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The PARIS cluster coupled to the BaFPro electronic module: data analysis from the NRF experiment at the γELBE facility

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Abstract. The first cluster of the constructed PARIS calorimeter was assembled and tested at the γELBE facility at HZDR, Dresden, Germany. The experiment was aimed at the evaluation of the performance of each detector separately as well as the whole PARIS cluster with discrete γ-ray energies seen by the PARIS ranging up to 8.9 MeV. As the detectors use *phoswich* configuration, with 2'' x 2'' x 2'' $LaBr_3(Ce)$ crystal coupled to 2'' x 2'' x 6'' NaI(Tl) one, great care must be taken during the data analysis process to obtain the best possible values for energy resolution. Two algorithms for data transformation from matrices created with slow vs fast pulse shaping to energy spectra were tested from which one was chosen for further analysis. An algorithm for adding back energies of γ-rays scattered inside the cluster was prepared, as well. Energy resolution for γ-rays in 2–8 MeV range was estimated and is presented in this paper.

1. Introduction

The **P**hoton **A**rray for studies with **R**adioactive **I**on and **S**table beams (PARIS [1]) is a new 4π calorimeter whose properties combine high detection efficiency and energy resolution for γ-rays in energy range from 500 keV to 50 MeV. It will be made of *phoswich* detectors, consisting of 2'' x 2'' x 2'' crystals of a new generation scintillator of $LaBr_3(Ce)$ backed by 2'' x 2'' x 6'' crystal of standard material of NaI(Tl) with a common PMT, arranged in clusters of nine (Fig. 1). This configuration ensures high efficiency, yet, as light impulses emitted from those materials differ significantly, resulting in distinguishable from each other signals shapes, Pulse Shape Analysis (PSA) methods must be engaged. Additionally, an event of the 511 keV γ-rays escape from a crystal is common in high γ-ray energy range, which calls for an extra off-line procedure to suppress that effect.

This array will be used in a number of nuclear physics cases spanning from time measurements of weak discrete transitions to measurements of properties of exotic collective modes such as Giant Quadrupole Resonances [2], [3] and Pygmy Dipole States [4], [5]. What all those

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experiments will have in common are complexity and high exclusiveness of the events of interest. Thus, it is crucial to fully characterise the PARIS performance and prepare algorithms and methods, which will help obtain the best possible results, beforehand.

2. Experimental setup

During the Nuclear Resonance Fluorescence (NRF) experiment at the γELBE facility [6] at HZDR, Dresden, Germany, a 16 MeV electron beam was converted into Bremsstrahlung photons, which subsequently irradiated the target of 4 g of ^{11}B. In this way mainly the states at 2125, 4445, 5020, 7285 and 8920 keV were excited and the respective transitions to the ground-state were measured. The PARIS cluster was placed at the backward angle of 125° and the detectors were shielded from the beam with the use of lead blocks. At the front, absorbers made of copper and lead were mounted. The used PMT coupled with each PARIS *phoswich* was Hamamatsu R7723-100.

Figure 1. PARIS cluster. Marked are numbers of the detectors.

Data were taken using an analogue BaFPro [7] electronic module which has two branches of pulse shaping: fast and slow, corresponding to amplitude and charge of the impulse respectively. Both signals were collected and obtained information was used to separate three kinds of events (with full photon energy deposition in LaBr$_3$(Ce), in NaI(Tl) and partial deposition in both materials). As an example a matrix containing data obtained with fast and slow pulse shaping of signals with marked its crucial properties is presented in Fig. 2. There were two time information sets, derived from both devices independently. Standard radioactive sources: ^{60}Co and ^{137}Cs were used for calibration.

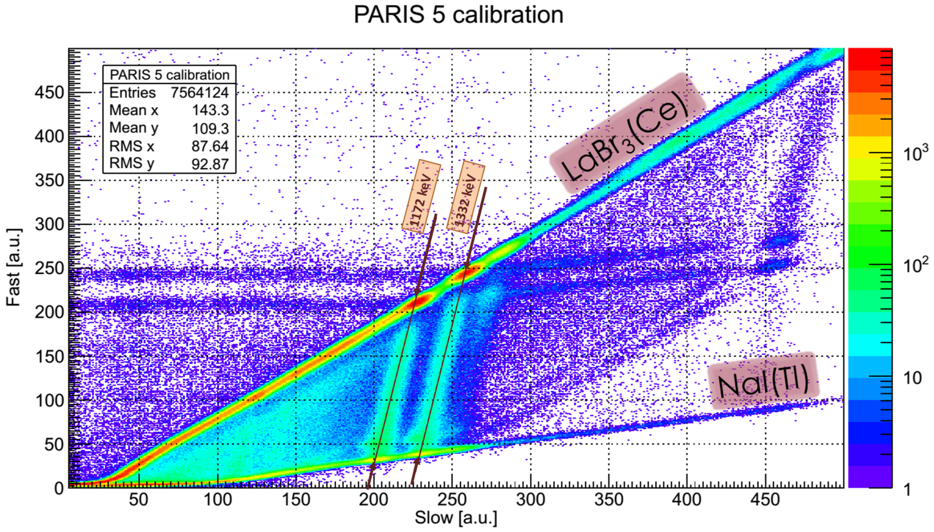

Figure 2. Fast vs. Slow matrix of one of the *phoswich* detectors from the calibration run with ^{60}Co and ^{137}Cs sources. Marked are lines of events understood as full energy deposition in one material only and parallel lines of the events corresponding to the same primary γ-ray energy.

3. Internal add-back

As was mentioned above, the signals from $LaBr_3$(Ce) and NaI(Tl) part of the *phoswich* detector differ by their rise time of typically 23 ns for $LaBr_3$(Ce) and 213 ns for NaI(Tl)[8]. Additionally $LaBr_3$(Ce) light yield is twice that of the one for NaI(Tl) which provides higher amplitude and bigger charge collected in the impulse for the same initial γ-ray energy. The process of separate, proper treatment of those signals and later building one common energy spectrum is a so-called *internal add-back*. The method would vary depending on the electronic set-up. In case of data from the BaFPro module it is possible to handle the fast and slow information as two versors and use a simple linear transformation of the basis they form.

There are two transformations of interest focusing on different aspects of Fast vs. Slow matrix. As one can see in Fig. 2, diverse events (pure deposition in one of the materials or scattered) with the same initial γ-ray energy form a line and lines corresponding to different γ-ray energies are parallel. Thus, energy spectrum can be simply obtained by rotation of a matrix by such an angle that those lines are parallel to Y-axis (Fig. 3). The energy spectrum can be built by taking into account only an X-component in the new basis.

The second approach uses the fact that the events with full energy deposition in only one material of the *phoswich* form a line. By the orthogonalisation process it is possible to change the basis to one where the energy deposited in $LaBr_3$(Ce) and energy deposited in NaI(Tl) part of the detector are used as versors (Fig. 4). This way the information of the place of the signal origin is conserved, however the number of needed parameters is larger resulting, due to uncertainties, in more unstable method. The energy spectrum is obtained by adding values of the two components.

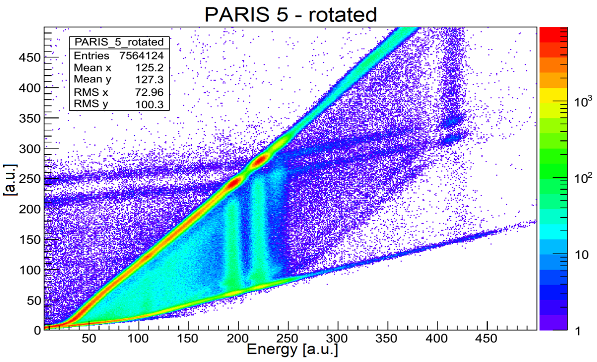

Figure 3. View of a rotated Fast vs. Slow matrix. Lines corresponding to events with the same primary γ-ray energy are parallel to the Y-axis.

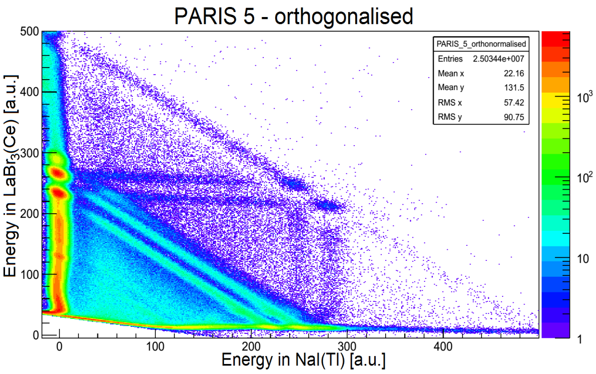

Figure 4. View of an orthogonalised Fast vs. Slow matrix. The angle of the lines corresponding to events with the same primary γ-ray energy is 135° in regard to the X-axis.

Unfortunately, the non-linearities of the data acquisition system for the low γ-ray energies exist. The angle between the lines of $LaBr_3$(Ce) and NaI(Tl) events is acute, thus the orthogonalisation stretches the plane between them, making the non-linearities especially visible in Fig. 4. Because of them the first approach, rotation transformation, proved to perform better than orthogonalisation and therefore became a method of choice for data from this experiment.

4. External add-back

For high energy γ-rays the primary interaction with the matter is via pair production. Hence, the creation of two secondary 511 keV photons is common, which in turn can escape from the detector creating single- and double-escape peaks in the energy spectra. The main advantage of the cluster configuration is a possibility to add the scattered γ-rays together and fill the original spectrum with the whole detected energy of the photon. This process is a so-called *external add-back*.

The employed algorithm is based on recurrence and is performed on calibrated data. When the detector provides a signal for an event, the surrounding detectors are also checked. All the energies are added together and fill the spectrum of the detector in which most of the energy was deposited.

In this analysis the external add-back procedure was performed after the internal add-back. Figure 5 illustrates the performance of the method showing spectra gated with multiplicities of photons detected in neighbourhood of the prime detector in one event. For higher multiplicities the ratio of single- and double-escape peaks to full absorption peak is getting smaller.

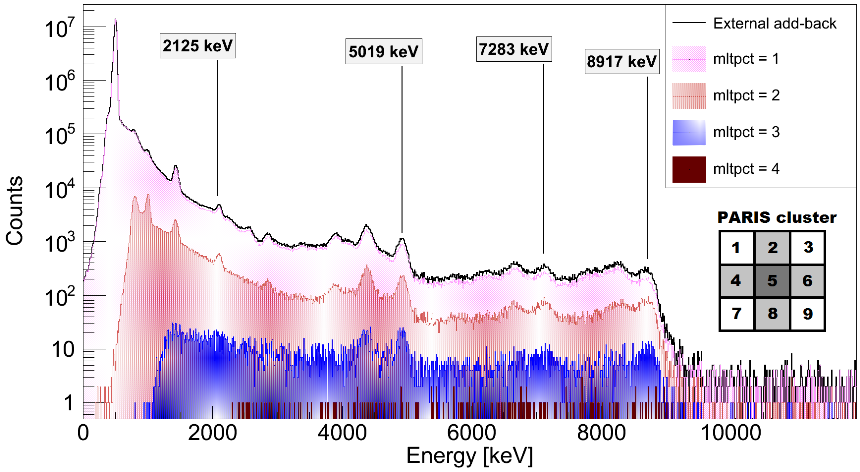

Figure 5. Reconstructed by external add-back procedure in-beam spectrum of γ-rays detected by the *phoswich* no. 5 and neighbouring detectors of the PARIS cluster (black line). Components of the external add-back spectrum corresponding to separate multiplicities are also shown. Marked are full absorption peaks. Increase in number of counts in the full absorption peak for 8917 keV line after external add-back is around 50%.

5. Energy resolutions

Energy resolutions were obtained with the use of ROOT framework Minuit library. Two fitting functions were used:

- $f(x) = p_1 + p_2 x + p_3 \exp\left(-0.5\left(\frac{x-p_4}{p_5}\right)^2\right)$ – a Gaussian function on linear background;
- $f(x) = p_1 + p_2 x + p_3 \exp\left(-0.5\left(\frac{x-p_4}{p_5}\right)^2\right) + p_6 \exp\left(-0.5\left(\frac{x-p_7}{p_8}\right)^2\right)$ – two Gaussian functions on linear background, where: p_1, p_2 – parameters of linear background; p_3, p_6 – parameters proportional to the peaks' integrals; p_4, p_7 – mean values of the peaks; p_5, p_8 – standard deviations of the peaks.

The second function was used for fitting peaks in the high-energy region where full absorption peaks significantly overlap with single-escape peaks. Those functions proved to stably reproduce standard deviation and centroids for various initial parameters. However, the rest of the fit parameters was more dependant on starting values.

Obtained preliminary values for the one of the detectors during subsequent steps and sum of all nine spectra after analysis (*full add-back*) are shown in Table 1. The values for pure

Table 1. Energy resolutions for one of the detectors during subsequent steps of data processing and for the whole cluster (full add-back).

Energy [keV]	Detector no. 5				Full add-back
	$LaBr_3$(Ce)	NaI(Tl)	Internal add-back	External add-back	
2124	2.59(31)%	3.40(85)%	3.33(15)%	3.28(19)%	3.26(05)%
5019	2.19(05)%	3.80(49)%	2.91(11)%	3.24(09)%	2.70(03)%
7283	1.81(16)%	3.17(1.0)%	2.31(29)%	2.64(25)%	2.60(09)%
8917	1.84(08)%	2.78(49)%	2.21(08)%	2.36(07)%	2.38(10)%

$LaBr_3$(Ce) and NaI(Tl) were evaluated with the use of gated on those events spectra from an initial, before any numerical procedure, Fast vs. Slow matrix. The number of events for high energy γ-rays in those spectra is small, resulting in high uncertainty for obtained values. As one can see the energy resolution of the *phoswich* is always worse than of the pure $LaBr_3$(Ce) part, yet it is better than of the pure NaI(Tl). The energy resolution slightly worsened for a spectrum after external add-back. It was possibly caused by the non-linearities of the data acquisition set-up. Evaluation of those non-linearities will be the next step of the data analysis.

6. Summary

The experiment held at the γELBE facility was an important step in evaluating the PARIS cluster performance. One of the noteworthy results of this test is the creation of the algorithms for the analysis of the data collected with the analogue BaFPro module. The evaluation of two algorithms for internal add-back showed, while using with BaFPro module, the better method to employ is the rotation transformation of a matrix. Comparing the energy spectra of $LaBr_3$(Ce) part only and the whole detector after internal and external add-back, a significant rise in full absorption peak height on the cost of slightly worse energy resolution was observed. This outcome, although expected, is promising.

Acknowledgements

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