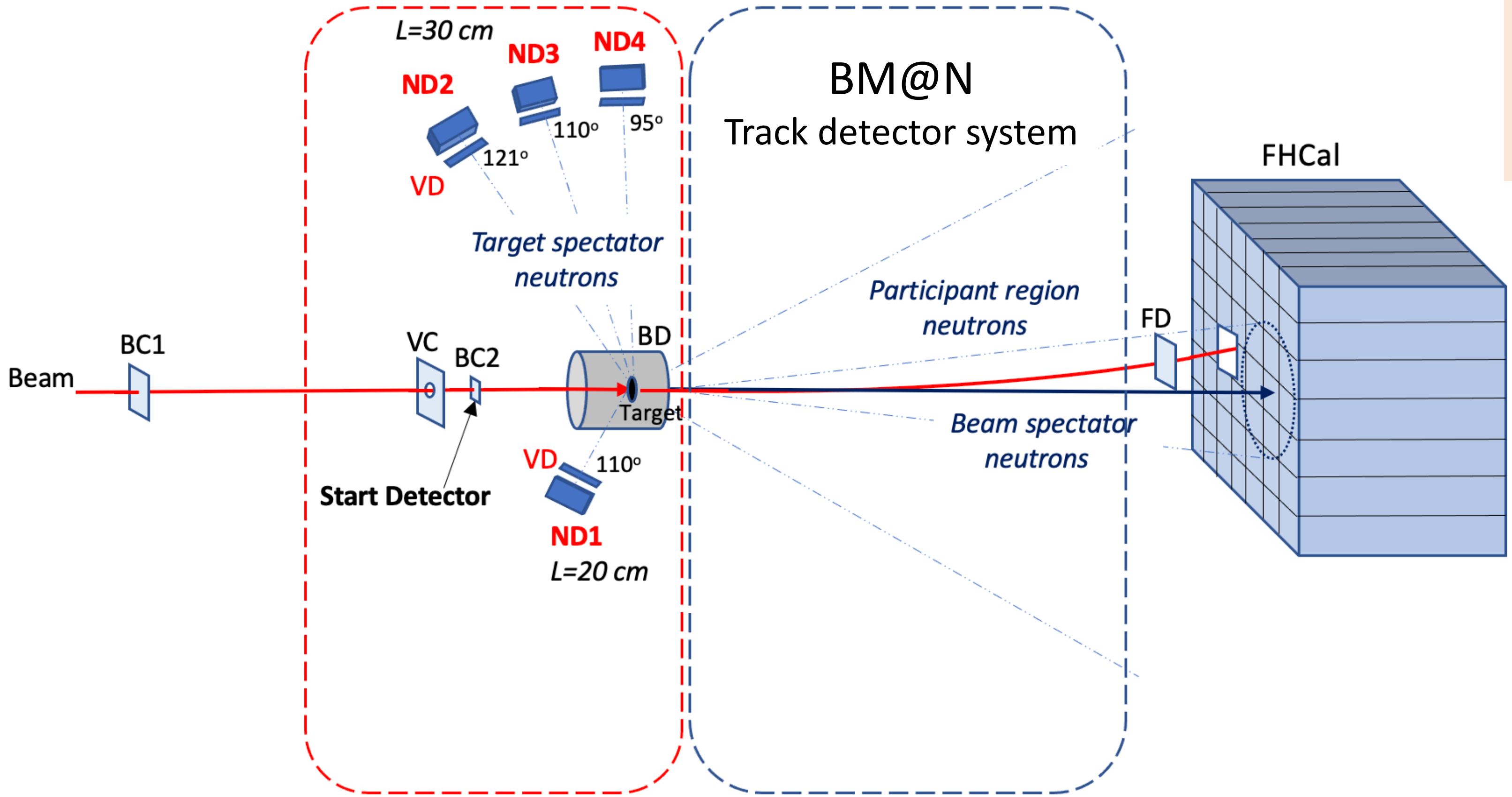
Measurement of neutron energy spectra in the region of large angles in Xe + CsI collisions at energy of 3.8 A GeV

N. Lashmanov*, V. I. Yurevich, S. A. Sedykh, V. Yu. Rogov, S. V. Sergeev, M. N. Kapishin, S. M. Piyadin

Experiments studied of neutron production in collisions of heavy nuclei at high and intermediate 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	$\langle M_n \rangle = f(b)$ $\theta = 0^o$
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	$\langle M_n \rangle = f(b)$ $\theta = 0^o$
GSI/SIS (2023)	^{107,124}Sn, ^{124}La + Sn	0.6 A GeV	TOF, LAND	$d^2N/dydp_T$, $\langle M_n \rangle = f(Z_{bound})$ $\theta \leq 2^o$
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

Compact Neutron TOF Spectrometer

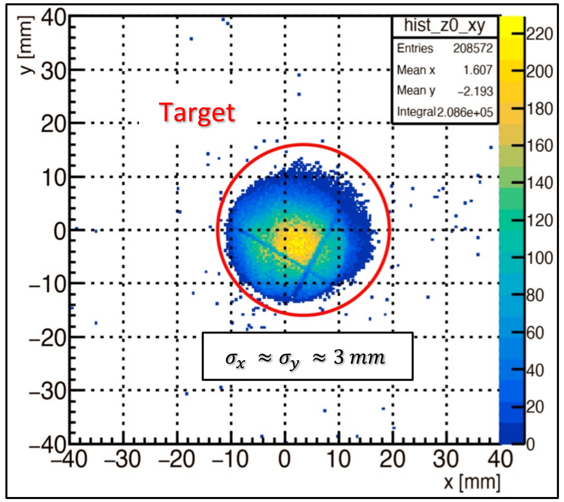


TOF measurements:

BC2(T0) – beam start detector

ND1 – ND4 – neutron stop detectors

Hits of Xe ions in the target position obtained with Si- trackers



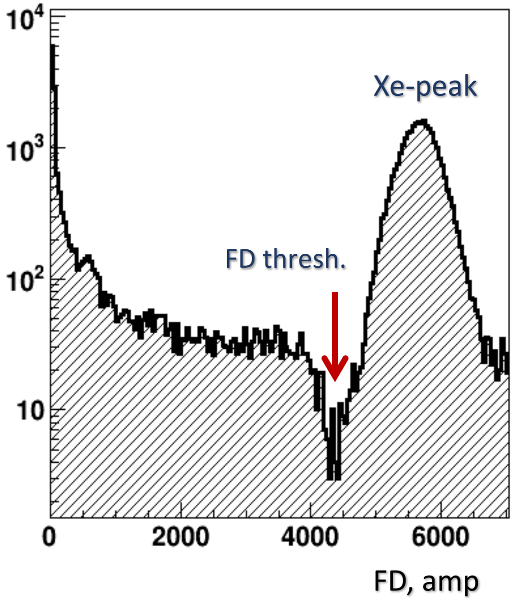
	Beam	Target
Beam ions:	^{124}Xe	CsI
Energy:	3.8 *A* GeV	D32 × 1.75 mm
Intensity:	~ 6 x 10^5 ion/spill	
Spill duration:	~ 2.5 s	

BM@N interaction trigger

used for selection and readout of events

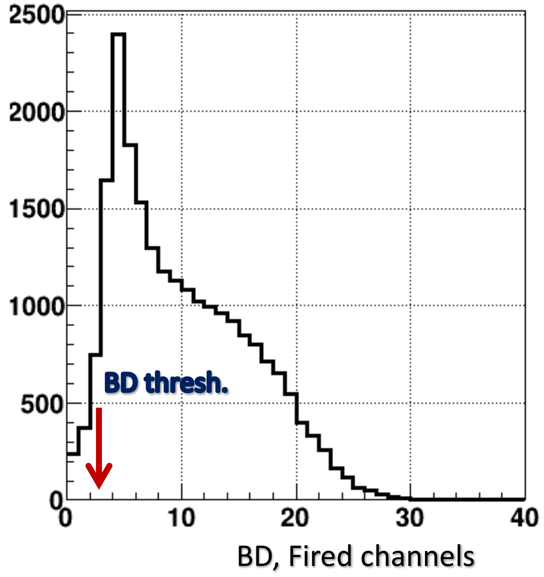
Min. Bias trigger:

MBT = BC1 * $\overline{\text{VC}}$ * BC2 * $\overline{\text{FD}}$

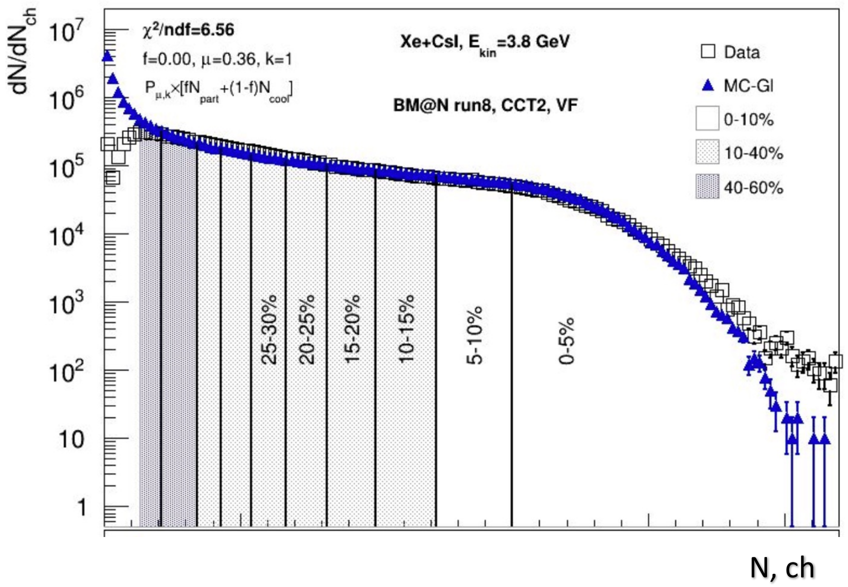


BM@N interaction trigger:

IT = MBT * BD(N>3)

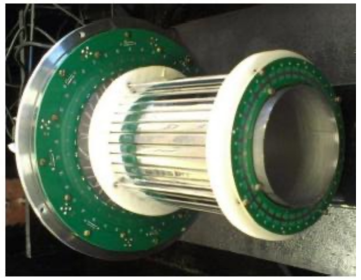


Centrality determination

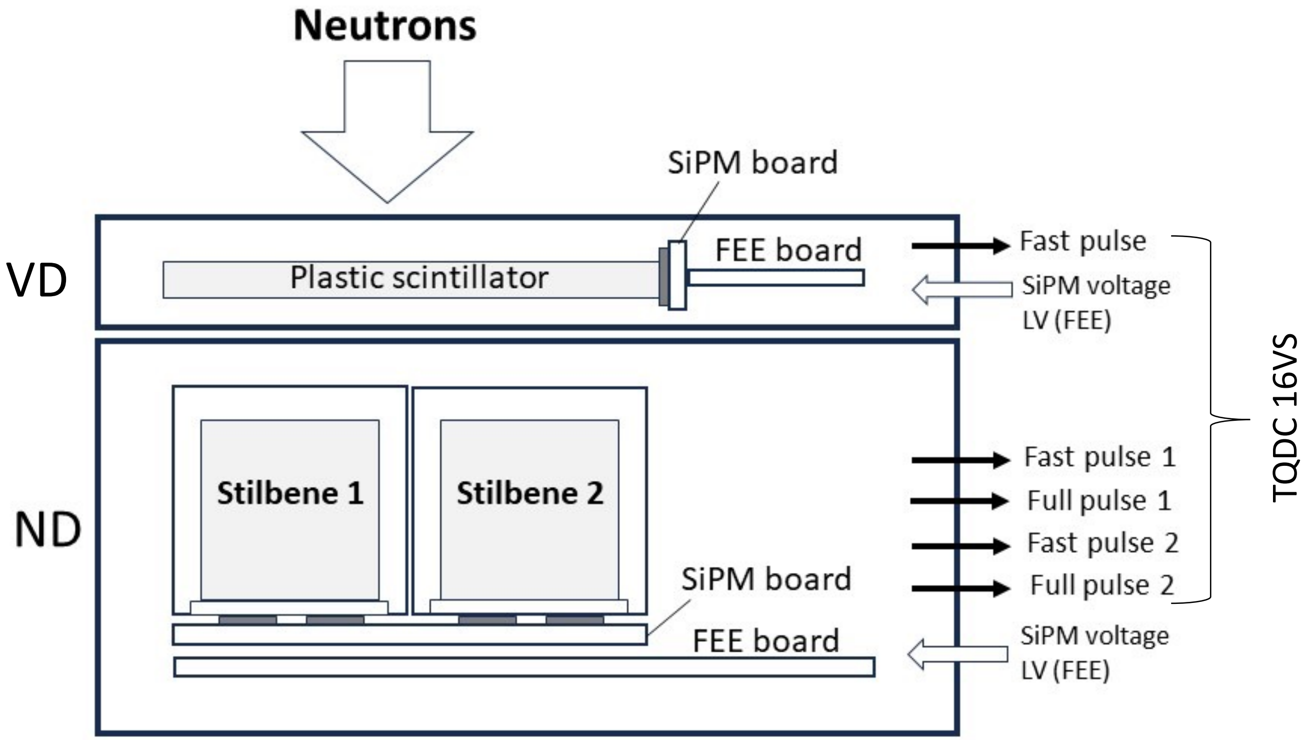


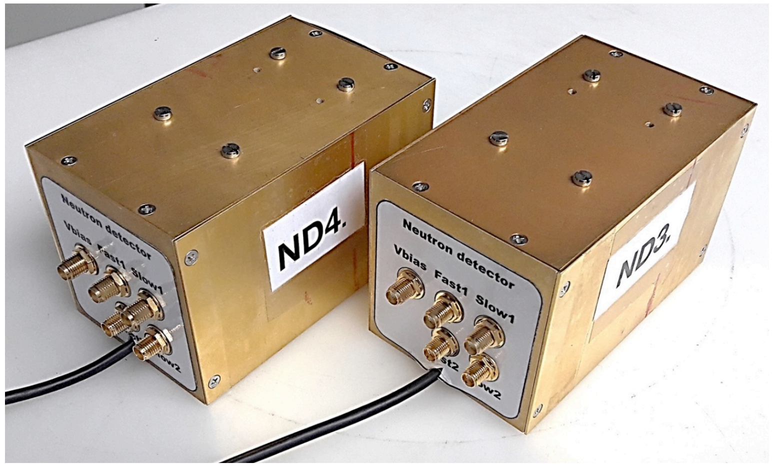
[Mamaev M., Taranenko A. et al., Presentation at the 12th BM@N Collaboration meeting, 13/05/2024]

BD detector
40 scint. strips
SiPM readout



Neutron Detectors

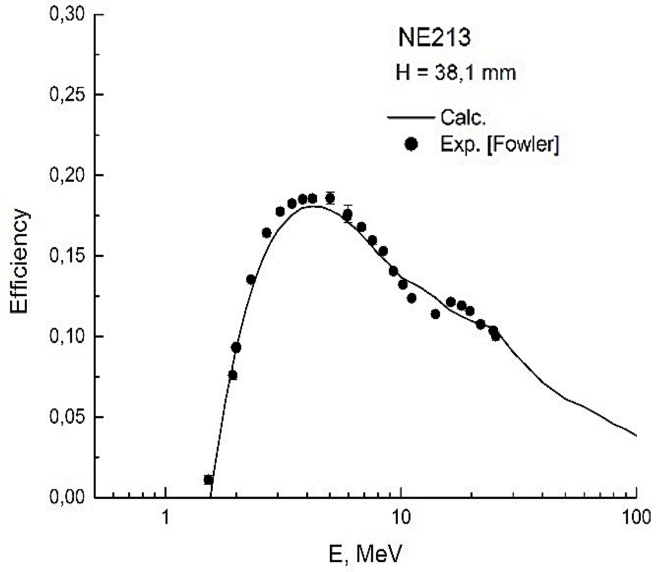


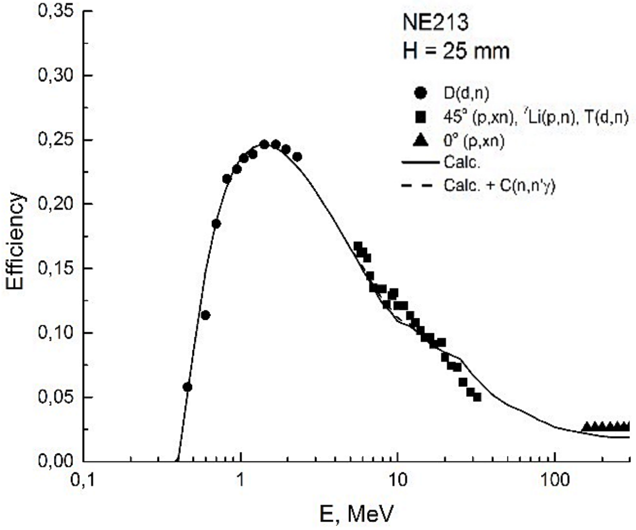


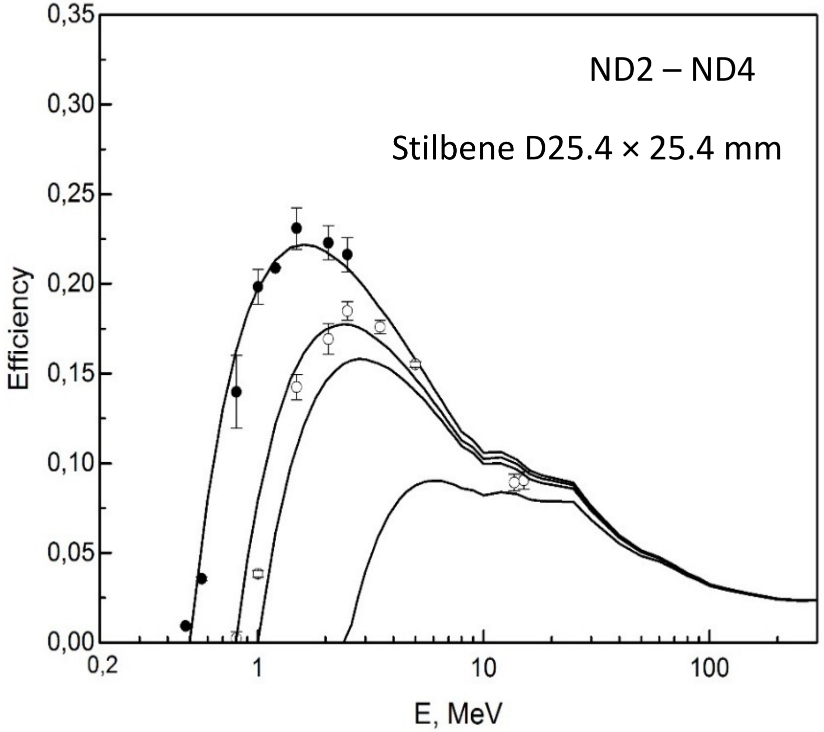
Detection of scintillation photons with four SiPMs 6×6 mm^2, SensL, J ser.

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

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

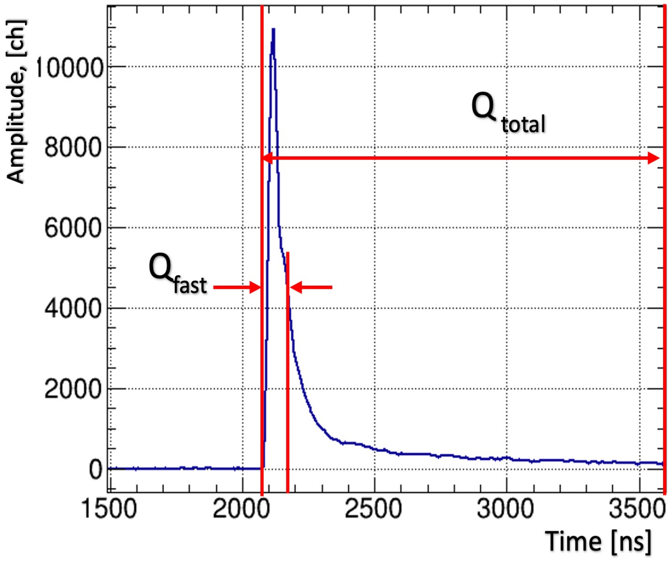
B_h – the threshold for recoil protons in np scattering

Pulse shape n/γ- discrimination

Quality of pulse shape discrimination:

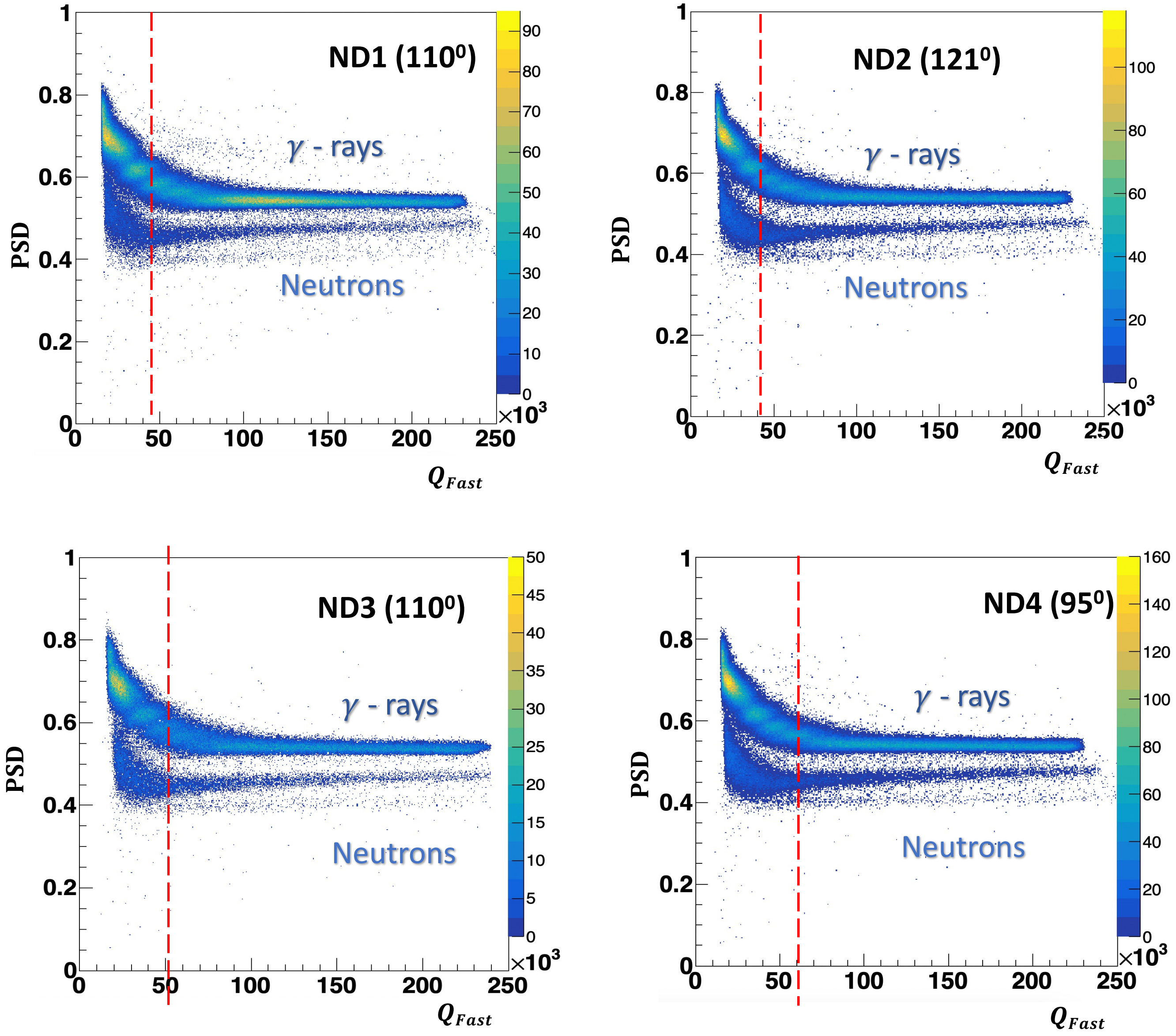
$$PSD = \frac{Q_{fast}}{Q_{total}}$$

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}

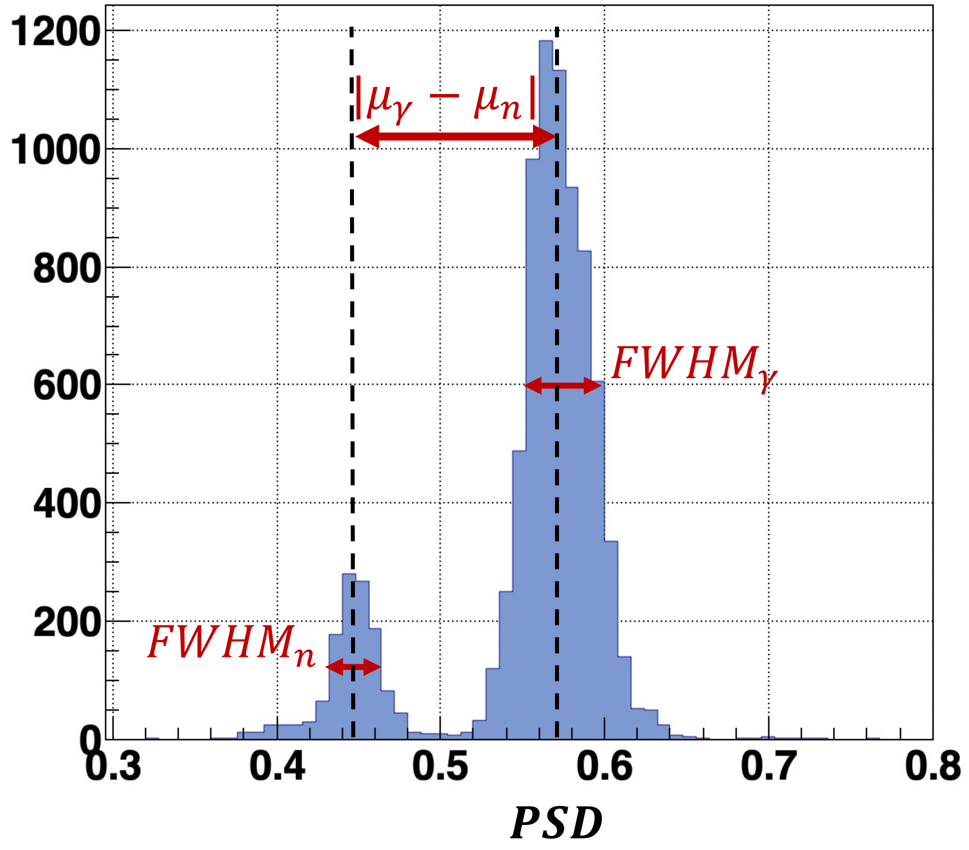


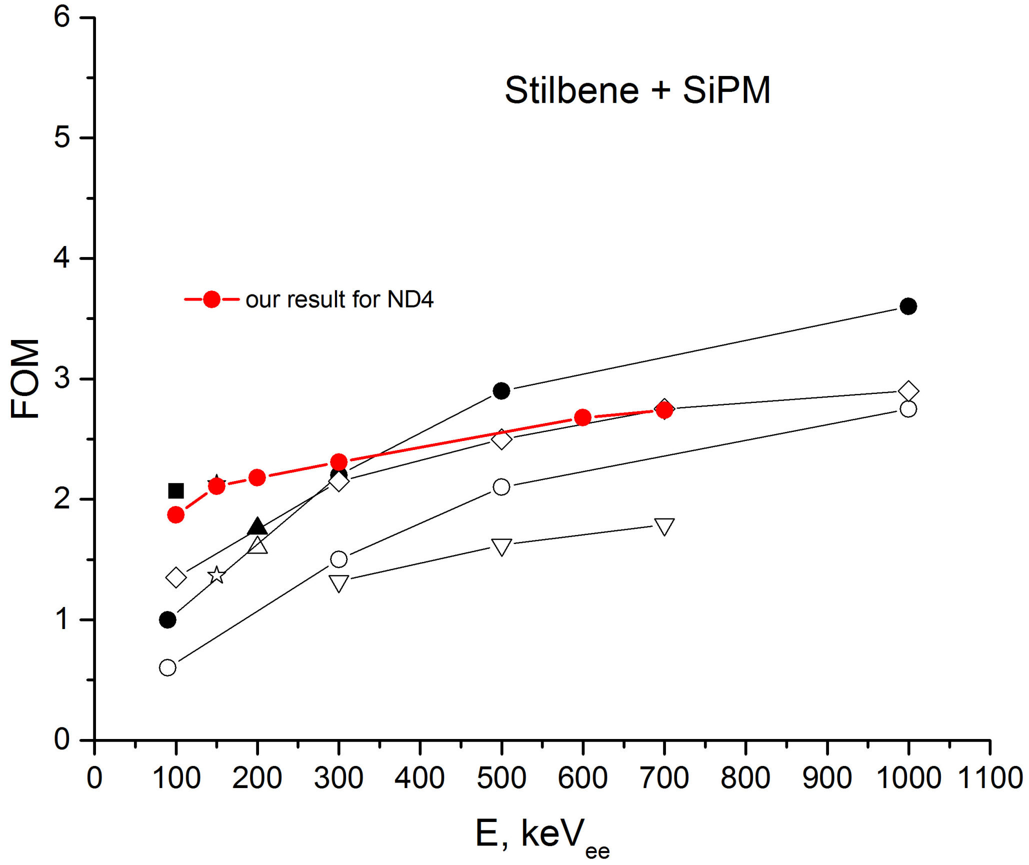
Pulse shape n/γ- discrimination

Figure of Merit:

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

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



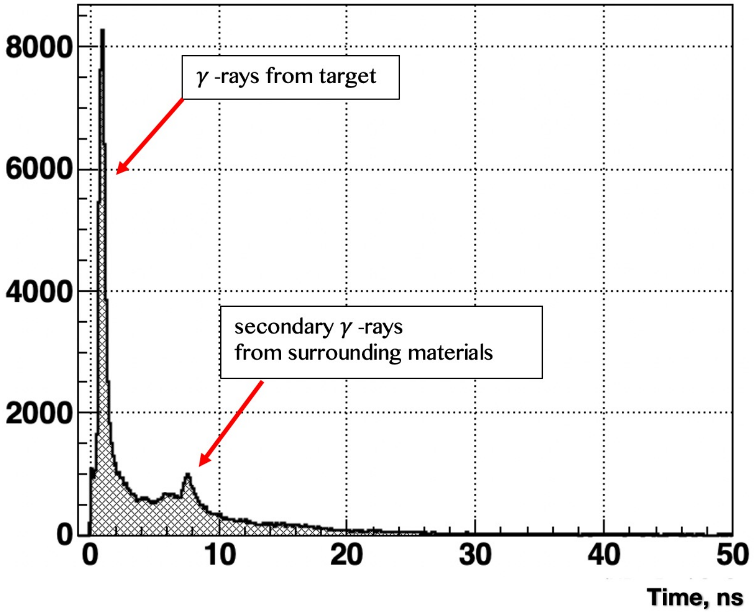


Time and Energy resolution

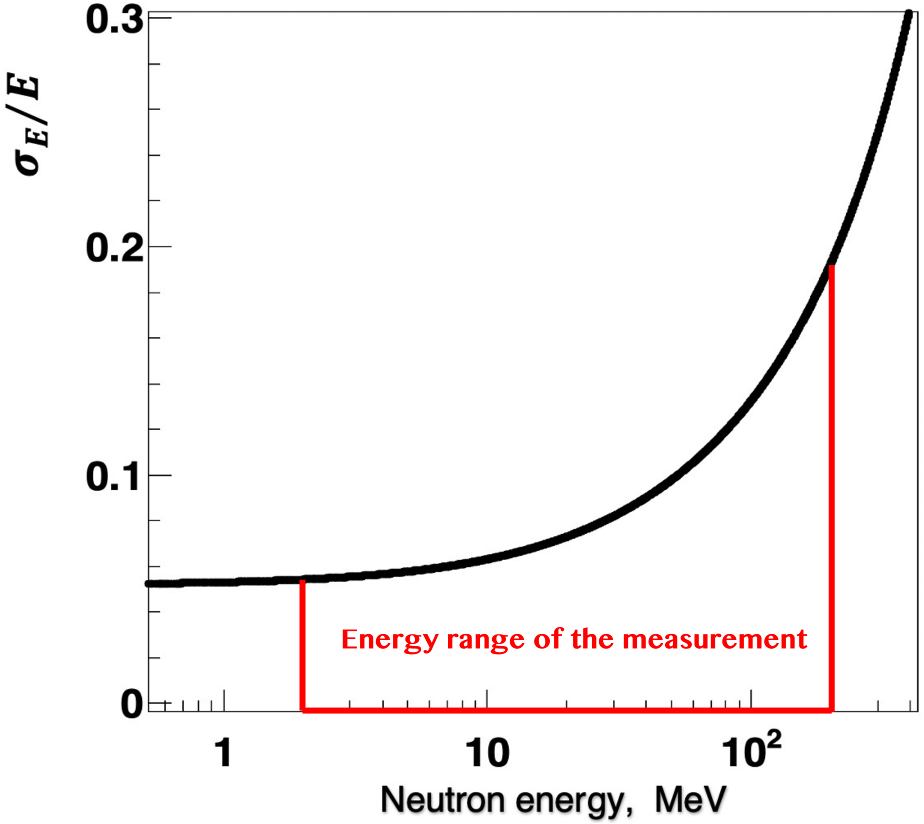
Time resolution

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

TOF spectrum of γ-rays



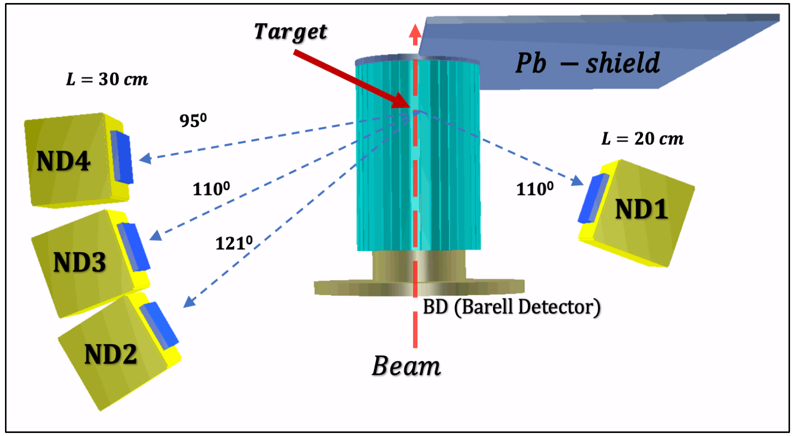
Energy resolution

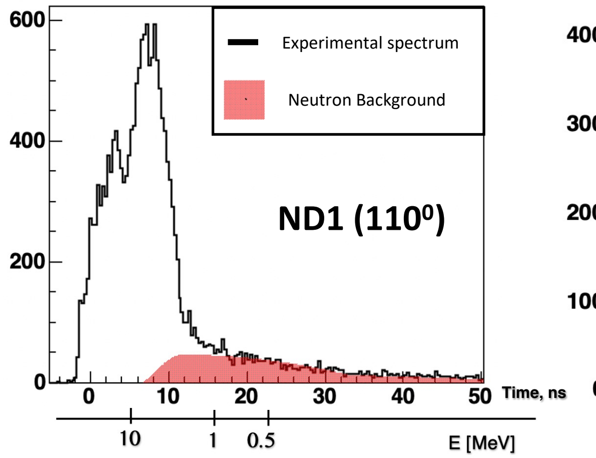


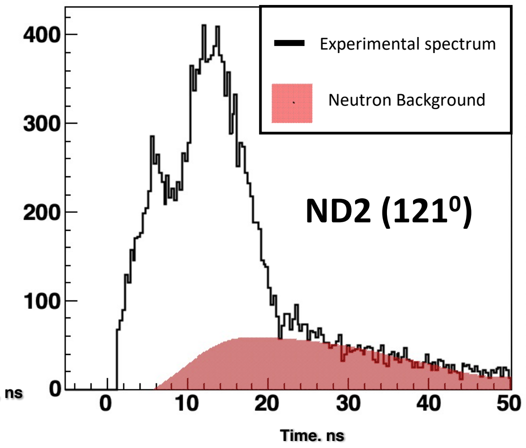
$$\frac{\sigma_E}{E} = \gamma(\gamma+1)\left[\left(\frac{\sigma_l}{l}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]^{1/2}$$

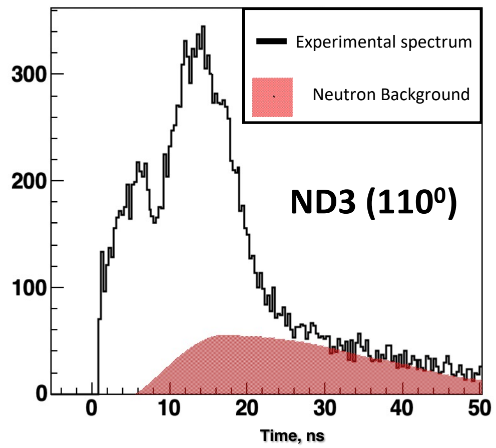
TOF spectra and neutron background contribution

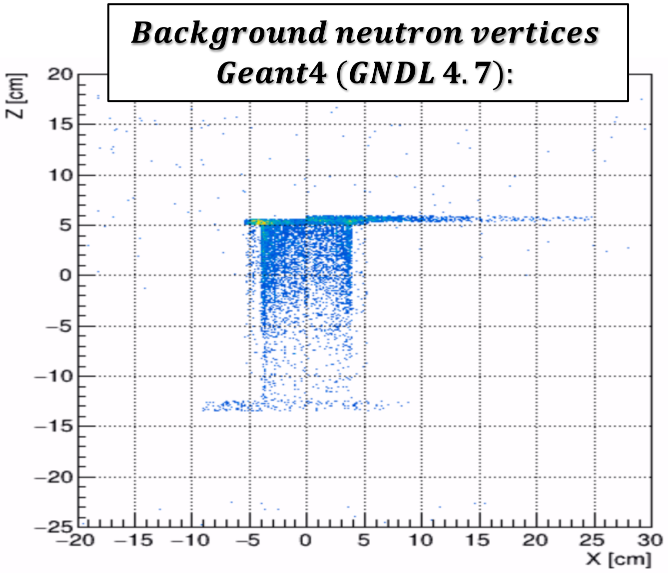
Neutron background is estimated by MC simulation with DCM-QGSM + GEANT4

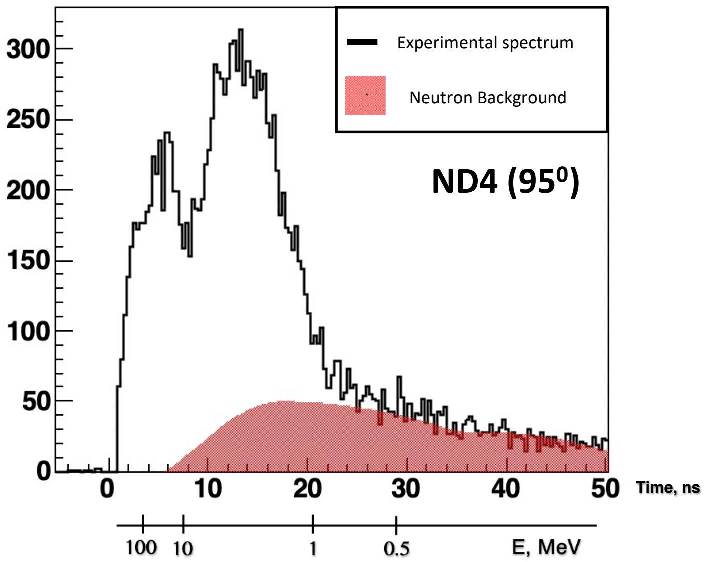


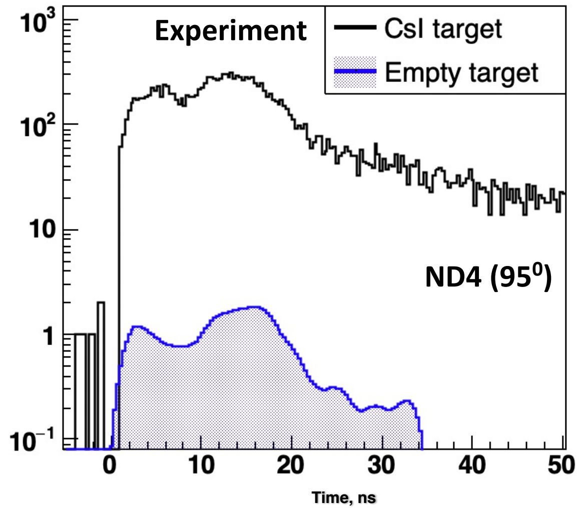












Energy spectra of neutrons

Data processing procedure

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

E – the kinetic energy of neutrons

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 factor for the dead time of the spectrometer

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

Corrections:

Time – pulse height correction to improve time resolution

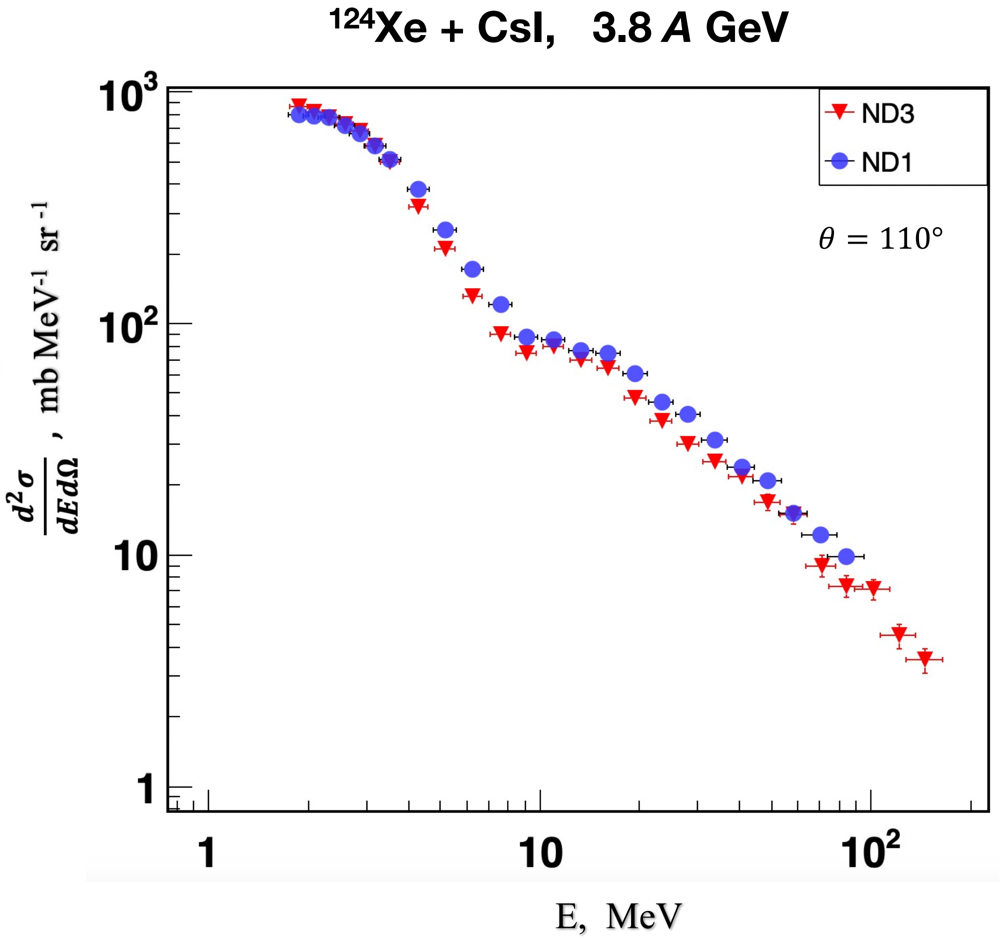
Pulse shape n/γ- discrimination

Neutron background contribution

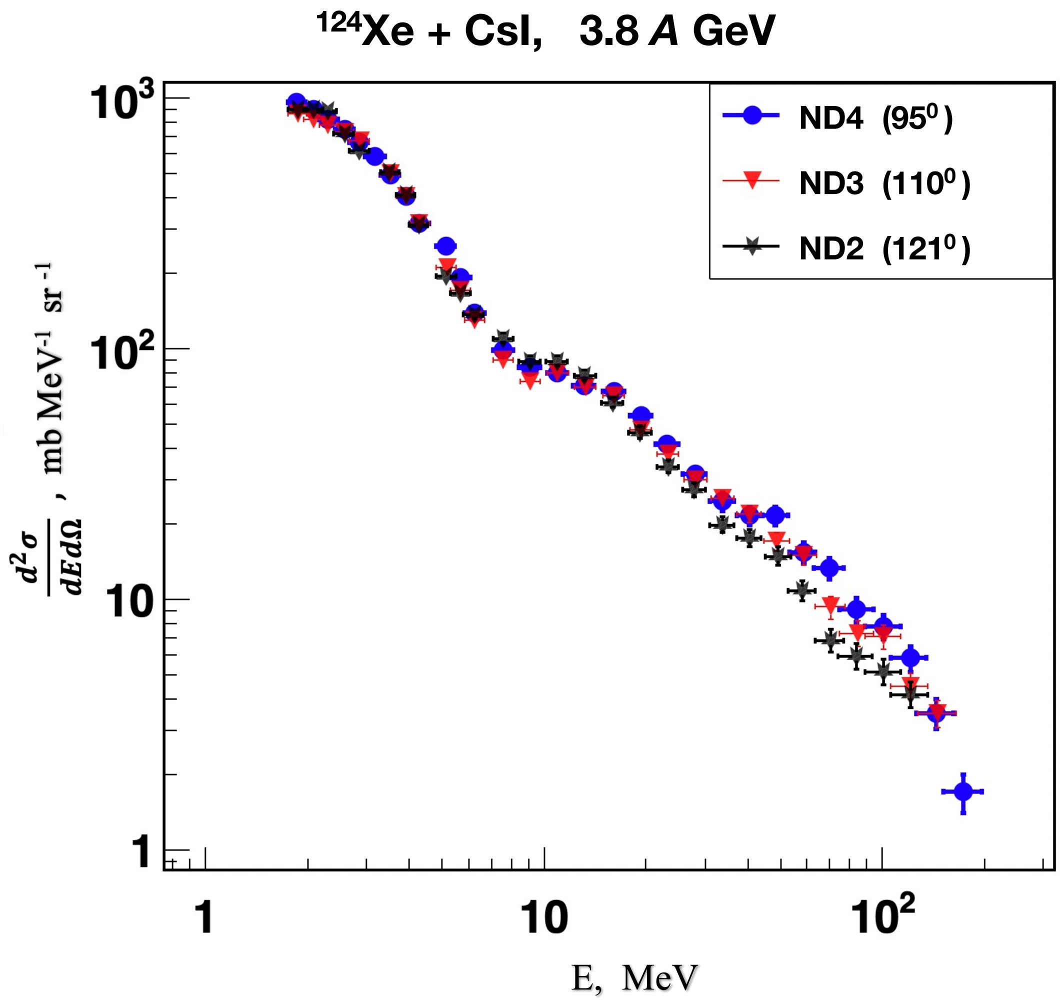
Energy spectra of neutrons

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

And it is clearly seen that results for ND1 and ND3 (110^0) 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.

Isotropic emission of neutrons below 10 MeV means that the source of these neutrons moves with very low velocity in the laboratory frame.

Summary and Outlook

- The developed compact neutron TOF spectrometer with detectors based on stilbene and SiPMs has ~ 110-ps time resolution with fully suppression of gamma-rays by PSD method.

- The spectrometer was successfully used in BM@N run with Xe ion beam and CsI target for measurement of neutron energy spectra at large angles in wide energy interval from 2 to 200 MeV.

- The data analyses is continued and in our plan to study dependence of neutron spectra on the collision centrality using information from other BM@N detectors.

  Also, we plan to use this spectrometer for study of neutron emission in Bi+Bi collisions in future BM@N runs.

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

BM@N
Baryonic Matter at Nuclotron

Thank you
for your attention !