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FOR NUCLEAR RESEARCH

Measurement of neutron energy spectra in the region of large angles in Xe + CsI collisions at energy of 3.8 A GeV

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Experiments studied of neutron production in collisions of heavy nuclei at high energies

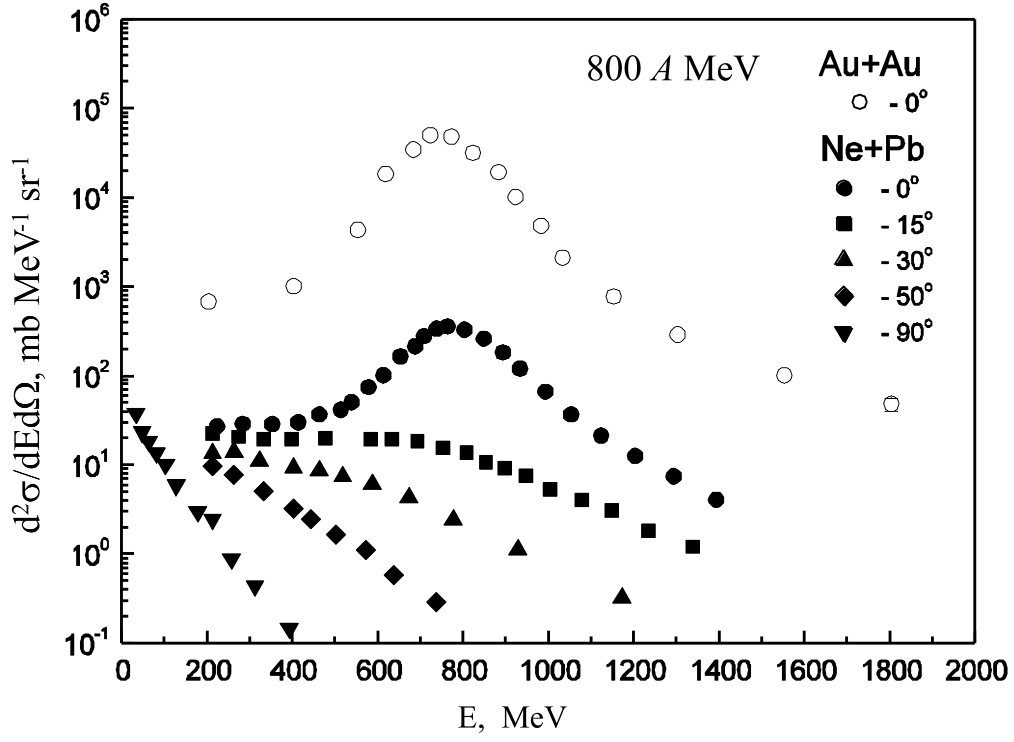
Lab./Accelerator (Year)	Reaction	Ion Energy	Method & Neutron Detector	Neutron Data
LBN/Bevalac (1988)	Nb + Nb Au + Au	0.8 A GeV	TOF, Plastic scintillators	$d^2\sigma/dEd\Omega$ $\theta = 0^o$, E > 200 (20) MeV
LBN/Bevalac (1990)	Nb + Nb Au + Au	0.8 A GeV	TOF, Plastic scintillators	$d^2\sigma/dEd\Omega$ $\theta = 0\text{-}42^o$, E > 200 (20) MeV
LBN/Bevalac (1995)	Au + Au	0.15, 0.25, 0.4, 0.6	TOF, Plastic scintillators	$d^2\sigma/dEd\Omega$ $\theta = 3\text{-}90^o$, E > 30 MeV
CERN/SPS (NA49) (1998)	Pb + Pb	158 A GeV	Veto hadronic calorimeter	$<M_n> = f(b)$ $\theta = 0^o$
BNL/AGS (1999, 2018)	Au + Pb	11.5 A GeV/c	Hadronic calorimeter	$d^2N/dydp_T$ $\theta = 0\text{-}10^o$
NIRS/HIMAC (2001 – 2006)	Ar, Kr, Xe + Cu, Pb	0.4 A GeV	TOF, Liquid organic scintillator	$d^2\sigma/dEd\Omega$ $\theta = 5\text{-}80^o$, E > 5 MeV
CERN/LHC (ALICE) (2020)	Pb + Pb	$\sqrt{s_{NN}}$ = 5.02 TeV	ZDC hadronic calorimeter	$<M_n> = f(b)$ $\theta = 0^o$
GSI/SIS (2023)	$^{107,124}Sn$, ^{124}La + Sn	0.6 A GeV	TOF, LAND	$d^2N/dydp_{T,}$ $<M_n> = f(Z_{bound})$ $\theta \leq 2^o$
JINR/Nuclotron (BM@N) Present Experiment	Xe + CsI (Bi + Bi)	3.8 A GeV	TOF, Stilbene	$d^2\sigma/dEd\Omega$ $\theta > 90^o$, 2 < E < 200 MeV

Example of Results

TOF measurements

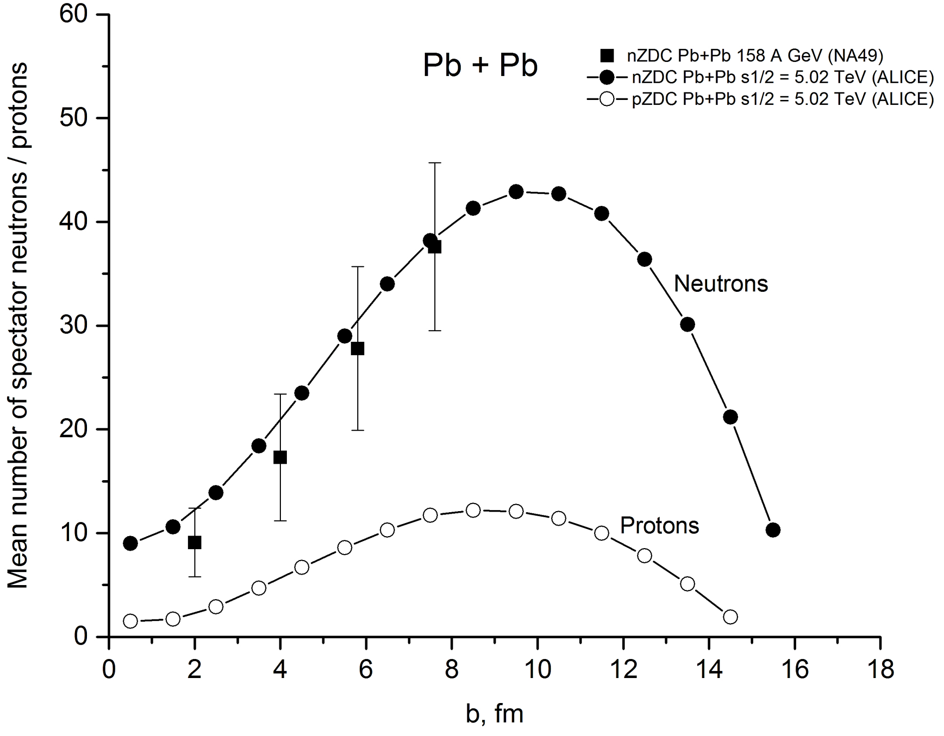
Neutron energy spectra

(BEVALAC experiments)

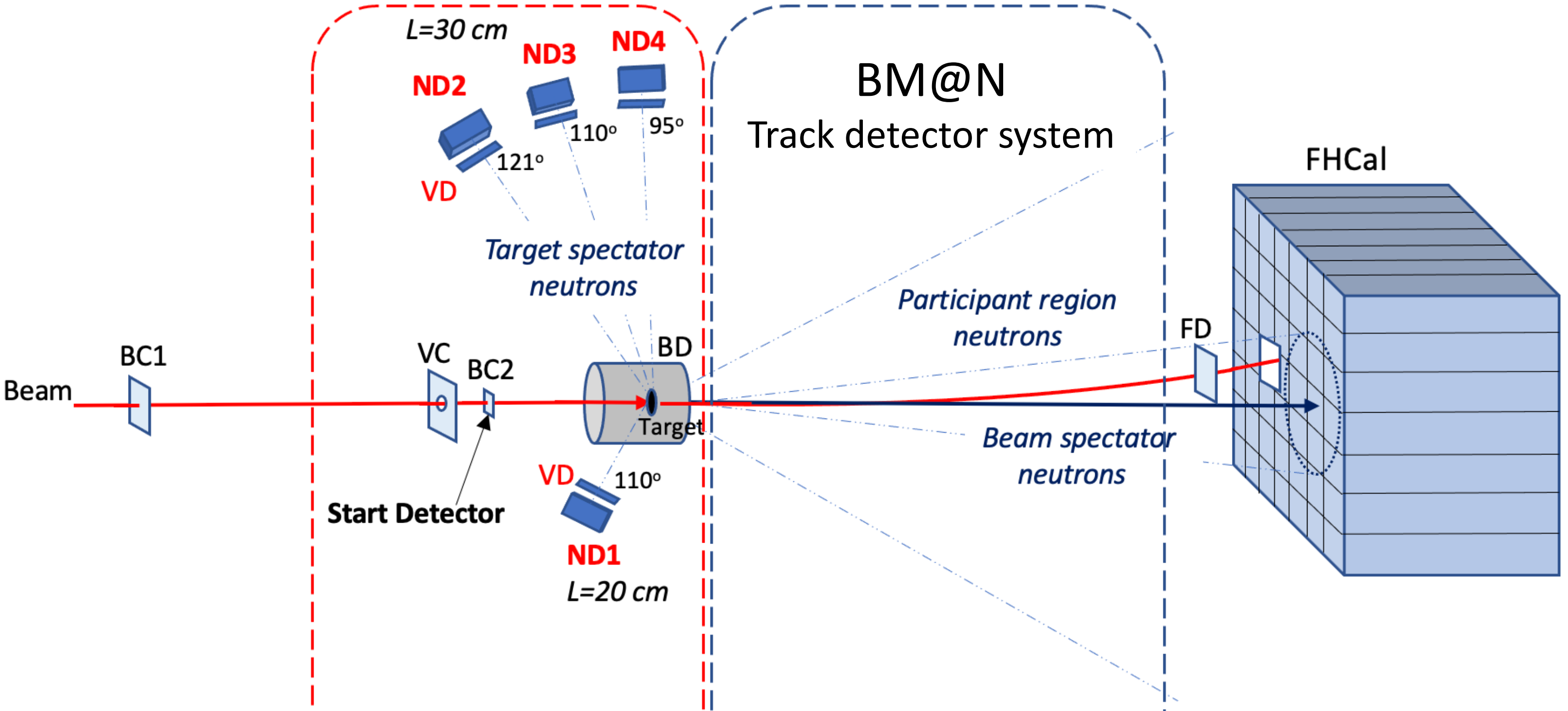


ZDC measurements

$<M_n>$ from decay of beam ion spectator measured at SPS and LHC energies as a function of centrality



Compact Neutron TOF Spectrometer



TOF measurements:

BC2(T0) – beam start detector

ND1 – ND4 – neutron stop detectors

Beam

Beam ions: ^{124}Xe
Energy: 3.8 *A* GeV
Intensity: ~ 6 10^5 ion/spill
Spill duration: ~ 2.5 s

Target

CsI
D32 × 1.75 mm

Interaction trigger:

$IT = BC1 * BC2 * \overline{VC} * \overline{FD} * BD(N>3)$

Method and Experimental difficulties

Time-of-Flight (TOF) method is applied for precise measurement of neutron energy spectra in energy interval 2 – 200 MeV.

The method requires:

- ✓ a long flight path
- ✓ a start and neutron detectors with well known efficiency and a good time resolution
- ✓ suppression and minimization of gamma-ray and neutron backgrounds

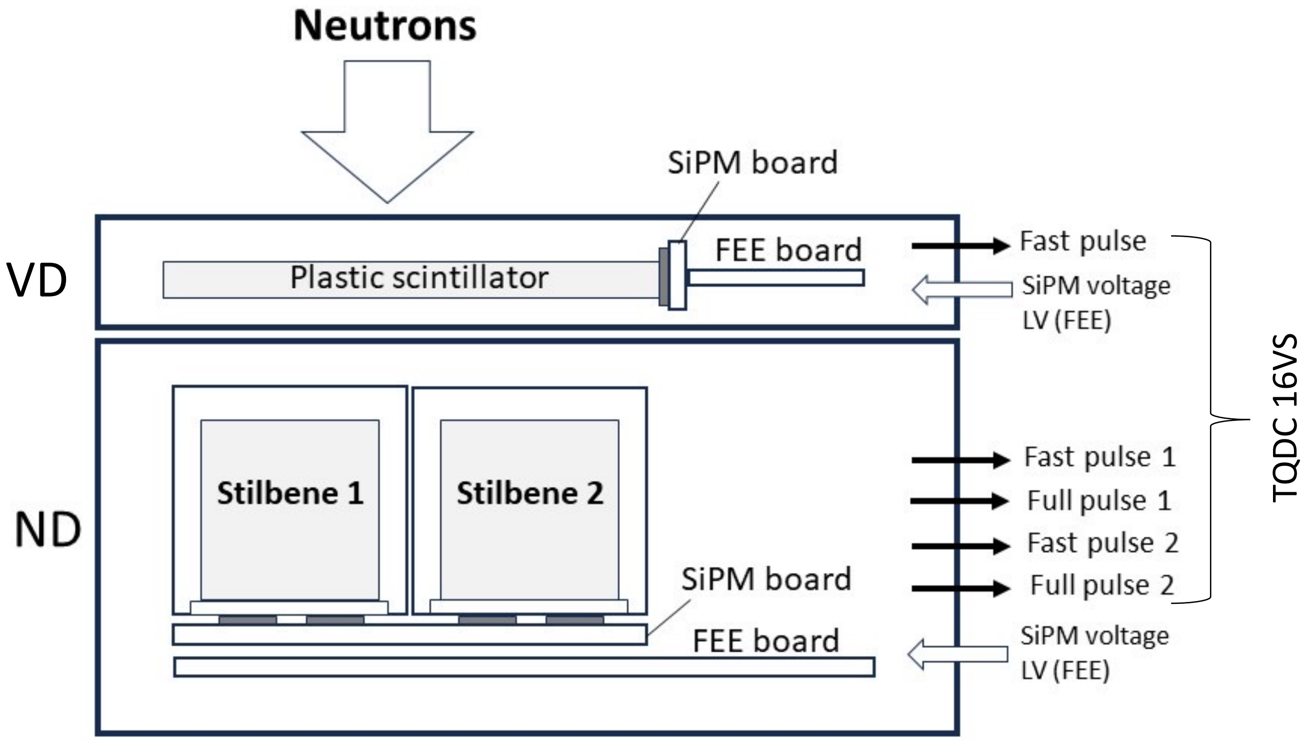
The last point is very important for measurements in open geometry (without collimators) and
it requires to remove any massive materials around (especially around neutron source and detectors).

Specific difficulty in BM@N experiment is location of TOF spectrometer inside large BM@N magnet with B = 0.9 T.

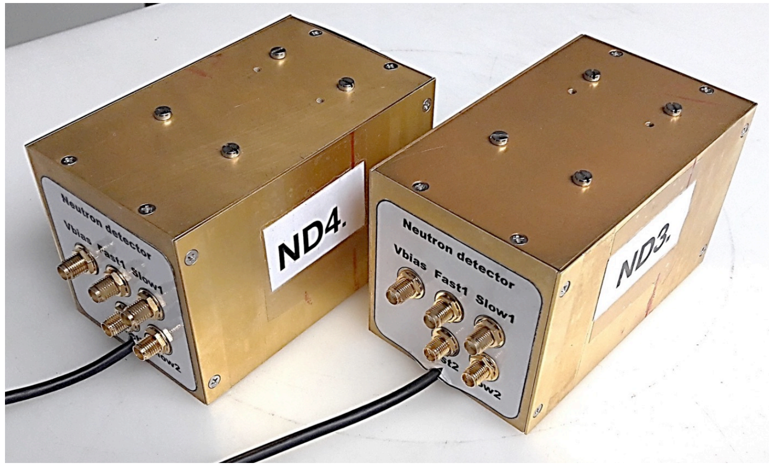
Additional requirements:

- ✓ small flight path $L < 0.5$ m
- ✓ to use SiPMs instead PMTs in neutron detectors for registration of scintillation photons

Neutron Detectors



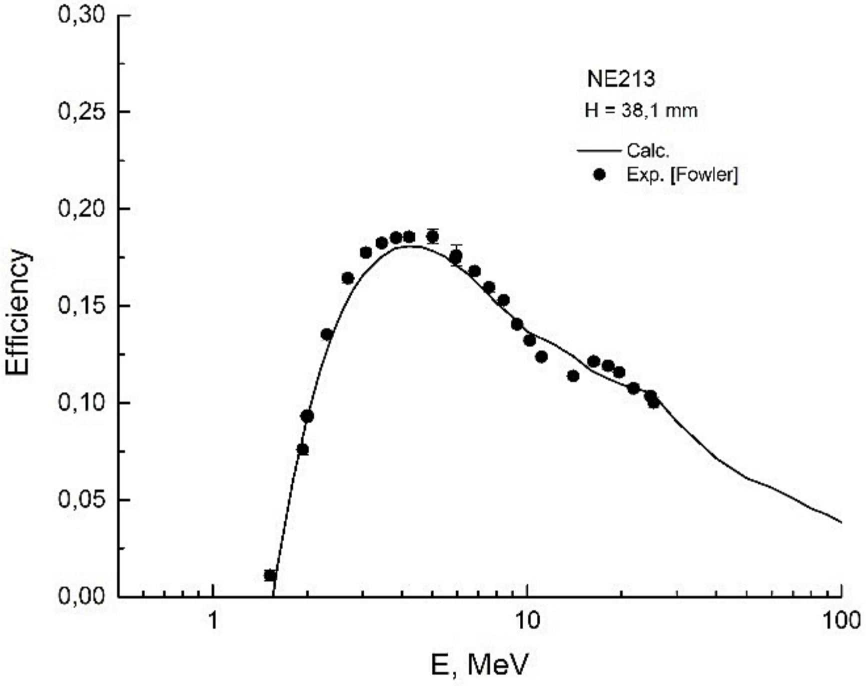
Detection of scintillation photons with four SiPMs 6×6 mm^2, SensL, J ser.

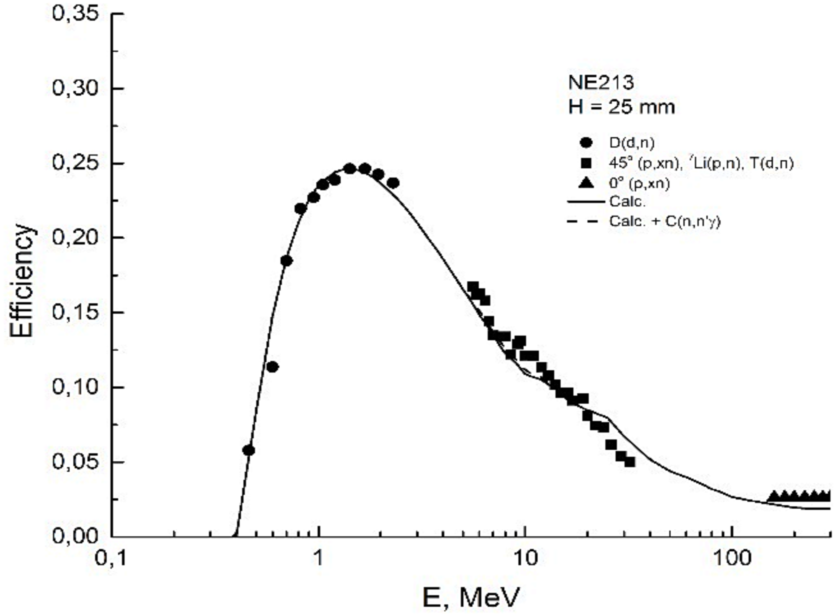


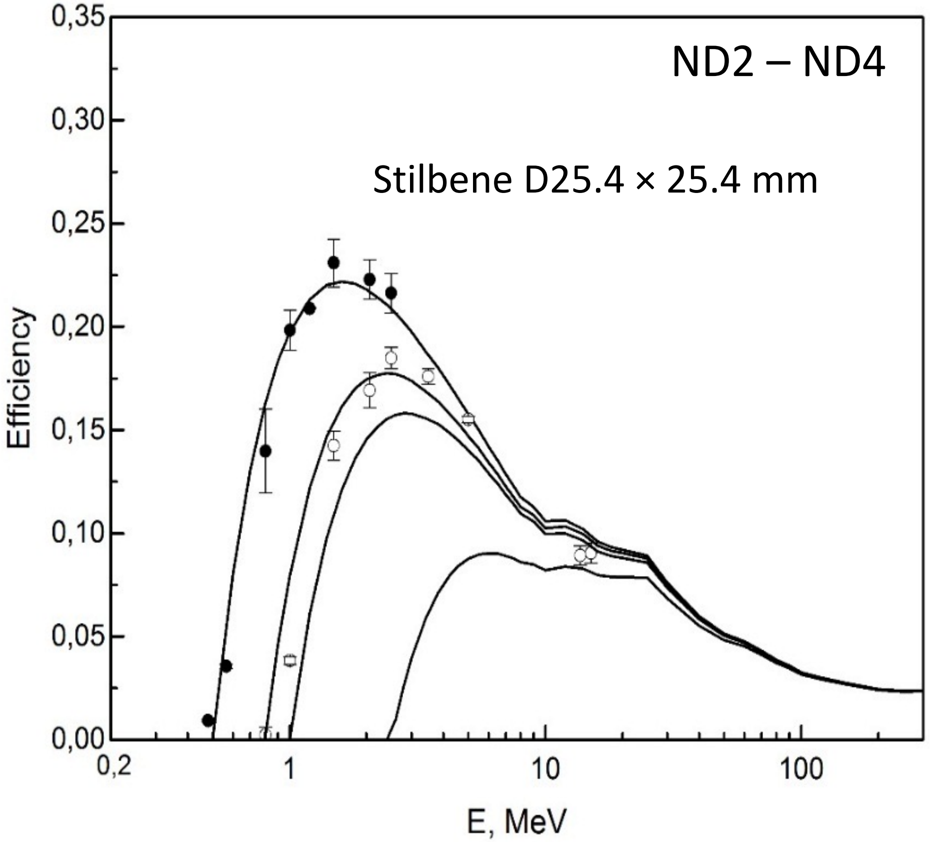
Detector	Stilbene*	Angle θ	Flight path
ND1	D3×1 cm	110°	22.1 cm
ND2	D2.5×2.5 cm	121°	31.9 cm
ND3	D2.5×2.5 cm	110°	31.2 cm
ND4	D2.5×2.5 cm	95°	28.6 cm

* 2 units per detector

Neutron Detector Efficiency







$$\varepsilon = \left(1 - e^{-\Sigma h}\right)\left[\frac{\Sigma_H}{\Sigma}\left(1 - \frac{B_H}{E}\right) + \frac{\Sigma_C}{\Sigma}\left(1 - \frac{B_C}{E}\right)\right]$$

$\Sigma = \Sigma_c + \Sigma_H = n_C\,\sigma ch(nC) + n_H\,\sigma(np)$

σ_{ch}(nC) – cross section of ch. particle production in reactions with carbon nuclei

σ(np) - cross-section of np scattering

h – the thickness of the stilbene crystal

B_c – the threshold for reactions with carbon

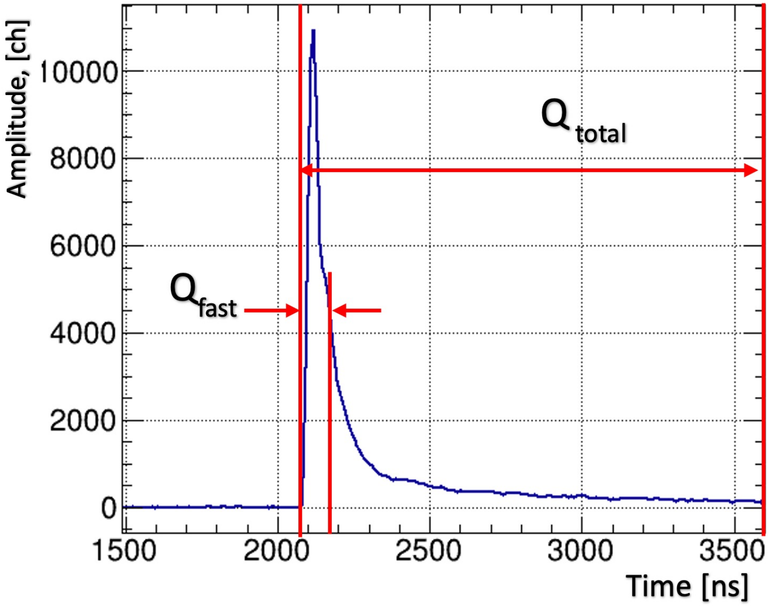
B_h – the threshold for recoil protons in np scattering

Pulse shape n/γ- discrimination

Quality of pulse shape discrimination:

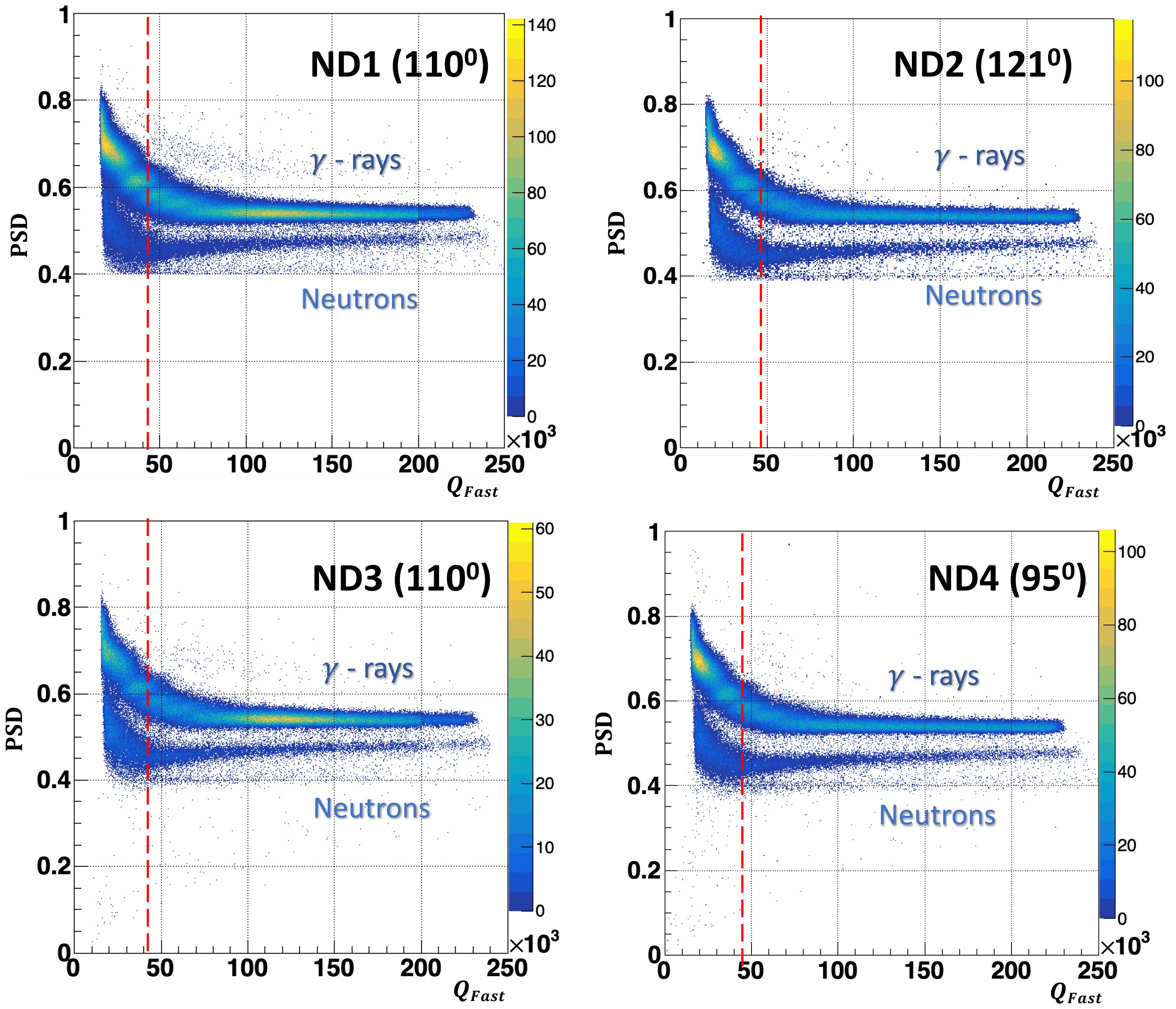
$$PSD = \frac{Q_{fast}}{Q_{total}}$$

Waveform of Neutron Detector (TQDC)



T_{fast} = 0.12 μs : time window for charge integration Q_{fast}

T_{total} = 1,5 μs. : time window for charge integration Q_{total}

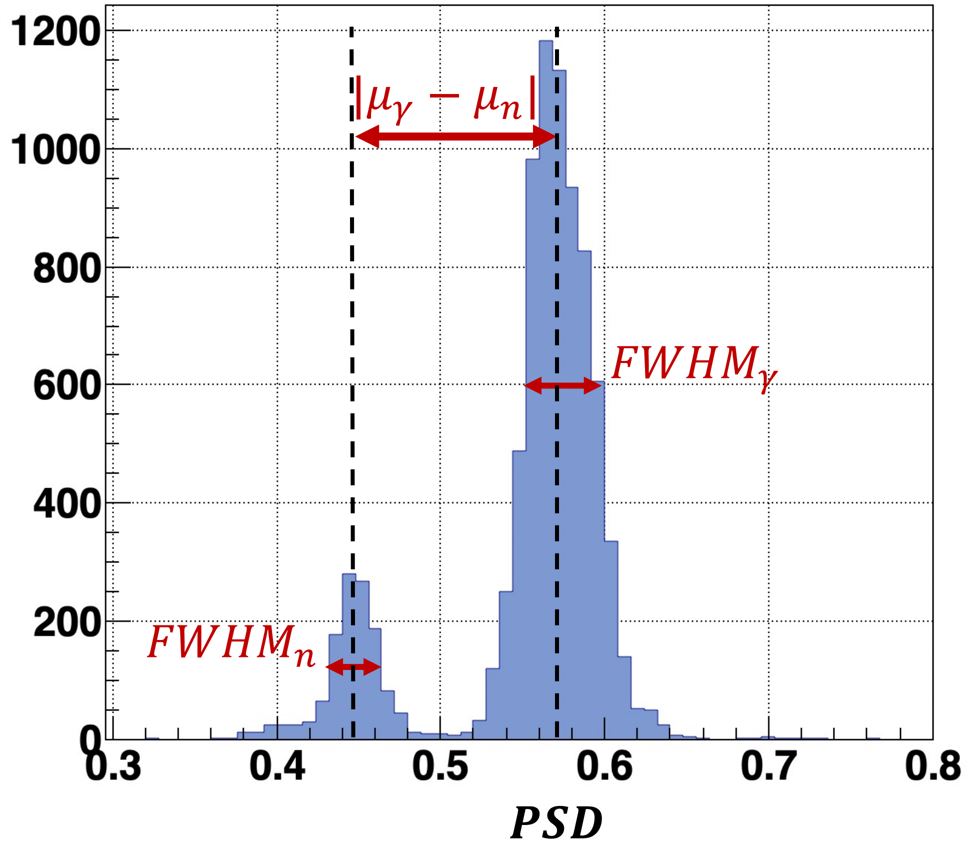


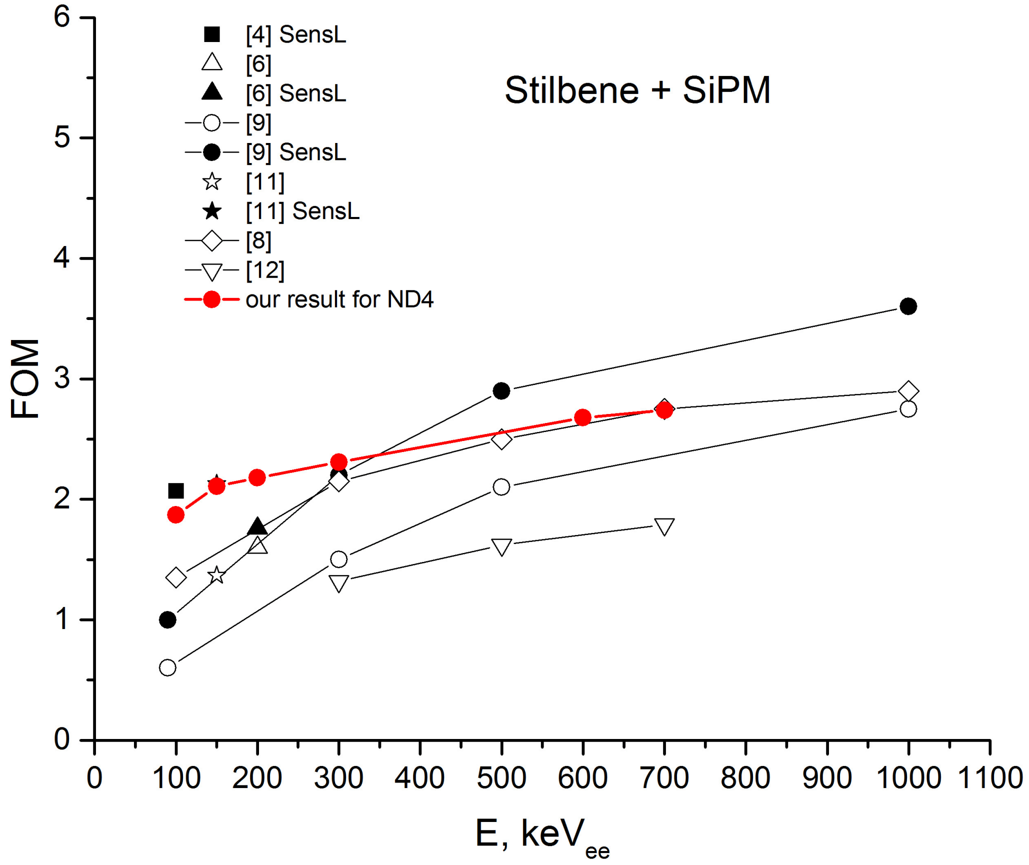
Pulse shape n/γ- discrimination

Figure of Merit:

$$FOM = \frac{|\mu_\gamma - \mu_n|}{FWHM_\gamma + FWHM_n}$$

	$ND1$	$ND2$	$ND3$	$ND4$
FOM(1 MeV)	1.98	2.17	2.28	2.47

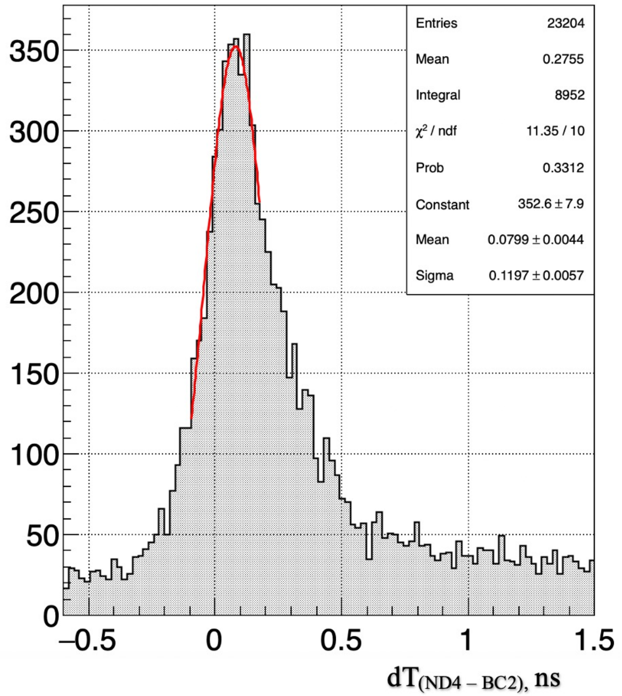




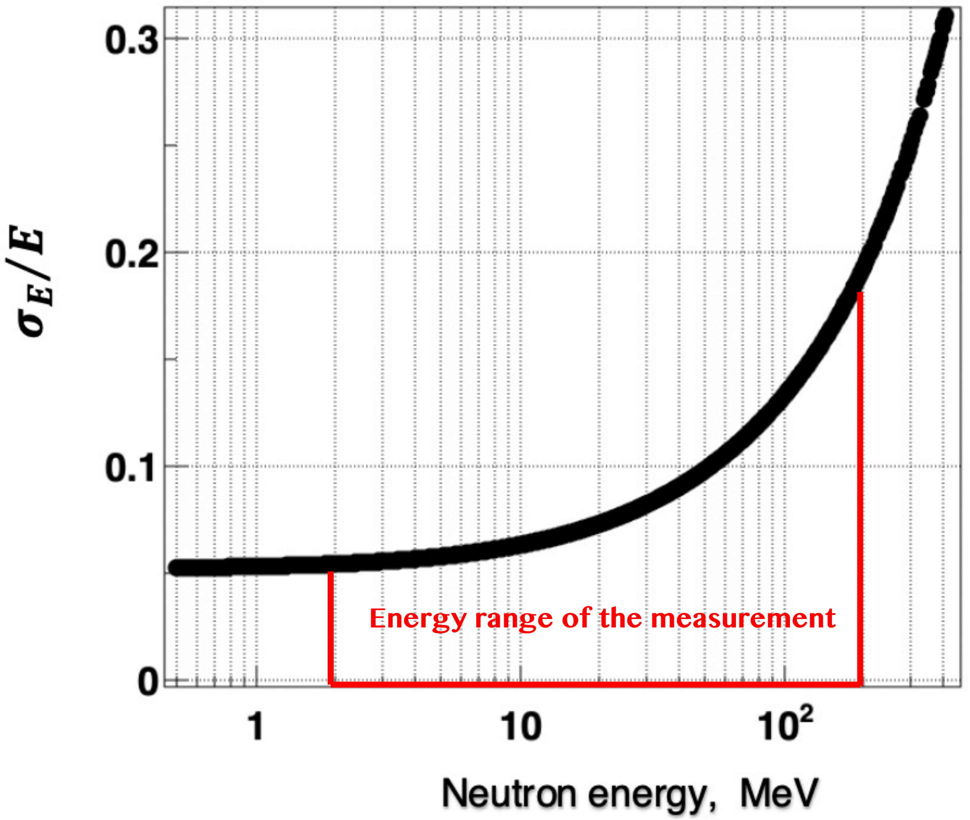
Time and Energy resolution

Time resolution

	$ND1$	$ND2$	$ND3$	$ND4$
σ_t (ps)	128	114	118	110

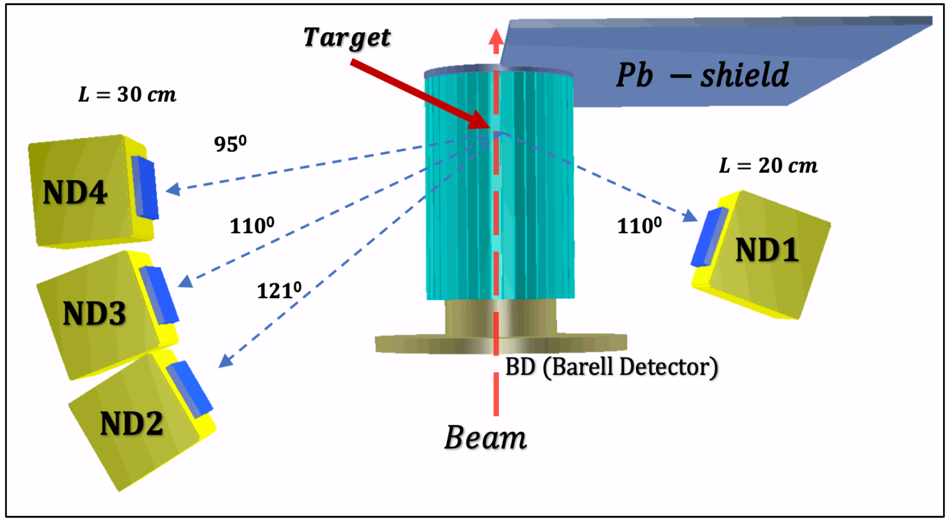


Energy resolution

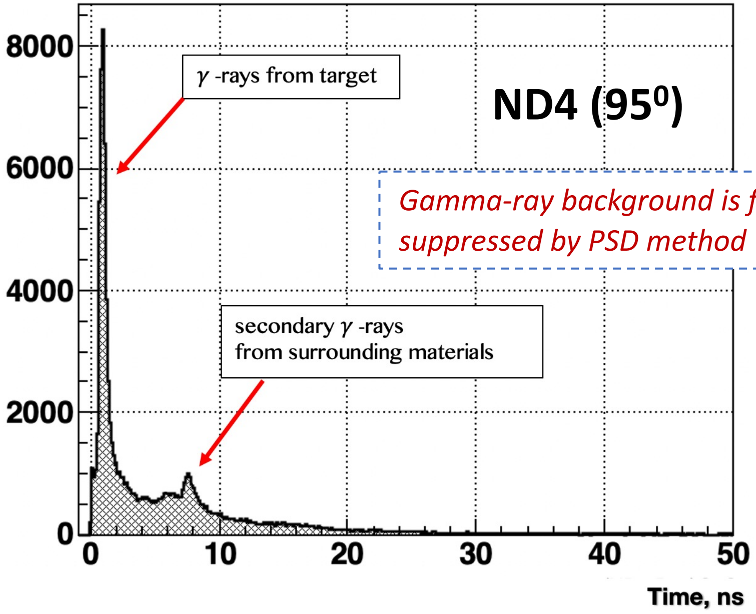


$$\frac{\sigma_E}{E} = \gamma(\gamma+1)\left[\left(\frac{\sigma_l}{l}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]^{1/2}$$

TOF spectra and background contribution

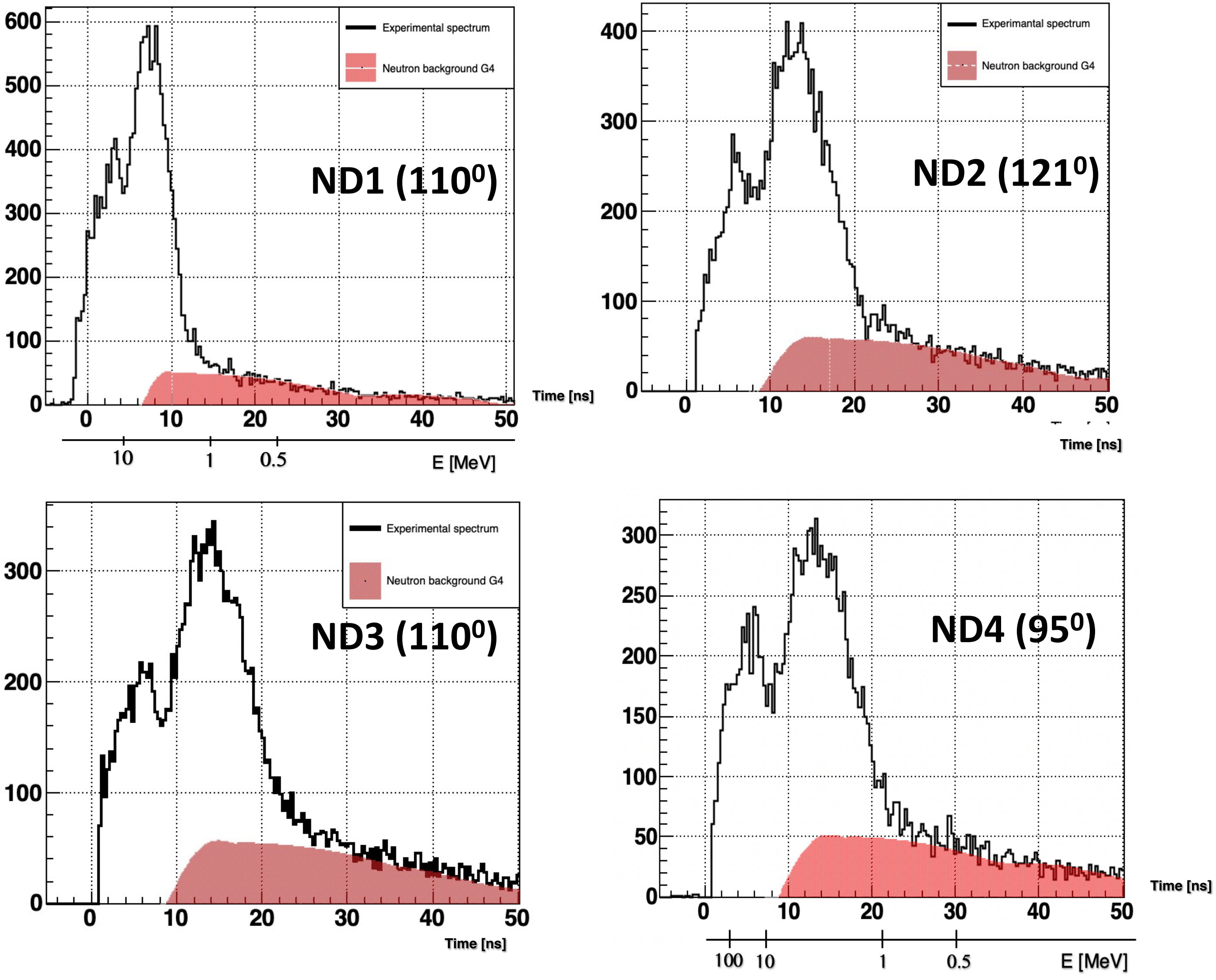


TOF spectrum of γ-rays



Gamma-ray background is fully suppressed by PSD method

TOF spectrum and neutron background contribution



Energy spectra of neutrons

Data processing procedure

$$\frac{d^2\sigma}{dEd\Omega} = \frac{\Delta N}{\Delta E \cdot \Delta\Omega \cdot \varepsilon(E) \cdot n \cdot I \cdot k_1 \cdot k_2}$$

ΔN – the number of events in the energy interval ΔE,

ΔΩ – the solid angle,

ε(E) – the detector efficiency at neutron energy E,

n – the number of target nuclei per 1 cm^2,

I – the number of beam ions,

k_1 – the correction factor for the dead time of the spectrometer

k_2 – the correction factor for the selection of events with one incident beam ion in a time interval of ± 1.5 μs

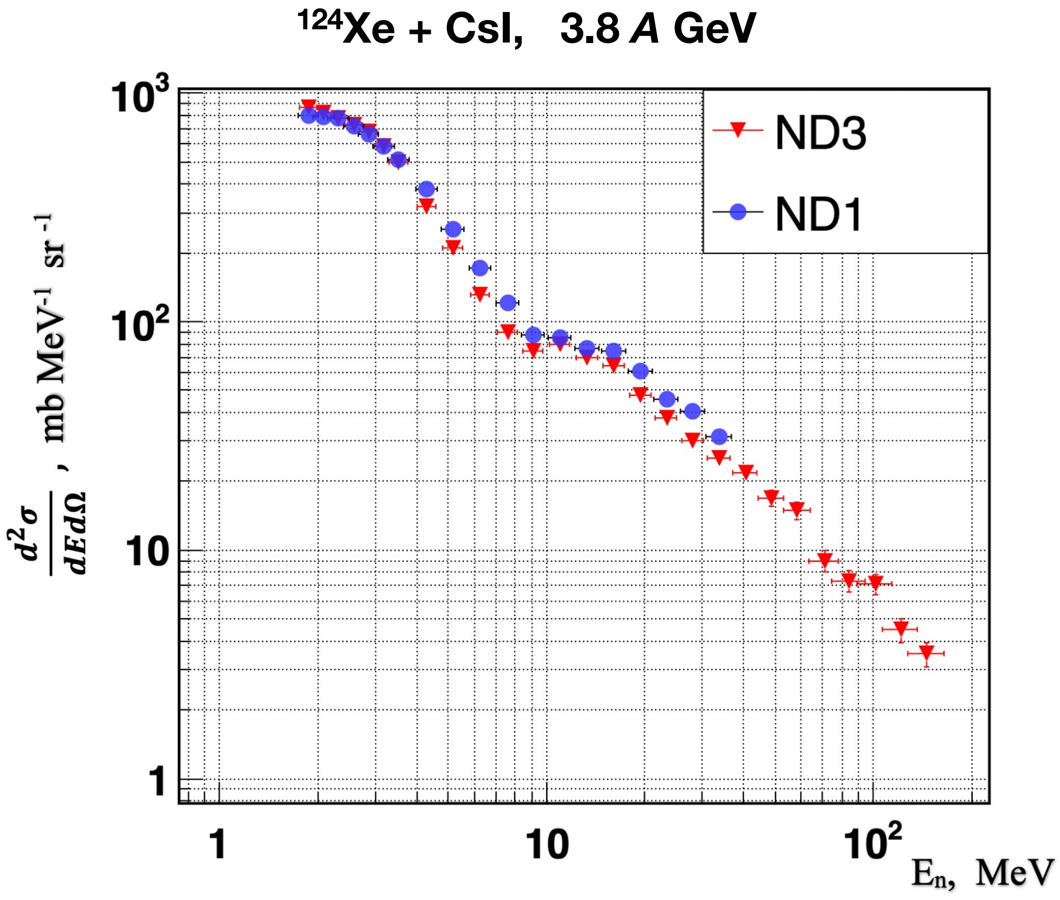
Comments:

- The number of beam ions *I* – is defined using the number of BT counts
- The correction factor for k_1 – is defined using the number of CCT2 counts with and without dead time
- The correction factor for k_2 – is defined by calculation of the fraction of events with one ion per spill

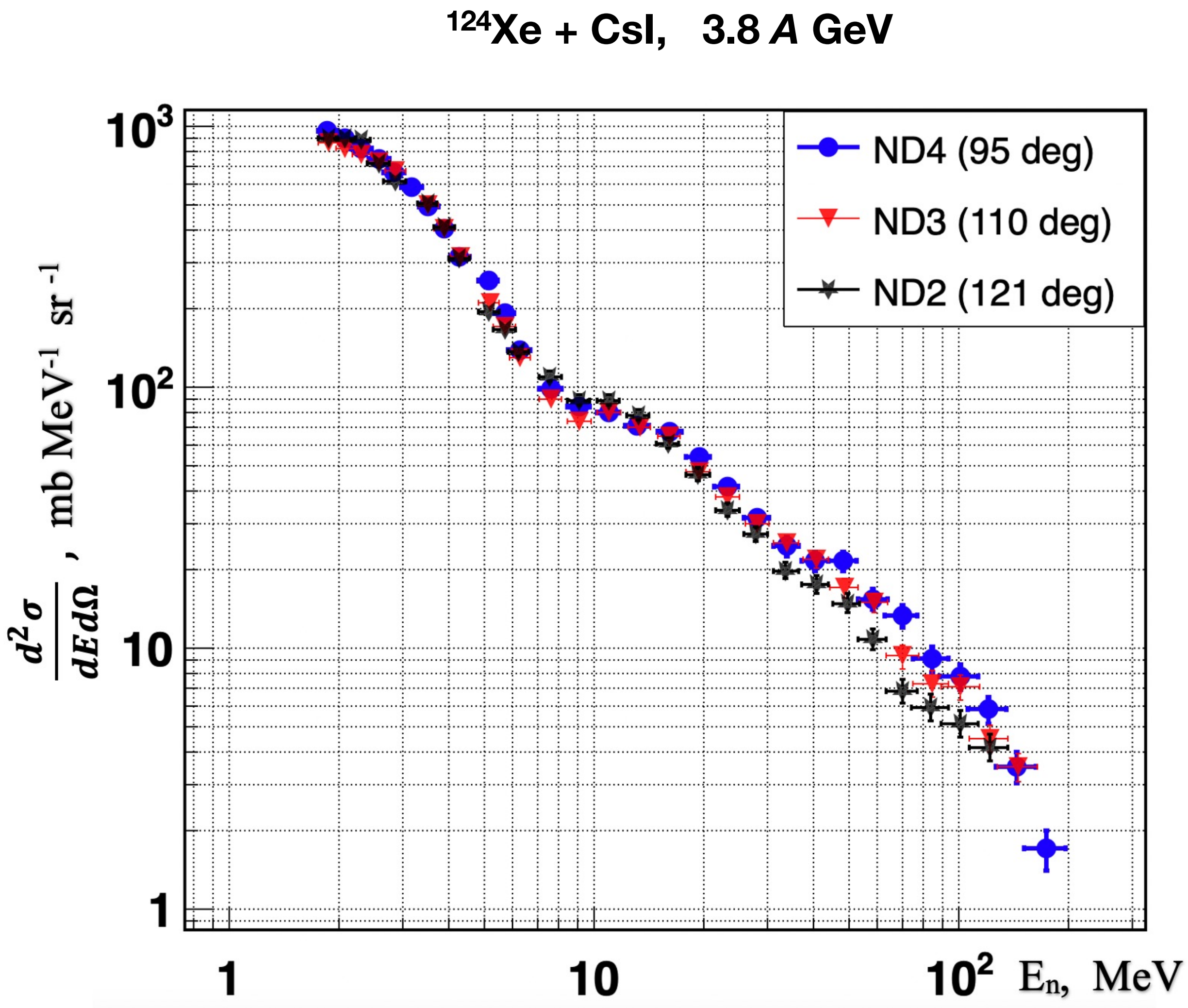
Energy spectra of neutrons

The measurements with different stilbene and flight path prove absence of methodical errors.

And it is clearly seen that results for ND1 and ND3 (110 deg) show good coincidence of energy spectra.



Energy spectra of neutrons



Good coincidence of energy spectra, measured at different angles with detectors ND1, ND2 and ND4, below 20 MeV and small difference at higher energies are observed.

It proves that in relativistic nucleus - nucleus collisions only a small fraction of beam ion momentum is transferred to the target spectator.

Summary

- In BM@N run with Xe ions we obtained good statistics of neutron events for analysis of neutron energy spectra
- The developed neutron detectors with stilbene and SiPMs have time resolution of ~110 ps that allows to use small flight paths of ~30 cm in TOF measurements and helps to minimize neutron background estimated by MC calculation
- High-quality n/γ- pulse shape discrimination was achieved in the spectrometer that helps to suppress gamma-ray background
- The neutron energy spectra were obtained at three angles 95^{o}, 110^{o} and 121^{o} in energy interval 2 – 200 MeV for BM@N interaction trigger selecting Xe + CsI collisions with centrality approximately less than 60%.

Outlook

- We continue analysis of neutron production cross sections
- Analysis of the data with Moving Source Model
- Also, in our plan – to get results with selection events for three centrality intervals 60-40%, 40-20%, 20-0% using information from other BM@N detectors

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BM@N
Baryonic Matter at Nuclotron

Thank you
for your attention !