WARSAW TIME-OF-FLIGHT NEUTRON DETECTOR*

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A set of neutron time-of-flight detectors, based on the design of the VANDLE detector, is currently being built at the University of Warsaw. The objective is to construct mobile, small form-factor detectors, suitable for use as auxiliary extension in the existing beta-decay spectroscopy decay stations in cases where beta-delayed neutron emission is an important decay path. The detectors are based on $15 \times 15 \times 200$ mm^3 plastic bars read from one end using silicon photomultipliers equipped with the custom-designed electronic front-ends and a fully digital electronic acquisition system. Preliminary results of time resolution and detector response to radiation measured with gamma-ray sources are presented.

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1. Introduction

In recent years rapid development in production of radioactive beams has brought us to more and more exotic nuclides on the neutron-rich side of the nuclear chart. The radioactive beams open possibilities of extending the reach of breakup reactions and inverse-kinematics reaction studies. Moreover, beta-delayed neutron emission constitutes one of the main decay processes in some recently discovered neutron-rich isotopes, due to a large Q_β value and a relatively small neutron separation energy S_n [1, 2]. The importance of neutron detection in such experiments was quickly recognized and a number of arrays of neutron detectors have been built or are under construction. One of the main methods to obtain neutron energy spectra is via time-of-flight (TOF) measurement, between the point of impact or decay, and a neutron detector placed at a known distance. Examples of detectors using the TOF method are Large Area Neutron Detector (GSI) [3], neutron wall (RIKEN) [4], MoNA [5], LENDA [6], VANDLE [7, 8] or NEDA [9].

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Design of these detectors is often aimed at detection of high-energy neutrons, other (VANDLE, LENDA, NEDA) are also suitable for low-energy neutrons, with a threshold of about 100 keV or less. The neutron detectors built at the University of Warsaw are designed to be modular, small form-factor, mobile and with extended detection limits towards small energies. They could be used in an experiment together with an existing decay station equipped with β-particle counters and germanium detectors, or as a part of another neutron array. Currently, there are 16 units completed, but we have used cost-effective solutions and additional detectors may be added in the future.

2. Detector design

The detector array currently consists of 16 identical modules, each one built of a $15\times15\times200$ mm^3 BC-408 plastic scintillator wrapped with a teflon layer and coupled with a SensL ArrayJ-60035-4P silicon photomultiplier at one end. The high-voltage supply (in a range of 30–45 V) and signal readout are provided by custom front-end electronic modules (Fig. 1). These units include a transimpedance amplifier and a temperature compensation system (for keeping constant gain). The overall size of each detector is about $18 \times 18 \times 300$ mm^3. The signals from the detectors are read by XIA Pixie-16F modules [10] with 250 MHz ADC (4 ns sampling) and full waveforms were recorded and analyzed by a custom software. Using zero-crossing algorithm [11], we are capable of extracting timing from waveforms with about 10 ps (FWHM) accuracy, which was tested with arbitrary signal generators.

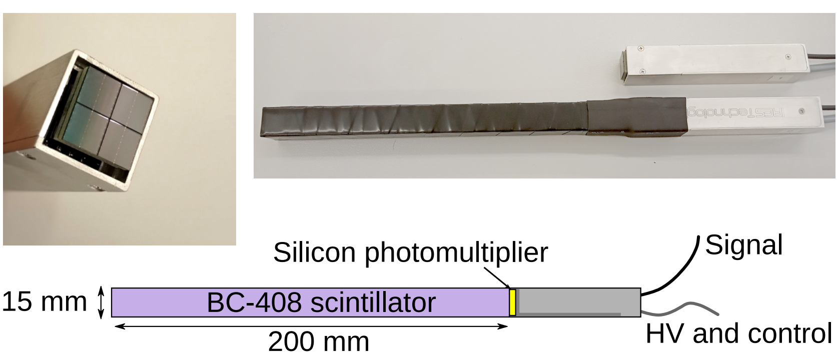

Fig. 1. Photography of a SensL silicon photomultiplier (SiPM) (left), a front-end electronic module with the SiPM and a complete assembled detector (right), and schematic diagram of the detector (bottom).

3. Performance

We have tested our detectors with a ^{22}Na radioactive source. Two annihilation 511-keV γ rays are emitted back-to-back, which allows for clean coincidence signals. Two detectors were placed 1 m from one another, and the source was moved along the line connecting the detectors, so the distance d between the source and the tested detector was set to 20, 30, 40, and 50 cm (Fig. 2), which are distance limits we foresee to use during the experiments.

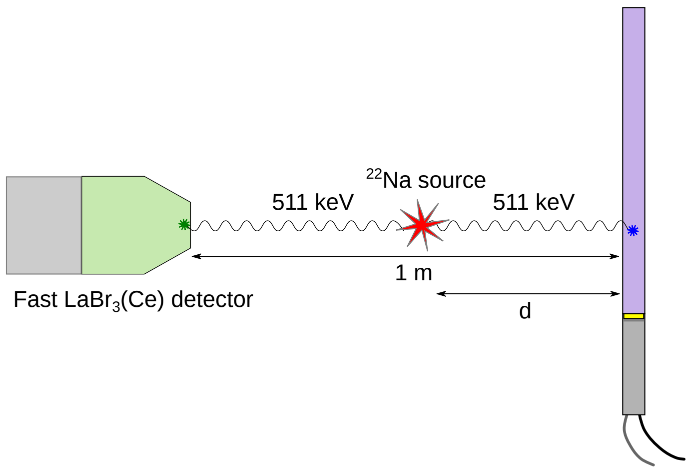

Fig. 2. Scheme of the detector timing resolution measurement (not to scale).

At first, we used two Hamamatsu H10570 photomultipliers coupled with fast $LaBr_3$(Ce) conical B380 crystals ($1 \times 1.5 \times 1.5$ inch^3). In this setup, we reached time resolution of $\sigma = 80(1)$ ps for each detector, which meets the photomultiplier specifications. Next, one $LaBr_3$(Ce) detector was used as a reference, and the second one was replaced with a tested neutron detector. In this setup, we obtained resolution of σ from 600(5) ps to 686(4) ps (Fig. 3 (a)). It is worth noticing that this value is the overall resolution including the photomultiplier resolution, the light propagation in plastic and the impact of single-end signal readout. Assuming that the resolution is a combination of a constant intrinsic factor and a geometrical factor, which depends on distance as d^{-2}, we estimate the intrinsic resolution to be equal to $\sigma = 580(3)$ ps (Fig. 3 (b)).

This resolution value meets our design goals. During the first planned experiment, we would like to use the detectors for measuring beta-delayed neutron spectra up to 2 MeV, by placing 16 modules in a distance of 25 cm from the source. In such a setup, a timing resolution of 1 ns is roughly equivalent to a 10% energy resolution for a 2-MeV neutron, and 2% for a

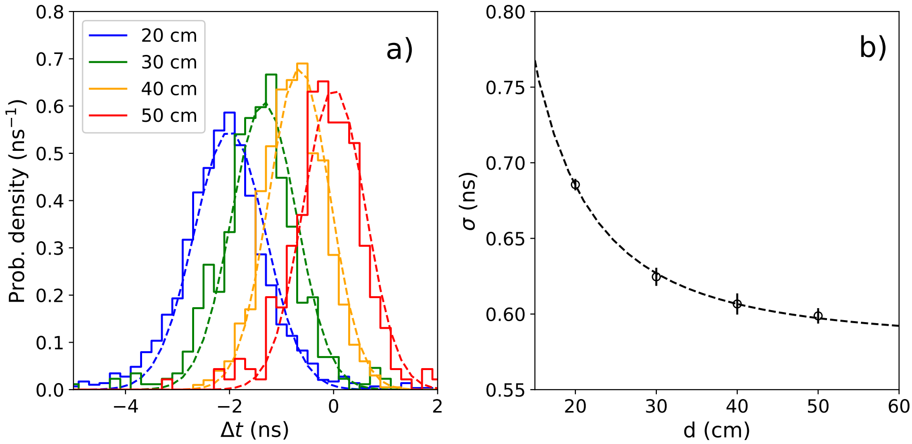

Fig. 3. (a) Detector timing resolution measured *versus* $LaBr_3$ for different distances between the ^{22}Na source and both the tested and the reference detector. (b) Dependence of the response width (σ) on the distance between the source and the detector. The dashed line shows a simple model estimate (see the text for more details).

100-keV neutron. A possible layout of the detection setup is presented in Fig. 4, where a β-particle counter and three germanium detectors were placed along with 16 neutron detectors. The start signal is provided by a β particle hitting the fast scintillator, the neutron emitted along the electron is then registered in one of the detectors. We have performed detailed Geant4 [12] simulations in order to optimize the size, shape and placement of neutron detectors in this setup.

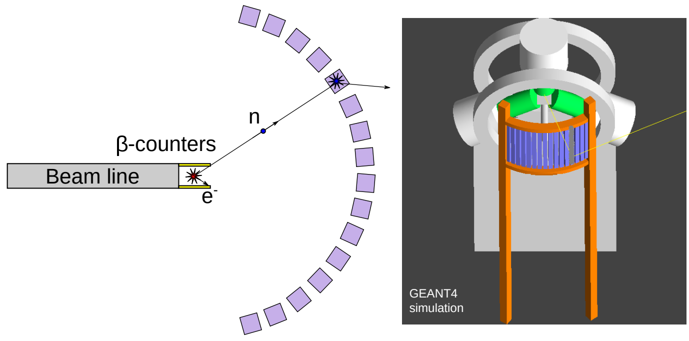

Fig. 4. Schematic view of planned beta-delayed neutron emission experiment and example of simulation in Geant4.

One of our goals is to extend the dynamic range of detected neutrons towards lower energies, compared to existing arrays such as VANDLE. In order to accomplish this, smaller bars are used with one-end readout, which should result in better light collection that is less attenuated than in designs with long bars read from both ends. For example, the minimal distance from the point of interaction to the photomultiplier is 30 cm in small VANDLE bars, whereas in our design the maximal distance is 20 cm. This should help reaching a better sensitivity for low-energy neutrons. We have tested the dynamic range of our detector with ^{137}Cs and ^{241}Am γ-ray sources. Since the scintillation plastic contains only light elements, the photo-peak will be seen only for low-energy γ rays, but the Compton edge also provides estimation of response for higher energies. An example of spectra obtained with these two sources is presented in Fig. 5.

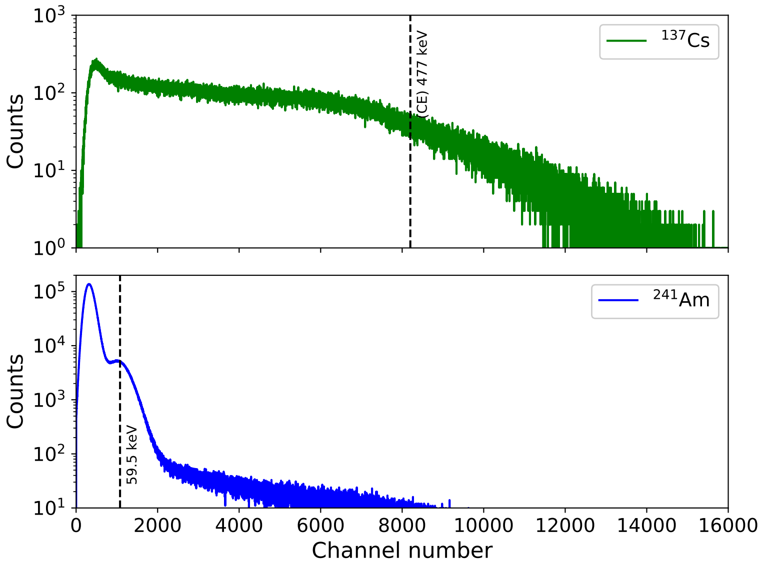

Fig. 5. Example of spectra obtained with the tested detector irradiated with ^{241}Am and ^{137}Cs γ sources. Position and energy of the Compton edge for the 662-keV line and the photopeak for 59.5 keV are marked.

The Compton edge is located at 477 keV for the ^{137}Cs 662-keV γ-ray line, while for ^{241}Am the photopeak of the most intense 59.5-keV γ-ray line is clearly visible. A rough calibration based on these points gives about 0.058 keV per channel, and indicates that the peak visible at lower energies in the ^{241}Am spectrum originates from the Compton scattering, as the location of the Compton edge for 59.5 keV at 11.2 keV is in agreement with the obtained spectrum. The energies of γ rays of 11.2 and 477 keV correspond to maximal signals, which a neutron of energy about 200 and 3000 keV can give [13]. It is clear that events of lower energies are also recorded and there is no visible noise limiting the low-energy detection limit. Therefore, we conclude that our detector is capable of registering neutrons with energies lower than 200 keV. This means that background radiation, such as Compton-scattered γ rays or X rays will be the limiting factor for the low-energy end of the neutron spectrum, rather than the dynamic range of the detector itself.

4. Summary

We have presented the current status of the Warsaw time-of-flight neutron detector. Preliminary tests with γ-ray sources were performed and the timing resolution as well as the dynamic range of the detector were estimated. These parameters are on par with the design goals. The detector array will be tested with neutron sources in a near future and should be ready for the first planned experiments with beta-delayed neutron emitters.

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