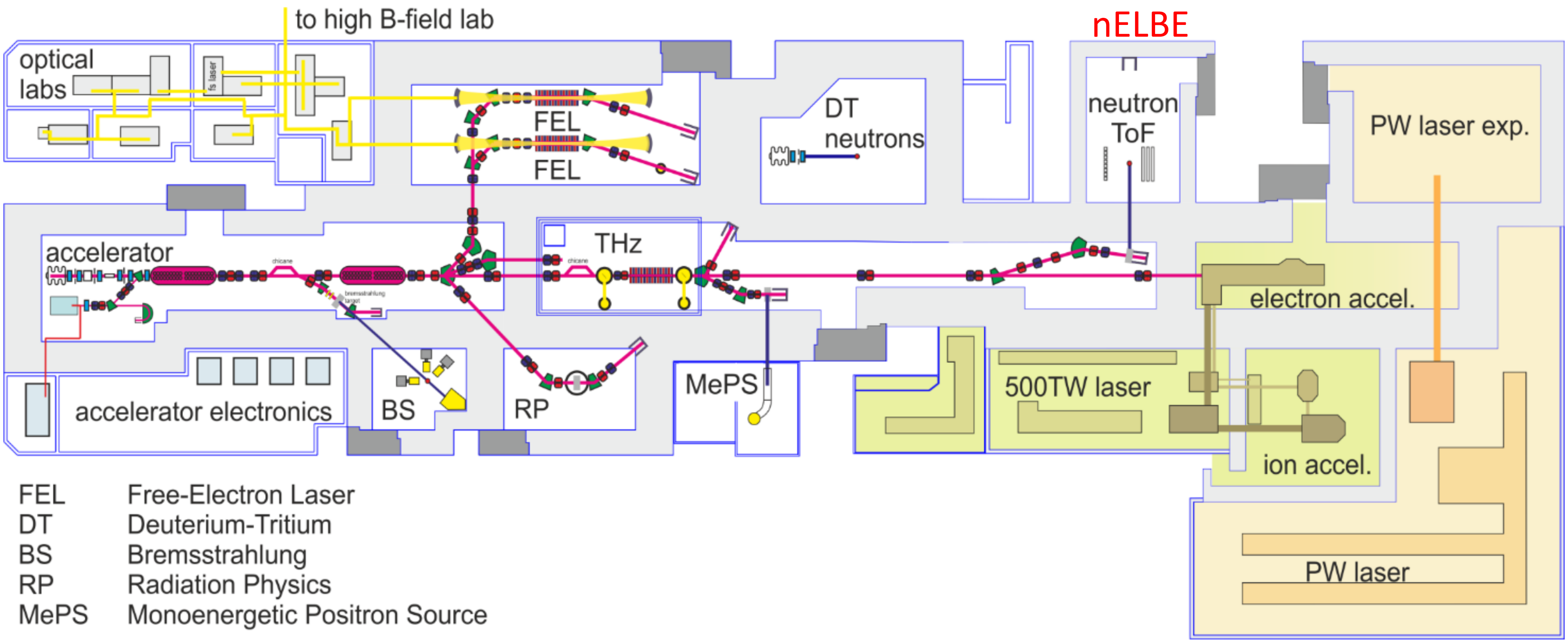
Institutes

- Ion beam physics and materials research
- **Radiation physics**
- High-magnetic fields
- Fluid dynamics
- Resource ecology (incl. nuclear waste management)
- Resource technology (natural resources)
- Radiopharmaceutical cancer research

The Center for High-Power Radiation Sources at HZDR



Superconducting electron accelerator ELBE:
Electron beam as driver for secondary beams:
neutrons, positrons, FEL, THz,
bremsstrahlung, …



FEL	Free-Electron Laser
DT	Deuterium-Tritium
BS	Bremsstrahlung
RP	Radiation Physics
MePS	Monoenergetic Positron Source

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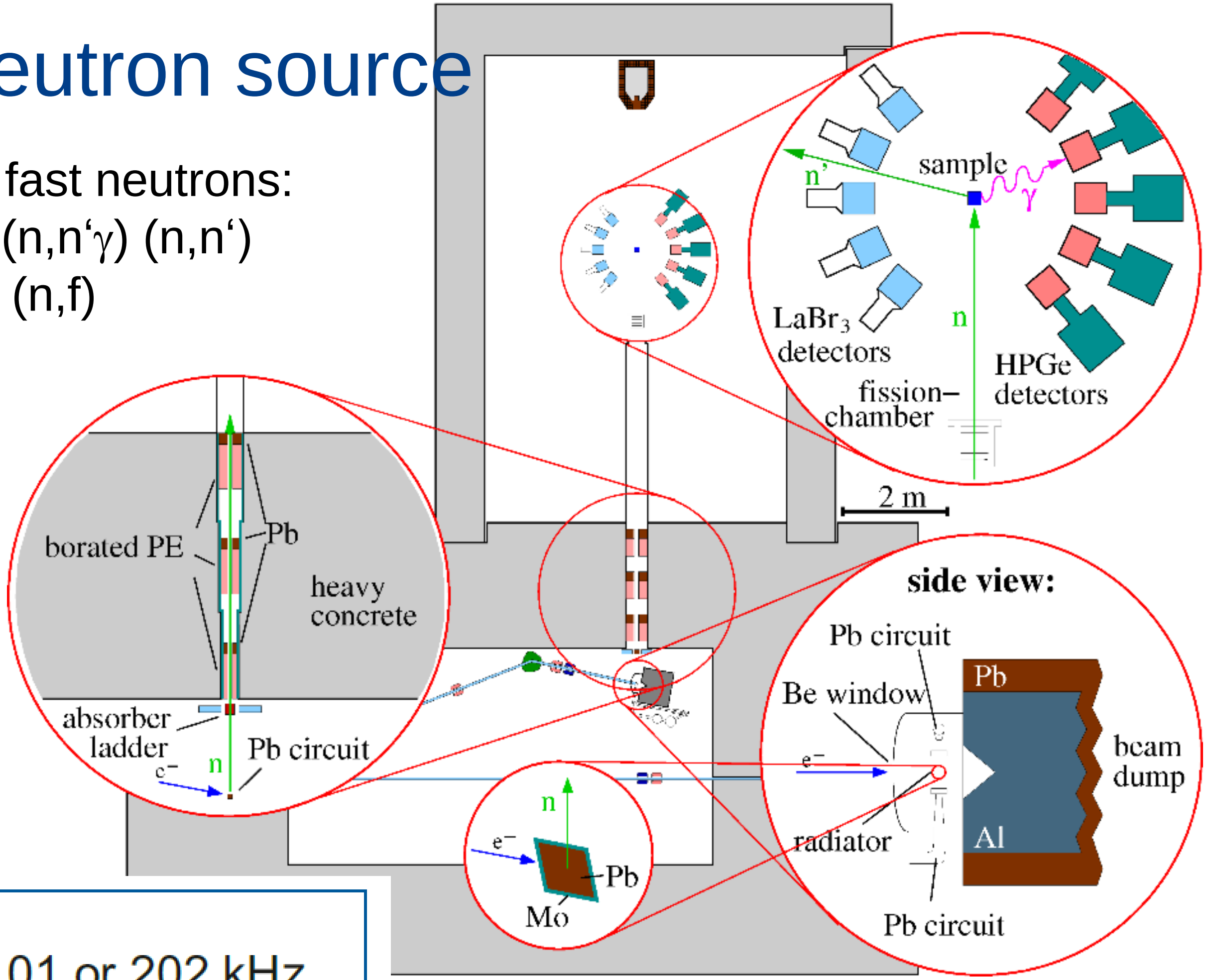
nELBE photo neutron source

Cross section studies with fast neutrons:

- Fast neutron scattering (n,n‘γ) (n,n‘)
- Neutron induced fission (n,f)
- Neutron transmission



Characteristic parameters:

repetition rate:	101 or 202 kHz
flight path:	5 - 11 m
source strength:	ca. $1.6 \cdot 10^{11}$ n/s
intensity @ target:	ca. $2.5 \cdot 10^{4}$ n/cm^{2}s
energy range:	10 keV - 10 MeV
energy resolution:	< 1 %

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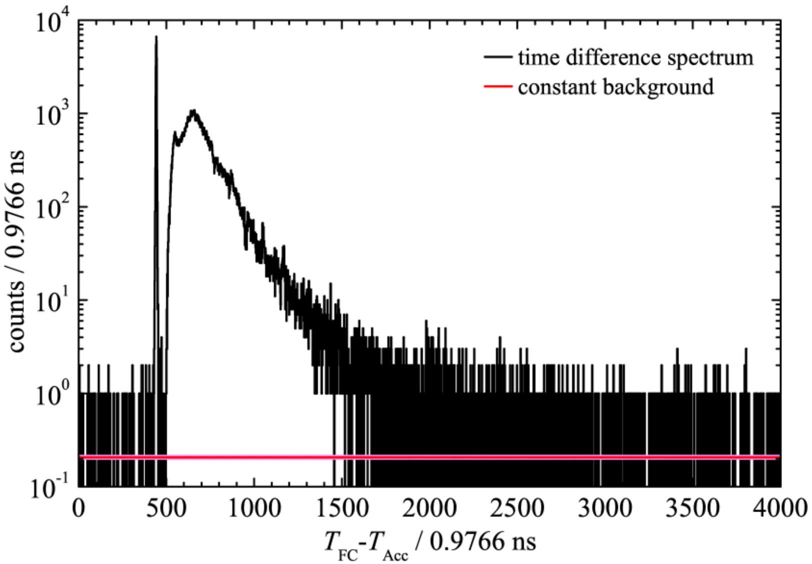
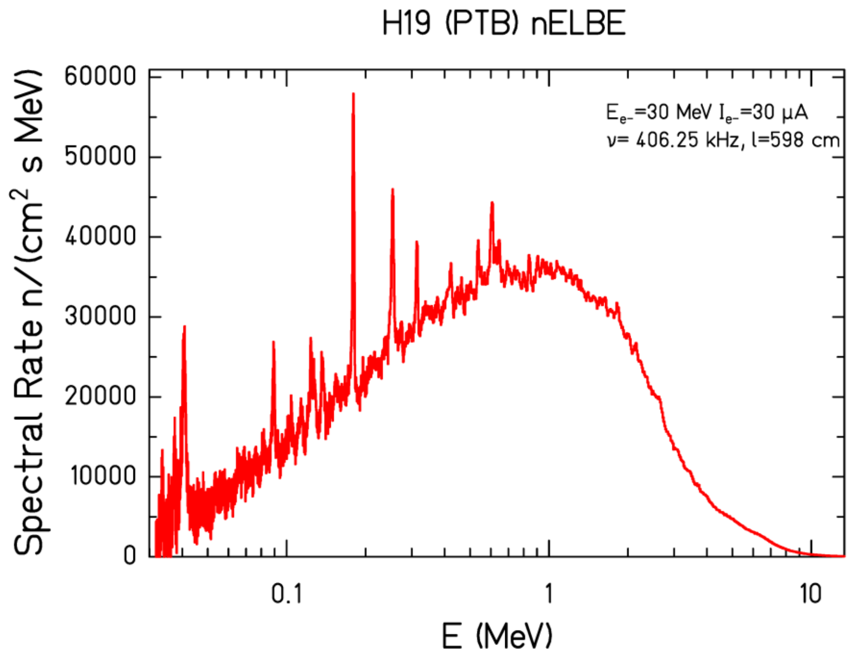
nELBE neutron spectrum

^{235}U fission chamber

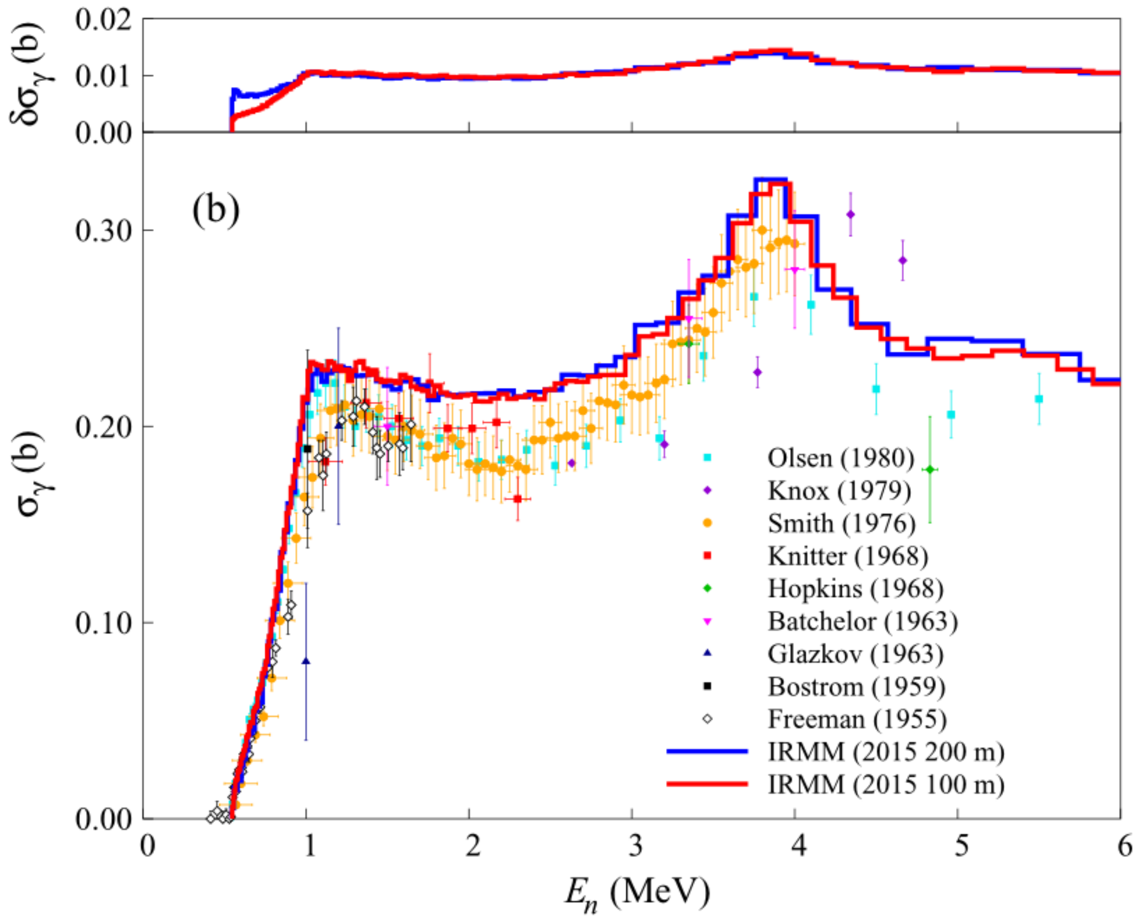




Photoneutron spectrum (measured with the PTB ^{235}U fission chamber H19)
TOF spectrum: Photofission from bremsstrahlung and neutron induced fission
Photoneutron spectrum similar to the fission neutron spectrum
Neutron time of flight range 100 ns – 2,5 µs
Neutron energy range from 100 keV – 7 MeV
Neutron spectral rate on target ca. $2*10^4$ n/(cm^2 s MeV)

Measurement time: 81 h, I_{e-} = 30 µA, E_{e-} = 30 MeV
Flight path 598 cm, no γ-ray absorber in the beam
Emission peaks: 40,89,179, 254, 314, 605 keV from near threshold photoneutron emission in ^{208}Pb (strong capture resonances of ^{207}Pb)
R. Beyer et al., NIM A723 (2013) 151

$^7Li(n,n'\gamma)$ inelastic scattering cross section



Two measurements with GAINS significantly higher and more precise than bulk of the experimental data

➔ Use the same LiF targets with nELBE

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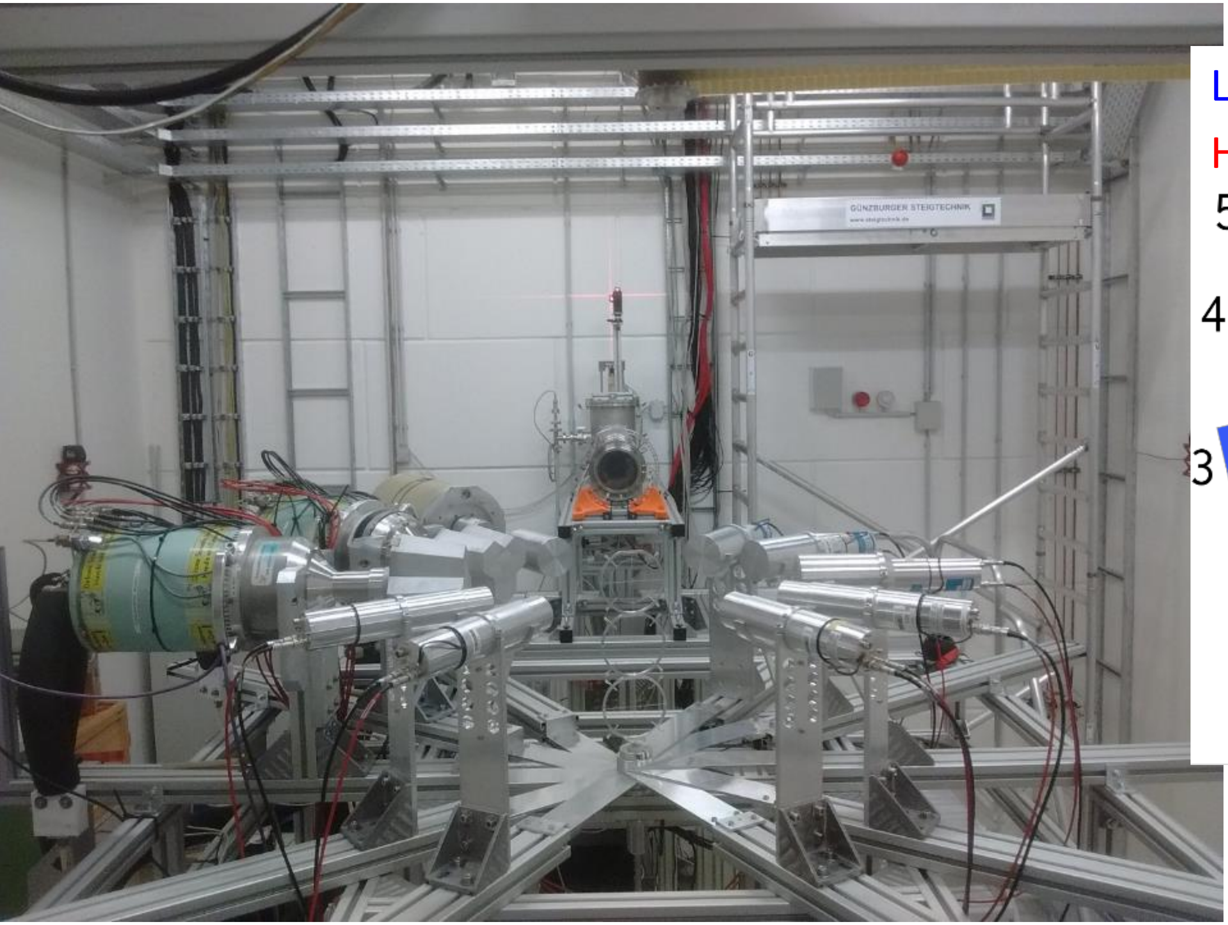
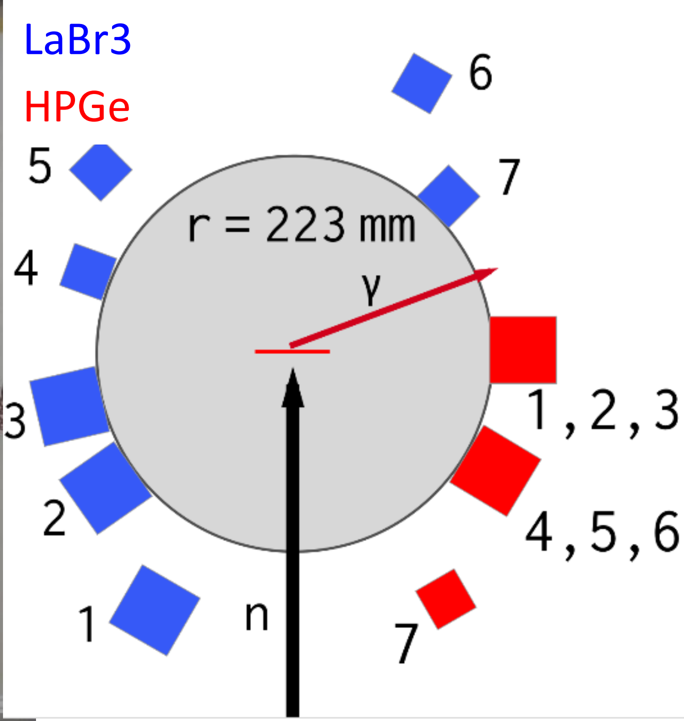
Experimental Setup for ^{7}Li(n,n'γ) Nov. 2016





HPGe, $LaBr_3$ gamma-ray detectors
H19 (PTB) ^{235}U fission chamber for neutron fluence
Gamma-ray detectors under different laboratory angles
→ 478 keV γ-ray emission from moving recoils
Master thesis: Axel Frotscher IKTP TU Dresden, 2017

flight path to target: 830 cm
flight path to H19: 598 cm

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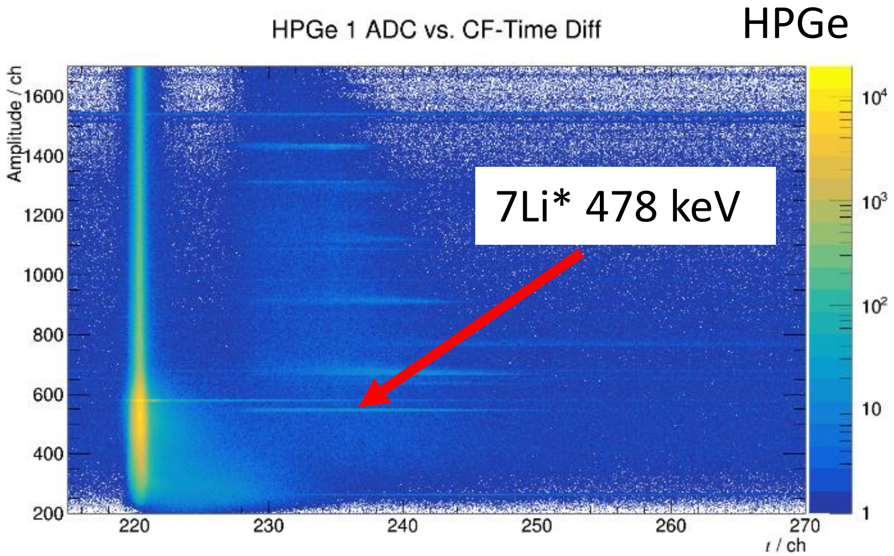
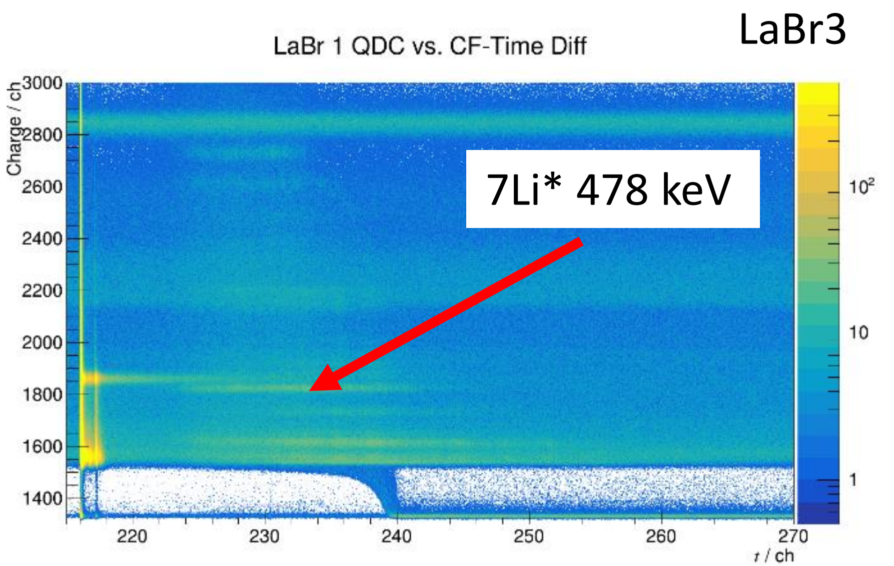
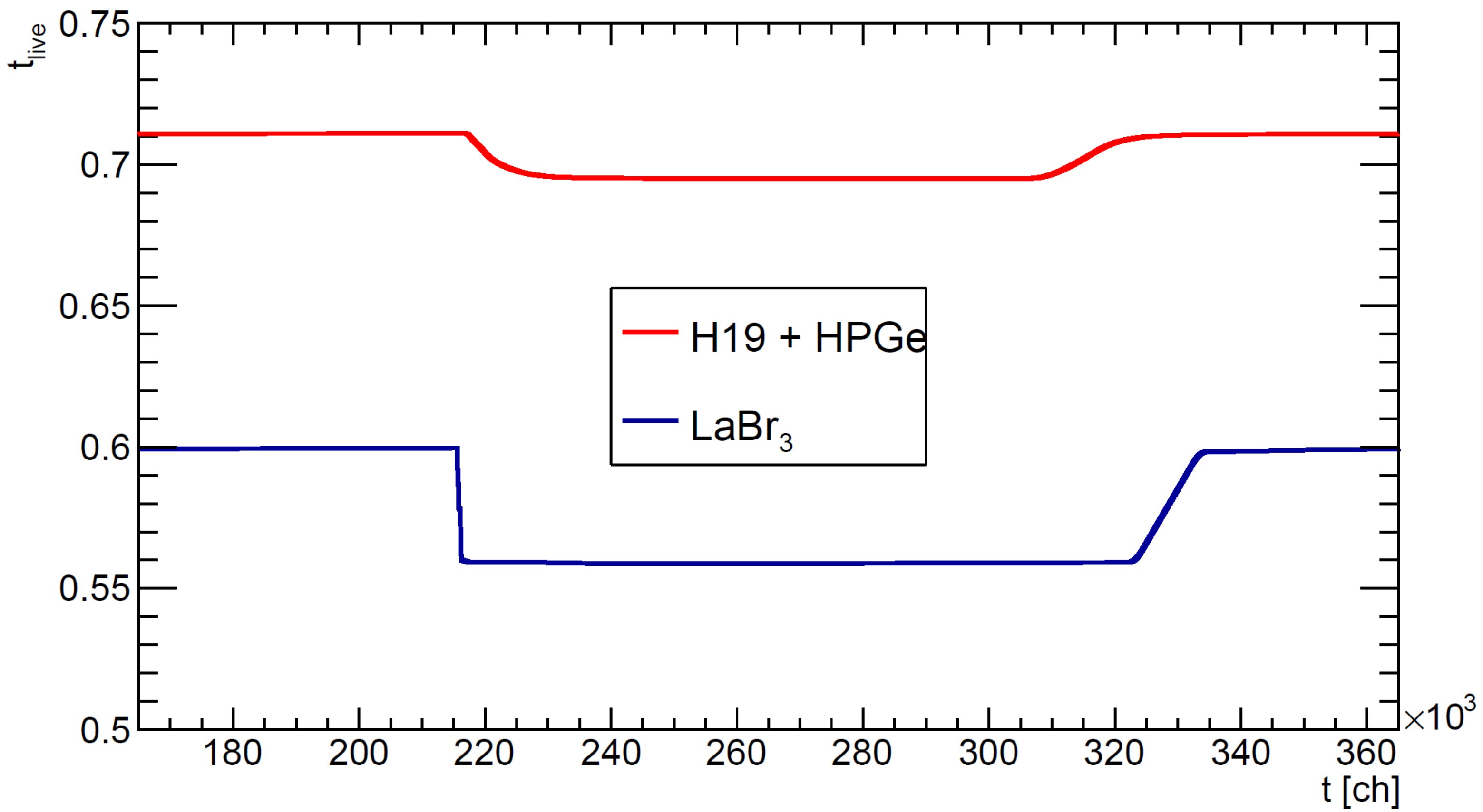
Energy vs. Time-of-Flight





Bremsstrahlung peak ➔ $\frac{\Delta t}{t} = 1\ \mathrm{ns}\ (\mathrm{FWHM})$

Dead time correction



Pulsed source: Dead time correction is time of flight dependent
Measure: dead time for each event, determine the tof channels that are
Blocked for each accelerator period of the experiment

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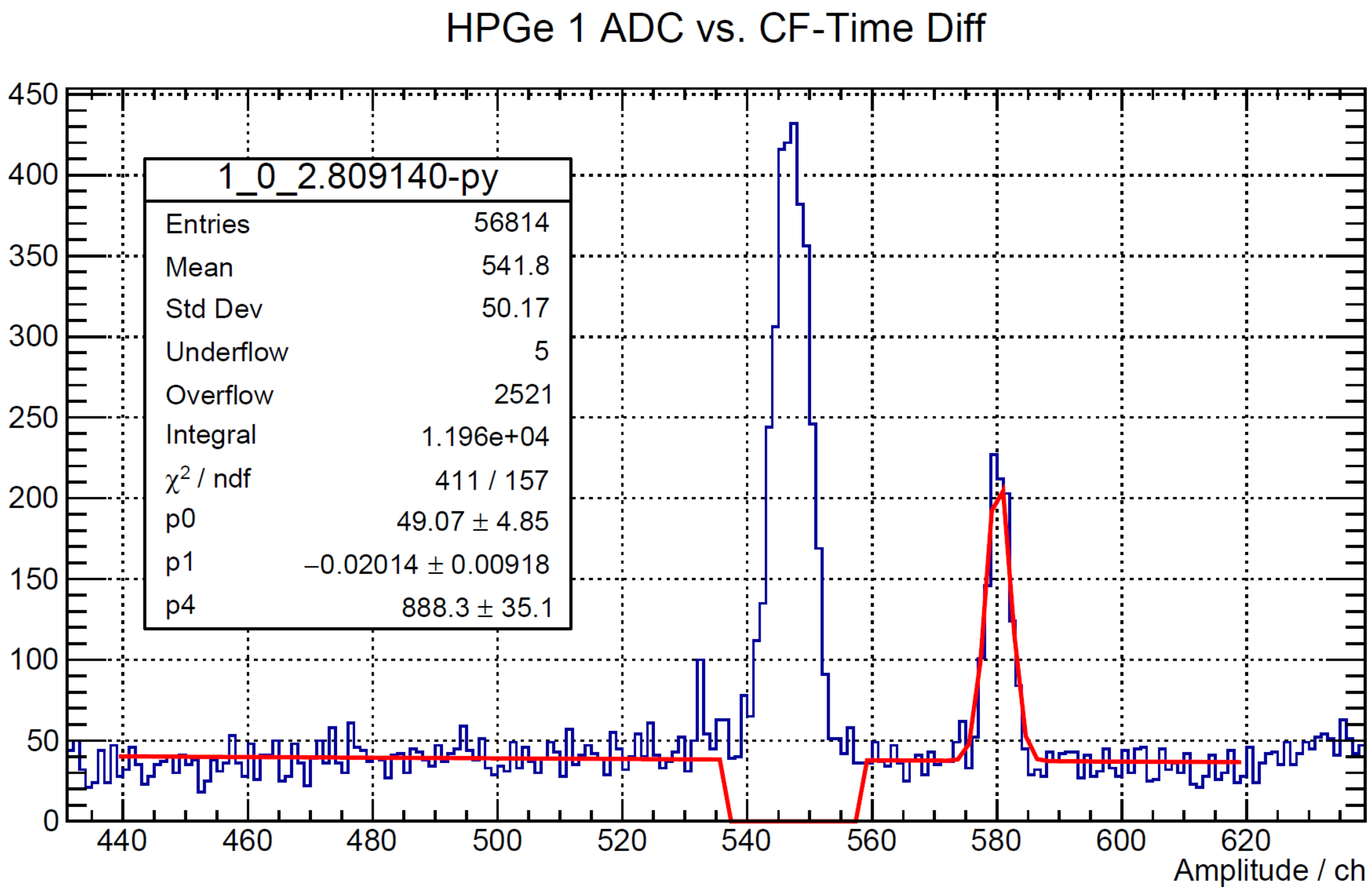
HPGe Count rate determination



Background fit and subtraction of background

No fit of the gamma-ray peak just summing of counts

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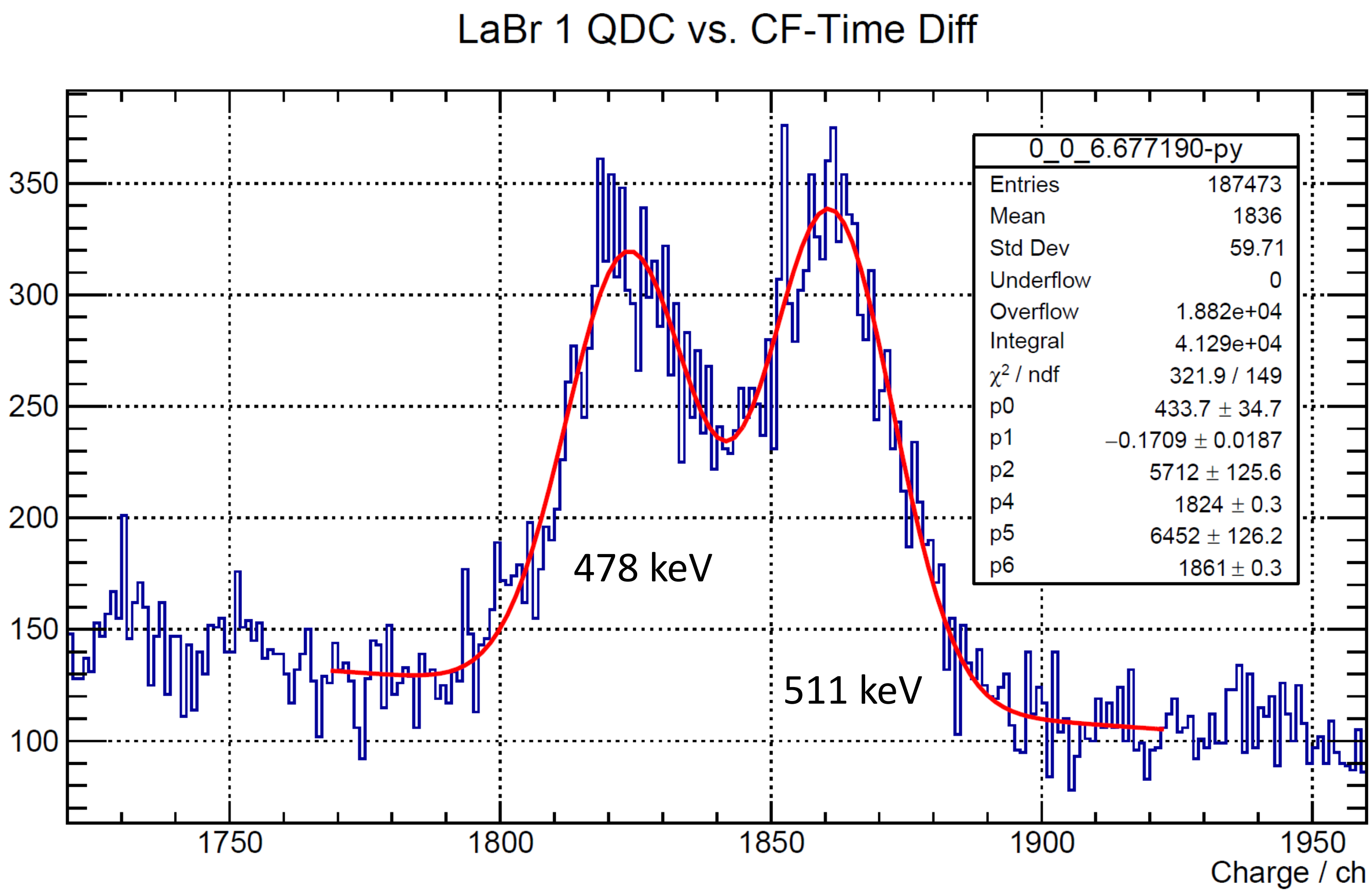
LaBr3 count rate determination



511 keV peak was fitted at short times after the gamma-flash before neutrons arrive And its exponentially decaying intensity used as a parameter in the range where 478 keV (signal) and 511 keV (background) occur.

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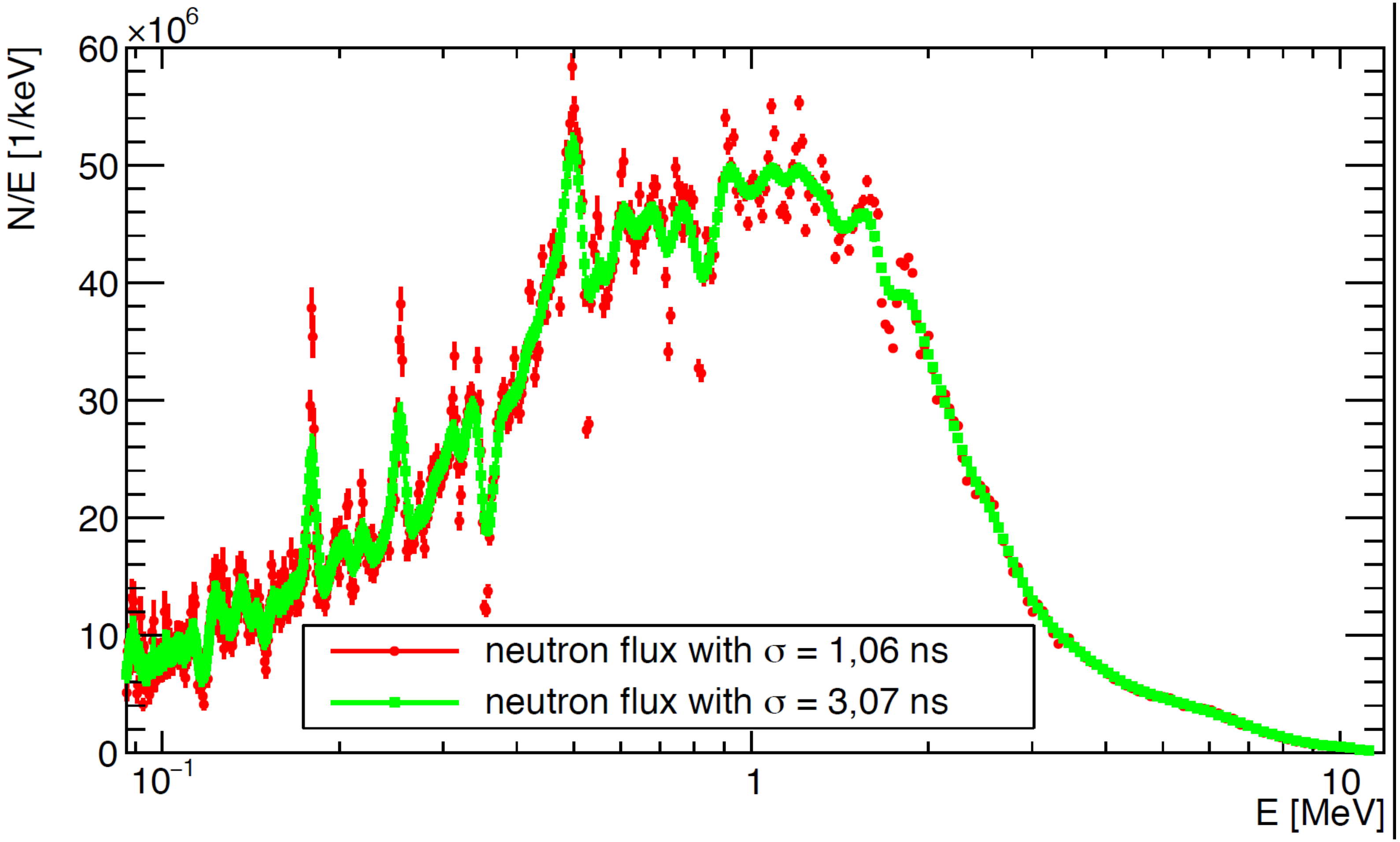
Neutron fluence from H19



Time resolution of H19 matched to HPGe time resolution.
Time resolution of $LaBr_3$ matched to fission chamber H19.

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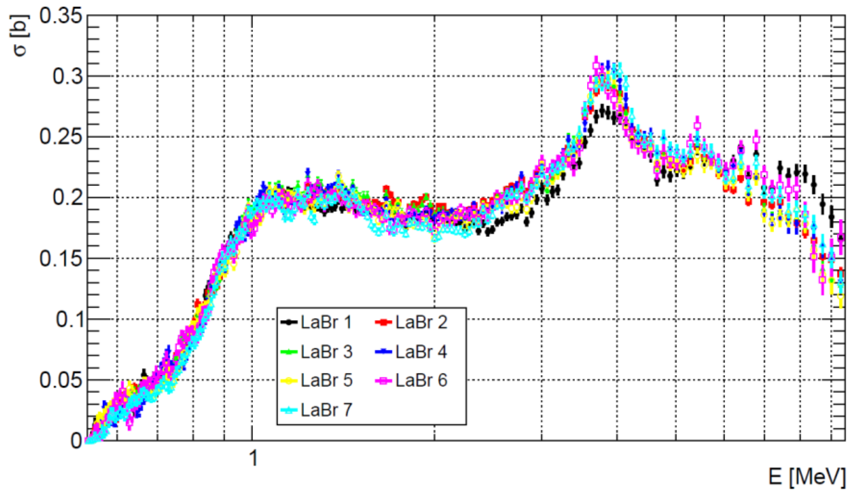
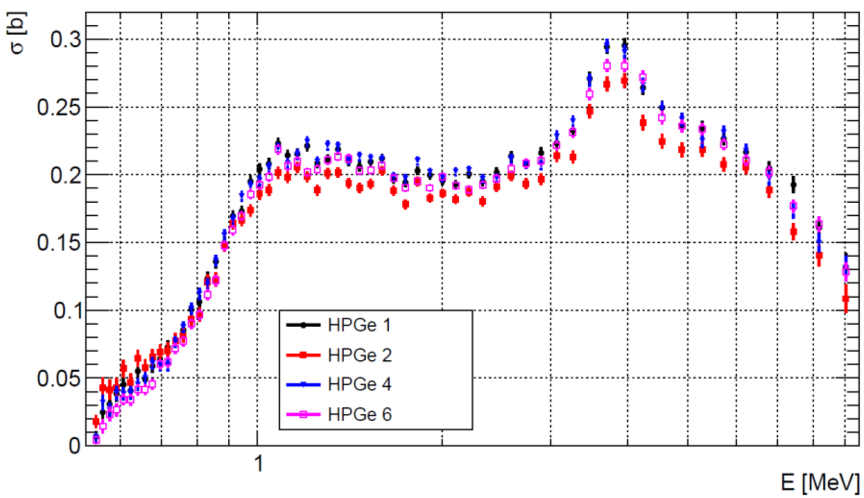
Gamma-ray production cross sections from $LaBr_3$ and HPGe detectors





RMS fluctuations 3 % in the range From 1 – 3 MeV (statistical uncertainty of each data point 2 %)

RMS fluctuations 3.4 % in the range From 1 – 3 MeV (statistical uncertainty of each data point 2 %)

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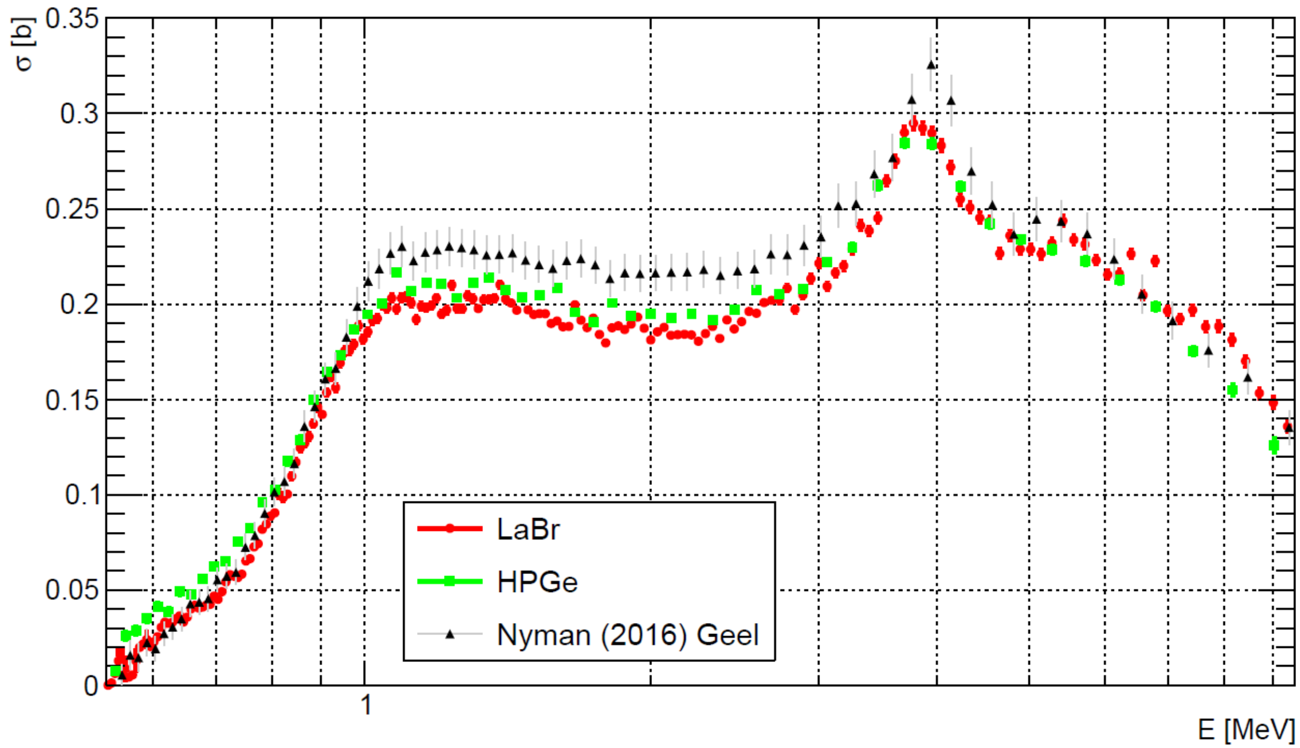
Preliminary results



Systematic uncertainties (not shown on the nELBE data) due to photopeak efficiencies,(calibration sources, coincident summing), neutron fluence, target thickness ca. 5 %

Data in the plateau region of the spectrum about 10-15 % lower

Master thesis: Axel Frotscher IKTP TU Dresden, 2017

R. Beyer et al. EPJ Web of Conferences 239, 01029 (2020)

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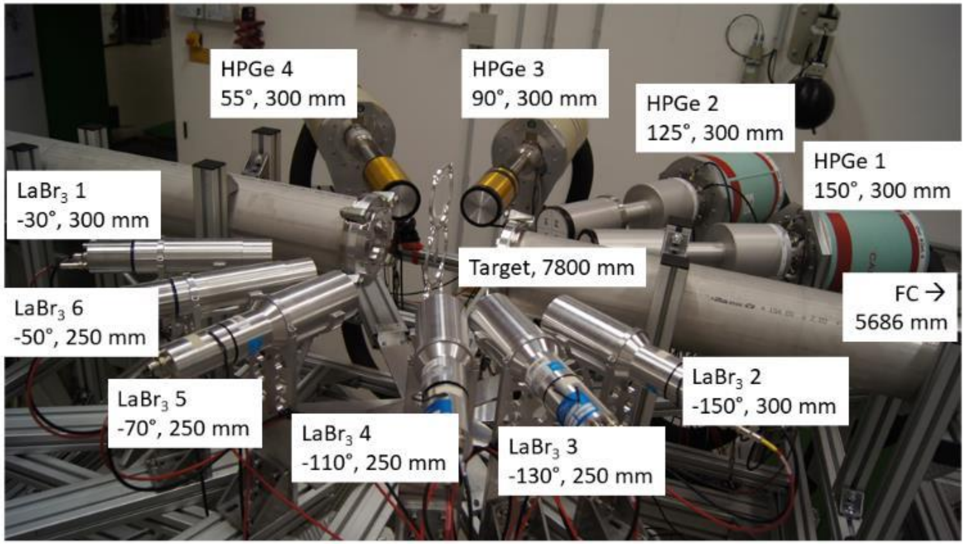
New Measurement May 2018



Extended beam tube to reduce positron annihilation in air.

Use of 100 % HPGe detectors with better Timing Filter Amplifiers

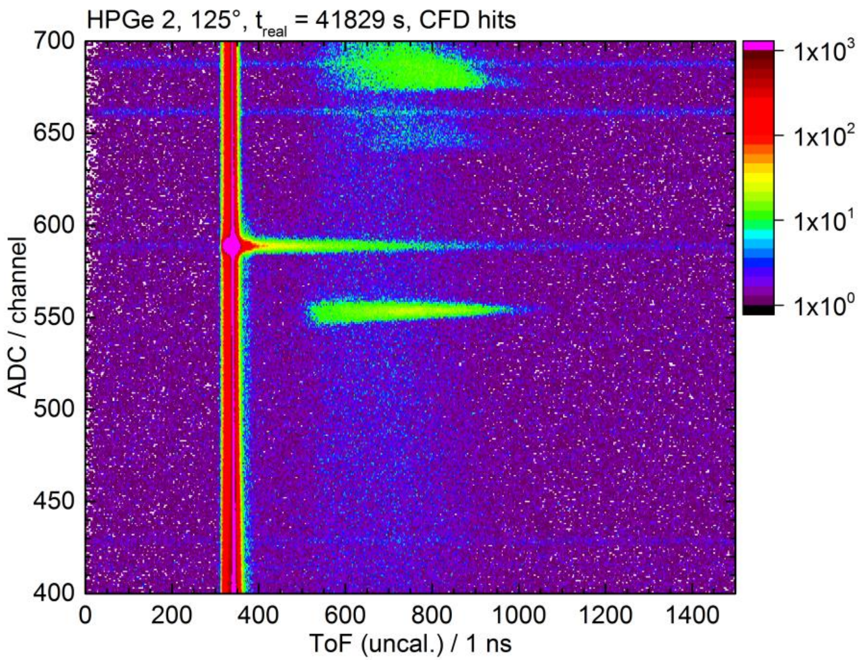
^{7}Be source for precise efficiency calibration

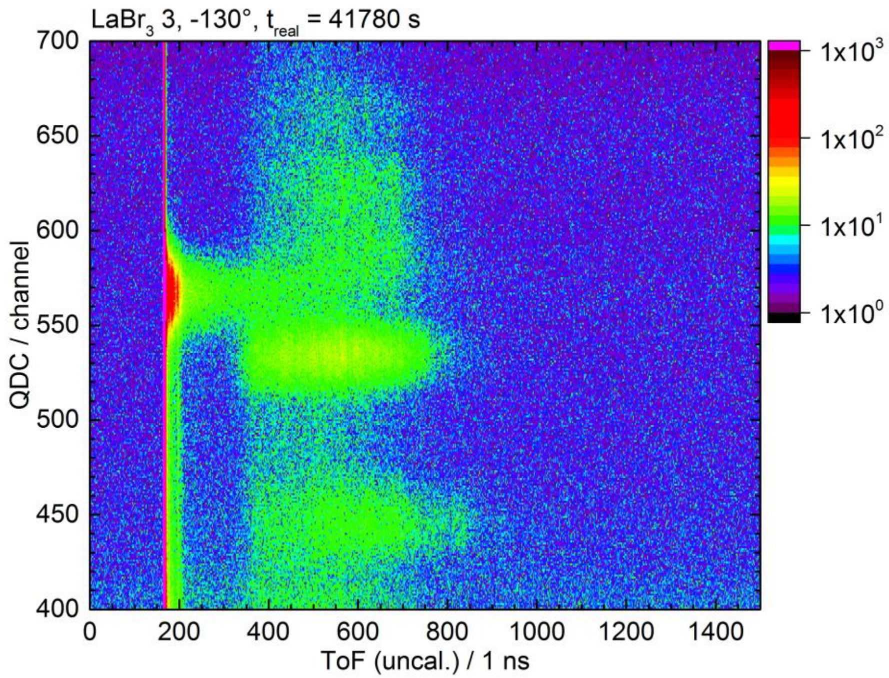
H19 fission chamber for neutron fluence

^{7}Be source for calibration
(G. Gyurki. Debrecen)

3 GBq ^{7}Be source
From proton irradiation of a LiF disk

$LaBr_3$ and HPGe spectra from $^7Li(n,n'\gamma)$





Delayed positron emission still visible
^{7}Be source calibration worked
Data analysis still to be completed

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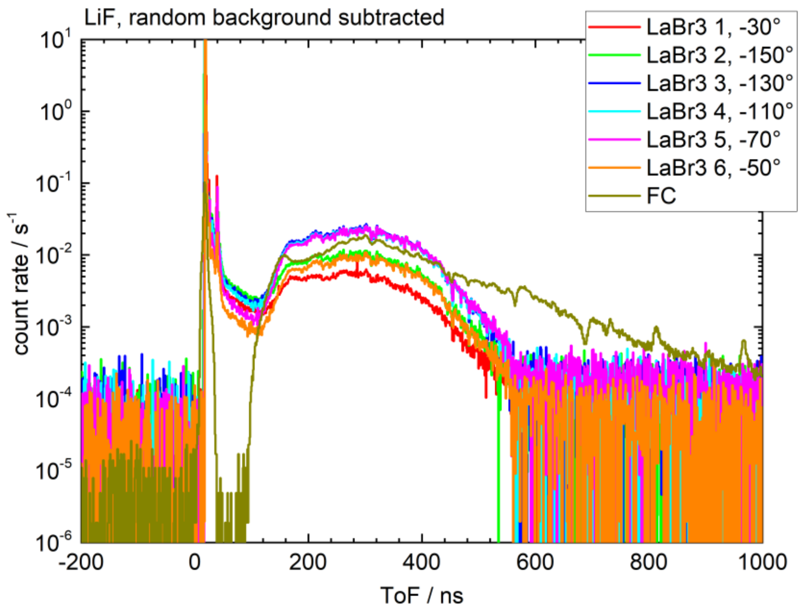
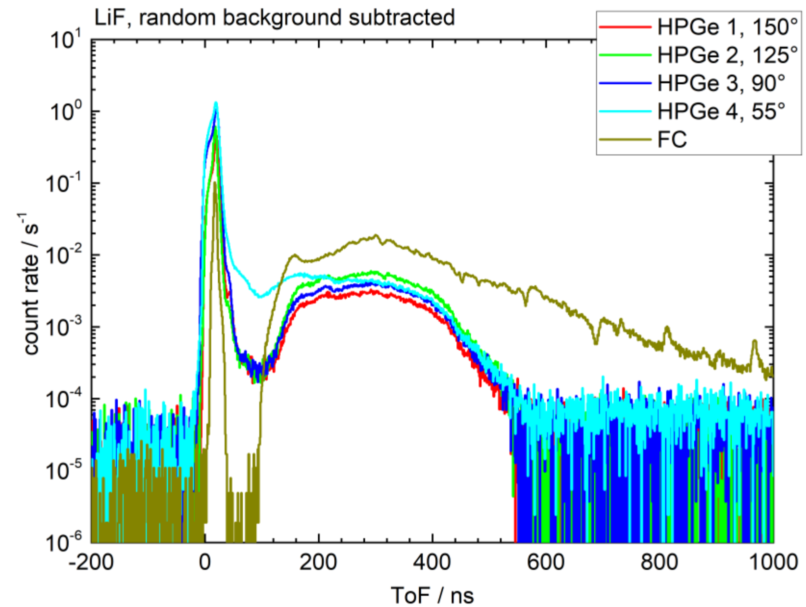
LaBr3 and HPGe spectra of the 478 keV γ-ray





LaBr scintillators (3“ size) No. 3,4,5 agree very well.
Same solid angle, same efficiency

HPGe spectra do not agree well,
Efficiency correction needs to be applied

LaBr No. 1,6 (2“ size) differ because
No. 1,2 are shadowed by a flange.

WIP: Neutron fluence determination, Efficiency correction …

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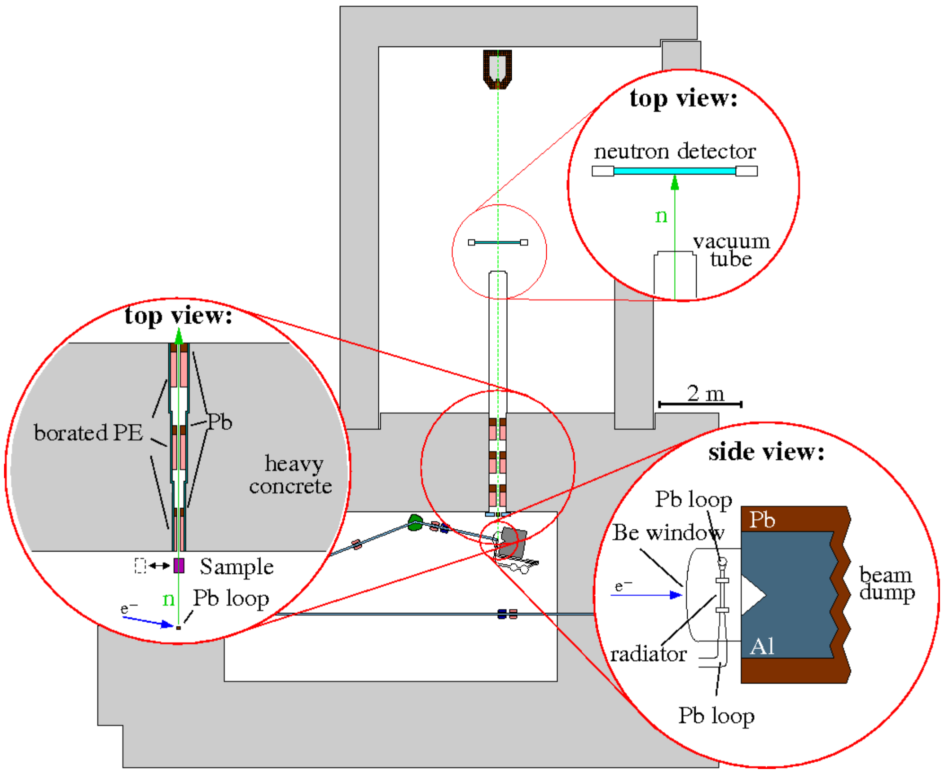
^{nat}Fe thick target transmission measurements



- reduced electron beam intensity
  40 MeV, ≈1.3 µA 100 kHz c.w., 5 ps width
- target samples (Ø 25 mm):
  - Mounted on translation stage in front of collimator entrance
  - Pb absorber for bremsstrahlung (l = 5 cm)
  - counting cycles 300 / 720 / 1380 / 2400 s
  - Flight paths 8678.5(30) mm
  - neutron time-of-flight detector: plastic scintillator ca. 10 keV thres.
  - diamond detector for neutron intensity monitoring

Earlier results Pt,^{238}U, ^{4}He, Ne, Xe, O presented at ND 2019, Bejing
EPJ Web of Conferences **239**, 01006 (2020)

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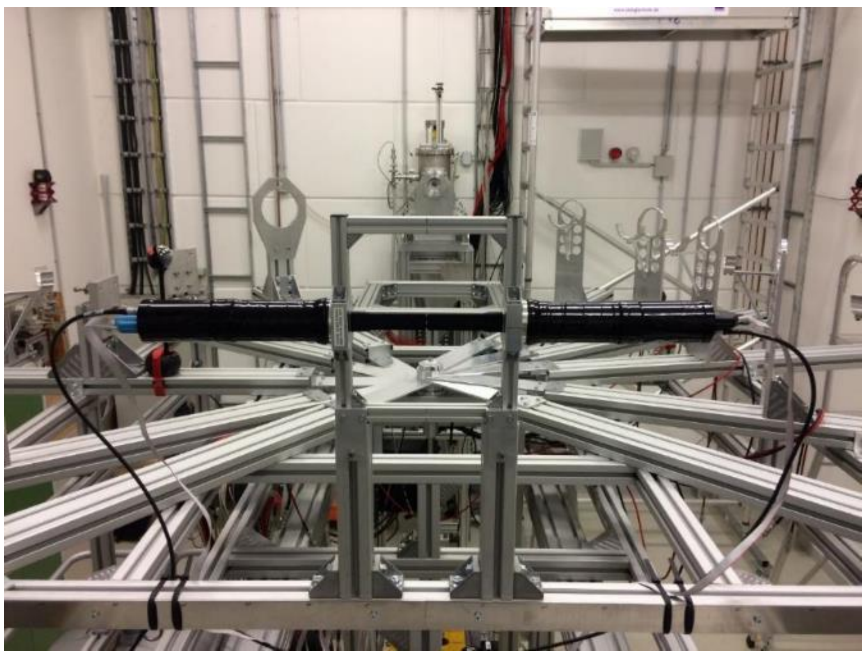
Transmission target and detector set up

Transmission targets:

- Puron pure iron samples (99.9226%)
  20, 50, 90 mm thickness
  0.16948, 0.42495, 0.76445 at/barn

Mounted in front of 2,5 m long collimator



Time of flight hall: flight path 6 - 9 m

EJ 228 200*10*5 mm^3 thickness plastic scintillator coincident read out by two high-gain R2059 PMTs
➔ threshold below single photo-electron peak
neutron detection threshold from proton recoils
$E_n < 10$ keV

Multi-hit multi event TDC (Caen) 25 ps/channel
dedicated FPGA trigger and veto logic
40 MHz clock to measure dead time per event
Measurement during readout,
veto length of 4 µs per trigger

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Transmission analysis at nELBE

$$T_{\text{exp}} = \frac{R_{\text{in}}}{R_{\text{out}}} = \frac{N_{\text{in}}/\alpha_{\text{in}} - B_{\text{in}}}{N_{\text{out}}/\alpha_{\text{out}} - B_{\text{out}}} \cdot f_{\text{norm}}$$

1. **time-of-flight dependent dead time**
   fraction of blocked tof channels accumulated for all accelerator periods $\alpha_{in}, \alpha_{out}$
2. **constant random background** $\boldsymbol{B_{in}},$
   dominated by beam-off background, nearly t.o.f. independent
   reduced by using position information (gate on Δt from PMT signals)
3. **neutron beam intensity fluctuations** $\boldsymbol{f_{norm}}$
   frequent absorber changes (target in / target out)
   normalisation factor f_{norm} from target out neutron rate
   and spectrum averaged neutron transmission
4. **inscattering of neutrons negligible (< 0.1 %)**
   target sample in front of a small solid angle collimator.
5. T_{exp} is larger than would be estimated on point-wise cross sections due to
   resonant self shielding in the **unresolved resonance range** at $E_n < 150\ \text{keV}$
   MCNP simulation with probability tables method ➔ F_T

$$\langle T_{exp} \rangle = F_T e^{-n\langle \sigma_{tot} \rangle}$$

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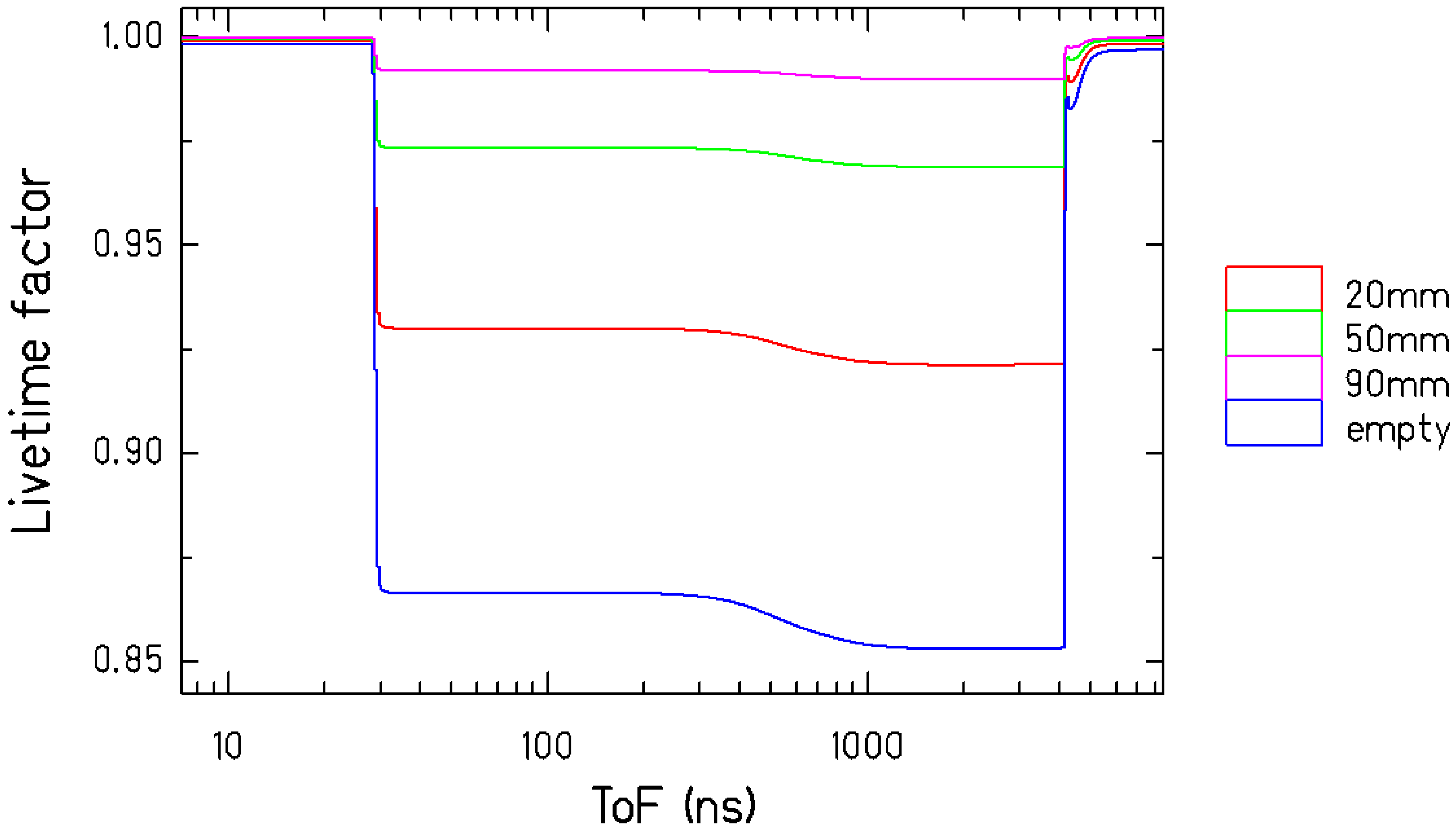
Time of flight dependent dead time correction



4 micro sec veto period after trigger

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Improvements of ^{nat}Fe total cross section minima

Tab.1 Assembly FE DIA100, R53; 200gpd, integral values, C/E
(Jansky, ND 2013, New York, [1])

	En.range[MeV]		main peak [keV]	Library used for MCNP Calculation					
No.	from	to	in measurement	ENDF/B-VII.1	BROND-3	JENDL-4.0	JEFF-3.2T2	TENDL-2012	CENDL-3.1
0	**0.013**	**1.290**	**total range**	**1.031**	**1.036**	**1.049**	**1.053**	**1.031**	**1.040**
1	0.013	0.030	24.4	0.918	0.836	1.029	0.989	1.221	0.891
2	0.030	0.075		0.909	0.835	0.903	0.967	0.858	1.146
3	0.075	0.090	82	1.008	0.912	0.999	1.017	1.119	1.402
4	0.090	0.150	137	0.845	0.828	0.920	1.004	0.970	0.732
5	0.150	0.200	167+183	0.907	0.898	0.974	1.015	1.012	0.909
6	0.200	0.250		1.012	1.051	1.024	1.018	0.872	1.196
7	0.250	0.289	272	1.075	1.097	1.011	1.015	0.948	1.115
8	0.289	0.333	309	1.423	1.366	1.338	1.245	1.317	1.129
9	0.333	0.410	350	1.269	1.256	1.278	1.235	1.335	1.474
10	0.410	0.520		1.044	1.177	1.046	1.085	0.779	1.036
11	0.520	0.780	610+650+703	1.147	1.366	1.122	1.064	0.835	1.152
12	0.780	1.060		0.946	1.017	0.863	1.050	0.730	0.681
13	1.060	1.290		0.910	0.710	0.834	0.866	0.826	0.777

M/C>1.15
0.97<M/C,1.03
important regions

- Leakage neutron measurements in thick iron spheres
  (M. Schulc ARI 130, 224, Fig. 4, and JEFFDOC-1918)
  shortcomings found in several cross section minima between 50 and 700 keV

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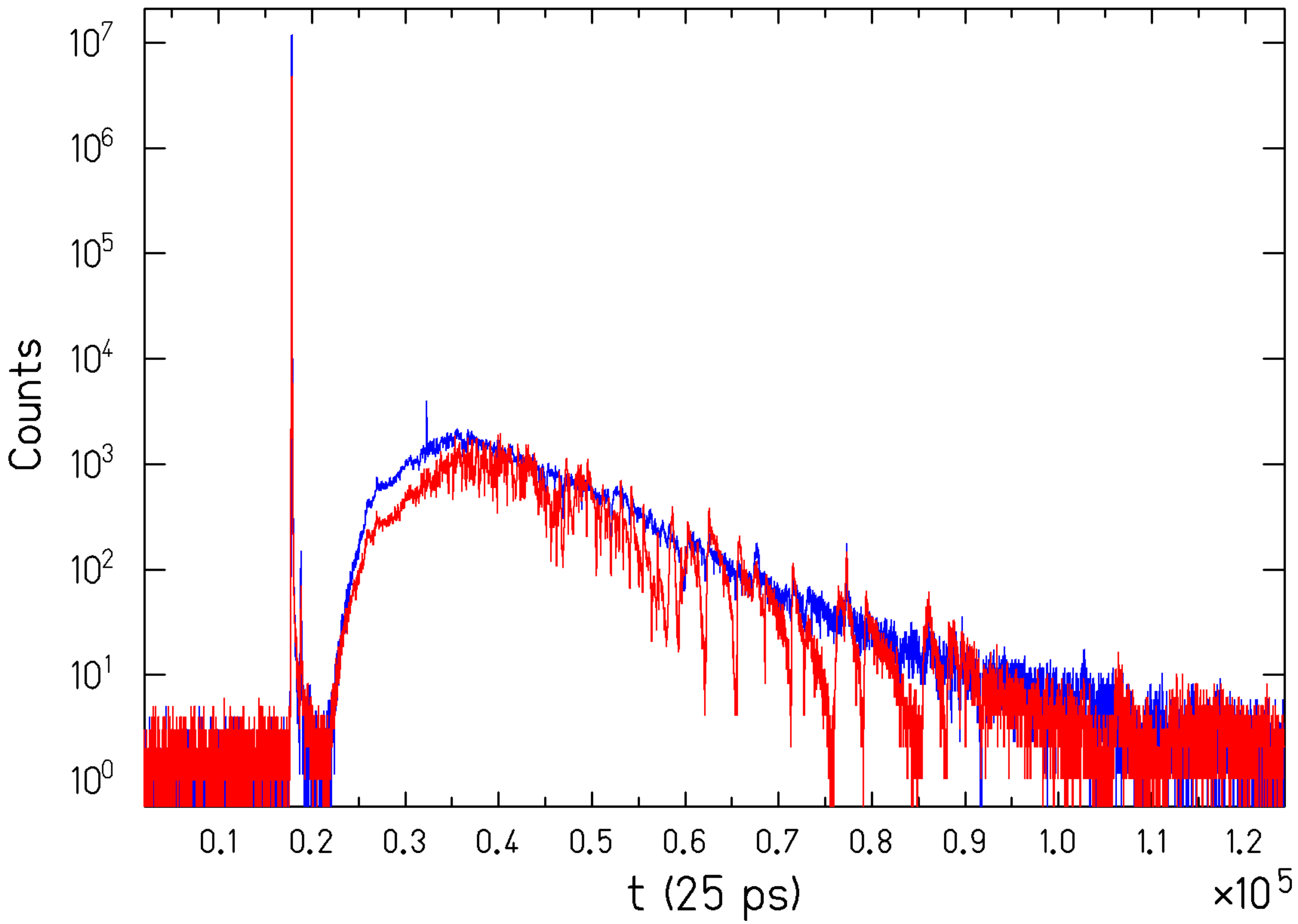
Time of flight spectra



Neutron rate
ca 200-500 s^{-1}

random background mostly
beam off background

Cross section maxima saturated at 90 mm thickness

Time resolution (1 std.dev): $\Delta t = 0.21$ ns

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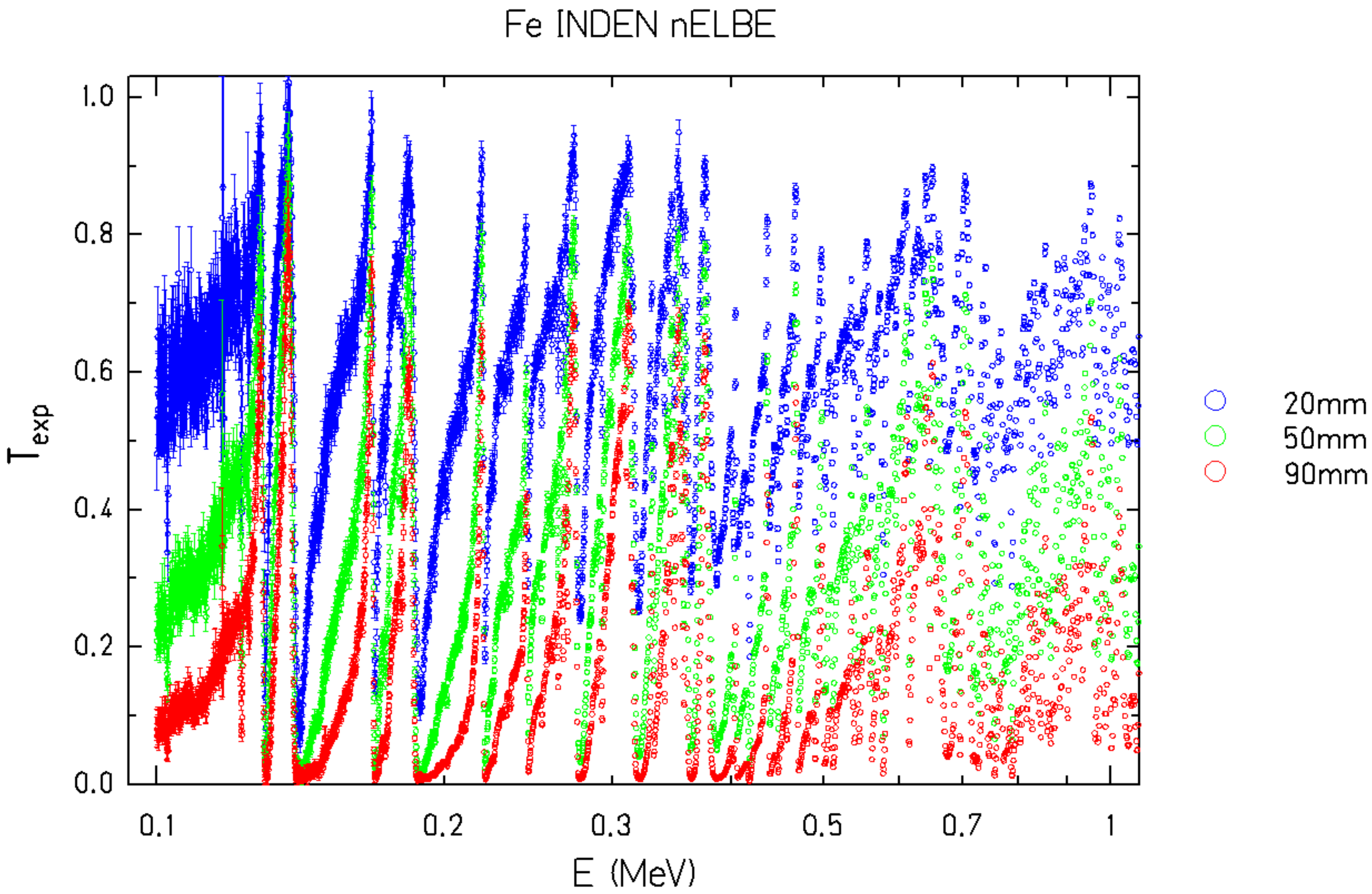
^{nat}Fe transmission results



Transmission measured from 0.10 to 12 MeV.

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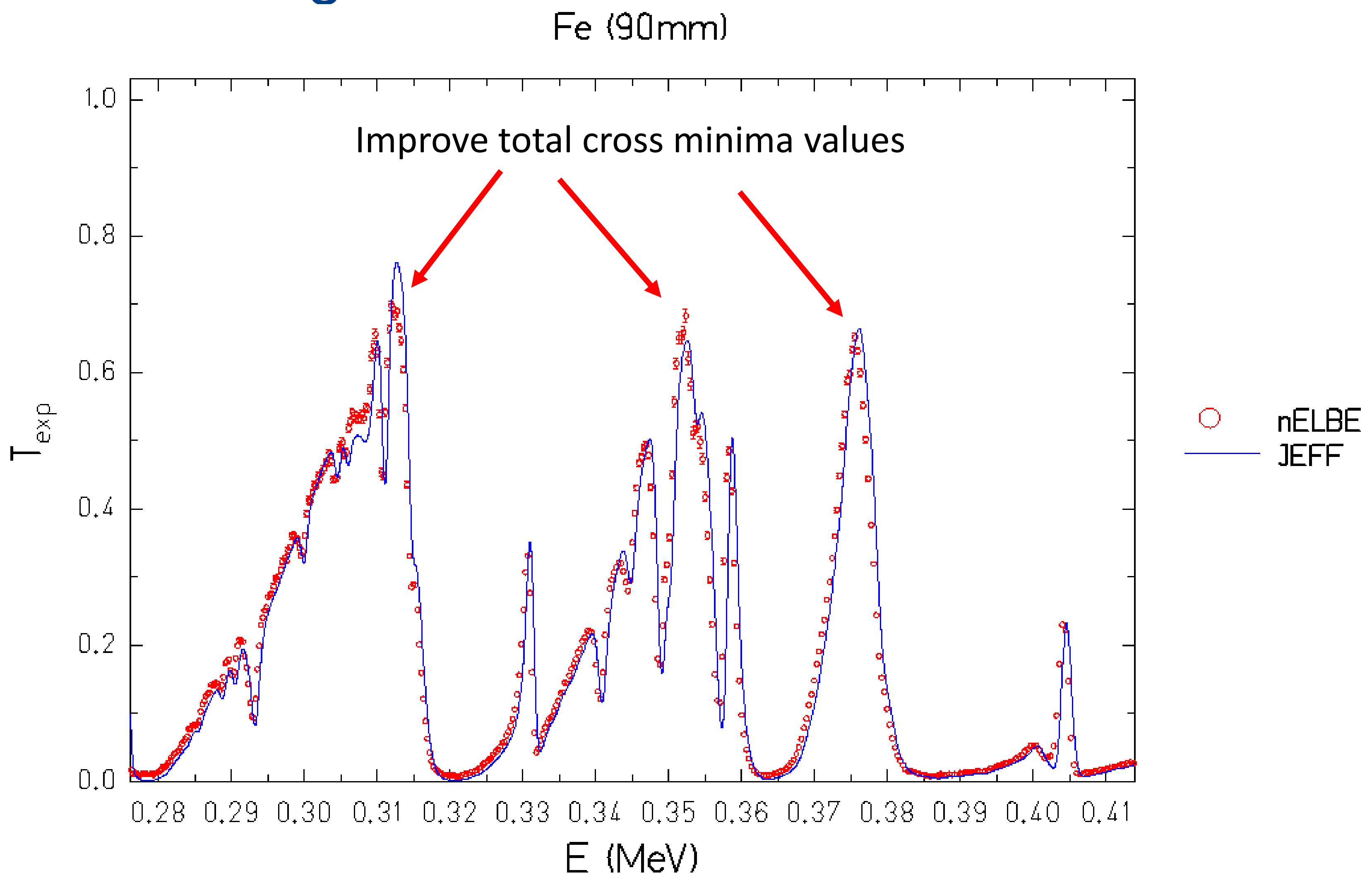
Thick target transmission



Gaussian resolution function $\Delta t = 0.21 \text{ ns}, \Delta L = 0.55 \text{ cm}$ (1 sigma)

See also: EPJ Web of Conferences **284**, 12002 (2023)

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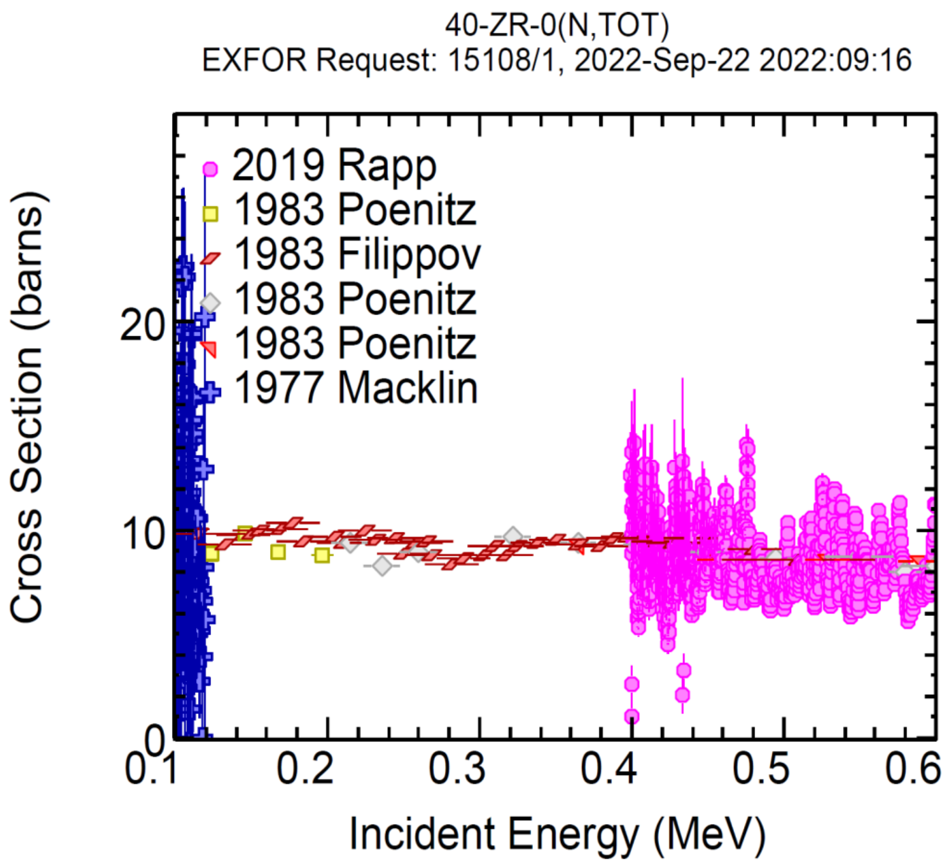
Zirconium total cross section



Gap without high resolution data Between 150 keV and 400 keV (ORNL, Macklin) and (RPI, Rapp)

Transmission measurement at nELBE with 12 and 25 mm nat-Zr samples

High purity sputter targets:
Zr+Hf ≥ 99,95%,
Hf < 0,008% (<80ppm)

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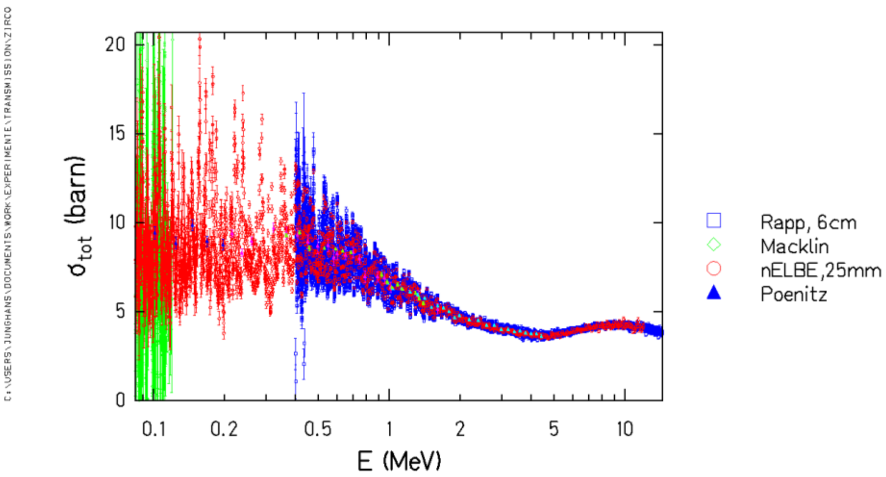
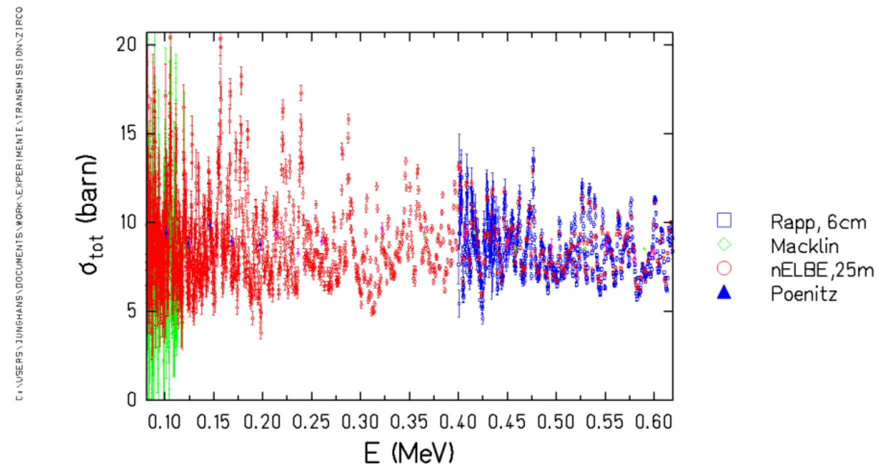
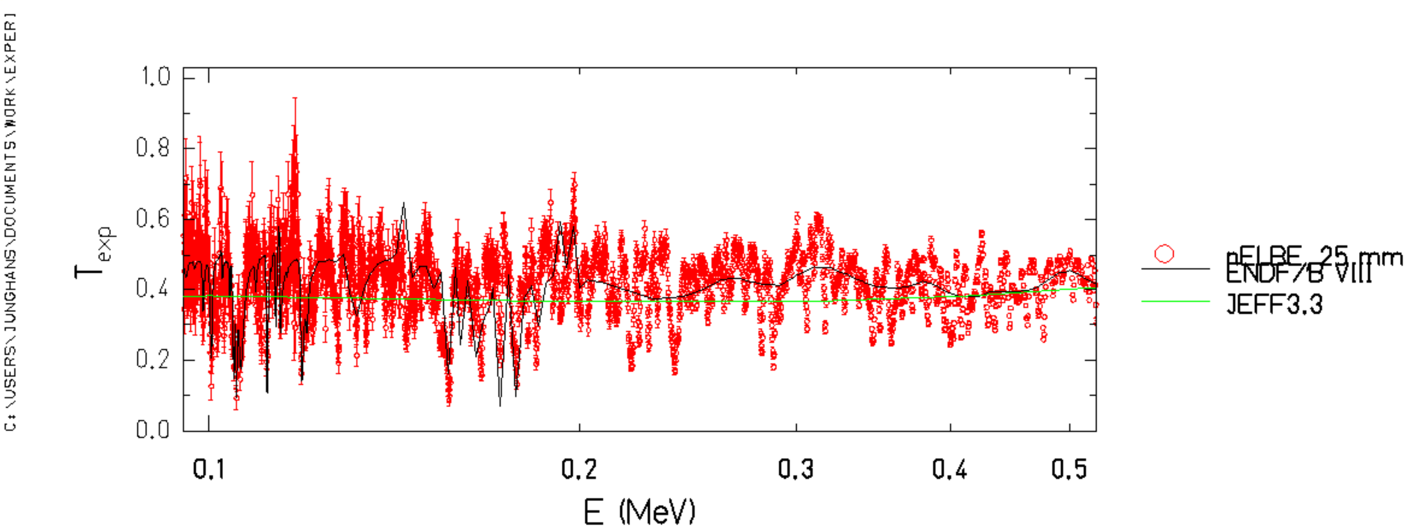
Zirconium total cross section







Cross section fluctuations can be evaluated in more detail

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Transmission with high pressure gas targets

Pb loop neutron producing target
Behind shielding wall
Collimator entrance is 100 cm
away from the target

Target ladder: from top: tungsten beam shutter
PE cylinder, evacuated cell, empty, filled gas cell
Flat ended cylinder 3mm stainless up to 200 bar

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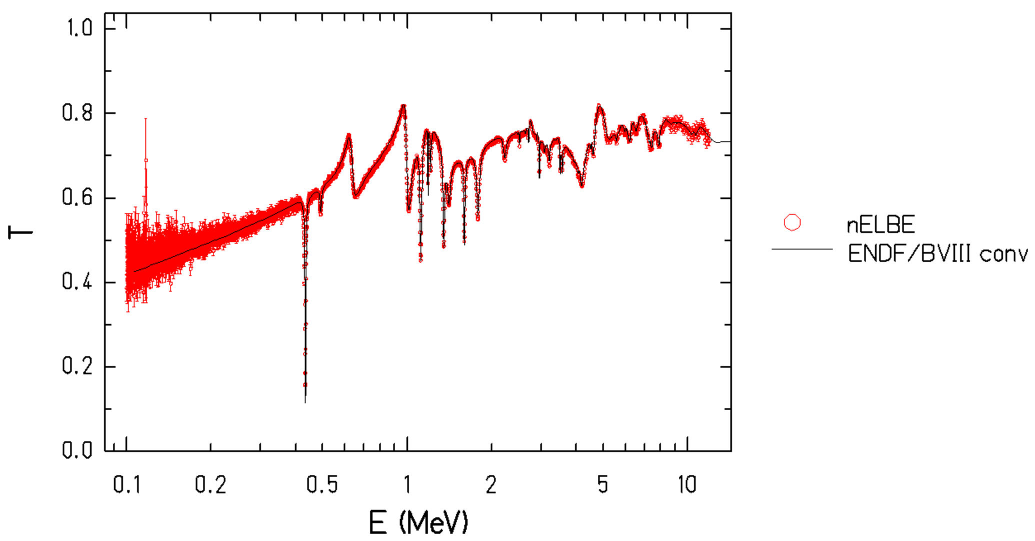
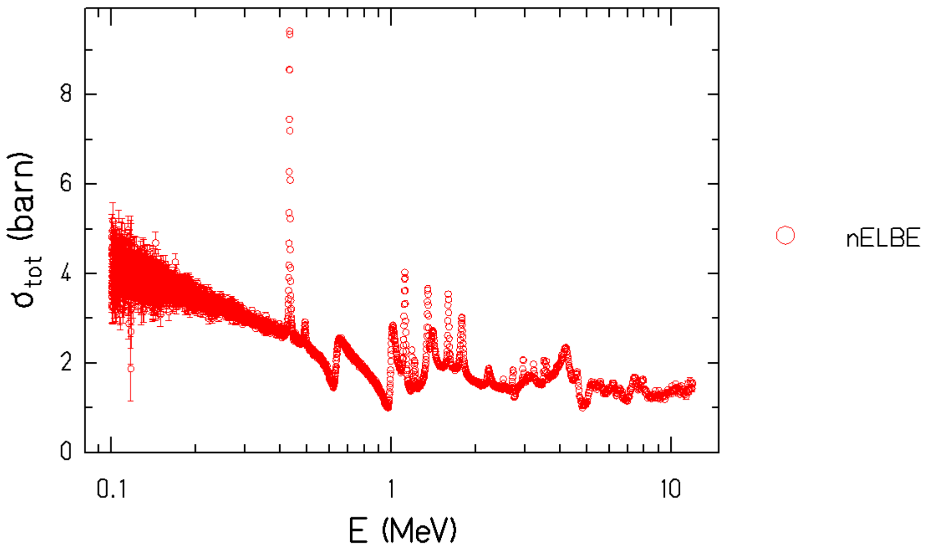
Transmission and total cross section of ^{14}N





absolute pressure 102 bar,
nl =0.19736 at/barn

Previous measurement from Harvey et al. (1992) used (0.3734 atoms/barn) transmission factor of the 433 keV resonance only 0.013

Avoid a too small transmission in the first resonance

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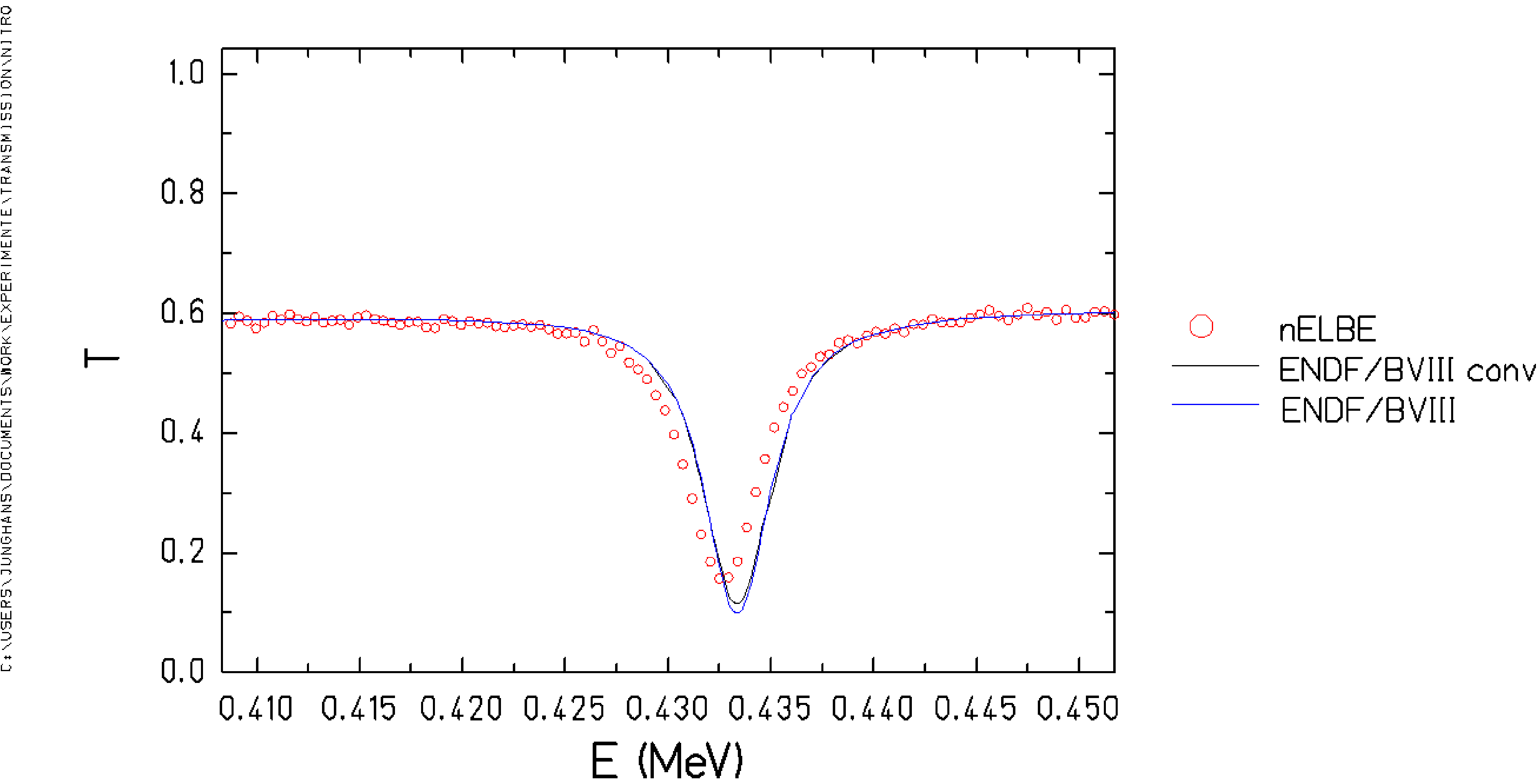
433 keV resonance



Transmission higher than calculated with ENDF/B-VIII

Resolution function does not have a large effect on this resonance

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Comparison with R-matrix 433 keV resonance

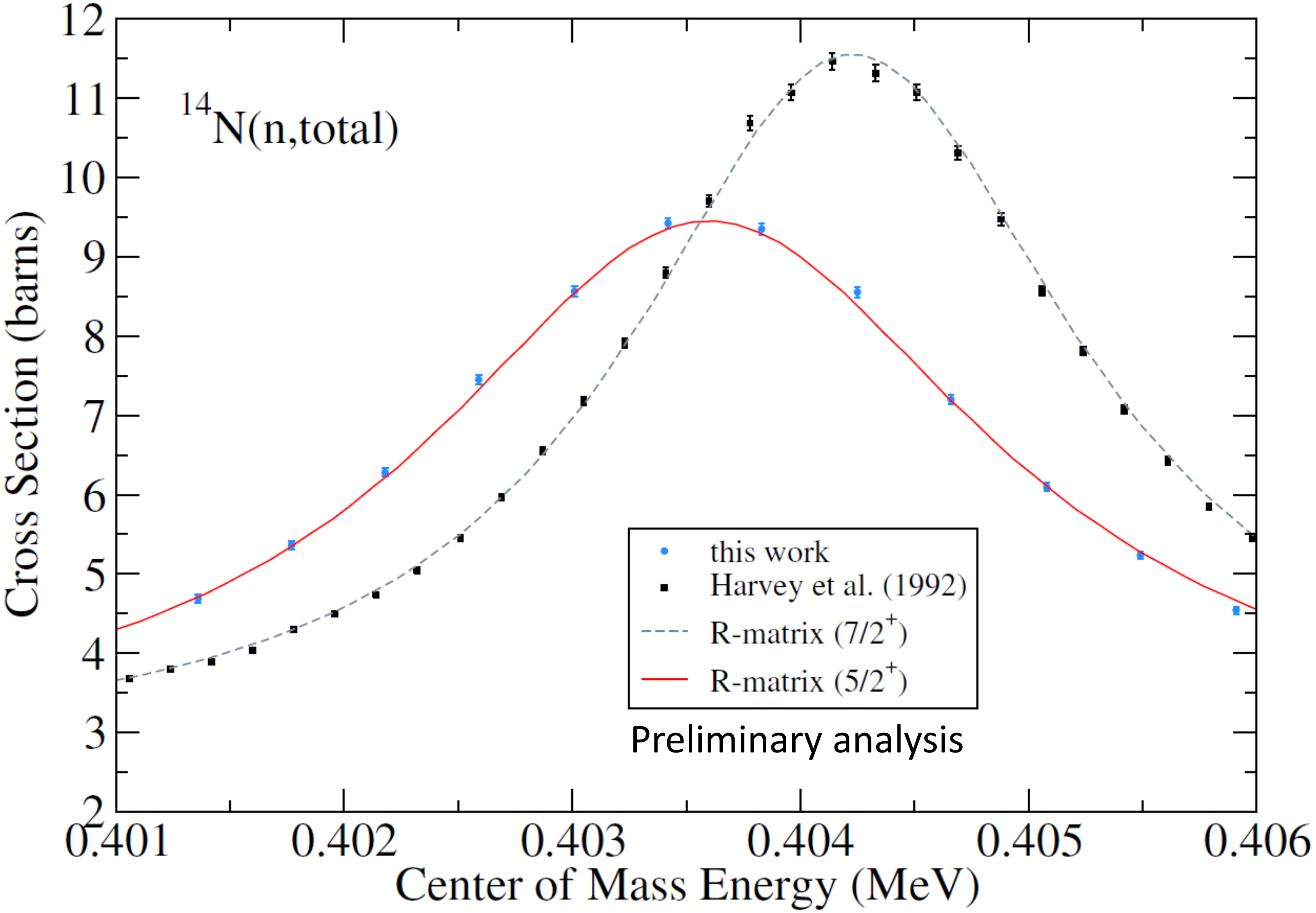

Figure courtesy R. de Boer, Notre Dame

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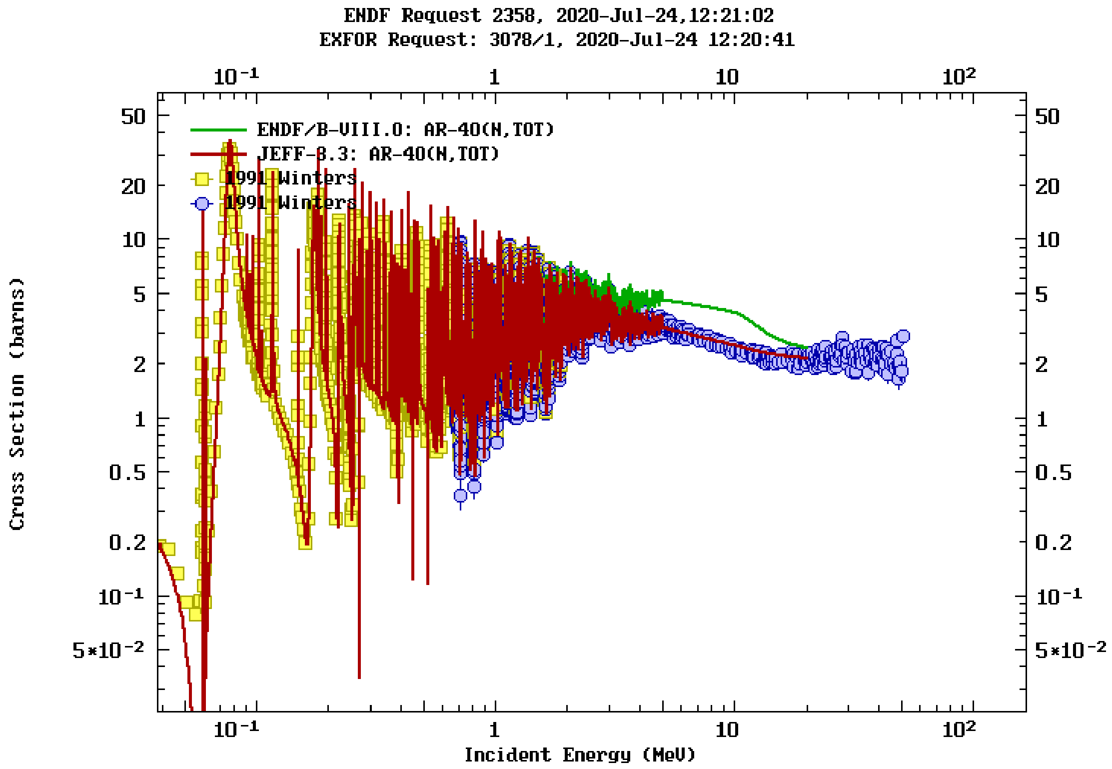
Transmission of Argon



Argon is an important detection material for direct dark matter (DarkSide) neutrinoless double beta decay searches (GERDA) and neutrino detection (DUNE).

- Cross section minimum below 60 keV
- ORNL measurement from Winters et al. (1991)
- ENDF/B VIII cross section is significantly higher at 3 MeV and above

➔ Remeasure at nELBE
Target areal density 0.20381 at/barn
(ca 200 bar max. pressure of gas bottle)

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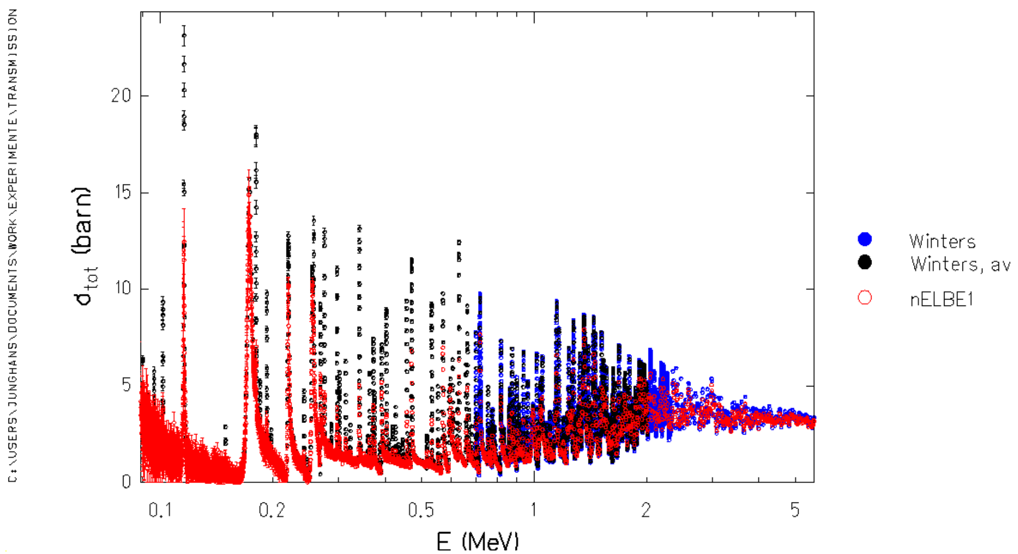
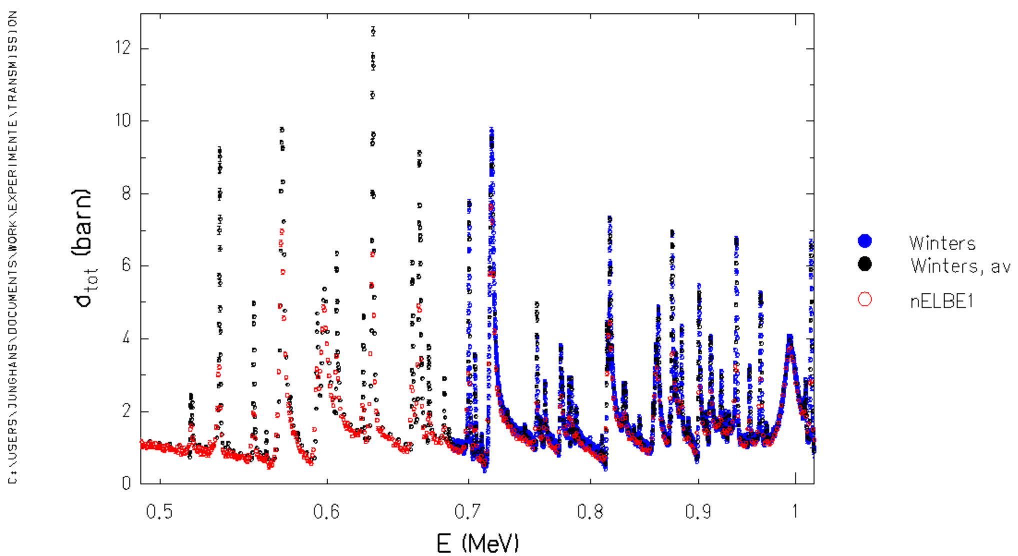
Ar(n,tot) comparison with Winters (1991)





- Argon has a strong resonant Structure with large changes in transmission.
- nELBE data have lower resolution than ORNL .
- nELBE Flight path is much shorter
- Both experiments agree in normalisation

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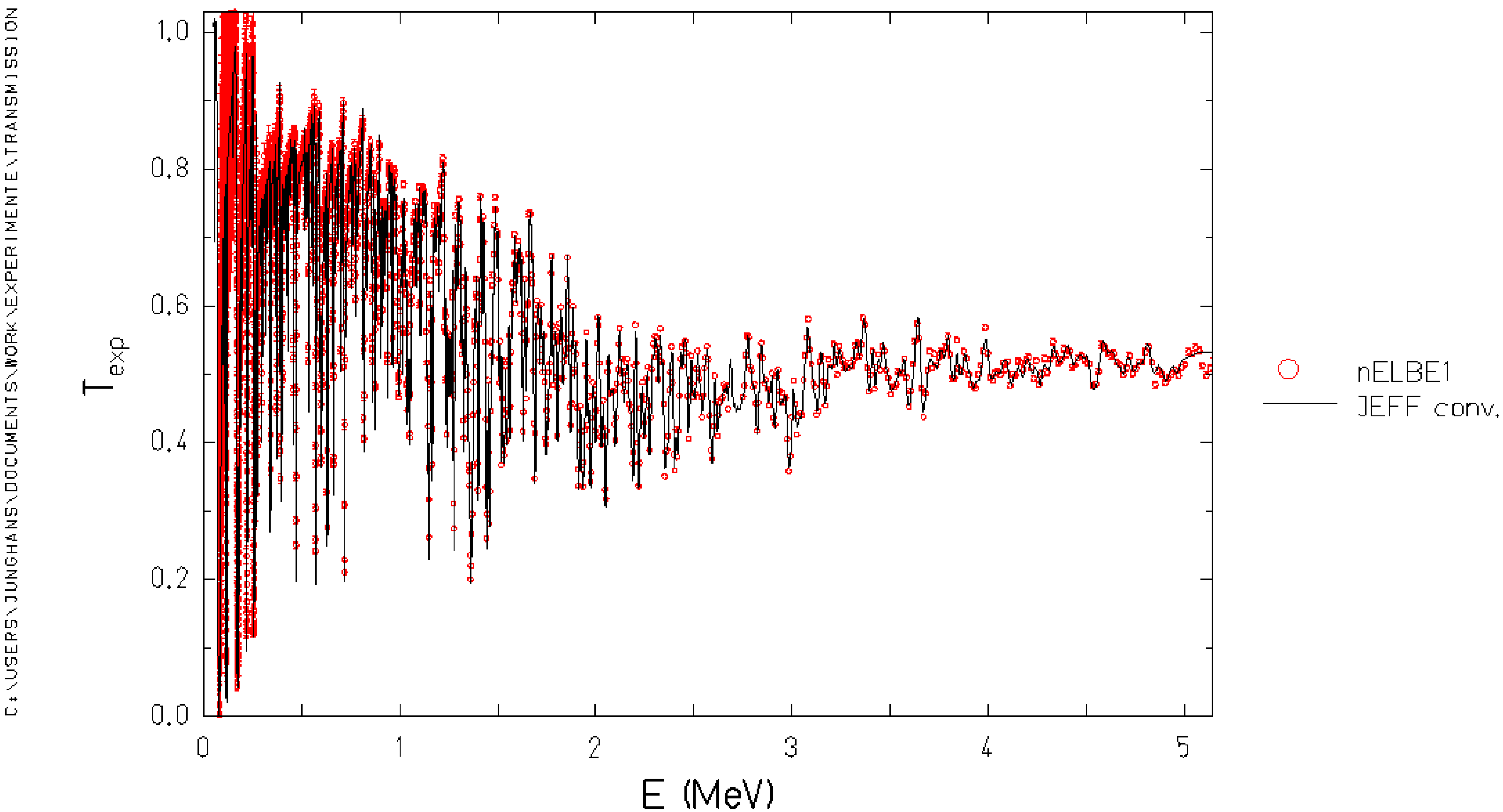
HZDR

Argon transmission with JEFF



JEFF 3.3. evaluation scaled by 1.02 and convoluted with nELBE resolution Function shows good agreement.

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Summary

- Gamma-ray production cross section experimental setup with using $LaBr_3$ and HPGe detectors at variable angles.
- ^{7}Li(n,n‘) experiment preliminary data lower than at Gelina
- nELBE experiment has been repeated in May 2018 with improved gamma-ray detection setup. Analysis is not finished yet.
- Transmission results:
  - thick nat-Fe sample (90 mm) shows better determination of cross section minima around 300 keV
  - Spin of 433 keV resonance in ^{15}N is smaller (5/2+) than previously deduced
  - Gap of high resolution transmission data in nat-Zr below 0.4 MeV. Rapp et al. (RPI) closed
  - Argon transmission normalisation of Winters et al. (1991) is confirmed,
    JEFF evaluation agrees with scaling of 1.02, ENDF-B/VIII evaluation of $\sigma(n, tot)$ is too high.

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End of talk

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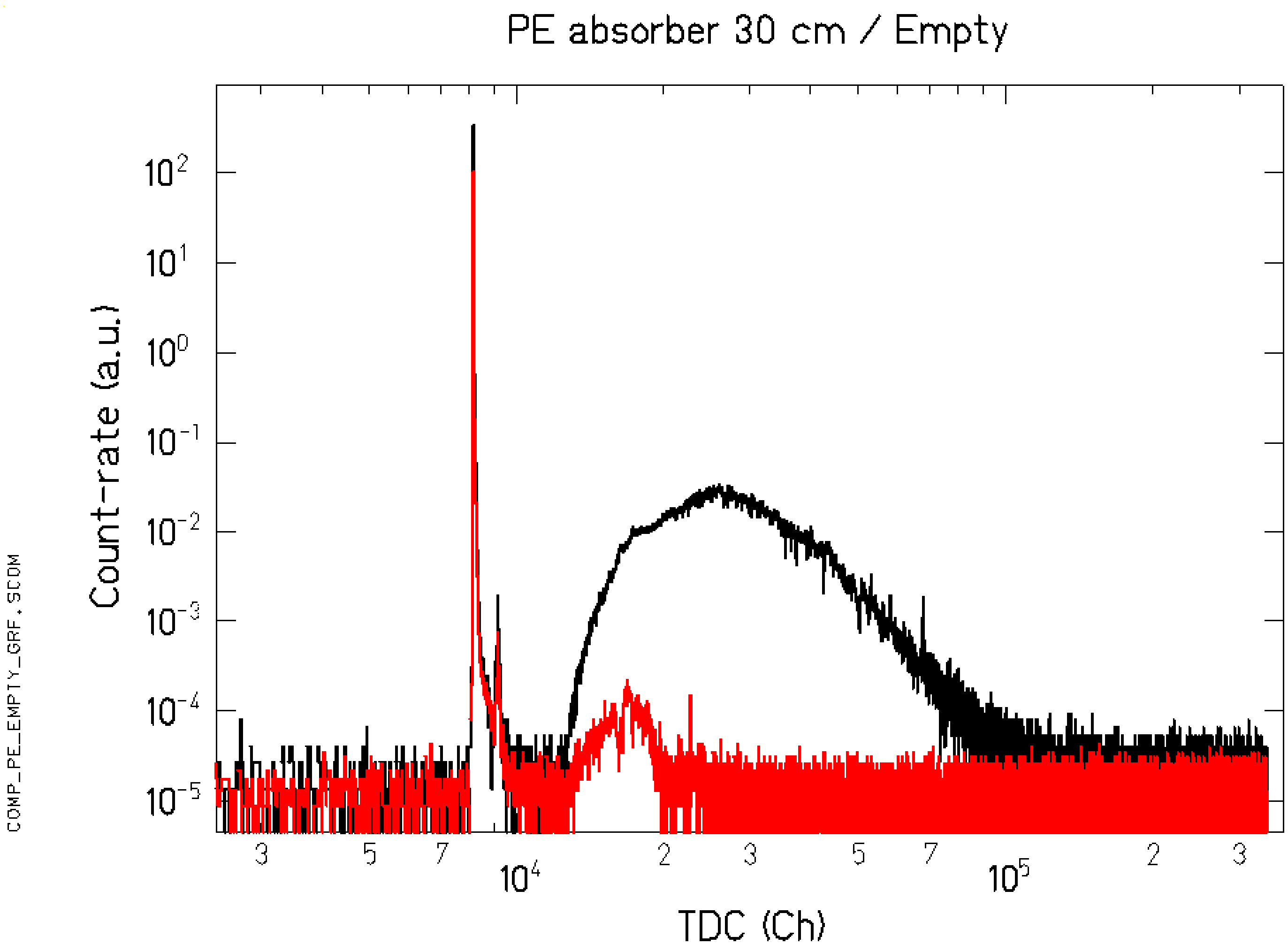
Transmission of thick 30 cm PE absorber



Some high energy neutrons above 4.4 MeV are transmitted through 30 cm PE.
Random background nearly constant

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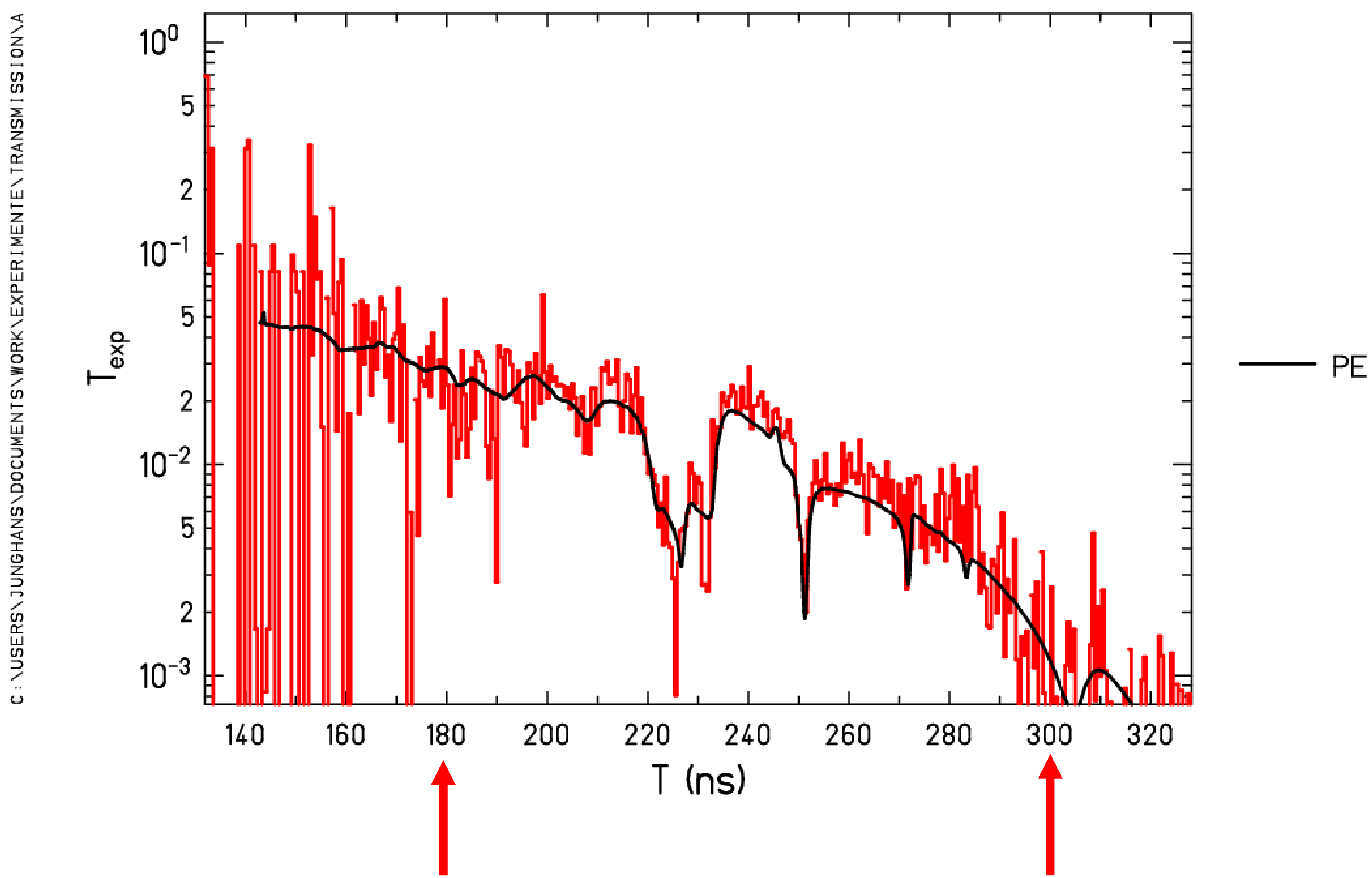
Transmission 30 cm Polyethylene



12.4 MeV

4.4 MeV

PE transmission curve with ENDF/B VIII cross section and Experimental resolution function

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