Double-differential cross sections of neutron production at large angles in ^{124}Xe + CsI Collisions at 3.8 A GeV

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INTRODUCTION

A grate number of neutrons are produced together with charged particles and fragments in high energy nucleus – nucleus collisions. But despite the importance of neutron data for testing and development of theoretical models the number of neutron measurements remains very limited due to the methodological difficulties.

In the Laboratory of High Energy Physics of Joint Institute for Nuclear Research we have developed a compact TOF neutron spectrometer as a part of the BM@N experiment with heavy ion beams of the Nuclotron.

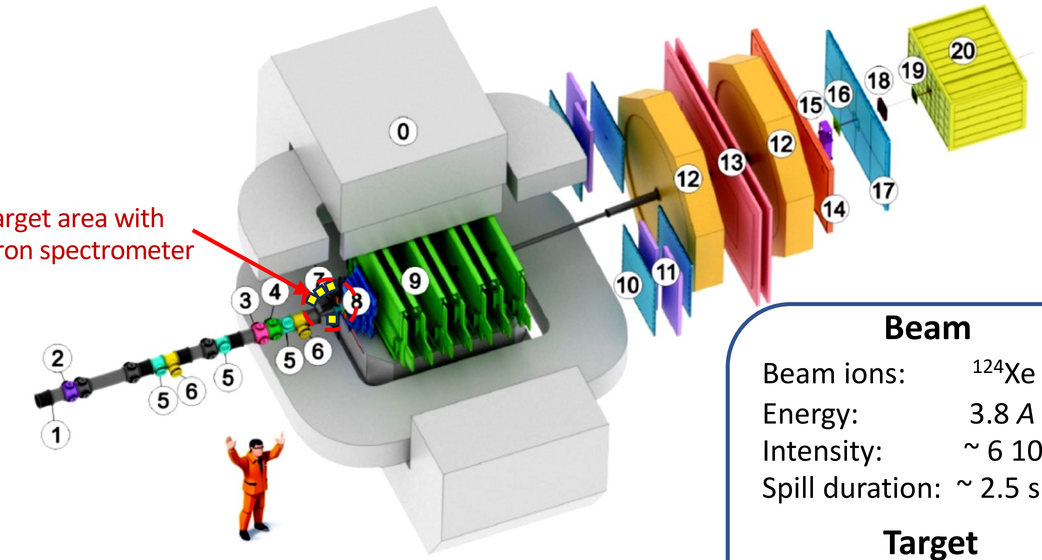
The aim of the spectrometer is study of neutron emission at large angles where contribution of target spectator decay dominates.

This talk is dedicated to the study of neutron emission from target fragmentation in ^{124}Xe + CsI collisions at 3.8 A GeV, including the experimental setup and the preliminary results.

TOF neutron spectrometer of BM@N experiment

BM@N experiment with HI beams of Nuclotron

Target area with neutron spectrometer



Beam

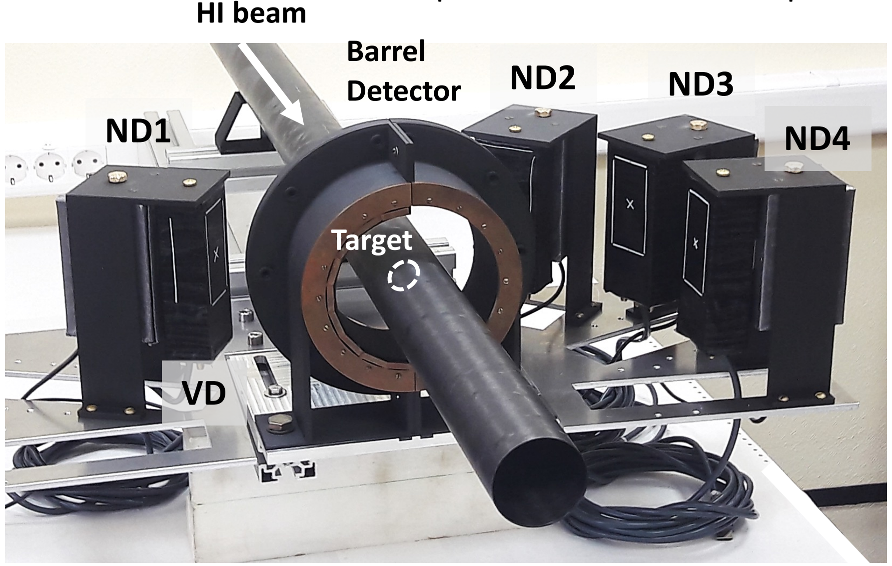
Beam ions:	^{124}Xe
Energy:	3.8 *A* GeV
Intensity:	~ 6 10^5 ion/spill
Spill duration:	~ 2.5 s

Target

2% CsI

D32 × 1.75 mm

A photo of TOF neutron spectrometer



Start Detector – Beam counter BC2

Scint. BC400B, H = 0.125 mm
Two MCP-PMTs XPM85112/A1
Time resolution σ_t = 40 ps

Stop Detectors – Neutron detectors

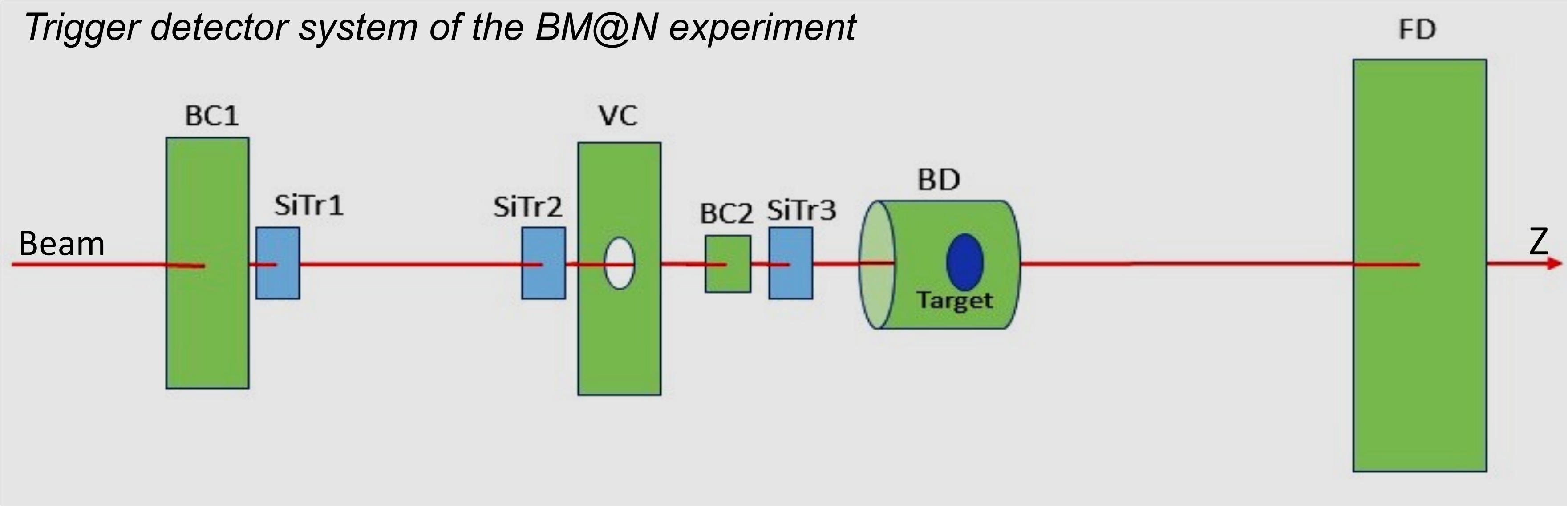
Detector	Stilbene*	Angle θ	Flight path	σ_t
ND1	D3×1 cm	110°	20 cm	128 ps
ND2	D2.5×2.5 cm	121°	30 cm	114 ps
ND3	D2.5×2.5 cm	110°	30 cm	118 ps
ND4	D2.5×2.5 cm	95°	30 cm	110 ps

* 2 units per detector

Main features of the spectrometer:

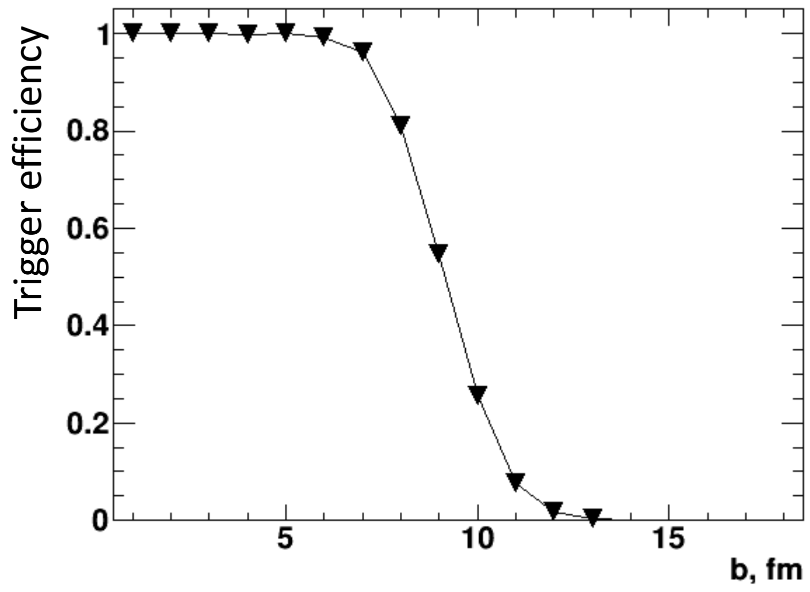
- ✓ Small flight path *L* ~ 0.3 m to minimize background
- ✓ High time resolution with $\sigma_t \approx$ 100 ps
- ✓ Effective suppression of gamma-rays by PSD method
- ✓ Digital signal processing
- ✓ Off-line event-by-event analysis
- ✓ Application of SiPMs instead of PMTs in magnetic field

Selection of interactions in the CsI target



Interaction Trigger Logic:

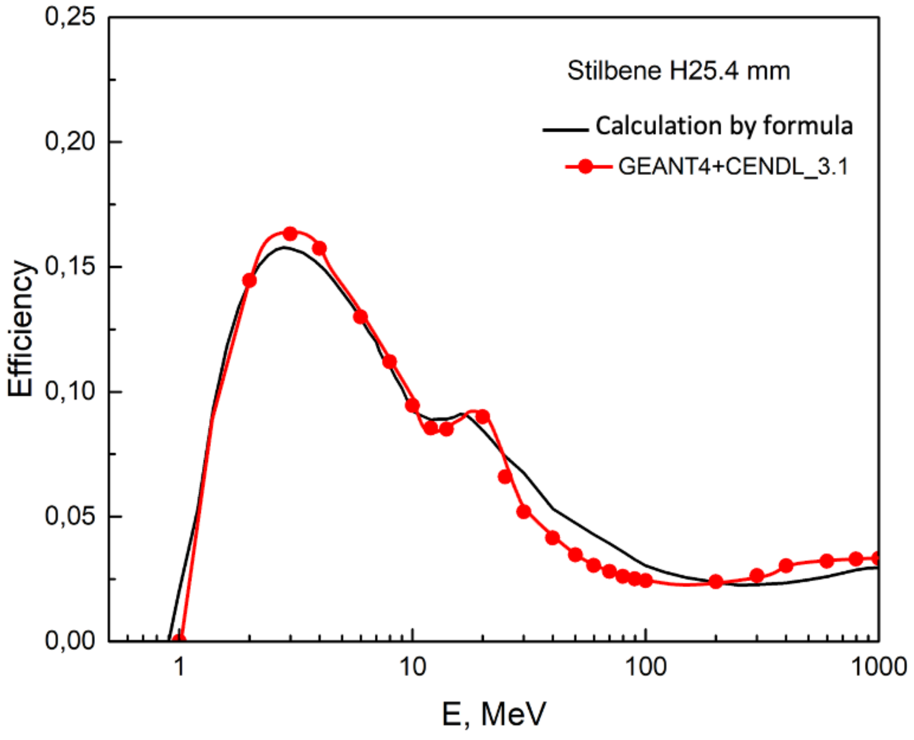
$$\textbf{IT} = BC1 * \overline{VC} * BC2 * \overline{FD} * BD(N>3)$$



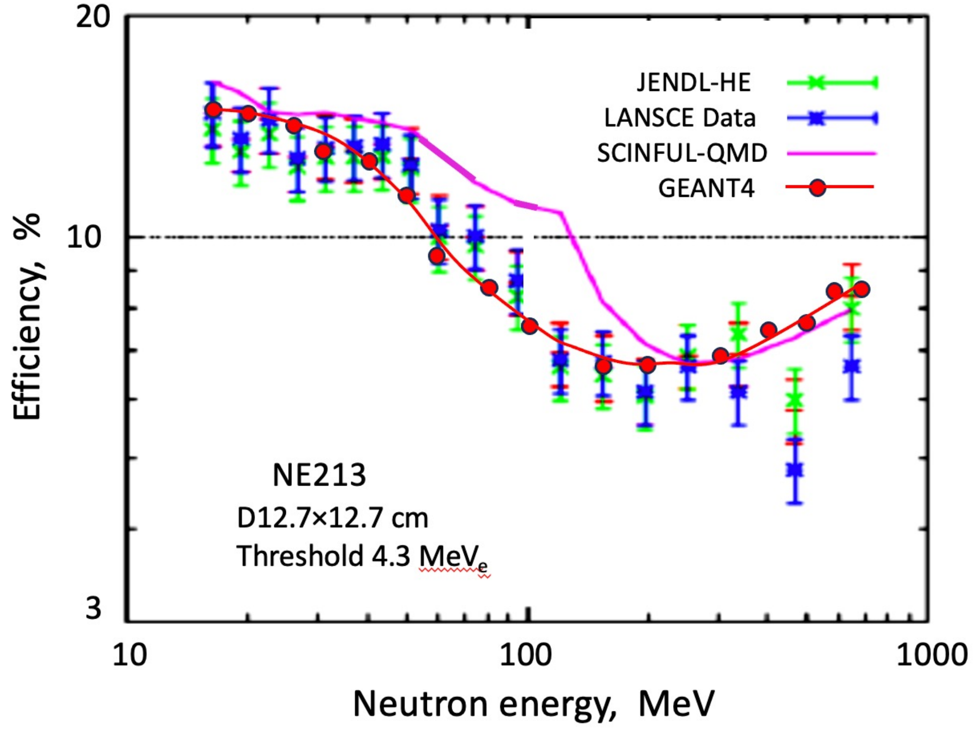
Trigger efficiency obtained with
DCM-QGSM-SMM + GEANT4 simulation

Neutron Detector Efficiency

Calculation of detector efficiency using single interaction approach based on cross sections of n-p scattering and n-C reactions with charged particle production

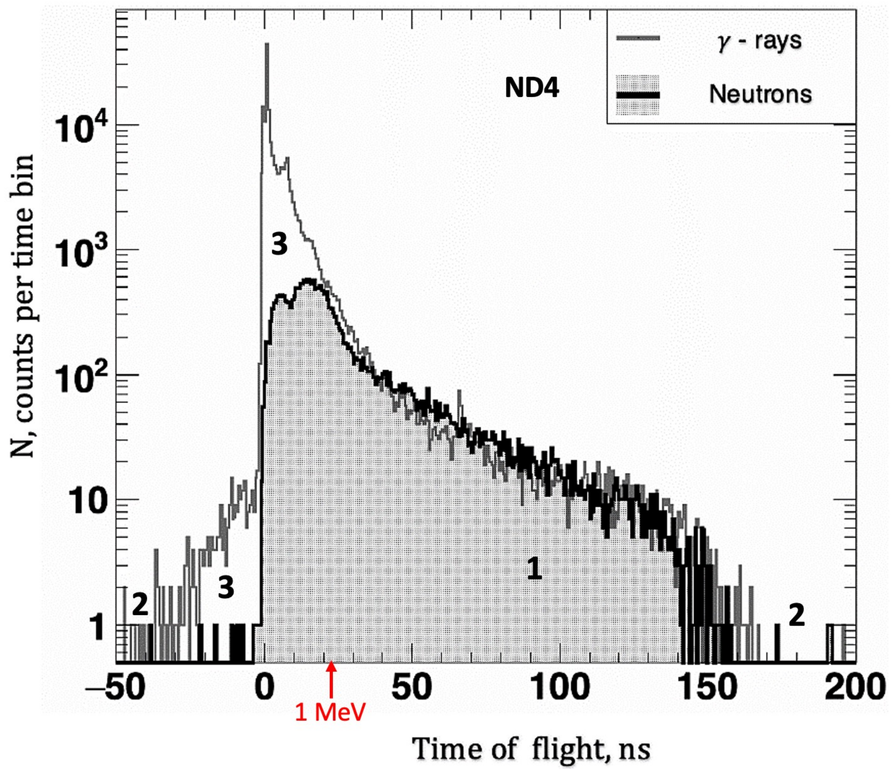


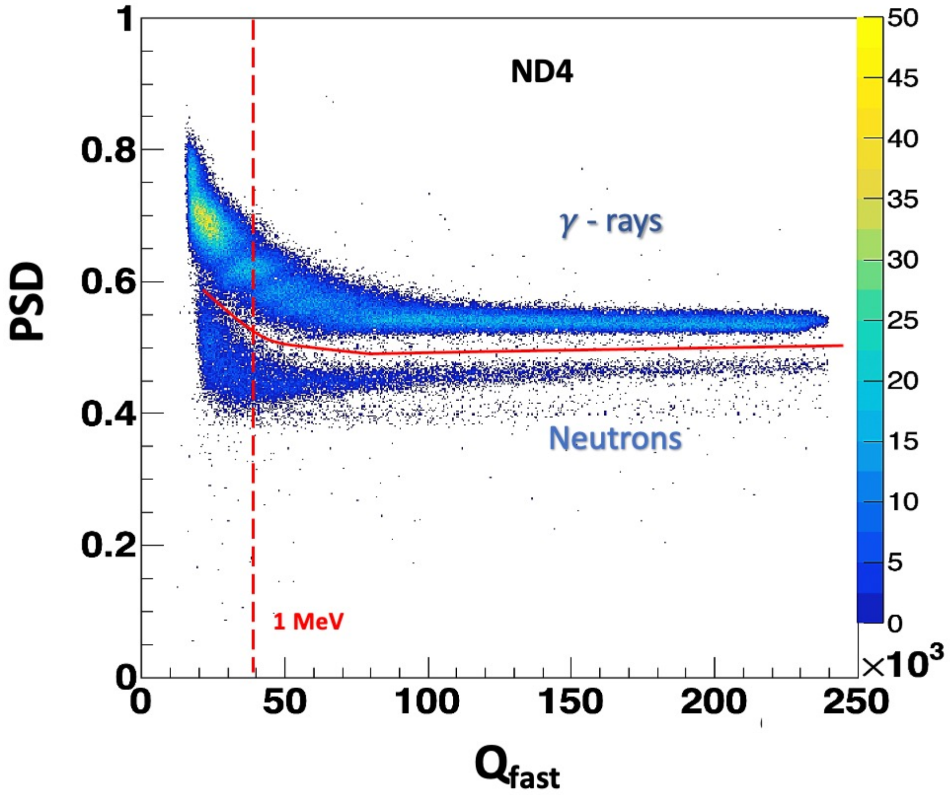
Testing of efficiency calculation with GEANT4



GEANT4 + CENDL 3.1 reproduces the experimental data with error ±10% in energy range up to 500 MeV and it can be used for calculation of neutron detector efficiency

Study of neutron background





1 – Contribution of background neutrons produced in surrounding materials by energetic particles emitted from the target

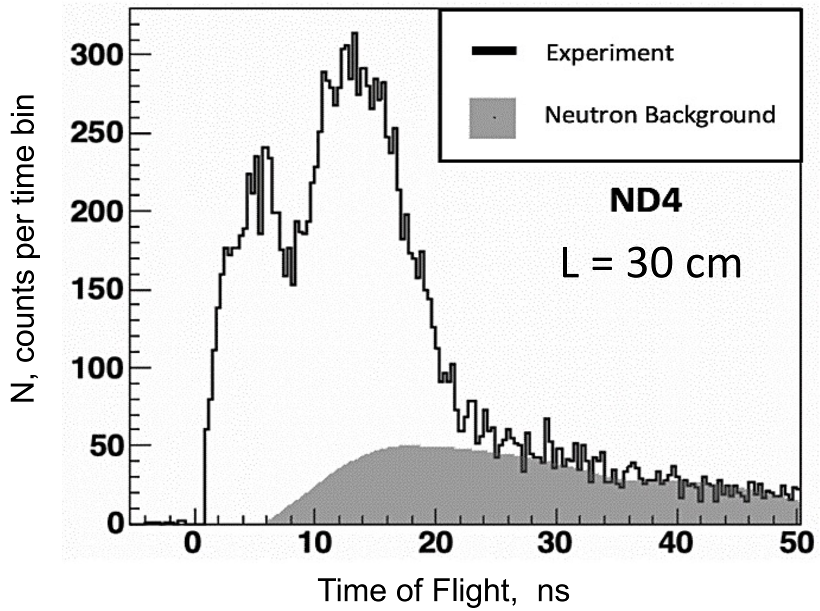
2 – Very low random background of neutrons and gamma-rays

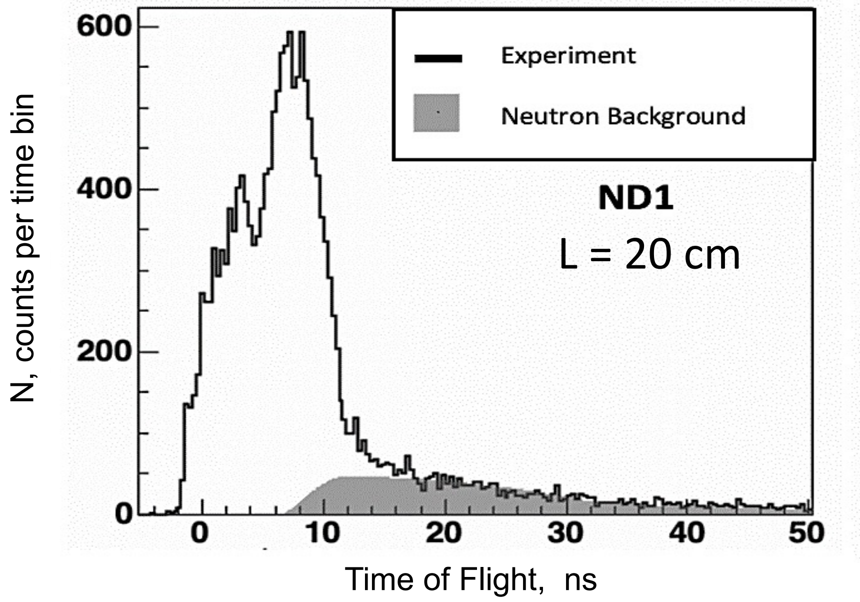
3 – Background of gamma-rays produced by Xe ion in the upstream beam line materials, target, and by particles in surrounding materials

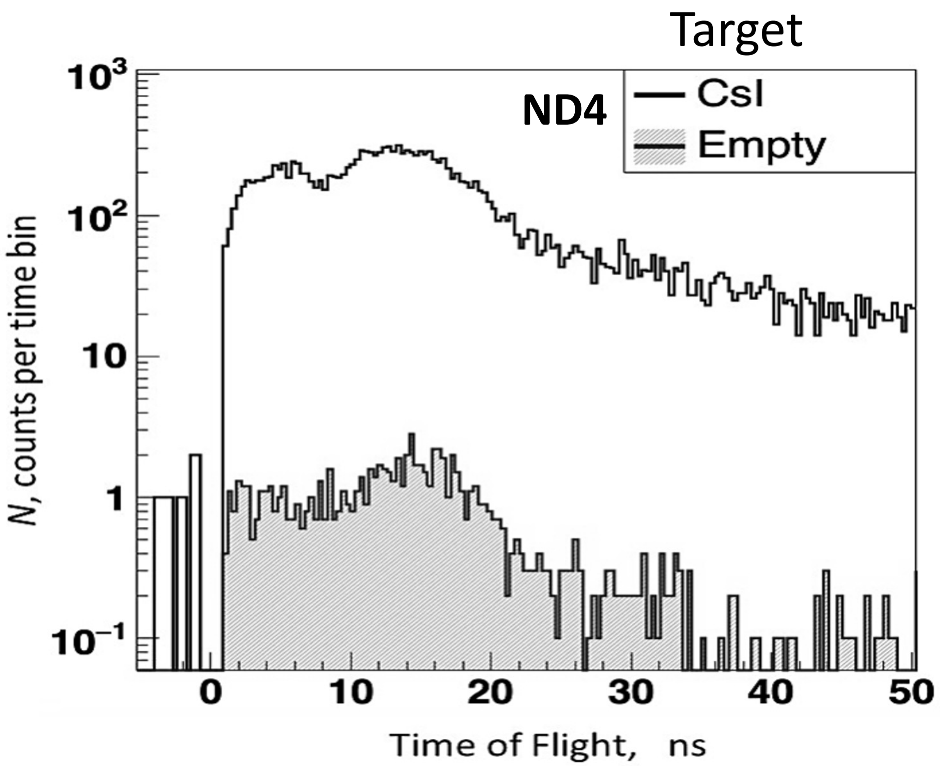
Figure of Merit

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

Neutron background contribution to the TOF spectra



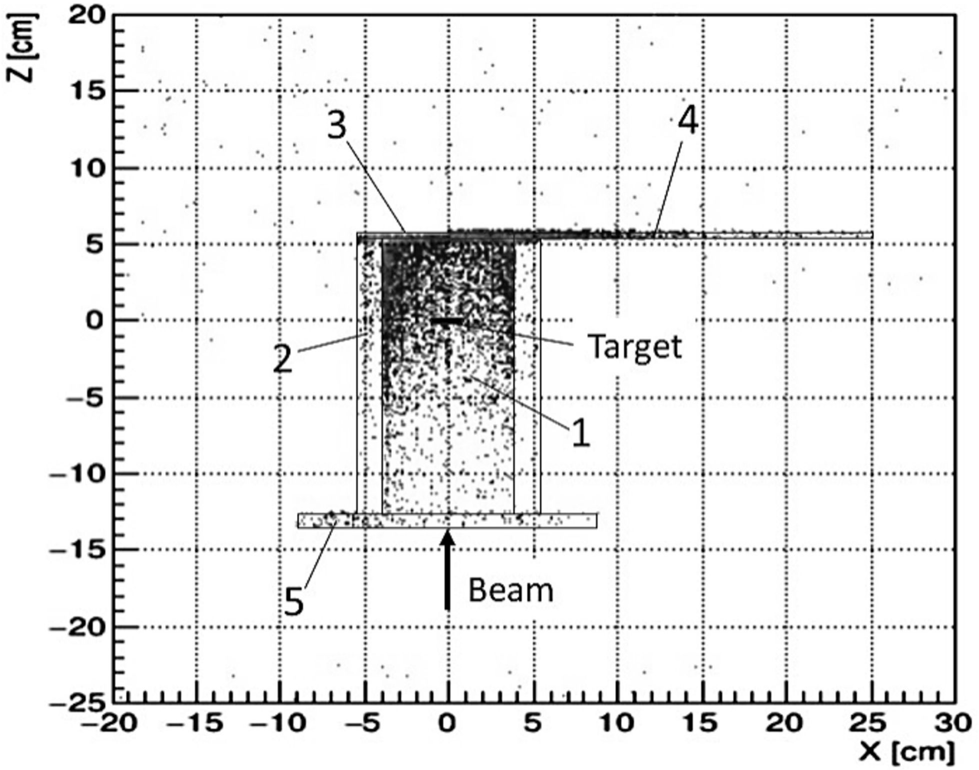




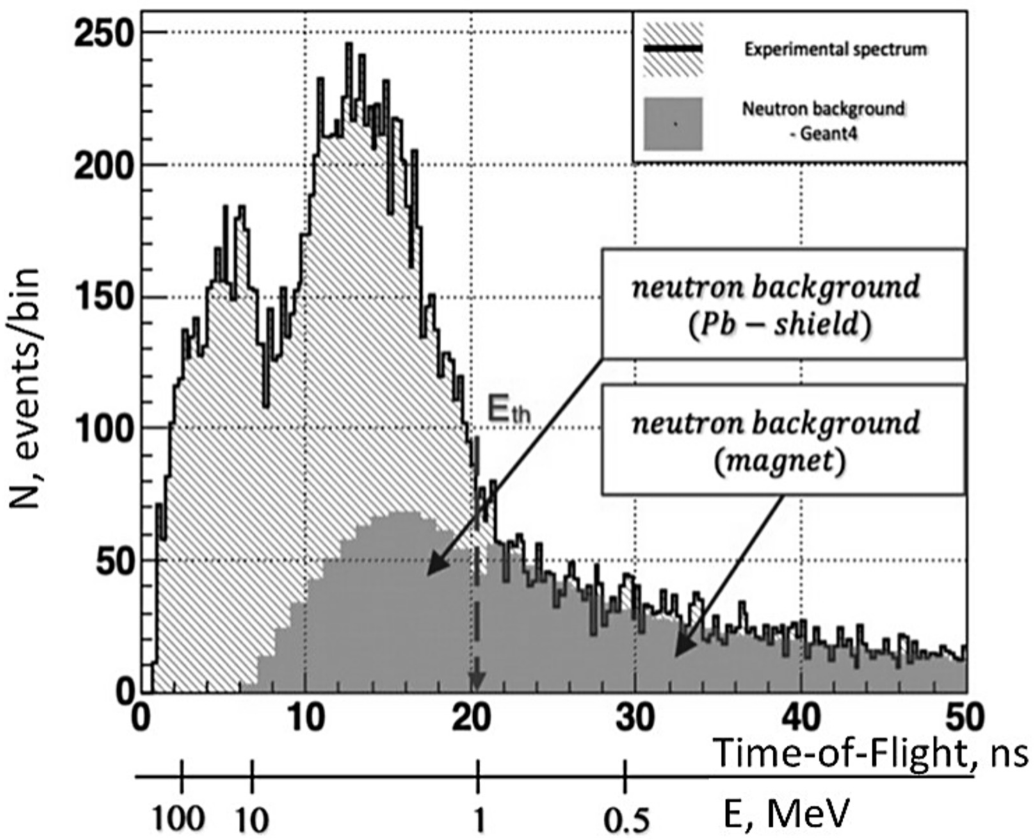
- ✓ Neutron background increases with flight distance
- ✓ Negligible contribution from the Empty target measurement

Study of neutron background

Simulation with GEANT4



The result of simulation with GEANT4 (GNDL 4.7) of the points of the background neutron production in the interactions of particles coming from the target with the materials of the BD detector: 1 - the internal 3-mm lead cylinder, 2 – theBD scintillators, 3 - the 5-mm lead ring , 4 – the 5-mm lead plate, - 5 – the BD mechanics.

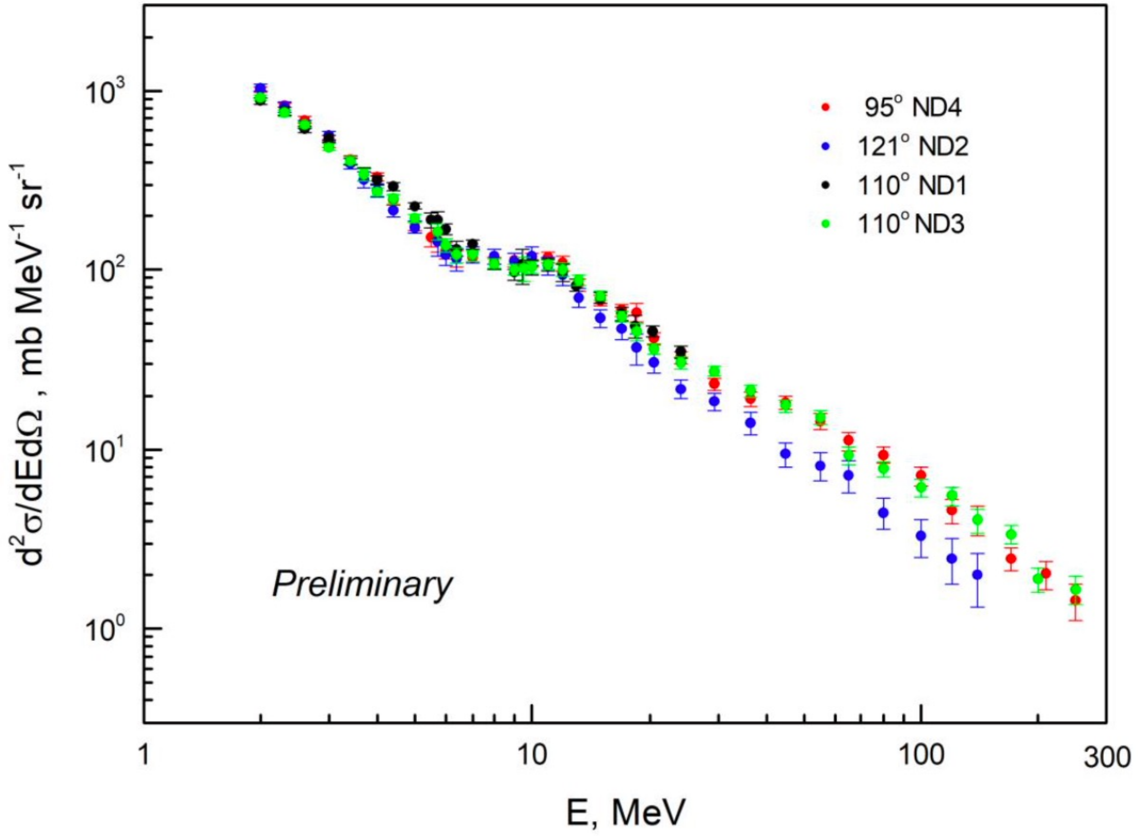


The neutrons TOF spectrum measured with the ND4 detector at an angle of 95^{o} and the contribution of background neutrons calculated using GEANT4.

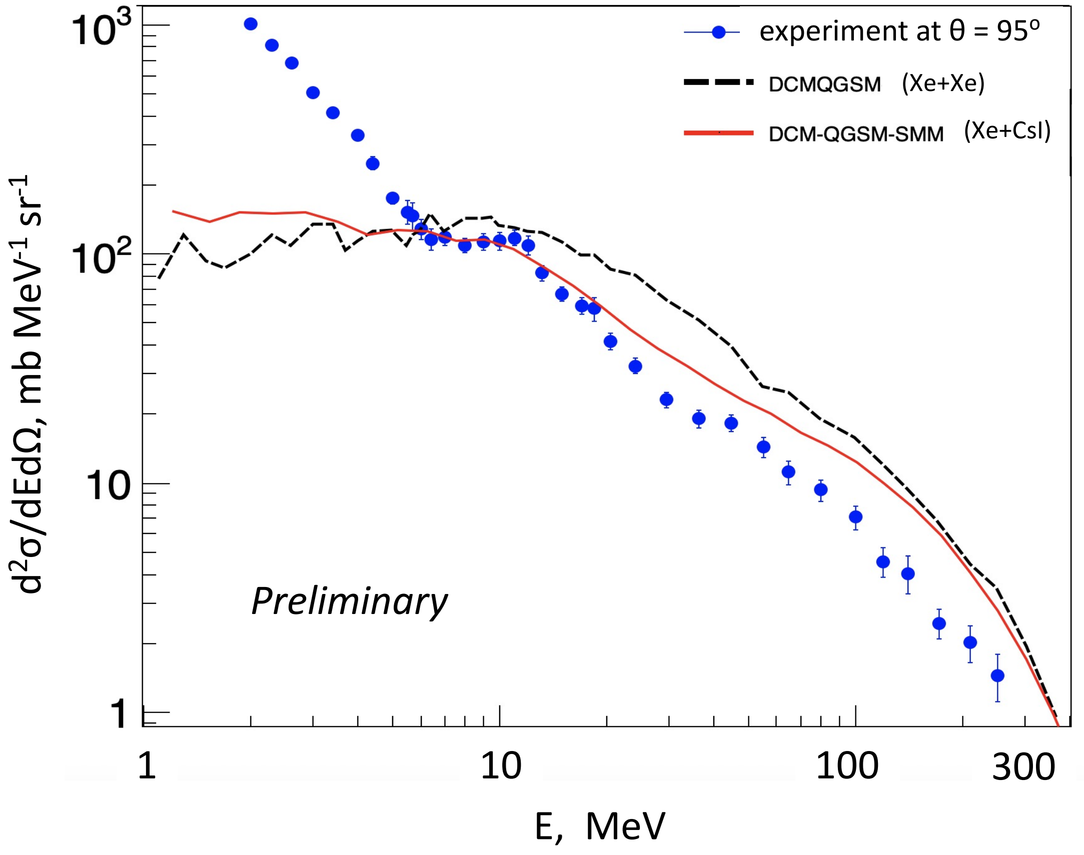
Energy spectra of neutrons

^{124}Xe + CsI, 3.8 A GeV

Energy spectra of neutrons measured with the spectrometer



Comparison with prediction of DSM-QGSM model



In calculation the dependence of trigger efficiency on impact parameter was taken into account

Moving Source Model

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

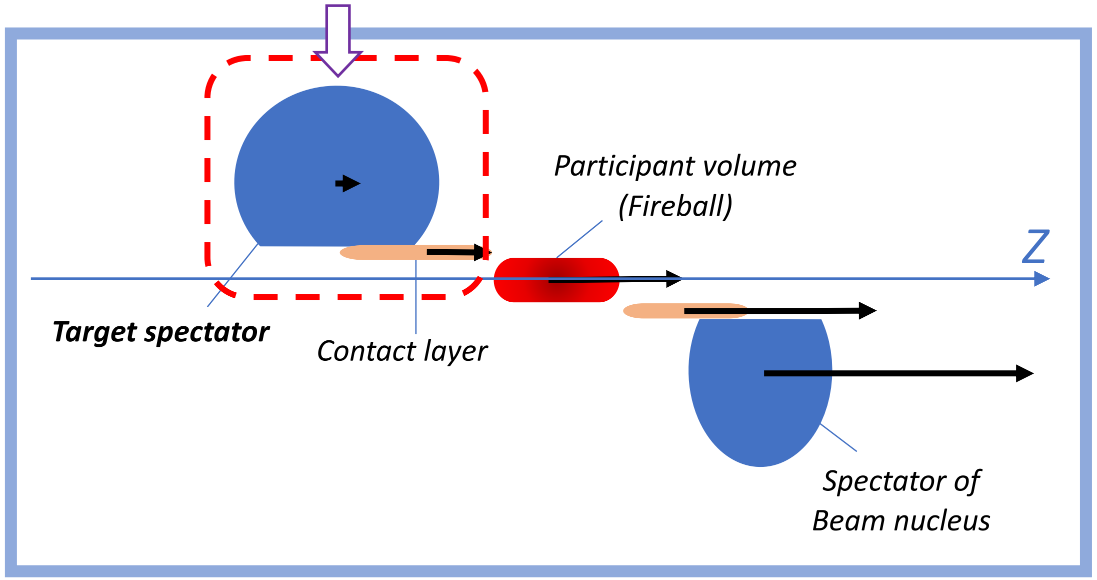
- ✓ The first source S1 reproduces the hard part of spectra (contribution of contact layer)
- ✓ The second source S2 gives main contribution in the middle part of spectra associated with multifragmentation decay
- ✓ The third source S3 dominates in the low energy part (fragmentation decay + evaporation)

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

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)

Neutron emission from this volume
Is measured with the detectors ND

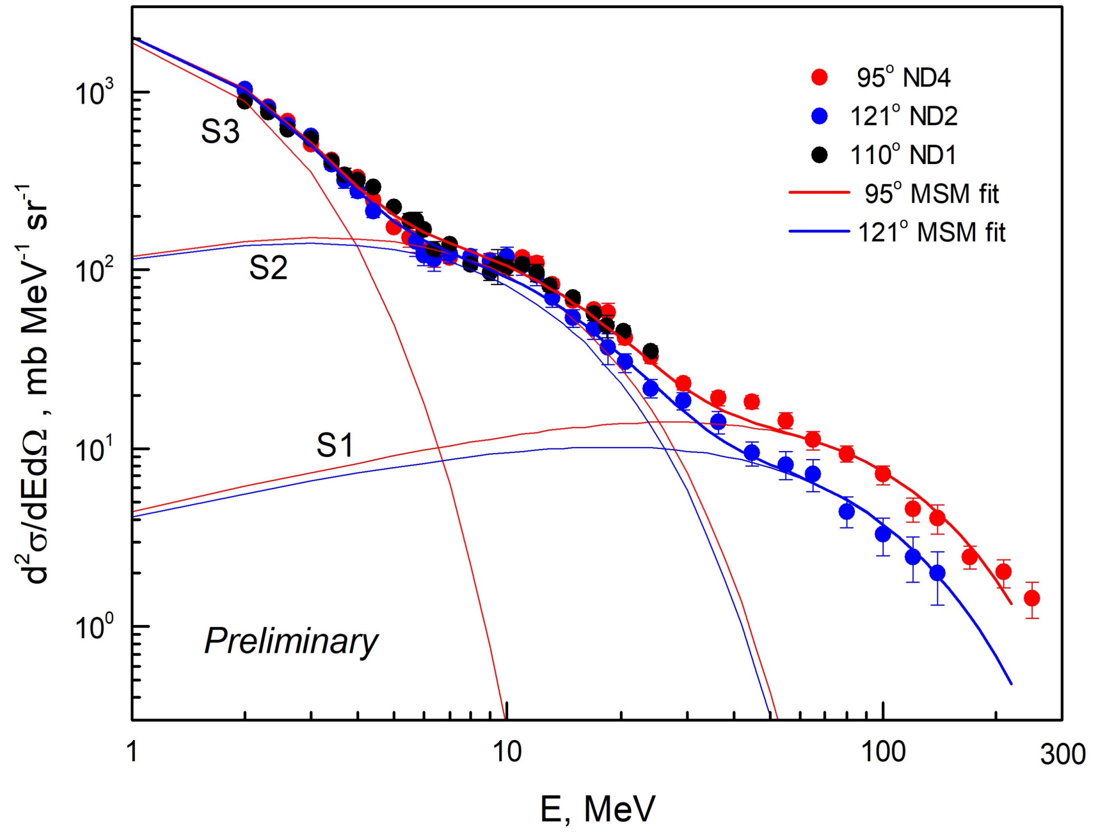


Phenomenological picture of nucleus – nucleus collision

V. I. Yurevich, R. M. Yakovlev, and V. G. Lyapin, Phys. At. Nucl. 75, 192 (2012)

Neutrons from target spectators

MSM fitting of the neutron energy spectra



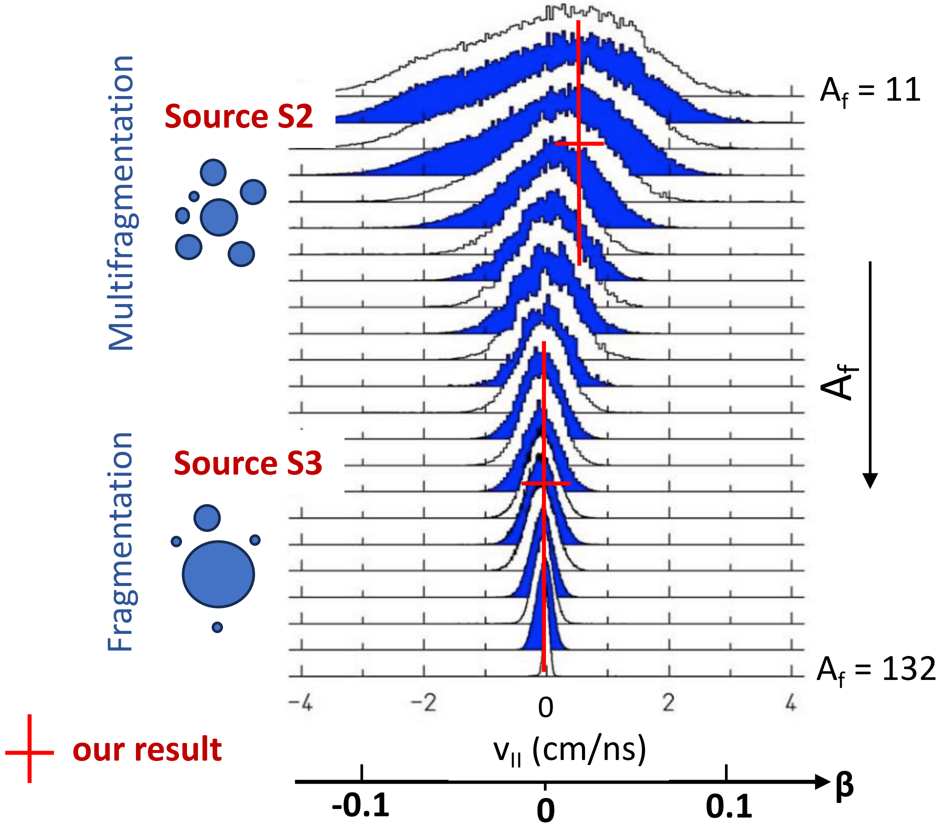
Source	A	T (MeV)	β
S1	0.15	60	0.21
S2	3.3	6.5	0.015
S3	132	0.9	0

- The spectra are well described by the MSM with three sources
- The energies of neutrons emitted from target spectators (sources S2 and S3) overlap interval up to 50 MeV

Comparison with the results obtained at GSI

The FRagment Separator (FRS)

^{136}Xe + Pb at 1 A GeV



Longitudinal velocity spectra of fragments

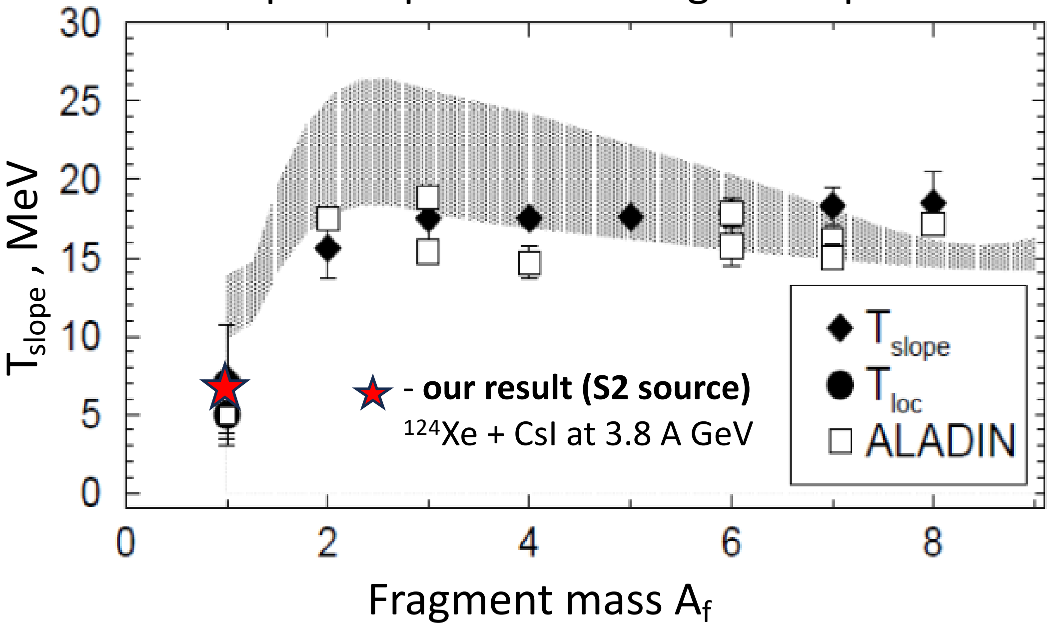
Kinematical properties of spectator fragments in heavy-ion collisions at relativistic energies, Antoine Bacquias, PhD Thesis, Strasbourg, 2008.

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,Physics Letters B,Volume 478, Issues 1–3, 2000,

Conclusion and Outlook

- The compact TOF spectrometer developed as a part of BM@N setup is able to study energy spectra of neutrons emitted from target spectators and to get reliable data in energy range from 2 to 200 MeV.
- Double-differential cross sections for neutrons were measured at large angles (95°, 110°, 121°) in ^{124}Xe+ CsI collisions at 3.8 *A GeV*
- A comparison with prediction of DSM-QGSM-SMM model shows satisfactory agreement above ~6 MeV and large underestimation in the lower energy region. It seems, the theoretical model needs in further development for description of low-energy neutron emission.
- 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 and select spectra of neutrons emitted from target spectators.
- Neutron emission from the target spectators is nearly isotropic and two decay processes, fragmentation and multifragmentation (the sources S2 and S3), form the energy spectra of emitted neutrons. The obtained velocities of these sources and the temperature of the S2 source are in good agreement with results of the FRS and ALADIN experiments at GSI.
- A new measurements with the spectrometer will take place in BM@N run 2025 with Xe ions at lower energies.

Thank You for Your Attention!