Study of neutron emission from target spectators in ^{124}Xe + CsI collisions at 3.8 *A* GeV

Nikita Lashmanov

Joint Institute for Nuclear Research, Dubna, Russia

BM@N meeting, Oct. 2024

INTRODUCTION

A large number of free neutrons are emitted in nucleus – nucleus collisions at high energies.

Characteristics of these neutrons bring an important information about all stages of the nuclear system evolution and thus, it very useful for checking and development of theoretical models describing nucleus – nucleus interactions.

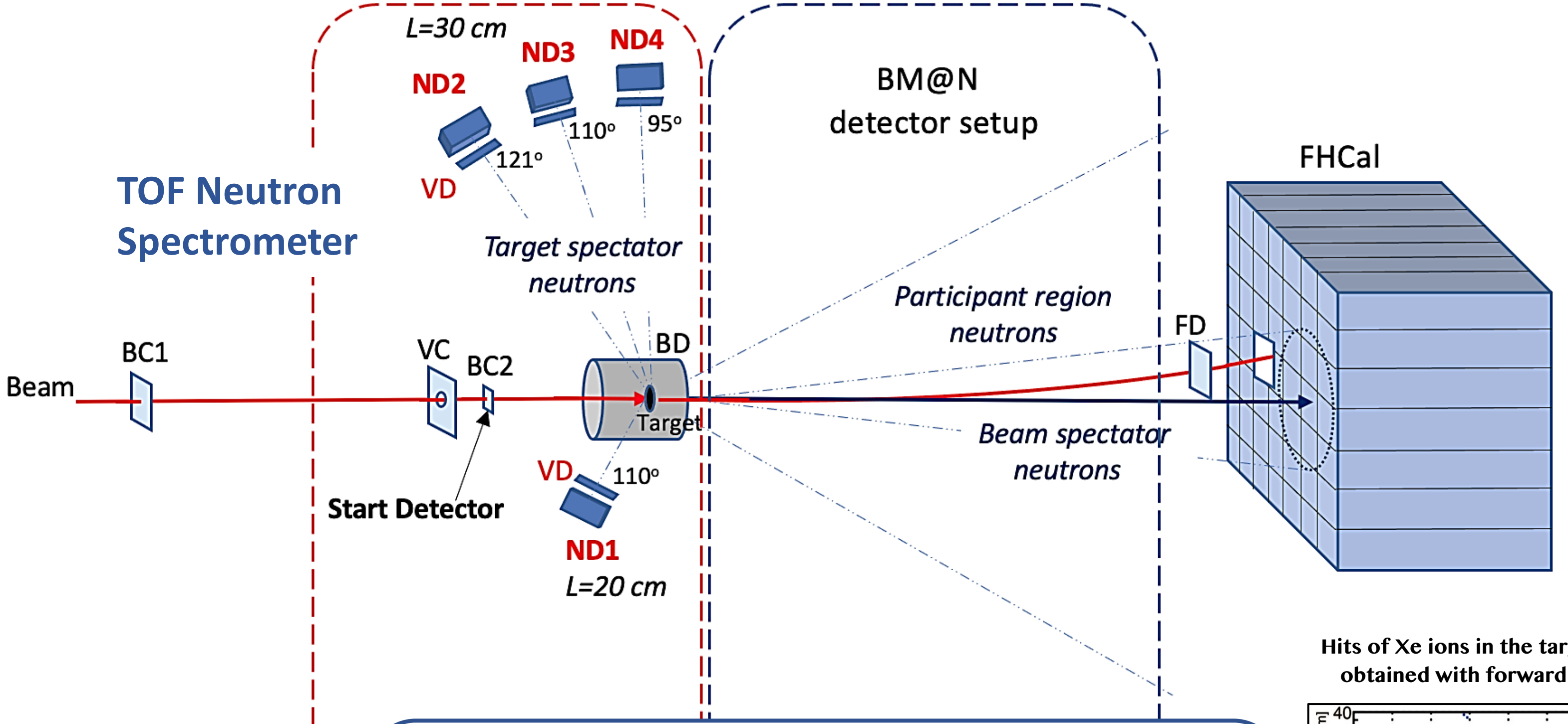
However, despite the importance of these data, the number of such experiments remains very limited, which is explained by the methodological difficulties of neutron measurements.

A compact TOF neutron spectrometer was recently designed as a part the BM@N experiment at the LHEP JINR. The aim of the spectrometer – to study neutron emission at large angles from decay of target spectators produced in nucleus – nucleus collisions at Nuclotron energies up to 4 *A* GeV.

In this talk I will present characteristics of the developed spectrometer and the first results obtained for ^{124}Xe + CsI collisions at energy of 3.8 *A* GeV.

Compact TOF Neutron Spectrometer

BM@N run Dec.2022 – Feb.2023



Neutron Detectors

Detector	θ (deg.)	L (cm)	Stilbene (mm)
ND1	**110°**	**20**	**D30×10**
ND2	**121°**	**30**	**D25.4×25.4**
ND3	**110°**	**30**	**D25.4×25.4**
ND4	**95°**	**30**	**D25.4×25.4**

BC2 – Start detector (T0)

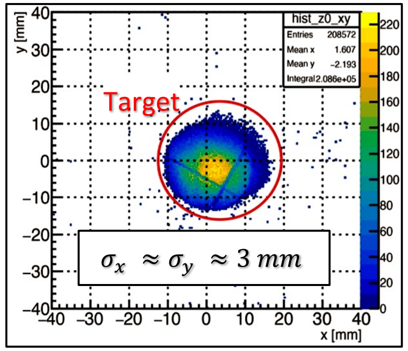
Scintillator: BC-400B, 34×34×0.15 mm^3

PMT: XPM85112/A1 (Photonis), 2 units

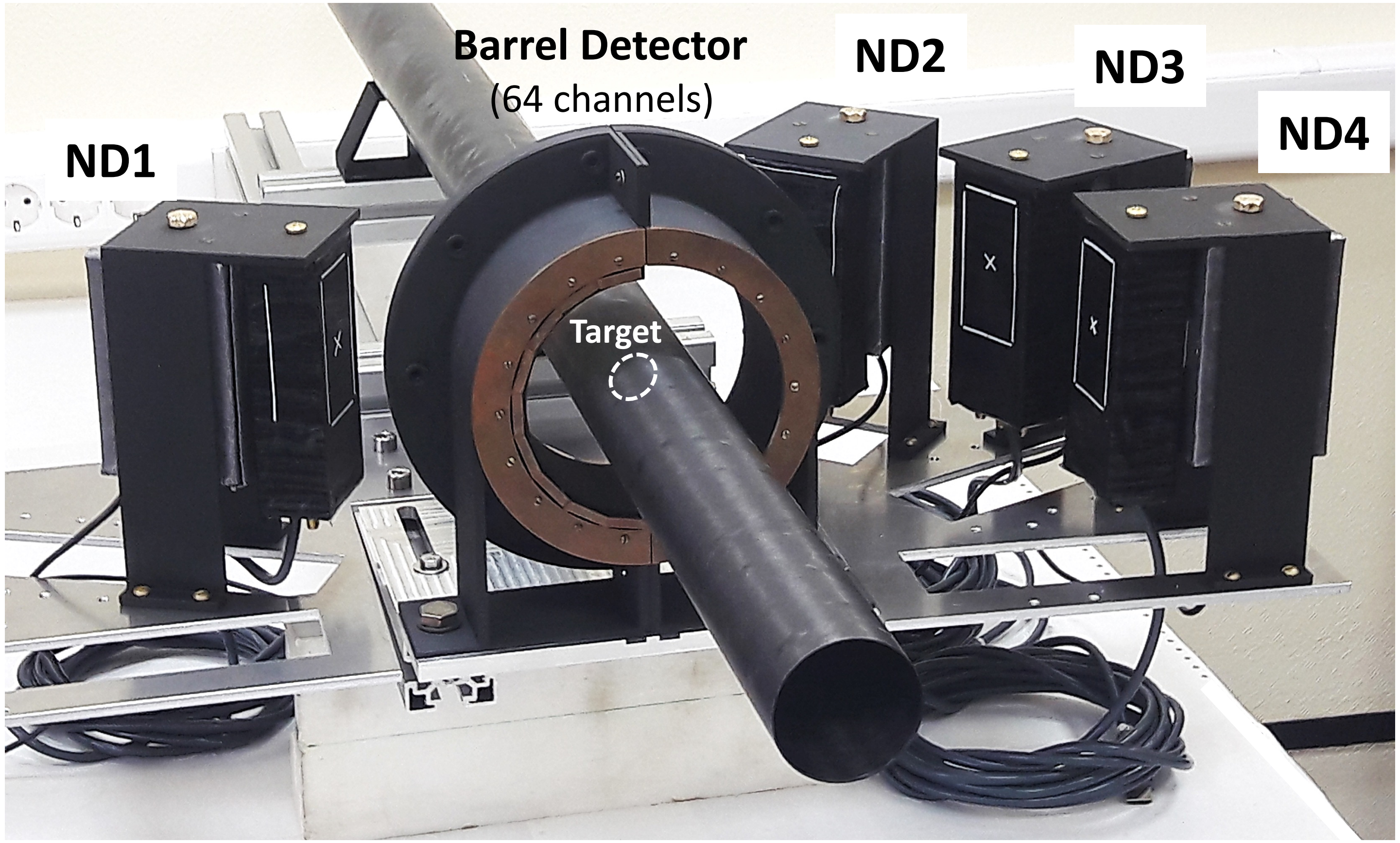
Time resolution: σ_t **= 40 ps**

	Beam	**Target**
Beam ions:	^{124}Xe	2% CsI
Energy:	3.8 *A* GeV	D32 × 1.75 mm
Intensity:	~ 6 10^5 ion/spill	
Spill duration:	~ 2.5 s	

Hits of Xe ions in the target position obtained with forward Si tracker



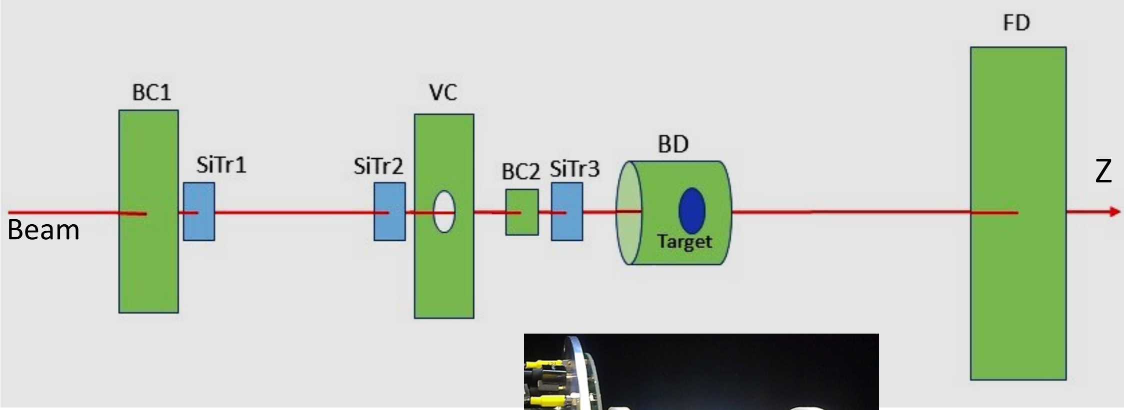
The compact TOF Neutron Spectrometer 2024

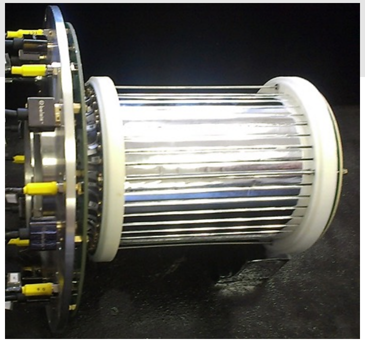


A new design of the neutron spectrometer (prototype)

Selection of Interactions in the Target

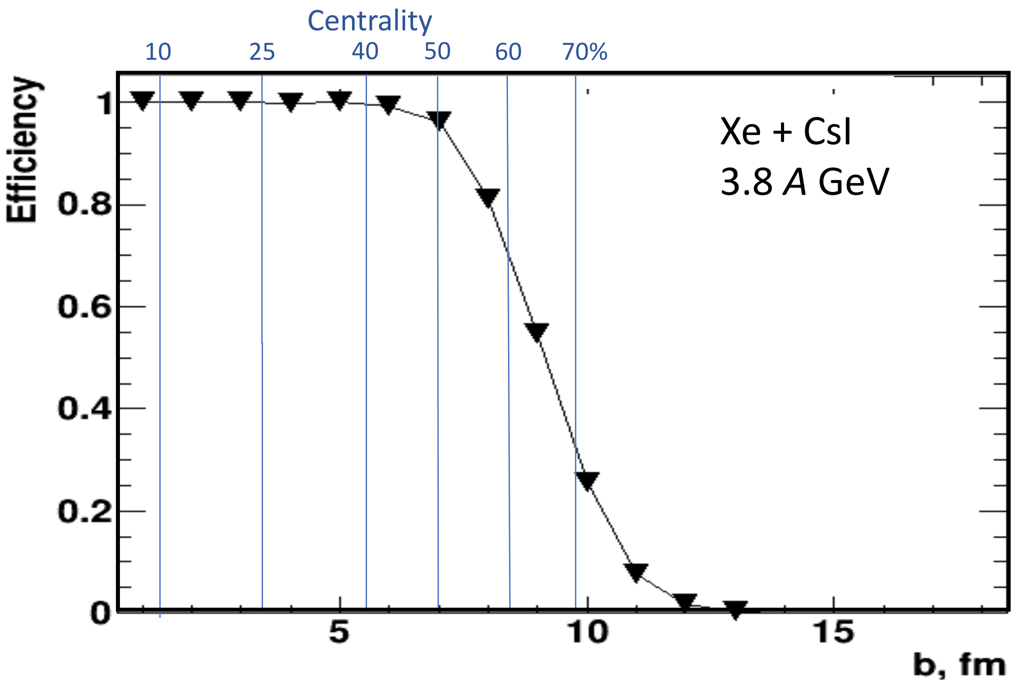
Trigger detector system





Barrel Detector (BD)
40 scintillation strips

Trigger efficiency



Interaction Trigger logic:

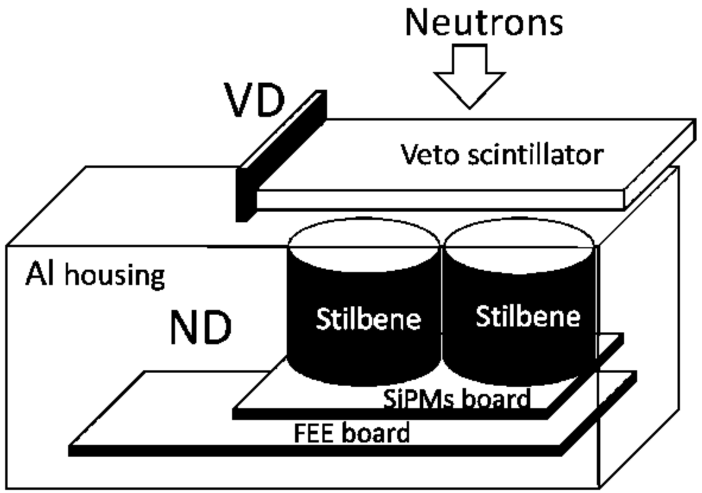
Min. Bias Trigger (MBT) = BC1 * $\overline{\text{VC}}$ * BC2 * $\overline{\text{FD}}$

Main interaction trigger (CCT) = MBT * BD(N>3)

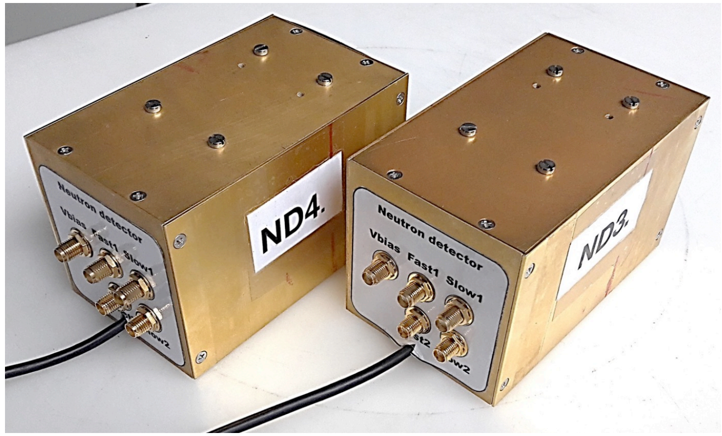
Only events with one Xe ion in 3.6- μs interval in BC1 were used in the neutron data analysis

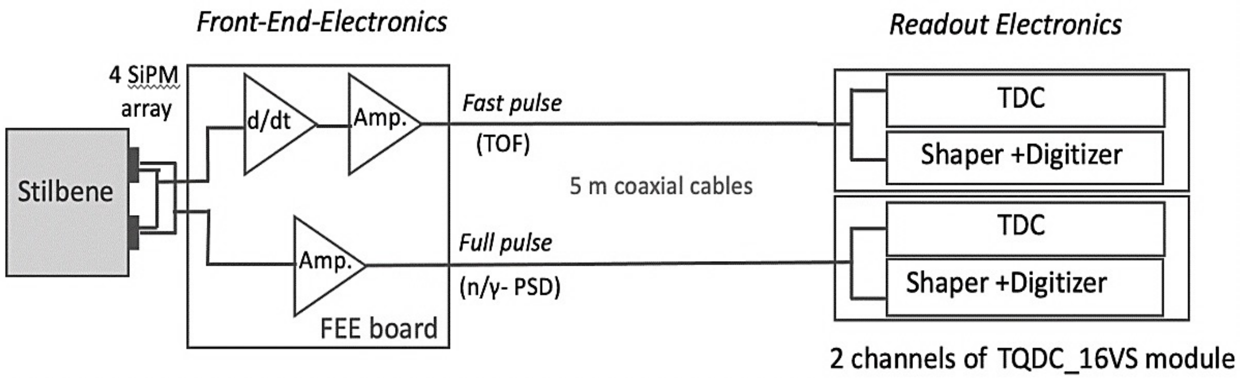
The neutron spectra were obtained in centrality interval from central to a part of peripheral collisions

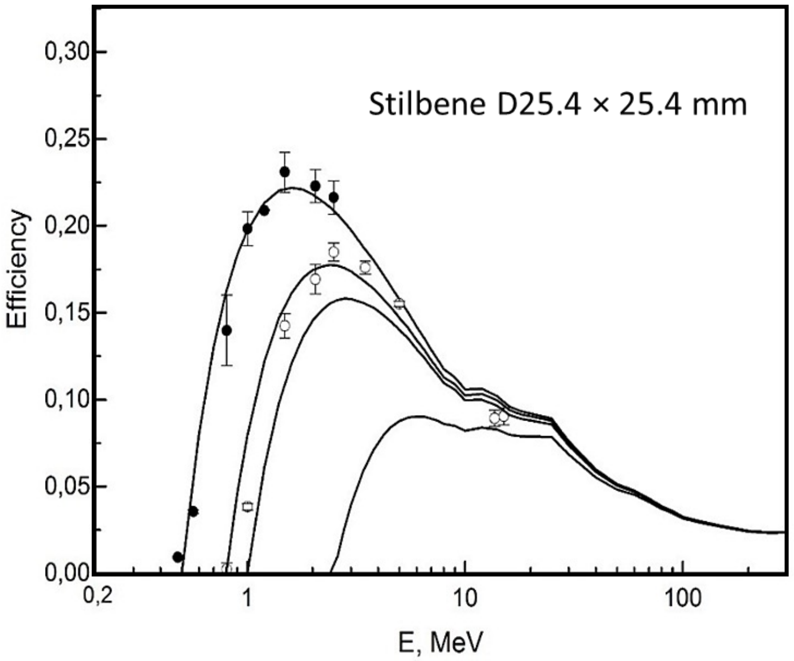
Neutron Detectors



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







Pulse shape n/γ- discrimination

Quality of pulse shape discrimination:

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

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

T_{total} = 1.5 μs. : time window for charge integration Q_{total}

The integration time intervals are determined by pulse processing in TQDC module

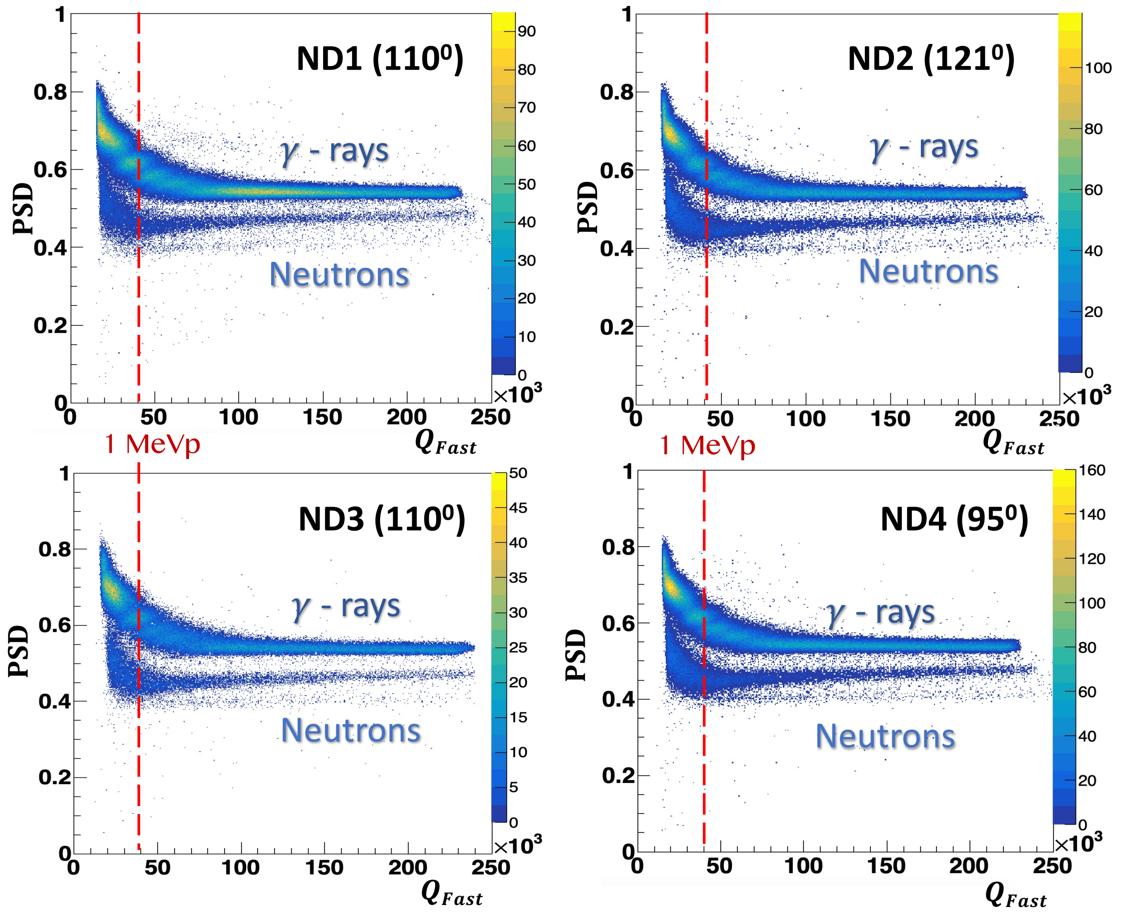
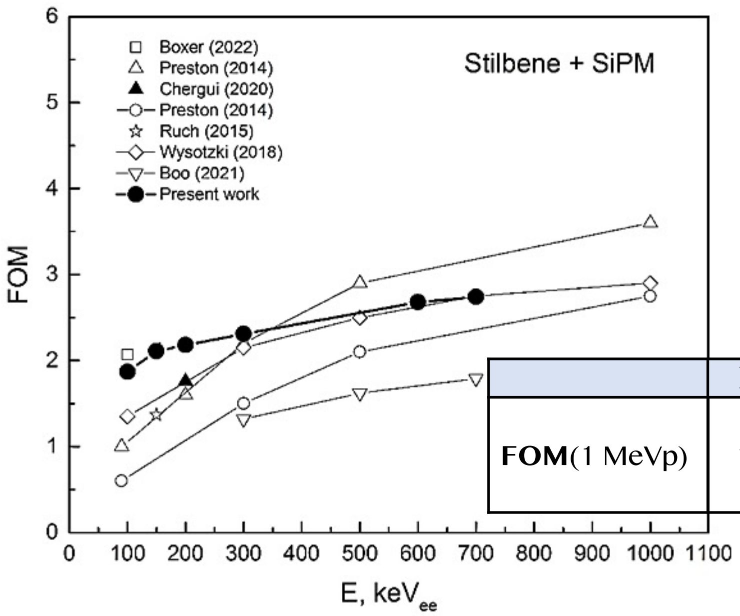
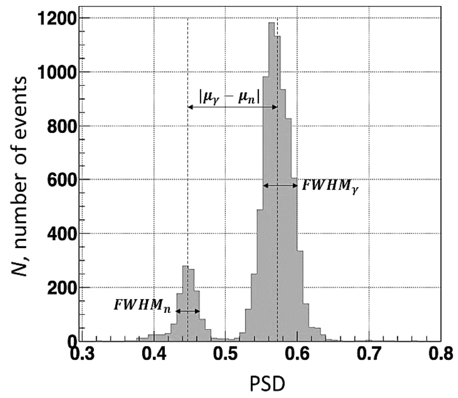


Figure of Merit: $FOM = \frac{|\mu_\gamma - \mu_n|}{FWHM_\gamma + FWHM_n}$





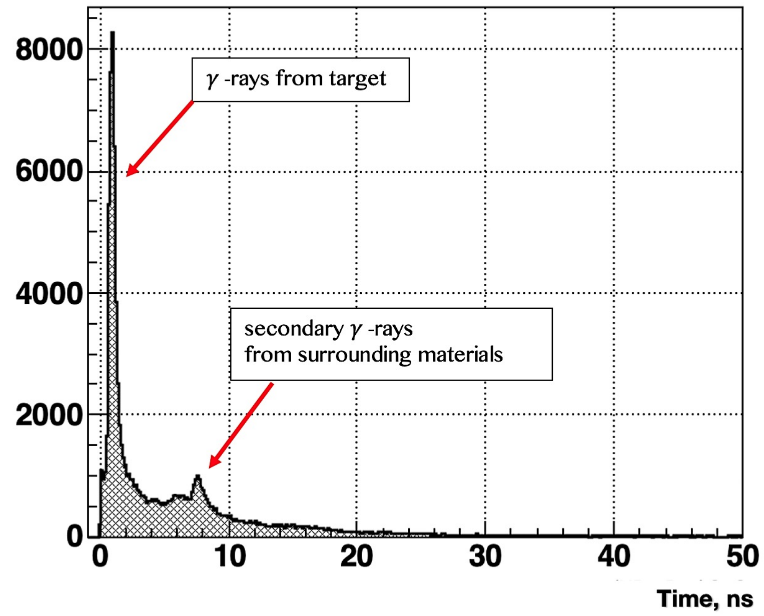
	ND1	ND2	ND3	ND4
FOM(1 MeVp)	**1.98**	**2.17**	**2.28**	**2.47**

Time and Energy resolution

Time resolution of Neutron Detectors is estimated by a half of maximum of gamma-peak and time resolution of the T0- detector

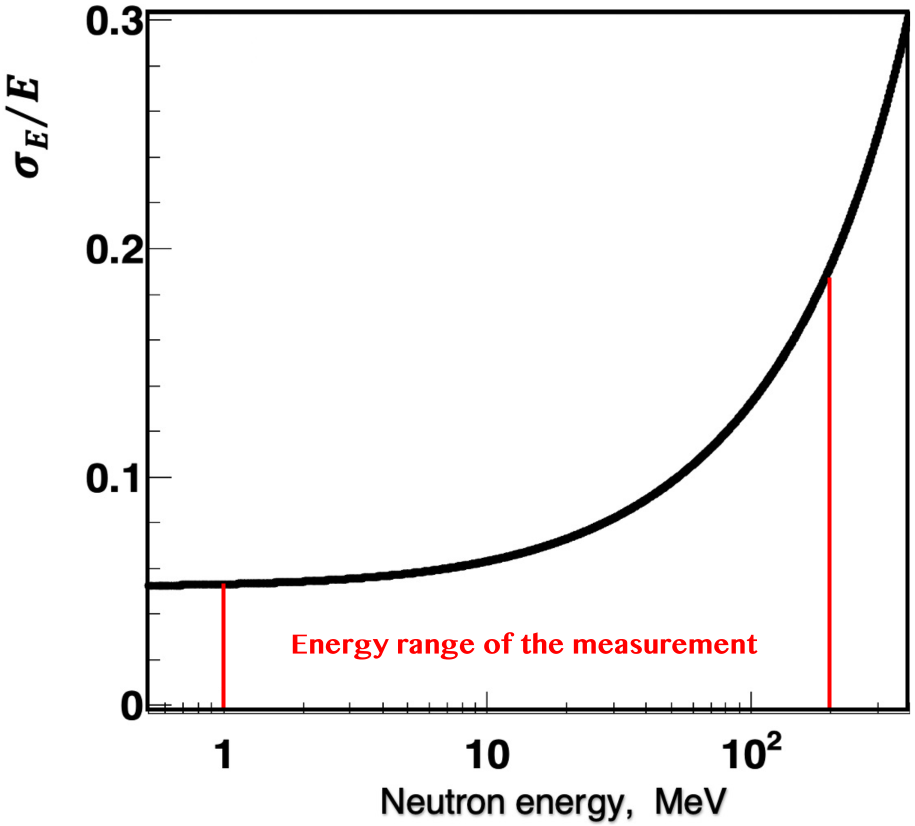
	ND1	ND2	ND3	ND4
σ_t (ps)	128	114	118	110

TOF spectrum of γ-rays



Energy resolution of the TOF measurements:

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



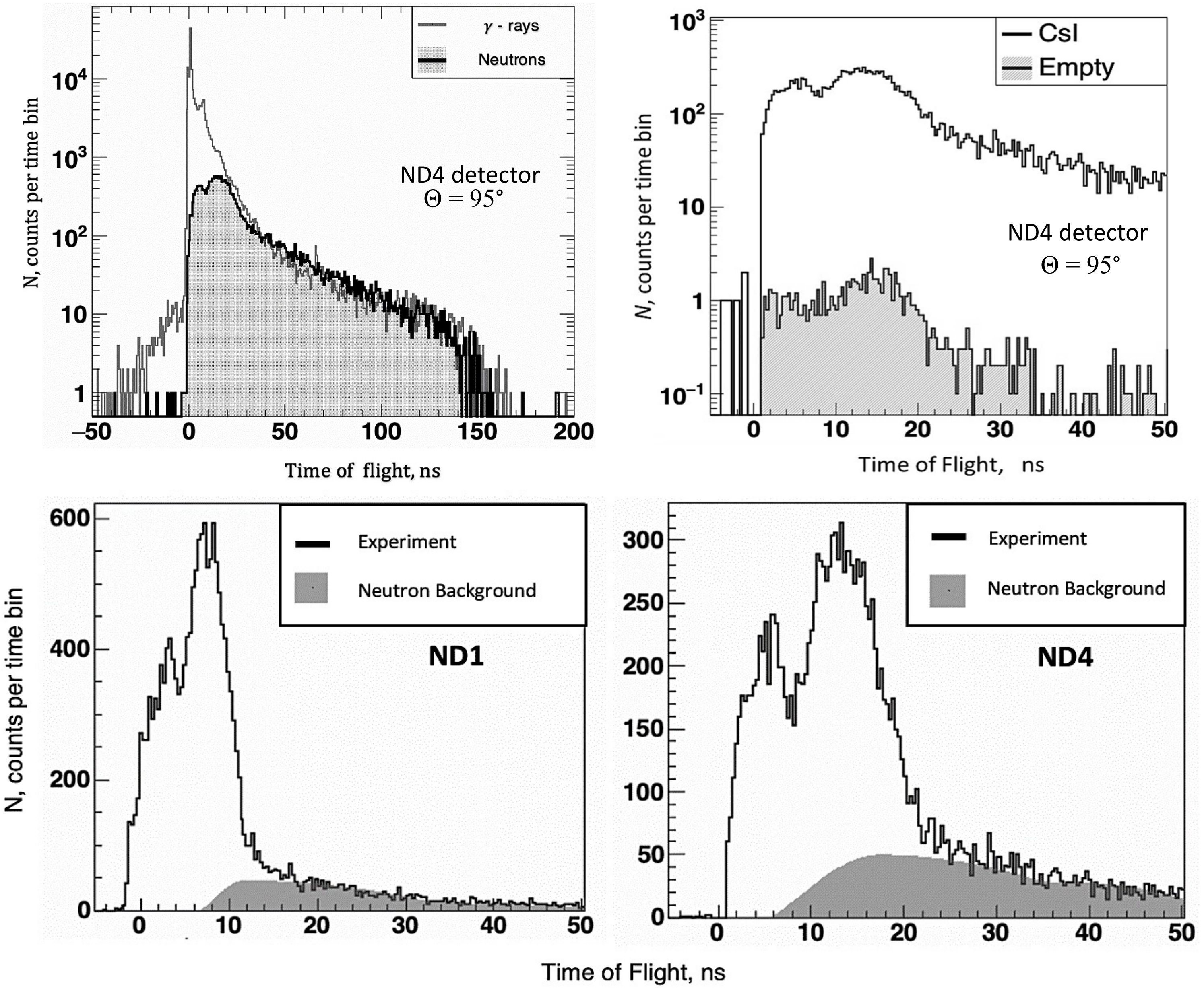
Event statistics used in the data analysis

Example of measurements with the detector ND4

	Run:	**Events:**
ND4 (93-runs)	7623, 7579, 7581, 7584, 7585, 7586, 7587, 7591, 7596, 7597, 7607, 7609, 7622, 7630, 7633, 7634, 7638, 7639, 7640, 7643, 7644, 7645, 7646, 7647, 7655, 7656, 7660 7662, 7663, 7664, 7665, 7666, 7668, 7669, 7670, 7671, 7673, 7674, 7675, 7681, 7682, 7684, 7685, 7687, 7689, 7690, 7692, 7693, 7717, 7718, 7721, 7723, 7724, 7725, 7726, 7727, 7728, 7729, 7730, 7732, 7733, 7734, 7737, 7751, 7753, 7761, 7762, 7763, 7764, 7766, 7767, 7768, 7778, 7779, 7780, 7781, 7783, 7784, 7786, 7788, 7789, 7790, 7795, 7796, 7797, 7798, 7801, 7802, 7803, 7814, 7816, 7825, 7828.	**N (CCT2)** = 93229896 N_1 **(CCT2 &&B/A $\pm$ 1.8 µs)** = 21785116 (23% N) BC1 N_2 **(γ)** = 221256 (1% N1) N_3 **(n)** = 34103 (0.16% N1)

In final analysis the statistics will be increased by factor of 3 by using another protection condition:
BC1 pulse with B/A-protection ±250 ns and interactions (BC1 * FD_{veto}) with the B/A protection interval of ±1.8 µs.

TOF spectra and background contribution

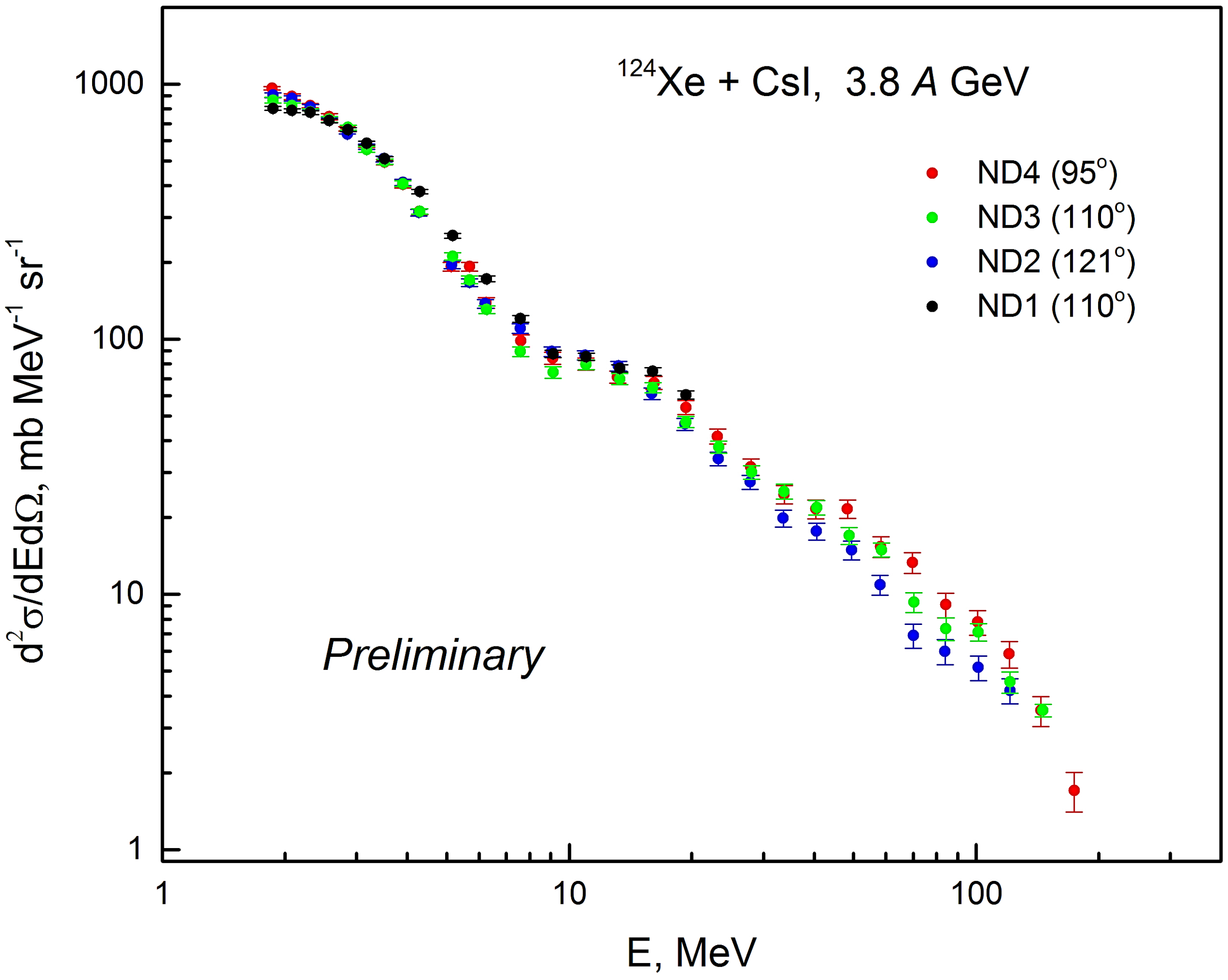


Energy spectra of neutrons

Data processing procedure

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

- **E** – kin. energy of neutron
- **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



Moving Source Model Fit

The experimental energy spectra of neutrons were analyzed in framework of three moving source model (MSM).

The first source S1 reproduces the hard part of the spectra and other sources S2 and S3 describe the neutron emission in fragmentation decay and evaporation process respectively.

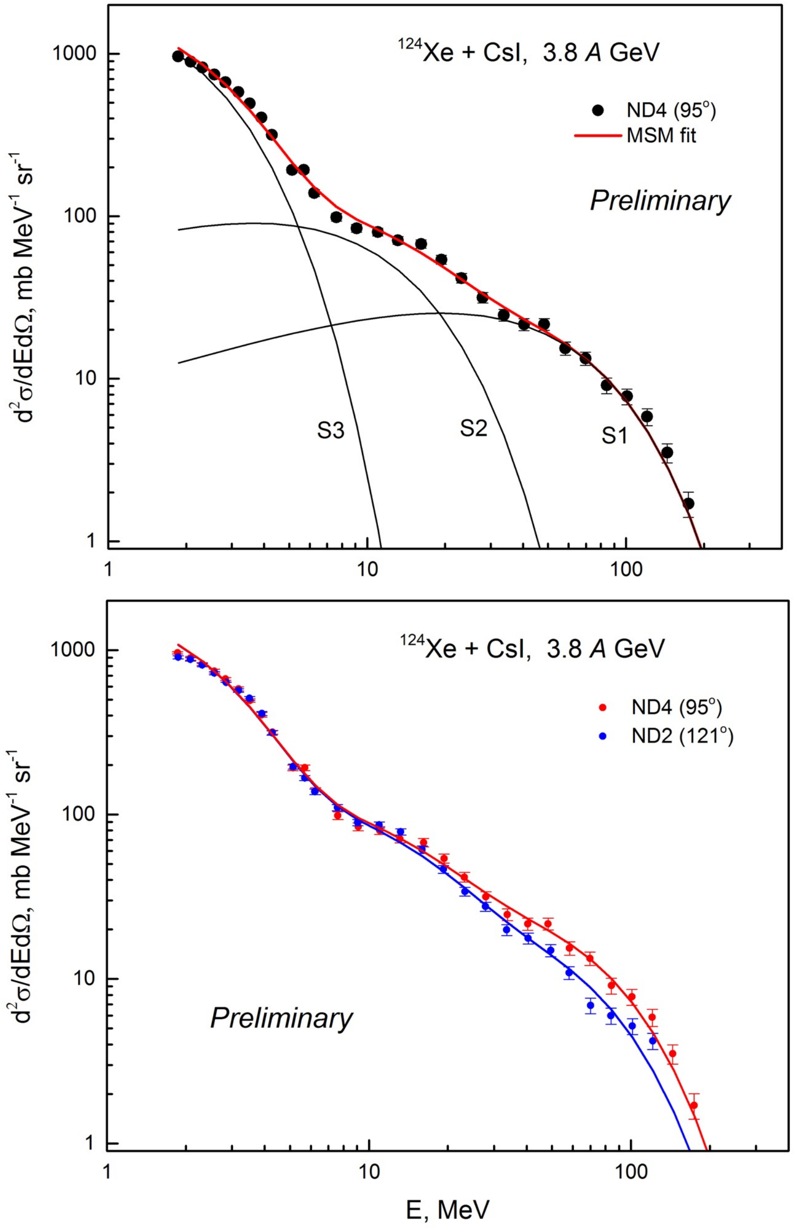
$$\frac{d^2\sigma}{dEd\Omega} = \sum_{i=1}^{3} pA_i \exp(-(\frac{E + m - p\beta_i \cos\theta}{(1-\beta_i^2)^{1/2}} - m)/T_i)$$

E, p – kin. energy and momentum in lab. frame
m – neutron mass
θ – angle in lab. frame

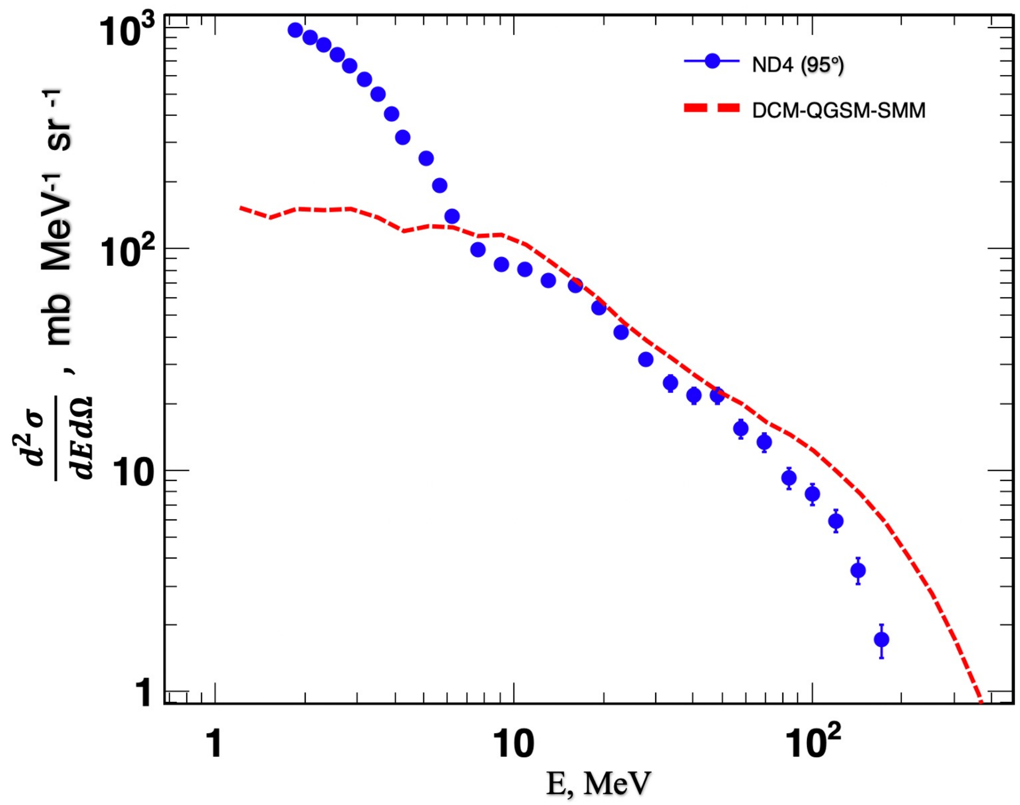
A_i – amplitude
T_i – slope temperature
β_i – longitudinal velocity

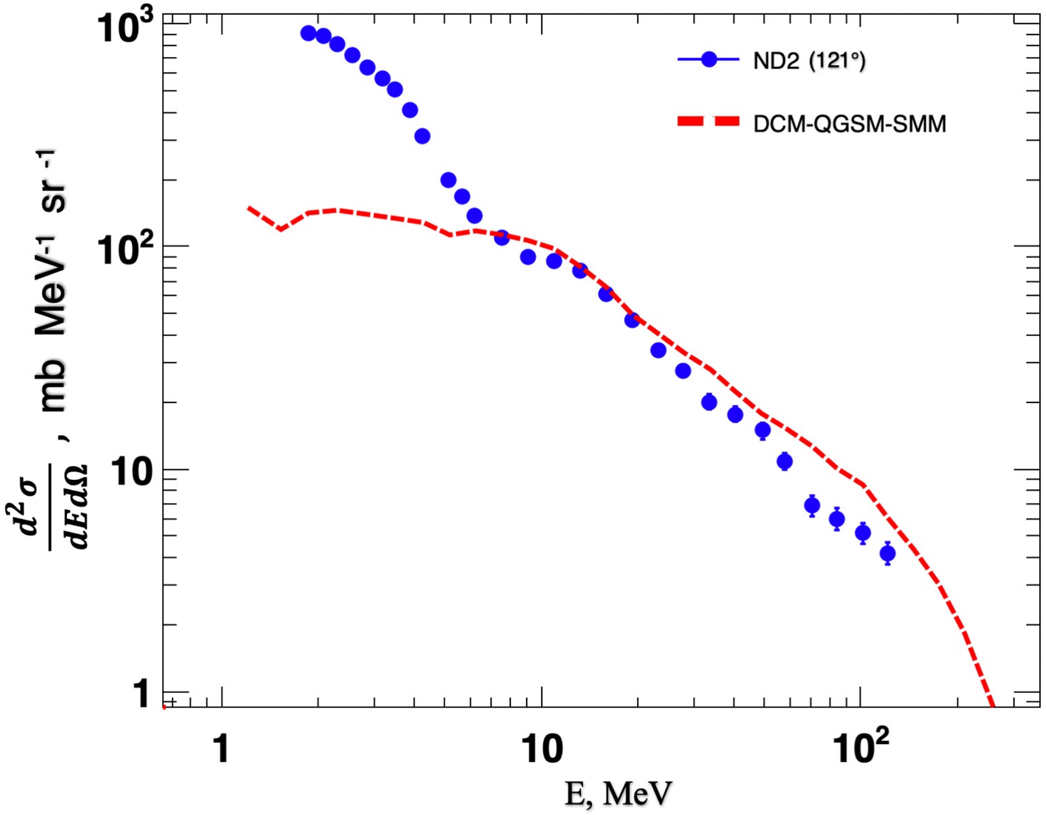
The obtained values of MSM parameters

Source	A_i	T_i (MeV)	β_i
S1	0.252	40	0.10
S2	1.8	7.3	~0
S3	78.8	1.2	~0



Comparison with prediction of DCM-QGSM-SMM model



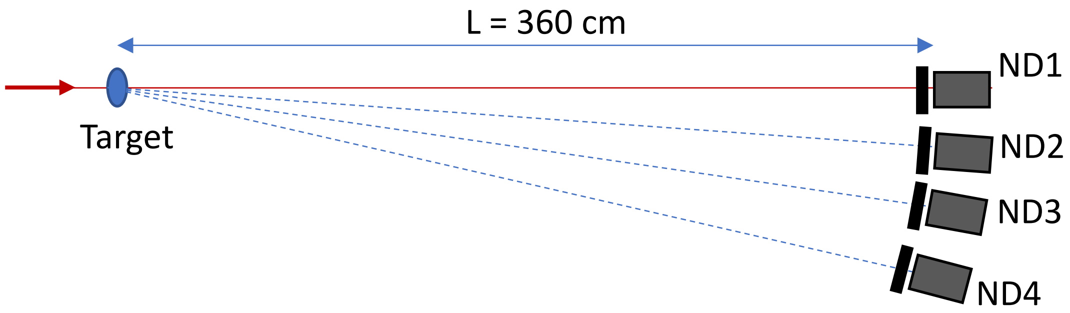


The model needs in further development to include neutron evaporation

A comparison with predictions of other theoretical models is in progress

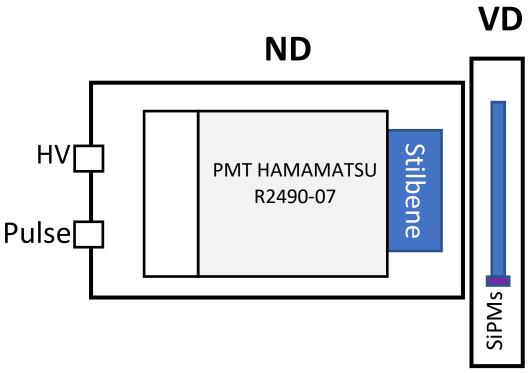
New neutron detectors for measurements at small angles

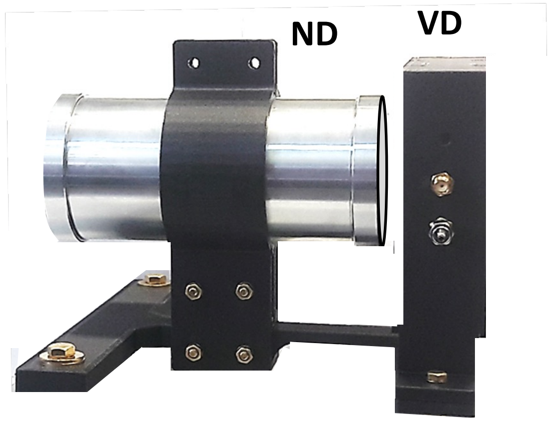
Energy range: 50 – 5000 MeV



Neutron Detectors

Detector	Stilbene	Angle
ND1	D31 × 31 mm	0°
ND2	D31 × 31 mm	3°
ND3	D40 × 20 mm	7°
ND4	D40 × 20 mm	12°





<u>Aim of the measurements</u>

- ✓ Study neutron emission from beam spectators and comparison with theoretical models and results of the compact TOF spectrometer
- ✓ To get reference data for HGND project
- ✓ Study of energy and angular distribution of neutrons coming to nZDC

The event statistics required is obtained in one-day measurement
(with and without target)

Conclusion

1. Existing neutron time-of-flight spectrometers use flight distances of several meters or more (hall scale). We have succeeded in creating a compact time-of-flight spectrometer (table scale) covering a wide range of neutron energies from 1 to 200 MeV.

2. The high time resolution of ~119 ps and very good gamma-ray discrimination with the PSD method are main features of the spectrometer.

3. With this spectrometer we studied the neutron emission from target spectators in Xe + CsI collisions at 3.8 *A* GeV. Double-differential neutron production cross section was obtained for collision centrality $< 60\%$.

4. The Moving Source Model with three sources of neutrons is well reproducing the experimental data. The neutron emission in low energy region is closed to isotropic with the source velocity $v \approx 0$.

5. Comparison of the experimental spectra with prediction of the DCM-QGSM-SMM model shows satisfactory agreement above energy of 8 MeV and essential underestimation by the model at low energies. It seems, the model needs improvement by including neutron evaporation stage.

6. The new design of the spectrometer including the detectors at small angles to the beam axis is developing for the future BM@N runs.