RESEARCH ARTICLE | SEPTEMBER 24 2021

Multilayer neutron detector based on a plastic scintillator

Valentin V. Ustinov; Sergey V. Afanasiev; Vladimir A. Baskov; Vasil I. Bekirov; Dmitry K. Dryablov; Boris V. Dubinchik; L'vov A. I.; Alexander I. Malakhov; Katerina Michalickova; Valery V. Polyansky; Dmitry G. Sakulin; Evgeny V. Sukhov

AIP Conf. Proc. 2377, 030018 (2021)
https://doi.org/10.1063/5.0063298

Multilayer Neutron Detector Based on a Plastic Scintillator

Valentin V. Ustinov[1,2,3,a)], Sergey V. Afanasiev[1,2,b)], Vladimir A. Baskov[3], Vasil I. Bekirov [1], Dmitry K. Dryablov[1,2], Boris V. Dubinchik[1], L'vov A.I.[3], Alexander I. Malakhov[1,2], Katerina Michalickova[1,4], Valery V. Polyansky[3], Dmitry G. Sakulin[1,2], and Evgeny V. Sukhov[1,2]

[1]*Joint Institute for Nuclear Research, 6 Joliot-Curie, 141980, Dubna, Moscow region, Russia*
[2]*Dubna State University, Universitetskaya 19, 141982, Dubna, Moscow region, Russia*
[3]*P.N. Lebedev Physical of the Russian Academy of Science, Leninskiy Prospekt 53, 119991, Moscow, Russia*
[4]*Pavol Jozef Šafárik University in Košice, Šrobárova 2, 041 80, Košice, Slovak Republic*

[a)] *Corresponding author: ustinov@jinr.ru*
[b)] *afanasev@lhe.jinr.ru*

Abstract. A precision hybrid magnetic three-arm «SCAN-3» spectrometer is being developed at the Joint Institute for Nuclear Research. The spectrometer is designed to detect charged particles ($\pi^{\pm}$, $K^{\pm}$, p) and neutrons produced in the target by collisions of the NUCLOTRON high-interactive beam particles with target nuclei. One of the tasks of the spectrometer is to detect neutrons from the decay of the η-meson nucleus via nπ- and pn- channels. To complete this task, two arms of the spectrometer will be created that consist of six multilayer neutron detectors based on scintillation blocks. The characteristics of a neutron detector that consists of five scintillation blocks are considered. The detector was studied using the cosmic rays and the neutron beam produced by the stripping reaction of the NUCLOTRON extracted deuteron beam on a fixed target.

INTRODUCTION

One of the tasks of the precision hybrid magnetic «SCAN-3» spectrometer [1, 2] at the Joint Institute for Nuclear Research (JINR) in Dubna is to register neutrons from the decay of the η-meson nucleus via πn- and pn- channels. The only way to provide fast neutron spectrometry is to use the time-of-flight (TOF) method. To reach the required accuracy of neutron energy measurements, it is necessary to measure the TOF (δt) with an accuracy not lower that δt = 2.2 ns for the πn-channel and δt = 0.4 ns for the pn-channel [2]. The energy of the resulting neutron for the nπ- and pn-channels is 90 and 300 MeV, respectively.

The disadvantage of existing neutron detectors is the large uncertainty of the flight length for the detected particles. This is due to the large thickness of the detector and the probabilistic character of neutron detection. Registration occurs only in case of nuclear interaction of incident neutrons with the detector media, and, as a result, the distance from the place of neutron production to the collision site can vary widely. In this case, the uncertainty in the flight length is a limitation on the accuracy of neutron energy recovery. The most promising approach to solve this problem is to develop the multilayer neutron detectors based on a block of scintillation blocks.

The method used for high-energy neutron time-of-flight spectrometry has an error $\delta\beta$ (1) in measuring the neutron velocity $\delta V = \delta\beta \cdot c$, which depends on the thickness and time resolution of the detector.

$$\delta\beta = \left[\left(\frac{\delta L}{ct}\right)^2 + \left(\frac{L\delta t}{ct^2}\right)^2 \right]^{1/2}, \quad (1)$$

where L is the distance traveled by the neutron from the origin point (of neutrons) to the registration point (m); t is the travel time of the path L (ns); c is the velocity of light (m/s); β – the relative velocity of neutrons. The variable δL of the equation (1) is the measurement error of the neutron detection point, which is determined by the thickness of the detector. The variable δt characterizes the error in determining the time of neutron detection. It is determined by the characteristics of scintillators and photomultiplier tubes (PMT).

Proceedings of the 24th International Scientific Conference of Young Scientists and Specialists (AYSS-2020)
AIP Conf. Proc. 2377, 030018-1–030018-5; https://doi.org/10.1063/5.0063298
Published by AIP Publishing. 978-0-7354-4132-3/$30.00

Accurate measurements of the nucleon energy require accuracy in determining the velocity with $\delta\beta = 0.8\cdot10^{-2}$, which is achieved by simultaneously measuring the TOF more accurately than δt = 400 ps (for the ***pn***-channel), as well as controlling the trajectory length better than δL = 8 cm [2].

DESIGN OF MULTILAYER NEUTRON DETECTOR PROTOTYPE

To check the parameters of performance of the multilayer neutron detector (MND), a prototype has been developed (Figs. 1, 2). The prototype consists of five 70×20×2 cm^3 blocks of a plastic scintillator produced by JINR [3]: polystyrene doped of 1.5% p-terphenyl and 0.01% POPOP. The scintillation blocks were polished on all sides. To improve light collection, each block was wrapped in DuPont Tyvek [4]. The light attenuation length of the selected scintillation blocks for the detector is about 60÷70 cm. The crosstalk between the blocks was not detected.

Extraction of signals from scintillators is performed by two independent sets of PMTs [5, 6]:

1. Two Philips XP2041 PMTs located on opposite ends of the blocks provide simultaneous readout of signals from all blocks. The diameter of the XP2041 photocathode is 11 cm, and it allows to effectively collect the total signal from all (5) blocks simultaneously. The signals from the ends of the scintillators are transmitted to the PMT through 15 cm long air light guides.
2. Two PMT-87s located on opposite ends of the blocks provide readout of optical signals from each scintillator. This allows getting additional and independent measures from each individual block. The use of PMT-87 is determined by the high time resolution of these PMTs. The PMT-87 photocathodes are coupled directly to the ends of the scintillators without lubrication. Only PMT-87 with time resolution in the range of 60÷100 ps were selected for the detector.

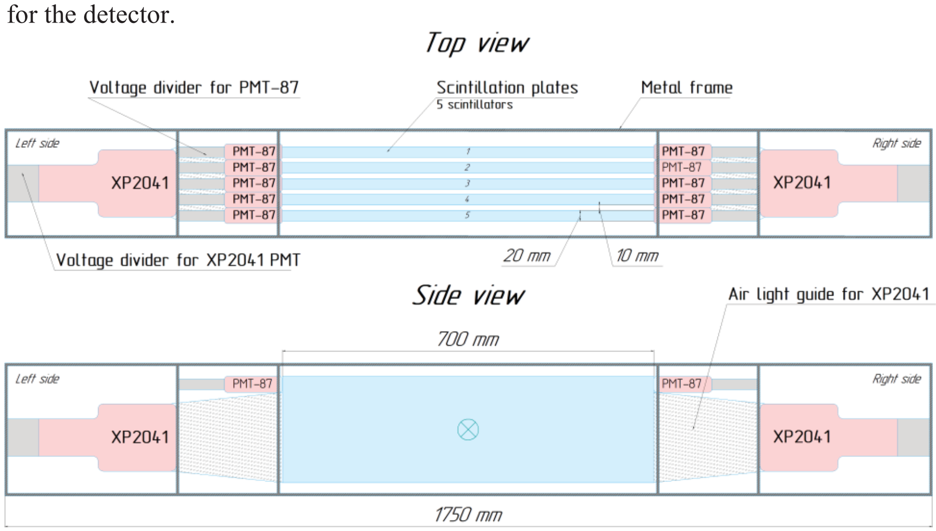

FIGURE 1. Scheme of the neutron detector prototype consisting of five blocks.

A 200×30×30 cm^3 case was prepared for the neutron detector prototype (Fig. 2). The frame with rigidly fixed scintillation blocks and the photodetectors was in the case. The case was covered with black paper from the inside, and the places where the case cover was pressed were sealed with a cloth. Output signals from PMTs and high-voltage cables were derived from the case by connectors installed in the sidewall.

The neutron interaction point in the detector media is a random variable. The multilayer geometry of the neutron detector allows reducing this inaccuracy. The neutron interacts with the proton in the scintillator and transmits part of its energy and momentum to it. Recoil protons moving in the scintillator produce light. Protons interact with three out of five blocks on average. Meanwhile, the neutron detection efficiency by scintillators is about 1% per 1 cm.

The detector contains five layers, which is a compromise between the neutron detection efficiency (which depends on the detector thickness) and the indeterminacy of the neutron interaction point in the detector media. To achieve the necessary spatial resolution, the detector was divided into five identical blocks. This makes it possible to improve the spatial resolution of the detector (the longitudinal coordinate) by determining the point of interaction of the neutron with MND up to the thickness of the block used. The block in which the neutron interacts determines the longitudinal coordinate and additionally gives the time information and the transverse coordinate. The transverse coordinate is calculated from the time difference of the signals between two PMT-87 (located on the same block). The proposed design of a MND with two independent readout systems improves the neutron TOF and, as a result, improves $\delta\beta$.

A close approach was applied in the Large-area neutron detector (LAND) [7]. The proposed design retains the advantages of the multi-layer LAND structure, but significantly increases the volume of the detector. However, we used only 2 cm scintillation blocks instead of a sandwich of 5 mm scintillation and iron plates (LAND design).

The previous version of the four-layer neutron detector was considered in the references [8, 9]. The reference [9] also provides an assessment of the neutron detection efficiency and the counting characteristic of the detector.

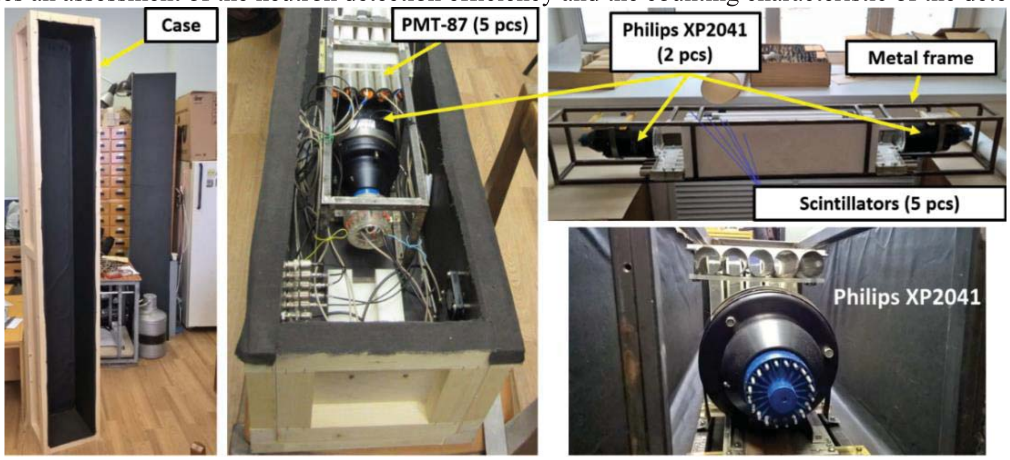

FIGURE 2. The main view of the 5-layer neutron detector in case.

CHARACTERISATION OF NEUTRON DETECTOR USING COSMIC RAYS

A preliminary study of the characteristics of the neutron detector was performed using cosmic rays. Two 10×10×1 cm^3 trigger scintillation counters were used to highlight the detector area under study. The trigger condition for starting the readout electronics was the coincidence of the signals from the trigger counters and the signal from one of the two XP2041. To measure time, signals from all the PMTs of the neutron detector (12 channels) and signals from trigger counters (2 channels) were fed to the TQDC input [10] of the data acquisition (DAQ) system in the VME standard.

Thus, the time resolution values for each channel were measured depending on the location of the trigger counters -30, -15, 0, 15 and 30 cm relative to the center of the detector. The average time resolution values for each channel are shown in Table I. The PMT-87 with No.1 in Table I showed worse parameters in relation to others PMT-87, it is obvious that it lost sensitivity under irradiation.

TABLE I. Time resolutions of the MND channels obtained using cosmic rays and 3.5 GeV neutron beam.

Channel number (PMT)	Time resolution $\sigma \pm \Delta\sigma$, ns		Block number	Position of the PMT
	Cosmic rays	3.5 GeV neutrons beam		
1 (PMT-87)	1.6 ± 0.33	1.36 ± 0.33	1	Left
2 (PMT-87)	1.34 ± 0.02	1.13 ± 0.03		Right
3 (PMT-87)	1.14 ± 0.04	1.1 ± 0.02	2	Left
4 (PMT-87)	1.27 ± 0.07	1.31 ± 0.03		Right
5 (PMT-87)	1.14 ± 0.08	1.31 ± 0.04	3	Left
6 (PMT-87)	-	1.81± 0.07		Right
7 (PMT-87)	1.06 ± 0.04	1.35 ± 0.02	4	Left
8 (PMT-87)	1.24 ± 0.05	1.22 ± 0.07		Right
9 (PMT-87)	1.3 ± 0.07	1.13 ± 0.02	5	Left
10 (PMT-87)	1.26 ± 0.09	1.27 ± 0.08		Right
11 (XP2041)	1.06 ± 0.06	0.48 ± 0.06	All blocks at once	Left
12 (XP2041)	0.79 ± 0.03	0.4 ± 0.03		Right

The spatial resolution σ_x of MND was defined as (2):

$$\sigma_x = V \cdot \sigma_{ij} , \tag{2}$$

and time resolution of blocks σ_{ij} was defined as (3):

$$\sigma_{ij} = \frac{\sqrt{\sigma_i^2 + \sigma_j^2}}{2} , \tag{3}$$

where σ_i and σ_j are the time resolution of a pair of PMTs that readout on a single block; V – the velocity of light in each scintillator block. The obtained values for the velocity of light distribution inside the scintillation blocks, spatial and time resolutions according to (2) and (3), respectively, are presented in Table II.

TABLE II. Characteristics of the multilayer neutron detector obtained using cosmic rays.

Block number	$V \pm \Delta V$, cm/ns	Calculated V, cm/ns	$\sigma_{ij} \pm \Delta\sigma$, ns	Required accuracy of σ_{ij}, ns	σ_x, cm
1	20.3 ± 7.6	18.9	1.04 ± 0.46	< 0.4	21.1 ± 7.9
2	12.8 ± 2.7		0.85 ± 0.08		10.9 ± 2.3
4	13.1 ± 2.7		0.82 ± 0.06		10.7 ± 2.2
5	18.1 ± 5.4		0.91 ± 0.11		16.3 ± 4.9
All blocks at once (including air light guide)	9.6 ± 1.4		0.66 ± 0.07		6.3 ± 0.9

Scintillator No.1 in Table II showed worse characteristics due to the low sensitivity of the PMT-87 No.1 (Table I). In addition, information about the scintillator No.3 is excluded from the paper due to technical problems with PMT-87 No.6 (Table I) during the study of MND using cosmic rays.

Since up to 12 time measurements are carried out independently in the MND prototype, the number of involved blocks will determine the time resolution of detector. The final time resolution σ_n of the detector is defined as $\sigma_n = \sigma_{ij}/\sqrt{n+1}$, where σ_{ij} is the common time resolution of 0.66 ± 0.07 ns and n = 1÷5 is the number of triggered blocks. The worst time resolution value will be when only one of the five blocks is triggered. According to the measurements, σ_1 = 470±50 ps (one block was triggered), σ_2 = 380±40 ps (if two blocks of MND were triggered), σ_3 = 330±35 ps, σ_4 = 495±30 ps and σ_5 = 270±30 ps if all blocks (5) were triggered.

CHARACTERISATION OF NEUTRON DETECTOR USING NEUTRON BEAM

The MND prototype was tested during the 54th run of the NUCLOTRON accelerator at JINR. The neutron beam was formed by the stripping reaction of the extracted 3.5 GeV/A deuteron beam on fixed thin ^7Li target (thickness is 1 g/cm^2). Detection of protons from the deuteron disintegration made it possible to perform a method of tagged neutrons [9].

The detector under study was located in the experimental b.205 at the «MARUSYA» facility [11] in the F4 focus of the transport channel of the extracted NUCLOTRON beam (Fig. 3). A target (S1) was placed in front of the 4-SP-12 magnet deflecting the deuteron beam. The distance between the point of neutron origin and the neutron detector was 7.235 meters. After the disintegration of the deuteron, the neutron flies directly towards the detector under study, and the proton is deflected by the 4-SP-12 magnet and is registered by the A2 charged particle detector. The beam deuterons that have not interacted with the target are transported further along the VP-1 channel to other consumers.

The scintillation detector A1 was a charged particle detector and was used in the anticoincidence scheme (the veto detector). The A2 detector registered a proton from the deuteron disintegration. An indication of the deuteron collapse was the coincidence of signals from MND and the detector A2. We measured the time-of-flight between A2 and MND. The neutron was detected only if the start signal from the fast counter placed in front of the S1 target, detector A2, and the signal in one of the blocks of MND coincided, as well as in the absence of signals in the veto detector. There was only air between the veto detector and MND (Fig. 3). The trigger window was about 50 ns.

Table I shows the time resolutions for neutron detector channels (PMTs) measured by irradiating ^7Li target by the 3.5 GeV/A deuteron beam. Time resolutions for almost all PMT-87s give values close to the values obtained during the study of the detector on cosmic rays. It was found that for the XP2041 PMTs (No. 11 and 12 in Table I) the time resolution obtained during irradiation of ^7Li target by a deuteron beam is about two times higher than the time resolution of the XP2041 PMT measured using cosmic muons. Table III presents general characteristics of the MND prototype obtained using the 3.5 GeV neutron beam. During testing, the neutron flux through the detector was about 1000 events per second. In this connection, the pile-up effects were not detected.

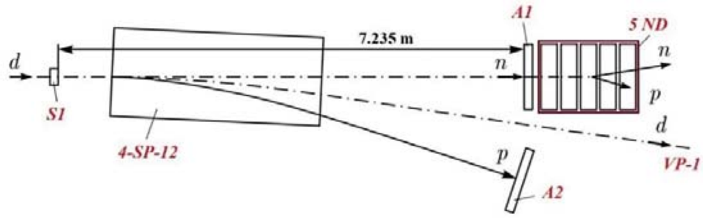

FIGURE 3. Scheme of the measurements at the «MARUSYA» facility (top view): S1 – target and place of fast counter, 4-SP-12 – magnet, A1 – veto detector, A2 – proton detector, 5 ND – neutron detector, VP-1 – deuteron beam transport channel.

TABLE III. Characteristics of multilayer neutron detector obtained using 3.5 GeV neutron beam.

Block number	$V \pm \Delta V$, cm/ns	$\sigma_{ij} \pm \Delta\sigma$, ns	Required accuracy of σ_{ij}, ns	σ_x, cm
1	20.3 ± 7.6	0.88 ± 0.33		17.9 ± 6.7
2	12.8 ± 2.7	0.86 ± 0.04		13.8 ± 2.3
3	16.1 ± 1.9	1.12 ± 0.08	< 0.4	18.0 ± 2.1
4	13.1 ± 2.7	0.91 ± 0.07		11.9 ± 2.5
5	18.1 ± 5.4	0.85 ± 0.08		15.3 ± 4.6
All blocks at once (including air light guide)	9.6 ± 1.4	0.31 ± 0.07		3.0 ± 0.4

According to the measurements performed using the 3.5 GeV neutron beam and the condition $\boldsymbol{\sigma_n = \sigma_{ij}/\sqrt{n+1}}$, σ_1 = 220±50 ps, σ_2 = 180±40 ps, σ_3 = 155±35 ps, σ_4 = 140±30 ps and σ_5 = 130±30 ps. The spatial resolution of the detector was 3.0±0.4 cm measured using the 3.5 GeV neutron beam, which fully satisfies the condition δL = 8 cm [2].

CONCLUSION

The multilayer neutron detector consisting of five scintillation blocks has been developed. The detector was tested using cosmic rays and the 3.5 GeV neutron beam. The best time resolution of 270±30 ps for muons and 130±30 ps for 3.5 GeV neutrons was obtained under the condition of simultaneous triggering of all blocks in the detector. The spatial resolution of the detector was 3.0±0.4 cm. This resolution is achieved by dividing the detector media into layers. Meanwhile, the accuracy of the velocity determination $\delta\beta$ was $0.5 \cdot 10^{-2}$, which also satisfies the task.

Based on the results obtained, a full-scale detector with a slightly modified design will be implemented at the «SCAN-3» spectrometer. Two sets of MND (12 detectors) will consist of four scintillation blocks of increased thickness to improve the coupling of PMT-87s with the ends of the blocks. It is assumed that the spatial resolution will not significantly decrease. And a detector with improved spatial resolution for the magnetic arm of the «SCAN-3» spectrometer will also be developed. High spatial resolution will be achieved by dividing the detector into 7-layers.

REFERENCES

1. S.V. Afanasev et al., EPJ Web of Conferences **138**, 09002 (2017).
2. SCAN-3 project, https://indico.jinr.ru/event/892/attachments/5949/7734/Project_SCAN-3_2019.docx.
3. M.G. Kadukov et al., Preprint of the Joint Institute for Nuclear Research. Dubna, 13-90-16 (1990).
4. DuPont Tyvek reflector, https://www.dupont.ru/brands/tyvek.html.
5. S.V. Afanasev et al., Instruments and Experimental Techniques, № 5, pp. 33-37 (2016).
6. S.V. Afanas'ev et al., Preprint of the P.N. Lebedev Physical Institute. Moscow, №22 – pp. 1-17 (2014).
7. P. Pawłowski et al., Nucl.Inst.Meth. **A694**, pp. 47-54(2012).
8. S.V. Afanasev et al., Instruments and Experimental Techniques, № 5, pp. 81-84 (2017).
9. S.V. Afanasev et al., Physics of Particles and Nuclei Letters, **Vol**. 16, № 4, pp. 327-332 (2019).
10. AFI Electronics, VME TQDC-16, https://afi.jinr.ru/TQDC-16.
11. A.A Baldin et al., Preprint of the Joint Institute for Nuclear Research. Dubna, P1-2007-180 (2007).