Neutron-gamma separation study for ZnS(Ag)/6LiF scintillator and silicon photomultipliers

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Abstract. Registration of thermal neutrons while simultaneously suppressing or rejecting accompanying gamma-ray background is an important task for many fields. We report on two different experimental neutron-gamma separation studies, utilizing a ZnS(Ag)/6LiF scintillator and pulse height discrimination technique: one is a comparison of the responses of a ZnS(Ag)/6LiF scintillator and a ‘reference’ GAGG(Ce) scintillator when irradiated by gamma sources 137Cs and 241Am; and the second is testing a dual readout, where a photosensor coupled to the ZnS(Ag)/6LiF scintillator screen on each side was irradiated by neutrons (252Cf neutron source). For all measurements the silicon photomultipliers (SiPMs) PM3315-WB-A0 (3x3 mm² sensitive area, 15 µm cell pitch) manufactured by KETEK were used as a photosensor. High-speed digital oscilloscope LeCroyWR 620zi with a sample rate of 10 GS/s was used as a data acquisition system.

1. Introduction
One of the most important steps in the development of a neutron detector is the selection of a scintillator. The silver-activated zinc sulfide ZnS(Ag) is one of the oldest inorganic scintillators [1] and is widely used for detecting charged particles. In addition, it can be used to detect thermal or fast neutrons if enriched with a lithium-6 compound. The advantages of the ZnS(Ag)/6LiF scintillator include a high light output (95,000 photons/MeV) [2], non-hygroscopicity, and relative ease of use. However, it is available only as a polycrystalline powder so that its utilization is limited to thin screens because of the opacity of the polycrystalline layer to its own luminescence, thicknesses greater than about 25 mg/cm² become unusable. As a rule, this scintillator is made in the form of screens with a thickness of 200 to 500 µm. At a thickness of more than 100 µm, the light output is significantly reduced due to multiple scattering and attenuation of scintillation flashes inside the scintillator due to its fine-grained structure [3].

ZnS(Ag)/6LiF scintillator neutron’s registration is based on the reaction
\[ ^6\text{Li} + n \rightarrow ^3\text{H}(2.74 \text{ MeV}) + \alpha(2.06 \text{ MeV}) + 4.78 \text{ MeV} \]
where two energetic charged particles are produced.

One of the most important characteristics of scintillators used for neutron detection is the sensitivity of the scintillator to gamma radiation, which in most applications should be as low as possible [4] to improve selectivity of neutron detector to neutrons when operating in mixed radiation fields (nuclear plants, accelerators).
It is shown in [5], that for the ZnS(Ag)/6LiF scintillator, the sensitivity to gamma radiation from the 60Co source can reach up to $10^{-6}$ depending on the discriminator threshold without affecting the neutron detection efficiency.

To discriminate signals caused by the interaction of neutrons and signals from gamma quanta and charged particles, the method of discrimination based on the pulse amplitude from the detector can be used [6]. This method is based on marking pulses with an amplitude higher than the specified threshold as useful. In this case, the distribution of the amplitudes of the selected pulses will have the form of a plateau. The form of amplitude distribution is determined by different positions of neutron interaction points with the Li nuclei within the screen volume. The closer an alpha particle or triton is formed to the photosensor surface (in our case a silicon photomultiplier – SiPM), the more photons will be registered. Due to poor light collection, the peak from neutrons in the amplitude spectrum cannot be obtained.

The goals of these experimental ZnS(Ag)/6LiF studies are the following: to estimate its sensitivity to gammas in comparison with the reference GAGG(Ce) scintillator crystal, which is effective for gamma detection, in order to obtain data for the next Monte Carlo optimization of the neutron detector, and attempt to improve an amplitude distribution of neutron signals by using SiPMs double side readout of ZnS(Ag)/6LiF screen.

2. Experimental study of a mixed radiation monitor on the basis of ZnS(Ag)/6LiF readout by SiPMs

2.1. Comparison of the response of a ZnS(Ag)/6LiF neutron monitor prototype with reference GAGG(Ce) scintillator to gamma radiation

The purpose of this work was to compare the response to gamma radiation from sources $^{241}$Am and $^{137}$Cs for the developed SiPM-based neutron monitor and the ZnS(Ag)/6LiF scintillator.

For measurements, two scintillation detectors were used. Both detectors used SiPM model PM3315-WB-A0 manufactured by KETEK [7], with an area of 3x3 mm$^2$ and a cell pitch of 15 μm. The first (studied) detector used a ZnS(Ag)/6LiF scintillator with an area of 3x3 mm$^2$ and a thickness of 400 μm [8]. The second (reference) detector used a GAGG(Ce) scintillator with dimensions of 3x3x9 mm$^3$. $^{137}$Cs and $^{241}$Am were used as gamma-ray sources.

To suppress β-radiation and low-energy gamma radiation from the $^{137}$Cs source, an aluminum plate of 5 mm thick was placed between the source and the scintillators. The measurements were carried on at a constant room temperature, where the detector assemblies (the scintillator and SiPM) were placed in a light-tight box painted black on inside to minimize stray light. The Keithley 2400 sourcemeter was used to supply the SiPMs with a bias voltage of -31 V; the SiPM signal was amplified by an inverting amplifier utilizing DC input, that caused a shift of +0.77 V on SiPM anode and was taken into account for overvoltage calculations. The data set was acquired using a LeCroyWaveRunner 620Zi digital oscilloscope randomly triggered by an external generator.

The amplitude spectra obtained from the reference and test detectors are shown in figure 1 and 2, respectively. Data collected from $^{137}$Cs with and without an aluminum filter plate is shown in black and red, the data from $^{241}$Am is marked in green.

From the data obtained, one can see that for ZnS(Ag)/6LiF scintillator there is no difference in spectra for $^{137}$Cs and $^{241}$Am sources in case of usage the aluminum plate. It means that ZnS(Ag)/6LiF screen is not sensitive to gammas in the selected range of energies. For gammas with higher energies, which are usually expected in nuclear plants or accelerators experimental hall environment, efficiency of gamma interactions with thin screen sheet should be negligible.

However, signals from $^{137}$Cs without aluminum plate are visible above SiPM noise level. They are mostly produced by electrons coming from $^{137}$Cs decay to $^{137m}$Ba and the conversion electrons from $^{137m}$Ba itself. Difference in spectra with and without aluminum plate for reference GAGG scintillator is clearly visible in figure 1. It means that for the applications in the radiation environments with
significant charge particles contribution (accelerators) special studies using charged particle test beams have to be carried out to understand and account for their influence on neutron detection.

**Figure 1.** Amplitude spectra from a reference detector with a GAGG(Ce) scintillator.

**Figure 2.** Amplitude spectra from the detector under study with a ZnS(Ag)/6LiF scintillator.

### 2.2. Study of a double side readout assembly of a ZnS(Ag)/6LiF scintillator and two SiPMs for a neutron monitor prototype

The aim of this work was to test an assembly of a ZnS(Ag)/6LiF scintillation screen and two SiPMs for the possibility of obtaining a peak from neutrons in the amplitude distribution, which would improve the accuracy of discrimination of neutron radiation.

For this, an assembly was developed in which the signal from the scintillation screen is received simultaneously by two photodetectors on both sides. Two SiPM models PM3315 manufactured by KETEK, with an area of 3x3 mm² and a cell pitch of 15 μm, were glued to both sides of the scintillation screen using optical glue. Each SiPM is mounted on its own 15 mm board (figure 3); the boards are connected to the front-end module in such a way that both SiPMs are powered by the same positive voltage, while SiPM current signals are summarized. The summarized signal from the both SiPMs is sent to the amplifier input and then to the LeCroy WaveRunner 620Zi oscilloscope, which was set to record waveforms of the signal with a duration of 20 μs. A self-triggering mode with a threshold value of 20 mV was used as a trigger. Each SiPM board can be easily disconnected, thus providing one-side readout scheme. All measurements were carried out in a light-tight box at a temperature of 25.5 ± 0.2°C.

**Figure 3.** Photo of the board with a soldered SiPM.

Five datasets were taken, 1000 waveforms each. The first two sets were made when only one of the two SiPMs with 3 V overvoltage was turned on (connected) – one side readout measurements, while the second board was disconnected. For the remaining three data sets, both SiPMs were connected and operated at 2.5, 3, and 4 V overvoltage, respectively, so the screen was read from both sides.

Using a script written in Python, the amplitude spectra (figure 4 and 5) were obtained from the recorded waveforms. It can be seen from the spectra that the peak from neutrons is absent both for
single- and double-side screen readout. The peak in the right part of spectra in both cases is due to the amplifier saturation.

![Figure 4](image4.png) **Figure 4.** Amplitude spectra at single-side readout.

![Figure 5](image5.png) **Figure 5.** Amplitude spectra at double-sided readout of the ZnS(Ag)/LiF scintillation screen.

3. Conclusion
The results of our study show that ZnS(Ag)/LiF scintillation screen readout by a silicon photomultiplier, due to its low density and a screen thickness has a much lower gamma detection efficiency than a GAGG(Ce) crystal in the studied energy region. The gamma rejection power of such assembly is a subject to a selected threshold and a background composition (gammas and charged particles) and should be further studied.

As for the second test we observe no visible improvements in the shape of the neutron spectra which could give us some kind of a reference point (no peaks), useful for calibration and maintaining stability of the detector. However, the observed increase in the dual readout signal amplitudes helps to improve signal-to-noise ratio and neutron detection efficiency.

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