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Determination of the hit locations in segmented HPGe detectors without the use of simulations or scanning systems

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ABSTRACT

A new method is proposed which allows the building of a signal basis, i.e. a matrix of traces corresponding to identified locations of gamma interactions with the crystal, directly from a set of signals delivered by the detector. The usual on-line algorithms dedicated to the location of the hits can apply this basis to perform signal decomposition. The method also provides Jacobian transforms that can be used to compute very quickly the hit locations in situations when signals are not overlapping.

1. Introduction

The major methodological advance in the detection of gamma rays, since the beginning of the century, is the ability to determine the locations of their interactions within HPGe crystals [1,2]. Knowing the location of the first interaction allows to define precisely the emission direction of a gamma ray, so that its energy can be corrected from the Doppler shift due to the velocity of its source.

The locations of the gamma/crystal interactions are obtained through the pulse shape analysis (PSA) of the signals [3,4] created by the drifts of the resulting electrons and holes in the field imposed to the crystal. A large number of methods and algorithms have been developed to solve this inverse problem. They consist of comparing each signal detected during the experiment to a basis of signals corresponding to identified hit locations. The simple but very fast grid search algorithm [5] involves the systematic comparison of the detector signals with all the basis signals. The problem can also be solved more effectively but more slowly [6,7] using different versions of non-negative least squares methods [8,9] or Bayesian backtracing [10]. Signal bases are obtained in two ways: they can be generated using a signal simulation code or they can be measured using a crystal scanning system [11,12], i.e. a device including a collimated gamma source and detectors surrounding the crystal that allow the identification of scattered gamma rays and thus the localization of the hit. Scanning systems based on other operating modes have also been developed [13,14]. Both methods have advantages but also shortcomings. Indeed, it is extremely difficult to include in a simulation all the physical characteristics of the crystal and the distortions induced by the associated electronics [15]. In addition, each detector has a response function of its own. Regarding scanning tables, the full characterization of a detector is extremely long (typically several months). Moreover it is difficult to reproduce the exact conditions of operation of the detector in its final environment.

In this paper, we introduce a new approach to the problem of pulse shape analysis which overcomes the need to use a simulation or a scanning system to generate the signal basis. We show how the location of the hits can be obtained directly from the shape of the signals delivered by the detector in the experimental conditions. We present here only the foundations of the method that can be applied to any kind of segmented HPGe detector. Its practical application to signals delivered by AGATA will be presented in a companion paper. AGATA (Advanced GAmma Tracking Array) [16] is the new generation European gamma-ray 4 π detector for nuclear spectroscopy. In its final version, it will be composed of 180 crystals (shown in Fig. 1, upper panel) forming a sphere.

This method allows doing without simulated signals. However, in order to validate it, we will use signals generated by two simulation codes: MGS [17] and AGATAGeFEM [18] in which the geometry of the AGATA detectors has been implemented.

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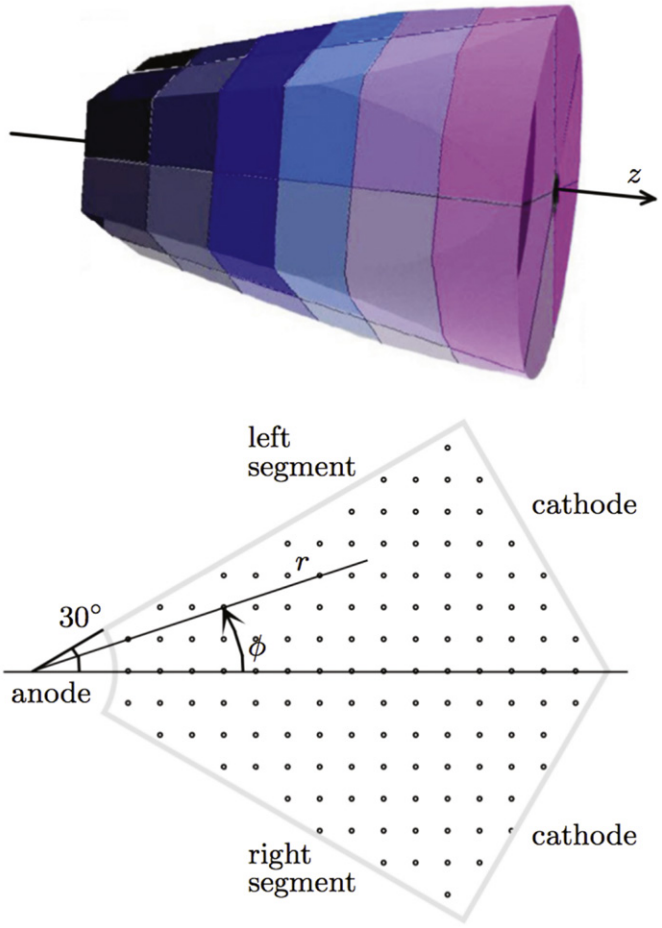

Fig. 1. (Color online). Upper panel: AGATA HPGe crystal. The outer surface is covered by 36 cathodes (six rings of six portions). A central hole along the z-axis is covered by the anode. The length of the crystal is 90 mm and its maximum diameter is 80 mm. Lower panel: typical segment as seen perpendicular to the z-axis. The dots show the locations of the simulated hits for a $2\times2\times2$ mm grid.

2. Method

2.1. Introduction

At first, we will focus on signals induced by isolated hits. Indeed, when several hits occur simultaneously in a segment or adjacent segments of the crystal, the resulting signals are added together. We will come back to the problem of signal decomposition in the last section.

To locate a hit from the signal shape, we will rely on some characteristics of the response function of segmented HPGe crystals:

- The shape of the net signal in the hit segment depends mainly on the distance of the interaction to the cathode.
- A hit induces signals in the neighboring segments. The closer the hit, the larger the induced signals.
- Inside a segment, the evolution of the shape of the signal as a function of the hit location is continuous.

We will also rely on some properties of gamma detection:

- The number of hits decreases exponentially with the depth z of penetration into the detector.
- The attenuation coefficient μ depends only on the energy of the gamma.
- The distribution of the interactions perpendicular to the z-axis is homogeneous (if the detector is not placed too close to the source).

2.2. Jacobian transforms

To determine a precise relation between the characteristics of the detected signals and the coordinates of the hit, we will use a Jacobian transform. To illustrate this, we first consider the angular coordinate ϕ, Fig. 1, perpendicular to the z-axis. Based on the properties of segmented crystals, this coordinate can be estimated using the variable φ equal to the normalized difference of the energies of the induced signals in the right and left neighboring segments:

$$\varphi=\frac{\sum_i S_{l_i}^2-S_{r_i}^2}{\sum_i S_{l_i}^2+S_{r_i}^2} \tag{1}$$

where S_l and S_r are the left and the right induced signals and i the number of the sample. The results of the correlation between the coordinate and its estimator for all the segments are shown in Fig. 2(a) for simulated signals. This correlation is not linear and its shape probably depends on the simulation or the detector. The distribution of the φ variable is shown in Fig. 3 (the values of the variable are multiplied by 30 so that its range becomes the same as the range of the ϕ coordinate). Its U shape is due to the accumulation of values close to ±1 as can be seen in Fig. 2(a).

We can now improve the correlation by using the property that the distribution of hits perpendicularly to z is flat. This means every value of ϕ has the same probability. To be more precise, we must also take into account the hexagonal shape of the crystal: the values of ϕ close to 0° are slightly more probable than those near $\pm30^\circ$ (see Fig. 1, lower panel). Thus, this density function can be calculated exactly using geometrical considerations only (Fig. 3). The density distribution of the variable φ is quite different (this could have been inferred from the S shape of the correlation). It is therefore necessary to modify the estimator φ so that its distribution is equal to that of the coordinate. The transformation $t(\varphi)$ enabling this is obtained from the following equation [19–21]:

$$f_\phi(t(\varphi))=\frac{f_\varphi(\varphi)}{\left|\frac{\mathrm{d}t}{\mathrm{d}\varphi}\right|} \tag{2}$$

where the functions f are the density functions. The denominator of the right hand side is the *Jacobian* of the transform. This method applies only if the relation $\phi(\varphi)$ is monotonous, which is our case within point dispersions. After integration, the above equation can be rewritten as follows:

$$t(\varphi)=F_\phi^{-1}(F_\varphi(\varphi)) \tag{3}$$

where the F are the cumulative distribution functions corresponding to the density functions f: $F(x)=\int_{-\infty}^{x}f(x)\,\mathrm{d}x$. This equation is valid when the relation $\phi(\varphi)$ is increasing. For decreasing relations, we have $t(\varphi)=F_\phi^{-1}(1-F_\varphi(\varphi))$. The new resulting variable will be used as estimator of ϕ, thus, in the following, we will note $\phi_{est}=t(\varphi)$. The variable φ will be referred to as a *raw estimator*. As can be seen in Fig. 3, the distribution of the ϕ_{est} estimator exactly matches the distribution of the ϕ coordinate. We underline the fact that the transform is obtained using only the density function of the coordinate and the density function of the raw estimator. The former is deduced from the geometry of the segments and the latter from the signals delivered by the actual detector. Thus, no simulation is required in the method. The correlation between the coordinate and its estimator is shown in Fig. 2(b). The Jacobian transform has two effects: the range of the estimator is now the