Neutron Detector Based on Polystyrene and Cadmium Layers

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Abstract. There is description of the development of detectors for neutrons, based on polystyrene and cadmium layers. Cadmium is used as neutron's converters via reaction (n,γ) and polystyrene is used as scintillation material to register the originated gamma quanta. The simulation and experimental investigations of proposed detectors design are presented. The main advantages of proposed detection are short measurement time - approximately 5 µsec. It is shown that the principle, suggested in the models, can be applied to the detection of neutrons from a pulsed neutron source, for example, secondary neutrons, generated by hadron showers in the space environment or by high-intensity pulsed sources based on accelerators. Detection efficiency for the $24*20$ cm^2 size detector model, measured during the experiment and simulated by the Monte Carlo technique is about 1% with the measurement time being approximately 5 µsec

1. Introduction

Neutrons are generally detected through nuclear reactions that result in particles as protons, alpha particles, photons and so on. These reactions served a base for the development and use of proportional counters, scintillators, solid-state, fiber-optical and other detectors [1].

^{3}He counters represent the most widespread neutron detectors in the majority of fundamental (e.g., astrophysical) and applied (e.g., radiation portal monitors) tasks. Unfortunately, the further application of the ^{3}He technology may become problematic due to the lack of this isotope in the coming years [2]. Here it is suggested to consider an applicability of Cd as a neutron converter in the neutron detector technology. The reaction to be used is the reaction of radiation capture on Cd: ^{113}Cd$+n=^{114}$Cd$+\gamma$. The reaction cross-section for the thermal neutrons is notable, it achieves $20*10^3$ barn.

The suggested paper presents a model neutron detector with a high time resolution, neutron-gamma discrimination and with the detection efficiency, dependent on the size. First and utmost, the suggested detector is aimed to the detection of pulsed neutron sources. The present-day high intensity pulsed neutron sources are mostly based on the physical reaction of interaction of a beam of charged particles (including high-energy ones) with the target material. The share of such neutron sources in the world practice, both in the use and under development, is growing [3]. For many basic and applied tasks, high neutron flux intensity represents a key factor [4]. To detect all neutrons is necessary to apply detector with the corresponded "dead time". The amount of "dead time loses" is proportional to the product of "dead time" and flux intensity [1]. The loses is negligible if the mentioned product is close to 0. Therefore, for the measurement of intensive flux it is necessary to use detector with minimum "dead time". The weaknesses of helium detectors are long signal duration and so "dead time"; full amplitude of pulse is not realized until after about 50 µsec [1]. The result is 'dead time losses' for high counting rates, as confirmed by the experience of the detector operation as part of PAMELA space research system [5,6]. Spun-out lithium glass as neutron detectors was proposed and patented US by

NucSafe [7]. Fast neutron scintillation detector, using spectrum-biasing fibers was proposed by the Institute of High Energy Physics, RF [8].

The principle of using Cd as a converter for neutron detection was proposed previously in several works.

Publication [9] suggests that a Cd converter be used in combination with a semiconductor high-purity germanium detector. Tasks were considered, where the problem of detection of neutron flux density 110 $cm^{-2}sec^{-1}$ was investigated. It was confirmed that operation in intense pulsed neutron fields is impossible. Detection efficiency made up 1.9% for [241]AmLi neutron source.

Researchers from the Birmingham Young University [10] developed a Cd-Plastic neutron detector, composed of alternating layers of metal Cd (0.5 mm) and plastic scintillator (EJ-200 1 cm thick, rise time is 0.9 ns and decay time is 2.1 ns). The signal is read using a 5-inch photo-electronic multiplier (5 inch PMT-4 R1250). It is shown that detection of neutrons from [252]Cf fission source using such a detector is technically possible. The principles of the model of detector [10] are similar to the principles of model presented in this paper. The main differences between two models are the following: 1) here low price polystyrene is used as scintillator, 2) here signals are collected inside the scintillator, 3) here layers of Cd is thinner than in model [10] but Cd layers are distributed inside scintillator, 4) the model here is studied for detection of intensive neutron fluxes.

2. Design of the detector proposed

The model, composed of alternating layers of a polystyrene-based scintillator and cadmium sheets was used for simulation and experiments. The size of the detector varied from 80x80 cm to 20x24 cm2. The detector thickness, defined by the number of layers, varied within 4 to 20 cm. Layers of polystyrene in the detector, each being 0.5 cm thick, alternate with cadmium layers, each cadmium layer being 200 µm thick. The thick of every Cd and polyethylene layers are the same for all models. The number of layers is changed. The polystyrene-based scintillator what is used here has response time 5 ns. A detector section schematic is shown in Figure 1.
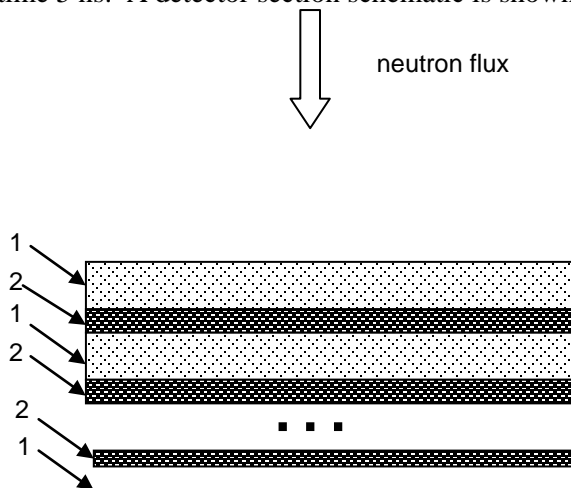

Figure 1. Neutron Detector Schematic
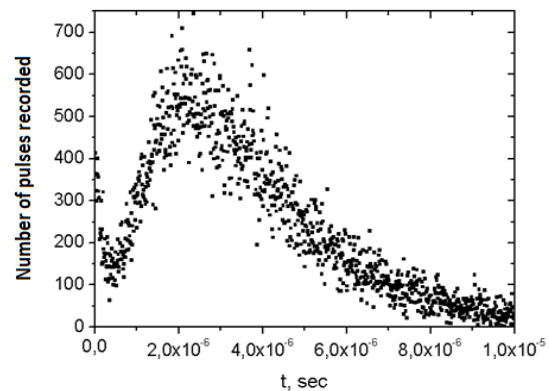1 – layers of polystyrene scintillator,
2 – cadmium layers.

Figure 2. Time profile of a signal from the detected electrons with 2.5 MeV detection threshold. The detector 15 cm aggregate thickness, front size-80x80 cm

Entering the plastic scintillator, neutrons produce a signals from recoil protons at double and triple collisions. The time of protons generation is about several dozen nsec from the moment, when the neutron penetrates into the detector. Those photons may be cut off by specified time delay. At a later stage, during the slow down recoil protons are also produced pulses, which may thus be cut off with detection threshold. Slowing-down neutrons interact with cadmium on the way (n,γ) reaction. Those

photons may be registered via energy release the secondary electrons. The produced photons interact with scinillatior and the electrons are originated via the Compton effect, pair production and photoelectric effect. The energy release of electrons may be detected as signal (pulse).　To discriminate the gamma background only those interactions, which resulted taken together energy release in the plastic scintillator (in terms of electrons), exceeding 2.5 MeV were taken into account. Photons are registered by the detector as a whole unit, irrespective of the position of cadmium layer, where the gamma quantum has occurred.

3. Evaluation of the neutron detection efficiency by simulation

GEANT4 was used to simulate the neutron detector readings [11]. The all process of radiation interactions was taken into account and simulated. The major types of interactions leading the counting events are the following. Neutrons from the pulse source enter the material of detectors and slow down. Slowing-down neutrons interact with cadmium on the way (n,γ) reaction. The produced photons interact with scintillator and the electrons are originated via the Compton effect, pair production and photoelectric effect. The history of electrons and energy release are tracked and analyzed.　If energy release is above then specified threshold this event is considered as event-recorded pulse. The simulation excludes production of secondary knock-on electrons.

The resulting time profile (number of pulses depending on time) with 10 ns time interval for electrons with 2.5 MeV energy release detection threshold produced is presented in figure 2. Diagram, presented in figure 2, is plotted for the number of neutrons falling onto the detector, which equals to 10^6. The time discrimination interval is 10 nsec, neutron energy equals to 1 MeV.

Let's consider the probability to have losses in event count due to signals overlapping and consider the probability to come two signals during one time discrimination interval. For the time range from $1.8*10^{-6}$ to $3*10^{-6}$ sec the highest event intensity is observed. The probability of a single event count into a single time channel makes up a value, which equals to the ratio of the number of pulses to the time interval, i.e. approximately $600/10^6=0.6*10^{-3}$. The probability of signal overlapping or occurring two (or more) events in the same time discrimination interval is product of two (or more) probabilities of single events and therefore below 10^{-6}. The reaction (n,γ) is possible in hydrogen and carbon, presenting in polystyrene. The photons are originated without presence of Cd in the detector. The simulation of detectors with and without Cd was carried out. It was shown, that because the cross section of (n, γ) on nuclei of materials without Cd is low, number of originated photons are negligible. Detection efficiency was calculated in accordance with the following

$$\varepsilon = \frac{\text{number of pulses recorded}}{\text{number of neutrons insident on detector}} 100\% \ \cdot$$

The efficiency was evaluated by simulation for the detectors with various aggregate thickness. The efficiency of model with 15 cm thickness is 42%, for the model 10 cm thickness is 23%. Figure 3 shows the dependence of efficiency on the detector aggregate thickness. It is proposed that detectors be developed with the thickness of no less than 15 cm.
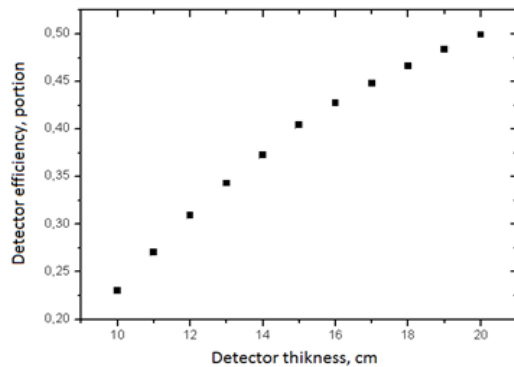
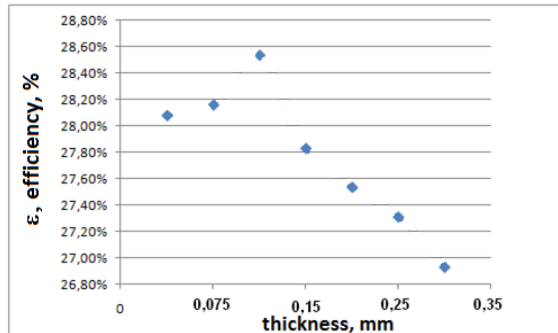**Figure 3.** Detection efficiency on aggregate detector thicknesses (80x80 cm^2 model).

Figure 4. Dependence of efficiency of neutron detection using an 80x80 cm^2 model on the thickness of the cadmium sheet (cadmium layers alternating with every polyethylene ones.

The efficiency of neutron detection depending on the cadmium sheet thickness was calculated using an 80 x 80 x 15 cm device. This dependence is presented in figure 4. The picture shows that the optimal thickness of the cadmium sheet makes up 0.1 mm.

4. Experimental test

4.1. Experimental design
To confirm data, obtained in the course of the simulation, a physical model of a detector was developed and an experiment was conducted. The neutron detector was installed on the same axial line as the Pulsed Neutron Generator (PNG) at a distance of R=1.33 m from the latter. The neutron and photon flux generated in PNG was neither collimated nor attenuated. The occurrence of a neutron pulse was monitored and controlled using the PNG electronics module. The latter was used to modify the neutron flux intensity and the neutron pulse repetition rate. To conduct the experiment an ING-101 type All-Russia Research Institute of Automatics (VNIIA) manufactured pulsed neutron generator was used [12]. ING-101 generates pulsed fluxes of 2.2 MeV neutrons with the yield of 5x10^8 neutrons/pulse from a deuterium target. The generation rate was up to 100 Hz, the neutron pulse duration – up to 5 µsec.

4.2. Experimental model of detector
A physical model of a neutron detector was developed (figure 5). This neutron detector consists of alternating polystyrene-based scintillator layers and sheets of cadmium. The size of the detector is 24x20x4 cm^3. The thickness of polystyrene layer is 5 mm, while that of cadmium layer – 200 µm. Cadmium layers alternating with every polyethylene ones. Each scintillator layer is covered with light-reflecting paper. The scintillator plates were made by die-casting method of BASF-143 mark polystyrene melt with scintillation additives (2% PTP, 0.02% POPOP). The plate dimensions are 120×100×5 mm^3, the mass of each plate is 58.4 g. Each plate has 12 grooves (6 on each side) their length, width and depth being 100 mm, 1.1 mm and 2.5 mm respectively. The die-casting technique, developed by and used at IHEP, ensures high-quality surface of the scintillation plates, therefore no additional machining is required [11]. The model detector speed did not exceed 50 ns, which was due to the use of a 5 ns speed scintillator and fast-response electronics employed for subsequent treatment of signal.

The fiber ends, escaping from the unit, are bunched and can be monitored by a single photoelectronic multiplier (PMT). For this purpose, 24R7899 Hamamatsu PMTs is used. For the sake of increased reliability and mechanical strength, the detector are separated into four 400x400 mm sectors, their scintillators being monitored by two PEMs at a time and the resulting signals being summated. The detector light output (ω = 28.7 photon (electron)/MeV) allows one to effectively

detect photons, charged particles and neutrons with several MeV energies, also in a spectrometric mode. The value ω = 28.7 photon (electron)/MeV is achieved when the detector is calibrated using monochromatic electrons.

A picture of the laboratory detector model is presented in figure 5.

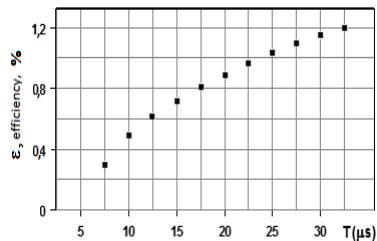**Figure 5.** Experimental model of a neutron detector

Figure 6. Dependence of experimental detection efficiency on the measurement time (24x20x4 cm³ size model).

Fast neutrons are moderated at the expense of multiple interactions with nuclei, composing the polystyrene-based organic scintillator. These moderated neutrons interact with cadmium in (n,γ) reaction and radiation capture gamma quanta possess a wide energy spectrum, varying from 0.01 MeV to 9 MeV (average energy making up about 3 MeV). Gamma rays interact with polystyrene (mostly via the Compton Effect). The length of the light attenuation in all polystyrene-based scintillators is very large, falling within $0 < l < 1.0$ cm interval. For that reason, to avoid a non-uniform response of scintillator-based detectors, the light should be picked up close to the location where it was generated. The pickup of light from the scintillator plates is performed using re-emitting fibers (WLS - WaveLength Shifting), in this case - WLS Y11(200) model.

4.3. Results of Experiments with a Model Detector

Discrimination of wanted capture gamma rays from gamma rays, accompanied the neutron pulse generation took place at the expense of a delay in the event detection process, which made up 5 µs. The neutron event counting is shown in figure 6. As seen from the diagram, the device does not detect the rays during the period of up to 5 µsec. This is because the time of E=2 MeV energy fast neutron moderation is about 2-5 µs, which ensures discrimination of nuclear particles occurring at the moment when a neutron pulse from the neutron emission is generated. To correlate the pulse generation period with the period of its detection, a signal from PNG was sent to an oscillator terminal. The additional experiment was conducted to study the possibility to increase the efficiency with adding moderating materials. In the experiment the detector was surrounded by 5 cm thick polyethylene moderator on the lateral sides. This resulted in only a 2-3% increase in the detection efficiency, therefore we think that the use of an additional polyethylene moderator does not lead to any substantial increment of the neutron detection efficiency, increasing at the same time the mass of the detector, consequently, the use of an additional polyethylene moderator seems to be impractical.

5. Conclusion

The reaction (n, γ) in Cd is proposed to use as neutron converter for neutron registration. Polystyrene scintillator is used to record signals from originated secondary electrons. The simulation shows that the proposed model of detector on base alternating layers of Cd and polystyrene is workable for registration of intensive flux. The experiments are confirmed possibility to use model for registration of pulse neutron flux to 10^8 neutron/sec, pulse duration – 0.8 µsec. The efficiency of detectors models was investigated by simulation and experimentally. Analyze of the efficiency value (figure 6), obtained in the course of the experiment, correlates well with the calculated efficiency value. Detection efficiency depends strongly on detector sizes. Detection efficiency for the model, for which

a mock-up was manufactured, made up only about 1% at the measurement time of about 5 µsec. Such negligible value of efficiency is explained by small dimensions of the mock-up.

Nevertheless, the proposed model possesses an advantage of detecting bursts of pulsed neutron emission, as necessary, with typical time periods of 10-12 sec (time periods, typical of cascades, initiated by hadrons). The measurement time, calculated according to the model, and that resulting from the experiment, using the model, confirm applicability of the proposed device for the detection of pulsed source neutrons with the pulse duration of µsec order of magnitude.

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