Impact of the detected scintillation light intensity on neutron-gamma discrimination

Massimo Caccia, Marco Galoppo, Luca Malinverno, Pietro Monti-Guarnieri, Romualdo Santoro

Abstract—This paper reports the method and the results of a study on the impact of the detected light intensity on gamma-neutron discrimination. In particular, the minimum number of photons required to achieve a statistically significant separation was measured and shown to be stable against a variation of the Photon Detection Efficiency (PDE) of the system under study. The method, developed using an EJ-276 scintillator bar coupled to a Silicon Photomultiplier (SiPM), is of general interest. For this specific system, the minimum statistics was measured to be 317 ± 16 photons, corresponding to different values of the deposited energy, as the PDE was changed.

Keywords: Silicon Photomultipliers, Plastic scintillators, Pulse shape analysis, Neutron-gamma discrimination, Photon statistics.

I. INTRODUCTION

Silicon Photomultipliers (SiPMs hereafter) are compact solid state light detectors with single photon sensitivity, photon counting capability, low bias voltage and low power consumption. In the last decade, SiPMs have been used in a variety of fields, such as particle and nuclear physics, medical imaging and homeland security [1]–[3]. It has been shown that SiPMs, coupled to specifically engineered scintillators with sensitivity to both fast and slow neutrons, represent a viable solution for the discrimination of light pulses originated by gamma rays against neutrons [4]. The enabling feature of this class of scintillators is the different light emission time in response to interactions of neutrons or gamma rays. Hence, a pulse shape analysis is usually implemented by defining a Pulse Shape Discriminating (PSD) observable [5]–[11].

For every detection system used for particle identification there exists a critical condition for which the signal produced by the impinging radiation does not convey enough information to achieve particle discrimination. This effect usually manifests itself through the existence of a system-specific energy deposit threshold below which the identification capability is lost. In case of a scintillator coupled to a light sensor, the energy deposit and thus the information carried by the signal is directly related to the intensity of the scintillation light. The idea behind this study is to investigate the correlation between the minimum amount of information required for particle discrimination and the photon statistics.

The results of the investigation reported here stems from a system based on a plastic scintillator (EJ-276, by Eljen Technologies) coupled to a SiPM, where the response and sensitivity were changed by varying the Photon Detection Efficiency (PDE) of the SiPM, acting on the biasing voltage. The outcome of this study is the definition of a procedure having a general applicability that not only sheds light on the correlation between the photon statistics and the information conveyed by the signal, but also yields the minimum photon statistics required for neutron-gamma discrimination.

II. MATERIALS AND METHODS

The analysis is based on a 6 mm × 6 mm area SiPM produced by HAMAMATSU Photonics (model S13360-6050PE), with the main features reported in Table I, as of the vendor’s specifications [12].

| Hamamatsu S13360-6050PE |
|--------------------------|
| Pixel pitch | 50 µm |
| \( V_{op} \) | 53 ± 5 V |
| \( V_{bd} \) | \( V_{op} + 3 \) V |
| Terminal capacitance \( C_t \) | 1280 pF |
| Dark count rate | 2000 Hz |
| Crosstalk probability | 3% |
| PDE \( ^{\circ} \) | 40% |

\( V_{bd} \) identifies the breakdown voltage. The uncertainty refers to lot-to-lot variations.

\( V_{op} \) is the suggested operational voltage.

\( ^{\circ} \)The PDE corresponds to the peak value (\( \lambda = 450 \) nm), at \( V_{op} \) and \( T = 25^\circ C \).

The sensor was coupled through optical grease to a 5 cm × 1 cm × 1 cm EJ-276 scintillator bar produced by Eljen Technologies, where pulse shape neutron-gamma discrimination is made possible by the differences in the scintillating time decay constants, as reported in Table II [13]. The bar was wrapped with Teflon tape diffuser to maximise light collection and the assembly was operated in a light tight box to prevent contamination from ambient light.

| Eljen EJ276 |
|----------------|
| \( \tau_1 \) (\( \gamma/n \)) | 13 ns |
| \( \tau_2 \) (\( \gamma/n \)) | 30/50 ns |
| \( \tau_3 \) (\( \gamma/n \)) | 270/460 ns |
| Photon MeV | 8600 |
| Density | 1.0096 (g/cm\(^3\)) |
| \( \lambda_{peak} \) | 425 nm |

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/
The energy calibration was performed exploiting the Compton spectrum shoulder for a series of gamma emitting isotopes ($^{22}\text{Na}$, $^{60}\text{Co}$, $^{133}\text{Ba}$ and $^{137}\text{Cs}$). Neutron-gamma discrimination was instead investigated using a $^{252}\text{Cf}$ source.

The system response in terms of detected photons per pulse was measured after a calibration performed by illuminating the sensor with an ultrafast blue LED emitting at 420 nm, pulsed by a PicoQuant PDL-800B unit.

For $\gamma$ and neutron detection, the signal produced by the SiPM was directly digitized with a CAEN DT5720 Desktop Digitizer (sampling frequency 250 mega-samples per second, 12 bit resolution, $2\text{ V}$ input range). For the calibration in photoelectrons the signals were amplified using the CAEN SP5600 unit, featuring a variable gain in the 0 dB to 50 dB range.

### A. ENERGY CALIBRATION

Due to the low $Z$ and density of the plastic scintillator, the gamma rays rarely interact through photoelectric effect. Hence, calibrations relied on the Compton spectrum shoulders. The energy associated to the edge of a shoulder, $E_{\text{edge}}$, can be derived from the theory of the Compton scattering [14] and is given by:

$$E_{\text{edge}} = \frac{E_\gamma^2}{2E_\gamma + m_e c^2}$$

(1)

whereas $m_e c^2$ is the energy of the electron at rest and $E_\gamma$ is the $\gamma$ ray energy or the weighted mean of multiple lines not resolved in the experimental spectrum (with the weights being the emission branching ratios). The edge shoulders used in the calibration are reported in Table III.

| Source | $E_\gamma$ [keV] | Branching Ratio | $E_{\text{edge}}$ [keV] |
|--------|----------------|----------------|------------------------|
| $^{22}\text{Na}$ | 511 | 99.85% | 341 |
| | 1275 | 99.98% | 1062 |
| $^{60}\text{Co}$ | 1173 | 1040 (mean) |
| | 1332 | 196 (mean) |
| $^{133}\text{Ba}$ | 276 | 7.13% | 196 |
| | 303 | 18.31% |
| | 356 | 62.05% |
| | 384 | 8.94% |
| $^{137}\text{Cs}$ | 662 | 478 |

$E_{\text{edge}}$ is the mean value, weighted by the branching ratios.

For these measurements, the DT5720 unit was self-triggered and signals exceeding a fixed threshold were sampled and digitized over a 8 $\mu$s long window, with the signal peak located 2 $\mu$s after the digitization gate opening. For every run at different conditions, about 250 000 pulses were recorded. For the duration of all experiments and the measurements of the main sensor figures, the SiPM was maintained at constant temperature of 18.0 $^\circ$C $\pm$ 0.1 $^\circ$C.

The calibration was repeated for every SiPM biasing voltage used to evaluate the impact of a PDE variation, namely from 3 V to 6.5 V above the breakdown voltage, at 0.5 V steps.
reported in Fig. 1. A typical calibration line at a fixed bias is shown in Fig. 2.

B. PHOTOELECTRON CALIBRATION
The charge corresponding to the avalanche generated in the silicon matrix by a single initial photoelectron depends on the gain of the SiPM, which is linked to the excess voltage, and the external amplification stage. It was measured by analyzing for each specific setting the multi-photon spectrum, namely the histogram characterising the sensor response to a low plurality of photons emitted by the ultrafast blue LED pulsed by the PicoQuant unit. An exemplary spectrum is shown in Fig. 3, where peaks correspond to the number of fired cells for every pulse, determined by the detected photons and the prompt optical crosstalk, while the significant background between the peaks is connected to delayed optical crosstalk, after pulsing and occasional spurious pulses (dark counts) occurring within the integration window. The shape of the histogram results from the convolution of the Poissonian distribution of emitted photons and the probability distributions of crosstalk and after pulsing. Since the main goal of the procedure is determining the calibration of the sensor response in photoelectrons (number of fired cells), the quantity of interest here is the peak-to-peak distance ($\Delta_{pp}$), providing the single pulse charge in ADC channel at the specified voltage and amplification gain. The single photon signal at gain $G = 1$ ($\Delta_{pp}^1$) and at fixed bias $V$, namely the condition in use for gamma and neutron detection, was measured by extrapolating the values of $\Delta_{pp}$ at different amplification settings, as shown for instance in Fig. 4, again for the reference bias of 55.5 V (4 V above the breakdown voltage). A residual difference between digitisation and integration of the direct output of the SiPM, DC coupled to the input of the digitiser, and the gain 1 setting of the AC coupled amplifier in the SP5600 unit was measured comparing the most probable value of the response of the system in the two configurations to a high light intensity pulsed illumination. This procedure lead to a final scaling factor $k_{AC/DC} = 0.8830 \pm 0.0001$, taken into account when calibrating the energy response in photoelectrons.

Moreover, the multi-photon spectrum offers the possibility to measure:

- The optical crosstalk, fitting the spectrum with the convolution of the Poisson probability describing photon emission by a pulsed light source and the geometrical distribution for the crosstalk [15]. This figure is required to extract the statistics of primary photoelectrons in pulses originated by gamma and neutrons.
- The relative PDE by a variation of the mean number of detected photons in a pulse at constant illumination for different SiPM biasing voltages [16].

As by-product of this analysis, the breakdown voltage of the sensor was also calculated as the value of $V$ where $\Delta_{pp}$ is null.

For these measurements, the data acquisition was synchronous to the PicoQuant pulsing and signals were digitised over a 4 $\mu$s long window, with the peak of the signal located located 2 $\mu$s after its opening. For every run at different conditions, about 150 000 pulses were digitised, recorded, integrated and histogrammed. A multi-gaussian function was fitted over every spectrum, in order to calculate $\Delta_{pp}$, defined as the mean distance between adjacent peaks. This procedure was repeated for amplification gains ranging from 24 dB to 38 dB with step 2 dB and biasing voltages ranging from 54.5 V (3 V above the breakdown voltage) to 58 V (6.5 V above the breakdown voltage). By the end of this analysis, an extrapolation of $\Delta_{pp}$, values obtained at different voltages and gain 32 dB returned a breakdown voltage $V_{bd} = 51.42 \text{ V} \pm 0.04 \text{ V}$.

The optical crosstalk and the variation of the PDE with
the biasing voltage were extracted by the same data set. However, it was instrumental to process the data to produce multi-photon spectra based on the use of the peak value of every waveform rather than the integral, since detector related spurious effects, notably after pulses, delayed crosstalk and dark counts are expected not to come into play. This is evident in the exemplary spectrum shown in Fig. 5, again for the reference bias 55.5 V.

Once $\Delta_{pp}$ is known, the average value of the amplitude distribution can be converted into number of fired cells ($\mu_{exp}$). This value accounts for the number of detected photons $\mu_0$ and the effective optical crosstalk $X$, with a dependence that can be modelled as [17]:

$$\mu_{exp} = \frac{\mu_0}{1 - X} \quad (2)$$

Under the assumption of a Poissonian distribution of emitted photons, the value of $\mu_0$ can be obtained as:

$$\mu_0 = -\log(P_0) \quad (3)$$

where $P_0$, the probability of having 0 fired cells, can be simply calculated as the fraction of the events with a pulse height $\leq 0.5 \times \Delta_{pp}$. Experimentally, crosstalk probabilities ranging from 13% to 25% were measured, corresponding to biasing voltages ranging from 3 V from 6.5 V above the breakdown voltage.

Since $\mu_0$ is proportional to the PDE of the sensor, its trend against biasing voltage variations actually maps changes in the PDE. Results are shown in Fig. 6, normalised according to the producer's specifications, namely PDE = 40% at $V_{ov} = 3 V$.

C. NEUTRON-GAMMA DISCRIMINATION

As of the characterisation reported in [3] and the comparative analysis performed in [18], neutron-gamma discrimination was based on a Pulse Shape Discrimination (PSD) variable corresponding to the energy deposited in the tail of the signal, normalised to the pulse height:

$$PSD = \frac{\int_{t_s}^{t_s+t_w} S(t) dt}{\max(S(t))} \quad (4)$$

where $S(t)$ is the digitized signal, $t_s$ marks the beginning of the tail and $t_w$ its length. The optimal limits for the tail integration were identified by scanning the parameter space and identifying the region with the highest discrimination power, quantified by a Figure of Merit (FOM) defined as [14]:

$$FOM = \frac{PSD_n - PSD_\gamma}{FWHM_n + FWHM_\gamma} \quad (5)$$

where $PSD_n$ and $PSD_\gamma$ correspond to the mean values of the PSD distributions for gamma rays and neutrons, respectively, while $FWHM_n$ and $FWHM_\gamma$ are their Full Widths at Half Maximum. Discrimination is assumed to be statistically relevant when $FOM > 1.27$, corresponding to a 3$\sigma$ separation between the distributions of the PSD variables for neutrons and gammas, presumed to be gaussians.

For each biasing voltage, on average, 500000 events were recorded, digitised and analysed. Fig. 7 shows an exemplary outcome of the optimisation procedure of the algorithm, showing the variation of the Figure of Merit against the PSDs parameters $t_s, t_w$ (data recorded at the reference bias of 55.5 V). Fig. 8 shows an exemplary 2D histogram of the PSD values against the deposited energy in response to $^{252}$Cf; here gammas and neutrons form two clearly separated regions, for energies above 1 MeV. An exemplary distribution of the PSD values in the $[1, 1.5]$ MeV range of deposited energy is shown in Fig. 9.

III. EXPERIMENTAL RESULTS

For every excess voltage, namely for every PDE, the value of the deposited energy required to achieve $FOM = 1.27$...
was estimated by analyzing the PSD variable distribution in different deposited energy bins, initially 100 keV wide for edges ranging from 150 keV to 1 MeV. Subsequently, the width was doubled at every bin, in order to compensate for the smaller size of the sample as the energy increased. The minimum energy necessary to reach $FOM = 1.27$ ($E_{1.27}$) was calculated by fitting the variation of the FOM with respect to the energy by means of an exponential function:

$$FOM(E) = a \cdot \left(1 - e^{-[(E-b)/c]}\right)$$  \hspace{1cm} (6)

An exemplary trend of the FOM variation at the 55.5 V reference voltage is shown in Fig. 10.

The minimum number of photoelectrons corresponding to an energy deposit of $E_{1.27}$, namely $N_{1.27}$, can be derived through the calibration of the deposited energy in photoelectrons taking into account the effective crosstalk and $k_{AC/DC}$, namely:

$$N_{1.27} = (m \cdot E_{1.27} + q) \frac{k_{AC/DC}}{\Delta_{pp}}(1 - X)$$  \hspace{1cm} (7)

whereas $\Delta_{pp}$ is the $\Delta_{pp}$ extrapolated at linear gain $G = 1$ and $m, q$ are the energy calibration coefficients.

The variation of $E_{1.27}$ as a function of the over-voltage of the sensor ($V_{ov}$) is shown in Fig. 11, with a statistically significant decreasing trend as expected by the PDE variation. However, when $E_{1.27}$ values are turned into photoelectrons, experimental data correspond to the results shown in Fig. 12, where the hypothesis of a constant “minimum amount of information”, corresponding to 316 ± 19 photoelectrons is statistically acceptable.

In order to verify this conclusion, data presented so far were complemented by a different set, coupling a bar of the same EJ-276 scintillator with a higher light yield to a SiPM from the same family. Difference in the light yield was possibly due to ageing in the scintillation properties, with the two bars tested right after the delivery by the producer and after three years on the shelf. Since the two detectors were tested at different over-voltages and featured differences in the PDE, data were displayed against number of photoelectrons per keV of deposited energy. Data on the trend of $E_{1.27}$ are shown in Fig. 13, where the dependence on the system sensitivity is made stronger, while the corresponding number $N_{1.27}$ of photoelectrons is shown in Fig. 14. The weighted mean number of photoelectrons required to reach $FOM = 1.27$ was...
found to be, in the two data sets:

\[
\begin{align*}
N_{1.27}^a &= 316 \pm 19 \\
N_{1.27}^b &= 314 \pm 35
\end{align*}
\]

The statistical compatibility of the results confirms the hypothesis of linking the minimum value of deposited energy for discriminating gamma from neutrons to the photoelectron statistics, with a combined value for the specific system under study of \(N_{1.27} = 316 \pm 17\).

### IV. CONCLUSIONS

A neutron sensitive plastic scintillator bar (EJ-276 by Eljen Technologies) coupled to a SiPM has been used to investigate the impact of the detected light intensity on neutron-gamma discrimination based on pulse shape analysis. The single photon sensitivity of SiPM has been exploited to go from a qualification based on a macroscopic observable, the minimum deposited energy for a statistically relevant discrimination, to the corresponding microscopic quantity, namely the number of detected scintillation photons. For the system under study and the implemented algorithm, based on the ratio between the signal peak value and the integral in the tail of the pulse over an optimal window, 316 ± 17 photo-electrons are required to discriminate pulses originated from gamma rays and neutrons. The value was shown to correspond to different deposited energy values as the PDE was changed in a controlled way for the sake of the investigation.
Fig. 14. Minimum number of detected photons ($N_{1.27}$) required to reach FOM = 1.27 shown as a function of the system sensitivity (in terms of p.e./keV). The labels “2021 data” “2019 data” are used in the same sense of Fig. 13. The blue line corresponds to the weighted mean and the $\chi^2$ value shows a fair agreement with the hypothesis of having a constant $N_{1.27}$ as the operational conditions are changed.

Apart from quantifying the rather obvious need for a high light yield material and optimal coupling to a highly sensitive photon detector, the method sheds light on the possibility to compare different gamma-neutron discrimination algorithms and procedures, qualified according to the efficiency in extracting information from the available statistics of photons and robustness against statistical fluctuations.

REFERENCES

[1] R. Klanner and F. Sauli, “Silicon Photomultipliers: Technology, characterisation and applications,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 926, pp. 1–152, 2019.

[2] S. West, D. Beckman, D. Coupland, N. Dallmann, C. Hardgrove, K. Mesick, and L. Stonehill, “Compact readout of large CLYC scintillators with Silicon Photomultiplier arrays,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 951, p. 162928, 2020.

[3] R. Santoro, M. Caccia, N. Ampilogov, L. Malinverno, C. Allwork, M. Ellis, A. Abba, F. Caponio, and A. Casimato, “Qualification of a compact neutron detector based on SiPM,” *Journal of Instrumentation*, vol. 15, no. 05, p. C05053, 2020.

[4] R. M. Preston, J. E. Eberhardt, and J. R. Tickner, “Neutron-gamma pulse shape discrimination using organic scintillators with Silicon Photomultiplier readout,” *IEEE Transactions on nuclear science*, vol. 61, no. 4, pp. 2410–2418, 2014.

[5] N. Dinar, D. Celeste, M. Silari, V. Varoli, and A. Fazzi, “Pulse shape discrimination of CLYC scintillator coupled with a large SiPM array,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 935, pp. 35–39, 2019.

[6] C. Liao and H. Yang, “Pulse shape discrimination using EJ-299-33 plastic scintillator coupled with a Silicon Photomultiplier array,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 789, pp. 150–157, 2015.

[7] M. L. Ruch, M. Flaska, and S. A. Pozzi, “Pulse shape discrimination performance of stilbene coupled to low-noise Silicon Photomultipliers,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 793, pp. 1–5, 2015.

[8] M. Taggart, J. Henderson, J. O'Neill, R. Hawrami, E. Ariesanti, A. Burger, and P. Sellin, “Fast-neutron response of the novel scintillator caesium hafnium chloride,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1012, p. 165224, 2021.

[9] M. Grodzicka-Kobyłka, T. Szczesniak, M. Moszyński, K. Brylew, L. Swiderski, J. Valiente-Dobón, P. Schotanus, K. Grodzicki, and H. Trzaskowska, “Fast neutron and gamma ray pulse shape discrimination in EJ-276 and EJ-276g plastic scintillators,” *Journal of Instrumentation*, vol. 15, p. P03030, mar 2020.

[10] T. Huang and Z. Zhang, “Characterization of 1-inch CLYC scintillator coupled with 8 x 8 SiPM array,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 999, p. 165225, 2021.

[11] M. Taggart, M. Nakhostin, and P. Sellin, “Investigation into the potential of GAGG: Ce as a neutron detector,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 931, pp. 121–126, 2019.

[12] “Multi-Pixel Photon Counter (MPPC) - S13360 series.” HAMAMATSU Photonics, datasheet: https://www.hamamatsu.com/resources/pdf/s13360_series_kapd1052e.pdf.

[13] “Pulse shape discrimination ej-276 & ej-276g.” Eljen Technologies, datasheet: https://eljentechnology.com/products/plastic-scintillators/ej-276.

[14] M. Taggart and P. Sellin, “Comparison of the pulse shape discrimination performance of plastic scintillators coupled to a SiPM,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 908, pp. 148–154, 2018.

[15] V. Arosio et al., “Reconstruction of the statistics of photons by a pulsed led using a silicon photomultiplier based set-up,” *Journal of Instrumentation*, vol. 10, p. C08008, 2015.

[16] M. Antonello et al., “Tests of a dual-readout fiber calorimeter with sipm light sensors,” *Nuclear Inst. and Methods in Physics Research A*, vol. 899, pp. 52–64, 2018.

[17] C. Piemonte and A. Gola, “Overview on the main parameters and technology of modern silicon photomultipliers,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 926, pp. 2–15, 2019.

[18] L. Malinverno, “An optimisation procedure for pulse shape discrimination algorithms tailored for hand-held nuclear security instruments,” *IL NUOVO CIMENTO*, vol. 41C, p. 123, 2018.