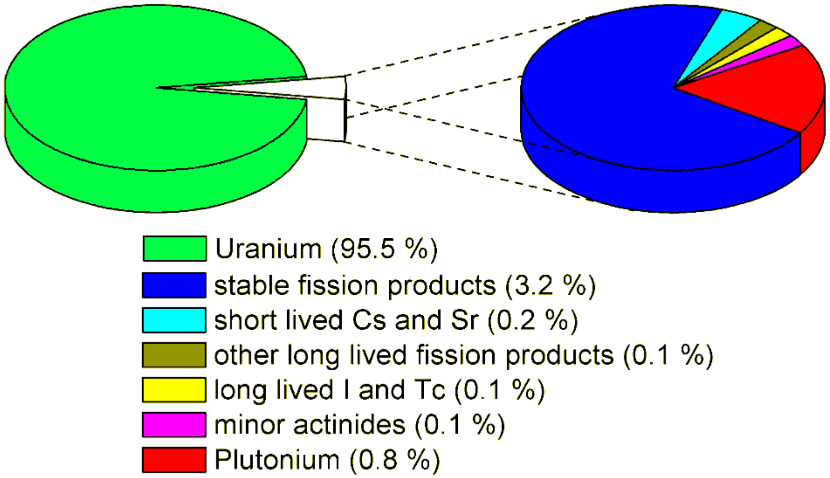
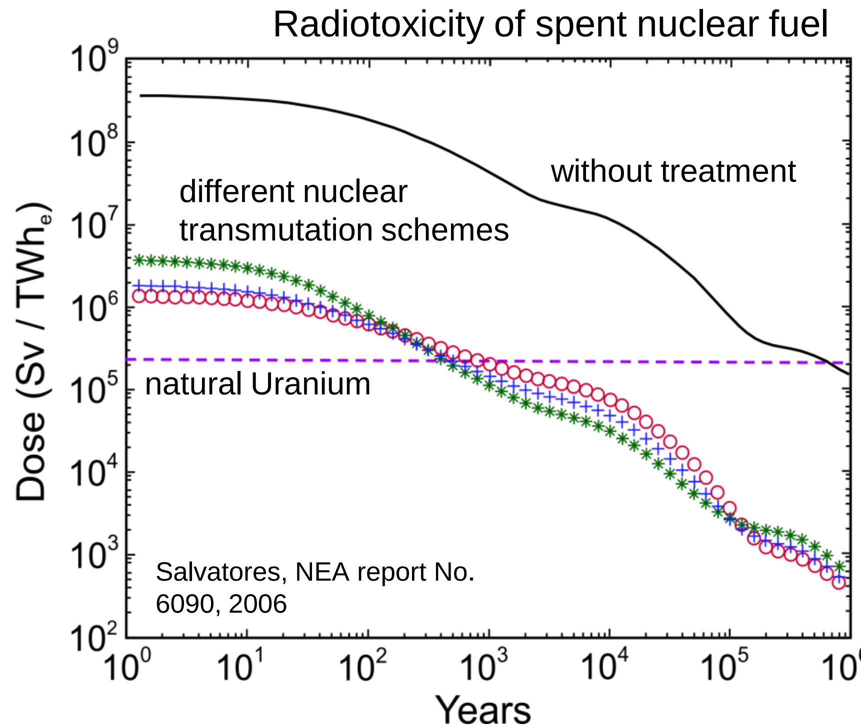
Inelastic neutron scattering at nELBE

Roland Beyer, Forschungszentrum Dresden-Rossendorf

The nuclear waste problem

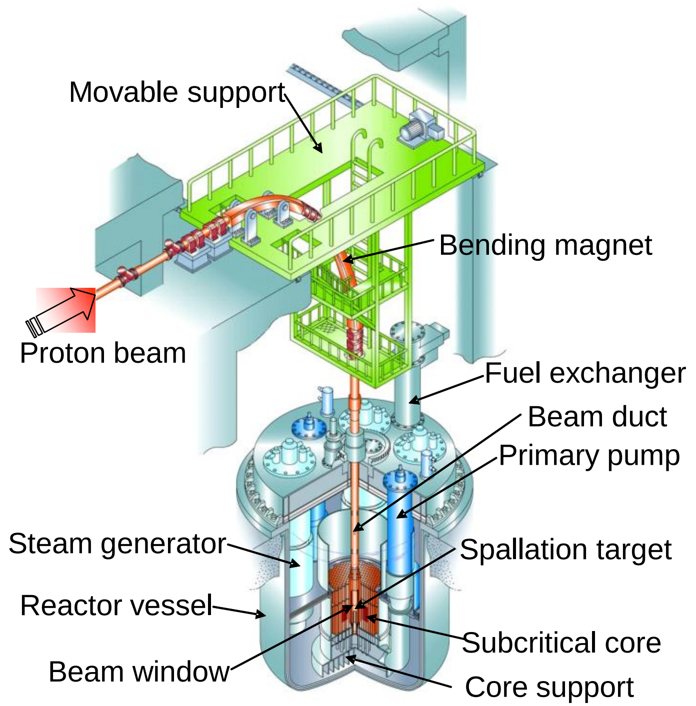


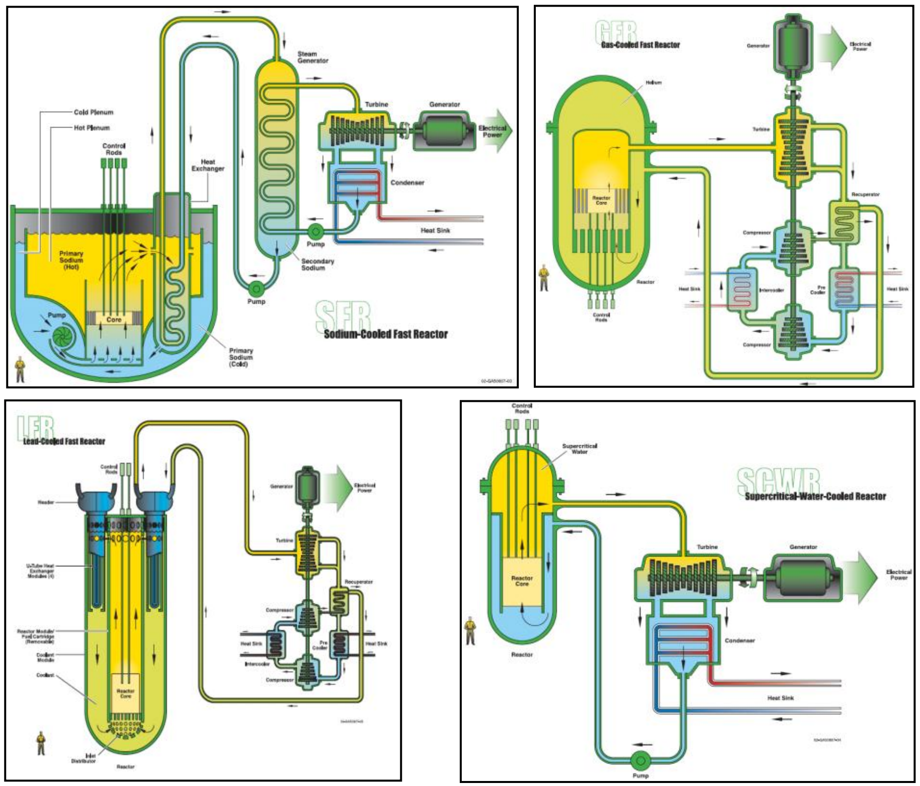


long lived isotopes cause main part of long term radiotoxicity
➔ **safe disposal is necessary for more 500,000 years**

➔ treatment of nuclear waste can **reduce disposal time by several orders of magnitude**
➔ **Partitioning:** separate actinides from the rest
➔ **Transmutation:** convert long lived isotopes into short lived ones

Accelerator driven systems / Generation IV nuclear reactors





➔ **fast neutron** induced fission is used to produce electrical power and to **burn up long lived actinides**

Hiroyuki OIGAWA
Presentation at Euratom PARTRA Cluster Meeting at FZK, Feb. 2008

http://www.gen-4.org/Technology/roadmap.htm

Data needs

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

- for simulations and calculations to design such facilities **detailed knowledge about the neutron interactions in the relevant energy region are necessary**

  ➔ for nuclei to be transmuted as well as for structural materials

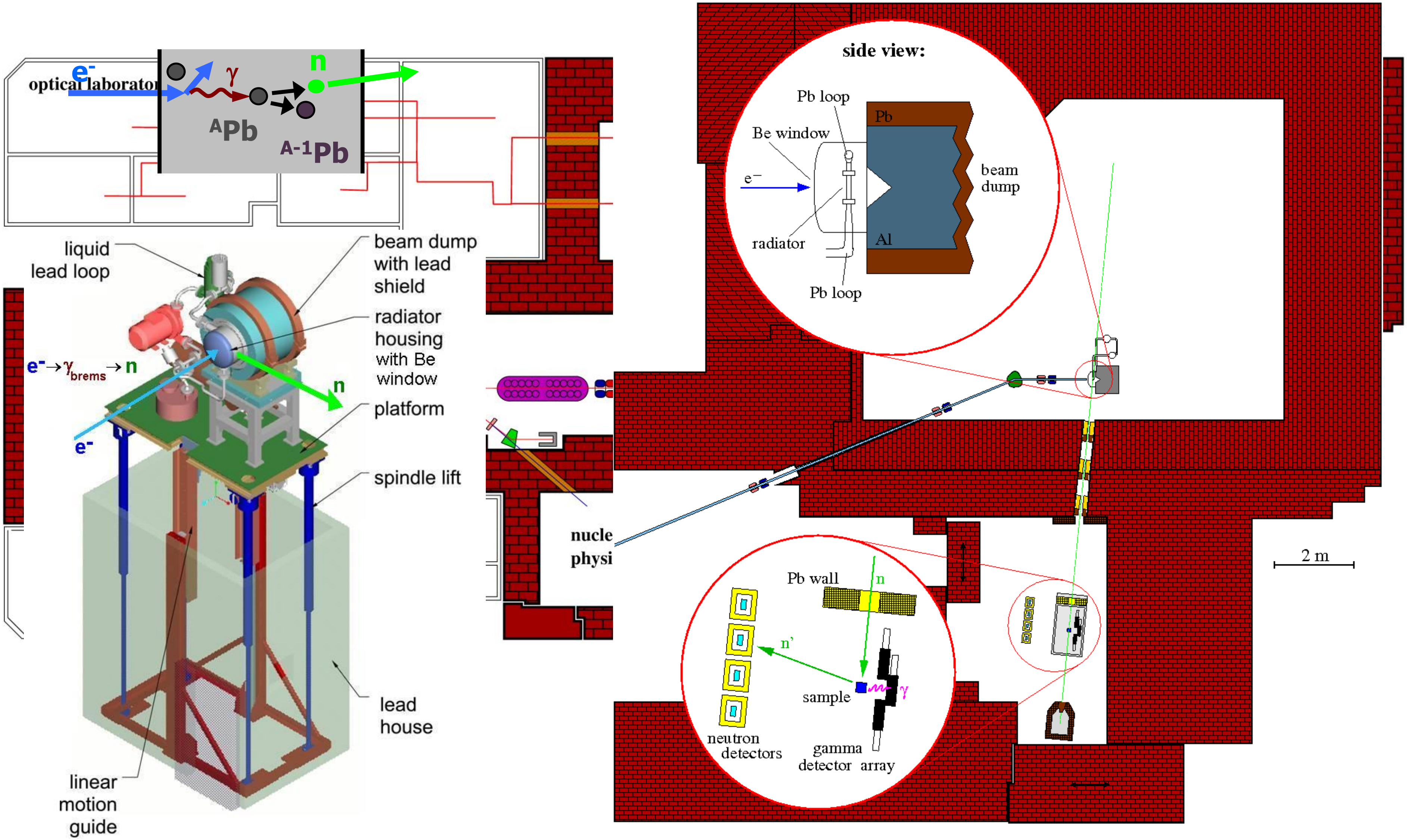
  ➔ fast neutron spectrum

  - neutron capture
  - neutron induced fission
  - neutron inelastic scattering

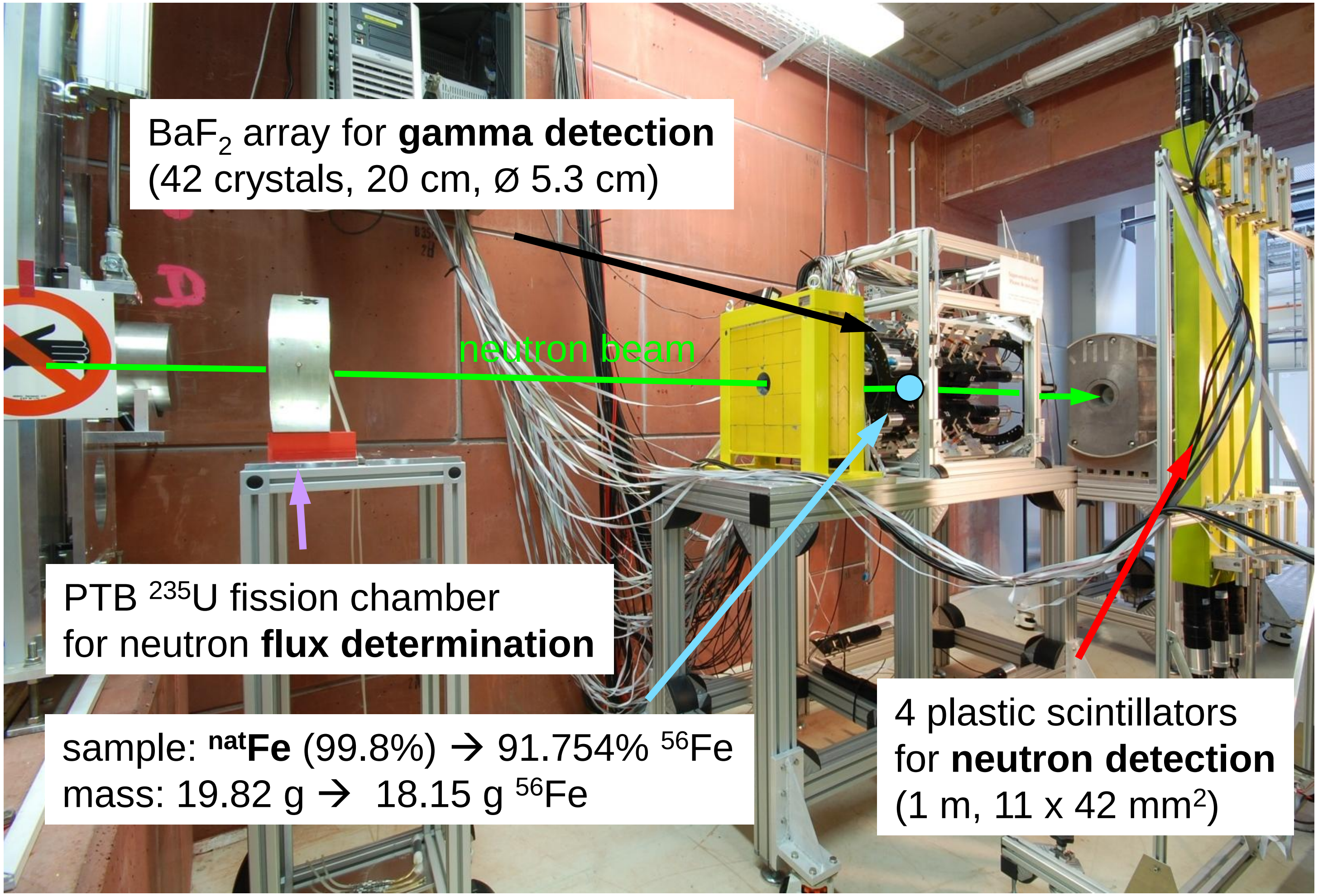
➔ ^{56}Fe (n,n'γ) ^{56}Fe

http://www.nea.fr/html/science/wpec/volume26/volume26.pdf

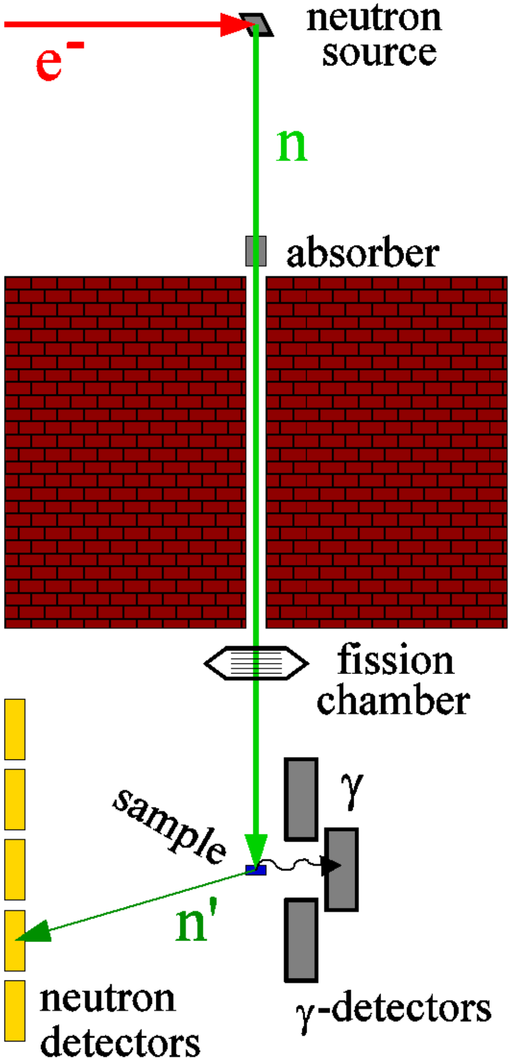
nELBE – neutron facility at ELBE



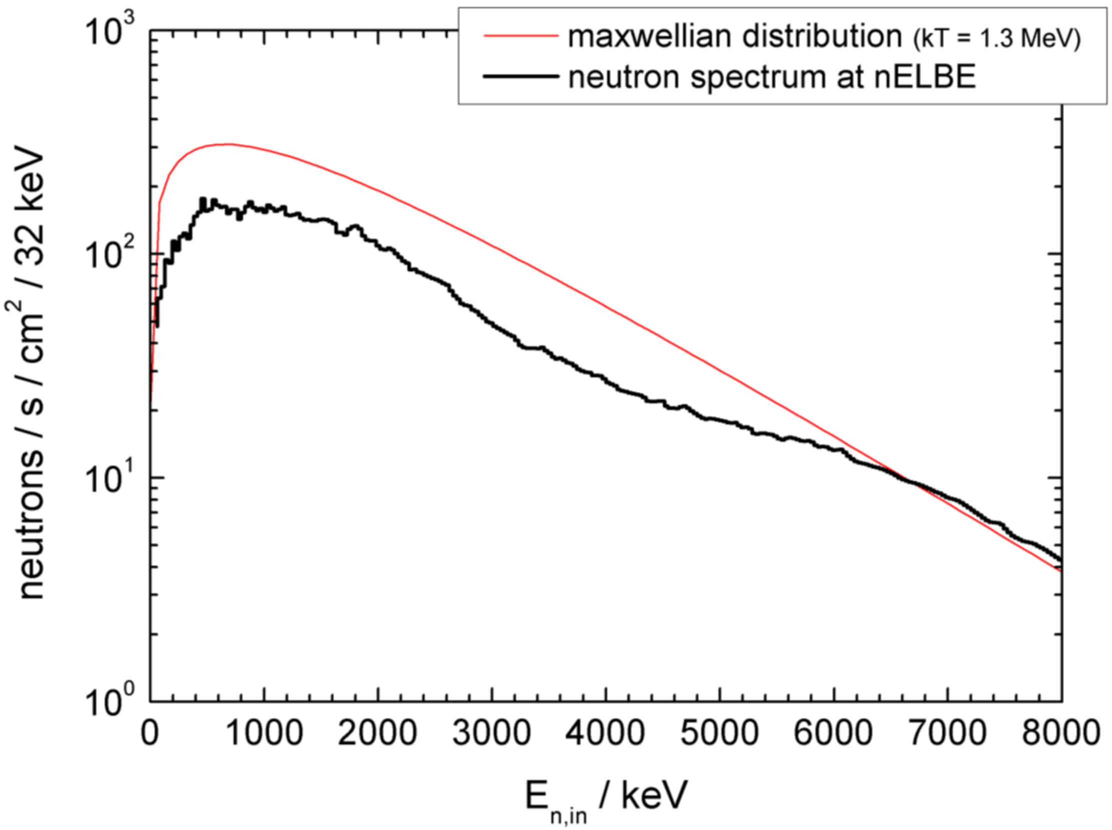
nELBE – detector setup



Experimental methods and results – Inelastic scattering

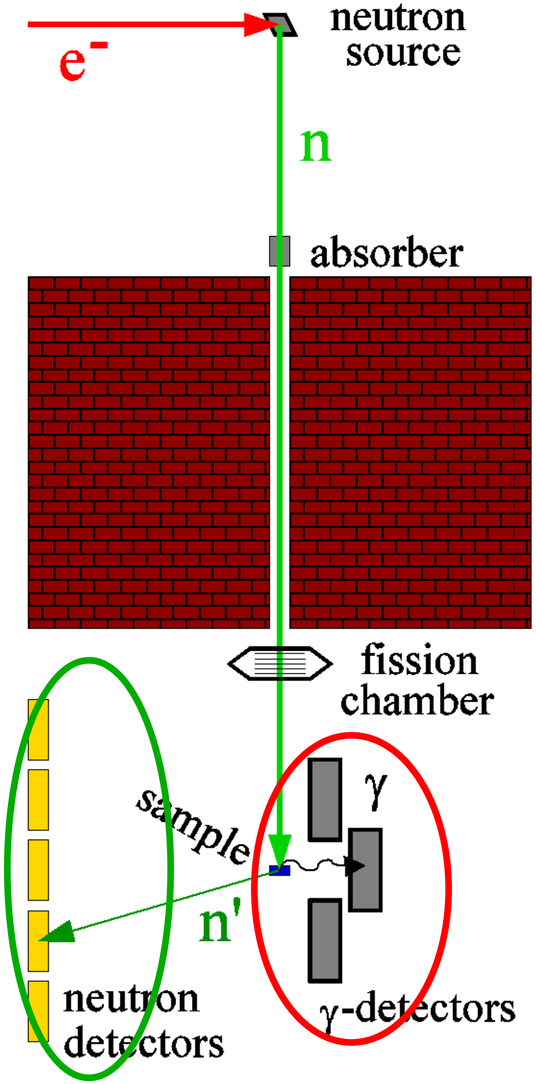


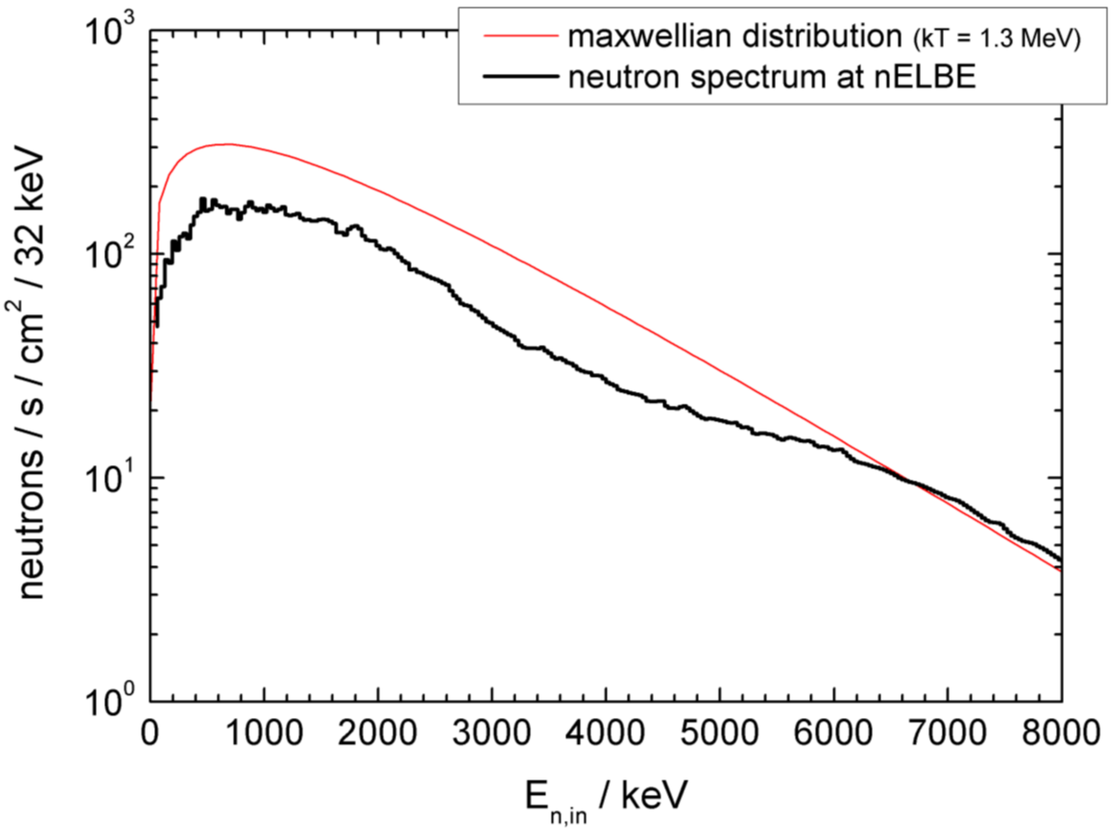
Integral at target: $2x10^4$ n/s/cm^2



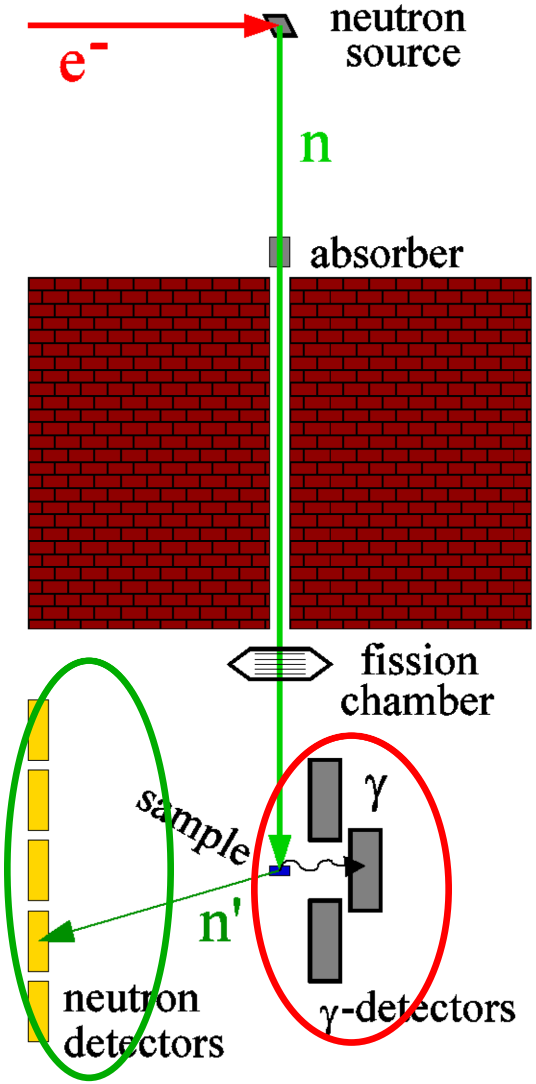
Experimental methods and results – Inelastic scattering

$$^{56}\mathrm{Fe}(n, n'\gamma)^{56}\mathrm{Fe} \quad \begin{cases} ^{56}\mathrm{Fe} + n \rightarrow {}^{56}\mathrm{Fe}^{*} + n' \\ ^{56}\mathrm{Fe}^{*} \rightarrow {}^{56}\mathrm{Fe} + \gamma \end{cases}$$





Experimental methods and results – Inelastic scattering



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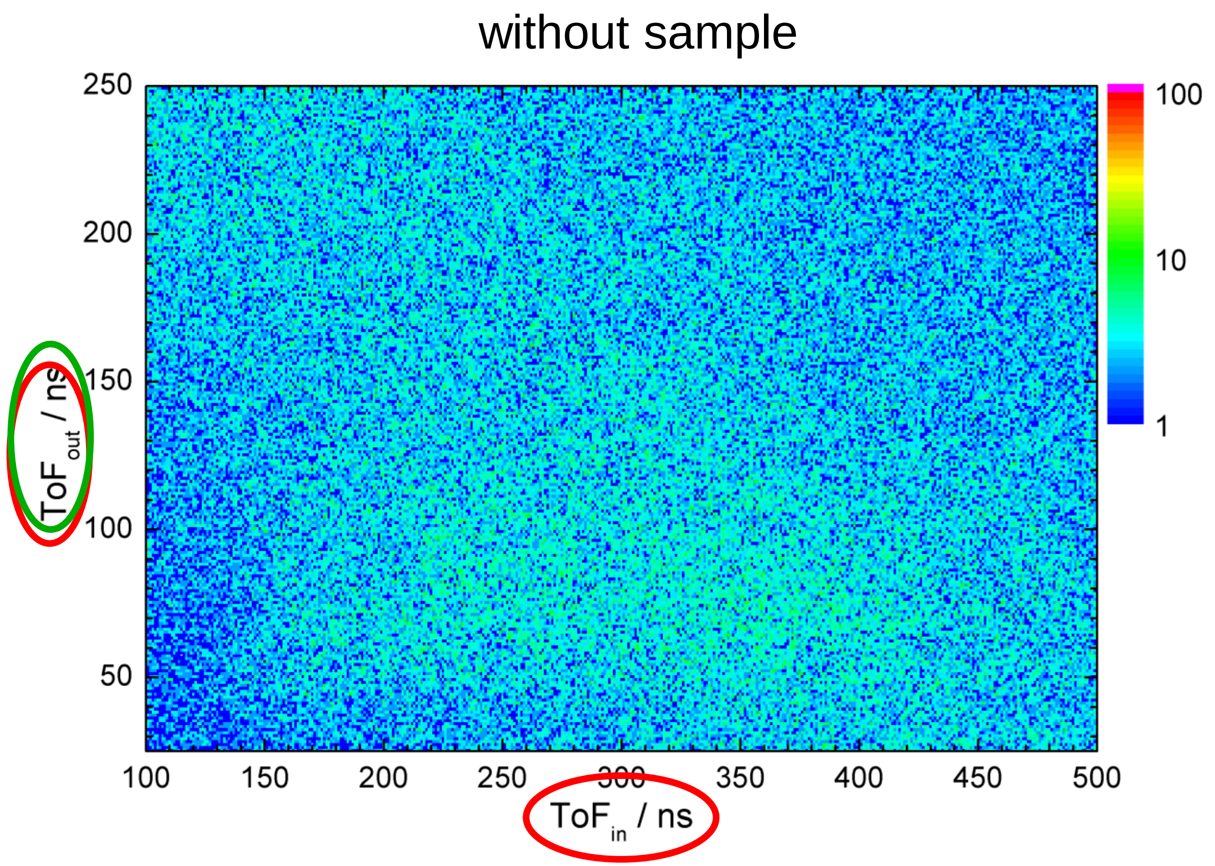
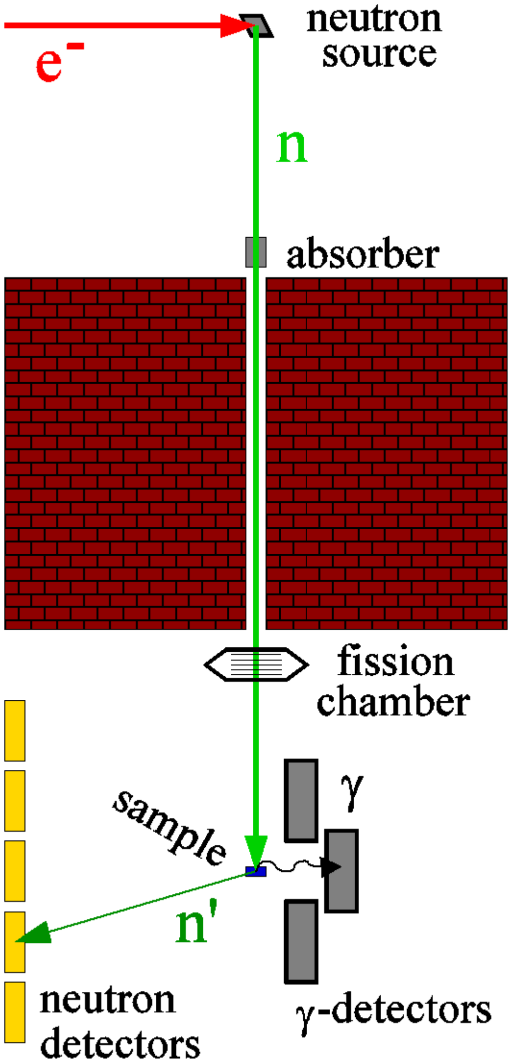
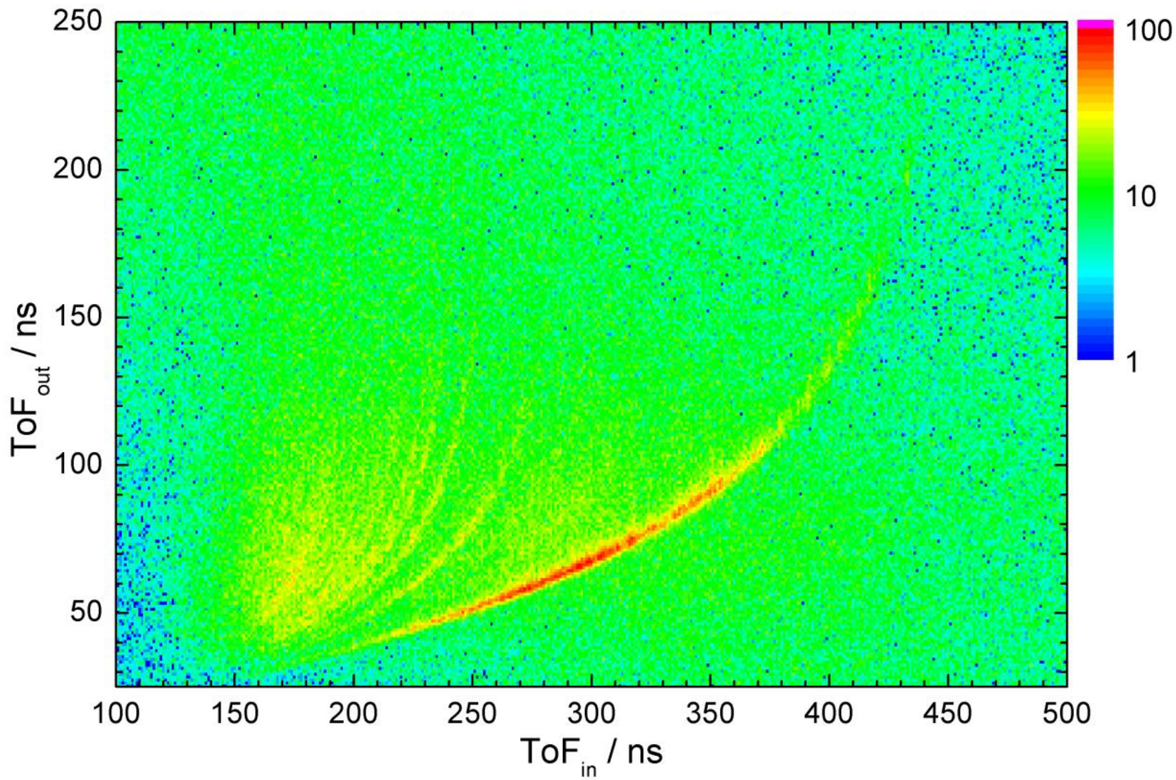


Experimental methods and results – Inelastic scattering

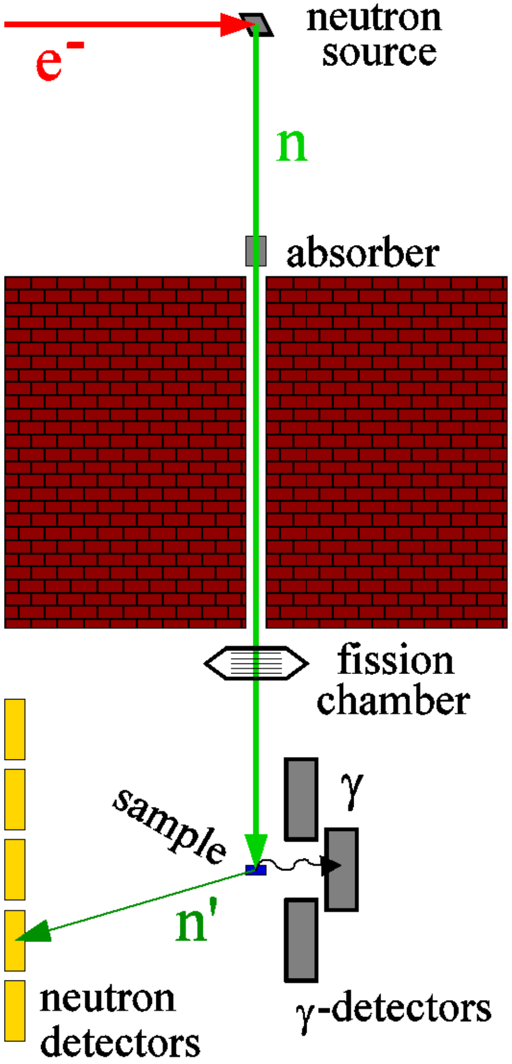


$$^{56}Fe(n, n'\gamma)^{56}Fe \quad \begin{cases} ^{56}Fe + n \rightarrow {}^{56}Fe^{*} + n' \\ ^{56}Fe^{*} \rightarrow {}^{56}Fe + \gamma \end{cases}$$

with sample

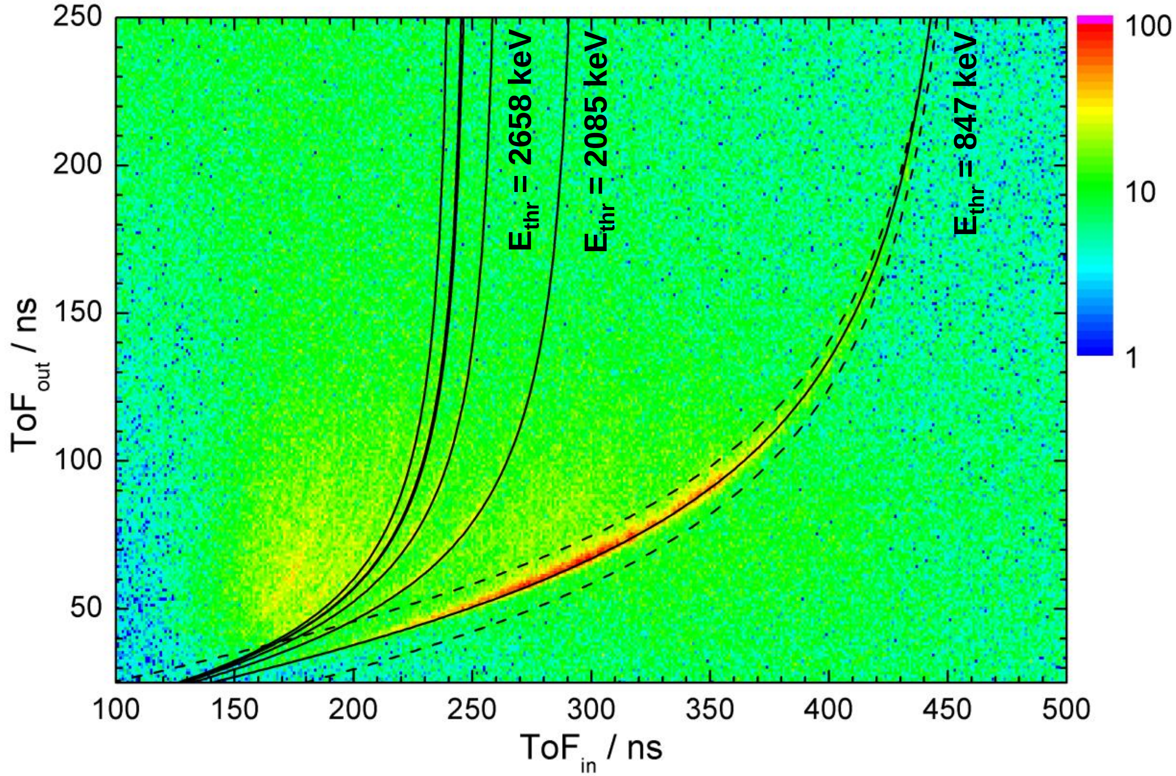


Experimental methods and results – Inelastic scattering

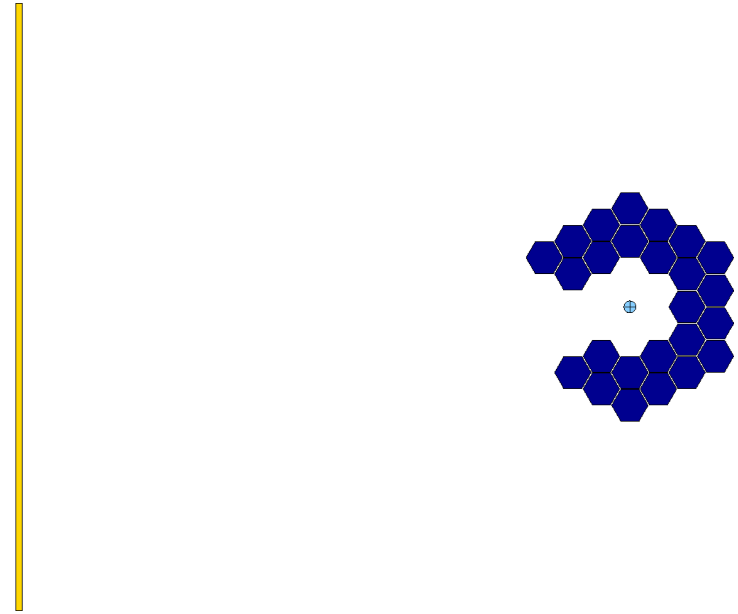


$$^{56}\mathrm{Fe}(n,n'\gamma)^{56}\mathrm{Fe} \quad \begin{cases} ^{56}\mathrm{Fe}+n \rightarrow {}^{56}\mathrm{Fe}^{*}+n' \\ ^{56}\mathrm{Fe}^{*} \rightarrow {}^{56}\mathrm{Fe}+\gamma \end{cases}$$

with sample + kinematics calculation



Investigations of background sources



Plastics

BaF_2-Setup

"good event": inelastic scattering in target

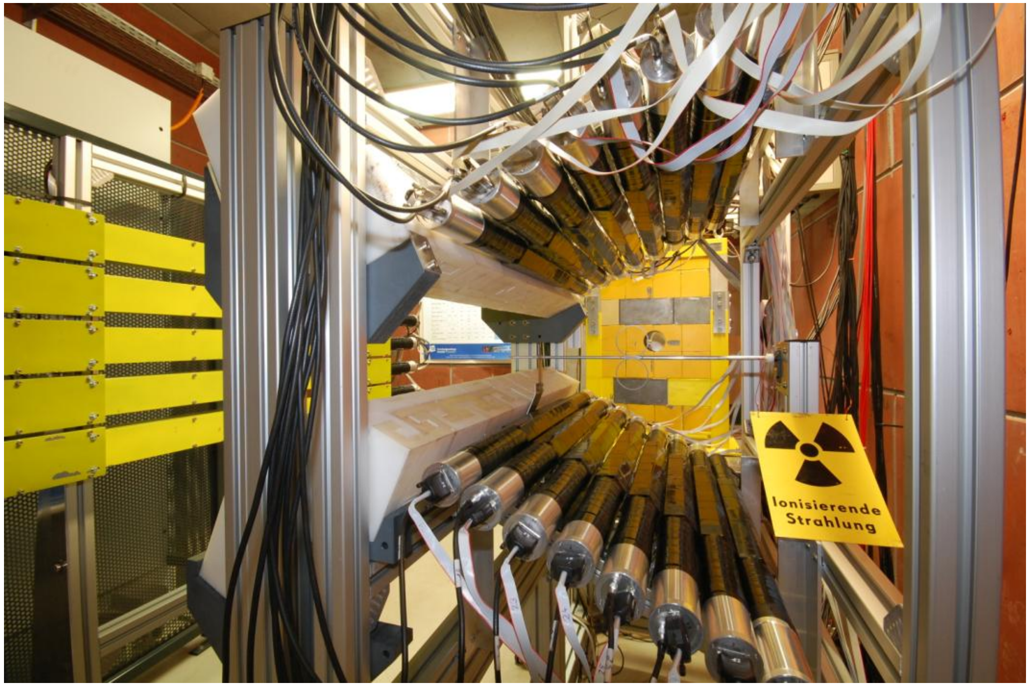
→ gamma detected in BaF2, neutron detected in plastic

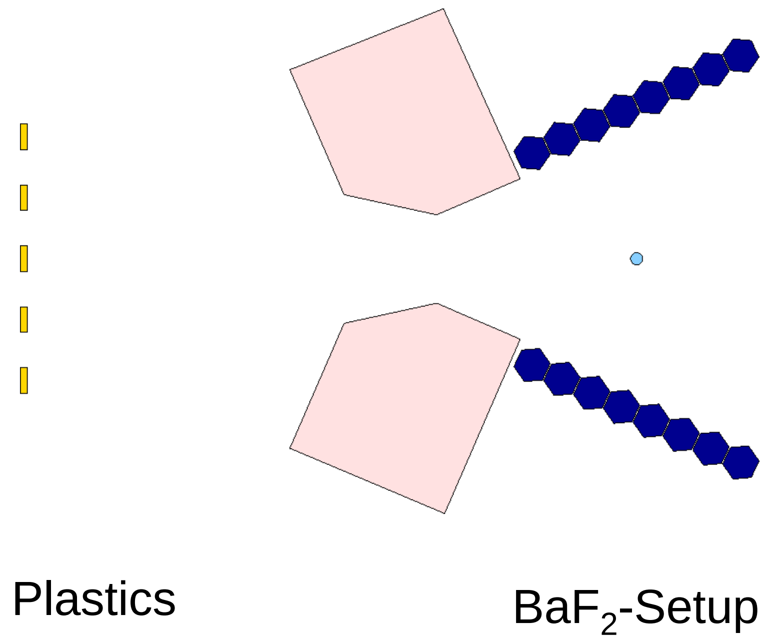
"bad event": elastic scattering in target/air and inelastic scattering in BaF2

→ neutron detected in plastic

→ prevent neutrons flying from BaF_2 to plastic

Investigations of background sources

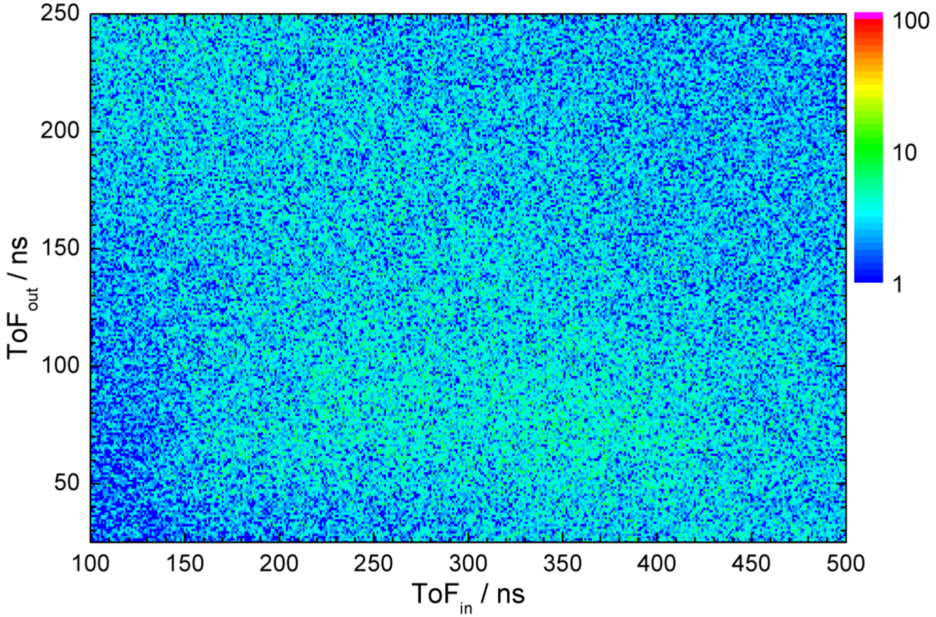




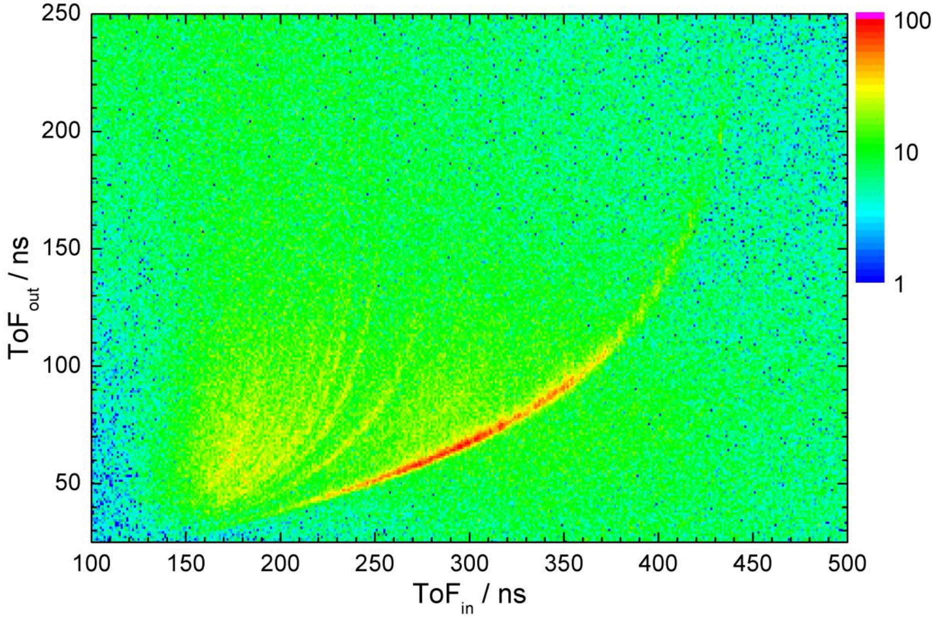
- ➔ borated polyethylene block between BaF_2 and plastics
- ➔ change in geometry
- ➔ combination of two single sided readout 20 cm long crystals to one double sided readout 40 cm long detector

2D ToF spectra from Feb'09 beamtime

empty target t_{live} = 79 604 s

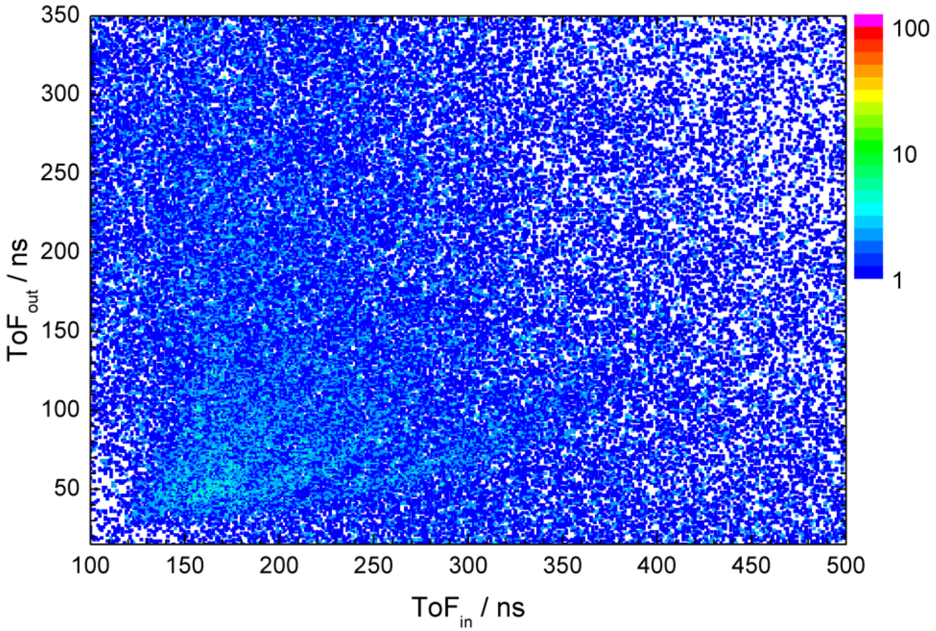


Fe-nat t_{live} = 84 251 s (68 %)

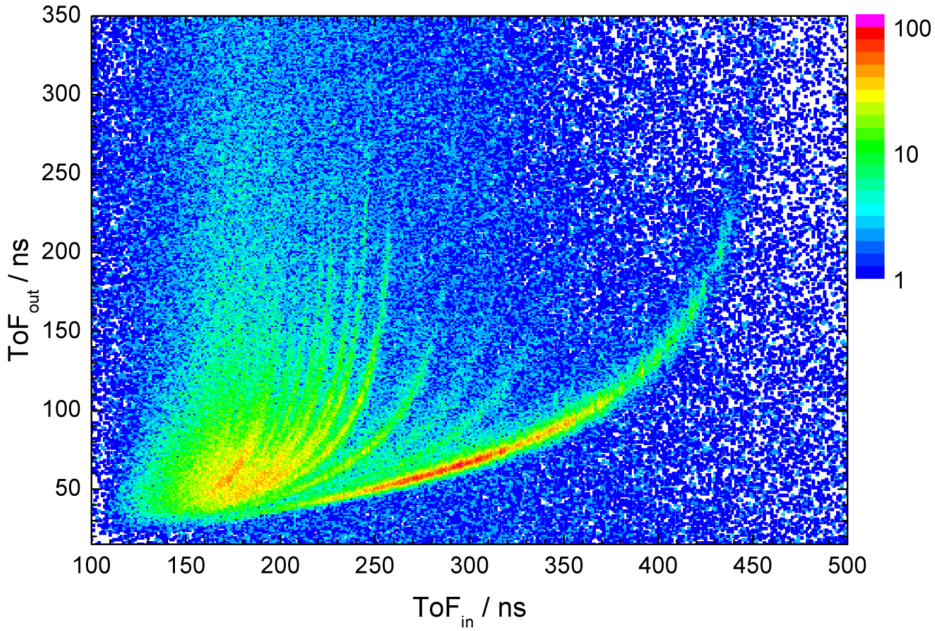


2D ToF spectra from May'10 beamtime

empty target t_{live} = 294 515 s

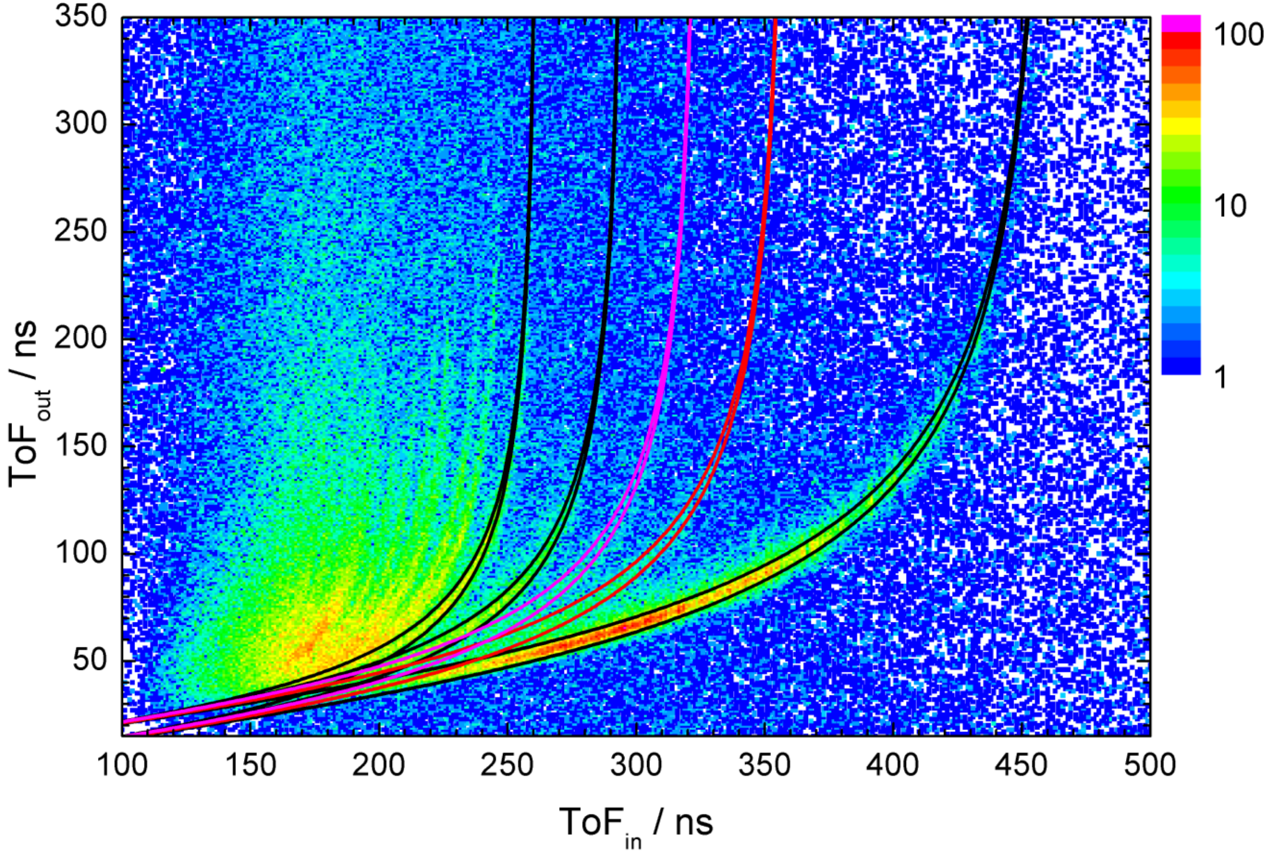


Fe-nat t_{live} = 280 567 s (83 %)



→ lower background (5x in empty, 10x in target run)
→ 10x better signal to background ratio
→ target structures also visible in in empty spectrum
(due to too small distance of target out position)

2D ToF spectra from May'10 beamtime



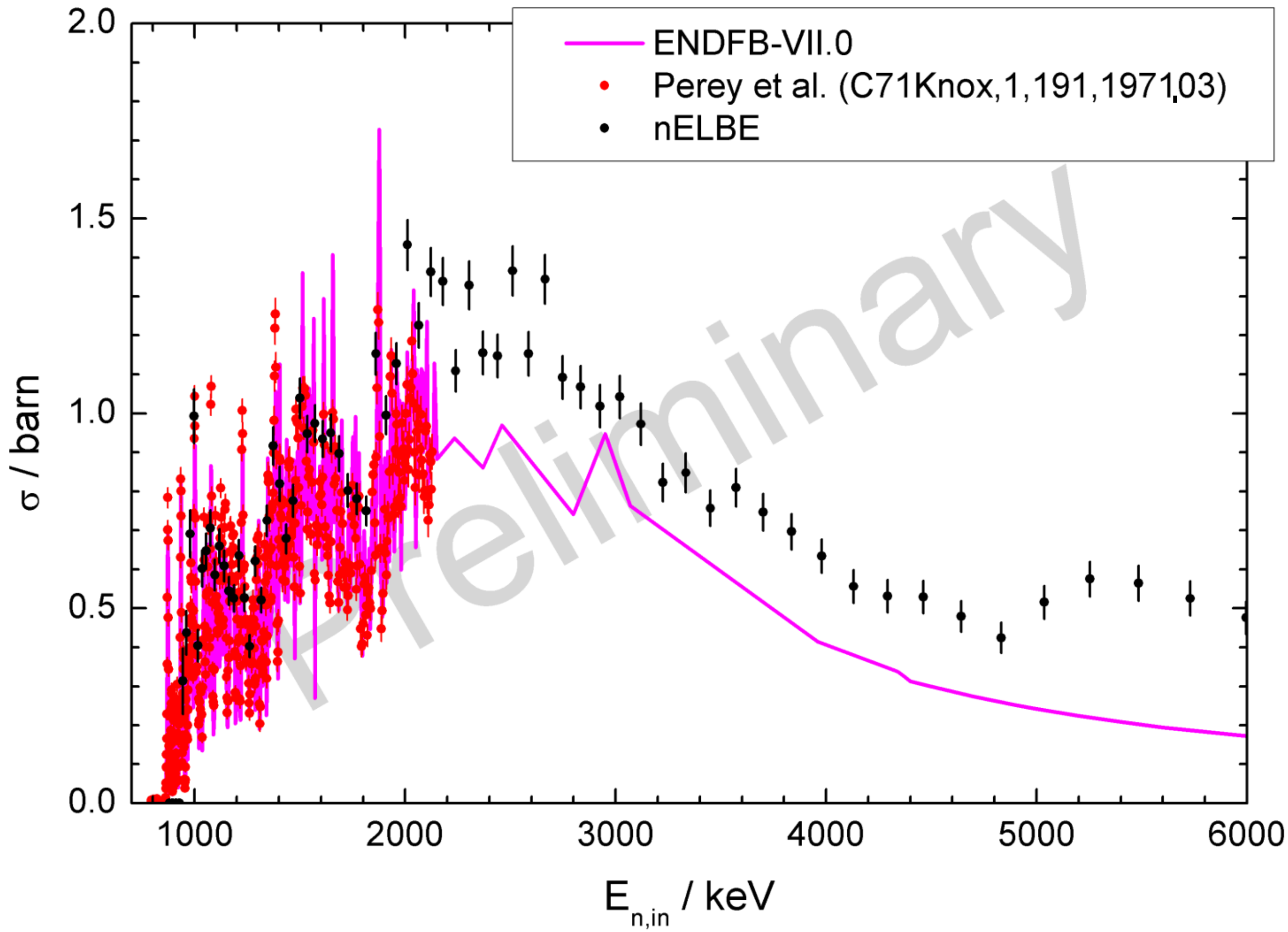
- Fe-56 (1.,2.,3. Level)
- Fe-54 (1. Level)
- ? 1700 keV

→is not:

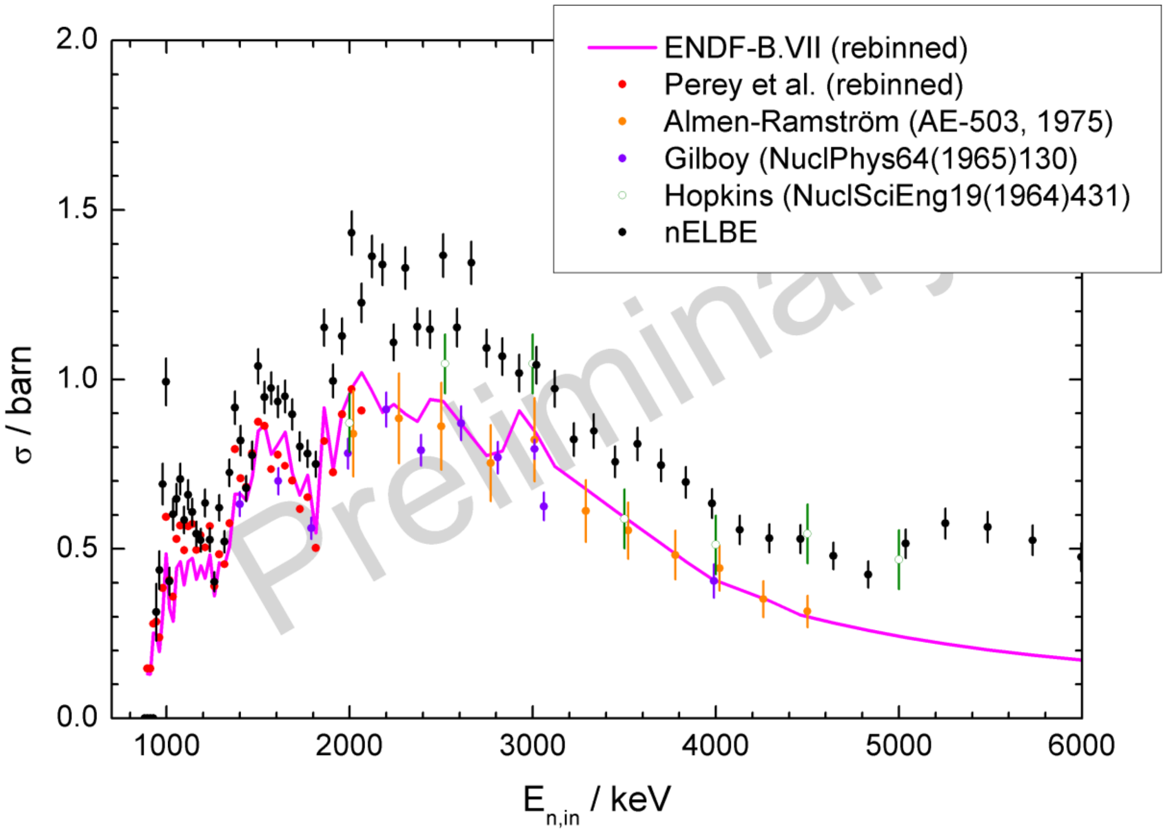
- Al-27
- C-14
- Fe-57
- Mn-55
- N-14
- O-16
- Pb-207
- Pb-208
- …

➔ double-scattering on Fe-56 1st level (847 keV)

The $^{56}Fe(n,n'\gamma)$ cross section for the 1st excited state

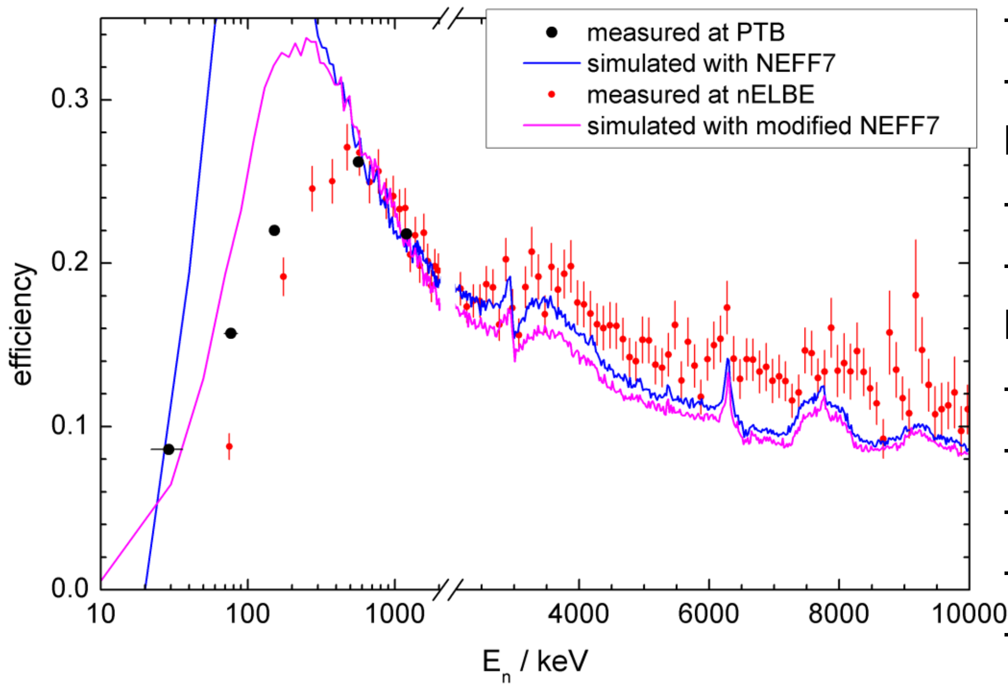


The $^{56}Fe(n,n'\gamma)$ cross section for the 1st excited state



<u>Uncertainties:</u>	@ 2 MeV
Fission chamber efficiency	2.2 %
Fission chamber counts	0.7 %
Fission chamber background	1.8 %
Loss due to ADC range	0.1 %
Scaling factor FC<->Target	0.9 %
→ Neutron flux	2.5 %
Sample in counts	2.3 %
Sample out counts	15.1 %
Normalization factor	1.7 %
BaF_2 efficiency	1.8 %
Plastic efficiency	5.1 %
→ Reaction rate	5.9 %
→ Cross section	6.4 %

Plastics Efficiency



Measurement at PTB:

- Monoenergetic neutrons
- Beyer et al., NIMA 575 (2007) 449

Measurement at FZD:

- nELBE spectrum
- Relative to ^{235}U fission chamber

Modified NEFF7:

- Cuboid detector geometry
- Double sided readout
- Scintillation light propagation/attenuation
- PMT Quantum efficiency
- Threshold = one photo electron per PMT

Problems:

In simulation:

- Unknown light output function at low energy transfer

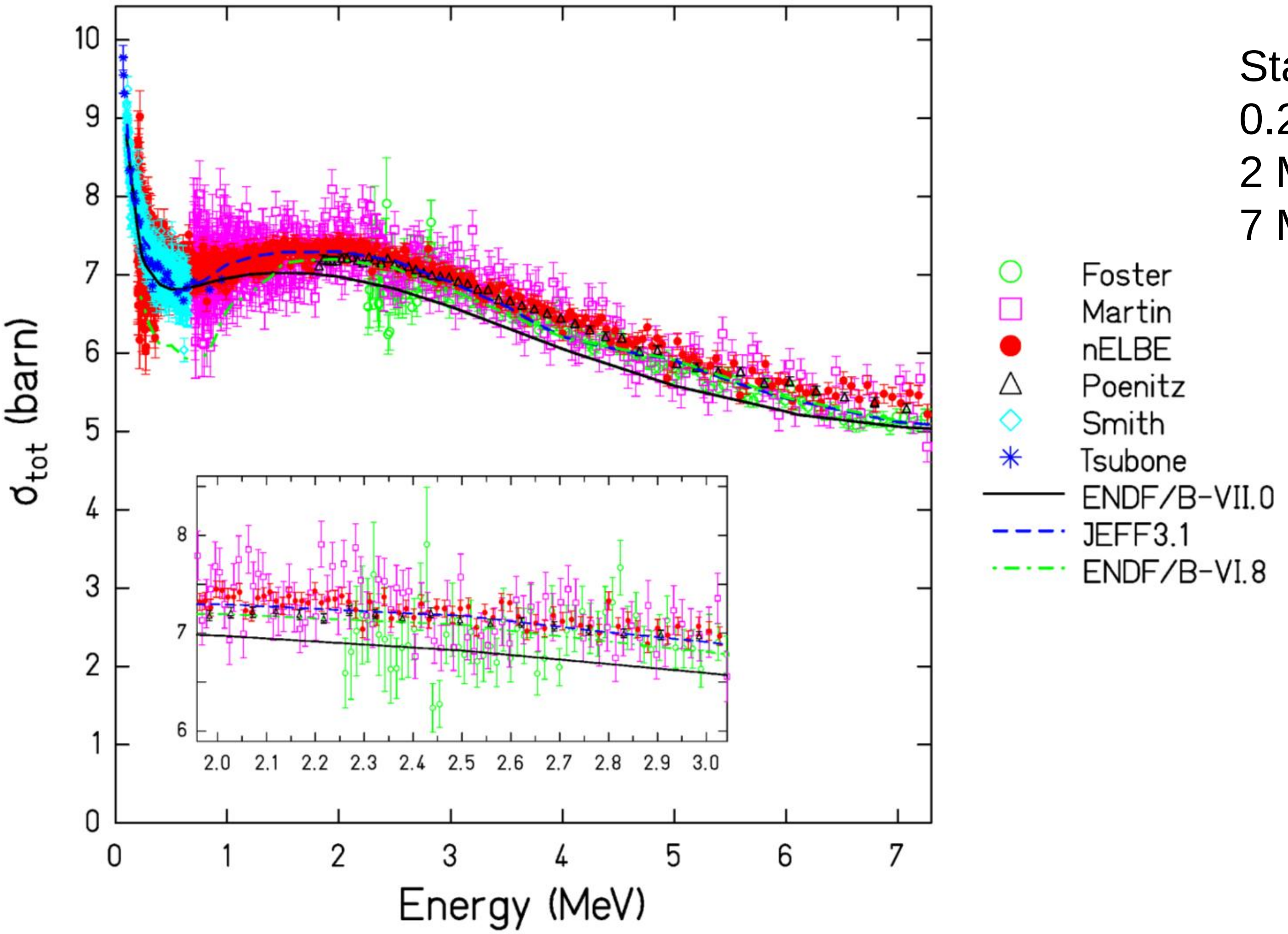
In measurement:

- Collimated beam at nELBE
- Influence of lead shielding

Summary and outlook

- nELBE is intended to deliver data on fast neutron induced reactions
- the ELBE electron beam delivers a high neutron flux
  (new injector will deliver ~60 times more)
- nELBE is the only photoneutron source at a superconducting cw linac
- total cross section measurements were performed on ^{nat}Ta

Total neutron cross section of ^{nat}Ta



Statistical uncertainty:
0.2 MeV – 5 %
2 MeV – 1.2 %
7 MeV – 2.3 %

Summary and outlook

- nELBE is intended to deliver data on fast neutron induced reactions
- the ELBE electron beam delivers a high neutron flux
  (new injector will deliver ~60 times more)
- nELBE is the only photoneutron source at a superconducting cw linac
- total cross section measurements were performed on Ta

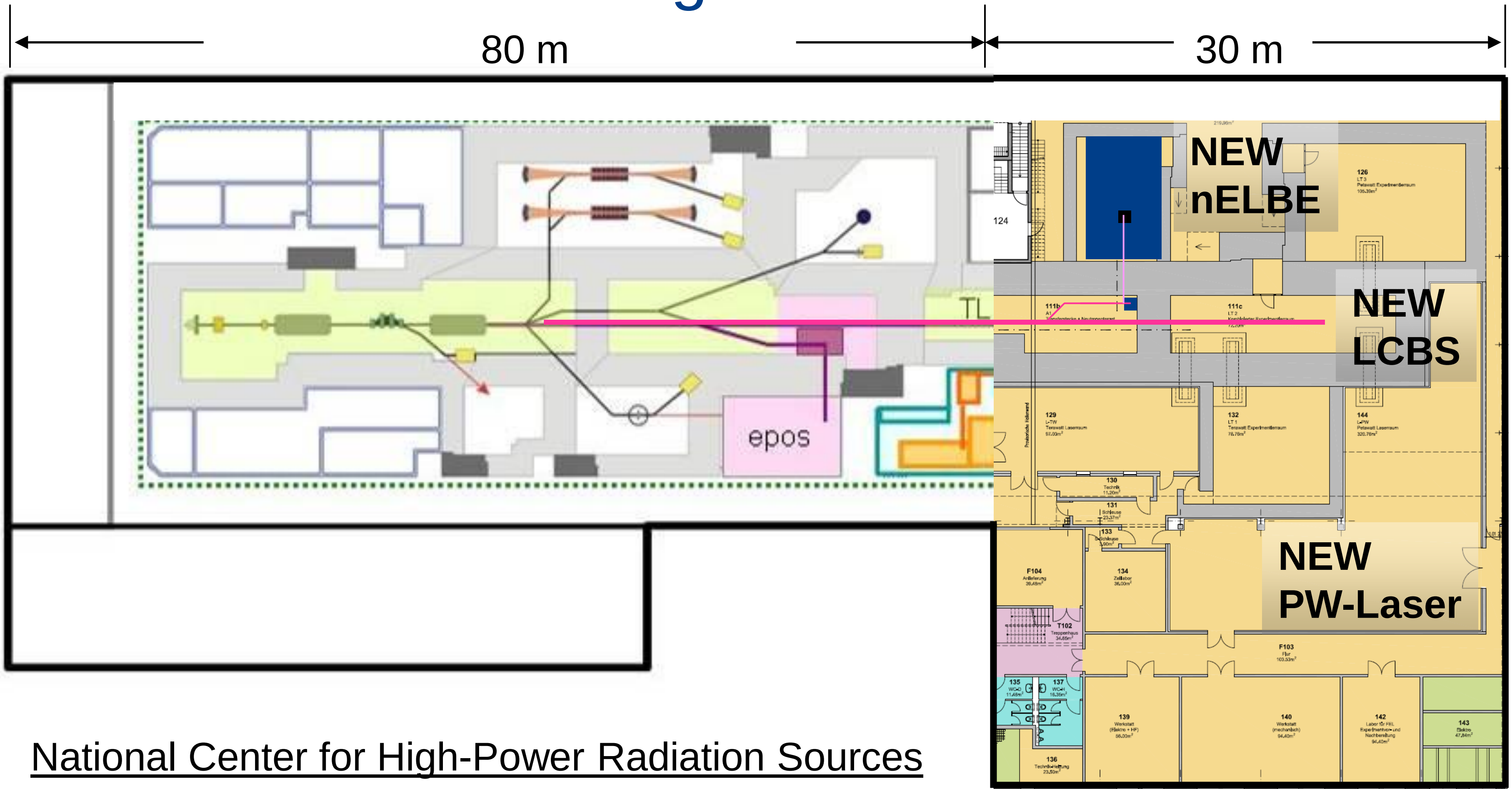
- first experiments were performed on inelastic neutron scattering using a double time of flight setup
- further investigations have to be done to:
  - re-measure plastics efficiency
  - determine influence of double scattering
  - correct for angular effects → neutron-gamma-angular correlation
- analyze data for higher levels of Fe-56 and 1st level of Fe-54

- measurement of Na-23(n,n'γ)

- prepare measurements of neutron fission cross sections

- new bigger experimental area within extension of ELBE facility

National Center for High-Power Radiation sources



ground breaking started April 2010

National Center for High-Power Radiation Sources

- X-ray source using Laser-Compton-Backscattering
- High-Power Laser (PW) for Ion Acceleration
- New Neutron Time-of-Flight Facility for Transmutation Studies

Thanks to all collaborators

FZD, Institute of Radiation Physics:

A.R. Junghans, D. Bemmerer, **E. Birgersson**, **E. Grosse**, R. Hannaske, A. Hartmann, K. Heidel, M. Kempe, M. Marta, R. Massarczyk, **A. Matic**, K.-D. Schilling, R. Schwengner, M. Sobiella, A. Wagner, The ELBE Crew

FZD, Institute of Safety Research:

E. Altstadt, C. Beckert, A. Ferrari, V. Galindo, K. Noack, F.-P. Weiss

FZD, Department Radiation Protection and Safety:

B. Naumann

FZD, Department Research Technology:

R. Schlenk, S. Schneider

TU Dresden:

H. Freiesleben, D. Gehre, M. Greschner, A. Klix, K. Seidel

Physikalisch Technische Bundesanstalt Braunschweig:

M. Mosconi, R. Nolte, S. Röttger

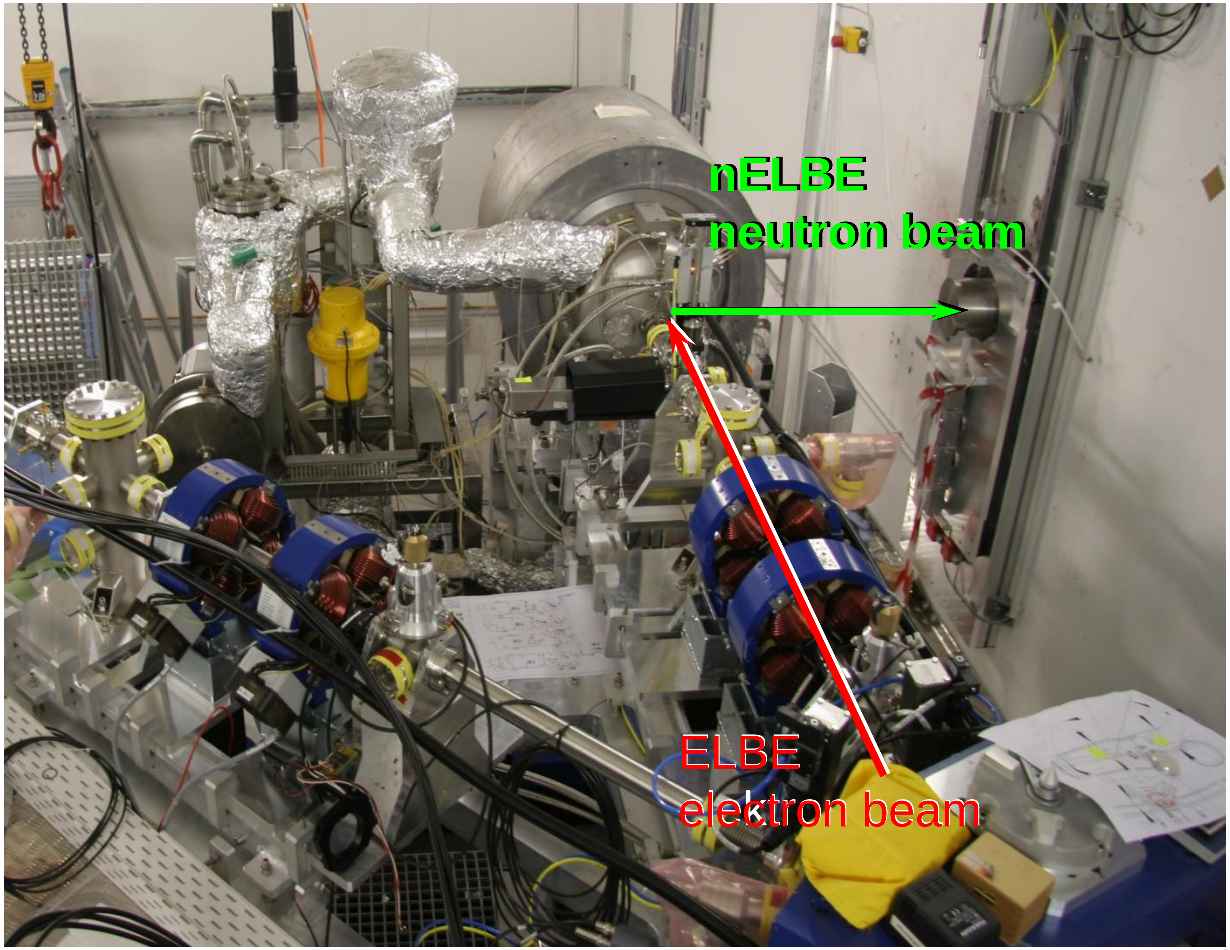
Others:

Th. Beyer, M. Erhard, J. Klug, K. Kossev, C. Nair, C. Rouki, G. Rusev

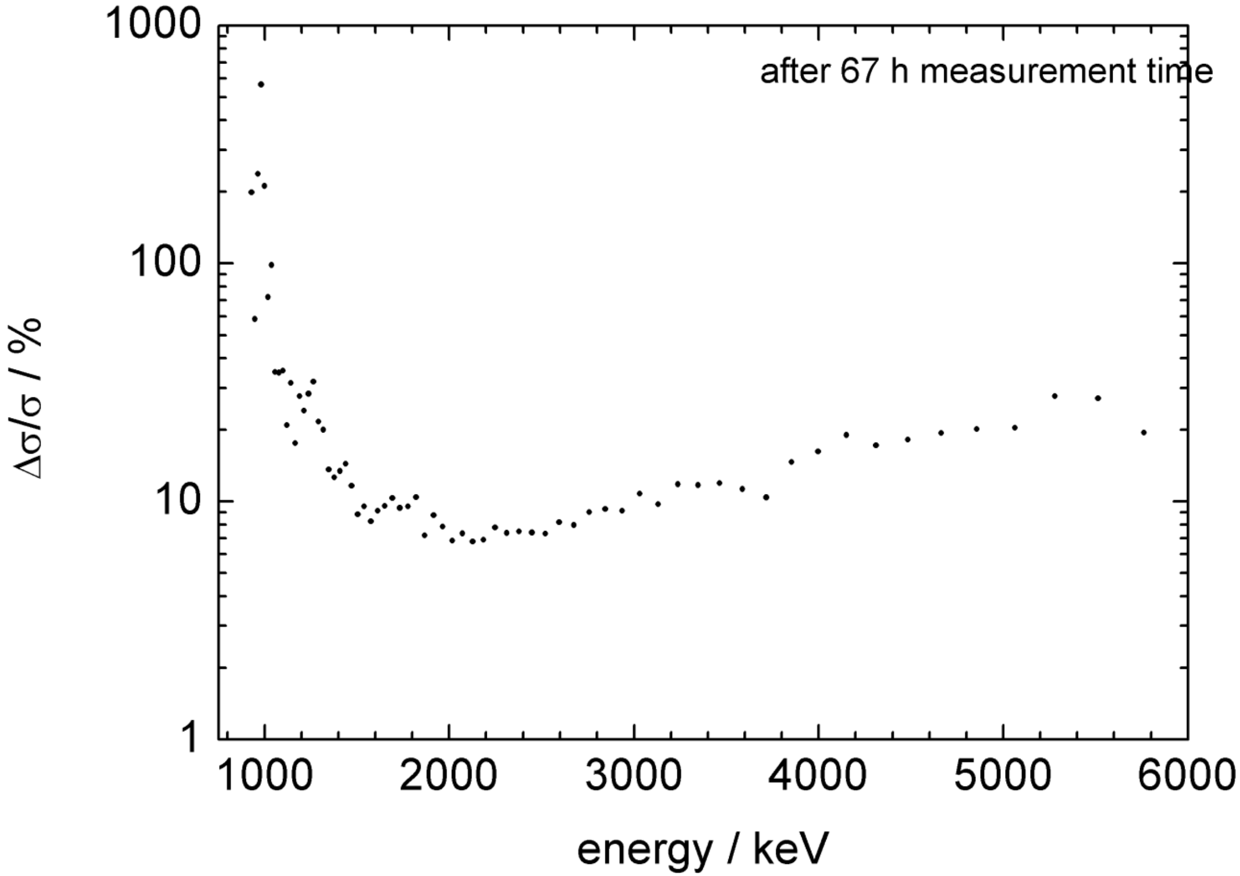
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Spare slides
(End of talk was one slide before)

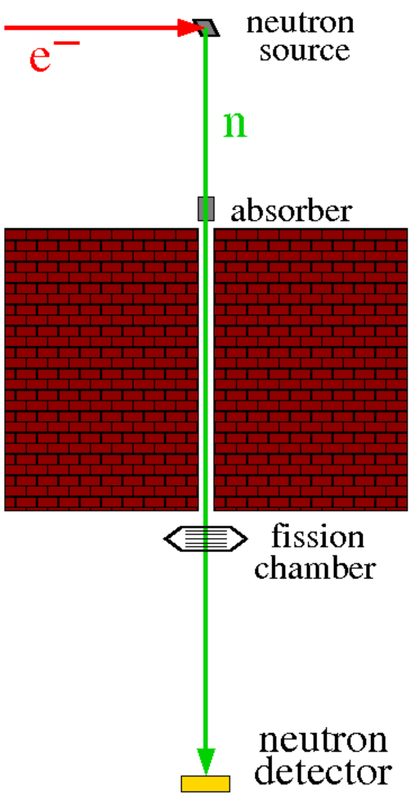
nELBE – neutron production

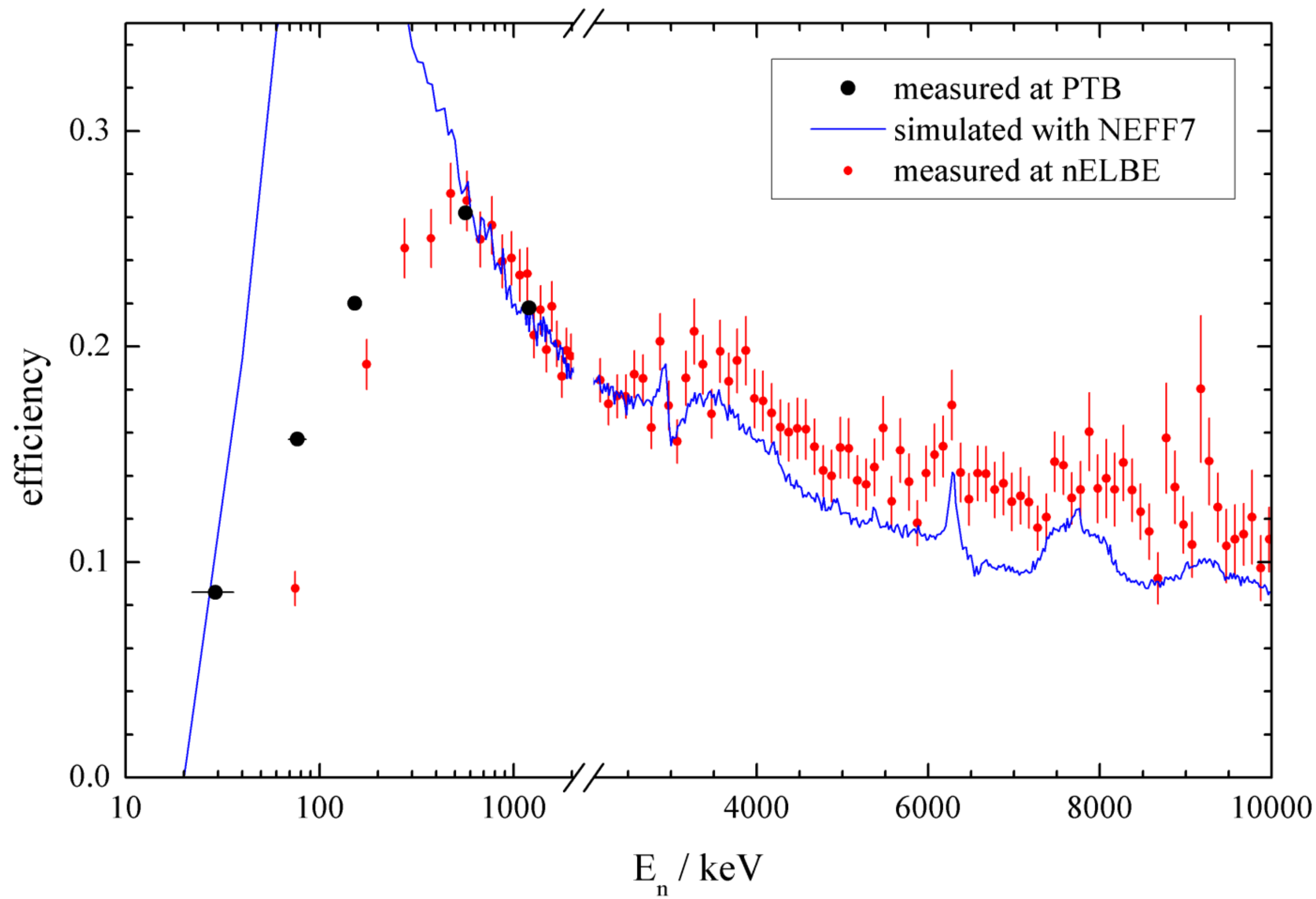


Uncertainties

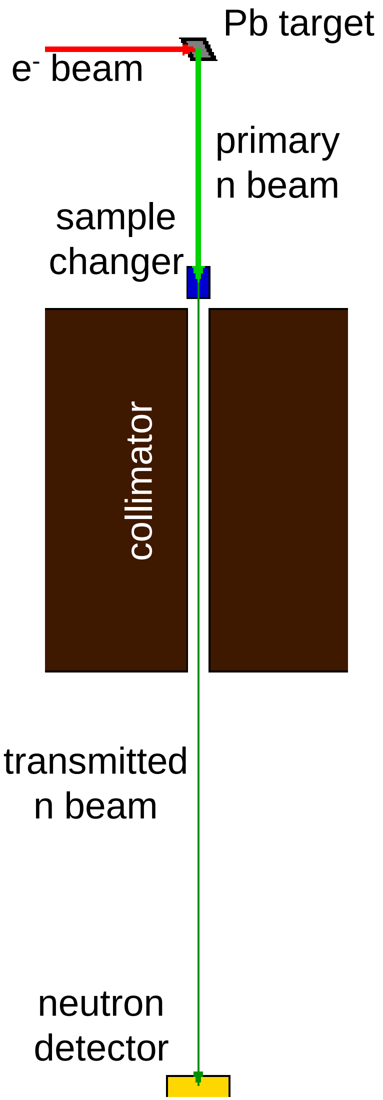


Neutron Detection Efficiency

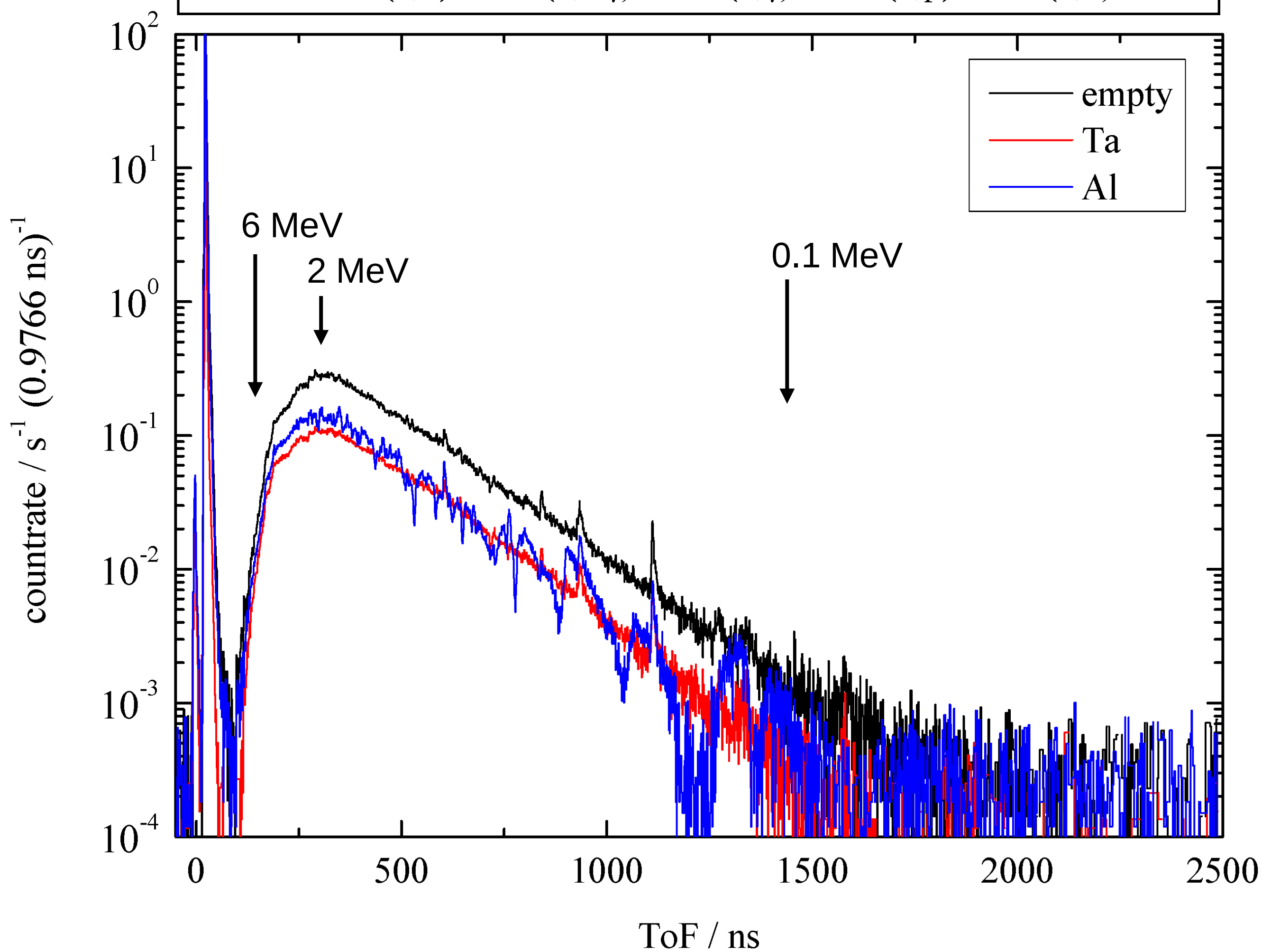




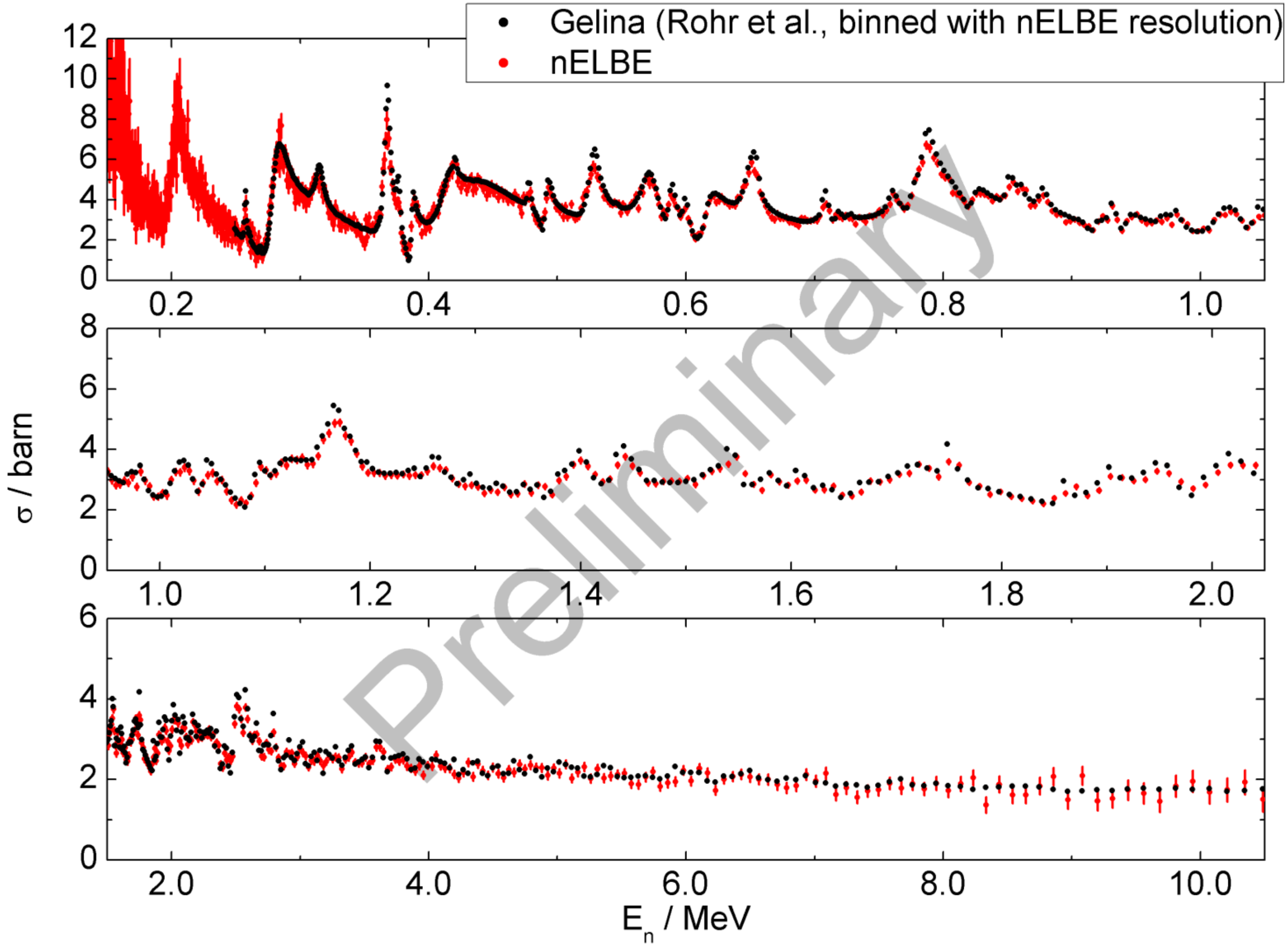
Experimental methods and results - Transmission



$$\sigma_{\text{total}} = \sigma_{(n,n)} + \sigma_{(n,n'\gamma)} + \sigma_{(n,\gamma)} + \sigma_{(n,p)} + \sigma_{(n,\alpha)} + \ldots$$



Total neutron cross section of ^{27}Al



good agreement with high resolution data

→

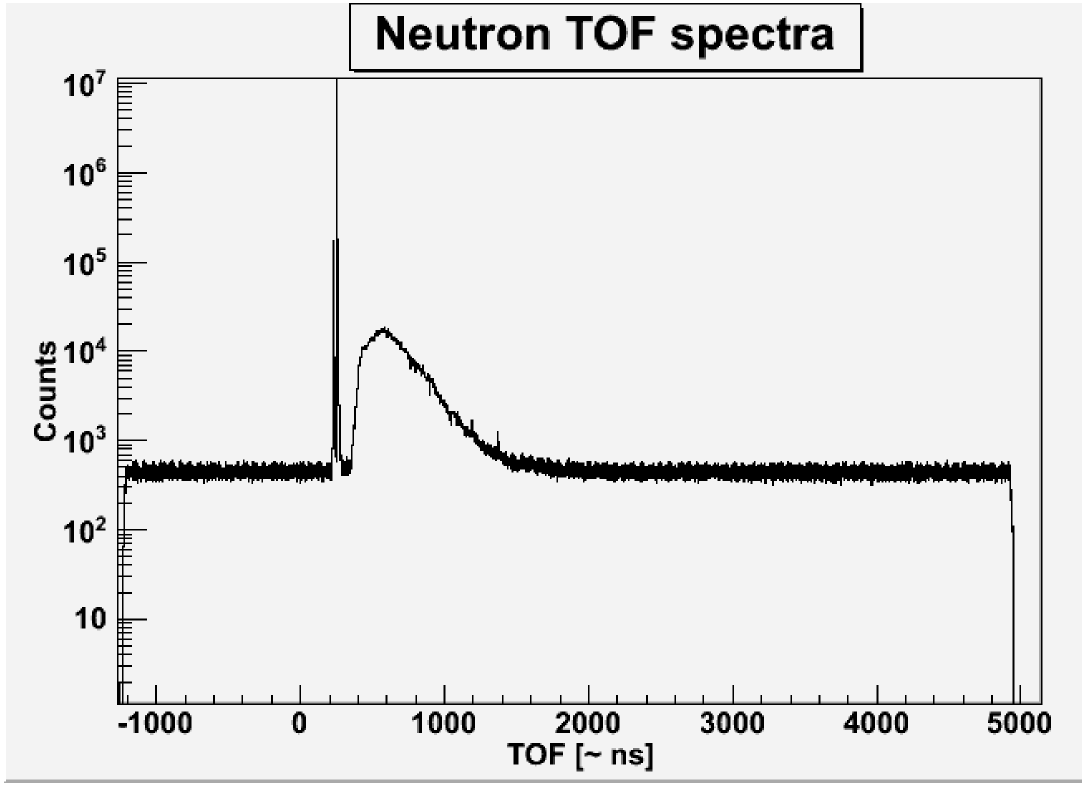
nELBE works fine for transmission measurements

Total neutron cross section

- Transmission measurement

$$T = \frac{N}{N_0} = \exp(-\sigma_{tot} n_t t)$$

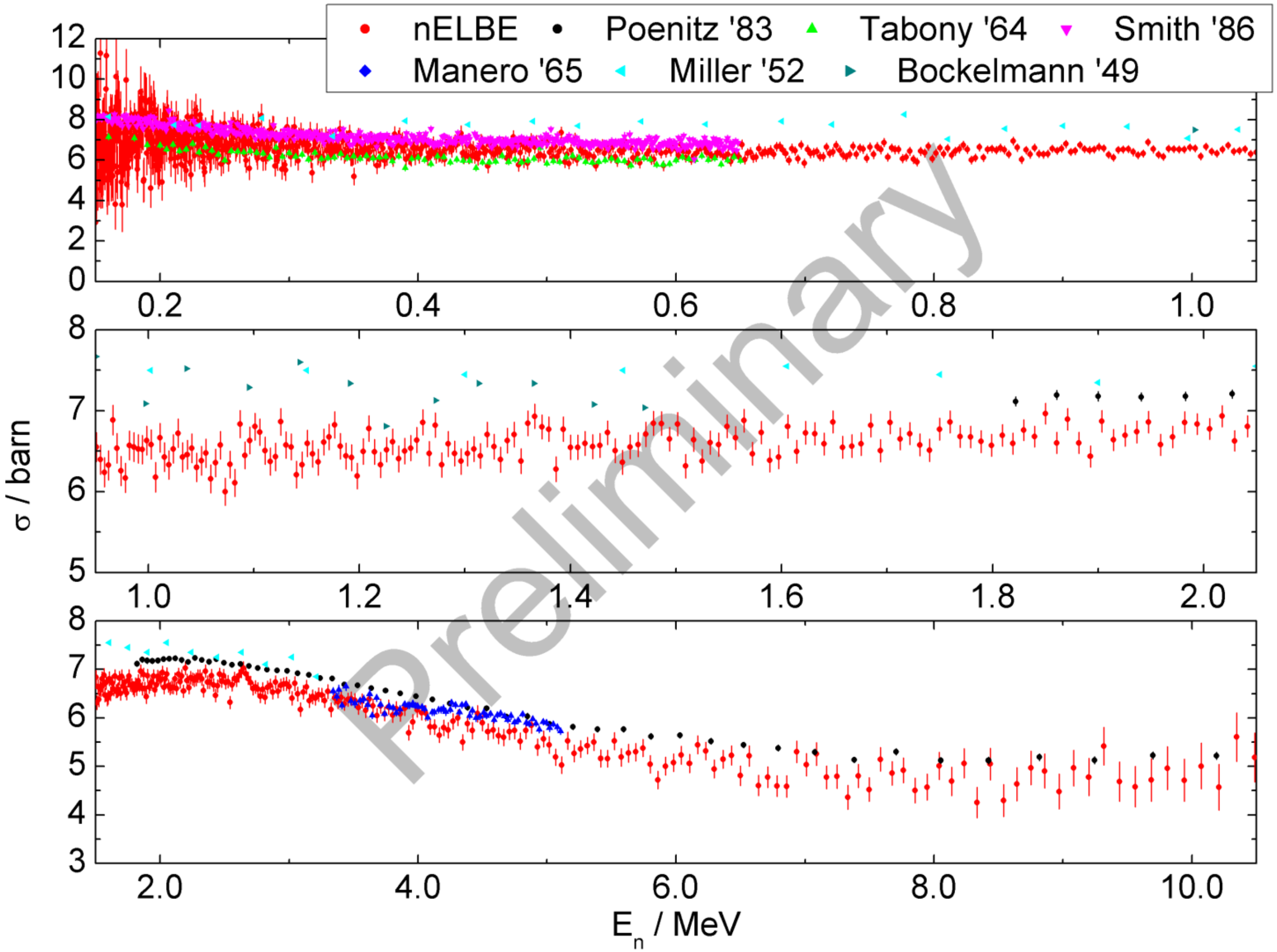
- Counting cycle*:
  80% target in (Ta, t = 3.52 cm)
  20% target out
- Pb absorber to reduce bremsstrahlung flash (t_{Pb} = 3 cm)
- Measurement time 48 hours
  live time - target in 92%
  live time – target out 80%
  measured with scalers



Flight path: 6.5 m
Repetition rate: 100 kHz

* Y. Danon, NIM A 485 (2002) 585

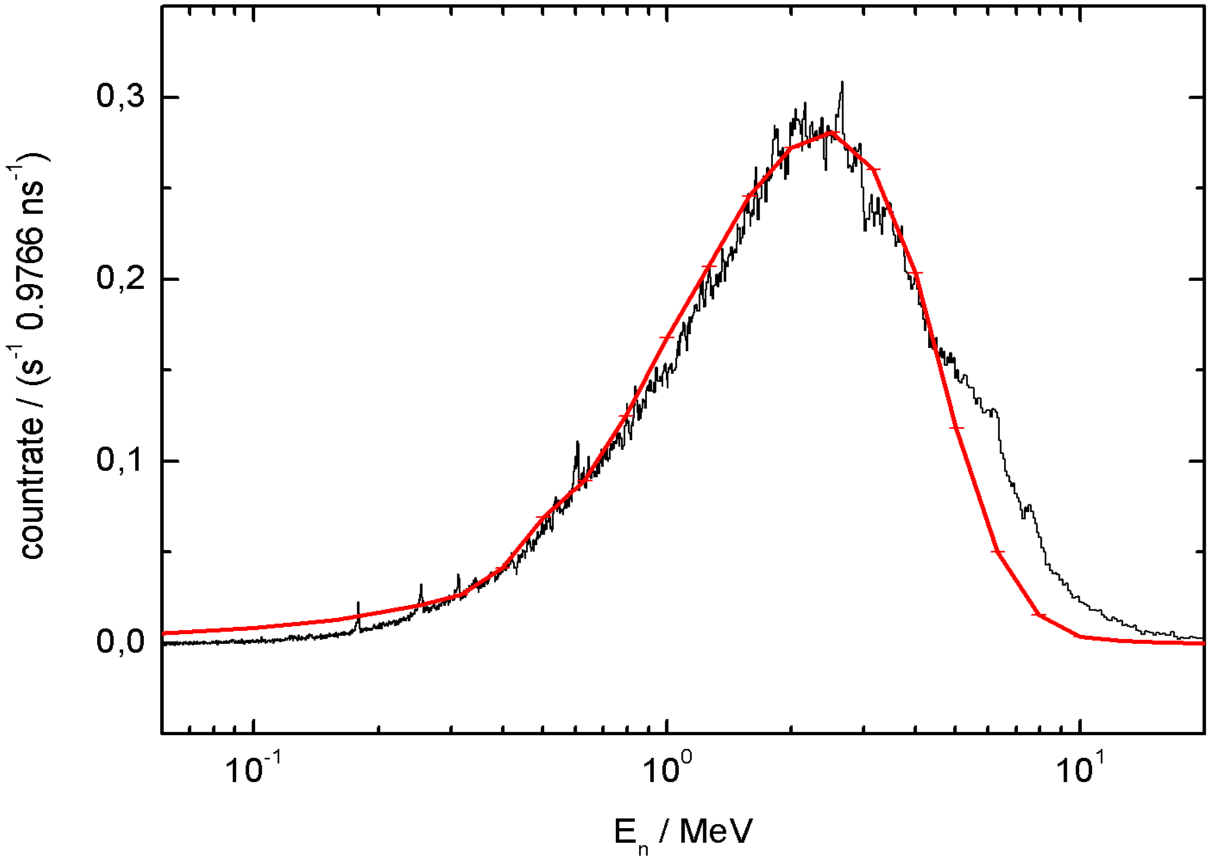
Total neutron cross section of ^{181}Ta



nELBE could close gap between 0.6 and 2.0 MeV

further investigations with different sample thicknesses are ongoing

nELBE Neutronenspektrum



- Elektronenstrahlenergie 33 MeV
- Simulationsrechnung stimmt gut mit der Messung überein
- Neutronenspektrum wie in einem schnellen Reaktor

Neutron beam intensity comparison

Facility	CERN n-ToF	CERN n-ToF Phase-2	LANL NSC	ORNL SNS	FZK VdG	ORNL ORELA	IRMM GELINA	nELBE	nELBE with SRF-gun
Pulse charge / nC	ca. 10^3	ca. 10^3	$4 \cdot 10^3$	$3 \cdot 10^4$	0.01	ca. 100	ca. 100	0.08	1.8
Power / kW	10	10	60	1000	0.4	8	7	5	40
Pulse rate / s^{-1}	0.4	0.4	20	60	$2.5 \cdot 10^5$	500	800	$5 \cdot 10^5$	$5 \cdot 10^5$
Flight Path / m	183	Ca. 20	60	84	0.8	40	20	4	4
n-pulse length / ns	>7	>7	125	100-700	ca. 1	>4	>1	< 0.4	< 0.4
E_{min} / eV	0.1	0.1	1	0.1	10^3	10	10	$2 \cdot 10^5$	$2 \cdot 10^5$
E_{max} / eV	$3 \cdot 10^8$	$3 \cdot 10^8$	ca. 10^8	ca. 10^8	$2 \cdot 10^5$	$5 \cdot 10^6$	$4 \cdot 10^6$	$7 \cdot 10^6$	$7 \cdot 10^6$
resolution at 1 MeV / %	0.5%	5%	> 10 %	> 20 %	ca. 5 %	< 1 %	< 2 %	ca. 1 %	ca. 1 %
n flux density / $s^{-1}cm^{-2}$ (E decade)$^{-1}$	10^5	ca.10^7	ca. 10^6	10^6 -10^7	ca. 10^4	10^4	$4 \cdot 10^4$	$1 \cdot 10^5$	$3 \cdot 10^6$

Generation IV nuclear reactor types

as selected by an international panel to be designed and evaluated numerically on the basis of accurate data, eventually to be tested later in integral experiments.

	type	dedication
GFR a	Gas-Cooled Fast Reactor	Efficient actinide management; closed fuel cycle. Delivers electricity, hydrogen, or heat.
LFR b	Lead-Cooled Fast Reactor	Small factory-built plant; closed cycle with very long refuelling interval (15-20 years). Transportable to where needed for production of distributed energy, drinkable water, hydrogen. Also larger LFRs are under consideration.
MSR c	Molten Salt Reactor	Tailored to an efficient burn up of Pu and MA; liquid fuel avoids need for fuel fabrication; inherently safe. Ranked highest in sustainability; best suited for the thorium cycle.
SFR d	Sodium-Cooled Fast Reactor	Efficient actinide management; conversion of fertile U; closed cycle.
SCWR e	Super Critical Water-Cooled Reactor	Efficient electricity production; option for actinide management; once-through uranium cycle in the most simple form; closed cycle also possible.
VHTR f	Very-High Temperature Reactor	Once-through uranium cycle; electricity production and heat for petro-chemical industry, thermo-chemical production of hydrogen.

Only for type e water is selected as coolant, thus accurate fast neutron data are required.

GENERATION IV NUCLEAR ENERGY SYSTEMS

	Neutron Spectrum	Fuel Cycle	Size	Applications	R&D
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	Med	Electricity, Actinide Mgmt., Hydrogen	Fuels, Materials, Safety
Lead-alloy Fast Reactor (LFR)	Fast	Closed	Small to Large	Electricity, Actinide Mgmt., Hydrogen	Fuels, Materials compatibility
Sodium Fast Reactor (SFR)	Fast	Closed	Med to Large	Electricity, Actinide Mgmt.	Advanced Recycle
Very High Temp. Gas Reactor (VHTR)	Thermal	Open	Med	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Supercritical Water Reactor (SCWR)	Thermal, Fast	Open, Closed	Large	Electricity	Materials, Safety
Molten Salt Reactor (MSR)	Thermal	Closed	Large	Electricity, Actinide Mgmt., Hydrogen	Fuel, Fuel treatment, Materials, Safety and Reliability