NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A: accelerators, spectrometers, detectors and associated equipment

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In-beam experiment with the \(\gamma\)-ray tracking detector MARS

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Abstract

The feasibility of the entire process of \(\gamma\)-ray tracking is demonstrated experimentally for the first time. The accuracy of the results is verified by the capability to carry out a Doppler correction of \(\gamma\)-rays emitted in flight. The resolution of the 846.8 keV transition detected with the MARS detector after Coulomb excitation of a \(^{56}\)Fe beam could be improved from approximately 16 up to 4.6 keV (FWHM). This result corresponds to an obtained position resolution of about 6 mm (FWHM).

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1. Introduction

In the near future, new facilities to produce beams of radioactive ions will enable the exploration of nowadays unknown territories of the nuclear landscape. However, such investigations require the development of innovative instrumentation. In the past decade, high-resolution \(\gamma\)-spectroscopy has been the most powerful method for nuclear structure studies and large-volume high-purity Germanium detectors (HPGe) arranged in 4\(\pi\)-arrays have been, and still are, the most front-line technology. The next generation of such detector arrays will be based on the new concept of \(\gamma\)-ray tracking that should allow to achieve both high photopeak efficiency (\(>40\%\)) and good peak-to-total ratio (\(>60\%\)). For a recent review on the topic see Ref. [1]. An exciting perspective of the future \(\gamma\)-ray tracking arrays is that this very good performance is maintained even for events with high multiplicity of \(\gamma\)-rays and at high counting rates. Additionally, as the very high effective granularity of the detectors implies a good Doppler correction capability, a tracking array will extend the scope of high-resolution spectroscopy to the broad field of experimental situations with \(\gamma\)-rays emitted at high velocities. Furthermore, the sometimes harsh experimental conditions like background of X-rays from atomic processes at high rates which are Lorentz-boosted to energies up to several 100 keV or irradiation with light particles can be addressed. Hence, a
In the recent years, research and technical developments demonstrated the practical feasibility of the Italian project to develop the necessary ingredients and to construct the MARS—Mini ARray of Segmented detectors—was the first one of the scattering sequence.

Currently, there are two actual Ray Tracking Arrays under construction: AGATA [7] in Europe and GRETA in the USA [8,9]. The research and development work of MARS has partially merged into the wider frame of the AGATA collaboration.

The complete process of γ-ray tracking consists of the following steps [7,9,10]:

1. Detection of the γ-rays by highly segmented HPGe crystals;
2. Digitisation at high sampling frequency of the induced charge signals from the individual segments;
3. Recognition and characterisation of the interaction points of the γ-rays within the individual detectors by analysis of the pulse shapes of the digitised signals, the so-called decomposition;
4. Identification of each γ-ray by reconstructing (from the recognised interaction points) its scattering path through the complete array, the actual tracking.

In the recent years, research and technical developments have obtained interesting results (see e.g. Refs. [7–16]) on the way to an array based on the ideas of γ-ray tracking. Most of the studies on algorithms for tracking have been based on the analysis of simulated data only. The main aim of our experiment was to demonstrate for the first time the feasibility of the entire process of γ-ray tracking with experimental data. A similar measurement has been performed also with the GRETA prototype detector [11].

For this purpose, signals originating from interaction points at known positions are needed. As a matter of course, for simulated signals the interaction points are known, but experimentally this is a challenging task. Single interactions can be easily created next to the outer surface of the detector by low-energy γ-rays, as described in Section 4.2. For sources with γ-rays at higher energies, a single collimator determines only the position of the first interaction in two dimensions. Single interactions at a position well defined in three dimensions within the detector volume can be ensured by using a double collimation technique, but at very low counting rates [12]. However, there is no practicable way to produce events with multiple interactions at defined positions. Therefore, by analysing signals obtained in experiments with collimated sources the accuracy of reconstructed interaction points can be tested only in a limited way [16].

We have chosen as challenging test for our approaches the analysis of events measured in an in-beam experiment performed at the XTU Tandem Accelerator at Legnaro. In an indirect way the correctness of our results is proven by the capability for Doppler correction of γ-rays emitted by the excited nuclei in flight. The knowledge of the emission angle of a γ-ray is identical with the determination of its first point of interaction in the detector. Hence, the obtained energy resolution of the γ-rays after Doppler correction is a measure of the three-dimensional positional error of the first interaction point. Among the reconstructed interaction points the tracking algorithm identifies the first one of the scattering sequence.

In the following, we give first a short introduction to our approaches for decomposition and tracking. Then, the MARS prototype detector and the preparatory work performed with radioactive sources are presented. Finally, the in-beam experiment will be discussed in detail. Parts of the analysis of this experiment have already been published previously (see Refs. [4,5,17]). Here we present the conclusive results.

2. Decomposition and tracking algorithms

The details of our approaches to determine number and properties of the interaction points from the signals, the decomposition, and the reconstruction of the scattering path of the γ-rays from these reconstructed interaction points, the actual tracking, have to be left to dedicated publications [16,18]. Here, we will give only a brief summary of features necessary for the understanding of the analysis presented later in this paper.

For γ-ray tracking the positions of the interaction points are needed with a precision of a few mm, hence better than the precision defined by the size of the segment, which, for the large volume detectors used in γ-ray spectroscopy, is typically of a few cm. An improved characterisation is obtained by analysing the shapes of the signals from the segments. The dependence of the pulse shapes on the position of the interaction has been discussed extensively in a previous paper [13]. Often, more than one interaction takes place in the detector or even in one segment and the measurable signals are the sum of the signals originating from the individual interactions. Hence, the decomposition algorithm has to identify the number of interaction points and to characterise each of them by determining the three-dimensional position and the energy deposited. Consequently, several events consisting of varying number of interaction points placed all over the segment(s), have to be taken into account and evaluated in this analysis. The only criterion for the algorithm to evaluate a possible solution is the difference between the calculated signals of a simulated event and the measured signals of the experimental event. It is important to note that the decomposition procedure has to rely on the accuracy of the calculated signals because for practical reasons a measured system of reference signals is not available. Our algorithm for this task is based on a technique of artificial intelligence (AI), a genetic algorithm (GA). In the analysis of simulated signals including also
noise, the points of interaction can be localised within an average error of 2.5–5.4 mm [16].

The next step is the reconstruction of the scattering path of the γ-rays through the entire detector. Exploiting the fact that the interaction points of one specific γ-ray are often close to each other (in the sense of distance within Germanium), in our approach for a tracking algorithm [2,7,18], nearby interaction points are initially grouped into clusters of candidate points of hypothetical γ-rays. Within these clusters the order of the points is permuted, but also the membership of points to a cluster can be changed. Each track under consideration is evaluated according to a "figure of merit", a plausibility based on the properties of the three main interaction types of γ-rays in matter: Compton scattering, photoelectric effect, and pair production. This includes the fact that the distance between subsequent interaction points has to be consistent with the interaction probability of γ-rays at the energy under consideration. A track is accepted as valid, i.e. as a reconstructed γ-ray, if its "figure of merit" is below an empirically determined threshold. The efficiency of the tracking algorithm drops significantly if the positional error of the interaction points exceeds 5 mm.

3. MARS prototype detector

The MARS prototype detector is 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. As sketched in Fig. 1, the outer contact of the detector is divided electrically in 25 segments: six angular "sectors" (labelled 1–6) and four transverse "slices" (labelled A–D) plus an additional segment with a diameter of 10 mm in the centre of the front face (labelled F).

The segments are equipped with cold FETs whereas the central contact has a warm FET. The energy resolution (FWHM) of the segments obtained with standard analogue electronics is around 1.2 keV at 121 keV and 2 keV at 1332 keV, as required in the specifications. The results are slightly worse in the front cap (slice A), possibly because of the longer wires to the FET and of incomplete charge collection in zones with low electric fields. Due to the warm FET, for the central contact the energy resolution is typically 4 keV at 1332 keV.

The detector was delivered in November 2000 and has worked since then. A one time problem of an increased reverse current in one of the rear segments was solved by a thermic cycle done at the Legnaro detector laboratory.

4. Off-beam tests

4.1. Pulse shape and data processing

The properties of the MARS detector have been investigated with radioactive sources and procedures for pulse processing and data analysis have been developed. The results from these measurements concerning the decomposition of multiple hit events are presented in Ref. [16]. Here we focus on the technical details of the signal processing.

While drifting towards the contacts, the electrons and holes produced by the interaction induce signals which are integrated by the charge sensitive preamplifiers. If the contact of a segment collects the net charge released by an interaction, its signal has an amplitude which corresponds to the energy deposited by the γ-ray. An important feature of segmented detectors is that not only the segment which eventually collects the net charge released by the interaction has a signal, but also signals are induced in the neighbouring segments [10,19]. Since these signals have no net charge at the end, they are referred to as transient signals.

At the start time of the project, the availability of high resolution high sampling frequency electronics was rather problematic and we decided to develop a data acquisition system (DAQ) using an array of seven digital oscilloscopes LeCroy LT244 [20]. These oscilloscopes have four channels, a sampling rate of 200 MSamples/s, and a resolution of 8 bit. For the measurements presented here, the oscilloscopes are triggered by the central contact. Every sampled pulse comprises 10 μs, starting approximately 2–3 μs before the rising edge of the signal. For our analysis both net charge and transient signals are of equal importance [16]. The latter can be bipolar and their amplitudes may be up to 45% of the corresponding net charge signals [13]. To cover the amplitudes optimally, the vertical offsets of the oscilloscope channels were adjusted with the baseline of the signals placed at approximately 1/2 of the dynamic range. Every 50 events the data are read out from the internal memory of the oscilloscopes and written to hard disk. A drawback of this DAQ system is the low acquisition rate of about 10 Hz due to the slow read-out of the oscilloscopes via the GPIB bus. All the analysis is done off-line.

The determination of the energy deposited in a detector is conventionally done in analogue electronics by a shaping
amplifier and a peak-sensing ADC. In digital electronics this information has to be recovered from the signals sampled by the ADCs. For this purpose we applied the “Moving Window Deconvolution (MWD)” algorithm [22] using typically a window of 5–7 μs to average the noise and determine the amplitude of the signals. This corresponds roughly to a semi-Gaussian shaping of 3 μs in a standard spectroscopy amplifier.

The energy resolution obtained for the transition of interest, the 846.8 keV line in $^{56}$Fe seen in the decay of a $^{56}$Co source, was 2.2 keV for the segments. With the same dynamic range, the 122 keV line from a $^{152}$Eu source could be measured with a resolution of 1.9 keV, as it can be seen in Fig. 2. Since the trigger is derived from the signal of the central contact, a segment may also have a net charge signal, but often there are only noise (or transient) signals resulting in the “noise peak” which dominates the spectra. Ideally, the output of the digital filter to recover the energy information, in our case the MWD algorithm, for such signals should always be exactly zero. In reality, a narrow peak centred around zero appears in the spectrum, the “noise peak” seen in Fig. 2. Also X-ray transitions from isotopes populated in the decay of $^{152}$Eu can be seen. Even if these low-energy transitions may be below the trigger threshold set on the central contact, they are seen if a further energy deposit in another segment has caused the trigger. Conclusively, the achieved results are sufficient for our purpose and, hence, the 8 bit resolution of the oscilloscopes is no severe limitation for our tests.

Concerning the quality of this sampling electronics we would like to remark that by properly adjusting the dynamic range to match the amplitude of the 122 keV line, the achieved energy resolution is the same as with analogue electronics.

An annoying feature of this electronics is the modest differential non-linearity of the ADCs which had to be compensated to obtain the mentioned energy resolutions. Non-linearities are a common problem for measuring the energy of γ-rays outside of the range covered by the calibration with radioactive sources. For highly segmented detectors the energy of a γ-ray has to be reconstructed by summing up the energies from individual segments or interaction points, hence non-linearities are an even more severe limitation compared to unsegmented detectors. Therefore, the whole spectrum from zero, i.e. practically the noise amplitude, up to the maximum amplitudes is of interest and a reliable calibration has to be assured all over, in particular at low energies.

We investigated the non-linearity of the full dynamical range of the ADCs by sampling $10^5$ linear ramps obtained from a precision signal generator. As an example, Fig. 3 shows the count rates obtained for one typical ADC channel. Without any non-linearity one would expect an equal number of counts in every channel. The actual result differs considerably from such a flat distribution, according to the fact that smaller/wider channel widths result in lower/larger count rates. The maximum deviation from the average width of a ADC channel is of the order of 50% of a channel width in agreement with the specs of the oscilloscopes. A second feature which can be observed is a cyclic repetition of a 64 channel pattern within the 256 channels (8 bit ADC). From this measurement, we derived a look-up-table which maps every integer ADC channel to a new linearised floating-point value. This remapping was...
determined for all channels and applied regularly to the sampled signals before any further processing.

In the analysis of the data from γ-ray sources it has been noticed that the full energy peak position depends on the segment multiplicity. Namely the sum of the properly calibrated individual energies is smaller than measured when only one segment is involved. This energy deficit increases with the number of segments contributing to the sum [20]. Fig. 4 shows the sum energy for different multiplicities of segments which collected a net charge. The same effect has been observed processing the signals from the MARS detector with conventional analogue electronics of the GASP array at the Laboratori Nazionali di Legnaro [23] (see Fig. 4), hence it is not due to the digital treatment of the signals. We investigated this effect further and found that it is also present in some of the composite detectors, i.e. detectors which are not segmented, but consist of individual crystals, used in the EUROBALL array [24]. The CLOVER detectors for which the individual crystals share the same high voltage exhibit clearly the same kind of deficit, but not the CLUSTER detectors for which every crystal has its own high voltage.

In order to correct for this deficit, we have determined an individual recalibration for every combination of segments analysing a large data set collected with a $^{152}$Eu source and processed with the conventional analogue GASP DAQ system. As it can be seen in Fig. 4 (bottom), applying the extracted recalibration, the resolution can be improved from $\approx 6$ to $2.7$ keV at an energy of 1408 keV, hence the original resolution can be recovered [20]. Notice that this value is larger than the $2.2$ keV because summing up the energies from segments means that also their noise contributions are summed.

The observed deficit is explained by one model with a capacitive coupling via the capacitor of the high voltage supply [25,26], but there is also a contribution due to the capacitive coupling between the segments via the central contact [27]. These capacities have been measured and the values are in good agreement with the values calculated for the geometry of the MARS detector, as it can be seen in Fig. 5. Assuming a true-coaxial detector, one would expect a capacity of $1.7$ pF per segment.

Before summing up the energies from different segments a cut has to be applied in order to avoid contributions from segments with only noise (or transient) signals, i.e. to exclude the “noise peak”. However, applying such cut segments with very low energy deposits are lost and therefore the peaks show some tail on the low-energy side. Obviously, the higher the cut the more this tail extends towards lower energies. As demonstrated in Fig. 2, this cut can be as low as 5 keV.

Before passing the pulses to the decomposition algorithm, the sampling rate was reduced from 200 to 100 MSamples/s by averaging over neighbouring samples. Given that the bandwidth of the preamplifiers is around 10 MHz, this procedure does not influence the shape of the signals in an appreciable way. On the other side, we reduce by a factor of two the amount of data to be analysed and gain a fraction of a bit in the resolution of the ADC. Also the actual sampling rate considered for the final electronics of the γ-ray tracking arrays is 100 MSamples/s [7,9]. The signals were also slightly smoothed over three consecutive samples in order to further average the noise. The alignment of the signals in time, the quality of which is rather critical to achieve good performance, is handled autonomously by the decomposition algorithm [16]. Eventually, the individual signals were normalised with respect to the total energy of the event.

A very basic zero-suppression is performed in order to avoid the further processing of signals containing only noise. For every segment the average noise amplitude is

![Fig. 4. The sums of the individual segment energies for different segment multiplicities $F$ without (top) and for all multiplicities before and after the correction for the sum deficit (bottom) at a γ-energy of 1408 keV [20].](image1)

![Fig. 5. Measured (●) [27] and calculated (solid lines) capacities of the segments against the central contact.](image2)
determined from the baseline before the rise of the actual signal, i.e. the beginning of the 10 ms window containing the actual pulse as mentioned above. A segment is validated if the signal has more than two samples above a threshold of 3 times the average noise level. More sophisticated digital filters to detect signals, net charge as well as transient signals, have been developed recently [28,29]. Eventually, a preprocessed event consists of the pattern of validated segments and for each of them the signal and an average noise value. Non-validated segments are handled in the decomposition algorithm later on as segments with no signal, as described in Ref. [16].

4.2. Improvement of pulse shape calculations

The decomposition of the experimental signals is done with reference to a calculated basis [16]. With respect to what is reported in Ref. [13], the computer code to calculate the signal basis has been enhanced by adding some features, namely the longitudinal gradient of the space charge density, the crystal anisotropy, and the response function of the preamplifier.

The gradient of intrinsic space charge density along the symmetry axis included in the calculation follows from the specifications of the manufacturer that in the actual crystal used for the MARS detector the concentration of impurities ranges from 1.09 × 10^{10} cm^{-3} in the front to 1.5 × 10^{10} cm^{-3} in the back.

The drift velocity of the charge carriers depends mainly on the strength of the electric field. Furthermore, detailed measurements of drift velocities have demonstrated also a distinct dependence on the temperature and, which is much more important for our application, on the orientation of the electric field with respect to the crystallographic axes [26,30–32]. Single crystals of Germanium have a face-centred cubic lattice (fcc) with a two-atomic base. The principal crystallographic axes are the edges of the cube (110) etc., the diagonals of the faces (111) etc., and the spatial diagonals within the cube (111) etc.

Starting from the measured drift velocities for these principal axes, the values in arbitrary directions can be calculated according to Ref. [32], but this formalism is valid only for the electrons. Since the variation of the drift velocities of the holes is much smaller than for the electrons, we used the drift velocities of the holes measured for the principal axes [30,31] and interpolated for directions in between.\(^3\)

In order to determine the directions of the crystallographic axes, we scanned the MARS detector with a collimated \(^{241}\)Am source twice, in the very front part of slice A and in the quasi coaxial part in the centre of slice C, as indicated by the dashed lines in Fig. 1. The low-lying transition (\(E_x = 60\) keV) assures single interactions near to the outer surface, hence experimentally the position of the interaction points is well controlled. Of course, this measurement is only sensitive on the drift velocity of the electrons. The positions of the segmentation lines have been determined from the relative counting rates obtained in these scans. In order to study and verify the accuracy of our calculations, we analysed instead of the total drift times the partial risetimes T90 from 10% to 90% of the amplitude, which can be determined more accurately, especially for signals with a small signal-to-noise ratio. It has to be noted that the partial risetime T90 depends not only on the drift velocity but also on the pulse shape of the signals [13], therefore it shows a variation on the position of the interaction point with respect to the segmentation lines. Due to the growing process the symmetry axis of the cylindrical crystal is in one of the \((100)\) directions. The direction with the largest risetime has been attributed to the crystallographic \((111)\) direction. It has been determined by averaging the four measured directions with the largest risetimes and taking into account that the angle between these directions should be 90°.

The influence of the crystal orientation on the signals is substantial, especially in the front cap of the detector. In the \((100)\)–\((010)\)-plane (scan of slice C) we found an average T90 of 218 ns with a small anisotropy of ±4% between the axes \((100)\) and \((110)\), respectively. In the very front part of the detector, an average T90 of 309 ns was measured with a larger anisotropy of ±14%. As it can be seen in Fig. 6, the calculated results are in very good agreement with the measurements.

Taking this effect into account brakes partly the symmetry of the segments and results in a larger amount of base systems to be used for the decomposition. In the current analysis, the complete formalism is applied only for the signals in the front cap of the detector implying that three different base systems are used for slice A. For the other slices B–C the signals are calculated averaging over the drift velocities with respect to the different principal axes, therefore every slice is still described by one base system.

As last step, the calculated signals have been folded with a simplified response function \(g(t)\) for the integrating preamplifier [32]:

\[
g(t) \approx -\exp\left(-\frac{t^2}{\tau_f^2}\right) + \exp\left(-\frac{t^2}{\tau_r^2}\right) \quad (t > 0).
\]

The values of the fast risetime \(\tau_r \approx 30\) ns and the slow falltime \(\tau_f \approx 58\) μs have been fitted to the experimental pulses. Since the latter is already deconvoluted from the measured signals by the MWD algorithm, it has not been considered any more in the convolution of the simulated signals.

5. In-beam experiment: set-up and simulation

5.1. Experimental details

In order to obtain \(\gamma\)-rays emitted in flight at large velocities, Coulomb excitation of a 240 MeV \(^{56}\)Fe beam
been used. After being scattered by a 3.7 m g/cm² lead target, the velocity is β ≈ 0.08 at an angle of θ_{lab} ≈ 60°. The cross-section for excitation of the first state of 56Fe at 846.8 keV in 56Fe at this scattering angle is about 250 mb/sr. The measurement was performed at the target point of the GASP array, positioning the MARS detector in place of one of its hemispheres. The other hemisphere (20 Germanium detectors) was run in parallel to the main experiment in order to calibrate the position of the particle detectors and to control the reaction.

Since the Doppler effect depends on the relative angle between the direction of the γ-ray and the direction of the emitting nucleus the complete kinematics had to be determined experimentally. The scattering angle of the beam ions was measured with PHOBOS, an array of eight PIN diodes and seven Si detectors of the ISIS array [33]. Each detector of PHOBOS was collimated to an opening angle of 2.6°. The collimation holes were covered by a thin Al foil to prevent that scattered Pb ions reach the detectors.

In order to obtain a maximum Doppler broadening, the MARS detector was placed at θ_{lab} ≈ 135° keeping the relative angle between the MARS detector and the PHOBOS detectors at approximately 90°.

The DAQ was triggered requiring a coincidence between the MARS detector and one of the PHOBOS detectors. In addition to the 26 sampled pulses from the MARS detector (25 segments and the central contact), the time between MARS and PHOBOS generated by a TAC as well as an analogue signal whose amplitude coded for the ID of the hit PHOBOS detector were also recorded in sampling mode, resulting in 28 signals per event. The event rate in this experiment was only about 2 Hz, very well within the limits of our simple DAQ system.

5.2. Simulation of the experiment

In order to get an estimate of which energy resolutions and which sensitivity on the position errors could be achieved, we simulated the whole experiment utilising GEANT3 [34].

The obtainable energy resolution depends on the opening angle of both the detectors for γ-rays and for the particles. Our set-up was chosen carefully in such a way that the contribution caused by the finite opening angle of the γ-detector, which is the variable to be reduced by the determination of the first point of interaction, is larger than the other contributions. Major effects to the resolution included in the simulation are the finite opening angle of the individual PHOBOS detectors (2.6°), the blur of the velocity distribution due to the energy loss of the projectiles in the target before and after the scattering, and the finite size of the beam spot which has been measured to be approximately 4 mm in diameter.

For each event the respective Doppler shift has been applied to the energy of the γ-ray. Subsequently, a Doppler correction with respect to the assumed knowledge of the emission angle has been performed (see below). The peaks were eventually folded with the intrinsic detector resolution of the MARS detector as obtained with our DAQ system, 2.2 keV at 846.8 keV.

In Fig. 7, the results of the simulation performing the Doppler correction with respect to the position of the crystal (opening angle of approximately 22°) and with respect to the barycentre of the individual geometric segments (opening angle of approximately 9°) are shown.

The relevant improvement of the energy resolution comes from the determination of the first point of interaction by decomposition and tracking. Assuming “perfect” tracking, position determination without any error and correct identification of the first point of interaction after reconstruction of the scattering sequence (this information is trivially available for simulated events), an energy resolution of 2.6 keV (FWHM) is obtained, which, after folding with the intrinsic detector resolution, would become 3.4 keV. In the pulse shape analysis of
simulated signals, the points of interaction can be reconstructed within an error of 3.6 mm (point of interaction with the largest energy deposit), 4.6 mm (first point of interaction), or 5.4 mm (all interaction points) [16]. Assuming the worst case, the positions of all simulated interaction points have been smeared with the distribution of positional errors corresponding to an average error of 5.4 mm. Now, performing the Doppler correction with respect to the first point of interaction an energy resolution of approximately 3.5 keV is obtained. After inclusion of the intrinsic detector resolution the final result obtainable by our approach for tracking should be around 4.2 keV, as it can be seen in Fig. 7. This is then the benchmark for the analysis of the experimental data.

6. In-beam experiment: analysis and results

The decomposition of the signals was done using the GA described in Ref. [16] with the enhancements reported in Section 4.2.

Fig. 8 shows the spectra obtained applying Doppler correction with respect to the crystal, to the segments, or to the reconstructed interaction point for different multiplicities $F$ of segments. For details see text.

Fig. 7. Simulation of the experiment: the 846.8 keV transition applying a Doppler correction with respect to the crystal, to the segments, or to the first interaction point. For details see text.
not very good in reconstructing the correct sequence of interactions.

As it can be seen in Fig. 8, adding up two or more segments the obtained energy resolution is always worse than for the single-segment case, because the noise of each segment contributes in quadrature to the final result, and it is therefore obvious that in order to get high-quality sum spectra the energy resolution of the segments should be as good as possible. In Fig. 8, the spectra are shown for multiplicities of segments with a net charge signal $F = 1$ (top), 2 (middle), and 3 (bottom). The relative intensities of the three multiplicities are about 3:3:1. No significant statistics could be obtained in our experiment for higher multiplicities.

The total energy resolution obtained experimentally has essentially four components:

1. the contribution from the Doppler correction due to the positional error with respect to the crystal ($\Delta E_{\text{pos}}$);
2. the contribution due to the experimental conditions like the opening angle of the PHOBOS detectors, the energy blur in the target, etc. ($\Delta E_{\text{exp}}$);
3. the intrinsic resolution ($\Delta E_{\text{int}}$) comprising the charge carrier statistics and the noise contribution;
4. a systematic contribution caused by the uncertainty of the position and the orientation of the crystal within the detector assembly and of the detector itself with respect to the target and the beam axis ($\Delta E_{\text{syst}}$).

In order to extract the contribution caused by the positional error, $\Delta E_{\text{pos}}$, the other three components have to be subtracted from the total energy resolution. The procedure is explained in the following, the individual results are listed in Table 1.

As the first step, the Doppler correction with respect to the barycentres of the geometric segments has been applied. For events with $F > 1$ the Doppler correction has been done with respect to the segment with the largest energy deposit. The errors quoted in row (I) of Table 1 are dominated by the slightly non-Gaussian shape of the peaks.

The contribution given in row (II) originating from the position error, $\Delta E_{\text{pos}}$ (using the barycentres of the geometric segments as reference points for the Doppler correction), and the experimental conditions, $\Delta E_{\text{exp}}$, has been determined with GEANT simulations. These simulations are the same as shown in Fig. 7, but analysed individually for the different segment multiplicities $F$. The obtained values have been subtracted from the total resolutions in order to derive the contributions $\Delta E_{\text{int}}$ and $\Delta E_{\text{syst}}$ listed in row (III).

The latter results can be interpreted in the following way. The intrinsic resolution obtained with the MARS detector mounted at the GASP set-up was affected by an increased noise contribution, resulting in a value of 3.3(1) keV, averaged over all multiplicities $F$, hence somewhat worse than the resolution presented in Section 4.1.

Assuming that the squared values of row (III) can be approximated by $F \cdot \Delta E_{\text{noise}}^2 + \Delta E_{\text{diag}}^2 + \Delta E_{\text{syst}}^2$, the values can be fitted with a noise contribution of 2.5 keV and a systematic contribution of 1.5 keV taking into account a fixed intrinsic resolution due to the charge carrier statistics of 1.5 keV. It has to be noted that these contributions do not depend on the reference point used for the Doppler correction.

As next step, the Doppler correction with respect to the reconstructed point with the largest energy deposit has been performed, the resulting energy resolutions are given in row (IV) of Table 1. After subtraction of the contributions $\Delta E_{\text{int}}$ and $\Delta E_{\text{syst}}$ determined above, the remaining resolutions comprising $\Delta E_{\text{pos}}$ and $\Delta E_{\text{exp}}$ are listed in row (V) and can be compared with the values obtained in the simulation. In order to be consistent, we used also in the simulation the expected distributions of position errors for the interaction point with the largest energy deposit individually for the different multiplicities $F$; the results are given in row (VI) of Table 1. Hence, we have to conclude that the experimentally obtained resolutions are 0.7–0.9 keV worse than we expected from the analysis of simulated signals.

In order to translate these results to a position error, we simulated the experiment again, but this time smearing the interaction points with a single Gaussian error distribution. The width of the Gaussian which reproduces the observed energy resolution best can be regarded as a rough measure of the obtained position resolution. The obtained widths (FWHM) are 6 mm ($F = 1$), 9 mm ($F = 2$), and 14 mm ($F = 3$). The errors of these values quoted in the last row of Table 1 are the limiting values required to reproduce the obtained resolutions (row (V) of Table 1) within their respective errors. However, as we have already underlined previously [16], the distributions of position errors for points reconstructed by our algorithm are not Gaussian. Therefore the given position resolutions in terms of a FWHM have to be taken with the adequate care as long as the actual shape of the distribution of position errors

<table>
<thead>
<tr>
<th>$F$</th>
<th>$\Delta E_{\text{tot}}$</th>
<th>$\Delta E_{\text{pos}}$</th>
<th>$\Delta E_{\text{exp}}$</th>
<th>$\Delta E_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.6 (2)</td>
<td>7.7 (2)</td>
<td>8.8 (2)</td>
<td>3.3 (4)</td>
</tr>
<tr>
<td>2</td>
<td>5.7 (1)</td>
<td>6.6 (1)</td>
<td>7.4 (1)</td>
<td>4.0 (4)</td>
</tr>
<tr>
<td>3</td>
<td>3.3 (4)</td>
<td>4.0 (4)</td>
<td>4.8 (4)</td>
<td>4.8 (4)</td>
</tr>
</tbody>
</table>

For details see text.
cannot be determined in our experiment. The value for single segments \((F = 1)\) is around 1 mm worse than the value obtained by the GRETA collaboration under comparable conditions with their 36-fold segmented detector \([11]\). However, we have not restricted our analysis to the assumption of having a fixed number of two interactions within this segment.

The reason that our experimental values are worse than the values expected from the analysis of simulated signals becomes obvious from Fig. 9. Here, the distribution of interaction points reconstructed by our algorithm projected onto the \(r-z\)-plane is shown. In fact, the distributions of points reconstructed from signals measured in the in-beam experiment exhibit two features which are not present for simulated data. The algorithm has the tendency to place interaction points rather in the centre of a segment than near to the border to a neighbouring segment. Furthermore, in the front slice of the detector, interaction points are placed more often in the centre of the bottom part and on the diagonal connecting the end of the inner hole to the edge of the front face. Since for irradiation from the front with moderate \(\gamma\)-energies most of the interaction points are within the front slice, the latter effect deteriorates the obtained resolution more severely. The explanation of these two effects is currently not clear. Possible reasons may be a too simple description of the preamplifier response or detector properties which are not included in the calculation of the pulse shapes. E.g. probably exists a radial gradient of the intrinsic space charge density caused by the production process of the crystal.

Fig. 9. Distribution of interaction points in the \(r-z\)-plane: reconstructed from simulated (left) and from measured signals (right).

7. Conclusion

The 25-fold segmented prototype detector of the MARS project has been used to demonstrate the feasibility of \(\gamma\)-tracking in practice. Most of the milestones of the \(\gamma\)-tracking process have been reached and some of the problems found in the work have been the starting points of further developments in this field.

Highly segmented HPGe detectors can be operated reliably. Procedures for digital signal processing of the electric signals from the segments have been developed. The computer program to calculate the pulse shapes of these signals has been improved considering the particular properties of the detector. From the analysis of these pulse shapes the interaction points of the \(\gamma\)-rays in the detector can be localised and characterised applying a genetic algorithm which makes use of a base system of calculated signals. Thus, the accuracy of the results of the decomposition proves the reliability of the pulse shape calculations. Eventually, the \(\gamma\)-rays can be identified by reconstructing their scattering paths from the interaction points. However, the entire analysis presented in this paper has been performed off-line. The next challenge in \(\gamma\)-tracking is to enable an on-line processing.

The whole procedure was tested analysing data taken during an in-beam experiment with the MARS detector. The accuracy within which the interaction points (the first or the point with largest energy deposit) can be localised has been investigated by the capability for Doppler correction of \(\gamma\)-rays emitted in flight. Following Coulomb excitation of a \(^{56}\)Fe beam at 240 MeV, the 846.8 keV transition in this nucleus has been detected with the MARS detector in coincidence with the scattered beam ions at a velocity of \(\beta = 0.08\). The experimental energy resolution has been improved from around 16 keV considering the whole detector to 4.6 keV applying our approaches for signal processing, decomposition, and tracking. The achieved resolutions are near to the expectations from simulations indicating that positional resolutions around 6 mm (FWHM) could be obtained.

At present and future radioactive ion beam facilities \(\gamma\)-spectroscopy is and will be an irreplaceable tool for the investigation of exotic nuclei and a \(\gamma\)-ray tracking array will be the adequate instrument to perform such studies. Within the MARS project essential ingredients for the process of \(\gamma\)-ray tracking have been developed. As a major step forward on the way to the realisation of a \(\gamma\)-tracking array, we have demonstrated in this paper the feasibility of the entire \(\gamma\)-tracking process with experimental data for the first time.

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