DD

ISSN 1343-2230
CNS-REP-49
December, 2002

CNS Report

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CM-P00045883

*Presented in 2002 IEEE Nuclear Science Symposium and Medical Imaging Conference and
submitted to IEEE Transaction Nuclear Science*

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Pulse Shape Simulation and Analysis of Segmented Ge Detectors for Position Extraction

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Abstract—Simulation method, which can predict the relation between the pulse shapes and the interacting points of incident γ -rays, has been established for the entire effective volume of the segmented Ge detector with planar geometry, and its accuracy was experimentally confirmed. Based on the simulated results, the method of pulse shape analysis for the extraction of the position information with smaller unit than the segment size and the expected resolution are discussed.

Index Terms—segmented germanium detectors, planar, pulse shape, position sensitivity

I. INTRODUCTION

GAMMA-ray spectroscopy with high-purity germanium (HPGe)-detector array has been a powerful tool for the investigation of nuclear structure because of the intrinsic high energy resolution of the Ge detector [1], [2], [3]. Also the resultant granularity of the array enables to correct the energy of Doppler-shifted γ -rays emitted from the moving source with high accuracy. Recent progress in the γ -ray spectroscopy with fast radioisotope (RI) beams requires higher granularity, which is achievable by extracting the position information on the interacting points.

For that purpose, an array of segmented Ge detectors with planar-geometry is being developed at Center for Nuclear Study (CNS), the University of Tokyo. Figure 1 shows a schematic view of the HPGe p-type detector used in the array. The detector manufactured by Eurisy Mesures has a thickness of 2.0 cm and an effective diameter of 6.0 cm. Front side of the detector is divided into nine segments, and an operation voltage typically of 2000 V is applied to the back side. To reduce the dead space, two crystals are encapsulated into one cryostat. Position within the detector is represented by the cylindrical coordinate system (r, ϕ, z) as indicated in the figure from now on.

Figure 2 demonstrates the improvement of the Doppler-correction accomplished by the higher granularity. In the figure, the energy spectra are obtained with a Monte Carlo simulation using the code GEANT4 [4] for 3.7 MeV γ -rays, which are emitted isotropically from the moving source with 30% of the light velocity. The distance between the emitting point and the

Fig. 1. Schematic view of the segmented Ge detector used in the present study. Numbers are given to identify each segment. Cylindrical coordinate system (r, ϕ, z) is applied to represent the position within the detector.

Fig. 2. Energy spectra obtained by a Monte Carlo simulation using the code GEANT4 [4], when 3.7 MeV γ -rays are emitted isotropically from the moving source with 30% of the light velocity. (a) Energy spectrum without Doppler correction. (b) Doppler corrected energy spectrum with the center position of the segment, in which the largest amount of energy is deposited. (c) Doppler corrected energy spectrum when the position resolution of 1 mm along the direction of z is applied to the incident point of γ -rays.

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center of the detector is assumed to be about 20 cm, and the side surface of the detector faces the point. The improvement by a factor of more than three is obtained in the energy resolution of Fig. 2(c) compared with that of Fig. 2(b). In Fig. 2(c), the position resolution for the incident point of γ -rays is assumed to be 1 mm in full width at half maximum (FWHM) along the direction of z . In Fig. 2(b), the center position of the segment, in which the largest amount of the energy is deposited, is used to define the direction of emitted γ -rays.

Thus, the high granularity or the position resolution is very important factor in the development of the array. The position information with smaller unit than the segment size is obtainable from the pulse shapes of the signals. The relation between the interacting position and the pulse shapes has been well investigated for a segmented detector with semi-coaxial geometry both from the simulation and the experimental observation of the pulse shapes [5], [6], [7].

On the other hand, the simulation method, which can be applied to predict the pulse shapes wherever the interaction occurs in the effective volume of the detector, has not been introduced yet for a planar detector. It may be due to that the required position resolution has been comparable to the segment size or the strip width in most of the applications. Therefore, the method fulfilling the above requirement has been established [8]. In the present article, the reliability of the predicted pulse shapes by the simulation method is experimentally confirmed by examining some properties expected from the simulation. Based on the properties observed in the pulse shapes, pulse shape analysis method to extract the position and expected resolution with the method are discussed.

II. SIMULATED PROPERTIES OF THE PULSE SHAPES

A Method to simulate the pulse shapes for a segmented Ge detector with planar geometry consists of three steps. In the first step, the amount of induced charge at an electrode is estimated for a unit charge at a certain point in the detector. In the second step, the position of the unit charge is calculated as a function of the time. These two steps are the procedures to obtain the evolution of induced charge at an electrode of a segment by electrons and holes, which are generated at around interacting point of an incident γ -ray and move toward their relevant electrodes by the electric field in the detector. The last step is to achieve the eventual pulse shapes observed as output signals from a preamplifier by taking into account the response function to the time differential of the induced charge. Further details are described in Ref. [8].

Pulse shapes for all of the nine segments were simulated. Here, depending on whether a segment containing an interacting point or not, the signal from the segment is called the net charge signal or the transient signal, respectively [5]. The analog summation of the nine signals is referred as the total signal in this paper.

Some properties of the pulse shapes are predicted from the simulation concerning with the interacting point as following.

Fig. 3. For the interactions with various values of r , simulated and experimentally observed pulse shapes of the total signals are drawn with dashed and solid curves, respectively. The interacting points have the fixed value of $z = 2$ mm.

A. Edge Effect

It has been known that the amount of the induced charge at an electrode with infinite extent has linearity with the fractional distance of a unit charge from the opposite electrode [9], namely $(L - z)/L$, where L denotes the thickness of the detector. Therefore, pulse shapes, which correspond with the evolution of the amount of induced charge, depends only on z of the interacting points and is independent of r and ϕ for the detector with infinite electrodes. For interactions at around the central axis of the detector, the pulse shapes are approximated to be those generated from the electrode with infinite extent. As the value of r becomes larger, dependence on r of the interacting point will be seen for the total signals, because the surface area consisting of nine segments is not regarded as infinite extent any more. To predict the edge effect on the induced charge, or to determine the threshold value of r whether the approximation is held or not, three-dimensional boundary conditions have to be taken into account. Simulated results on the effect is shown in Fig. 3, where the pulse shapes of the total signals are drawn for the interactions with various values of r but with fixed value of $z = 2$ mm. The independence of r is almost complete in the region of $r < 2.0$ cm. On the other hand, the curvatures are increasing function of r for the pulse shapes in the region of $r > 2.0$ cm.

B. Rise Time Dependence

The z dependence of the rise time, which is reported for the detectors with planar-geometry [10], [11], and for the "quasi-true-coaxial part" of a semi-coaxial detector [5], is also simulated. In the case that the interactions occur in the region where the edge effect is negligibly small, simulated pulse shapes of the total signals are given in Fig. 4 for various values of z . The selection of the total signal generated in the region is due to that the pulse shapes are determined only by the values of z and are not affected by r and ϕ of the interacting point as mentioned. Since the rise time is correlated with the longer

Fig. 4. For interactions in the region where the edge effect is negligibly small, simulated and measured pulse shapes of the total signals are given with dashed and solid curves, respectively. The z values of the interaction points are given in the figure.

Fig. 5. For the interactions taken place in the segment #2, simulated and observed pulse shapes from its neighbouring segment #5 are given with dashed and solid curves, respectively. Interacting position (ϕ, z) is set to be ($0^\circ, 2$ mm).

drift time between those for the electrons and holes, the time decreases for small z and increases for large z .

C. Amplitude of the Transient Signal

The amplitude of the transient signals is correlated with the distance between the interacting point and the segment border [6], [12] as shown in Fig. 5, where the pulse shapes for the segment #5 are drawn for the interactions in the segment #2. The interacting points are on the line of $\phi = 0^\circ$.

III. COMPARISON WITH EXPERIMENTAL OBSERVATION

THE predicted position dependence of the pulse shapes were examined experimentally. Figure 6 shows the experimental setup schematically. An interacting point of a γ -ray was

Fig. 6. Experimental setup to measure the pulse shapes from the preamplifiers.

selected two-dimensionally by changing the positions of the two lead collimators with 1 mm gap. One collimator was placed between a 1275 keV ^{22}Na γ -ray source and the first Ge detector to obtain the data for interactions at aimed values of z . The other one was placed between the two detectors to determine the interaction point in the transverse direction of the detector. To improve the ratio of the events with a single interaction [6], the summation of the deposited energies in the segment of interest E_1 and in the second detector E_2 was required to be in the range of 1275 ± 10 keV. Deviation was also restricted to be less than 10 keV among the total amount of the deposited energy in the first detector E_1' and that for the segment E_1 . The energy information was obtained by measuring the pulse height of the output signals from the corresponding shaping amplifiers with a digital oscilloscope. Signals for each segment and for the analog sum of the nine segments were recorded by a digital oscilloscope with a sampling rate of 1 ns to investigate the pulse shapes of the net charge signals, the transient signals and the total signals. To normalize the pulse height of the observed pulse shapes, energy information E_1 and E_1' were applied.

To confirm the predicted edge effect, dependence on r was investigated for the pulse shapes of the total signals. The depth of the interaction points in the first detector were restricted in the vicinity of $z = 2$ mm by placing the first collimator at the point. In order to observe the pulse shapes, which are comparable to the simulated ones in Fig. 3, signals were collected by changing the position of the second collimator from the center to the outer radius of the detector step by step. By choosing the events, which generated the transient signals with the same amplitudes between the segment # 1 and # 3 (or # 4 and # 6), the scattering at $\phi = 0^\circ$ and consequently at aimed values of r were achieved. Pulse shapes of the total signals thus selected are given in Fig. 3 together with the simulated results. Based on the consistency between the two results, the accuracy of the predicted edge effect was established, and applicability of the simulation method was also confirmed to the interactions near the border of the effective area of the detector ($r = 3.0$ cm).

The observed pulse shapes of the total signals in Fig. 4 were obtained by changing the irradiating points, which was

Fig. 7. Measured maximum amplitude of the transient signal is plotted as a function of r together with the simulated results (solid curves).

adjustable by replacing the position of the first collimator. The position of the second collimator was shifted from the center position of the detector toward the transverse direction of the detector by 1.2 cm. The distance was determined so that the number of events with $r < 2.0$ cm (sect. II-A) was maximized by avoiding the scattering prior to the interesting point. The resultant maximum value of r was less than 1.6 cm for the signals from the segment #2. The expected behavior of the rise time as a function of z is well reproduced by the experimental observation.

The pulse shapes given in Fig. 5 were collected from the spectator segment #5 under the same setup with which was adopted for the observation of the pulse shapes in Fig. 3. The predicted amplitude for the transient signal is in good agreement with the one obtained from the measurement within the noise level of the data.

IV. DETERMINATION OF THE INTERACTING POSITION

A. Transverse Direction with $\phi = 0^\circ$

THE observed maximum amplitude of the transient signal, which is extracted from the pulse shape in Fig. 5, is plotted as a function of r in Fig. 7. By making use of the presented correlation between the maximum amplitude and r , position information along the transverse direction can be extracted for the events with $\phi = 0^\circ$. The resolution is determined by the noise level of the transient signals. Based on the position dependence given in the Fig. 7, the present noise, which is almost comparable to the size of the symbol, will give the resolution of better than 1 mm in the region of $r < 2.0$ cm. If the deposited energy is higher than 910 keV, which is the deposited energy by the Compton scattered 1275 keV γ -ray to the direction of 90° , better resolution will be achieved accompanied with the improvement of the signal to noise ratio. On the other hand, in the region of $r > 2.0$ cm, the expected resolution is worse than 5 mm. The situation is even worse for the case of $z \simeq 6$ mm. The maximum amplitude is very small and shows little dependence on r . In such a case, the extraction of the position information seems to be difficult with

Fig. 8. The rise time T_{19} (see in the text) is plotted as a function of z for the total signals given in Fig. 4. The experimental data are compared with the simulated results (solid line).

the present noise level. The situation is unavoidable, because the small amplitude is the results of the compensation of the induced charges by electrons and that by holes. To improve the resolution, noise reduction is the most important subject.

B. Direction of z with $\phi = 0^\circ$

As already mentioned in sect. II-B and as shown in Fig. 4, the rise time of a signal pulse is expected to be used in measuring the z of an interacting point. The z -dependence of the rise time is shown in Fig. 8 for the signals given in Fig. 4. To avoid the ambiguity in determining the time of total charge collection, the rise time T_{19} , which is defined as the interval between the time of 10% and 90% charge collection, is plotted. The error bars correspond to the statistical errors of $\pm 1\sigma$ estimated from the fluctuation of the experimental data. The rise time obtained from the simulated pulse shapes is also shown by solid curve. The accuracy of the simulated dependence is well supported by the experimental data. However, the dependence is different from which is often observed in the detector of the double-sided strip structure, where the rise time obtained from the both sides exhibit almost monotonic increase or decrease as a function of z , and hence the difference of the two timings gives a good measure of z [10], [11]. The property for the rise time is generated by "the small pixell effect" [13], [14], [15]. On the other hand, the behavior of the T_{19} has a parabolic shape for the total signals, because the signals in Fig. 4 are approximated to be those generated from the surface with infinite extent. The difference of the two timings extracted from the net charge signal and from the total signal does not seem adequate to obtain the position information. Though, the behaviour of the total signals in Fig. 4 is the same with that for the signals extracted from the back side of the detector except for their polarities. Two timings should be recorded simultaneously in the detector of present type.

In Fig. 9, two timing informations are plotted as a function of z for the total signals (upper panel) and for the net charge signals (lower panel). In the figure, the performance of the

Fig. 9. Simulated zero-cross timing, which is picked up after the $(CR)^2$ -(RC)⁴ shaping of the output signals from the preamplifier, is plotted as a function of z for the total signals (a) and for the net charge signals (b).

zero-cross timing after $(CR)^2$ -(RC)⁴ shaping of the output signals from the preamplifier is examined by the simulation for the interactions with $\phi = 0^\circ$. The shaping time CR for the differential and RC for the integration are set to be 50 ns by considering the range of the rise time. The parabolic shape for the total signal is well reproduced by the timing information in the case of $r = 1.2$ cm. For the net charge signal, the dependence is an increasing function in wider range of z than that for the total signals, because of the appearance of the small pixel effect. Thus, the expected tendencies are well produced by the method employing the $(CR)^2$ -(RC)⁴ shaping.

As seen from the figure, the two timing informations still remain some ambiguities in the determination of z , because of the spread of the timings for the fixed value of z . For instance, in the case that the timings of the total signal and the net charge signal are 400 ns and 450 ns, respectively, corresponding value of z is only limited from 15 to 18 mm, where the both requirements for the two timings are fulfilled. For the aim to eliminate the ambiguity, the relation given in Fig. 7 is useful. By measuring the maximum amplitude of the transient signals, the value of r and z will be obtained as the results. Consequently, the resolution along the direction of z is affected by that for the transverse direction. If the resolution of around 1 mm is achieved from the transient signals, the resolution of the same grade will be also accomplished along the direction of z . In other words, in the region where the amplitude of the transient signal is small, the maximum amplitude of the transient signals does not help to extract the value of z . The resolution of around 3 mm is expected in the worst case.

V. SUMMARY

Recent progress of the γ -ray spectroscopy with fast radioisotope (RI) beams requires higher granularity of the Ge-detector array, which is achievable by obtaining the interacting points of incident γ -rays. The position information on the point is extracted by analyzing the pulse shapes. In order to determine the analyzing method, the relation between the pulse shapes and the interacting point should be predicted.

For a segmented Ge detector with planar geometry, the simulation method to predict the relation has been established. The detector is adopted in the array which is under construction at Center for Nuclear Study (CNS), the university of Tokyo for the spectroscopy of γ -rays emitted from the fast moving nuclei. The applicability of the simulation method was confirmed for the entire effective volume of the detector by experimentally examine the simulated properties of the pulse shapes.

Based on thus confirmed properties, the analyzing method of the pulse shapes is discussed to extract the position information. For the transverse direction of the detector, signals from the spectator segment, which is in the neighbor of the segment containing the interacting point, is useful. The maximum amplitude of the signal is correlated with the distance between the interacting point and the segment border. In the region, where the correlation is strong, the resolution better than 1 mm is expected. On the other hand, in the edge region of the detector and in the vicinity of $z = 6$ mm, where z is the distance to the segmented surface, noise reduction is subjected to extract the position information.

For the direction of z , the rise times for the two kinds of signals are useful. One of them (net charge signal) is the signal from the segment containing the interacting point, and the other one (total signal) is the analog summation of the signals from all of the segments. Each dependence of the rise time on z is well reflected in the zero-cross timing of the signal after the $(CR)^2$ -(RC)⁴ shaping of the net charge or the total signal. Here, CR and RC denote the differential and the integration, respectively. The combination of the two timings gives the rough position information better than 5 mm along the direction of z . More precise information is achieved with the help of the information on the transverse direction. Therefore, the resultant resolution will be determined by that for the transverse direction.

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