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Gamma-ray Tracking with Segmented HPGe Detectors

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This paper gives a brief overview of the technical progress that can be achieved with the newly available segmented HPGe detectors. Gamma-ray tracking detectors are a new generation of HPGe detectors which are currently being developed to improve significantly the efficiency and resolving power of the 4π germanium detectors arrays for high-precision γ -ray spectroscopy. They consist of highly segmented HPGe detectors associated with fast digital front-end electronics. Through the pulse-shape analysis of the signals it is possible to extract the energy, timing and spatial information on the few interactions a γ -ray undergoes in the HPGe detector. The tracks of the γ -rays in the HPGe detector can then be reconstructed in three dimensions based on the Compton scattering formula. Such a detector has been used for the first time during an in-beam experiment. The γ -decay of the Coulomb excitation of a ^{56}Fe nucleus was measured with the highly segmented MARS prototype positioned at 135 degree. The energy resolution has been improved by a factor of 3 as compared to standard HPGe detectors due to very precise Doppler correction based on knowledge of the γ -ray track.

I Introduction

The future facilities for radioactive beams will allow, for the first time, the exploration of a new large area of the nuclear landscape. In connection with the study of the γ -radiation, it is important to point out that the intensity of such radioactive beams is expected to be much smaller than that of stable beams, Doppler Effects in many experiments are expected to be much stronger and an intense background of X-rays could be present. Consequently, a new generation of powerful HPGe arrays with segmented detectors is being designed. Both in USA and in Europe several projects, based on segmented HPGe detectors, have already started and are in an advanced status of realization. The objective of the more recent R&D efforts is to improve the total efficiency by removing the BGO shields without affecting the P/T ratio with the use of the tracking technique, namely the reconstruction of the γ -ray path to identify the γ -incident direction (for the Doppler correction), the removal of the background and to check whether or not the γ was fully absorbed in the array. Such development implies unprecedented R&D efforts where completely new technology has to be applied, tested

or developed in all the constituents of an HPGe array, from the detector to the front-end electronics. The typical feature of the energy deposition of a γ -ray is that of interacting in a limited number of positions. γ -tracking of this hits is a very challenging and ambitious task. First, one has to identify, isolate and localize each hit inside a segmented detector with pulse shape analysis based on the study of the physical mechanism of the pulse generation or with Artificial Intelligence techniques (like Neural Networks or Genetic Algorithm [1]) of the direct and induced electrical pulses produced by every interacting γ -rays. Second, a tracking algorithm has to reconstruct the real trajectory from the list of interaction points through statistical techniques. The result is expected to be the complete reconstruction of the track of the incident γ , namely the complete description of the interacting γ -ray. Worldwide efforts have been done using simulations and proof-of-principle measurements and turned out to be successful. The feasibility of the entire process of γ -ray tracking is demonstrated in this paper based on an experiment, done at the LNL in Italy, using the MARS prototype detector.

II Segmented HPGe detectors and tracking

Before building tracking arrays like AGATA [2] or GRETA [3], the design and performance of single segmented detectors has to be tested and evaluated. It is a crucial point to decide the design of the single modules which will be inserted into the 4π tracking arrays. It is of great importance to study the behaviour of these detectors under real experimental conditions, as well as the properties like eventual cross talk, transient signals, superposition of signals in one segment, long time performance, heat flux etc. The performance of the arrays built out of these segmented detector modules will be much higher than that of present arrays (Euroball, Gammasphere, GASP...) with an total efficiency of about 50% and a P/T better than 60% for single gammas of 1 MeV. The total efficiency is calculated to be about 30% for high multiplicity γ -events, this means one order of magnitude better than the actual arrays. Both in USA and in Europe several projects, based on segmented HPGe detectors, have already started and are in an advanced status of realization. In Germany the Miniball [4] project is based on encapsulated HPGe crystals which are six fold segmented. The EXOGAM [5] and the VEGA [6] arrays are composed by several segmented clovers. At the NSCL (MSU) [7] an array consisting of HPGe crystals, each segmented into 32 sections (4 segments in its surface base and 8 segments in its depth) will be installed. Some prototypes of compact and cylindrical 24-36 segmented HPGe detectors are already available and under study. For example, the TIGRE detector at the university of Liverpool is a 24-fold detector (6×4). The GRETA detector at the Lawrence Berkeley National Laboratory is a 36-fold prototype segmented six ways in depth and six ways longitudinally. The 37 FET's are located and cooled in the same vacuum as the crystal. Cold FET's provide low noise, which is important for optimising the energy and position resolution. The MARS prototype detector (Fig. 1) is a highly segmented HPGe detector manufactured by Eurisys with Köln type preamplifiers. It consists of a cylindrical crystal with 90 mm length and 72 mm diameter. It has a closed-end geometry with an inner hole of 10 mm diameter and 75 mm length. The outer contact of the detector is divided electrically in 25 segments: six angular sections and four transversal in depth. Cold FET's are used. The resolution obtained with standard analogue electronics at 1.33 MeV is about 2.2 keV. With the newly developed Milano type preamplifiers, the resolution is much better about 1.7 keV, together with a larger bandwidth and giving less noisy signal shapes [8]. With all these segmented detectors wide ranges of tests and source-experiments have been done. A complete scan inside one segment using γ sources and a collimated Compton coincidence setup [9] has been done and shows the pulse shapes as a function of the Compton interaction position. Crystal orientation effects on the drift velocity of the electrons and their influence on the pulse shape have been thoroughly studied with the GRETA and MARS prototype [10] [11] [13]. Precise simulations of pulse shapes with

the weighting field method have been made for the MARS [11] and GRETA detectors. The influence of the crystallographic orientation on the drift velocity of the electrons and holes (and therefore also on the pulse shape) is remarkable, especially in the front cap of the detector. Geant [14] simulations of single and multiple γ -interactions were done to get information about signal distribution [12] and mainly to develop tracking algorithms based on the Compton scattering formula [13] to reconstruct the path of the interacting γ -rays inside the detector. Two main types of algorithm are used, the cluster tracking algorithm [14] and the backtracking algorithm [16]. A major part of these R&D projects is to develop newly digital electronics for signal processing and amplification. Pulse shapes have been simulated [17] and algorithms have been developed to disentangle multiple interactions [18] in the single segments. For tests and experiments with the MARS prototype the pulse shapes are measured with a DAQ system made by an array of seven digital oscilloscopes. The signals from the preamplifiers were stored with a sampling rate of 200 MSamples/s and a resolution of 8 bit. The oscilloscopes are triggered by the preamplifier signal of the central contact of the detector. All possible proof of principle tests have been made with different types of segmented detectors. It is of great interest to test their performance and the feasibility under in beam experimental conditions. The analysis of data from segmented HPGe detectors have been widely studied. First, the signals from the FET's have to be preamplified and then digitally stored. These pulses have to be analysed to disentangle the three dimensional position of each interaction which has produced the pattern of pulses. Then a tracking algorithm has to reconstruct the most probable track the γ -ray may have followed inside the detector. Two pieces of basic information have to be determined. One is the first interaction point of the γ impinging the detector, which is necessary to estimate the γ -ray emission angle for the Doppler correction. The second is to determine the nature of the track, whether or not the γ has released all its energy within the germanium array and therefore useful to reject background events.

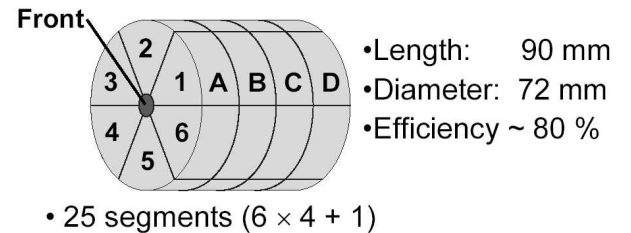


Figure 1. Schematic view of the $6 \times 4 + 1$ segmented HPGe MARS prototype detector.

III In beam experiment

A measurement of the γ -rays emitted from the Coulomb excitation of the ^{56}Fe nucleus was made using the MARS pro-

prototype detector. The setup and the reaction has been simulated using GEANT libraries in order to reduce as much as possible the Doppler broadening effect by determining the first point of interaction. The scattered particles were measured in coincidence with the PHOBOS Si pin-diodes to control the whole kinematics of the reaction (Fig. 2). The MARS detector was mounted under 135 degree (in the laboratory frame) in backward direction in the GASP setup. The PHOBOS Si-diodes (with an opening angle of 2.6 degree) were mounted at approximately 90 degree with respect to the MARS detector, to maximize the Doppler broadening for the scattered ^{56}Fe nuclei (Fig. 2). The FWHM of the measured peak is determined mainly by the Doppler broadening which is dominant over the other major contributions to the energy resolution as the finite opening angle of the individual si-detectors, the energy straggling due to the energy loss of the projectiles in the target before and after the scattering, and the finite size of the beam spot (about 4 mm diameter). The ^{56}Fe beam at an energy of 240 MeV has been delivered by the XTU Tandem Accelerator at Legnaro

and impinged on a 3.7 mg/cm^2 lead target. The scattering angle was 60 degrees in the laboratory system and the corresponding velocity was 8% of the light velocity. The cross section for excitation of the first 2^+ -state in ^{56}Fe at this scattering angle is about 250 mb/sr. The 847.8 keV peak of the first transition of the ^{56}Fe Beam was measured with a FWHM of 15.5 keV. Using the information of the central angle of the segment which undergoes the first interaction (highest deposited energy for energies higher than 500 keV) the peak width can be reduced by a factor of better than two. Assuming a "perfect" tracking, position determination and correct reconstruction of the scattering path, one expects an energy resolution of 2.7 keV (FWHM) as deduced from simulations. If a realistic position error of 5mm will be assumed for the simulation, the FWHM of the 848 peak will be 3.4 keV (FWHM). These values have to be folded with the intrinsic energy-resolution of the detector of 2.2 keV. Therefore, the present resolution for tracking was expected to be 4.2 keV.

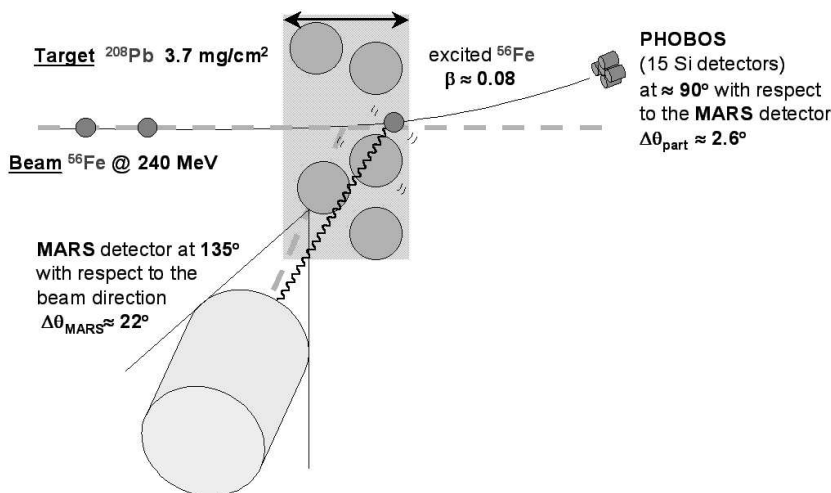


Figure 2. Setup of the in-beam experiment done at LNL with the MARS detector. A ^{56}Fe beam of 240 MeV is impinging on a 3.7 mg/cm^2 lead target. The velocity of the scattered nuclei corresponds to 8% of the light velocity. The excited ^{56}Fe is detected in the PHOBOS Si-detector array which consists of 15 single detectors with 2.6 degree opening angle. The γ -rays are detected in the MARS prototype which has an opening angle of 22 degree. The complete kinematics of the reaction is defined experimentally by detecting the γ -rays in coincidence with the excited ^{56}Fe ions.

IV Results

To retrieve the energy information of the digitally stored pulses of the described MARS experiment at the LNL (Italy) the moving windows deconvolution algorithm [19] was used. The decomposition of the signals (giving the position information of the gamma interaction) was done by the approach developed by Th. Kröll based on a genetic algorithm [1]. Weighting field calculations of different pulse shapes with a spatial resolution of some mm have been made to build a matrix for the genetic algorithm. This method was

developed and verified in collaboration between the MARS and the GRETA project. The simulated pulse shapes showed a good agreement with pulses recorded with the coincidence setup of the GRETA detector [3]. The effect of crystal orientation dependence of the pulse shapes was taken into account in the calculation of the base systems needed for the genetic algorithm. Pulses, which represent one or two interactions of gammas in one segment of the detector, have been used. The genetic algorithm evolves and aims to maximize possible random solutions of the problem regarding their fitness to reproduce the measured response. A defined stop-

criteria ends the evolution, the fittest event pattern found is taken as the result of the decomposition. The genetic algorithm and the cluster tracking algorithm could determine the first interaction point of the impinging γ -rays with a position resolution of 5mm. This is enough to improve the FWHM of the measured 847.8 keV γ -transition from 15 keV to 4.5 - 5.0 keV (Fig. 3).

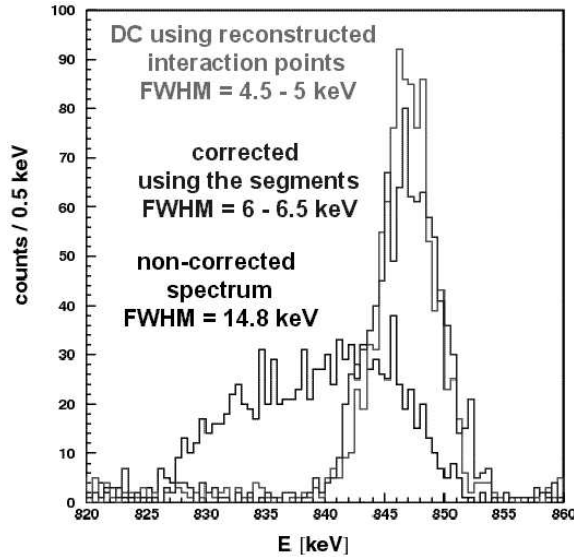


Figure 3. Measured (FWHM = 14.8 keV) and Doppler corrected spectra of the 848 keV peak. If the segment information (opening angle 9 degree instead of 22 degree of the whole MARS detector) is used for the Doppler correction, the peak can be corrected to a FWHM of 6-6.5 keV. If pulse shape analysis with genetic algorithm and tracking is applied for Doppler correction, the FWHM of the peak will be reduced to 4.5 keV.

V Conclusion

Worldwide efforts in developing simulation algorithms, tracking codes, pulse processing and analysing tools, digital data treatment and signal processing units have shown that tracking γ -rays is possible. In the first in beam experiment the feasibility of the major steps of the γ -tracking process have been successfully demonstrated. A preliminary analysis of the MARS experiment shows that the FWHM of the Doppler broadened 845 keV peak can be reduced by a factor of 3 namely from 15.5 keV down to 4.5 keV. This is in good agreement with the simulation predictions for a 5mm position resolution corresponding to a FWHM of 4.2 keV (see also Th. Kröll et al. [17]). This experiment is very promising for the design of future tracking arrays like Agata [2] or Greta [3]. The achieved performance of the Doppler correction outranges classical non-segmented germanium detectors by a factor of more than 3. Further work and R&D has still to be done to disentangle multiple interactions in single segments. In particular the whole digital electronic setup has to be built, signal shape analysis and

tracking should be made possible "on-line", before the final geometry of the single capsules for a big array is chosen for a large 4π array based on tracking.

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