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

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INTRODUCTION

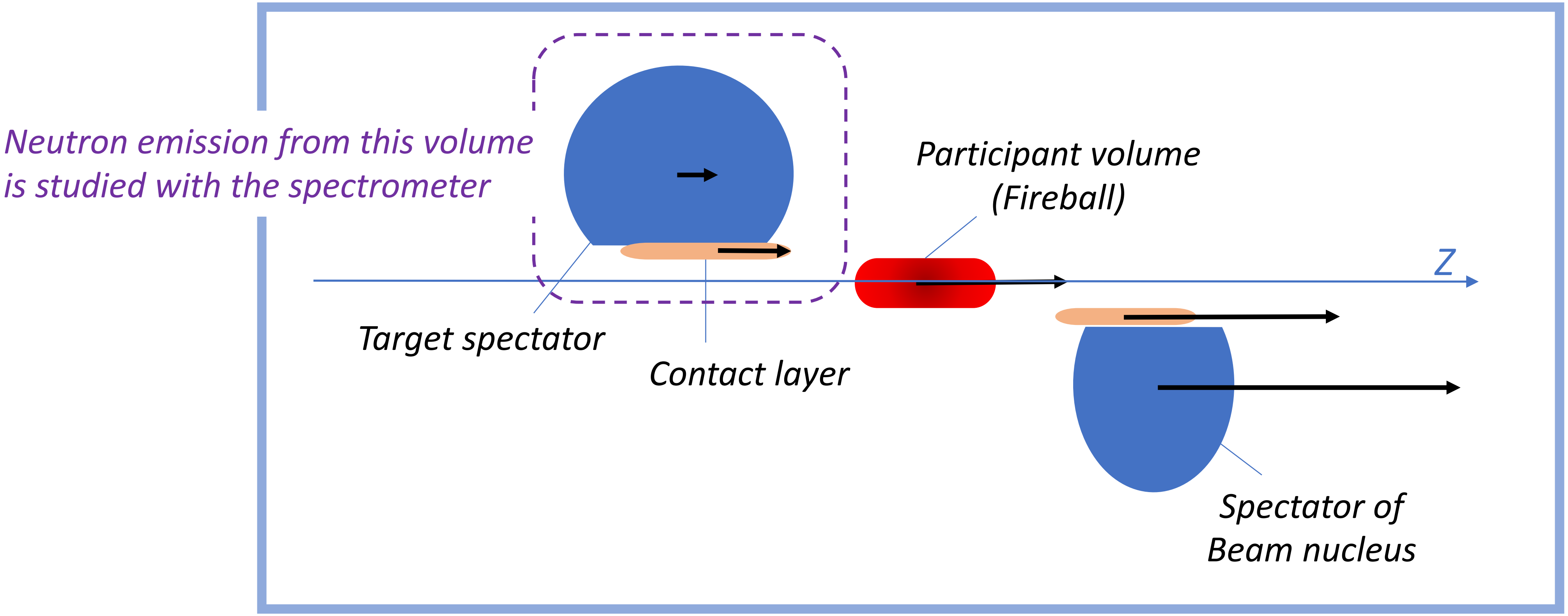
In high energy nucleus – nucleus collisions a large number of free neutrons are emitted and characteristics of these neutrons give an important information about evolution of the nuclear system produced in the collisions. Also, these neutron data are very important for testing and development of theoretical models of nucleus – nucleus interactions at high energies.

However, despite the importance of these data, the number of such experiments remains very limited due to the methodological difficulties of neutron measurements.

A compact TOF neutron spectrometer was recently created as a part the BM@N experiment on beam line of the Nuclotron at Laboratory of High Energy Physics of Joint Institute for Nuclear Research. The aim of the spectrometer is study of neutron emission at large angles where decay of target spectators dominates.

This talk is dedicated to the first results obtained for ^{124}Xe + CsI collisions at energy of 3.8 *A* GeV with the compact TOF neutron spectrometer.

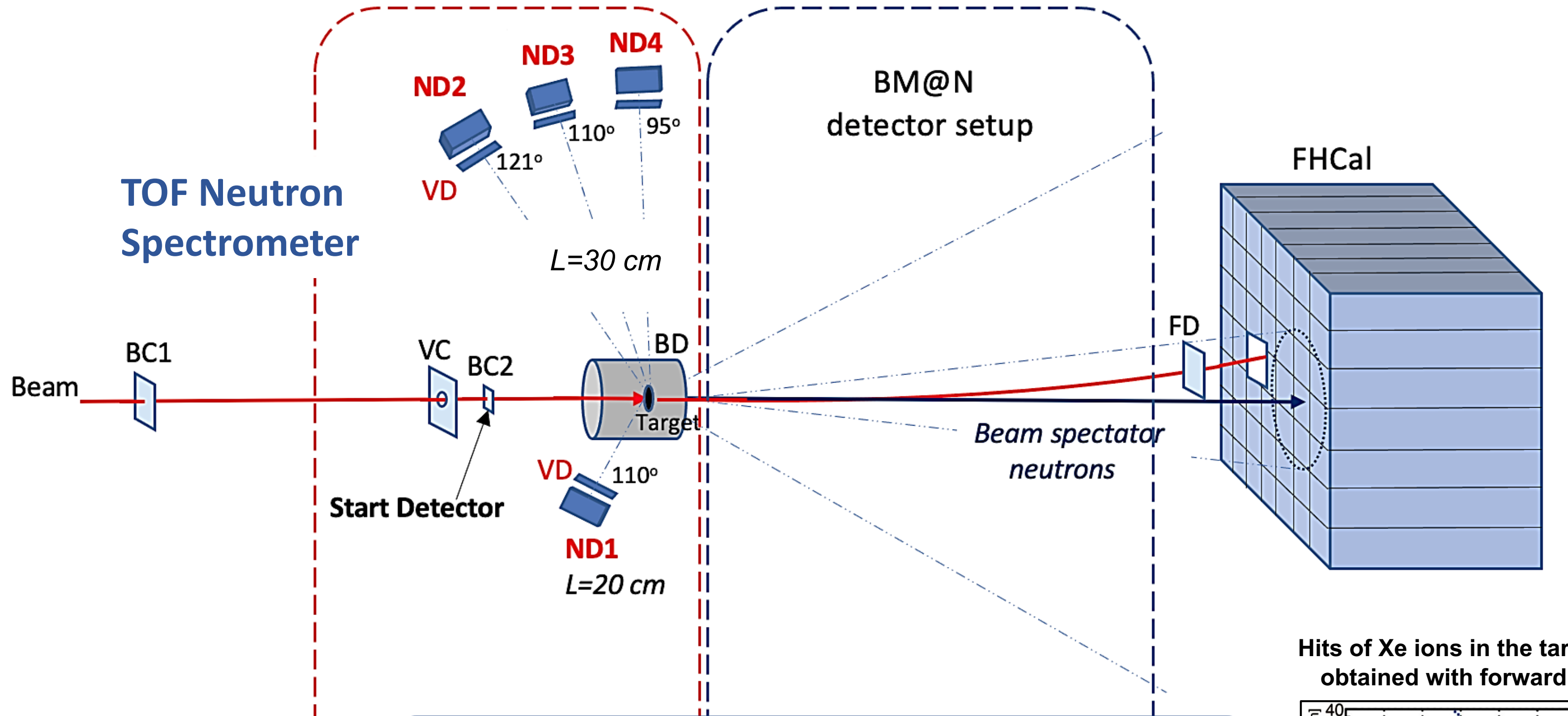
Phenomenological picture of *AA* - collisions



With the neutron spectrometer we study neutron emission in back hemisphere where contribution of target spectator decay dominates

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)

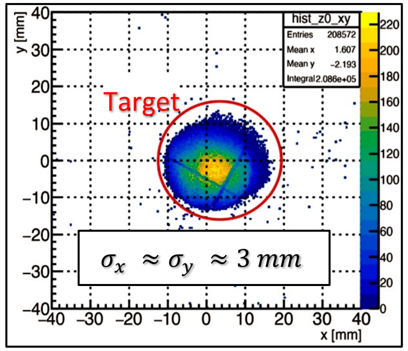
Scintillator: BC-400B, 34×34×0.15 mm^3

PMT: XPM85112/A1 (Photonis), 2 units

Time resolution: **σ_t = 40 ps**

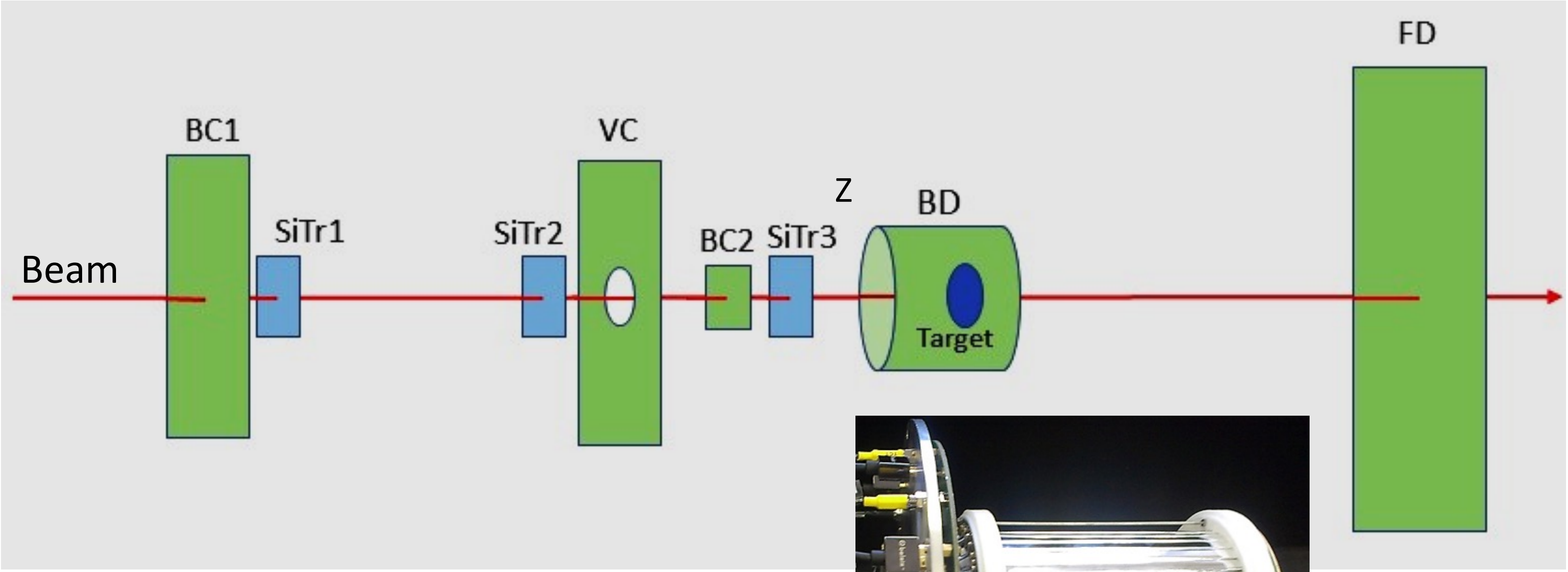
	Beam	**Target**
Beam ions:	^{124}Xe	2% CsI
Energy:	3.8 A GeV	D32 × 1.75 mm
Intensity:	~ 6 10^5 ion/spill	
Spill duration:	~ 2.5 s	

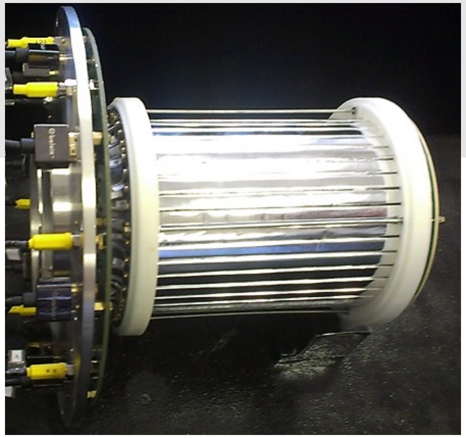
Hits of Xe ions in the target position obtained with forward Si tracker



Selection of interactions in the target

Trigger detector system of the BM@N experiment





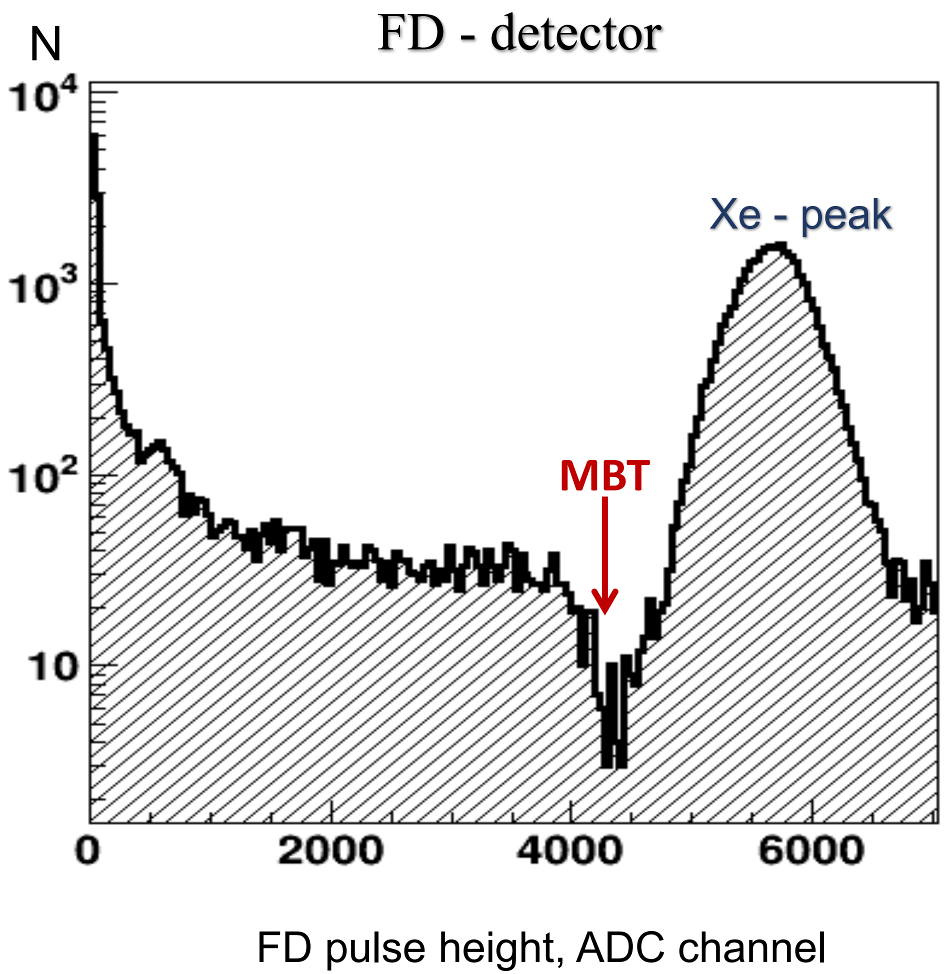
Barrel Detector (BD)
40 scintillation strips

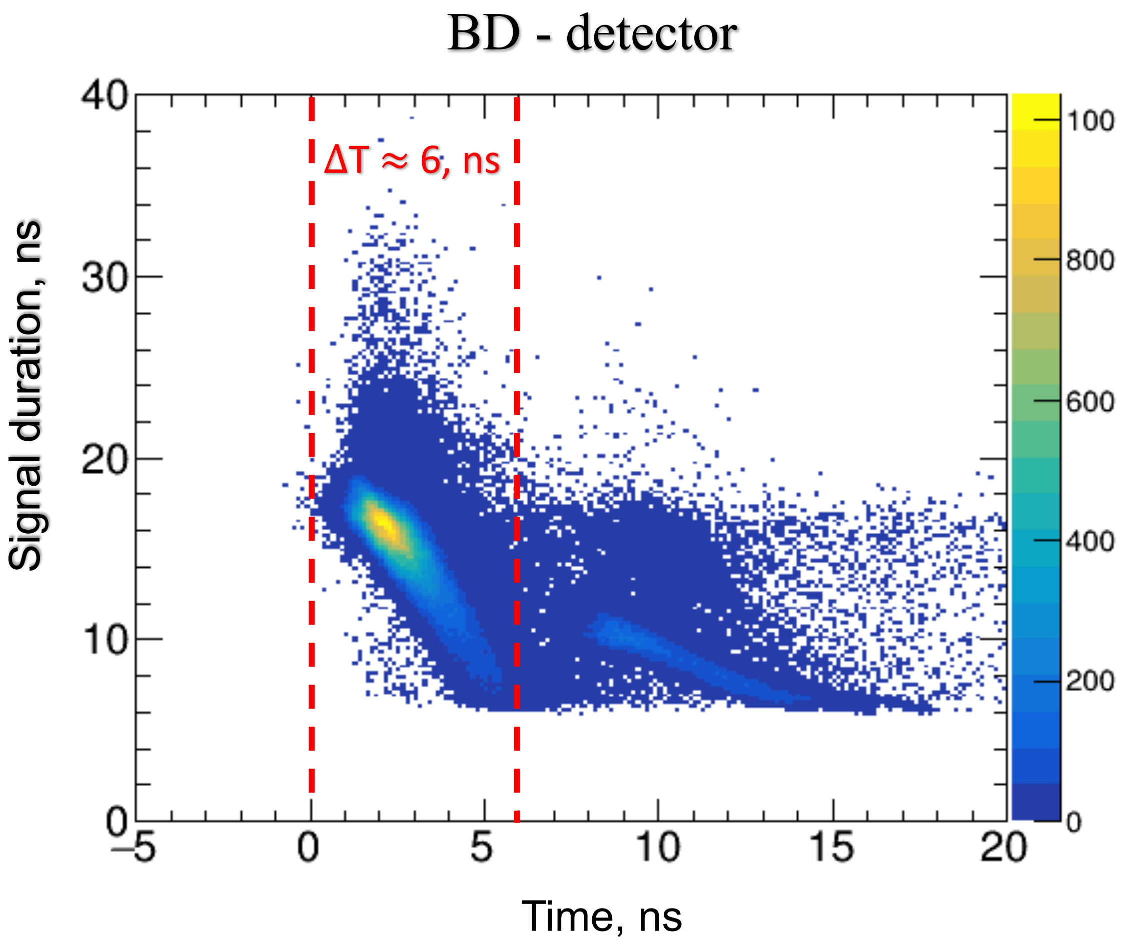
Interaction Trigger Logic:

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

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

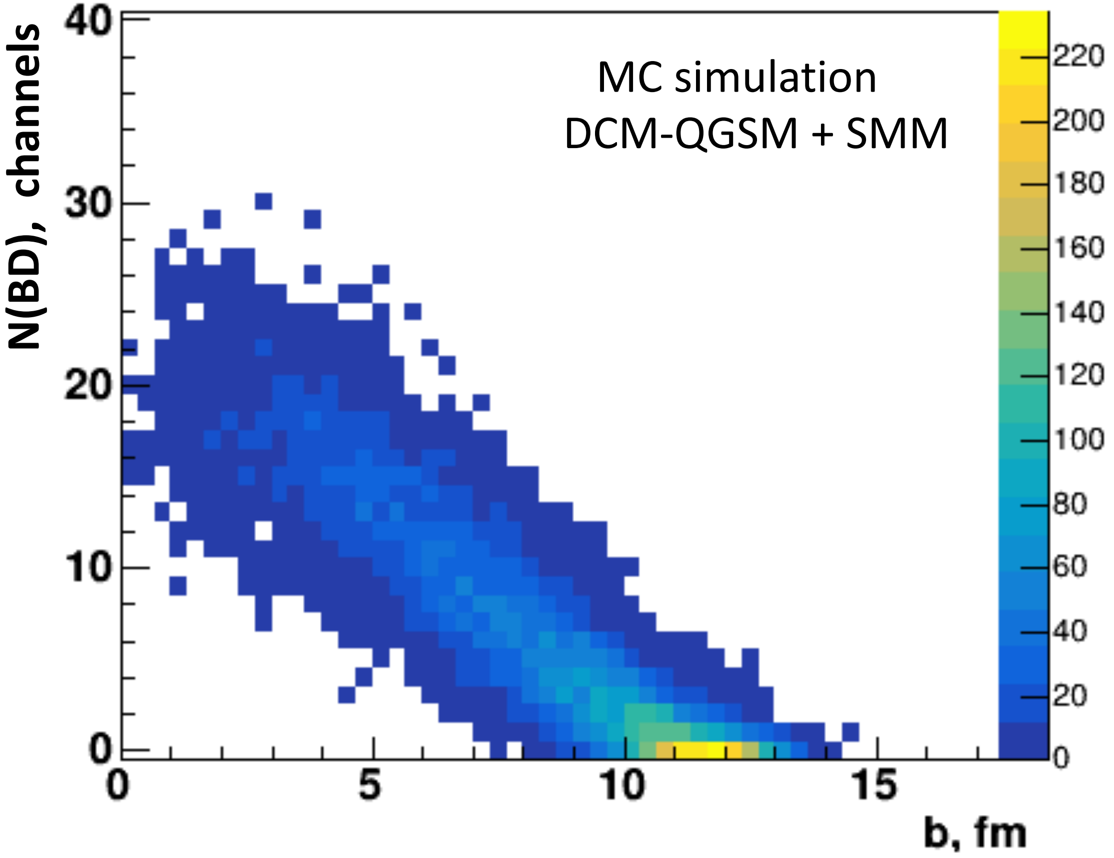
Conditions for FD and BD

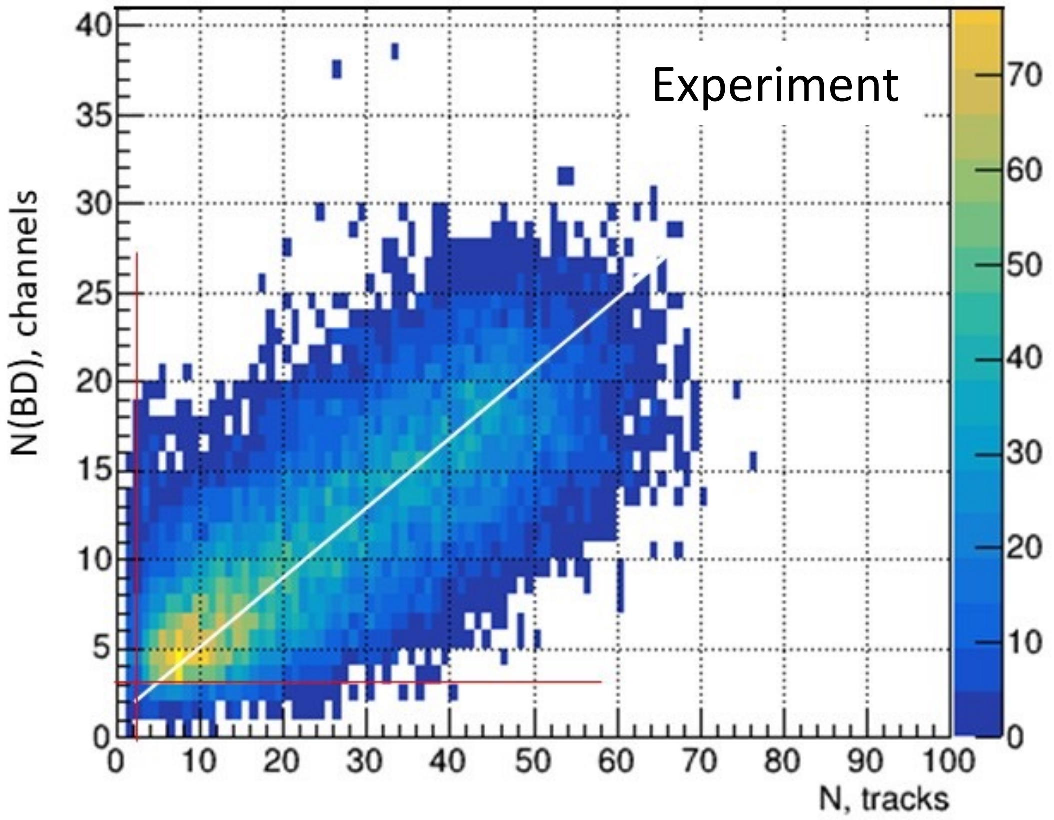




Barrel Detector performance

^{124}Xe + CsI at 3.8 *A* GeV

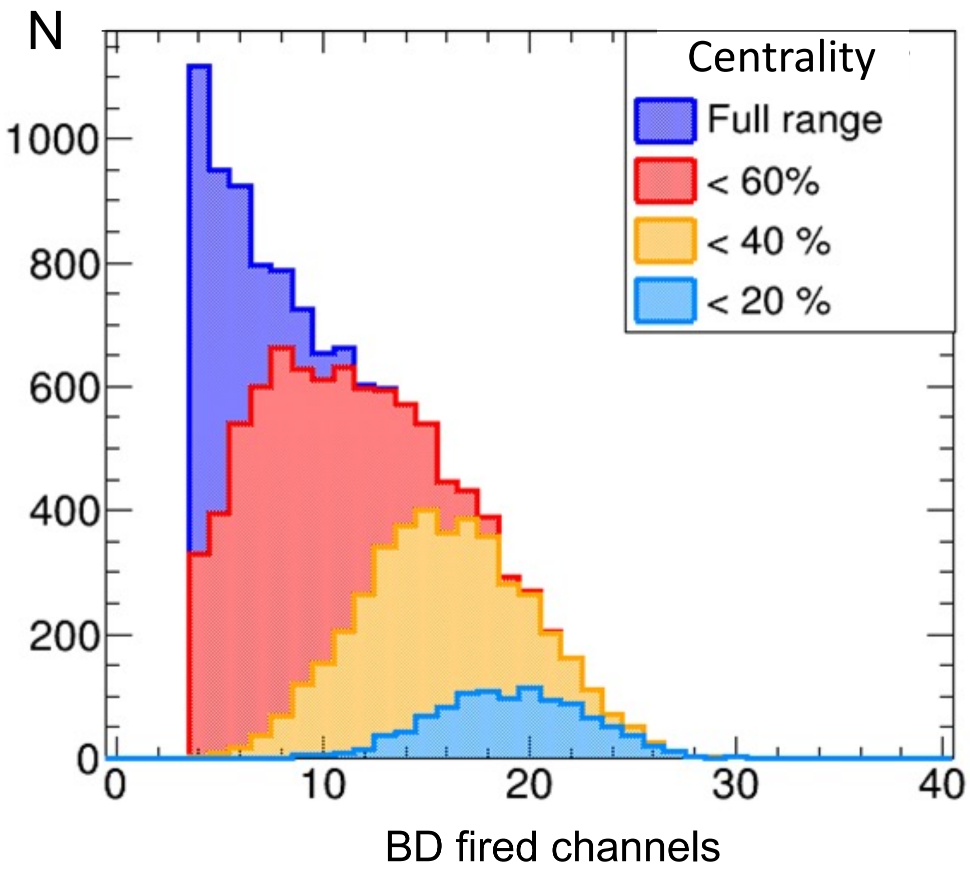


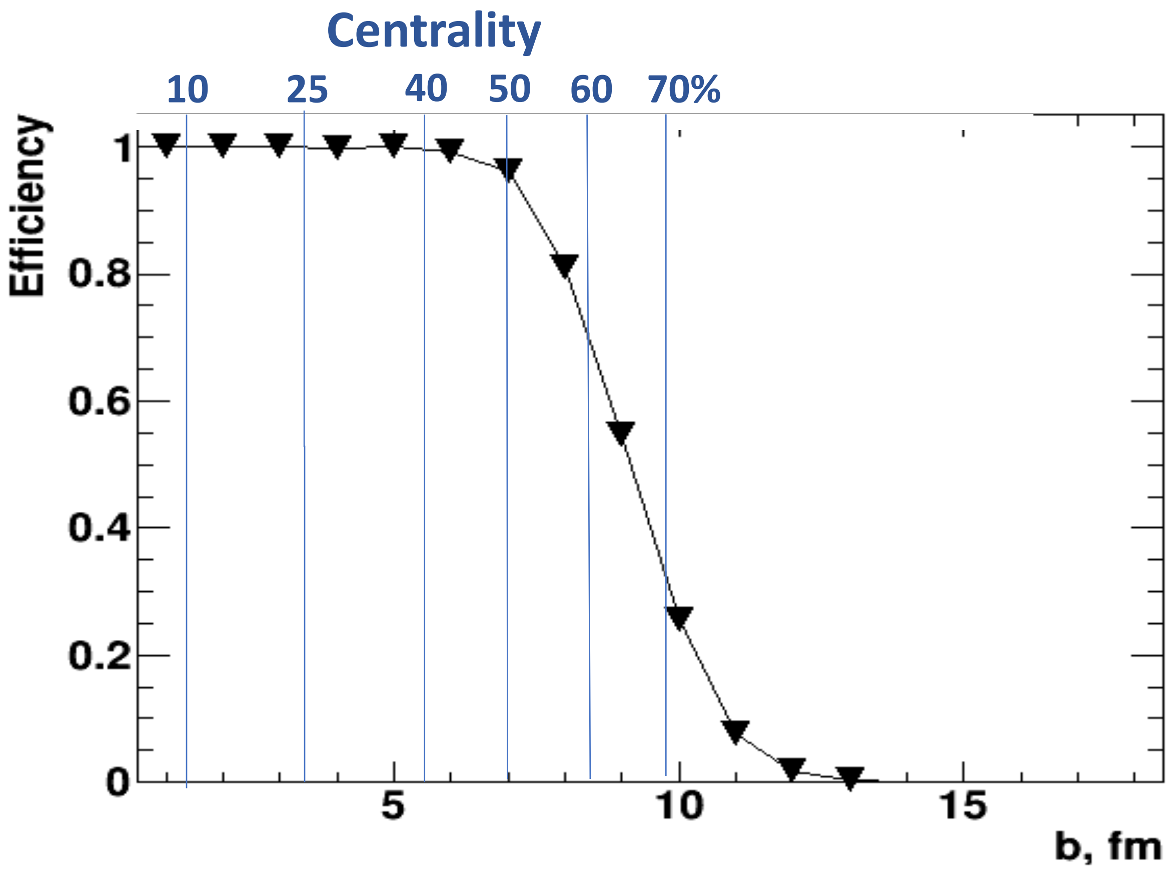


Trigger Efficiency

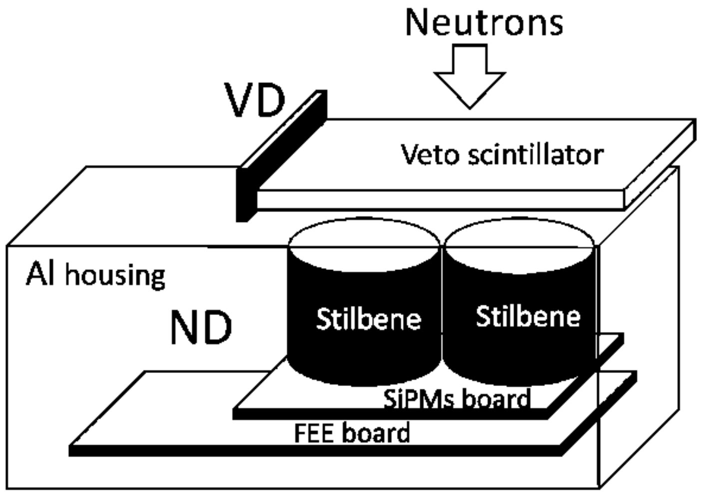
MC simulation
DCM-QGSM + SMM

^{124}Xe + CsI at 3.8 *A* GeV

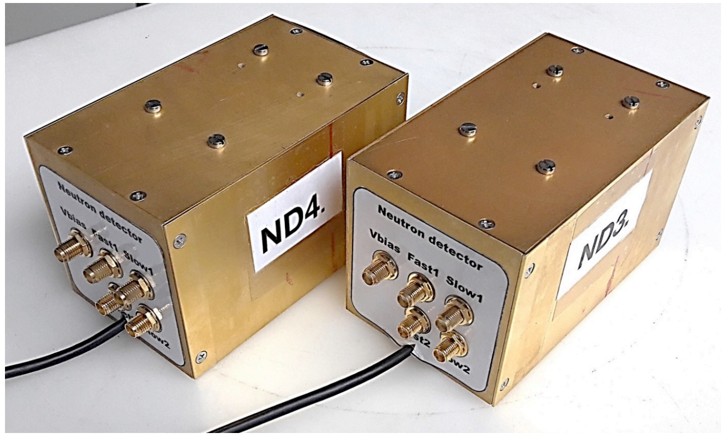


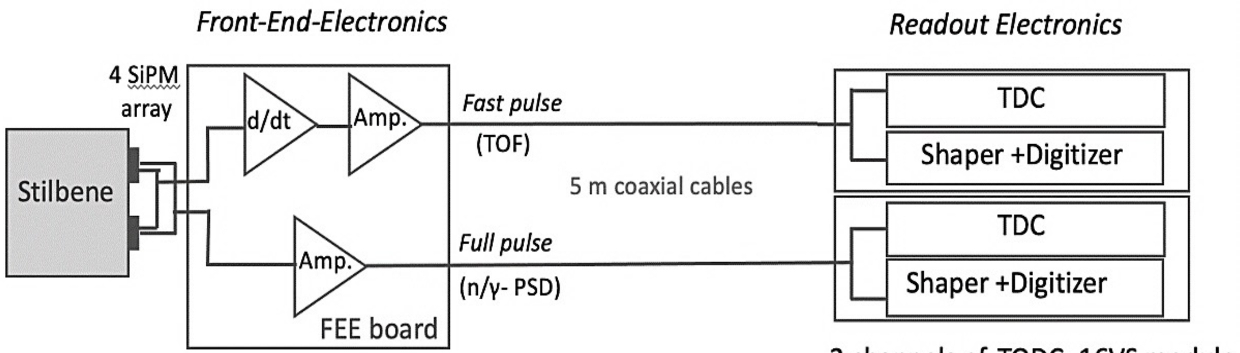


Neutron Detectors

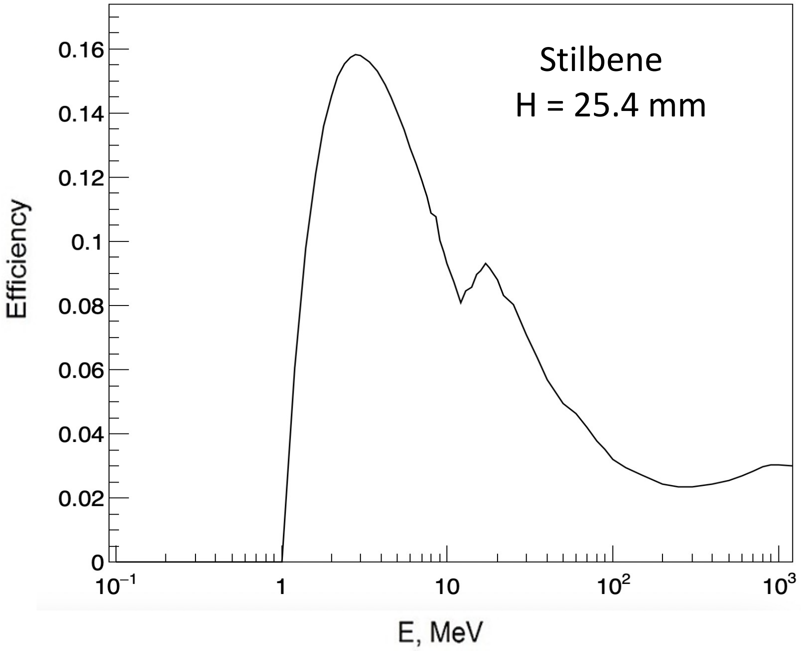


Detection of scintillation photons with four SiPMs 6×6 mm^2, SensL, J ser.





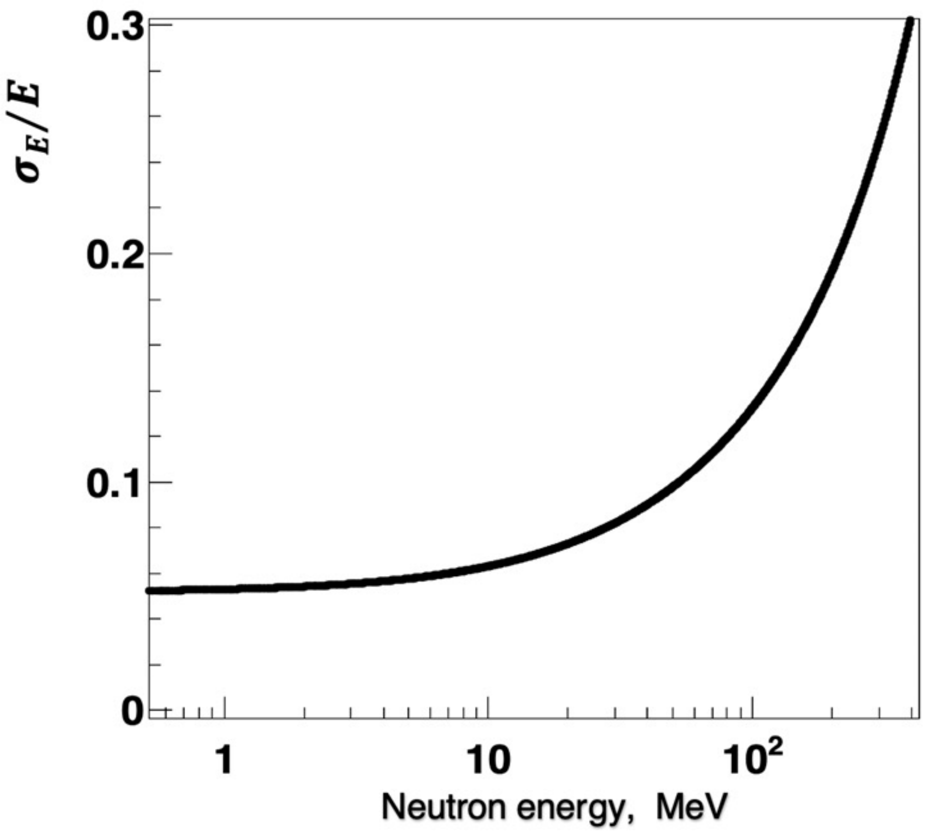
2 channels of TQDC_16VS module



Spectrometer characteristics

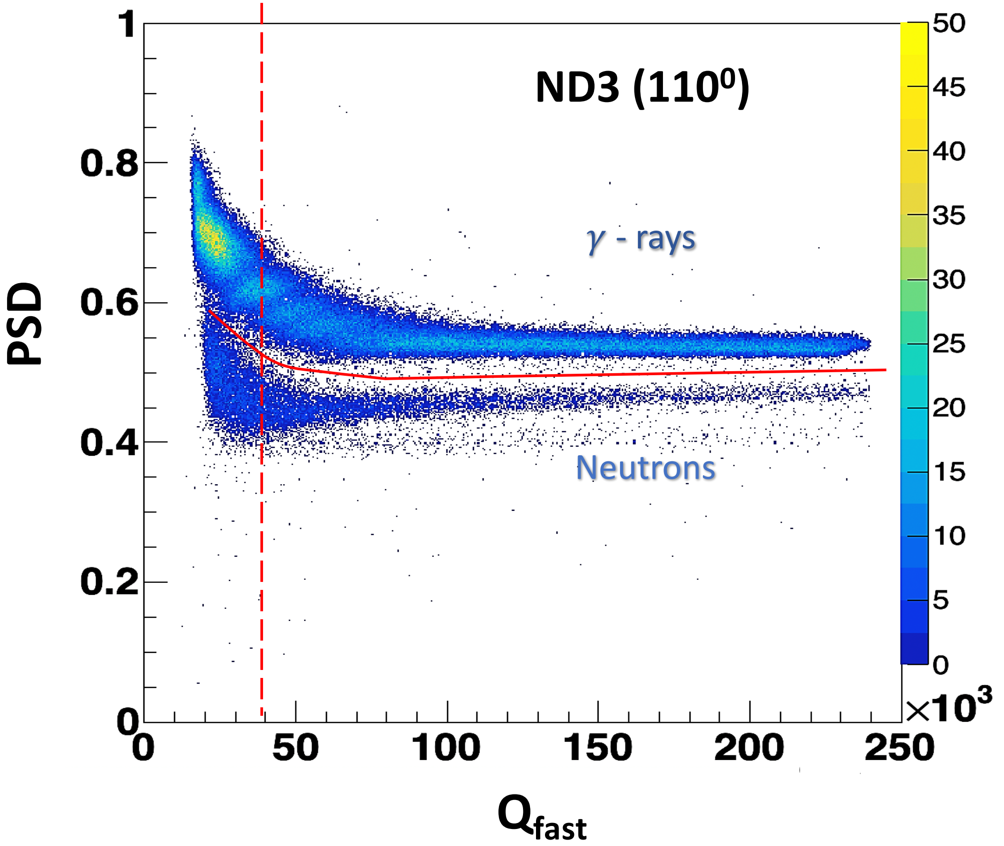
Time resolution

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

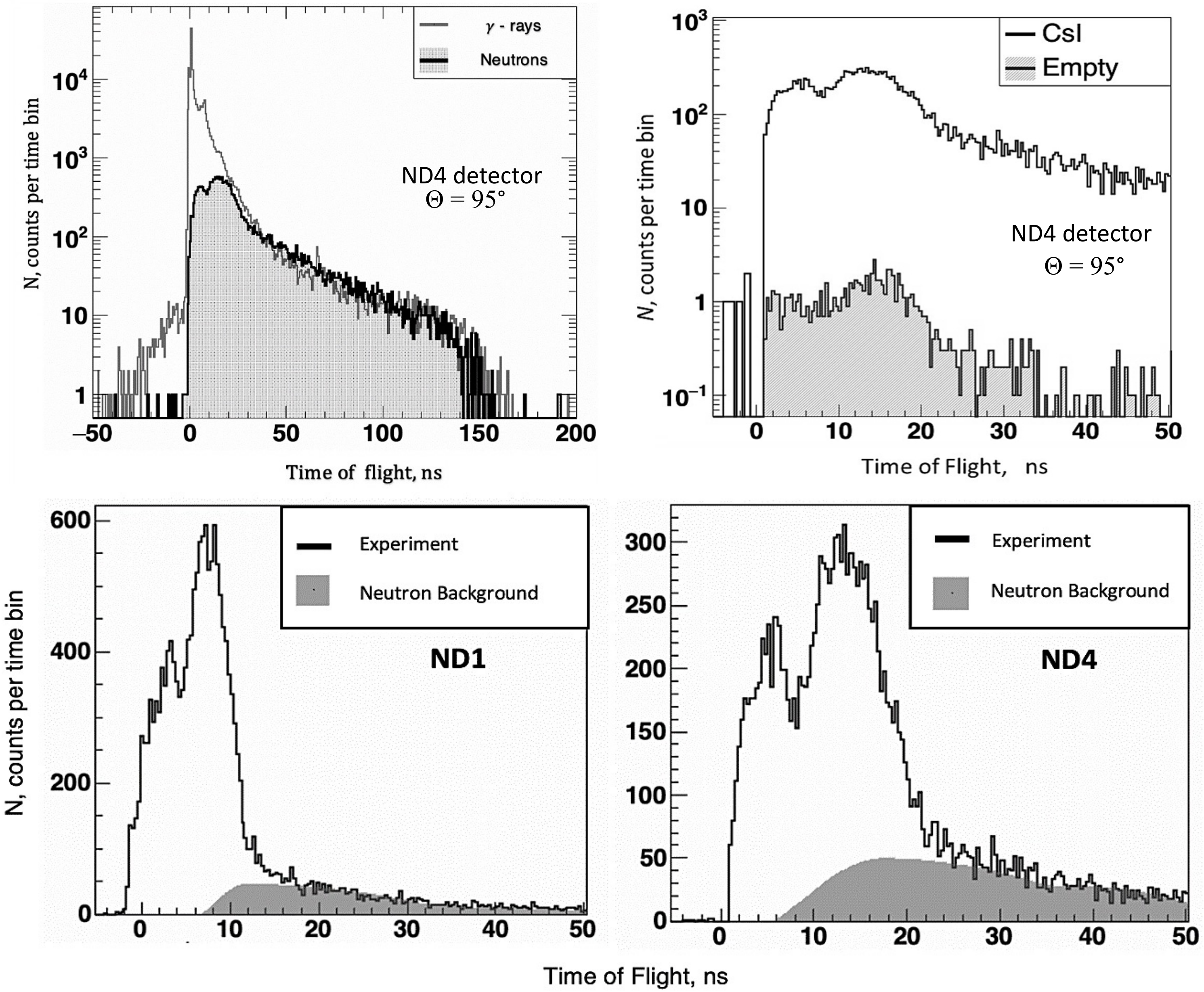


n/γ – pulse shape discrimination (PSD)

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



TOF spectra and background contribution



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 $\mathbf{N_1}$ **(CCT2 &&B/A** $\pm$ **1.8 µs)** = 21785116 BC1 (23% N) $\mathbf{N_2}$ **(γ)** = 221256 (1% N1) $\mathbf{N_3}$ **(n)** = 34103 (0.16% N1)

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 (DAQ busy) and B/A protection

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

Corrections:

DAQ busy correction

Time – pulse height correction to improve time resolution

Efficiency of neutron detectors

Selection of neutron events using pulse shape analysis

Neutron background contribution

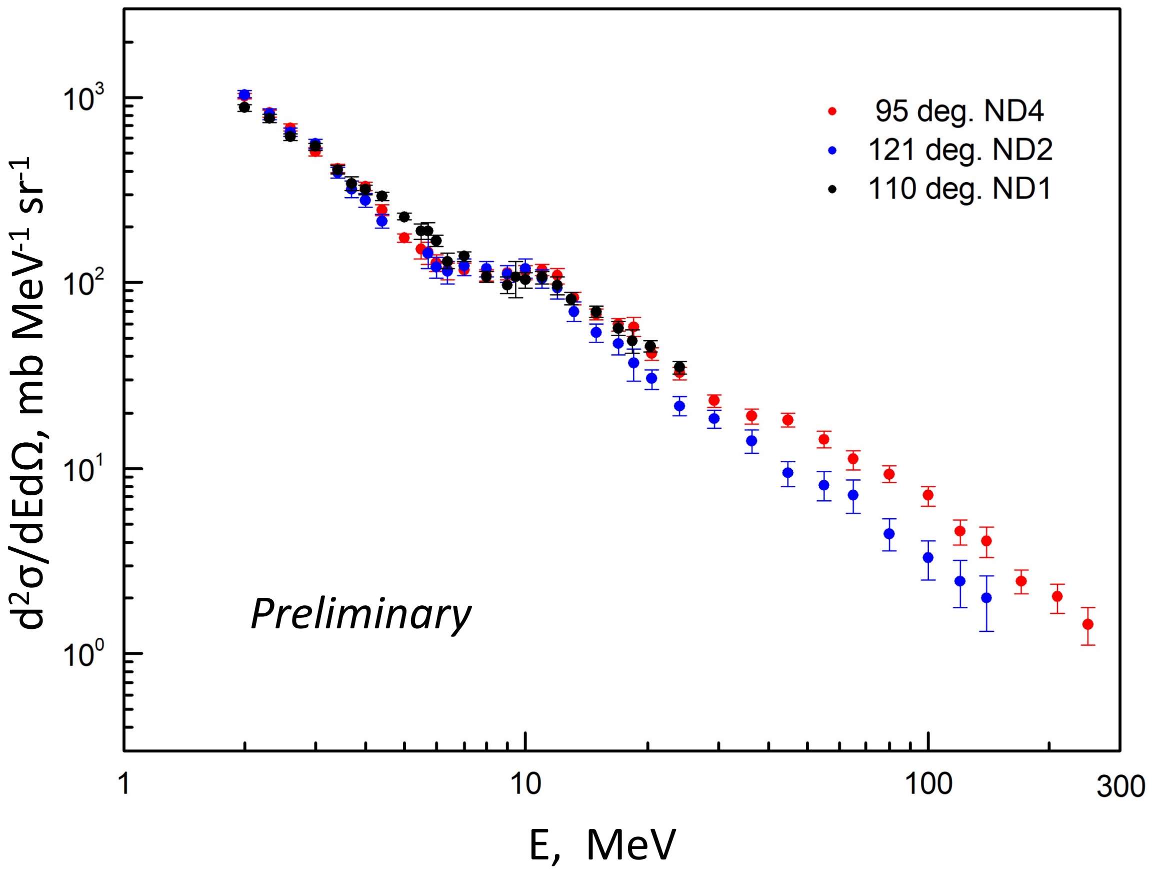
Conditions used for event selection:

Interaction Trigger: CCT = BT* FD(A<A_{beam}) * BD(N>3)

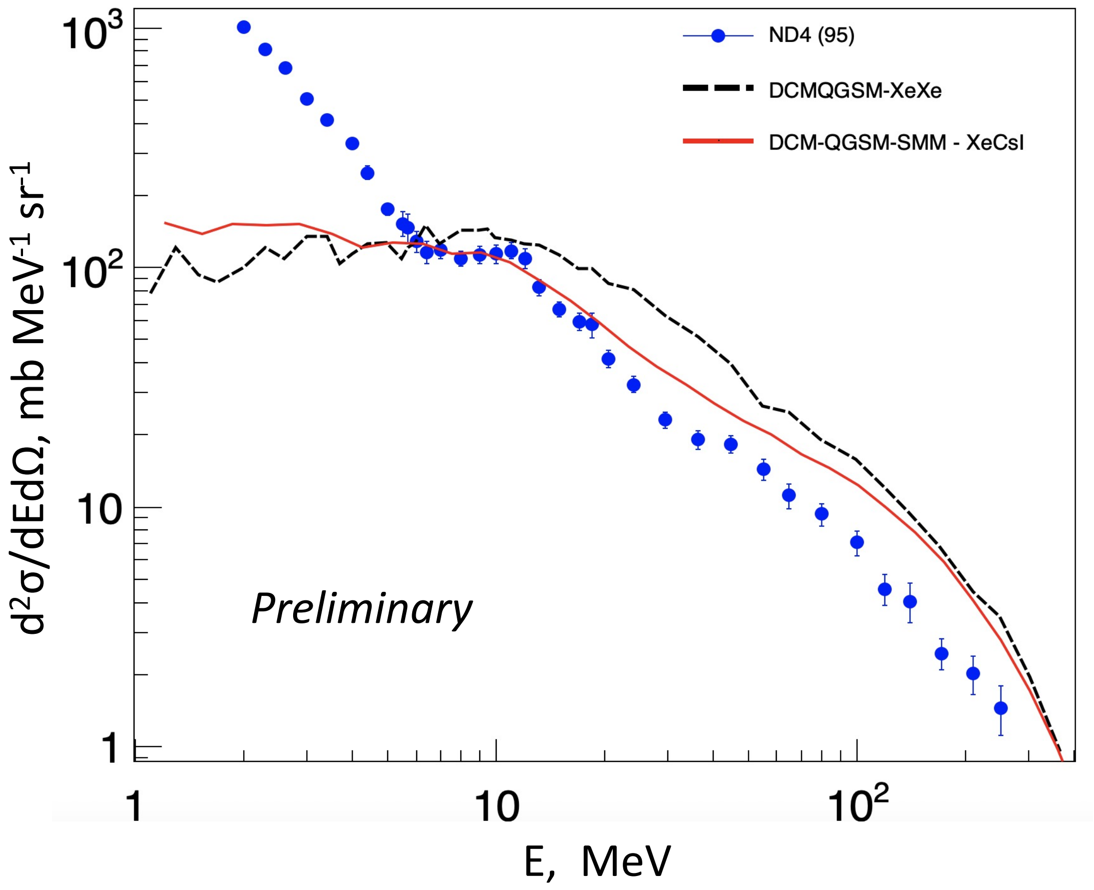
Off-line B/A selection

Energy spectra of neutrons

^{124}Xe + CsI, 3.8 A GeV



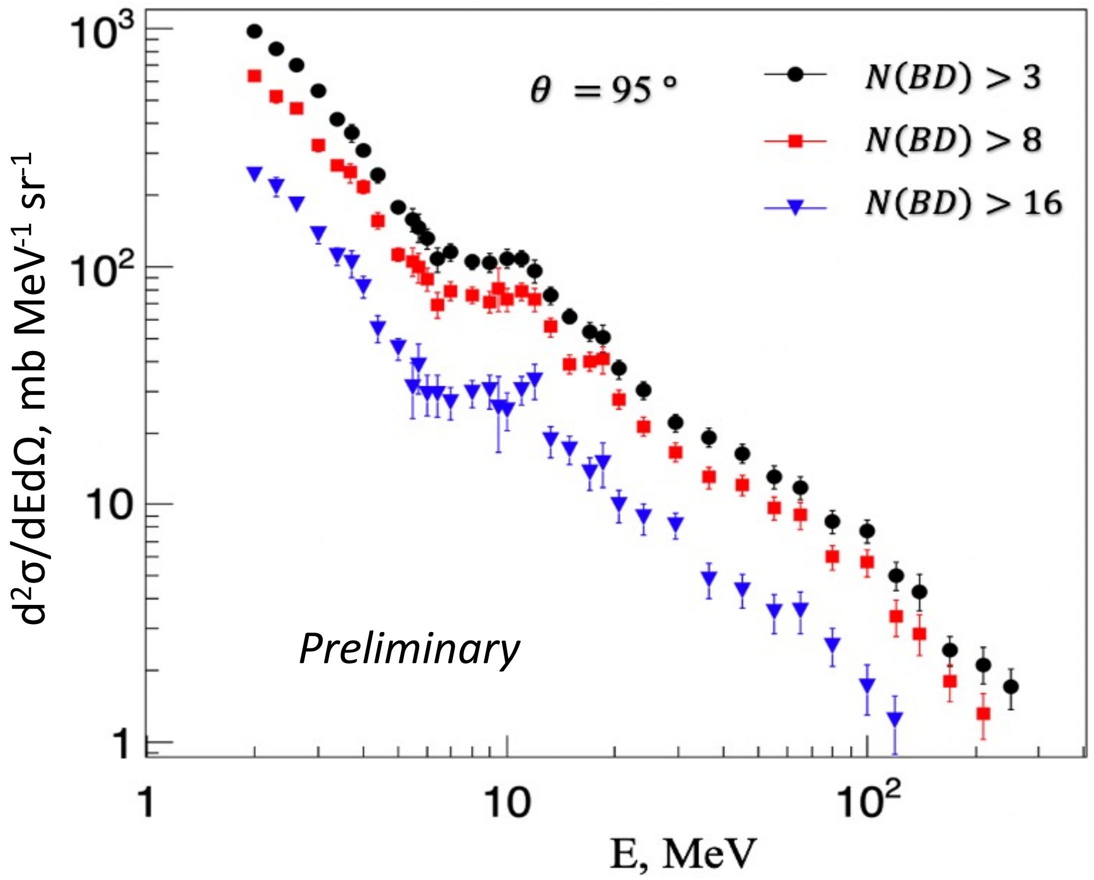
Comparison with prediction of DSM-QGSM model

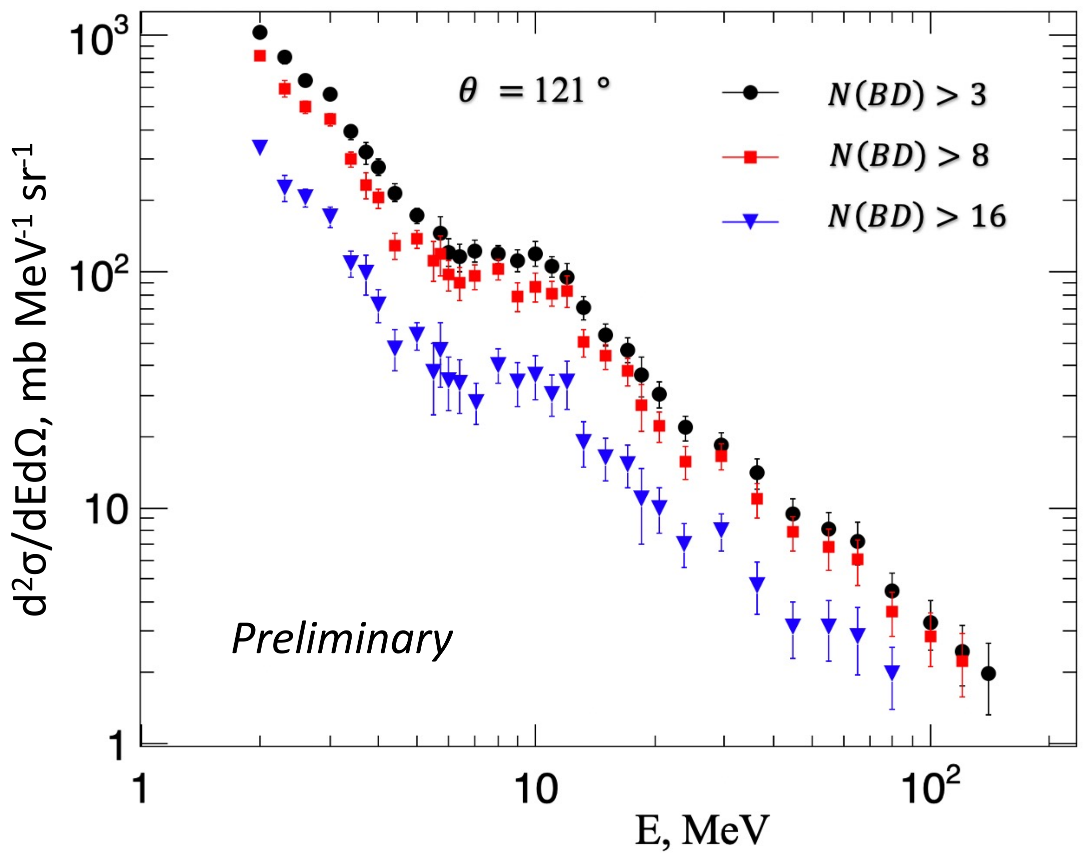


The trigger efficiency was not taken into account

Neutron spectra for different N(BD) intervals

^{124}Xe + CsI, 3.8 A GeV





The trigger efficiency was not taken into account

Moving Source Model

The experimental energy spectra of neutrons were analyzed in framework of Moving Source Model (MSM) with three sources:

- ✓ The first source S1 reproduces the hard part of spectra (contact layer)
- ✓ The second source S2 gives main contribution in the middle part of spectra (multifragmentation decay)
- ✓ The third source S3 dominates in the low energy part (fragmentation decay + evaporation)

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

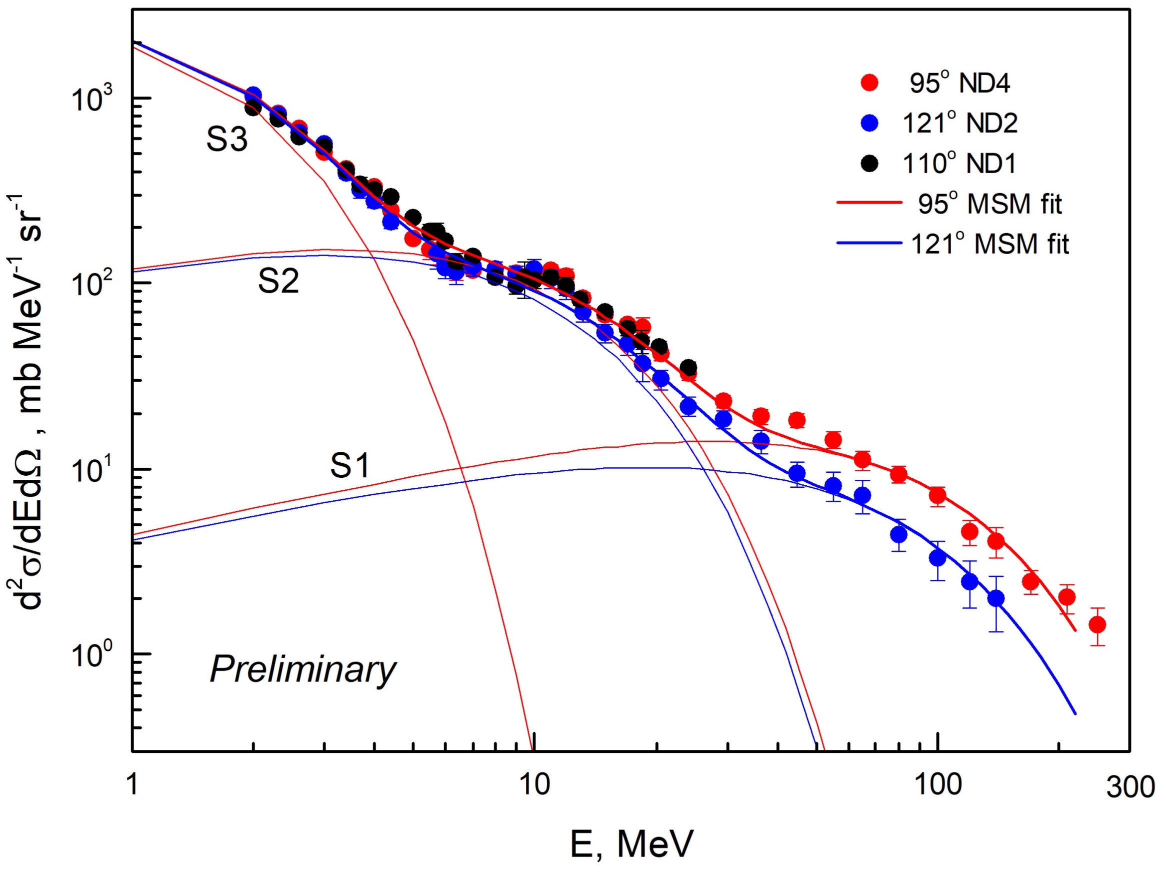
E, p – kin. energy and momentum in lab. frame
m – neutron mass
θ – angle in lab. frame

A_i – amplitude
T_i – slope temperature
β_i – longitudinal velocity (v/c)

MSM fitting of the neutron spectra

^{124}Xe + CsI, 3.8 A GeV

Total neutron spectra



The trigger efficiency was not taken into account

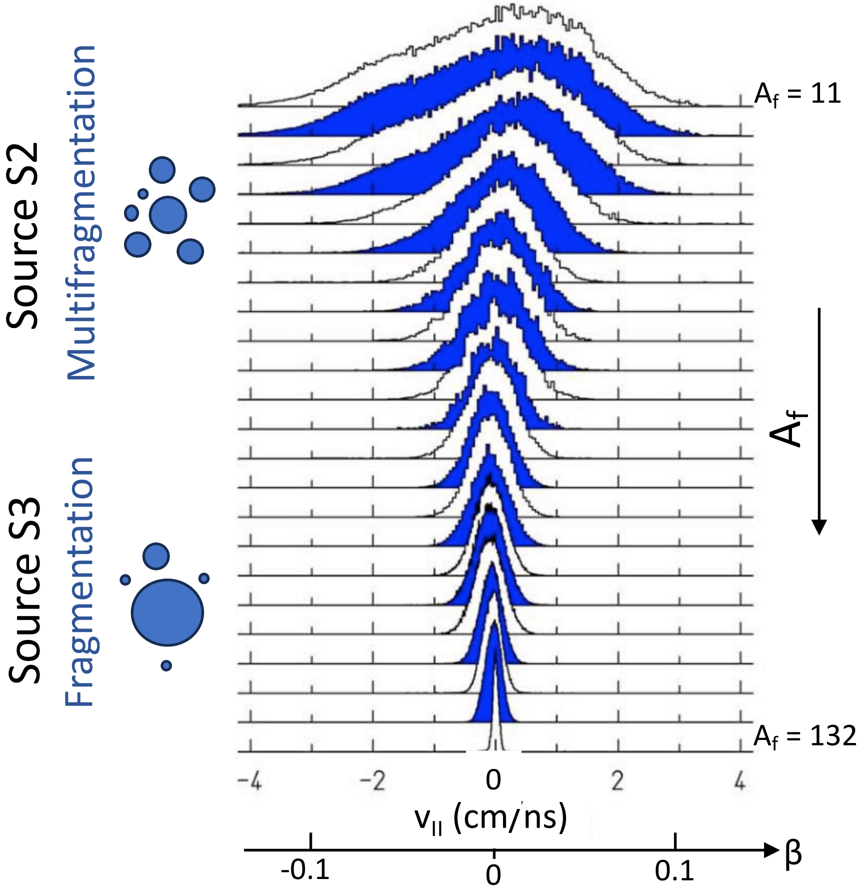
MSM parameters obtained by fitting (preliminary)

Source	A_i	T_i (MeV)	β_i
S1	0.157	55 (±5)	0.18 (±0.2)
S2	3.27	6.5 (±0.5)	0.015 (±0.010)
S3	205	0.8 (±0.1)	~0

Comparison with the results obtained at GSI

The FRagment Separator (FRS)

^{136}Xe + Pb at 1 A GeV



Longitudinal velocity spectra of fragments

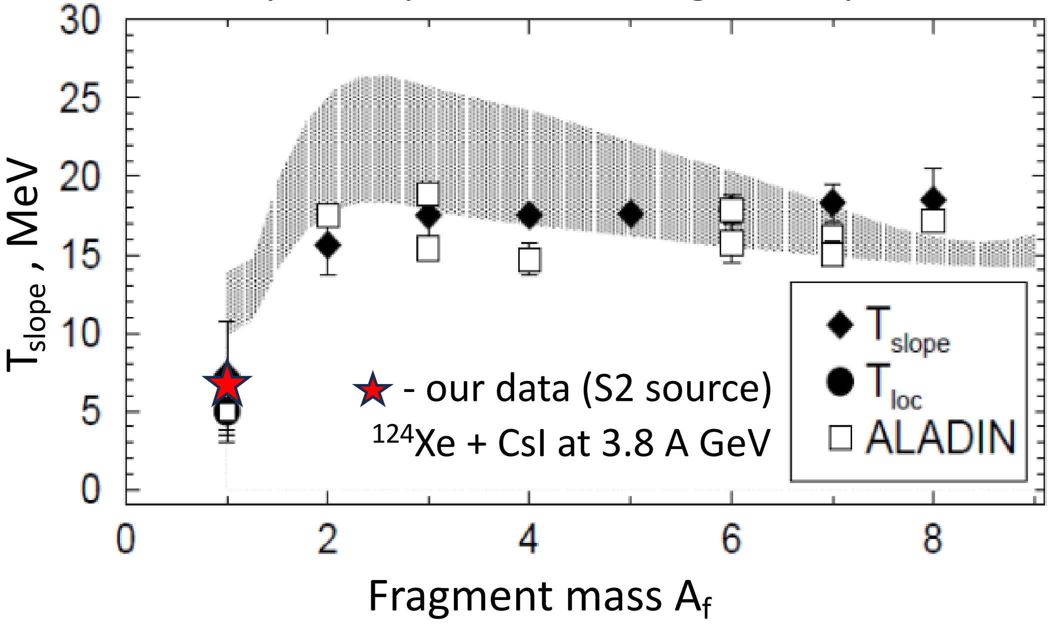
Kinematical properties of spectator fragments in heavy-ion collisions at relativistic energies, Antoine Bacquias, PhD Thesis, Strasbourg, 2008.

ALADIN Collaboration

Au + Au at 600 A MeV

Study of charged fragment production in decay of beam spectators

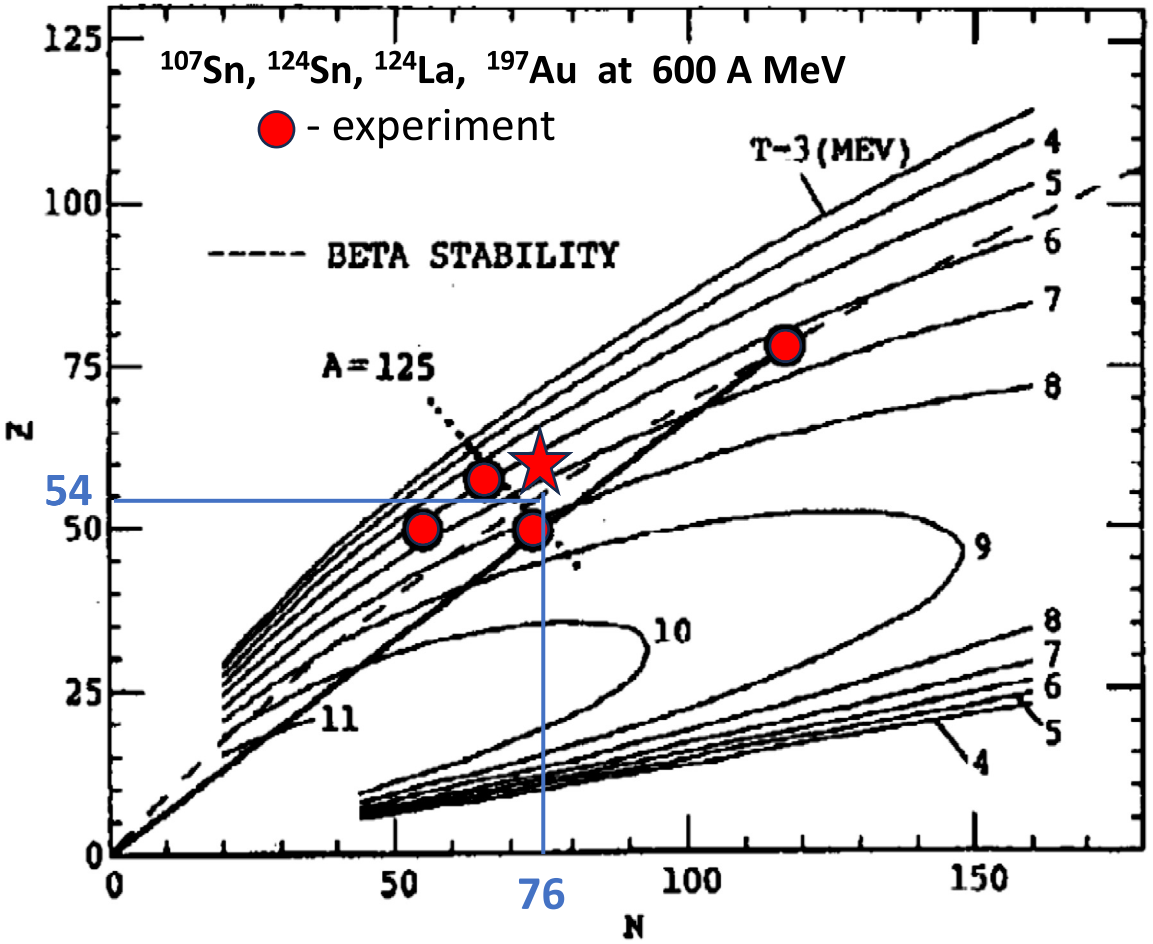
Slope temperature of fragment spectra



Spectator and participant decay in heavy ion collisions
T. Gaitanos, H. H. Wolter, C. Fuchs, arXiv:nucl-th/9905020v2 1 Mar 2000

Comparison with the results obtained at GSI

ALADIN experiment



^{124}Xe + CsI, 3.8 A GeV

- our result (S2 source)

Target CsI

<Z> = 54

<N> = 76

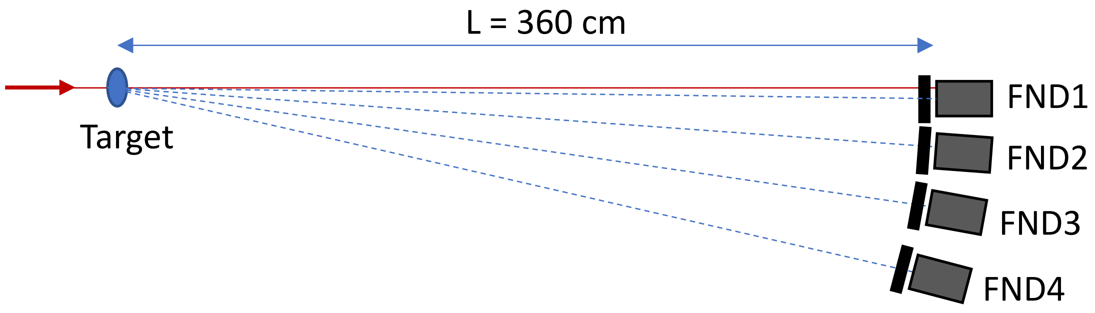
<A> = 130

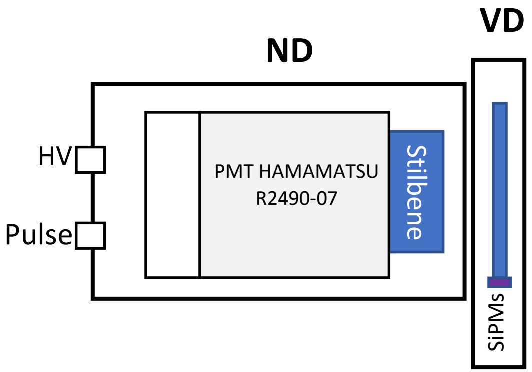
Isotopic Dependence of the Caloric Curve

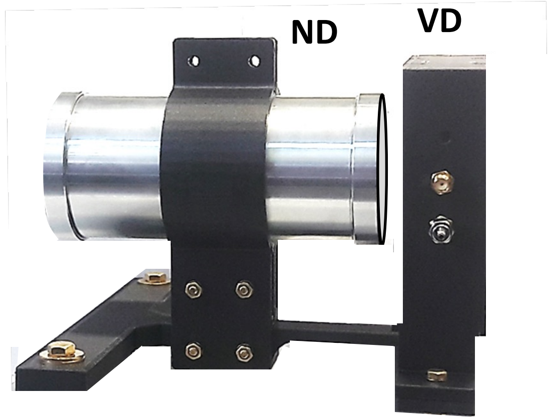
W. Trautmann, GSI Darmstadt, Erice 2008

New neutron detectors for measurements at small angles

Energy range: 50 – 5000 MeV







Neutron Detectors

Detector	Stilbene	Angle
FND1	D31 × 31 mm	3^o
FND2	D31 × 31 mm	6^o
FND3	D40 × 20 mm	9^o
FND4	D40 × 20 mm	12^o

Aim of the measurements

- ✓ 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 and Outlook

- The spectra of neutrons produced in Xe + CsI collisions at 3.8 A GeV were measured at large angles in wide energy interval from 2 to 200 MeV with the compact TOF spectrometer.
- A comparison with prediction of DSM-QGSM-SMM model shows satisfactory agreement above ~6 MeV and large underestimation in low energy region.
- It is clearly seen that the measured spectra are formed as a sum of three components/sources. The fitting with MSM expression allows to obtain parameters of the sources.
- The longitudinal velocities of the sources S2 and S3 are small that are in good agreement with results of the FRS experiment at GSI ; the slope temperature of the multifragmentation source S2 is 6.5 MeV and this value is well agreed with the slope temperature of emitted protons obtained in ALADIN experiment. The nature of hot source S1 with slope temperature of 55 MeV is explained as contribution of the contact layer moving along beam direction with velocity β = 0.18.
- Selection on collision centrality shows that semi-central collisions give main contribution to the neutron spectra measured.
- In 2025 the second run with Xe ions will take place and we plan to confirm the results obtained and to improve the statistics.
- We continue development of the TOF spectrometer and this year a set of new neutron detectors will be installed for spectra measurements at small angles.