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Fast-neutron heterogeneous scintillation detector with high discrimination of gamma background

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Abstract

Neutron detectors have been widely used for monitoring security and illicit transportation of nuclear and radioactive materials. Distinguishing feature of such application is the necessity to measure neutron flux caused by the monitored items that is close to the natural background flux. This paper examines potential improvement of characteristics of a multi-layer neutron detector with optic fiber sensors based on lithium-silicate (^{6}Li) glass, by replacing the polyethylene layers with layers of hydrogen-containing scintillating plastic. Combination of two types of neutron-sensitive sensors enables two-phase discrimination of gamma background when measured in mixed n- and gamma-fields, by the amplitude and time criteria. The proposed heterogeneous scintillation detector has much higher gamma-background discrimination factor as compared to the existing examples of multilayered neutron detectors, while maintaining rather high neutron registration efficiency, typical for multilayered detectors.

Keywords: Heterogeneous scintillation detector; Multilayered neutron detector; Gamma-background discrimination; Optic fiber sensors based on lithium.

Neutron detectors are widely used for monitoring security and illicit transportation of nuclear and radioactive materials (NRM), which is one of the main tasks in assuring of NRM nonproliferation. Distinguishing feature of such application is the necessity to measure neutron flux caused by the monitored items that is close to the natural background flux or even less neutron (n) and gamma (γ) background fluxes whose values at the Earth's ground level are [1–3]:

$\varphi_{t,n} \sim (1.1–1.5)10^{-3}$ n/cm^2 s – for thermal neutrons with energies $E_n < 0.4$ eV;
$\varphi_{i,n} \sim (1.9–2.9)10^{-3}$ n/cm^2 s – for intermediate neutrons with energies $E_n \sim (0.4–10^5)$ eV;
$\varphi_{f,n} \sim (2.9–3.2)10^{-3}$ n/cm^2 s – for fast neutrons with energies $E_n \sim (0.1–10)$ MeV;
$\varphi_\gamma \sim 5–10\,\gamma$/cm^2 s – for gamma-particles with energies $E_\gamma \sim 1$ MeV.

These data define the following requirements to fast neutron detectors applied to the above mentioned tasks:

- *High sensitivity:* To ensure the counting rate of $\sim 0.5\,s^{-1}$ for the effect comparable with the density of fast neutron flux $\varphi_e \sim \varphi_{f,n}$, the sensitivity must be $C \sim 170\,cm^2/n$.
- *High gamma discrimination ratio:* To neglect the natural gamma background while detecting fast neutrons with flux $\varphi_e \sim \varphi_{f,n}$, this ratio must satisfy $K_\gamma > 3\cdot 10^4$; in case of additional sources of gamma background, its value must be even higher.
- *Ability to operate as a spectrometer:* To identify the monitored sources of fast neutrons and to decrease the impact of neutron background flux on to measurements in particular energy intervals.

To the most extent these requirements are satisfied by the wide-aperture, multi-layer neutron detector (MND) [4,5] developed at the Pacific Northwest National Laboratory (PNNL), USA. It is made of several layers of polyethylene with the thickness of $\sim$1 to 2 cm interlaced with detecting

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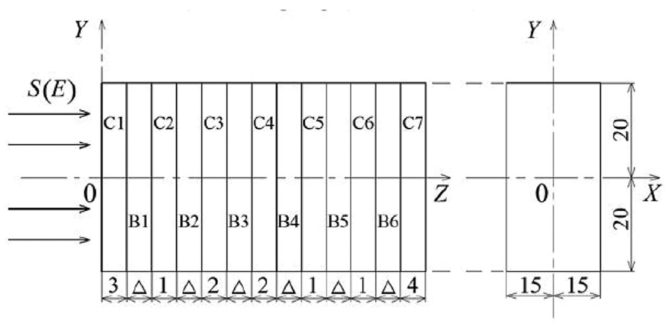

Fig. 1. Scheme of MND [6,7]: C_i, $i = 1, 2, \ldots, 7$ – polyethylene layers (CH_2, $\rho = 0.96\,g/cm^3$); B_i, $i = 1, 2, .., 6$ – ^6Li-activated scintillating optic fiber layers ($Si_{1.0}\ O_{2.58}\ {}^6Li_{0.363}\ {}^7Li_{0.027}$, $\rho = 2.58\,g/cm^3$, $\Delta = 0.014\,cm$); $S(E)$ – neutron (gamma) source with energy E. All sizes are given in cm.

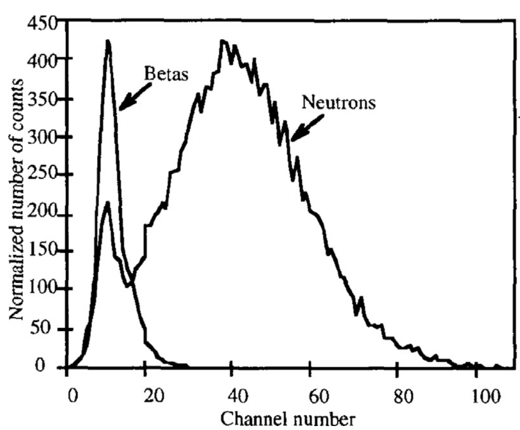

Fig. 2. Pulse-height spectra of scintillating glass fibers in neutron and beta-ray (^{90}Sr, $E_{\beta max} \sim 0.55\,MeV$) fields [8].

layers of $\Delta \sim 0.014\,cm$ effective thickness, made of cerium-activated (Ce^{3+}), lithium-silicate (with increased amount of ^6Li isotope) scintillating glass fiber (diameter $\sim 120\,\mu m$) with characteristic gamma emission time of ~40 to 60 ns in the blue spectra range with wavelength of ~470 nm. Fig. 1 shows scheme of the PNNL detector [6,7].

The operating principle of the detector is based on neutrons slowdown in C-layers up to thermal energies in elastic scattering by hydrogen nuclei and undergo in B-layers the exothermic $^6Li(n, \alpha)T$ reaction ($Q \sim 4.8\,MeV$), which high-energy products (T and α) induce the scintillations that are detected by photomultiplier tubes (PMT) attached to the optic fiber layers.

Investigations have shown that the total efficiency of all sensor layers to 0.5–10 MeV neutrons varies in the range 300–120 cm^2/n. The detector is sensitive to gamma radiation as well, but due to large difference in the ranges of fast electrons, born mainly via Compton scattering of gamma particles in the detector material, as compared to the ranges of heavy charged products of the $^6Li(n, \alpha)T$ reaction taking place in the sensor layers, the amplitudes of the correspondent signals differ considerably (Fig. 2), so that discrimination of the gamma background is possible with the gamma discrimination ratio $K_\gamma \sim (1–8)10^3$ [5].

As it is noted in [7,9,10] that when signals from separate layers are detected separately, the MND can be used to assess spectral characteristics of the neutron source.

Characteristics of the MND with optic fiber sensors based on lithium-silicate (^6Li) glass shown in Fig. 1 can be improved by replacing the polyethylene layers with layers of hydrogen-containing scintillating plastic. This MND modification, referred to as heterogeneous scintillation neutron detector (HSD-n), contains two types of detectors that are sensitive to neutrons: optic fiber glass containing ^6Li and organic plastic scintillator, which makes possible to realize a multi-step discrimination of the gamma background, leading to higher values of K_γ as compared to the original MND containing only optic fiber sensors.

Numerical analysis of HSD-n has been performed with the Monte-Carlo method for the model similar to that shown in Fig. 1, except layers C_i ($i = 1, 2, \ldots, 6$) were filled with polystyrene scintillator ($CH_{1,1}$, $\rho = 1.06\,g/cm^3$), $S(E)$ is a planar homogeneous monodirectional source of neutrons and photons with energy E. The sum of signals in all B_i ($i = 1, 2, \ldots, 6$) and C_i ($i = 1, 2, \ldots, 6$) layers is calculated. Results are normed per one source particle (neutron or photon). The following values have been calculated:

- The rate of $^6Li(n, \alpha)T$ reaction in the B layers for source neutrons with energy $E_n = 0.1–0.8\,MeV$, which describes the detecting efficiency of these neutrons in B layers, $\epsilon_n^B(E_n)$
- Time dependence of this value for a prompt 1–8 MeV neutron source, normalized to its maximal value,

$$W_n^B(t,\ E_n) = \epsilon_n^B(t,\ E_n)/\epsilon_n^B(E_n) \tag{1}$$

- Energy spectrum of the neutron fluence $\Phi(E)$ in C layers, and the correspondent spectrum of recoil protons that arise in elastic scattering by hydrogen nuclei, for source neutrons with energy $E_n = 0.7–8\,MeV$

$$R(E_p, E_n) = \sum_{i=1}^{6} V_i \int_0^{E_n} \Sigma_H(E') \frac{1}{E'} \left[\eta(E_P) - \eta(E_p - E')\right] \times \Phi_i(E')dE' = \sum_{i=1}^{6} V_i \int_{E_p}^{E_n} \Sigma_H(E') \frac{\Phi_i(E')}{E'} dE' \tag{2}$$

and the source neutron detecting efficiency taking into account the recoil-protons detecting threshold $E_{p,t} = 0.5\,MeV$ in C channels,

$$\epsilon_n^C(E_n) = \int_{E_{p,t}}^{E_n} R\left(E_p,\ E_n\right)\, dE_p, \tag{3}$$

where $\Sigma_H(E')$ is the elastic scattering macroscopic cross-section of neutrons with energy E'on hydrogen nuclei, V_i – volume of layer C_i, $\eta(E')$ – the Heaviside step function and $E_{p,n}$ – the proton detection threshold.

- For photon source with energy $E_\gamma = 0.5–10\,MeV$, probability distribution $W_\gamma^B(\varepsilon)$ of energy ε absorbed in B layers,