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

N.A. Lashmanov*, V. I. Yurevich**, V. Yu. Rogov, S. A. Sedykh, S. V. Sergeev, V. K. Velichkov, V. V. Tikhomirov, A. A. Timoshenko and V.N. Azorskiy

[a] *Joint Institute for Nuclear Research, Dubna, 141980 Russia*

**e-mail: lashmanov@jinr.ru*
***e-mail: yurevich@jinr.ru*

Abstract — The double-differential cross section of neutron production in ^{124}Xe + CsI collisions at 3.8 *A* GeV was measured at large angles with a compact time-of-flight spectrometer of the BM@N experiment. Preliminary results on the energy spectra of neutrons show near isotropic emission of neutrons from target spectators. The spectra are well described by a model with three moving sources. The measured energy spectra of neutrons are compared with prediction of DCM-QGSM-SMM model. The low energy part of the experimental spectra is not reproduced by theoretical models, which greatly underestimate the yield of these neutrons.

INTRODUCTION

Interactions of relativistic heavy ions are accompanied by the production of a large number of secondary particles, including a significant yield of neutrons. The study of neutron yields provides important information for testing and developing theoretical models describing heavy ion collision dynamics and properties of produced nuclear matter. Of particular interest are data on the formation of free neutrons during the decay of spectators of colliding nuclei.

However, despite the importance of this data, the number of experimental neutron measurements remains limited due to significant methodological difficulties.

A compact time-of-flight (TOF) neutron spectrometer was developed and commissioned as a part of the BM@N experiment [1] at the Laboratory of High Energy Physics of JINR. The spectrometer aims to measure the energy spectra of neutrons in the range of 2 – 200 MeV at large angles, where the dominant contribution is made by neutrons from the spectators of target nuclei. The first measurement was performed using a beam of ^{124}Xe ions with an energy of 3.8 *A* GeV bombarding a thin CsI target. Here we briefly describe the experiment and discuss the preliminary results of the measurement.

NEUTRON SPECTROMETER

A compact TOF neutron spectrometer is located near the target inside the analysing magnet of the BM@N setup [2]. Its main features are: (1) small flight path 20 – 30 cm to minimize background, (2) high time resolution with $\sigma_t \approx 100$ ps, (3) effective suppression of gamma-rays by PSD (Pulse-Shape-Discrimination) method, (4) digital signal processing, (5) off-line event-by-event analysis, (6) application of SiPMs instead PMTs in magnetic field.

The neutron detectors (ND) are placed around the target at three different angles of 95°, 110°, and 121°. A photo of the spectrometer is shown in Fig. 1 (left). Stilbene scintillators 25.4

diam. × 25.4 mm^3 and 30 diam. × 10 mm^3 are used for neutron registration in the detectors, two identical scintillators are in each ND as it is shown in Fig. 1 (right). Each scintillator is coupled with four SiPMs 6 × 6 mm^2, (SensL, J-ser.) [3] that gives immunity to the strong magnetic field of the BM@N magnet. Applying stilbene in the detectors give a high suppression of a gamma-ray background by PSD method.

The charged particles are discriminated with veto-detectors (VD) located in front of the neutron detectors. In the veto-detectors 5-mm plastic scintillator is viewed by two SiPMs.

A vacuum pipe is used for transport of beam ions through the experimental zone. The target and scintillators of upstream beam counters are placed inside the vacuum pipe.

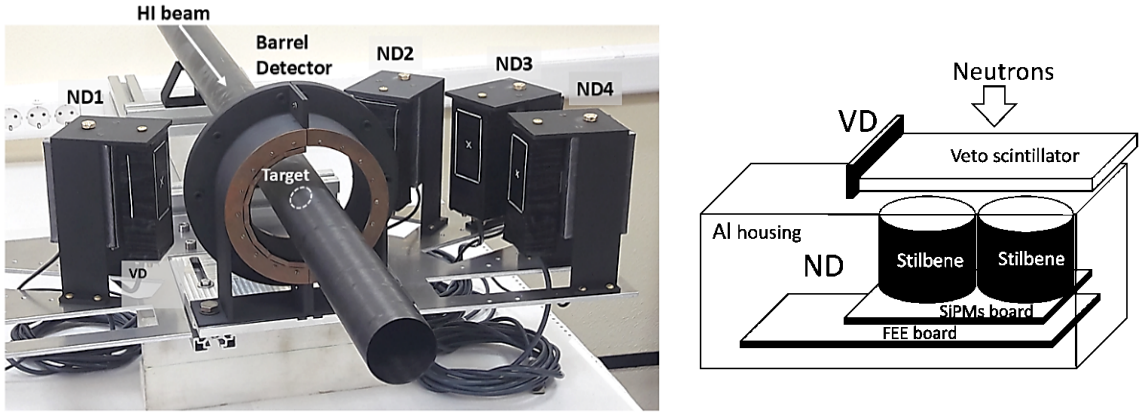


Fig. 1. A photo of the neutron spectrometer (left) and a scheme of the neutron detector (right).

In the TOF measurements the start pulse is generated by beam counter with 150- μm thick plastic scintillator BC400B [4] providing 38- ps time resolution. The stop pulses are produced by the neutron detectors.

The TQDC16VS electronic modules in the VME standard are used to record events from the neutron and veto detectors. These modules are a part of the BM@N data acquisition system and digitize the time and shape of the input pulses.

The efficiency of neutron detectors was calculated by two methods, using single interaction approach and with GEANT4 code [5]. In both cases we did some test calculations for comparison with available measured efficiencies for stilbene and NE213 scintillators. The experimental data were reproduced by the GEANT 4 + CENDL 3.1 calculation with error less than 10% in energy range up to 500 MeV.

Before/After protection with beam counter pulse in time interval of ±1.8 μs is used to avoid overlapping of events.

The BM@N trigger is used for collection of the events. The interaction minimum bias trigger is produced as coincidence of pulses of upstream beam counters with a veto pulse from a downstream counter. The main interaction trigger includes fast response of a barrel detector (BD) with 40 scintillation strips placed around the target and detecting secondary charged particles emitted from the target. For Xe + CsI interactions a threshold N(BD) > 3 fired channels allow to select the collisions with centrality < 60%.

THE MEASUREMENTS

Getting reliable neutron spectra in the wide energy interval in the study of ^{124}Xe + CsI collisions assumes minimization and suppression of background induced by gamma-rays, rescattered or secondary neutrons and charged particles. The high suppression of gamma-ray background is reached by the Pulse-Shape-Discrimination (PSD) method. The PSD parameter is calculated as the charge ratio Q_{fast}/Q_{total}, Q_{fast} is the integral of the fast component of the pulse and Q_{total} is the total charge. The quality of the neutron events selection is shown in Fig. 2 (left), which displays the 2D distribution of the PSD parameter versus the fast charge Q_{fast} in channels. The dashed line on the plot indicates the graphical cut used to separate neutron events from the gamma-rays background. Only events located below this line were selected for further analysis. Minimization of the neutron background is obtained by using a short flight path in the spectrometer. The neutron background contribution to the TOF neutron spectrum measured at angle 95° with a flight path of 30 cm is shown in Fig. 2 (right). MC simulation with GEANT4 + G4NDL software package was applied in order to accurately determine and subsequently subtract the background spectrum. The effective discrimination of events induced by charged particles is made with the veto-detectors.

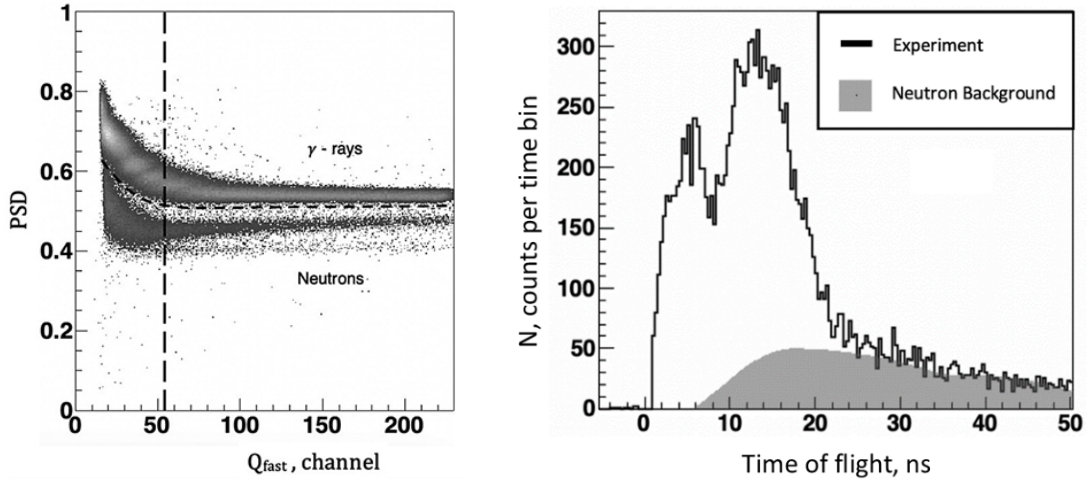


Fig. 2. The quality of n/γ-separation, the dashed line corresponds to the threshold of 1 MeV_p (left) and the measured TOF neutron spectrum at angle of 95° with the estimated neutron background (right).

NEUTRON ENERGY SPECTRA

Recently, neutron spectra emitted from beam spectators in similar Sn, La + Sn collisions at 600 A MeV were measured at small angles using the LAND detector at GSI [6]. However, due to the Lorentz boost, neutrons emitted with low energies in the rest frame of the beam fragment appear as high-energy particles in the laboratory frame, with energies close to that of the beam. Such experimental spectra are typically well-described by a Gaussian distribution, which limits the ability to perform a detailed analysis of the spectral shape reflecting different emission stages. In contrast, our approach involves measuring neutron spectra from target spectators in their rest frame, providing a unique opportunity for a more comprehensive study of the characteristics of neutrons produced during spectator decay.

The preliminary energy spectra measured in ^{124}Xe + CsI collisions at different large angles are shown in Fig. 3. In the low energy region below 20 MeV, the spectra measured at different angles show good agreement with each other. This indicates an isotropic emission of these neutrons from the excited target spectators. Some difference in spectra is observed at higher energies. This part of neutron spectrum becomes harder with decreasing emitted angle. This effect can be explained by the presence of longitudinal velocity at the emitting source. Also, a shoulder effect is clearly seen in the middle part of spectra. It can be related to an additional stage of spectator decay.

In our analysis of the energy spectra of neutrons, a model with three moving sources (MSM) [7] with different kinematical and thermodynamical characteristics was applied. The source S1 reproduces the hard part of spectra and is associated with the contact layer of colliding nuclei. The source S2 dominates in the middle part of spectra. This source is associated with multifragmentation decay. The source S3 is responsible for emission of low-energy neutrons. Thus, the sources S2 and S3 are associated with the stages of disintegration of target spectators. The Maxwell - Boltzmann distribution with three free parameters (amplitude, temperature, and longitudinal velocity) is used for each source in the model.

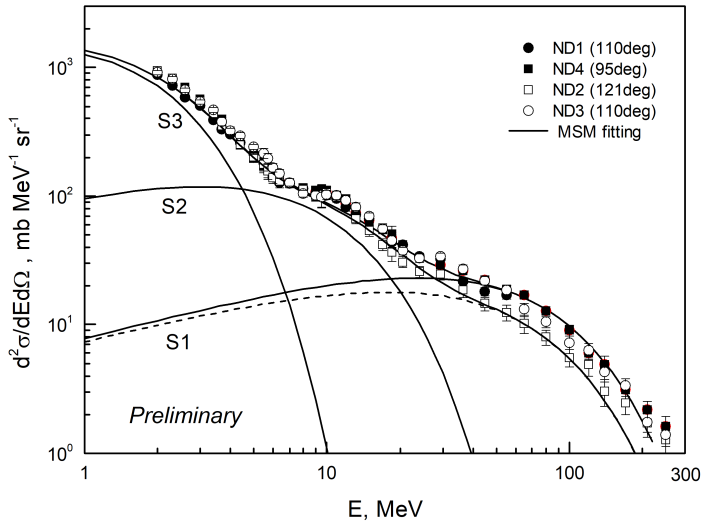


Fig. 3. The energy spectra of neutrons measured for ^{124}Xe + CsI collisions at 3.8 A GeV with neutron detectors at three angles 95°, 110° and 121°. The lines are the result of MSM fitting, the lines marked as S1, S2, and S3 are the contributions of the neutron sources to the spectra.

The best fitting to the spectra was obtained with the temperature values of the sources S1, S2, and S3 of 50 ± 5 MeV, 6.0 ± 0.5 MeV, and 1.1 ± 0.1 MeV respectively.

The obtained experimental spectra were compared with the prediction of the DCM-QGSM-SMM model [8]. As shown in Fig. 4, the model satisfactorily describes the experimental data in the energy range above 10 MeV, but it significantly underestimates the neutron yield in the low-energy region. This fact indicates the need for further development of the theoretical model for description of free neutron production in nucleus – nucleus collisions at high energies.

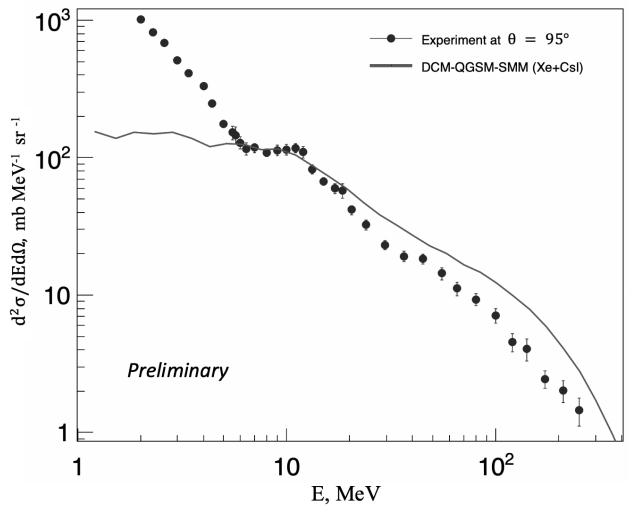


Fig. 4. A comparison of the experimental neutron spectrum at angle of 95° with prediction of DSM-QGSM-SMM model.

CONCLUSION

The double-differential cross sections of neutron production in ^{124}Xe + CsI collisions at 3.8 A GeV were measured in energy range from 2 to 200 MeV at large angles of 95°, 110°, and 121° using the compact TOF spectrometer in the BM@N experiment. Preliminary results on the energy spectra of neutrons show near isotropic emission of neutrons from target spectators. The observed shape of the spectra is a superposition of the contributions of three components – sources. Analysis of the results was made in frame of the model with three moving sources associated with different processes of neutron emission. The model well describes the experimental spectra with temperature parameters of the sources of 50 ± 5 MeV, 6.0 ± 0.5 MeV, and 1.1 ± 0.1 MeV.

Comparison of the experimental neutron spectrum with prediction of the DCM-QGSM-SMM model revealed a significant underestimation by the model in the low-energy part of the spectrum. It indicates the need for further development of the theoretical model for correct description of neutron emission in high energy nucleus - nucleus collisions.

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