A 2D pixelated stilbene scintillator detector array for simultaneous radiography with fast neutrons and gammas

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ABSTRACT: For radiography applications using fast neutrons simultaneously with gammas we have developed a detector with 16 stilbene crystals in a 4×4 2D array with 5 mm pitch and a depth of 25 mm. The crystal array is read out by Silicon photomultipliers and custom signal processing electronics. The detector prototype was tested using a custom D-D fast neutron generator at the Paul Scherrer Institute. By applying a pulse shape discrimination algorithm the detector is able to detect and distinguish fast neutrons and gammas simultaneously. Various attenuating samples placed between the source and detector with different composition and thickness were tested and the measured macroscopic fast neutron cross sections were compared to the expected cross sections. Deviations were studied with the help of detailed Geant4 simulations. The detection efficiency for D-D fast neutrons was measured to be around 10%.

KEYWORDS: Neutron detectors (cold, thermal, fast neutrons), Neutron radiography, Inspection with gamma rays, Scintillators and scintillating fibres and light guides
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1 Introduction

Transmission radiography and tomography are powerful non-destructive testing techniques which allow visualization of the internal structure of an object. Photons and neutrons behave differently in this context depending on their energy and the materials present in the object being investigated. The application of X-ray imaging up to roughly 300 keV (or sometimes more) is well established due to X-rays being both easy to produce in large quantities using X-ray tubes and easy to detect in a position-sensitive way with good spatial resolution (e.g., with a flat panel detector). Disadvantages of using X-rays include their polychromatic nature when produced by typical X-ray tubes, which can result in imaging artifacts such as beam hardening, and the fact that higher energy ranges (MeV range) are typically not accessible by compact or portable devices (i.e., without the use of a
linear accelerator or something of comparably large scale and complexity). X-rays have a strong Z-dependence of attenuation, in particular at lower energies, meaning that getting good image contrast in low-Z material (e.g., water or oil) when shielded by high-Z material (e.g., a steel pipe or container) is challenging, due to the high-Z material dominating the attenuation in the image. In addition, the potential problem with larger objects in general is that if the object is too attenuating then beam starvation and poor imaging statistics can occur.

The use of gamma photons for imaging can provide the advantage of a typically mono-energetic nature (one or several emission lines) and the convenient availability of higher energies, e.g. 662 keV from $^{137}$Cs or 1.17 and 1.33 MeV from $^{60}$Co. These higher energies are more penetrating, which is useful in industrial cases where objects of interest can be large (e.g., tens of cm). The higher penetrating nature also tends to correspond to more difficulty in achieving a high detection efficiency, meaning thicker detector materials are preferred, and some traditional methods (such as the use of storage phosphor films) are excluded due to their low efficiency. This detection efficiency is important because typical gamma sources have much less output than X-ray sources, so the flux available should be used efficiently in order for imaging to be feasible.

Another useful imaging modality is that of fast neutrons (MeV range), which tends to provide even more penetration than gammas and, in particular, does not have a strong Z-dependence of attenuation. This means that, for example, steel and water (and most other materials) have macroscopic attenuation coefficients of the same order. Information from a fast neutron image can complement that from a gamma image. With fast neutrons, however, convenient, compact, high flux sources (comparable to X-ray tubes) do not exist. Comparatively low output neutron generators using the D-D or D-T reaction do, however, provide a modest neutron flux which can be used for imaging. These devices also typically produce X-rays in addition to neutrons, which in some detector types can be a source of unwanted signals. Larger scale facilities such as reactors or spallation sources can provide higher fast neutron flux beamlines. In the latter, a gamma flux is always also present. In other words, X-ray and/or gamma photons are always present to some degree in a fast neutron imaging context.

The highly penetrating nature of fast neutrons which can be an advantage when imaging large objects also creates difficulty in achieving good detection efficiency and spatial resolution for imaging. One common approach to fast neutron imaging detection is reading out a screen consisting of a mixture between ZnS(Ag) scintillator and polypropylene with a CCD camera. Another is to use an array of plastic scintillator detectors. These two options and most other comparable alternatives can be used to produce fast neutron images but always include a parasitic sensitivity to X-rays and gamma photons which cannot be separated from the desired fast neutron contribution.

This work aims to achieve a position-sensitive fast neutron detector which simultaneously allows for measurement of gamma or X-ray photons of sufficiently high energy by means of pulse shape discrimination in a 2D detector array, while achieving a high detection efficiency of both. This means that X-ray/gamma signals can either be rejected or used as image data complementing the fast neutron image data. In practice typically only gamma photons are present in the relevant energy range, so this paper mostly refers to the higher energy photon signals only as gamma signals, although, as is discussed in a later section it might be that in the experiments performed in the context of this paper some lower energy X-ray photons produce signals which look comparable to a gamma signal of a higher energy. The prototype presented is a 4x4 pixel array, and measurements
were performed to illustrate the basic performance and characteristics of the prototype system in combination with a D-D fast neutron generator.

2 Detector and set-up

2.1 The 4 × 4 pixel detector

The detector consists of 16 stilbene scintillator cuboids that are arranged in a 4 × 4 array allowing the detection of neutrons and gammas with spatial resolution. The scintillators are cuboids of size 5 × 5 × 25 mm³ and are coupled to a Hamamatsu MPPC® S13361-6050AE-04 SiPM array [1]. The cuboids are separated by a grid made from black PVC. Everything is surrounded by a black PVC housing to shield it from ambient light. All PVC surfaces facing the scintillators are covered by Vikuiti™ ESR (Enhanced Specular Reflecting) foil to enhance the light collection efficiency. For the same reason, an Elastosil® RT 604 silicone pad is used to couple the scintillators to the SiPM array. This optical coupling pad is separated by a white PLA grid reducing the amount of optical crosstalk between the pixels. In Figure 1, photographs of the detector components are shown.

2.1.1 Stilbene

The usage of the organic scintillator crystal stilbene (chemical formula C₁₄H₁₂) enables the discrimination of neutron- and gamma-induced signals. For gamma interactions, the scintillation light is created by electrons while for neutron interactions, the scintillation light mainly comes from proton recoil events. Stilbene shows longer decay times of scintillation light emission for neutron-induced signals than for gamma-induced signals [2]. Therefore, neutron-induced signals have a longer falling edge, allowing neutron-gamma discrimination by pulse shape discrimination methods. Stilbene shows a significant quenching effect. The same amount of deposited energy leads to much fewer scintillation light when caused by heavy charged particles (e.g. protons) instead of electrons. For electrons, a linear relation between the deposited energy and the scintillation light output can be assumed, while the relation is non-linear for heavy charged particles [3, 4]. Also, an anisotropy

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¹Polyvinyl chloride
²Polylactic acid
of Stilbene’s light response for proton recoils is reported, depending on the direction of the recoil relative to the crystal axes [5].

2.1.2 Electronics

The detector readout system is shown as a schematic sketch in Figure 2a. It consists of two main parts: The SiPM array plus the front end custom electronics board developed in-house, and the digitization system.

The front end electronics board includes the amplifier circuits for all 16 SiPM channels as well as the SiPM power supplies. For each channel, a positive and a negative unipolar output signal is provided to enable the use of different digitizer types. For the SiPM power supply, two Hamamatsu MPPC® C11204-02 slow control chips [6] are used. This chip allows for a temperature correction of the SiPM’s bias voltage in order to keep the SiPM gain constant. Figure 2b shows a photograph of the $4 \times 4$ detector mounted on the front end electronics board. The detector and the board are placed inside an aluminium box.

For signal digitization, two CAEN N6730B FADCs [7] are used. They have a sampling rate of up to 500 MS/s, a resolution of 14 bits and a dynamic range of 2 Vpp.

Figure 2: (a): Schematic sketch of the detector readout. (b): Photograph of the $4 \times 4$ detector with its front end electronics.

2.2 Pulse Shape Discrimination

The classification of signals as neutron- or gamma-induced is based on the Tail-to-Total pulse shape discrimination (PSD) method. All analyses described in the following are done individually for each detector pixel.

In a first instance, the recorded signals are baseline-corrected and pile-up events and microwave-induced portions of the signal (caused by the neutron generator ion source) are filtered. For each remaining event, a PSD variable is calculated that is defined as the ratio of the tail integral $Q_{\text{Tail}}$ and the total integral of the pulse $Q_L$:

$$PSD = \frac{Q_{\text{Tail}}}{Q_L} = \frac{Q_L - Q_S}{Q_L}$$

(2.1)
\( Q_{\text{Tail}} \) can also be expressed using \( Q_L \) and the short integral \( Q_S \) over the beginning of the pulse. The integrals are defined relative to the trigger position, \( t_{\text{Trg}} \), where 50\% of the pulse height is reached, and are given by

\[
Q_{L,S} = \int_{t_{\text{Trg}} + \Delta_{\text{off}}}^{t_{\text{Trg}} + \Delta_{\text{off}}} S(t) \, dt
\]

with the signal \( S(t) \). The integration limits were optimized with regard to the neutron-gamma separation to \( \Delta_{\text{off}} = -40 \text{ ns} \), \( \Delta_S = 24 \text{ ns} \) and \( \Delta_L = 270 \text{ ns} \).

### 2.2.1 Energy calibration

An energy calibration was performed to translate the pulse integral in mV \( \cdot \) ns into the energy deposited in keV electron equivalent (keVee). For the calibration, a \( ^{22}\text{Na} \) and a \( ^{207}\text{Bi} \) radioactive source were used. The calibration was done using the compton edge position, as no photopeak is visible in the recorded gamma spectra due to the low atomic number of the elements present. The position is determined following the procedure described in [8]. A linear relation between the pulse integral and deposited energy is assumed, based on a fit to the four measured calibration compton edge energies and their corresponding pulse integrals.

### 2.2.2 Neutron-gamma classification and particle detection rate

When creating a 2D histogram with the energy in keVee on the x-axis and the PSD variable on the y-axis, a plot with two distinct bands is created. An example plot is shown in Figure 3. The upper band can be assigned to neutron events ("neutron band"), the lower band to gamma events ("gamma band").

To quantify the amount of neutron and gamma events, 1D histograms of the PSD variable can be produced over the range of energies over a given bin width, corresponding to vertical slices from the 2D histogram. If neutron and gamma events are separated, within such a 1D histogram, two peaks form which can be described by a double-Gaussian fit. The peak region at lower PSD corresponds to gamma events and the other one to neutron events. For higher energies, almost no events occur in the neutron band region. Therefore, only the gamma band is fitted in this region. From the fit results, the neutron and gamma band limits are calculated as the 3\( \sigma \) boundaries of the Gaussians at each energy. These boundaries can then be portrayed as lines on the 2D histogram. In Figure 3, the 3\( \sigma \) boundaries of both bands are shown as green and red lines. Here, the neutron band limits are extrapolated horizontally into the energy region where almost no neutron events occur. A criterion for the separation is the Figure of Merit (FOM):

\[
FOM = \frac{\mu_n - \mu_g}{FWHM_n + FWHM_g} = \frac{\mu_n - \mu_g}{2 \sqrt{2 \ln(2)} (\sigma_n + \sigma_g)}
\]

In case the separation is exactly 3(\( \sigma_n + \sigma_g \)), the formula simplifies to \( FOM = \frac{3}{2 \sqrt{2 \ln(2)}} \approx 1.27 \).

When calculating the FOM for all slices, one can see that it increases towards higher energies, exceeding the 3\( \sigma \) separation value of \( FOM = 1.27 \). In Figure 3, the energy where \( FOM = 1.27 \) is exceeded is marked as red dashed line. For the region to the right of the \( FOM = 1.27 \) position, an event is classified as neutron (gamma) if it lies inside the 3\( \sigma \) region of the neutron (gamma) band. The region to the left of the \( FOM = 1.27 \) position is not taken into account as sometimes fit
problems occur and the determined event type separation would be highly dependent on the chosen fitting parameters.

The accepted neutron and gamma rates are calculated from the particle counts in the acceptance regions divided by the measurement time. The rates differ from pixel to pixel, typical values for neutrons lie around 10 Hz for the measurements described in this paper. For the example shown in Figure 3, the accepted neutron rate is $(11.06 \pm 0.06)$ Hz, corresponding to 2.2% of the recorded events. The accepted gamma rate is $(3.57 \pm 0.03)$ Hz, corresponding to 0.7% of the events. Most of the other recorded events lie at very low pulse integrals where no reliable separation between gammas and neutrons can be determined.

The $3\sigma$ limits described above are always determined for measurements without any object in front of the detector. In case additional measurements with objects are done with the same detector settings, the limits are re-used and applied to these measurements. The reason is that the absorption measurements are always put in relation to the measurement without object (the so-called calibration image), see also section 4.2.

Figure 3: Left: Example PSD plot, detector pixel A4. The $3\sigma$ limits of the neutron and gamma band are shown in green and red. Extrapolations are performed to the regions where too few events for Gaussian fits are located. The red dashed line marks the energy where $FOM = 1.27$. Right: Detector pixel labeling, as seen from the incoming particle’s perspective.

3 Experimental setup

3.1 D-D neutron source

The compact neutron generator used for measurements is based on the D-D fusion reaction. It is a custom device developed at the Paul Scherrer Institute with an emphasis on imaging, with its most notable feature being a relatively small emitting spot size of roughly 2 mm diameter intended to reduce imaging blur. Significant simulation and experimental efforts were made in order to characterize as much as possible the emitting spot size, the absolute neutron output, and the flux distribution within the room where the device is operated. These characterization techniques are described in [9] and [10]. This section aims to give a short overview of the device and some important characteristics as they relate to the measurements described in this paper.
The neutron generator uses a microwave ion source at ground potential which has an aperture (circular hole) through which deuterium ions are extracted. The ions are accelerated by electrostatic potential within a vacuum chamber towards a target rod biased at negative high voltage (typically -120 kV or less). The target rod is rotated so that the emitting spot is stationary but the heat from the ion beam is spread over a larger surface area consisting of a ring around the target rod. The rod is titanium-coated copper and is actively air-cooled. The ion beam itself loads the titanium target with deuterium, ideally forming TiD$_2$ (although in reality it is likely not entirely loaded with deuterium) with which subsequent incoming deuterium ions can interact with. A stationary suppression electrode also surrounds the target rod except for a hole where the ions can pass through from the ion source to the target rod. This electrode is biased slightly more negatively than the target rod such that electrons which are sputtered off of the target rod by the deuterium ions ideally do not backstream towards the ground potential, but rather return to the target rod. These backstreaming electrons can cause, among other problems, an unwanted production of Bremsstrahlung X-rays up to the acceleration energy which is applied to the deuterium ions. Not all backstreaming electrons are avoided, however, meaning some X-rays are always produced at the same time as when fast neutrons are produced. A sketch of the main components of the system can be seen in Figure 4.

![Sketch of PSI neutron generator with some key features labelled.](image)

**Figure 4:** Sketch of PSI neutron generator with some key features labelled.

When a D-D fusion occurs, about half of the time it produces an alpha particle and a neutron, where the latter has an energy of 2.45 MeV in the center of mass frame. In the lab frame, the neutron energy depends on the energy and direction of the deuteron which initiates the fusion (while the other deuteron is assumed stationary). This is generally considered relative to the nominal direction of the ion beam, referred to as the emission angle. For one deuterium ion direction and energy, a given emission angle has a mono-energetic nature. Two effects cause this spectrum to become slightly polychromatic. One is that the deuterium ions do not occur at one specific energy, but over a range of energies, as they are gradually slowing down in the target rod and undergoing fusion not...
only at the acceleration energy at which they enter the target. Second, the ions are deviating slightly as they slow down, meaning the nominal direction is not exactly the direction of a given deuteron when it undergoes fusion. These two effects were taken into consideration in detail in [11].

A photo of the neutron generator with some features indicated can be seen in Figure 5. There the “forward direction” or zero degree direction is indicated which corresponds to the ion beam path line. The measurements in this paper were all made in the horizontal plane at either the forward direction or one of two angles to the side (90° and 115°), as indicated in the photo. The D-D reaction generally has a maximum emission energy in the forward direction and a minimum in the 180° direction. The nominal acceleration voltage used for the measurements in this paper was 115 kV, although slight fluctuations were present and assumed to be negligible. The expected neutron spectra at this acceleration voltage emitted from the source towards those three directions is shown in Figure 6. Neutrons are emitted over 4π but with a bias towards the forward and 180° directions. At emission angles of 0°, 90°, and 115°, the neutrons rates emitted per steradian were respectively 1.45, 0.70, and 0.79 times the average over 4π for the aforementioned acceleration energy of 115 kV.

The output fluctuates over time but was typically about $3.5 \cdot 10^7 \text{ s}^{-1}$ in total over $4\pi$. That yield was measured using an LB6411 neutron probe as described in [9], where simulations were used to calibrate the LB6411 response relative to the absolute total neutron output. In that past work it was checked how reliable this estimate was by comparing the yield value indicated by many different LB6411 positions within the room, relative to each other and a second detector kept in a fixed position as a reference. Ideally all measurement positions would indicate the same neutron output relative to the reference detector response. A variation was found, however, up to a maximum of 15% relative to the average, with a standard deviation of 10%, and therefore the latter value was taken as the absolute neutron output uncertainty for the purposes of estimating things like
neutron detection efficiency. However, in cases where a relative value is measured, for example from a detector response with and without an attenuating material between source and detector, this systematic uncertainty is cancelled out, leaving only stochastic uncertainty based on the finite count rate of the LB6411 detector. With a measuring time in the order of minutes this stochastic uncertainty is often negligible.

![Figure 6](image)

**Figure 6**: Simulated emitted neutron spectra (normalized probability distribution function) from the PSI neutron generator at the three emission angles used for measurements at an acceleration energy of 115 kV.

3.2 Detector arrangement

As mentioned above, measurements at three different angles relative to the ion beam path line, i.e. three different mean initial neutron energies, were performed. In Table 1, the angles and the corresponding mean neutron energies are given. Photographs of the measurement setup are shown in Figure 7. The detector is positioned on an aluminium plate at a distance of approximately 80 cm away from the neutron emission spot. The exact distances are listed in Table 1. A sample holder is attached to the detector to be able to position small absorber objects in front of the detector. The objects are further described in section 4.2. A lead plate of approximately 1-2 mm thickness is placed around the neutron generator to shield low-energetic X-rays. There is also the possibility to place a polyethylene (PE) block of size $21 \times 10 \times 5.5$ cm$^3$ in between the generator and the detector to determine the neutron background. The PE block is expected to shield more than 99.5% of the neutrons directly coming from the generator. The remaining detected neutrons are therefore assumed as “background” neutrons which did not travel directly from source to detector, but rather scattered off of the floor, ceiling, walls, etc. Measurement times per configuration setup varied between approximately 0.5 h and 1 h.
Table 1: Measurement positions and corresponding mean neutron energies. The angle is relative to the ion beam path line. The distances are determined from the neutron emission spot to the scintillators’ front surface positions.

| Angle | Mean $E_n$ [MeV] | Distance [cm] |
|-------|------------------|--------------|
| 0°    | 2.84             | 81.0 ± 2.0   |
| 90°   | 2.47             | 81.8 ± 2.0   |
| 115°  | 2.33             | 79.4 ± 2.0   |

Figure 7: Photographs of the measurement setup (in forward direction). (a): Overview. (b): Detector and absorber sample. (*) PE block only used for background measurements.

4 D-D generator measurement results

In the following, selected measurement results obtained with the D-D generator setup are presented. A determination of the detection efficiency for D-D neutrons is presented and discussed. Furthermore, neutron absorption images of different objects are evaluated.

4.1 Detection efficiency for D-D neutrons

The detection efficiency $\epsilon$ is defined by

$$\epsilon = \frac{R_{\text{det}}}{R_{\text{inc}}}$$

with the detected neutron rate $R_{\text{det}}$ and the incoming neutron rate at the scintillator position $R_{\text{inc}}$, which can be expressed by

$$R_{\text{inc}} = R_0 \cdot \frac{F_{\text{det}} \cdot f_{\text{geom}} \cdot f_{\text{abs}}}{4\pi d^2}$$

Here, $R_0$ is the emitted neutron rate, $d$ is the distance to the detector and $F_{\text{det}}$ is the scintillators’ front surface area. The factor $f_{\text{geom}}$ describes the non-isotropic neutron emission of the generator, see also section 3. The factor $f_{\text{abs}}$ describes the attenuation of neutrons in the generator itself or in the lead plate used to shield X-rays. For the estimation of $f_{\text{abs}}$, microscopic cross section data from the JEFF 3.3 [12] and ENDF/B-VII.1 [13] database evaluated for the neutron generator output spectrum is used. An uncertainty of 2% is assumed, due to uncertainties on the lead plate thickness,
the cross sections and the neutron paths through the generator. For the detected rate $R_{\text{det}}$, two measurements are necessary. First, a measurement without any object between the generator and the detector, which includes detected neutrons both directly from the generator and scattered from other directions (background neutrons). For the efficiency calculation, only the direct neutrons are needed. Therefore, the background rate $R_{\text{BG}}$ needs to be subtracted. The background is determined from a measurement with PE block, as described in section 3.2. The neutron rate from this measurement must be weighted by the neutron generator output during the efficiency measurement, as the output varies with time.

4.1.1 Uncertainty estimation

The uncertainty on the efficiency consists of two parts: a statistical uncertainty from the particle counts that varies from detector pixel to pixel, and a correlated systematic uncertainty for all pixels due to the incoming neutron rate. This systematic uncertainty would shift all efficiencies in the same direction.

The statistical uncertainty can be subdivided into a Poisson error based on the number of counts as well as an uncertainty from the $FOM = 1.27$ position. The main contributions to the systematic uncertainty are the errors on the initial neutron rate $R_0$, on the distance $d$ and on the factor $f_{\text{abs}}$. The errors are propagated to $\epsilon$ via Gaussian error propagation.

The weighted mean over all pixels is calculated taking only the statistical uncertainties into account. To illustrate the effect of the correlated uncertainty, the weighted mean is also calculated after shifting the data by $1\sigma_{\text{sys}}$ up or down.

4.1.2 Results

In Figure 8, the detection efficiencies for each pixel determined from a measurement in the forward direction are shown. In Figure 9, the same is shown for measurements along the 90° and the 115° directions.

The efficiency lies overall in the order of 10%, but fluctuates from pixel to pixel. Especially pixel A3 has a much smaller efficiency than the other pixels in all measurements. A closer look at this pixel shows that its pulses are smaller and the separation between neutrons and gammas is worse than for most other pixels. In contrast, the pixels B2, C4, and D4 show an above average efficiency. In these pixels the neutron band ends at relatively high energy combined with good particle separation. The fluctuations from pixel to pixel may be explained by setup differences such as the coupling qualities between the scintillators and the SiPMs, or by differences of the crystals themselves. Differences can occur in light propagation (e.g., different surface structures), but also in scintillation light creation, e.g., due to Stilbene’s anisotropy [5].

When comparing the forward direction with the 90° and 115° direction, it is seen that the efficiency in 90° direction seems to be approximately 2.4 percentage points larger, while in 115° direction, the efficiency is slightly smaller. The variation from pixel to pixel however looks similar in all measurements. A larger efficiency in 90° direction is a priori unexpected, as the neutron energy is smaller and therefore the number of events above the energy threshold should be smaller. This effect should only be slightly compensated by the higher proton recoil interaction cross section in stilbene at around 2.45 MeV. The difference is probably not explained by the uncertainty in the total neutron generator output, as this error corresponds to a shift of the output that should be in the same
direction for all measurements. Also, the uncertainty on the distance and the self-absorption cannot explain the large difference. We therefore think that the reason lies within the way the signal data was processed, in terms of what signals are considered neutron events and which not. As described in section 2.2, only the \( FOM > 1.27 \) energy region in the PSD plot is considered for neutron counting, and this is determined separately for each angle. For the 90° measurement, \( FOM = 1.27 \) is reached at \( E = 303.2 \text{ keVee} \) when averaging over all pixels, for the forward direction, it is reached at \( E = 318.7 \text{ keVee} \), indicating a better separation of neutron and gamma band in 90° direction. The lower threshold needed to achieve the defined \( FOM \) leads to a larger energy range that is considered for the neutron counting, and effectively a higher detection efficiency. When applying an arbitrarily chosen constant higher energy threshold of 450 keVee across all measured data, which is slightly above the largest \( FOM = 1.27 \) position, the mean efficiency in the 90° direction is 4.7 %, which is smaller than the forward direction value of 5.4 %, which fits qualitatively much better to the expected trend. One possible explanation for the variation in neutron to gamma separation is a varying amount of gamma flux around the source, for example if one direction was better shielded with lead than another. The lead shielding was not applied in a precisely uniform way, and that might contribute to this effect and the variation in efficiency from one direction to another. This effect might be even stronger if X-rays (not gammas) are contributing to the “gamma” contribution, as they are more sensitive to variations in the lead shielding. Even though they are nominally of too-low energy to be registered as gamma events, it might be that a very small percentage of them interact within the stilbene very close to the surface of the SiPM, and therefore produce an abnormally large signal which appears as a relatively high energy. However, to be certain this should be studied more carefully in the future.

**Figure 8**: Detection efficiency in 0° direction for each detector pixel. Three uncertainties are shown. The statistical (Poisson) uncertainty due to the particle counts (in black), an uncertainty due to the error on the \( FOM = 1.27 \) position (in blue) and a combined uncertainty including the systematic error arising from the error on \( R_{inc} \) (in green). Also, the weighted mean (green line) with its statistical and systematic error (green dotted lines) is shown.
Figure 9: Detection efficiency in 90° and 115° direction for each detector pixel. For an uncertainty description, see Figure 8. (*): No data for pixel C4 available as it wasn’t connected to the readout electronics in this measurement.

4.2 Attenuation measurements

The goal of the attenuation measurements is the experimental measurement of fast neutron attenuation in different materials, leading to the calculation of the macroscopic cross section and its comparison to literature values. The attenuation of gammas is not considered, as the neutron generator does not produce initial gammas but they are rather created from activation processes in all surrounding materials, so that their direction of origin is unknown. The recorded gamma interactions are rejected by pulse shape discrimination.

Three different attenuation objects (see Figure 10) are investigated by placing them on a sample holder directly in front of the detector. The detector is placed in the forward direction relative to the generator.

Figure 10: Photograph of the absorber objects. Left and mid: Small step wedges, step sizes \{0.5, 1.0, 1.5, 2.0\} cm. The material combinations are Al-PMMA and PVC-Steel. Right: Large step wedge with step sizes \{1, 2, 4, 6\} cm. The materials are steel, Al, PMMA.
To determine the attenuation of an object, three measurements (images) must be taken: a so-called calibration image without any material placed in front of the camera, the so-called absorption image with the object and a background image with the PE block. In each case, a neutron rate $R_i$ with $i \in \{cal, obj, BG\}$ relative to the incoming neutron rate is calculated. The neutron attenuation can then be expressed by the differential rate ($\Delta Rate$) that can be defined as

$$\Delta Rate = \frac{(R_{obj} - R_{PE}) - (R_{cal} - R_{PE})}{R_{cal} - R_{PE}} = \frac{R_{obj} - R_{PE}}{R_{cal} - R_{PE}} - 1$$  \hspace{1cm} (4.3)$$

From the differential rate, the macroscopic cross section $\Sigma$ can be calculated by

$$R_{obj} - R_{PE} = (R_{cal} - R_{PE}) \cdot e^{-\Sigma \cdot x}$$ \hspace{1cm} (4.4)$$

$$\Sigma = -\frac{1}{x} \ln \left( \frac{R_{obj} - R_{PE}}{R_{cal} - R_{PE}} \right) = -\frac{1}{x} \ln \left( \Delta Rate + 1 \right)$$ \hspace{1cm} (4.5)$$

The uncertainties of $\Delta Rate$ and $\Sigma$ are calculated via Gaussian error propagation from the uncertainties of $R_i$. Since the detector is not moved during a given measurement series, the uncertainties related to the detector position do not need to be considered.

### 4.2.1 Results

Figure 11 shows the differential rates for the large step wedge and the small Al-PMMA\(^3\) and PVC-Steel step wedges (photo in Figure 10). The large step wedge covers the detector pixel columns 1, 2 and 3 with steel, aluminium and PMMA. The pixel column 4 is left uncovered. The pixel row A is covered with 6 cm of material, B with 4 cm, C with 2 cm and D with 1 cm (for detector pixel arrangement, see Figure 3). Looking at the differential rates, one can clearly identify the steps of the step wedge. Also, differences between the materials can be seen. The smallest attenuation is seen for 1 cm aluminium, the largest attenuation for 6 cm steel. Overall, aluminium is the weakest attenuator, steel the strongest. For the uncovered row, no significant rate reduction is seen, indicating especially no shadowing effect.

The small step wedges cover all detector pixels. Always two neighbouring pixels are covered by the same material thickness. The pixel columns 1 and 2 are covered with Al (PVC), the columns 3 and 4 with PMMA (steel). Pixel rows C and D are covered by 0.5 cm or 1.5 cm, A and B by 1 cm or 2 cm of material. In the differential rates, these small thickness differences are still visible, despite some fluctuations. As for the large step wedge, aluminium is the weakest attenuator, it absorbs less than PMMA and slightly less than PVC. The strongest attenuator is Steel. However, the differential rates also show a characteristic problem of the radiographic imaging method. For example, $\Delta Rate$ for 1.5 cm Al and 1 cm PMMA are comparable, so, for an unknown sample, it would be impossible to discriminate between two such objects in case both material and thickness are unknown. If one or the other is known a priori, then the other can potentially be determined from a radiographic image, as long as the materials to be identified have sufficiently different attenuation coefficients. With a tomographic image, this problem is not present, and a spatial distribution of the attenuation coefficient could be determined.

\(^3\)Polymethyl methacrylate
Figure 11: Measured neutron differential rates for the step wedges. (a): Steel-Al-PMMA step wedge. Materials from left to right: Steel \{6, 4, 2, 1\} cm, Al \{6, 4, 2, 1\} cm, PMMA \{6, 4, 2, 1\} cm, not-covered. (b): Al-PMMA and PVC-Steel step wedge. Materials from left to right: Al (PVC) \{1, 1, 0.5, 0.5\} cm, Al (PVC) \{2, 2, 1.5, 1.5\} cm, PMMA (Steel) \{2, 2, 1.5, 1.5\} cm, PMMA (Steel) \{1, 1, 0.5, 0.5\} cm.

From the $\Delta$Rates, the macroscopic cross sections are calculated according to equation (4.5). The resulting values are shown in Figure 12 both for the large step wedge and the small step wedges Al-PMMA and PVC-Steel. The figures also show the theoretically expected values according to literature microscopic cross section data (JEFF3.3 and ENDF/B-VII.1 database) combined with the previously given fast neutron spectra. It can be seen that the experimentally determined cross sections are generally significantly smaller than the literature values. For the large step wedge, the difference gets larger as the material thickness increases, especially for steel. However, the relative attenuation from one material to another qualitatively follows the expected trend. This discrepancy was further studied using simulations, as described in section 4.3. The results from the large and the small step wedges for steel, Al and PMMA are within the uncertainties. The material sequence is correctly reproduced within the uncertainties.

Figure 12: Macroscopic cross section for steel, aluminium, PMMA, and PVC, determined from measurements with the Fe-Al-PMMA step wedge (in (a)) and the small step wedges (in (b)). The literature values calculated from JEFF 3.3 and ENDF/B-VII.1 microscopic cross section data are marked in the plots as dotted lines.
4.3 Comparison with Geant4 simulations

Geant4 simulations of the setup were done to better understand the neutron interactions in the attenuator objects and in the detector.

4.3.1 Geant4 setup

The Geant4 simulation setup consists of a detailed detector model as well as a model of the attenuator objects and optionally a PE block. In Figure 13, the setup is shown. For the incoming neutrons, it is assumed that they are emitted from a point source at 80 cm distance from the detector. The simulated neutron energy spectrum corresponds to the neutron generator output spectrum either in the forward or 90° direction.

The simulation stores the neutron interactions in the step wedge and the interactions, energy losses by particle type and amount of created scintillation light in the detector pixels. Geant4 version 10.05.p01 [14] is used, the physics list essentially corresponds to the QGSP_BIC_HP list, but using G4EmStandardPhysics_option4 and G4OpticalPhysics [15]. The JEFF3.3 library is used for the neutron interaction data. The particle dependent scintillation light output is modeled based on Birk’s law [16].

![Geant4 detector model with attenuator step wedge (Fe-Al-PMMA) placed in front of the detector. In the simulation, steel is approximated as pure iron because the exact steel composition is unknown, but the difference in attenuation should be very small.](image)

**Figure 13:** Geant4 detector model with attenuator step wedge (Fe-Al-PMMA) placed in front of the detector. In the simulation, steel is approximated as pure iron because the exact steel composition is unknown, but the difference in attenuation should be very small.

4.3.2 Spectra and Efficiency

One aspect of the simulation is the amount of scintillation light, which can be transferred to an energy spectrum in keVee by dividing the number of photons by stilbene’s light yield. When excluding scintillation light caused by electrons and gammas, one gets a spectrum that can be compared to the measured one. In Figure 14, two example spectra are shown for two different camera pixels. A very good agreement between the simulated and measured spectra can be seen. In order to achieve this agreement, the simulation parameters Birk’s constant, $k_B$, and the intrinsic resolution were optimized. A larger value of $k_B$ means that proton recoils lead to less light compared to electron recoils.
interactions. The intrinsic resolution describes the fluctuation of the amount of created scintillation light. It turned out that to get a good agreement for most pixels at least two different classes of stilbene need to be defined, one with a Birk’s constant of \( k_B = 0.135 \) mm/MeV and one with \( k_B = 0.185 \) mm/MeV (red or blue stilbene crystals in Figure 13). These values of \( k_B \) cannot be seen as a physical Birk’s constant but are simply parameters used to increase the simulation accuracy. The same is true for the intrinsic resolution. A reason for the pixel to pixel differences may be the anisotropy of stilbene [5], but also differences in the light propagation within the scintillators and the light detection at the SiPMs could play a role. This light propagation is not included explicitly in the simulation, so its effect is instead represented by the tuning of these parameters.

Figure 14: Example simulated (black) and measured (green) spectra, representing the two different stilbene classes. The red and blue dashed lines mark the experimental FOM=1.27 position and the artificial energy cut at 450 keVee. Left: Pixel A1. Right: Pixel B1. The energies are significantly smaller than for pixel A1.

To calculate the simulated detection efficiency, the experimentally determined \( FOM = 1.27 \) values are applied to the spectra pixel per pixel and the integral of the remaining spectra is calculated. Also, a simulation with a PE block was performed and its resulting spectrum subtracted. By dividing by the expected incoming neutron rate at the detector, the efficiency is obtained. For the optimized simulation setup, a mean detection efficiency of \((9.87 \pm 0.01)\%\) in the forward direction was determined. This is approximately 0.3 percentage points higher than the experimentally determined value and compatible with this result within the overall experimental uncertainty. When applying a 450 keVee threshold instead of the \( FOM = 1.27 \) thresholds to the simulated data, the mean efficiency is with \((6.25 \pm 0.01)\%\) approximately 0.9 percentage points larger than the experimental value.

In the 90° direction, however, the simulated efficiency is only \((9.36 \pm 0.01)\%\), so approximately 2.5 percentage points smaller than the experimental one, and particularly smaller than in the forward direction. One reason for the higher experimental efficiency is the behavior of pixels A2 and A3, where the experimental efficiencies have quite large uncertainties compared to the other pixels, while the simulation uncertainties are similar for all pixels. This influences the weighted mean efficiency. However, also for the other pixels, the simulated efficiencies are around 1.5-2 percentage points smaller. When applying the 450 keVee threshold instead, the mean efficiency is \((4.70 \pm 0.01)\%\), which is very close to the experimental result. It is therefore still an open question where the discrepancy for the FOM criterion comes from. Also, to get a good agreement between the simulated and measured spectra, the values of the \( k_B \) parameters need to be set to
0.125 mm/MeV and 0.175 mm/MeV, indicating a tendency to larger pulse heights at the same amount of deposited energy than for the forward direction measurement. It is an open question what causes these differences. It could be a temperature effect in the measurements, e.g. a higher SiPM overvoltage, even though a temperature correction is applied to the SiPM bias voltage. The SiPM temperature during the 90° measurements was approximately 2 °C lower than during the forward direction measurements.

4.3.3 Simulated images and macroscopic cross section

Figure 15 shows the simulated macroscopic cross section $\Sigma$ determined from a simulation with the Fe-Al-PMMA step wedge which assumes a perfect alignment of the step wedge in front of the pixels and the detectors with respect to the source. The determination method of $\Sigma$ is similar to the experiment.

As in the experiment, the calculated cross sections are significantly smaller than the literature values for all three materials. Two possible reasons were identified in the simulation. The first contribution is from neutrons interacting in both the object and the detector, which cause up to approximately 8% of the detected neutrons in the simulation. It is seen in the simulation that this effect alone cannot fully describe the discrepancy between simulated and literature cross sections. Another contribution could come from multiple interactions in the detector, either in two or more different pixels or in the detector housing and then in a pixel, leading to a background rate of neutrons. The background generated in this way reduces the determined cross section and is of relatively greater importance for pixels covered with a higher-attenuating material and/or a greater material thickness. This effect is not corrected by subtracting the PE measurement, as the PE block is much larger than the detector volume. Multiple interaction events in detector pixels with at least one interaction above the required FOM threshold occur in about 20% - 25% of the simulated events when assuming the mean FOM threshold of 318 keVee in the forward direction. However, this value also includes very small energy losses of a few keV and does not consider if the neutron was scattered into the pixel where it was detected or vice versa. Using e.g. an arbitrarily chosen 100 keV threshold, which corresponds to approximately 3.5% of the initial neutron energy, the multi-pixel interaction fraction already reduces to approximately 13%. Additionally, neutrons that interact in the detector box and then in the detector need to be considered. It would be interesting for the future to extend the simulation so that neutrons that interact first somewhere in the detector box or e.g. in an uncovered pixel and then in a certain covered pixel are counted to quantify the influence on the determined macroscopic cross section.

The decrease of the cross section towards higher material thicknesses is smaller in the simulation than in the experiment. Also, the simulated cross sections for small material thicknesses seem to be smaller than in the experiment. A possible explanation could be a slight misalignment of the step wedge in the experiment. This could either be a shift or a rotation of the step wedge compared to the direct neutron direction of flight. To investigate effects of shifts, the step wedge in the simulation was misaligned in the vertical and horizontal direction by ±1 mm and ± 2mm. It should be mentioned that a 2 mm shift in the experiment is quite unlikely as great effort was made to correctly position the step wedge in front of the detector.

A misalignment in horizontal direction to the right, shifting the PMMA part slightly into the empty detector row can be limited to (much) less than 1 mm as this misalignment would cause a much
larger shadowing of up to approximately –12% in the empty row than observed in the measurement. Also, a shift of 2 mm to the left can be excluded, as this would cause a smaller experimental cross section for PMMA than for Al, which is also not observed. The decrease of the cross section towards higher material thicknesses could be i.a. explained by a shift upwards. In this case, a pixel e.g. covered with 1 cm of material would also be partially covered by 2 cm of material, leading to a higher cross section. This effect is as a percent larger for the small material thicknesses. A simulation with such a shift of 1 mm fits better to the data than the unshifted simulation. To illustrate this, correction factors for the cross section can be calculated from the simulated data by dividing the literature macroscopic cross sections by the simulated ones. When multiplying the experimental values by the correction factor, the resulting values should ideally correspond to the literature cross sections. Figure 16 shows the results for the original and the vertically shifted case. The shifted simulation leads to better agreement between corrected values and literature values, even though there are still some deviations (e.g. 6 cm of PMMA). However, it can be concluded that lower experimental macroscopic cross sections are expected, and the exact dependency of the thickness is probably explained by alignment difficulties.

5 Conclusion and Outlook

The 16 pixel detector prototype presented in this paper was successfully tested with a D-D neutron generator with mean emission energies between approximately 2.3 and 2.8 MeV. The detector’s scintillation material stilbene allows neutron-gamma separation using pulse shape discrimination techniques. Applying these techniques, a neutron detection efficiency, averaged over all pixels, between (9.11 ± 0.11)% and (11.95 ± 0.12)% was determined, applying a conservative lower energy cut by requiring \( FOM > 1.27 \). A higher detection efficiency would be achievable by requiring a less conservative \( FOM \) criterion with the disadvantage of a (slightly) larger contamination e.g. of neutron counts by gamma events and difficulties in the comparison with simulations, as neutron
events need to be filtered if they lie in a region where they are mixed up with gamma events. This would be interesting if the measurement time needs to be reduced or a weaker neutron source shall be used. The detection efficiency was determined for three different angles relative to the generator’s ion beam direction, i.e. three different mean neutron energies. Here, it was seen that the efficiency in 90° direction was larger than in the 0° direction, which is an unexpected result. Further studies should be done to explain this discrepancy.

With radiographic attenuation measurements of three different objects, it was shown that the detector setup allows distinguishing different materials and also the presence of material thickness differences of only 0.5 cm for measurement times of approximately 0.5 h to 1 h by calculating a differential rate between measurements with and without object. The accuracy could possibly be improved by increasing the measurement time. However, if material and thickness would be unknown, in this radiographic measurement approach it would be impossible to accurately identify simultaneously unknown material composition and thickness as there would be too many free variables.

From the differential rates, the macroscopic cross section for the attenuators’ materials was calculated, showing a systematic underestimation compared to literature values. By using detailed Geant4 simulations, two main contributions for these deviations were identified: Neutrons that interact in the attenuator but still arrive at the detector and multiple interactions in different detector pixels or in the detector box and then in a pixel. Additionally, a possible misalignment of the step wedge was investigated by comparing the simulated and the measured macroscopic cross section values. It would be interesting to further study the effect of multiple interactions on the determined cross section using the simulations.

In the future, it is planned to further test the potential of the detector concept focusing on two aspects. First, neutron and gamma radiographic images of test objects shall be taken simultaneously, using different neutron sources, e.g. an Americium-Beryllium (AmBe) source. First measurements of this type were done during a master thesis [17] in our group. Second, the potential of taking
simultaneous neutron and gamma tomographic images shall be investigated based on the detector concept of a PSD capable solid scintillator such as stilbene coupled to SiPMs. These studies shall be done using Geant4 simulations and test measurements mainly with an AmBe source. A test stand allowing both types of measurements to be performed simultaneously is currently under development. It is also planned to test the capability of combining our detector concept with a HPGe detector for Neutron Activation Analyses.

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