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Study of the interaction trigger and development of a TOF neutron spectrometer in the BM@N experiment

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INTRODUCTION

The investigation of the properties of hot and dense nuclear matter formed in nucleus-nucleus collisions is the main focus of the BM@N experiment at the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research [1, 2]. The development of an efficient fast trigger system for nucleus-nucleus collisions is a crucial requirement for the realization of the physics program of the BM@N experiment.

The report presents the results of studying the characteristics of trigger detectors and the trigger efficiency for nucleus-nucleus interactions in the BM@N experiment. The performed simulation based on the DCM-QGSM + GEANT4 code demonstrated that including the fast interaction information from the beam fragments detector and the hadron calorimeter in the trigger ensures reliable event selection based on centrality for Xe + Sn collisions. One of the main trigger detectors is the multi-channel scintillation Barrel Detector (BD) located around the target. The simulation revealed that relativistic nuclei passing through the target generate a significant background of δ-electrons in the BD detector, which can be minimized by employing lead shielding of a certain thickness. The efficiency of event selection by the trigger during the recent BM@N run with a Xe-124 beam at an energy of 3.9 GeV/nucleon and CsI target is discussed.

The second part of the report is dedicated to the development of a compact time-of-flight neutron spectrometer emitted at large angles in the nucleus-target fragmentation region. Neutron detection was performed using stilbene crystals coupled with an assembly of four SensL SiPMs, allowing measurements to be conducted in a strong magnetic field of 0.9 T. The use of the n/g-pulse shape discrimination method is an important feature of the spectrometer, enabling the discrimination of gamma-ray background and the identification of neutron events. The concept of the spectrometer, construction of neutron detectors, and data processing methodology are discussed. The report will cover the current status of processing neutron data obtained in Xe+CsI collisions.

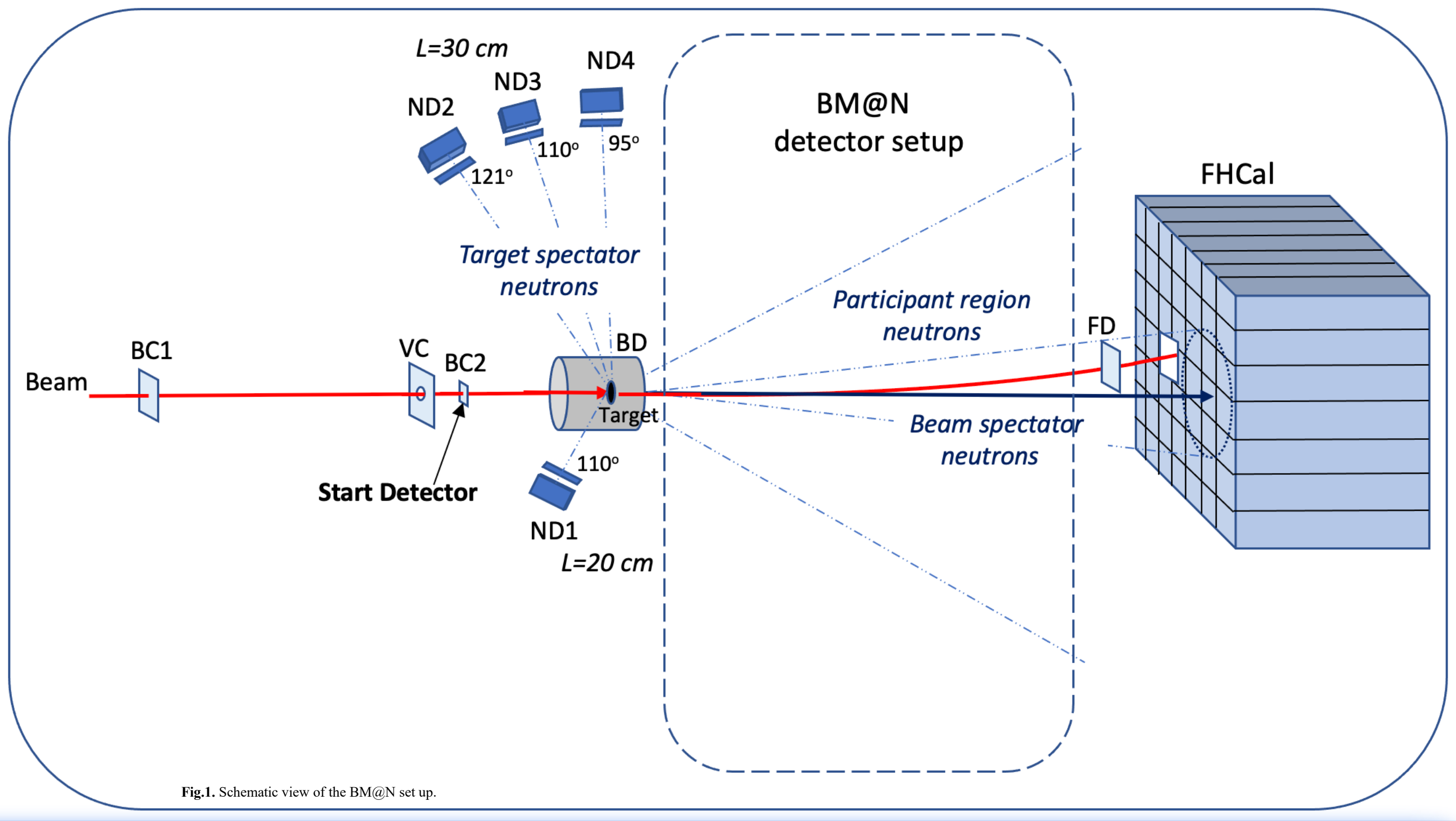


Fig.1. Schematic view of the BM@N set up.

TARGET AREA DETECTOR

Figure 2 shows the multichannel BD. The BD consists of 40 scintillation strips with sizes of 150 × 7 × 7 mm³, attached at one end to SiPM with sizes of 6 × 6 mm². The radius of location of the scintillation strips measured from the beam axis is 46 mm. This segmentation of the detector provides an efficient selection of nuclear interactions by the impact parameter depending on the number of triggered strips.

In the experiment, CsI targets with thicknesses corresponding to 1% and 2% nuclear interaction probabilities were used. The target region is situated inside the BM@N magnet with a magnetic field of B = 0.9 T.

The δ-electrons generated by Xe ions in the target can significantly contribute to the number of activated channels in the BD detector. This background reduces the detector's ability to select interactions in the target, as trigger signals can be generated even when the incoming ion passes through the target without interaction. To suppress the background of delta electrons generated during the passage of the ion beam through the target, lead shielding was employed for the BD detector.

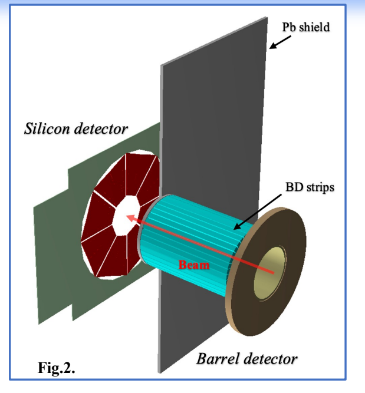


Fig.2.

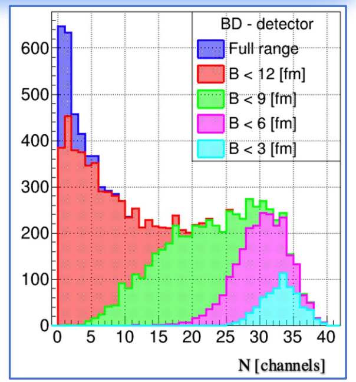


Fig.3. Simulation of the BD response for various centrality of Xe + Sn collisions at an energy of 3.9 A GeV.

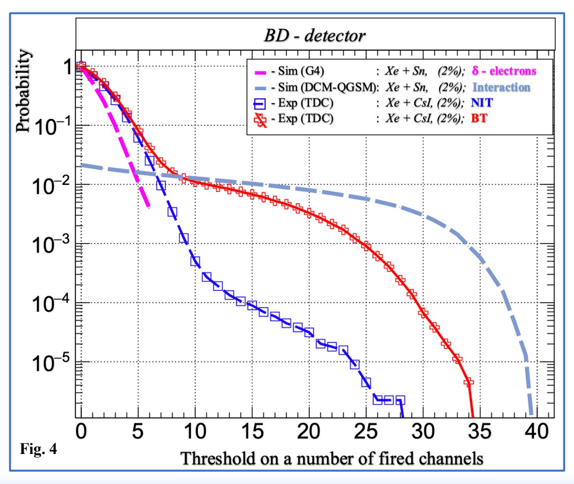


Fig. 4

BEAM DETECTORS

The components and characteristics of the beamline detectors BC1, VC, BC2, and FD are presented in Table 1. The scintillators of BC1, VC, BC2 detectors, and the target were positioned inside a vacuum beamline tube, which terminated just before the FD detector, effectively minimizing the contribution from background ion interactions. The purpose of the front beamline detectors BC1 and BC2 was to identify events with incoming ^{124}Xe ions interacting with the target, provided that no signal was detected in the veto detector VC.

The FD function is to register a beam of ^{124}Xe ions in events without interaction and fast nuclear fragments formed during the interaction of ^{124}Xe ions in the target. Figure 7 shows the two-dimensional X–Y distribution of nuclear fragments recorded by the FD. Figure 8 shows the FD response in the form of the sum of charges squared of nuclear fragments as a function of the impact parameter. The active area of the detector makes it possible to reliably register all nuclear fragments with charges Z > 6. In this case, detector response increases strongly with the appearance of heavy fragments with high charge values in peripheral collisions. The FD response is small for central and semicentral collisions and does not enable discrimination of the interactions by the impact parameter.

Table.1.

Detector	PMT	Radiator	Time resolution, σ, ps	Amplitude resolution, $\frac{\sigma}{<A>}$
BC1	Hamamatsu R2490-07	Scint. (100x100x0.25 мм³)	43	0.047
VC	Hamamatsu R2490-07	Scint. (113x113x4 мм³, Ø25mm)		
BC2	MCP-PMT XPM85112/A1-Q400 (Photonis)	Scint. (34x34x0.15 мм³)	38	0.082
FD	Hamamatsu R2490-07	Scint. (150x150x0.5 мм³)		0.053

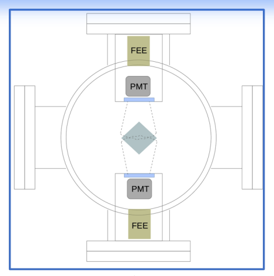


Fig.5. BC2 - detector

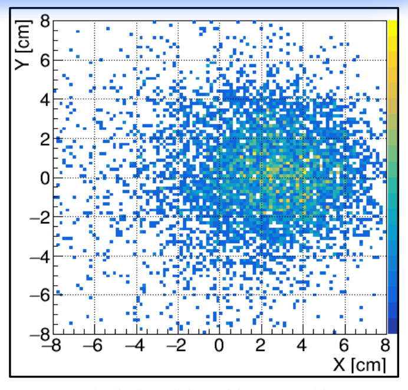
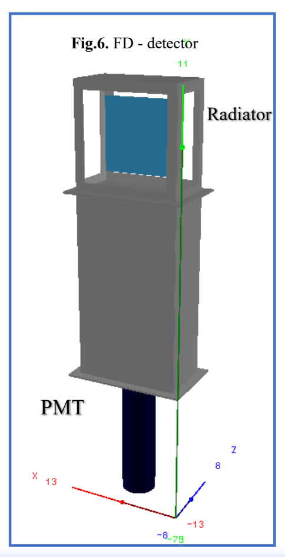


Fig.7. Distribution of charged fragments with charges Z > 6 in FD (simulation).

Fig.6. FD - detector



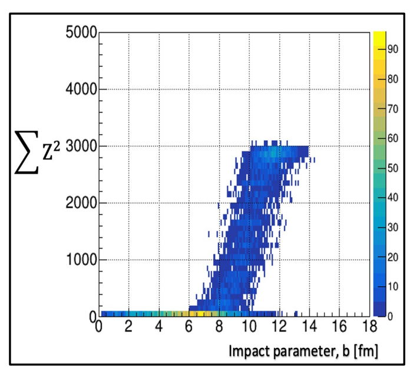


Fig.8. Sum of the charges squared for the fragments incident on FD as a function of the impact parameter (simulation).

INTERACTION TRIGGER CONCEPT

In the BM@N session, the following trigger logic was implemented for studying the collisions of ^{124}Xe ions with an energy of 3.9 GeV/nucleon on CsI target :

- ☐ **Beam Trigger (BT) = BC1 * BC2 * VC$_{veto}$** - trigger generation based on the incoming ^{124}Xe ion.
- ☐ **Min. Bias Trigger (MBT) = MBT = BT * FD$_{veto}$** - generation of a trigger enabling the selection of Xe+CsI interactions where the incident Xe nucleus is absent after passing through the target.
- ☐ **Central Collision Trigger (CCT) = MBT * BD(N>3)** - event selection for interactions in the target was performed based on the information about the number of triggered (N) strips in the BD detector.

During the BM@N Xe+CsI session, the main dataset was collected using the **Central Collision Trigger (CCT)**. This type of trigger demonstrates a high efficiency in selecting nucleus-nucleus interactions in the target.

Figure 9 shows the distribution of Xe beam nuclei on the target (with the target size indicated by the red circle), as selected by the BT (Beam Trigger). The position of the incoming beam nucleus on the target was determined using information from the silicon beam trackers (SiBT1, SiBT2, SiBT3), which were located in front of the target inside a vacuum beamline tube. Figure 10 shows the number of triggered channels in the BD detector depending on the number of reconstructed tracks at the vertex. Figure 11 shows the positions of track convergence points (vertices) along the beam axis, measured by the BM@N track detection system.

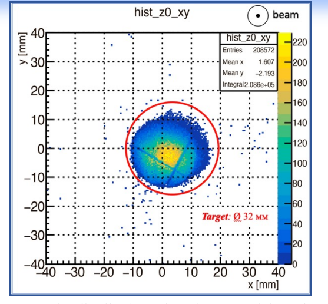


Fig.9. The distribution of Xe beam nuclei on the target (with the target size indicated by the red circle), as selected by the BT (Beam Trigger.)

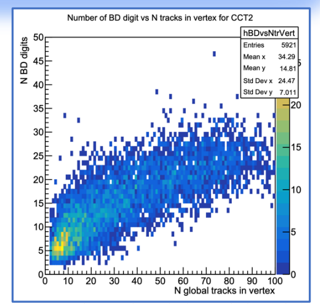


Fig.10. The number of triggered channels in the BD detector depending on the number of reconstructed tracks at the vertex;

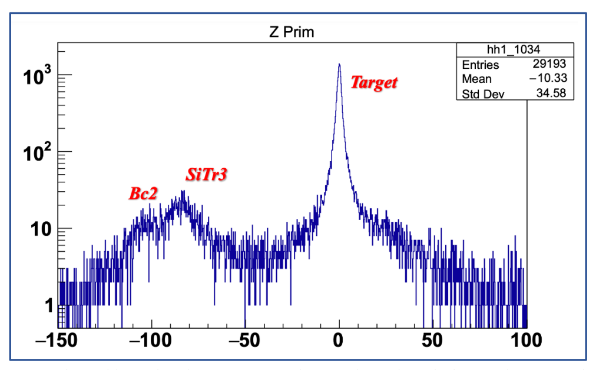


Fig.11. The positions of track convergence points (vertices) along the beam axis, measured by the BM@N track detection system.

TOF NEUTRON SPECTROMETER

Aim of neutron measurements

Study of neutron emission from decay of target spectator in high-energy *AA*- collisions by measurement of neutron energy spectra at large angles and different collision centrality.

These data are very important for development of theoretical models and codes. At present the description of spectator fragmentation is one of the key problems of the existing models. It is important to say that selection of events with direct neutrons on a high level of background from gamma-rays, neutrons and charged particles is ambitious and not trivial methodical task. The difficulty to perform such measurements is the reason why there are no such experimental neutron data in beam energy range above 1 GeV per nucleon.

During the run with beam of 3.9- A GeV Xe ions and CsI target we made the first attempt to measure the energy spectra of neutrons from target spectator decay in wide energy interval from 1 to 300 MeV. For this purpose, a special concept of the neutron TOF spectrometer was developed and applied in the last BM@N run.

Concept of Neutron Spectrometer

☐ Small flight path (L = 30 cm)	⇨ Important for separation of direct neutrons from background neutrons in time-of-flight spectrum
☐ High time resolution (σ_t ~ 150 ps)	⇨ Important for good energy resolution
☐ Suppression of gamma-rays using stilbene crystals and PSD method	⇨ Important for discrimination of gamma-ray background
☐ Suppression of ch. particles with Veto-detector and PSD method	⇨ Important for discrimination of ch. particles background
☐ Neutron detectors with SiPM readout	⇨ Important for operation in magnetic field of 0.9 T
☐ Information about collision centrality comes from main BM@N detectors (number of tracks)	⇨ Important for study of neutron emission as a function of centrality

Neutron detectors

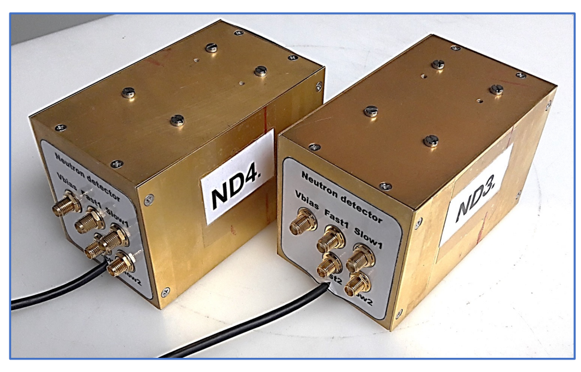


Fig. 11. Neutron detectors

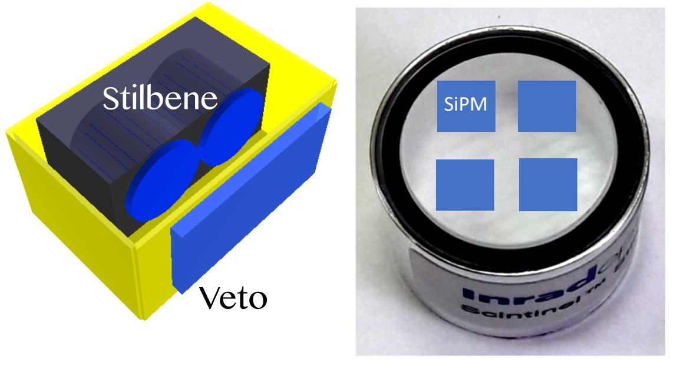


Fig. 12. Stilbene with SiPMs

ND1 with 2 stilbene crystals 30-mm diam. × 10 mm.
ND2, ND3, ND4 with 2 stilbene crystals 25.4-mm diam. × 25.4 mm.
Scintillation photons are detected with 4 units of SiPMs 6x6 mm², SensL, J-ser.
Veto-Detectors: plastic scintillators with 2 units of SiPMs.

Electronics and DAQ

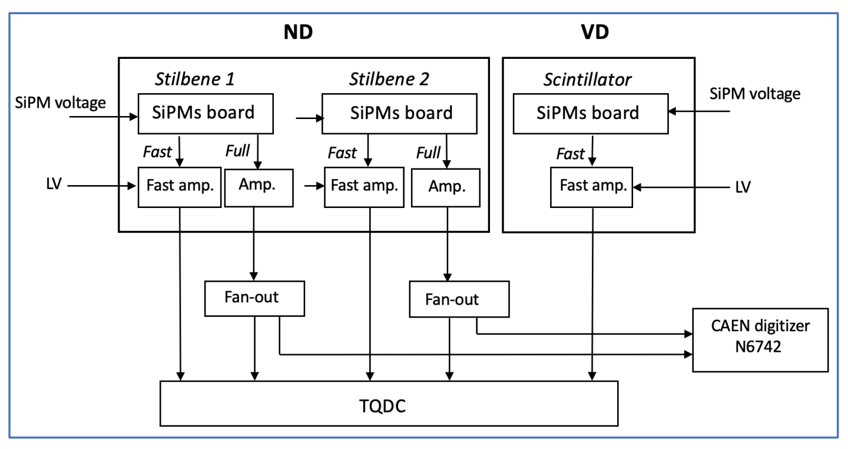
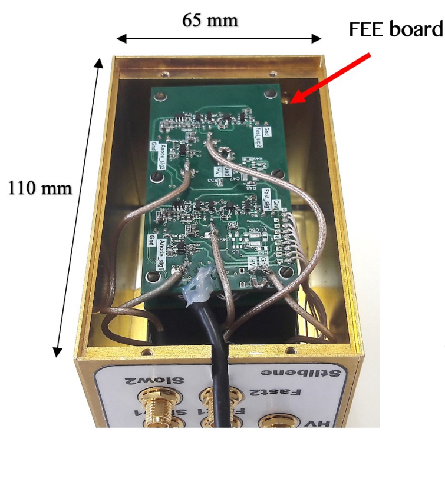


Fig. 13. Front-end electronics block diagram and DAQ.



During the data acquisition process, the neutron detectors were controlled using the CAEN N6742 digitizer. To record events, 16-channel electronic modules TQDC16VS, developed in the VME standard at the JINR LHEP, were employed. These modules were integrated into the BM@N detector data acquisition system and were responsible for digitizing the time and amplitude of the input signal.

Neutron detection efficiency

The efficiency of the neutron detectors was determined using a calculation method. It was assumed that the registration is based on n-p scattering and reactions on carbon nuclei. In this case, the neutron registration efficiency of the stilbene crystal-based detector can be calculated using the following expression:

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

$\Sigma = \Sigma_C + \Sigma_H = n_C\,\sigma_{ch}(nC) + n_H\,\sigma(np)_C$

σ_{ch}(nC) - is the microscopic cross-section of reactions on carbon;

σ(np) - is the microscopic cross-section of np scattering;

h – is the thickness of the stilbene crystal;

B_c – is the threshold for registering reactions on carbon (MeV);

B_h – is the threshold for registering recoil protons in np scattering (MeV);

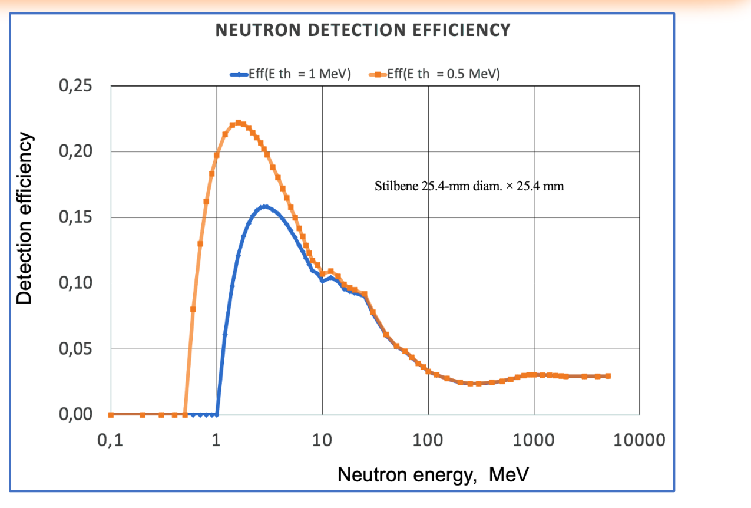


Fig. 14. The efficiency of the neutron detectors at registration threshold values of 0.5 and 1 MeV, respectively.

Neutron data acquisition was performed using the **Central Collision Trigger (CCT)**. Beam monitoring and particle time stamping were carried out using a system of beam counters with thin plastic scintillators. Neutrons were detected within an angular range of 95-121⁰ degrees using four neutron detectors based on organic scintillators. Veto counters with thin plastic scintillators, 5 mm thick, were positioned in front of the neutron detectors to discriminate against charged particles.

The neutron spectrometer was based on the time-of-flight method with a short flight path and high time resolution. To suppress gamma-ray background in the stilbene crystal detectors, a method of neutron-gamma pulse shape discrimination was employed, analyzing the total charge and the charge of the fast component of the signal, digitized in the TQDC module (Figure 15). The figure 16 demonstrates that all events cluster into two branches (upper branch - neutrons, lower branch - γ -rays). The figure 18 shows the (PSD) pulse shape discrimination parameter as a function of the charge of the fast component of the signal. Comparison of time-of-flight spectra histograms for neutrons and γ-rays demonstrates almost complete suppression of the γ- peak in the neutron spectrum. As can be seen from the figure, the application of pulse shape discrimination method for gamma-ray allows for a significant expansion of the measurable energy range of neutrons and enhances the reliability of the obtained data.

As a result of the measurements, a preliminary energy spectrum of neutrons from the decay of the target spectator was obtained in a wide energy interval from 1 to 300 MeV at an angle of 95° (Figure 19).

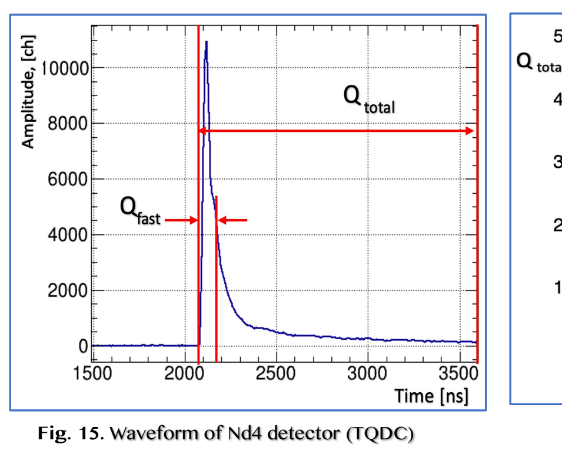


Fig. 15. Waveform of Nd4 detector (TQDC)

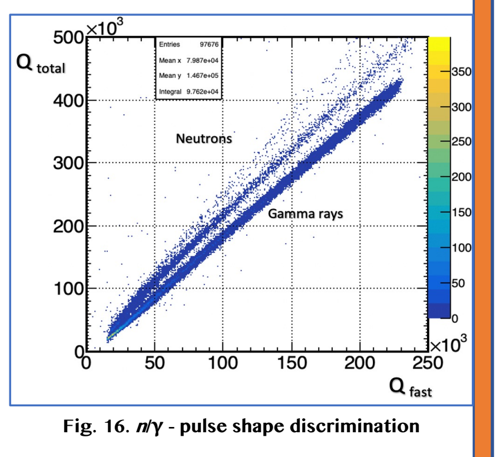


Fig. 16. ***n/γ*** **- pulse shape discrimination**

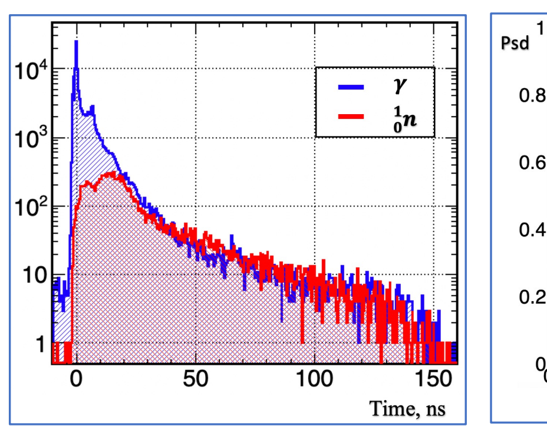


Fig. 17. n_γ - TOF spectrum

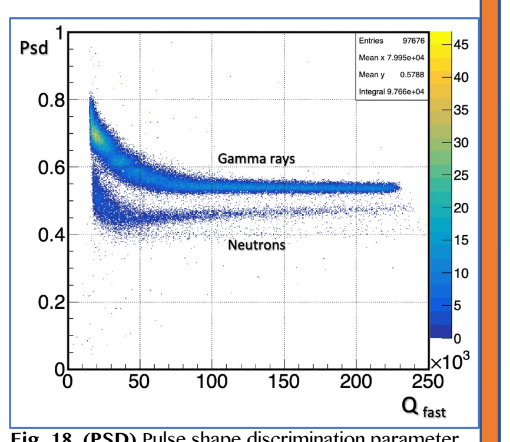


Fig. 18. (PSD) Pulse shape discrimination parameter.

$$Psd\ parameter = 1 - \frac{Q_{total} - Q_{fast}}{Q_{total}}$$

Example of Neutron Energy Spectrum

^{124}Xe + CsI collisions

Beam energy – 3.9 GeV/nucleon;

Trigger – CCT = BC1 * BC2 * VC$_{veto}$ * FD$_{veto}$ * BD(N>3);

Detector – ND4;

Angle – 95⁰

Time resolution – 113 ± 12, ps

$$\frac{d^2F}{dE d\Omega} = \frac{\Delta N}{\Delta E \cdot \Delta\Omega \cdot \varepsilon(E) \cdot k}$$

ΔN - is the number of detected neutrons;

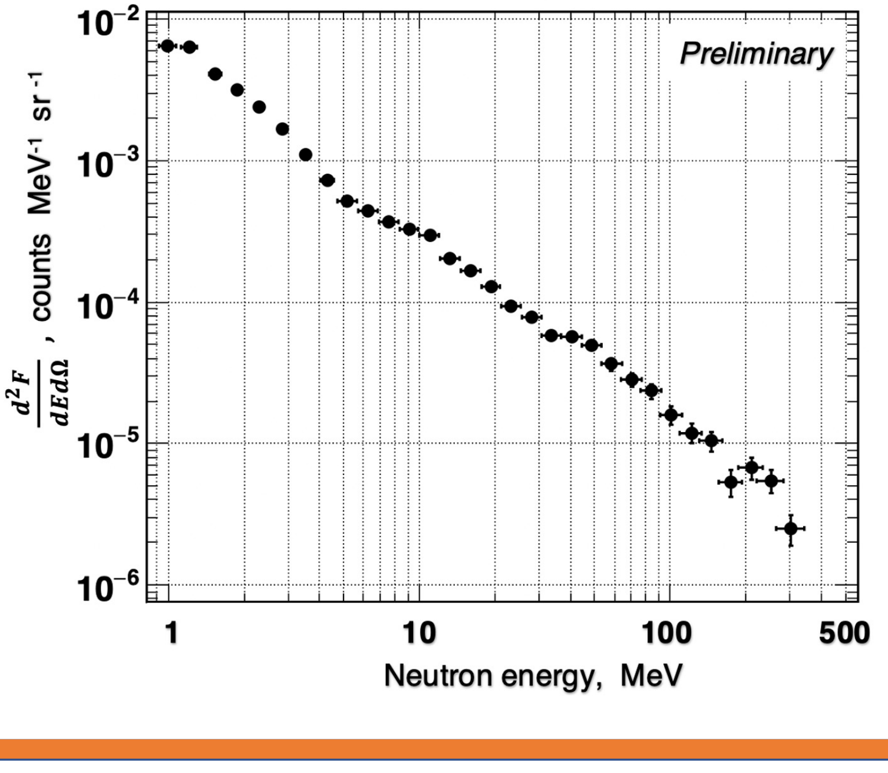
ΔE - is the energy bin width;

$\Delta\Omega$ - is the solid angle for each neutron detector;

$\varepsilon(E)$ - is the neutron detection efficiency;

k - is a factor which corrects data acquisition.

Fig. 19. The Neutron Energy Spectrum (ND4)



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