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# Specific features of 3-D detection arrays of plastic scintillators

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ABSTRACT

This paper describes the 3-D array of scintillation detectors made of a plastic scintillator. Its operation is based on obtaining simultaneously the signal arrival time, spatial coordinates, and amplitude of scintillation signal produced in detection elements by radiation. Such arrays are capable of identifying and localizing neutron and gamma sources, discriminating signals from these sources, and reducing the background caused by gamma rays, cosmic-ray muons, and neutrons.



## 1. Introduction

The 3-D array of scintillation detectors is a three dimensionally configured system consisting of scintillation elements coupled with photoreceivers and front-end electronics. The principle of the array operation is based on the collection of data on signal arrival time, spatial coordinates, and amplitudes of the scintillation signals acquired simultaneously. One of the most important features of 3-D arrays is the capability of radiation source imaging [1,2].

There were some attempts to use the segmented detection arrays for detection of special nuclear material (SNM), SNM search, and SNM characterization in the presence of normally occurring radioactive materials (NORM) and background radiation. Most of the designs, suggested for solving these tasks to date [3–6], are of limited practical applicability due to several reasons—the need to use cryostats [3], strong requirements for temporal resolution [4], sensitivity only to gamma radiation [3], impossibility of imaging [5,6], and comparatively high cost [3,4].

This paper describes a new system [7] and presents the simulation of its operation. The device is free of most of the drawbacks mentioned above. The main distinguishing features of its design are better spatial homogeneity, improved degree of segmentation and weak dependence of the device cost on the number of detection elements.

## 2. Design

The design concept of the 3-DDA is illustrated in Fig. 1, where (1) are the detection elements and (2) are the wavelength shifting (WLS) fibers. The detection elements can be located close to each other or at a distance. They should be coated by a reflecting material and optically separated from each other. Two sets of crossed wavelength shifting fibers are positioned on the opposite sides of the detection element; they read out the scintillation signal and transmit it to the photoreceiver. The scintillation is localized by the intersection point of two WLS fibers, from which the signals arrive at the photoreceiver approximately at the same time. The overall dimensions of the device are limited by the light attenuation length for WLS fibers, which is about 3 m [8,9].

Generally, a 3-D array can contain different scintillators located in a specific pattern for detecting various types of radiation.

## 3. Radiation source identification and localization

The performance of the described design was simulated using a Monte Carlo Code. The basic input data for the performed simulations are listed in Table 1.

It was assumed that the 3-DDA was irradiated with a parallel beam; the detection elements were made of polystyrene and closely packed. The detection elements made of an appropriate scintillator might be used for the registration of thermal neutrons. Thermal neutrons are produced in the device due to thermalization of fast neutrons.

The overall dimensions of the assembly, specified in Table 1, provide effective moderation of the fast neutrons with energies up to 14 MeV on one side, and effective registration of gammas on the other side. Significantly smaller overall dimension (about 10 cm) is sufficient to moderate fission neutrons.

A position sensitive MCP–PMT was chosen as the photoreceiver. The electron transit time spread of the photoreceiver and the cross-talk were neglected. The scintillation generated in a detection element was considered as the detected one when the number of photoelectrons exceeded one photoelectron for either of the two registration channels corresponding to the crossed WLS fibers. The energy conversion efficiencies, the scintillation decay time, and the overall dimension of the detection element were varied.

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### 3.1. By spatial distributions

Neutron/gamma radiation is attenuated in the assembly at a distance from the irradiated surface. The spatial distribution of the radiation flux and the induced scintillation signal depend on the source position and radiation spectrum. Fig. 2 shows the normalized scintillation signal produced by thermal and fast neutrons vs. the distance X from the irradiated surface of the assembly in the cases of the fission neutrons source and of the Pu–Be source. The source can be identified by the match for the measured distribution and a predetermined distribution from the database. The amplitude distribution of the scintillation signal can also be used for the purpose of identification.

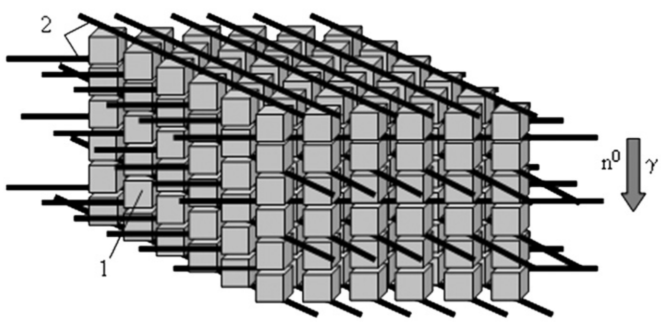


**Fig. 1.** 3-D detection array: 1—detection elements and, 2—wavelength shifting fibers.

**Table 1**
Input data for simulations.

| | |
|---|---|
| Overall dimension of the assembly ($cm^3$) | $24 \times 24 \times 24$ |
| Size of the detection element (cm) | $\approx 0$; 1 |
| Scintillation decay time (ns) | $\approx 0$; 0.7; 1.5 |
| Energy conversion efficiency for a recoil proton | |
| (eV/photon) | 500 |
| (keV/photoelectron) | 100; 200 |
| Energy conversion efficiency for a Compton electron | |
| (eV/photon) | 100 |
| (keV/photoelectron) | 20; 40 |

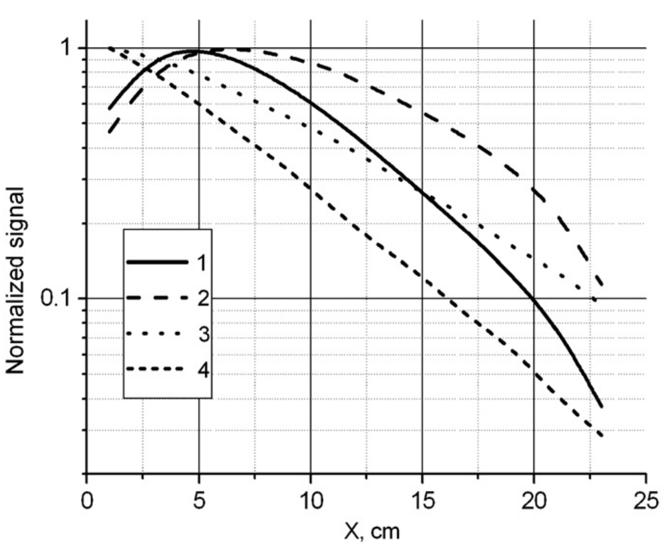


**Fig. 2.** Normalized scintillation signal produced by thermal (1, 2) and fast (3, 4) neutrons vs. the distance *X* from the irradiated surface of the assembly in the cases of the fission neutrons source (1, 4) and of the Pu–Be source (2, 3).

The direction towards the source can be determined by two methods: (1) as the vector between the geometric center of the 3-DDA and the center of the 3-D spatial distribution of the registered signal and (2) by the direction of the fastest growth of the signal. Both the methods are characterized by systematic and statistical errors.

The systematic error is related to symmetry of the device and is caused by the radiation leakage through the device surface. The systematic error varies with the relative source/device position. For the fast neutron flux it does not exceed approximately 50′. For the thermal neutron flux this error is about one order of magnitude higher due to the significantly stronger influence of the leakage effect.

The first method of direction to the source position determination is statistically better defined. In this case, the statistical error is related to the error in determining the centroid position of the 3-D distribution of the scintillation signal. For the fast neutron distribution, this error can be roughly estimated with a semi-empirical expression $\approx (240/N^{0.5})^{\circ}$, where $N$ is the total number of incident fast neutrons. For the thermal neutron flux distribution, the statistical error is larger due to the leakage and thermal neutrons absorption during their thermalization. The number of detected thermal neutrons is less approximately by a factor 2 than the number of detected fast neutrons.

### 3.2. By scattering kinematics

The other method is to use the scattering kinematics for several successive neutron/gamma scattering events. At least two elastic scatterings on hydrogen for a fast neutron and three Compton scatterings for a gamma quantum are needed to determine their energy and a conical surface, on which the source is positioned [10,11]. The projection of this surface onto a remote spherical surface results in a circle. A number of conical surfaces provide a set of intersecting circles. Fig. 3 shows the density distribution of the intersection point projections onto the plane normal to the source direction.

The imaging capabilities of the device are characterized by detection efficiency and angular and spectral resolution. These parameters were simulated for fission neutrons and gamma quanta of energies 0.414, 0.650, and 1.461 MeV.

As in kinematics, the imaging capabilities of the 3-DDA are in general affected by the errors in particle energy $E$ measurement, coordinates of the registered scintillations, and the time interval $\Delta t$ between them. These errors relate accordingly to the energy conversion efficiency, the size of the detection element, $\Delta S$, and the scintillation decay time, $\tau$. The timing properties of the scintillator are important not only for accurate measurement of $\Delta t$, but also for proper successive scatterings orderings. The effects of these factors are demonstrated in Table 2.

The detection efficiency for fission neutrons and gammas depends first of all on the conversion efficiency of the particle energy to photoelectrons. In the case of the fission neutrons, the detection efficiency depends strongly on $\Delta S$. This fact can be explained by a comparatively small distance between the two successive scattering events. The mean distance value for polystyrene is about 2 cm. Energy and angular resolutions in the case of neutron radiation depend on the error in energy and direction measured for the scattered neutron, which depend on $\Delta t(\tau)$ and $\Delta S/S$.

The effect of decay time is more significant for gamma than for fast neutron detection efficiency. This can be explained by the comparatively small average time (about 0.1 ns) between the two