DEVELOPMENT OF A TOF NEUTRON SPECTROMETER IN THE BM@N EXPERIMENT

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Abstract – A compact time-of-flight neutron spectrometer is developed as a part of the BM@N facility for study of energy spectra of neutrons at large angles, in the region of fragmentation of target spectator, with beams of heavy nuclei of Nuclotron in energy range of 2 – 4 GeV/nucleon. The concept of spectrometer and neutron detectors, and the study of the spectrometer performance in BM@N run with Xe-ion beam are discussed.

INTRODUCTION

Collisions of heavy nuclei at high energies produce a large number of free neutrons, which carry important information about the mechanism of nucleus-nucleus interaction and the evolution of the resulting nuclear system. Such neutron data are highly significant for testing theoretical models and codes and for their further development.

The neutron spectrometer is developed for the fixed target BM@N experiment [1] with an extracted beam of nuclei from the Nuclotron accelerator with an energy of 2 – 4 GeV/nucleon. The purpose of the neutron spectrometer is to study the emission of neutrons in the collision of heavy nuclei at large angles to the beam axis which corresponds to the decay region of target nucleus spectator.

THE NEUTRON SPECTROMETER

The time-of-flight method is used to measure the neutron production double-differential cross sections in interactions of high-energy heavy ion beam with a thin target of the BM@N setup. Neutron spectra are measured at angles $\theta > 60°$ to the beam direction and cover the energy range up to several hundred MeV. Therefore, to ensure high energy resolution over the entire neutron energy range, the spectrometer must have a time resolution of $\sigma_t < 0.5$ ns normalized to 1- m flight distance.

The location of neutron detectors inside the large analyzing magnet of the BM@N setup leads to the need to use a compact design of the spectrometer with flight paths less than 50 cm. Stilbene crystals are used for neutron detection because stilbene allows to apply suppression of γ-ray background by the n/γ pulse shape discrimination method (PSD). The scintillation light is registered by SiPM array well operating in the magnetic field of the BM@N magnet with $B = 0.9$ T.

The T0 beam detector of the BM@N setup, based on BC400B scintillator with dimension of 30×30×0.15 mm^3 and two MCP-PMTs XPM85112/A1 from Photonis, is used as the start detector in the TOF neutron spectrometer. The time resolution of this detector is $\sigma_t = 38$ ps.

During the measurements a collection of events is carried out according to the trigger conditions of the BM@N experiment realized in a programmable trigger module T0U [2]. The readout electronics is based on 16- channel modules TQDC_16VS [3] where each channel consists of a TDC with 25- ps binning and a pulse shaper plus digitizer with 8- ns binning.

NEUTRON DETECTORS

The neutron detectors ND1 – ND4 are equipped with a rectangular aluminum housing that contains two identical stilbene crystals (30 diam.×10 mm^3 in ND1, and 25.4 diam.× 25.4 mm^3 in ND2 – ND4) and a front-end electronics (FEE) board as it is shown in Fig. 1.

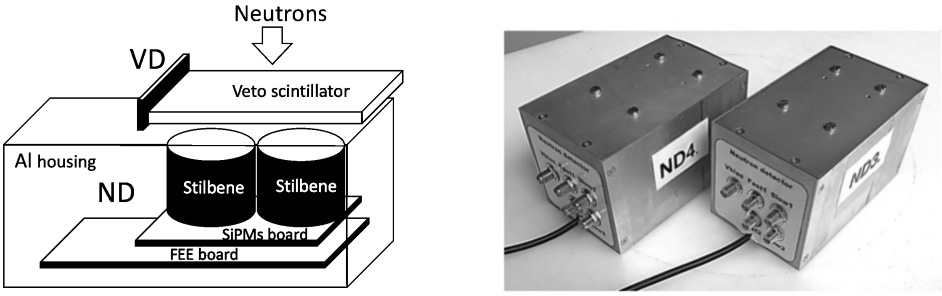

Fig. 1. A scheme of the neutron detector (left) and a view of neutron detectors (right).

Each stilbene crystal is viewed with four SiPMs 6 × 6 mm^2, J-ser. from SensL. The fast output is used as a stop pulse in TOF measurements, while the slow output transmits the full pulse shape and it is used for n/γ pulse shape discrimination.

To suppress the background of charged particles generated together with neutrons in the target, scintillation veto-detectors (VD) are placed in front of neutron detectors. VD consists of a plastic scintillator 80×40×5 mm^3 viewed with two SiPMs.

The neutron detection efficiency is determined by calculation based on the single interaction approximation where neutron can be detected by n-p scattering or reaction with carbon nucleus. The obtained efficiency for detectors ND2 – ND4 with two thresholds on neutron energy of 0.5 and 1.0 MeV is shown in Fig.2 (left). The right figure demonstrates the approbation of the calculation method with experimental data obtained for detector NE-213 (51 diam.× 25 mm^3) [4]. The calculation well reproduces the experimental results in wide energy interval.

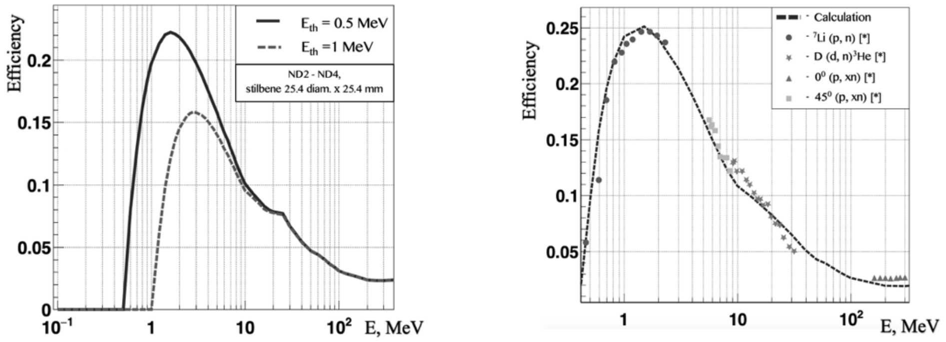

Fig. 2. Neutron detection efficiency as a function of the neutron energy (left), and a comparison of the calculation method with experimental data [4] (right).

STUDY OF THE SPECTROMETER PERFORMANCE

The study of the spectrometer performance was carried out during the BM@N run with beam of ^{124}Xe ions with energy of 3.8 GeV/nucleon. The typical beam intensity was ~ 5×10^5 ions/spill with the spill duration of 2 – 3 s. The beam profile on the target position had Gaussian shape with $\sigma_x \approx \sigma_y \approx 3$ mm. The target was a CsI disk with thickness related to 2%-probability of nuclear interaction.

The neutron detectors ND2 – ND4 generated the stop pulse in the TOF measurements and they were located inside the analyzing magnet of the BM@N setup at a distance of 30 cm from the target and angles $\theta = 95^\circ$, 110° and 121°. The detector ND1 had a flight path 20 cm and angle $\theta = 110^\circ$.

The time resolution, estimated from the width of prompt γ-rays peak, is $\sigma_t = 110$ ps. The energy resolution for measurements with the ND2 – ND4 detectors is shown in Fig.3 (left).

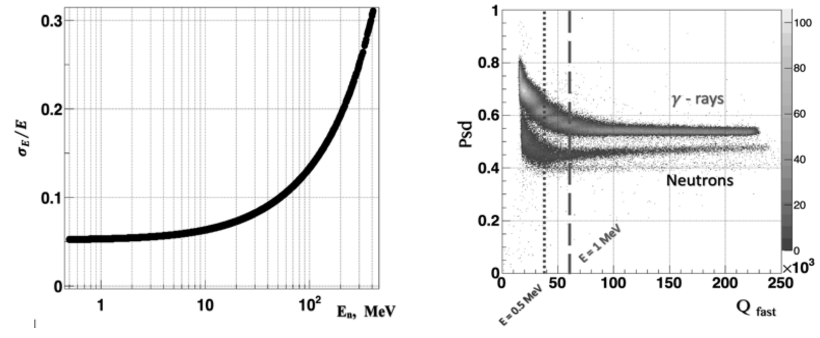

Fig. 3. Energy resolution of ND2 – ND4 detectors (left), and separation of n and γ events by n/γ pulse shape discrimination obtained with the ND4 at $\theta = 95^\circ$ (right).

The separation of neutron and γ -ray events by PSD method showed that the best result for our registration chain with the TQDC module is achieved using 120- ns and 1.5- μs intervals for integration of the fast component and total pulse, as it is shown in Fig.3 (right). It is clearly seen that the neutron events used for neutron spectrum analysis are fully separated from the γ- ray events. The figure of merit (FOM), used for estimation of PSD quality, is 2.87 that is higher than the value of 1.89 obtained in [5] with stilbene detector and SiPM readout for 0.7 MeV neutron energy. The TOF neutron and γ- ray spectra obtained with ND4 at the threshold corresponding to neutron energy of 1 MeV are shown in Fig.4. It is well seen that the PSD method provides full suppression of the γ- ray peak and background of secondary γ-rays.

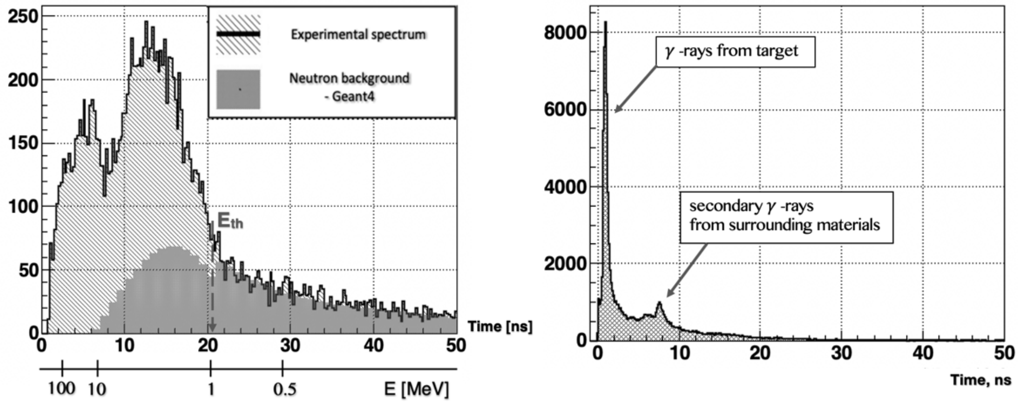

Fig. 4. Time-of-flight spectra obtained by the ND4 detector for neutrons (left) and γ-rays (right).

The background of secondary neutrons, also shown in Fig.4 (left), was estimated by calculation with the GEANT4 code [6]. The main background contribution in time range $t < 20$ ns comes from interactions with materials located around the target while for $t > 20$ ns the background neutrons coming from other surrounding materials dominate. Selected neutron events minus the neutron background were used for further analysis.

The neutron production double-differential cross section is obtained as

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

where ΔN - the number of counts in the energy interval ΔE, $\Delta\Omega$ - the solid angle of neutron detector, $\varepsilon(E)$ - the neutron detection efficiency, I - the number of beam ions on the target, n - the number of target nuclei per 1 cm^2, k_1 - the correction factor for dead time of the spectrometer, k_2 - the correction factor for Before/After protection time of 1.5 μs.

The result obtained in the energy interval from 2 to 200 MeV at $\theta = 95^\circ$ with the detector ND4 and the threshold of 1 MeV is shown in Fig. 5.

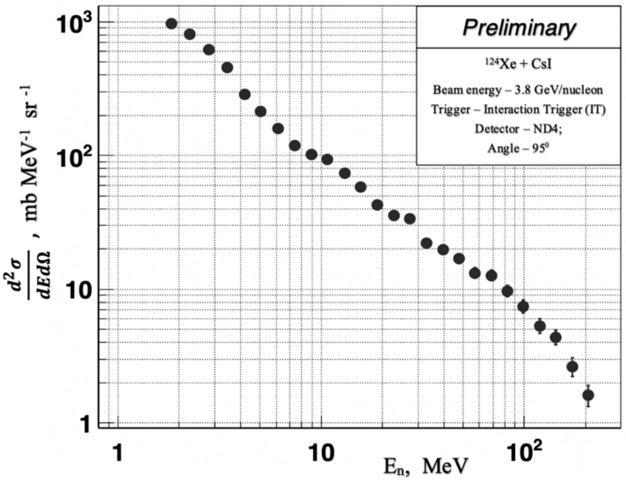

Fig. 5. Neutron production double-differential cross section for ^{124}Xe + CsI collisions at energy of 3.8 GeV/nucleon measured with ND4 detector at $\theta = 95°$.

CONCLUSION

The TOF neutron spectrometer with stilbene crystals and short flight path has been developed for measuring energy spectra of neutrons at large angles in the BM@N experiment. The study of the spectrometer performance was carried out with beam of Xe ions and CsI target during the BM@N run. The measurements show the importance of n/γ pulse shape discrimination for reduction of γ- ray background. The obtained time resolution $\sigma_t = 110$ ps allowed to create the compact TOF spectrometer with flight path of 30 cm and as a result, to measure the energy spectrum of neutrons in energy interval from 2 to 200 MeV.

The performed analysis proves that using the developed spectrometer we can obtain reliable neutron spectra in wide energy interval with good statistics. The analysis of data is continued. In future we plan to use the spectrometer for study of neutron emission in collisions of heavy nuclei as a part of physics program of the BM@N experiment.

REFERENCES

1. M. Kapishin Nuclear Physics A 982 (2019) 967.
2. D.N. Bogoslovsky et al., *Trigger and beam monitoring system of BM@N and SRC experiments*, Proc. of the 27th Inter. Symp. Nuclear Electronics and Computing (NEC'2019), Budva, Montenegro, 2019, p.241.
3. https://afi.jinr.ru/TDC
4. S.D. Howe et al., NIM in Phys. Res. 227 (1984) 565.
5. J. Boo et al., Nature, Sci. Rep. 11 (2021) 3826.
6. J. Apostolakis et al., Geometry and physics of the Geant4 toolkit for high and medium energy applications. Radiation Physics and Chemistry 78 (2009) 859.