First tests of a gamma-blind fast neutron detector using a ZnS:Ag-epoxy mixture cast around wavelength-shifting fibers

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\textbf{A B S T R A C T}

There are many applications for a fast neutron detector with a very low gamma sensitivity such as homeland security, nuclear nonproliferation, and, the main focus of this work, spent nuclear fuel rod characterization and post irradiation examination (PIE). Currently, gamma-blind detectors are often \(^{3}\)He based, but the scarcity of \(^{3}\)He has created a strong demand for alternatives. In this work, a novel detector design is presented which can help to meet this demand. The detector consists of silver-activated zinc sulfide (ZnS:Ag) as a scintillator with embedded wavelength shifting fibers. This was implemented by casting a scintillator-epoxy mixture into molds with the fibers already in place. A small prototype was constructed using 56 fibers and an active volume of 3 × 10 × 30 mm\(^3\). It was shown that the count rate of the detector at a gamma flux of up to \(2.3 \cdot 10^3 \text{ s}^{-1}\) from a \(^{60}\)Co source can be reduced to \(< 1 \text{ s}^{-1}\) while still having a detection efficiency of 0.7\% for the fast neutrons emitted by a \(^{252}\)Cf source. This makes the presented design a promising candidate for fast neutron detection in high gamma environments. Most of the \(^{60}\)Co counts were found to be caused by a pileup of gamma interactions, which gives the possibility of decreasing the gamma sensitivity further by segmenting the detector. Additionally study of the time behavior of the scintillation light decay of ZnS:Ag, when excited by recoil protons, was performed. Overall, this work demonstrates the basic feasibility of this detector type, gives first insights into its physics, and lays a basis for future development and optimization of the approach for a wide range of applications.

1. Introduction

The Hot Laboratory (AHL) at the Paul Scherrer Institut (PSI) in Switzerland operates a series of hot-cells in which spent fuel rods from Swiss nuclear power plants are routinely characterized. The characterization comprises, among other things, the measurement of the axial distribution of the gamma rays emitted by full-length spent fuel rods with hyper-pure germanium detectors before cutting the rods in smaller segments for additional tests. The neutron emission of spent nuclear fuel rods has also been measured at AHL but only sporadically and on selected spent fuel segments \cite{1}. This information is valuable as it correlates with the isotopic concentration of spontaneous neutron emitters such as \(^{244}\)Cm, \(^{242}\)Cm, and \(^{252}\)Cf, which are the main neutron emitters in typical light water reactor (LWR) spent fuel. This can subsequently be used, for example, to validate depletion and decay calculations and burn-up estimates. In addition, the axial distribution of the neutrons emitted by the spent fuel rods play an important role in the design of transport and storage casks. Measuring such distributions routinely, not only for selected samples, is the goal of the collaborative research project Neutron Emission Measurement With Scintillators (NEWS) between PSI and an association of the Swiss nuclear power plant (swissnuclear).

The main challenge of such a neutron measurement is the large amount of parasitic gamma rays which are emitted by spent fuel and the limited space which is available to place a detector. In the context of the NEWS project, Papadionysiou et al. estimated that the gamma flux through the detector is on the order of \(10^7 \text{ s}^{-1}\) even when considering a fuel rod segment of only 40 cm length instead of a complete 4 m long rod, and with a relatively long cooling time of 13.5 years. The corresponding neutron flux is only on the order of \(10^4 \text{ s}^{-1}\) \cite{2,3}. These numbers are for a detector 23 cm away from the fuel segment and without additional shielding in front of it in the collimated channel of the hot-cell. They can vary significantly when considering for example other distances or additional shielding in the channel. The numbers above are therefore only used to give an idea of how the measurement environments compare to the hot cell conditions. There are options to reduce the amount of gamma rays arriving at the detector at the cost of an increased measurement time, and the other way is to some extent possible as well. For an efficient measurement setup it is therefore

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important to have a detector which can reliably measure neutrons in an environment with a lot of gamma rays present.

There are a number of commercially available detector types which were considered for this application. One was a $^4$He detector with moderator. However, due to the scarcity of $^3$He and the limited space available to insert moderator, this solution is not feasible. Detection efficiency of an unmoderated $^3$He-based detector, i.e. detecting the fast neutrons directly, would be far too low to be practical. Another detector option would be a $^4$He fast neutron detector as, for example, produced by Arktis [4]. However, these pressurized gas detectors are not gamma blind at the desired level of gamma radiation due to pileup sensitivity. They are also hard to produce in a small size due to the need of a high pressure container. This prohibits using multiple small detectors to reduce pileup. An organic scintillator was considered as well. However, their gamma blindness depends entirely on pulse shape discrimination. This would again limit the gamma rate at which the detector can reliably work because pile-up would interfere with the pulse shape discrimination. The overall conclusion was that the most promising option was to develop a detector specifically for this application.

The aim of the work presented here is to investigate a fast neutron detector design based on the work of Mosset et al. in which a thermal neutron detector was developed [5]. The main difference in addition to a change from thermal to fast neutron sensitivity is an emphasis on use in a very high gamma flux environment. The fast neutron detection operating principle is elastic scattering with hydrogen to produce a recoil proton which deposits energy in silver activated zinc-sulfide (ZnS:Ag) to generate scintillation light, and wavelength-shifting fibers to collect that light. The aim is to give a proof of concept and experimentally show that the proposed detector is feasible. Future work will focus on optimizing the detector parameters (e.g. by finding the perfect pitch of the grid of fibers or optimizing the readout electronics) and designing a final detector for the NEWS project.

The Theory section of this paper covers the design principle of the detector and the most important properties of the materials used. In the Experimental Setup section, the assembly process of the detector and the electronics are described as well as the conditions under which the prototype was tested. The Results and Discussion section presents the information gathered during the testing of the prototype. In the Conclusion and Outlook section, the results are summarized and future plans are laid out.

2. Theory

ZnS:Ag is an inorganic scintillator. It is a crystal with silver impurities. Large ZnS:Ag crystals are hard to produce and it usually comes in a fine powdery form. There are multiple resources giving different and partially contradicting information in regard to the decay time of ZnS:Ag for $\alpha$-particles. Asada et al. for example report an exponential component with a decay time of $100\,\mu$s and an additional non-exponential part [6], while the vendor of the ZnS:Ag used for this study claims a decay time of $200\,\mu$s [7]. Hildebrandt et al. measured a 6-component exponential decay for ZnS:Ag activated by $\alpha$-particles and tritium nuclei produced by $^6$Li fission [8]. We have not found any direct experimental data in published literature on ZnS:Ag scintillation decay times for proton activation.

ZnS:Ag has already been used in several fast neutron detectors, where it demonstrated good gamma blindness capabilities [9]. Most of the energy which is deposited in the ZnS:Ag by gamma rays is first transferred in a fast electron which then deposits energy along its path. These ZnS:Ag based fast neutron detectors predominantly use recoil protons from elastic neutron scattering to excite the ZnS:Ag. As protons and $\alpha$-particles are both positively charged and are on the order of 1000 times more massive than electrons, the previously mentioned difference in temporal distribution between alpha and gamma excitation decay is expected to exist for gamma rays and protons as well. If so, this could give means of improving differentiation between gamma events and proton events, thereby increasing the gamma blindness. Overall, these properties of ZnS:Ag make it a good candidate for detecting fast neutrons via recoil protons in a high gamma environment.

In order to use ZnS:Ag for fast neutron detection in the way described above, hydrogen needs to be present in the vicinity of the ZnS:Ag. This is achieved by mixing ZnS:Ag powder with a hydrogen-containing epoxy. This also has the advantage that the resulting mixture is initially liquid and can be cast into almost any shape. It then solidifies into an easy to handle neutron-sensitive material. It is also low cost and does not require any special equipment to manufacture. ZnS:Ag has a low transparency for its own scintillation light with a penetration length in the order of $0.1\,\text{mm}$ in the pure powder form. Simple detectors usually collect light from the surface of an active volume. Such a detector which efficiently collects light from ZnS:Ag can therefore not have a useful thickness of ZnS:Ag much more than about $0.1\,\text{mm}$ as light from the middle would then almost never escape the bulk of scintillator material. The mean free path of fast neutrons in solids is typically a few cm. A detector with a thickness on the order of $0.1\,\text{mm}$ would result in a very small fraction of neutrons interacting with the detector. A detector with reasonable efficiency therefore requires a much thicker active volume. As a result, a method of collecting light from within a thick active volume containing ZnS:Ag is required.

The design presented here uses wavelength shifting fibers (WLSFs) embedded in the ZnS:Ag-epoxy mixture to collect the scintillation light produced inside a bulk of the sensitive material. A WLSF is an optical fiber with additional fluorescent material inside the core. Around the core, there is a cladding of a lower refractive index. If a photon enters the fiber, it has a certain chance of activating the fluorescent material inside. If that happens, the fluorescence light is emitted in a random direction. With a certain probability this direction is such that the light experiences total internal reflection at the boundary between core and cladding and is trapped inside the fiber. It is then guided to one of the fibers ends. This process allows the WLSF to collect light everywhere along its length and therefore enables the construction of an effective detector with a useful volume of ZnS:Ag which is much thicker than $0.1\,\text{mm}$. Fig. 1 illustrates the complete light production and collection process.

As mentioned in Section 1, the design is based on a detector by Mosset et al. [5]. It uses the same grid of parallel WLSFs to collect the scintillation light including the same $0.7\,\text{mm}$ pitch between the fibers.
The main difference between the two designs is the scintillation light generation. Instead of elastic scattering of fast neutrons with hydrogen, the detector designed by Mosset et al. uses plastic sheets containing ZnS:Ag as a scintillator and $^6$Li as a thermal neutron converter through the process shown in Eq. (1).

$$^n\text{Li} + ^1\text{H} \rightarrow ^3\text{He} + ^1\text{H} + 4.8\text{ MeV}$$  \hspace{1cm} (1)

The light collected by the WLSFs is converted to an electrical signal by a silicon photomultiplier (SiPM) which is connected to a custom high frequency amplifier board developed at PSI and based on two Mar-6, as described by Stoykov et al. [10]. The amplified signal is then processed further by readout electronics. There are other sources than neutrons which can generate a signal at the SiPM such as dark counts and gamma rays. The main task of the readout electronics is therefore to decide whether a signal pattern coming from the SiPM should be counted as a neutron event or not. For this, the detector uses a so called moving sum algorithm which has already been shown to work for the thermal neutron detector of Mosset et al. [11]. It is a digital algorithm, which can be implemented, for example, on an FPGA to have a large quantity of readout channels at a relatively low cost, or in post processing on a CPU for testing purposes, e.g. checking simulations and exploring the parameter space.

The MSD algorithm can be separated into four steps. In the first step, the time axis is divided into intervals of a given length $\Delta t$. Here, the intervals are enumerated with the index $i$ so that the $i$th interval contains the time between $i \cdot \Delta t$ and $(i+1) \cdot \Delta t$. For each interval $i$, the number of photons $q_i$ arriving within this interval is counted. In the second step an integer $m$ is chosen as the summing length. For every $i$ (except the first $2m-1$), $d_i$ is calculated according to Eq. (2).

$$d_i = \sum_{j=-m+1}^{i} q_j - \sum_{j=-m+1}^{i-m} q_j$$  \hspace{1cm} (2)

The value $d_i$ is the moving sum after differentiation which gives the algorithm its name. In the last step, events are recognized by setting a trigger level $k$ and looking for positions $i$ where $d_i \geq k$.

To get a more consistent timing of the trigger, the MSD algorithm triggers on the first local maximum of the MSD after $d_i \geq k$. In addition, a blocking window $\Delta t_g$ is selected which prohibits the triggering within an interval of given length after an event has been recognized. This is to prevent triggering multiple times on the same event. Fig. 2 illustrates the MSD algorithm with the help of an example. Henceforth, the combination of $\Delta t$, $m$, $k$, and $\Delta t_g$ is called the MSD algorithm setting. By varying the MSD algorithm setting, the detector can be optimized with respect to different qualities such as neutron detection efficiency, gamma blindness, or timing accuracy. Mainly two settings are used in this work: the gamma sensitive setting which is $\Delta t = 200\ \text{ns}$, $m = 9$, $k = 20$ and $\Delta t_g = 10\ \mu\text{s}$, and the gamma blind setting which is $\Delta t = 400\ \text{ns}$, $m = 13$, $k = 45$ and $\Delta t_g = 10\ \mu\text{s}$.

3. Experimental setup

3.1. Prototype assembly

The first step in the assembly process was to fabricate spacers. These spacers are plates with a $14 \times 14$ grid of holes with a diameter of 0.35 mm. The grid has a pitch of 0.7 mm and will later be used to hold the fibers in place. Additionally, two large holes for screws were put in the plate. Fig. 3(a) shows a schematic representation of such a spacer. Custom designed printed circuit boards (PCBs) with a thickness of 1.55 mm were used as spacers. This was because such PCBs are cheap, while having sufficiently precise dimensions and the possibility for small features such as the 0.35 mm holes.

The second step was to feed WLSFs with a 0.25 mm diameter through the small spacer holes. For this, four spacers were stacked on top of each other in such a way that all the holes align. Screws were put through the large holes and fastened by a nut to fix the relative position of the spacers. After that, the fibers were fed into the holes by hand, each one going through all four spacers. The WLSFs used were Y-11(400)M from Kuraray [12]. Fig. 3(b) shows a picture of the result. This step can be done with a stack of more than four spacers. For example using a stack of 12 spacers would allow to construct three detectors of the proposed design at once, without a considerable increase of work for this step. This is significant when considering production of larger quantities of such a detector, as it is very time consuming to feed all the fibers through the holes by hand, but this effort is almost independent of the stack size. It is important to note that for the prototype which was used in the measurements later, WLSFs were only fed in the lowest four rows of holes in the spacers, giving a total of 56 WLSFs instead of 196. This was done because 56 was determined to be close the maximum number of fibers which can easily be coupled to a single readout channel later.

The third step was the preparation of casting molds. A rectangular U-channel piece with grooves for the spacers to slide into was made as a 3D printed nylon part. The screws were removed from the stack of spacers and the spacers were pulled apart so that there was a grid of fibers of about 1 cm length between each of them. Next, all of the spacers were slid into the groves of the U-channel simultaneously. They then formed three casting mold regions, separated by spacers. Fig. 4(a) shows the result of this step. Each of the three regions has a volume of $1 \times 1 \times 1\ \text{cm}^3$. The side with the opening of the casting mold is henceforth called the top side of the detector.

The fourth step was the preparation of the casting mixture. It consists of ZnS:Ag powder (EJ-600, [7]) and optical epoxy (EPO-TEC 301, [13]). The assembly of the first prototypes showed that the physical properties of the casting mixture are a critical part of the assembly process. Indeed, the assembly of several prototypes failed at the casting step until a suitable procedure was developed. The best result was achieved with a mass ratio of 1: 1.5 of epoxy to ZnS:Ag and by heating the mixture in a 40 °C water bath for 10 min. The mixture was then cast into the three molds and cured for 24 h at room temperature. Fig. 4(b) shows a photo of a detector after curing.

In a final step, the ends of the WLSFs were prepared for electronic readout. At one end, the fibers were bundled together and fixed in a block of acrylic. The WLSFs were then coupled to a single light spreader, connected to a SiPM. Fig. 5(b) shows a schematic of this connection. The light spreader distributes the light of every fiber over the whole surface of the SiPM. This reduces the chance of photons being lost due to the dead time of the individual cells of the SiPM and is especially important when a single fiber puts out significantly more light than the others (which is exactly what should happen if a neutron event occurs). In that case the photons leaving the light spreader will be distributed over a circle with the diameter of the light spreader (5 mm) instead of being concentrated in the area of a single WLSF (diameter of 0.25 mm). The light spreader can also fulfill an additional function: If space or a hazardous environment (such as intense radiation) are a concern in a given measurement setup where a detector should be used, the light spreader can also be extended to allow the SiPM and any attached electronics to be far away from the sensitive volume of the detector. The SiPM is an AdvanSiD ASD-NUV4S-P with a sensitive area of $4 \times 4\ \text{mm}^2$. It was operated with a bias voltage of 29 V at ambient temperature. At the other end of the WLSFs a mirror was fixed in such a way that the light coming out of that end is reflected back into the fiber. This improves the light collection efficiency at the SiPM. Fig. 5(a) shows a picture of the sensitive volume of a finished prototype.

The readout electronics consist of an amplifier connected to the SiPM, and a 5244A Picoscope [14] programmable oscilloscope to record the amplifier output. A schematic of the electronics is shown in Fig. 6(a). The amplifier includes a pulse shaping functionality, reducing the width of the pulses from the SiPM to about 5 ns. The Picoscope records the output of the amplifier continuously (in sections of 0.3 s length) and sends it to a computer. There, a script finds the rising edges of the individual single- and multi-photon pulses of the SiPM and saves
Fig. 2. (a): A schematic of how the MSD algorithm works, using an \( m \) of 3. Arriving photons are marked by black lines in the top of the picture. Within each interval of the length \( \Delta t \), the number of photons is counted and written down as a red number below the interval. The MSD is calculated by adding the last \( m \) values and subtracting the \( m \) values before. This is illustrated for 4 numbers of the MSD by marking the red numbers to add with a green bar and the numbers to subtract with a yellow one. (b): The photon counts within each interval and the corresponding MSD for a real neutron event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. (a): A schematic of a spacer. Only a \( 5 \times 5 \) grid instead of a \( 14 \times 14 \) grid of small holes is shown in order to keep the depiction clear. The real spacers are about 1.5 cm wide and 3 cm tall. (b): A picture of a stack of spacers clamped together by screws and with fibers fed through the small holes in the spacers. The fibers in this picture are not WLSFs, but normal optical fibers used only for testing of the assembly process.

Fig. 4. (a): The four spacers are spread out and held in place by the white U-channel. The spacers form three casting mold regions with the U-channel. Each mold has a grid of clear optical fibers going through it. (b): The casting molds are filled with the white ZnS:Ag-epoxy mixture. The fibers shown in both pictures are not WLSFs, but normal optical fibers used for testing the assembly process.
3.2. Event rate for gamma rays and neutrons

The measurements described in this section were conducted to test the neutron detection efficiency and gamma blindness of the detector. The detector was exposed to radiation from a $^{60}$Co gamma source and a $^{252}$Cf neutron source first separately and then simultaneously. The $^{60}$Co source had an estimated output of $3.1 \times 10^8 \text{ s}^{-1}$ gamma rays and the $^{252}$Cf source had an estimated output of $1.6 \times 10^5 \text{ s}^{-1}$ neutrons. The detector was placed with the top side facing the source, resulting in a exposed area of $3 \text{ cm}^2$ with a thickness of $3 \text{ mm}$. The WLSFs were orthogonal to the incoming radiation flux. The MSD parameter settings were varied with the interval length $\Delta t$ between 0.2 and $2 \mu\text{s}$, the summing length $m$ between 4 and 16, the trigger level $k$ between 8 and 50, and the blocking time $\Delta t_B$ fixed at $10 \mu\text{s}$.

The first measurement was done without any source. For the second measurement, the $^{60}$Co was placed at various distances between 5 and $15 \text{ cm}$ from the detector. The third measurement was done with the $^{252}$Cf source at various distances between 5 and $15 \text{ cm}$ from the detector. For the fourth measurement, the $^{252}$Cf source was placed at a constant distance of about $2.5 \text{ cm}$ from the detector. It was also not put directly in front of the detector but slightly off center. This was done to get a clear path for the $^{60}$Co source, which was placed directly in front of the detector and at various distances from 2.5 and $15 \text{ cm}$ away. The rates of events recognized with each source configuration and MSD algorithm setting were saved and compared. The results of these measurements are presented and discussed in Section 4.1.

3.3. Time-dependence of neutron event light output

In addition to count rate measurements previously described, the temporal shape of the decay of ZnS:Ag scintillation light generated by recoil protons was measured. For this the detector was exposed to radiation from a $^{252}$Cf source at a distance of $50 \text{ mm}$. The orientation of the detector with respect to the source was the same as described in
Section 3.2. The MSD algorithm settings were varied within the same parameter space as described in Section 3.2 as well.

For every recognized event, the timestamps of photons arriving at the SiPM near the time the trigger occurred was saved. The information of all events was then combined to an average scintillation light decay shape by calculating the average photon rate as a function of the time relative to the trigger. The theoretical average decay shape should consist of a steep rising edge at a time corresponding to the neutron interacting with the detector, followed by a decay tail of some unknown shape. However, in reality, the trigger will not always occur in a fixed relation to the time the neutron hits the detector. This jitter in the delay between the time the neutron interacts with the detector and the trigger is registered causes a spreading of the rising edge. This rising edge spread can be used to estimate the magnitude of this trigger delay jitter, i.e. the timing precision that the detector is capable of for a given set of MSD parameters. The MSD parameter setting which resulted in the lowest jitter was chosen to then analyze the decay tail shape. The results of this measurement are presented and discussed in Section 4.2.

4. Results and discussion

4.1. Event rate for gamma rays and neutrons

4.1.1. Results

This section shows the result of the measurements described in Section 3.2. Only the results for the gamma blind and the gamma sensitive MSD settings (described in Section 2) are shown. Fig. 7(a) shows the data gathered by the measurement with only the $^{252}$Cf source present. The data points gathered by the different MSD settings are each fit to a straight line. The resulting slopes are $(7.1 \pm 0.2) \cdot 10^{-3}$ and $(12.6 \pm 0.3) \cdot 10^{-3}$ events per neutron entering the detector for the gamma blind and gamma sensitive settings, respectively. The errors indicate one standard deviation. Both fits have coefficient of determination ($R^2$) values of 0.99.

Fig. 7(b) shows the data gathered by the measurement with only the $^{60}$Co source present. For the gamma blind settings, an event rate lower than 0.1 s$^{-1}$ is observed, independent of the gamma flux. For a relatively low level of radiation, the gamma sensitive setting produces a low count rate as well. However, the rate increases for higher fluxes in a non-linear fashion. The rate of events per gamma ray incident to the detector gets higher if the incoming gamma flux increases.

Fig. 8 shows the result of the measurement with both sources present. The event rate for the gamma blind setting is roughly independent of the gamma flux at $23 \pm 1$ s$^{-1}$. The error corresponds to one standard deviation. The count rate for the gamma sensitive setting has a similar shape as the one with the same setting but no $^{252}$Cf source present, shown in Fig. 7(b). It also shows an over-proportional increase of the count rate. The main difference is that the rate does not go to zero if there is no gamma flux but is offset by about 43 s$^{-1}$.

4.1.2. Discussion

The results for the gamma blind settings for the two sources separately demonstrate a gamma rejection better than $2 \cdot 10^{-3}$ at a gamma flux of $5.5 \cdot 10^6$ s$^{-1}$ while counting 0.7% of the neutrons entering the detector. The neutron to gamma detection efficiency ratio of the detector is about $4 \cdot 10^5$ for those conditions. The gamma source only measurement was not performed with the higher flux values expected for the PSI Hot Lab scenario ($10^7$ s$^{-1}$). Higher gamma rates were, however, measured in the simultaneous $^{60}$Co and $^{252}$Cf source measurement, reaching directly what is expected in the PSI Hot-Lab.
The strength of the pile-up effect depends on the absolute gamma flux entering the detector, not the flux density. A smaller detector would suffer less from pile-up in the same gamma field. This can be exploited to reduce the gamma sensitivity without impacting the neutron detection efficiency. A single big detector will have the same neutron detection efficiency as multiple small detectors with a combined volume equal to the big one. However, multiple small detectors count fewer gamma rays as the multi-gamma events now have to originate from gamma rays in a single small detector. The proposed detector design can use this mechanism easily. The detector can be seen as an array of small detectors, whose active volumes each consists of a single WLSF embedded in the ZnS:Ag-mixture. These small detectors are isolated by the ZnS:Ag between them, which is very intransparent.

The design presented in Section 3.1 couples all WLSFs to a single SiPM, essentially creating a single, big detector but this can be easily changed. The fibers of the detector can be separated into different bundles, each of them going to a separate SiPM. With this simple modification, the detector would behave like multiple small detectors. The 9/10 counts from gamma rays in the Hot-lab scenario previously mentioned can therefore dramatically reduced by segmentation, likely to a point where the contribution to the overall count rate from gamma rays is negligible.

4.2. Time-dependence of neutron event light output

4.2.1. Results

This section presents the results gathered during the measurement described in Section 3.3. The MSD setting chosen to minimize the jitter was \( \Delta t = 200 \text{ ns} \), \( m = 4 \), \( k = 13 \) and \( \Delta t_B = 10 \text{ µs} \). In Fig. 9(a) the measured average scintillation light decay shape between 10 \( \mu s \) before the trigger and 40 \( \mu s \) after the trigger is shown as blue dots. The measured light decay shape was fit to a theoretical event shape. This theoretical shape consists of a constant background level of \( 1.7\pm 0.1 \text{ µs}^{-1} \) before the event, an infinitely steep edge at \(-0.8\pm 0.2 \text{ µs} \) and a slow decay back to ground level afterwards. The decay was modeled as a double exponential plus a constant term, as shown in Eq. (3).

\[
\begin{align*}
\lambda_a \cdot e^{-\lambda_a \cdot t} + \lambda_b \cdot e^{-\lambda_b \cdot t} + b
\end{align*}
\]

where the contribution to the overall count rate from gamma rays is negligible. These multi-gamma events become more likely if more gamma rays hit the detector. It is expected that the gamma blind setting would show a similar upwards curve if the gamma flux were high enough.

The light output then decreases back to ground level over time. This flux gets higher and this causes the over-proportional increase. Pile-up is a phenomenon where the detector is not measuring individual particles but rather counts events caused by multiple gamma rays. These multi-gamma events become more likely if more gamma rays hit the detector. It is expected that the gamma blind setting would show a similar upwards curve if the gamma flux were high enough.

The expected behavior of the detector is that at one point an incoming neutron indirectly excites the ZnS:Ag which then slowly decays back to the ground state and thereby emits photons. The ZnS:Ag emits the highest number of photons per unit time directly after it is excited. The light output then decreases back to ground level over time. This behavior is what is modeled by the fitted function in Section 4.2.1 by the sharp edge and the double exponential decay afterwards. The fit models the data points very well. This is especially interesting when considering the rising edge. It shows that the trigger mechanism is capable of determining the time of the neutron hitting the detector with an
accuracy of about 200 ns, which is the used time resolution. Otherwise, the rising edge would not be sharp but smeared out by the uncertainty in the timing. This is very important for some applications such as coincidence and noise measurements. It is important to remember that the MSD setting used to obtain the data points for this measurement (given in Section 4.2.1) is different from the gamma blind setting. In general, the particular MSD setting used for an application has to be a trade-off between timing accuracy, neutron detection efficiency, and gamma blindness requirements.

The results presented in Section 4.2.1 are of interest for more fundamental research as well. The decay of the scintillation light of ZnS:Ag when activated by recoil protons is a topic which is not well covered in literature. The presented results are a first step to fill this gap. The scintillation light decay properties of ZnS:Ag are very important for producing accurate simulations of detectors which use the MSD algorithm or similar methods to analyze the ZnS:Ag light output. The measured decay of the scintillation light after the maximum is modeled well by the double exponential fit. However it is important to notice that the time resolution of 200 ns limits the decay components which can be recognized. It is possible that there are additional components which decay faster than 200 ns. To look for such components, an improved triggering algorithm or an external trigger could be used. Additionally, the constant factor $b = 0.41 \mu s^{-1}$ in the fit model Eq. (3) indicates that there are decay components with a time constant which is too long to be determined reliably by the measurement. To determine these components accurately, a data set containing a larger portion of the decay shape could be measured.

As mentioned in Section 2, we have not been able to find a significant effect from the scintillation light decay shape for ZnS:Ag activated by protons in the literature. However there is data on ZnS:Ag activated by comparable particles such as the measurements by Hildebrandt et al. [8]. They used a reaction of $^6$Li with thermal neutrons to create $^3$H nuclei and $\alpha$-particles as described in Eq. (1). These then excite the ZnS:Ag instead of the recoil protons. As protons, $^3$H nuclei, and $\alpha$-particles are all positively charged hadronic particles with a mass in the same order of magnitude, it is reasonable to think that they could have a comparable scintillation light decay shape. As can be seen in Fig. 9(a), the scintillation light measured by them is significantly higher than the fitted curve for a very short time after the rising edge. This can be explained by the limited time resolution of the data points which inhibits a measurement of the very fast components of the decay. More accurate measurements are therefore required to identify if this is a difference between the activation of ZnS:Ag with protons and $^3$H-neutron reaction products. After this short time period, the decay from Hildebrandt et al. shows a small non-constant deviation from the data points up to about 15 $\mu$s as can be seen from the relative residuals shown in Fig. 9(b). However this difference is small and the two exponential fit is also imprecise in this area which makes it difficult to tell whether there this is a difference in the fundamental decay shape or simply an unresolved component due to imprecise data. Only a small, constant offset to the measured data is visible after that, which is the same for the decay from Hildebrandt et al. and the two exponential fit. This shows that at least for the later part of the decay, ZnS:Ag activated by protons behaves similarly to ZnS:Ag activated by $^3$H nuclei and $\alpha$-particles. When looking at the values presented in Table 1 and comparing them to the fitted values, it seems that the first component of the 6-exponential decay was too fast to be captured by the measurement and that the last two components were too slow to be resolved and essentially correspond to the additional constant in the fit. The second to fourth values seem to correspond to the double exponential decay shape which was fitted but, probably due to the time resolution of only 200 ns, the second component of the 6-exponential fit seems to be not fully resolved, resulting in the second to fourth components of the 6-exponential decay to merge into only two components for the fitted shape.

5. Conclusion and outlook

5.1. Conclusion

A design for a gamma blind fast neutron detector has been proposed. It consists of a ZnS:Ag-epoxy mixture which creates scintillation light from neutrons via elastic proton scattering. The scintillation light is collected by WLSFs, captured by and SiPM, and analyzed by digital readout electronics. It has been shown that the fabrication of a detector of this design is feasible. Several prototypes have been built to demonstrate that. The assembly process does not require specialized tools and can be carried out in any laboratory. The choice of using 3D printed parts, custom PCBs and especially a ZnS:Ag-epoxy mixture means that the design can easily be varied in shape, size, and even internal structure such as the distance between the WLSFs. This gives great versatility when considering applications with space restrictions and gives a lot of opportunities for further optimization. Additionally, if space or a hazardous environment (such as intense radiation) are a concern, longer WLSFs or light spreaders allow to place the readout electronics far away from the sensitive volume with minimal changes to the design.

One prototype has been tested by using a $^{252}$Cf and a $^{60}$Co source. It has been shown that, when using the gamma blind MSD setting and with a gamma flux of up to $2.3 \times 10^7$ s$^{-1}$, the gamma sensitivity of the detector is below $5 \times 10^{-4}$ while the neutron detection efficiency is 0.7%. The neutron to gamma ray detection efficiency ratio was determined to be about 10$^3$. The mechanism of reading out fibers by different SiPMs has been proposed as a method of increasing the gamma blindness further, in order to reach a specific degree of gamma blindness necessary, for example, for measurements at the PSI Hot-Lab.

It has been shown that the detector is capable of determining the arrival time of neutrons with an accuracy of 200 ns which makes the detector suitable for example for coincidence or noise measurements. This ability has been used to determine the decay of the scintillation light of ZnS:Ag when activated by recoil protons. The results where compared to measurements of the light decay shape of ZnS:Ag activated by $^3$H nuclei and $\alpha$-particles. With the current accuracy, no significant difference could be identified between the decay shape when ZnS:Ag is activated by $^3$H nuclei and $\alpha$-particles and the decay shape when ZnS:Ag is activated by recoil protons. However, additional measurements are needed to be able to compare the very short and the very long decay components.

5.2. Outlook

So far a proof of concept has been presented, but there is a lot of room for further optimization of the detector, generally as well as for specific applications. This can include investigating the fiber pitch, ZnS:Ag-epoxy mixture, powder grain size, electronic readout parameters, and other variables of interest. It could also be interesting to consider the use of different ZnS:Ag-epoxy mixtures at different places in the detector, similar to what Ososvitzky et al. did for cold neutron detectors [15]. Simulations and experiments to explore this are planned. The light output temporal shape of ZnS:Ag when excited by...
protons can also be investigated further, especially the very fast and very slow components. Another interesting direction is the possibility of creating an imaging screen. By reading out the fibers separately, the position of the neutron interaction can be determined. Alternatively, by crossing the fibers perpendicularly and using coincidences, the N² readout positions could be identified by 2N readout channels, another interesting imaging option. The detector was proven to be capable of having a very high degree of gamma blindness. Development to improve this quality further is currently ongoing and actual measurements of spent fuel samples are planned. Some improvements for the easy use of the detector are planned as well, including a mechanically more convenient container for the active volume, a spatial separation of active volume and electronics, and real-time processing (e.g. with an FPGA).

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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