Nuclear Instruments and Methods in Physics Research A 596 (2008) 409–416

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Investigation into the properties of CdTe detectors for in-situ measurements

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ARTICLE INFO

Article history:
Received 17 January 2008
Received in revised form
16 June 2008
Accepted 18 August 2008
Available online 2 September 2008

Keywords:
CdTe
Gamma-ray spectra
Rise-time discrimination

ABSTRACT

As part of a program investigating means to improve gamma-ray spectra obtained with CdTe detectors, we report results obtained with two $10 \times 10 \times 5\,mm^3$ CdTe detectors, one planar the other of quasi-hemispheric geometry. Applying a combination of cooling and pulse rise-time discrimination with the quasi-hemispheric detector, we obtain a resolution of 4 percent at 662 keV and a peak-to-valley ratio of 92 at a loss of approximately 25 percent of the counts in the full-energy region.

1. Introduction

In case of a release of radionuclides into the environment, it is necessary to have reliable methods to estimate the potential effects on population and ecosystem. Identification of the emitting radionuclides and determination of the total photon flux above the contaminated area are straightforward, for example using HPGe detectors. However, in order to determine the effects on the ecosystem total activity and its distribution are of importance [1–3]. Determining these from the photon flux above ground is not trivial, due to photon absorption caused by surface roughness and/or burial of the activity. Utilizing in addition to the flux of unscattered (characteristic) gamma rays also the intensity of scattered radiation, reliable estimates of surface activity and (effective) burial depth averaged over areas ranging from a few hundred to a few thousand square meters may be obtained from HPGe spectra measured in situ [4].

Migration of radionuclides into the soil is normally a slow process (a few centimeters a year) [5], but may be accelerated if the deposition occurs in rain as did in Sweden the major part of the deposition of the fallout following the Chernobyl accident. A similar complication occurs if the activity is deposited during or before snow fall [6]. Process of deposition, ground properties and topography can lead to large fluctuations even over small distances [3,6,7]. Traditionally, local variations in activity and depth distribution are determined by laboratory analysis of extracted soil samples, a labor intensive and slow process. In addition, it is not entirely reliable. Even though the laboratory analysis may be driven to any desired accuracy, the procedures used to take samples are inherently uncertain because of the limited volume of the sample compared to typical variations in soil composition (stones, roots, etc.) and the massive deformation of the sample when it is extracted. As an alternative to the traditional soil sampling, we are investigating the possibility of determining the local variations in the depth distribution of the deposited activity by measurements in situ with small detectors inserted into the ground. For this purpose we have been investigating the properties of CdTe detectors, and in particular methods to improve the spectral resolution obtainable with these detectors.

As a detector for gamma rays CdTe is rugged and requires no cooling. However, its application is hampered by poor charge collection in particular due to trapping of holes. The pulse shape, therefore, is strongly dependent on where in the crystal the energy is deposited. We have previously reported results obtained with a small $5 \times 5 \times 2\,mm^3$ detector feeding the preamplifier output to two shaping amplifiers in parallel with different shaping times [8]. Fig. 1 shows a scatter plot of events obtained with a ^{137}Cs source. In the plot the digitized pulse height from the shaping amplifier with a shaping time of 0.5 μs determines the vertical position of the event, whereas the horizontal position corresponds to the pulse height from the second amplifier with a shaping time of 3 μs. Events with the fastest rise time, corresponding to a small contribution from holes, fall along the diagonal. Events with a larger contribution from holes fall below the diagonal. From the figure it is apparent that for this detector, disregarding the finite resolution, the pulse-height deficit was a single-valued function of the ratio of the two pulse heights. The measured spectrum could then be corrected for pulse-height

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doi:10.1016/j.nima.2008.08.132

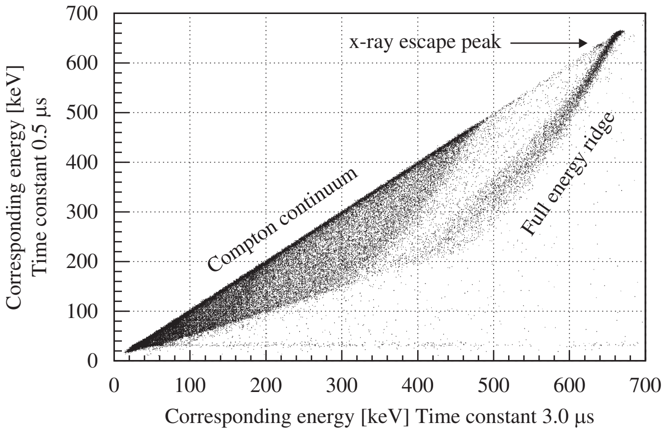

Fig. 1. Scatter plot of pulse-height spectrum for ^{137}Cs from a small planar CdTe detector using two amplifiers with 0.5 and 3.0 μs shaping times (from Ref. [8]).

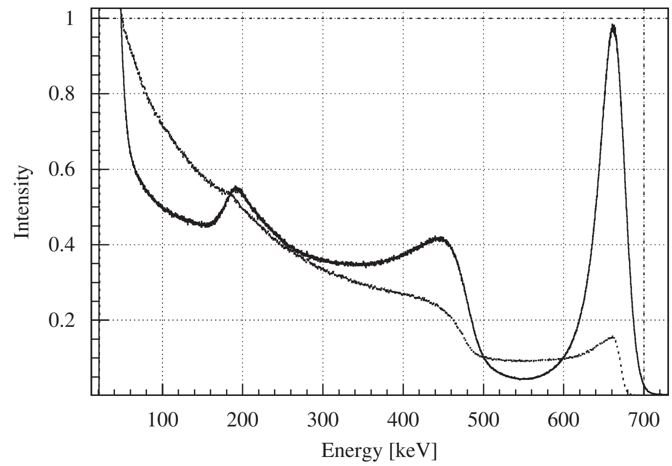

Fig. 2. Pulse-height distribution for ^{137}Cs for the planar (dots) and the quasi-hemispheric (line) CdTe detector both of 500 mm^3 volume. Applied high voltages are 500 and 1000 V.

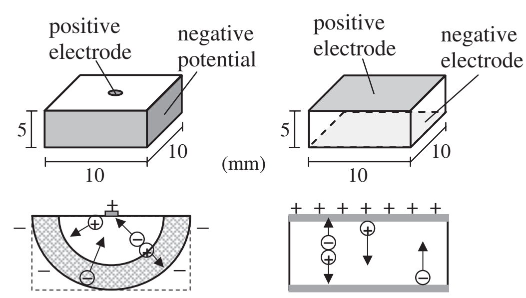

Fig. 3. Illustration of the quasi-hemispheric and planar crystal geometries (upper) and principles of charge collection for a truly hemispheric and a planar detector (lower).

deficit obtaining a resolution of 2 percent at 662 keV including all events.

In light of these results work has continued with detectors of larger size and correspondingly larger efficiency necessary in order to shorten the time required for the field measurements. Our aim, in particular, has been to minimize the detrimental effects of incomplete charge collection. Using a coincidence technique, we have created samples of events all characterized by the same energy deposition in the CdTe detector. For these samples the pulse-height distribution shows directly the effects of pulse-height deficit.

In the present paper, we report results obtained with two $10 \times 10 \times 5\,mm^3$ detectors one planar, the other of quasi-hemispheric geometry. A brief description of the detectors is given in the next section, followed in Section 3 by a description of the experimental apparatus. The results obtained in measurements at room temperature and at $-7.5\,^{\circ}C$ are presented in Section 4. Our main conclusions are summarized in Section 5.

2. Description of the detectors

The pulses from a CdTe detector are sum of two components, one originating from the drift of electrons and the other from holes. The proportion of the pulse generated from each one of these components depends on the distance from the point of interaction in the crystal to the respective electrode. The drift velocity of holes is approximately a tenth of that of electrons, but the trapping time is of the same order of magnitude [9]. Hence, the hole contribution to the pulse height is more severely affected by trapping effects, resulting in a final pulse height depending on where in the crystal the interaction takes place.

Typical pulse-height distributions from the two detectors are shown in Fig. 2. The pulse-height distribution from the planar detector is similar to that reported for the small planar detector before correction [8]. It is quite different from the hemispheric detector.

The major differences in the distributions can be understood by studying the crystal geometries and the electric field configurations for the two detectors. The detector referred to as hemispheric is actually a quasi-hemispheric detector [10]. Both the quasi-hemispheric and the planar detector have rectangular dimensions, $10 \times 10 \times 5\,mm^3$. On the hemispheric detector all surfaces except one are held at negative potential. The remaining surface has a circular positive electrode with a diameter of 1.5 mm at its center (cf. Fig. 3).

The planar detector has (ideally) a uniform electric field and both charge carriers contribute to the pulse height. The pulse-height distribution is distorted mainly due to incomplete collection of holes. The hemispheric detector on the other hand has an electric field that is (ideally) radial and therefore much stronger near the positive electrode. This field configuration accelerates the collection of electrons and slows down the velocity of holes. As a result, the device works (in principle) in a single charge-collection mode. In addition, most interactions occur in the hatched region of the crystal in Fig. 3, close to the cathode, because this region contains the major part of the crystal volume. Hence the contribution due to electrons is further accentuated.

3. Experimental setup

In order to create samples of events all corresponding to the same absorbed energy in the CdTe detector, mono-energetic photons were Compton scattered in the CdTe detector and then detected in an HPGe detector.

The CdTe detector was irradiated by a collimated photon flux from a ^{137}Cs source. Small-angle scattering in the lead collimator was investigated experimentally and also by simulations. The effects were found to be small. A second detector (HPGe) was positioned at a given angle and carefully shielded from the radioactive source. Requiring a coincidence between the two detectors, events that correspond to a photon being scattered in the CdTe detector at an angle such that it could be detected in the HPGe detector were selected. Due to the extended size of both crystals and the close distance between the detectors, a range of scattering angles (and therefore a range of deposited energies) were covered in one position. By selecting a certain energy in the HPGe detector, a certain deposited energy in the CdTe crystal could be selected. The scattering angle was approximately 130°, corresponding to a deposited energy in the CdTe detector of approximately 450 keV. The electronic scheme for the coincidence experiment is shown in Fig. 4. The analog-to-digital converters were read out by a data acquisition system developed in-house [11] including a digital oscilloscope making it possible to sample the pulse shape from the CdTe detector for each event.

4. Measurements and results

4.1. Planar detector

In Fig. 5 distribution of pulse heights from the amplifier with shorter shaping time is shown for all events corresponding to an energy deposition between 448.6 and 450.3 keV in the planar CdTe detector. The events above approximately 480 keV stem from random coincidences (two independent photons have triggered the system). Judging from these events the total contribution from random coincidences is small. Although all (truly coincident) events correspond to the same energy deposition the pulse-height distribution is dominated by a very large tail extending all the way to the smallest corresponding energies. The scatter plot for the output of the two amplifiers in the CdTe branch is shown in Fig. 6. The majority of the coincidence events are located close to the diagonal as opposed to what was the case for the small planar detector where the events depositing the same energy fell (mainly) along ridges extending well below the diagonal (cf. Fig. 1). For this larger detector, therefore, it is not possible to correct for pulse-height deficit based on the ratio of pulse heights from the two amplifiers. However, a small deviation from the diagonal is apparent in Fig. 6 for events a little below the coincidence peak. It should therefore be possible to obtain a somewhat better energy resolution by a cut in the ratio of pulse heights discarding events below the diagonal in Fig. 6. However, to have effect such a cut would lead to a large loss of events also in the region above 400 keV.

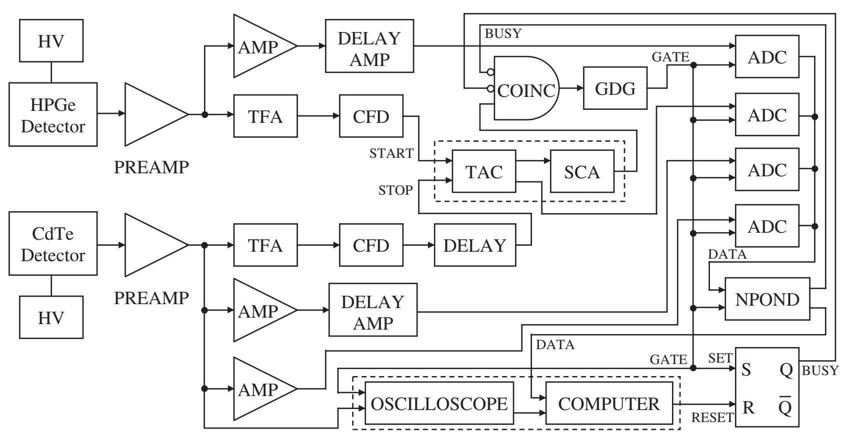

Fig. 4. Electronic scheme for the coincidence experiment using for the fast coincidences timing-filter amplifiers (TFA) constant fraction discriminators (CFD) and a time-to-amplitude converter (TAC) with a built-in single-channel analyzer (SCA). The NPOND unit is part of the data acquisition system [11].

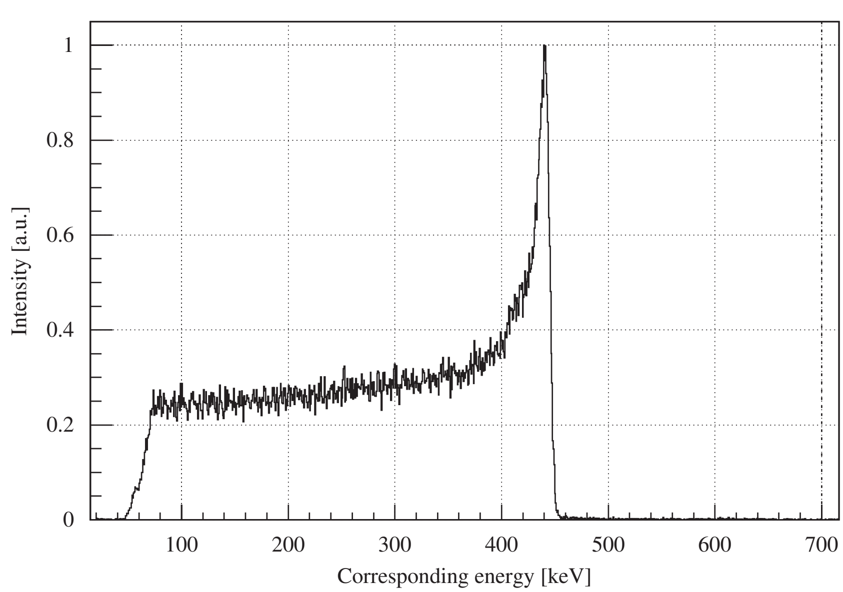

Fig. 5. Pulse-height distribution for the planar CdTe detector in coincidence with events depositing between 211.3 and 213.0 keV in the HPGe detector. The low-energy tail is due to incomplete charge collection. Applied high voltage was 500 V.

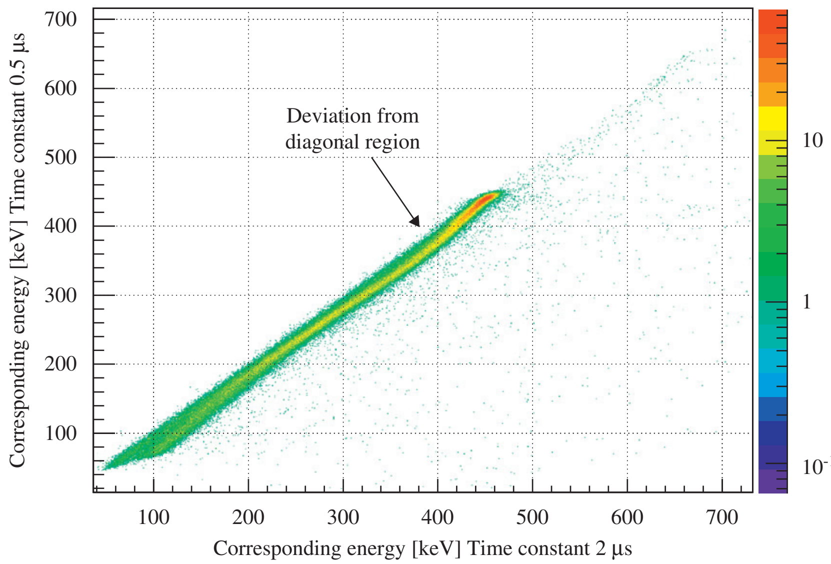

Fig. 6. Scatter plot of pulse-height spectrum for coincidence events depositing between 448.6 and 450.3 keV in the planar CdTe detector using two amplifiers with 0.5 and 2.0 μs shaping times. Applied high voltage was 500 V.

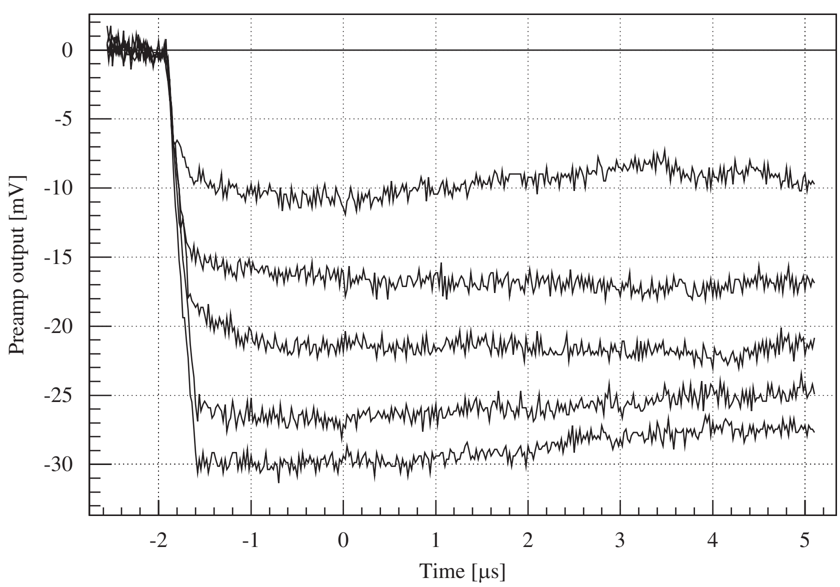

Fig. 7. Pulse shapes at the preamplifier output from the planar CdTe detector. All pulses correspond to approximately the same deposited energy. Applied high voltage was 500 V.

In all experiments the planar CdTe detector was irradiated from the side of the cathode. Pulse shapes from the sample of events depositing between 448.6 and 450.3 keV in the CdTe detector (same as in Figs. 5 and 6) reveal that the hole contribution to the total pulse is small, probably due to trapping of charge carriers (cf. Fig. 7). Due to the small differences in rise time, the pulse shapes after the main amplifiers will have almost the same amplitude independent of the shaping time and, hence, all the events will fall close to the diagonal in Fig. 6. Increasing the applied high voltage, hence decreasing the charge-collection time increases the separation of the events from the diagonal but not to such an extent that the simple algorithm developed in Ref. [8] can be successfully applied.

Besides trapping of holes a secondary source of pulse-height deficit is due to escape of electrons and secondary photons out of the crystal. This effect being associated with events where the energy deposition occurs in the immediate vicinity of the detector surface is expected to be small in case of detectors of the present size. In order to confirm this and in order to make sure that the contribution is small also for events where a photon after Compton scattering is required to be detected in the external HPGe detector simulations were made of the energy deposition in the CdTe detector. Using the program package PENELOPE [12] the electromagnetic cascade following the primary interaction of 662 keV photons in the CdTe detector was modeled for the actual geometry of the experiment including the HPGe detector. In approximately 4 percent of all events electron escape was a significant source of energy loss out of the crystal either requiring a 212 keV photon to hit the HPGe detector or not. Electron escape thus accounts for approximately 4 percent of the events ending up in the low energy tail in Fig. 5 as compared to the measured total of approximately 30 percent.

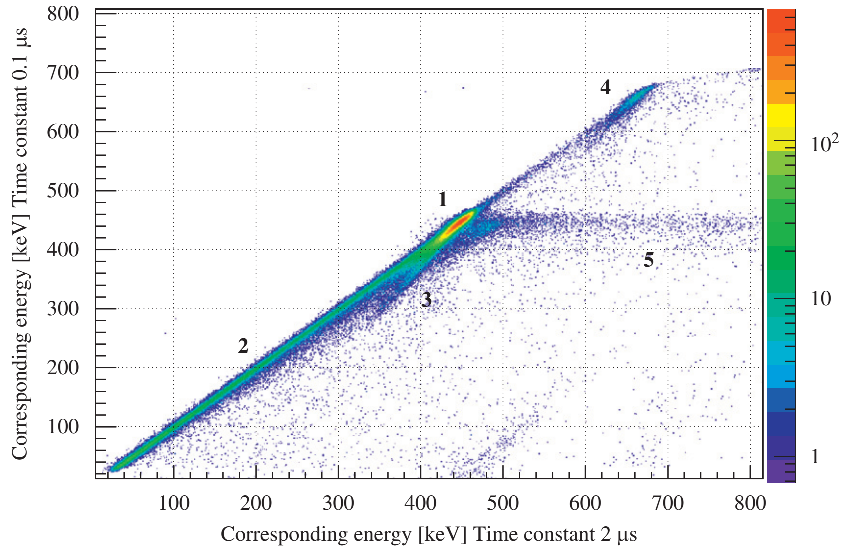

Fig. 8. Scatter plot of pulse-height spectrum of coincidence events depositing between 446.0 and 447.8 keV in the hemispheric CdTe detector using two amplifiers with 0.1 and 2.0 µs shaping times (cf. text). Applied high voltage was 1000 V.

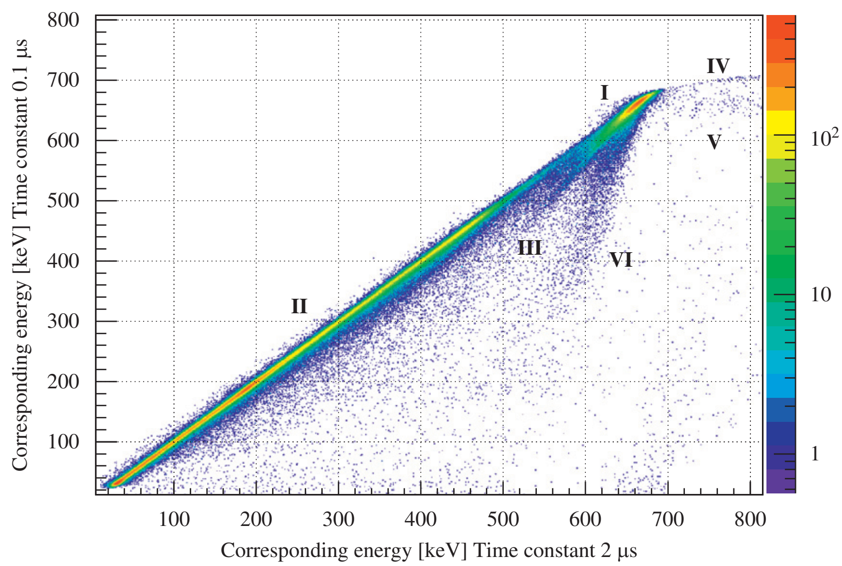

Fig. 9. Scatter plot of pulse-height spectrum of single events in the hemispheric CdTe detector using two amplifiers with 0.1 and 2.0 µs shaping times (cf. text). The full-energy peak marked I corresponds to a deposited energy of 662 keV. Applied high voltage was 1000 V.

4.2. Hemispheric detector

The scatter plot corresponding to events depositing between 446.0 and 447.8 keV in the hemispheric detector is shown in Fig. 8 and the scatter plot recorded in singles mode (the CdTe detector alone triggers the system) is shown in Fig. 9. Typical pulse shapes from the preamplifier are shown in Fig. 10. The pulse shapes are sampled in singles mode, but are representative also for coincidence events. In all cases, the primary radiation enters the detector through the surface opposite to the anode.

In the plot of coincidence events (Fig. 8) three distinct regions can be seen. Firstly, the coincidence peak (1) that accounts for approximately 45 percent of the total number of events, secondly a large number of events of lower pulse height along the diagonal (2) and, thirdly, a tail where the events are clearly separated from the diagonal (3). An example of the pulse shape for events along the diagonal (including the peak) is shown in Fig. 10(a). These events are characterized by a negligible hole contribution to the total pulse height. Just as in the case of the planar detector the pulse-height deficit for the events below the peak has manly two origins, hole trapping (emphasized by the electric field configuration) and energy losses due to the escape of electrons. For the hemispheric detector the importance of the latter effect is more difficult to calculate than for the planar detector. However, the crystal geometry being the same, escape of electrons and secondary photons is expected to contribute similarly for both detectors. The effect of escape on the pulse-height distribution from the hemispheric detector is therefore expected to be small as was the case for the planar detector.

The pulse shape corresponding to the tail (3), shown in Fig. 10(b), reveals a phenomenon similar to what was seen for the events belonging to the tail in case of the small planar detector (see Ref. [8]). A fast increase in amplitude (due to the electron current) is followed by a much slower increase (due to the hole

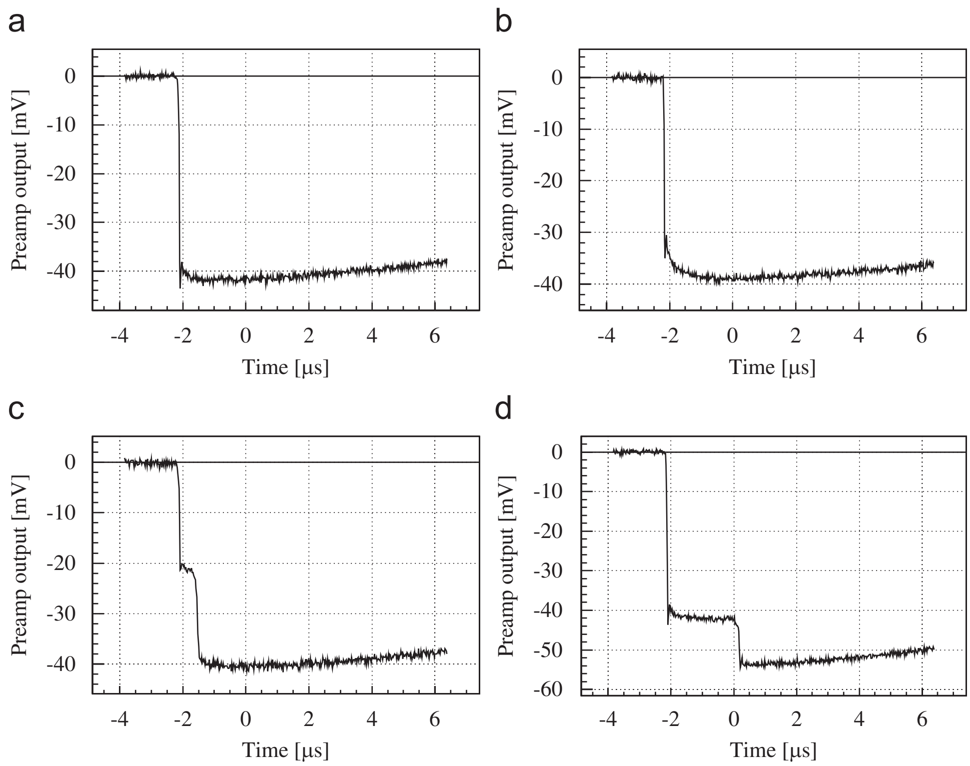

Fig. 10. Pulse shapes at the preamplifier output from the hemispheric CdTe detector. The pulses are typical for (a) full-energy peak (1, 4 and I), (b) first tail (3 and III), (c) second tail (VI) and (d) horizontal band (5 and V) in Figs. 8 and 9. Applied high voltage was 1000 V.

current). The bending is due to both trapping and a continuous decrease of the hole drift velocity due to the electric field gradient. This type of events is most likely to occur in the high field region, because there the hole drift velocities are large enough to produce a significant contribution to the pulse shape. Because this region constitutes a minor part of the total detector volume, these events are relatively rare.

Beside the three regions of coincident events two regions of random events can be discerned. One region (4 in Fig. 8) corresponding mainly to 662 keV photons from the cesium source depositing some or all its energy in random coincidence with an event in the HPGe detector and a horizontal band (5) corresponding to pile-up events. In this case in addition to the true coincidence event a second interaction occurs in the CdTe detector within a time interval such that the first amplifier (short shaping time) mainly responds to the coincident event, but the second amplifier (long shaping time) responds to both. This interpretation is supported by the pulse shape characterizing these events, Fig. 10(d), where the plateau is randomly distributed both in time and amplitude.

In the scatter plot of single events (Fig. 9) two additional structures are found besides those already addressed in the discussion of Fig. 8 (I, II, III and V in Fig. 9). The additional features are the bent band of events above the full-energy peak (IV) and a second tail of events (VI) extending below the full-energy peak. The bent structure of high-energy events is also present in Fig. 8. These events are mainly due to background radiation. Bending is an artificial effect due to saturation of the pulses in the delay amplifier. The second tail below the full-energy peak is much weaker in the coincidence plot, which indicates that these events are not produced in a single Compton scattering that is the dominant source of accepted coincidences. The corresponding pulse shape (cf. Fig. 10c) is similar to that corresponding to pile-up events (Fig. 10d), but differs in two respects. The amplitude is less than or equal to the amplitude corresponding to the events contributing to the peak, and the width of the plateau is less than or equal to approximately 0.5 μs. These pulse shapes are believed to be the result of multiple interactions within the crystal. Assuming two interactions occurring at different distances from the positive electrode, the electrons liberated in the interaction closest to the positive electrode will reach the high field region first giving rise to the first steep slope. The plateau corresponds to the time it takes for the electrons liberated at the other interaction point to drift to the strong field region, when the second steep slope arises. In order to lend support to such an interpretation, we made simulations with the same program package PENELOPE as above.

For single events (no photon reaching the HPGe detector) we required all of the primary energy (662 keV) be absorbed in two interactions each contributing at least 66 keV. The observed fraction of all full-energy events in the tail (VI in Fig. 9), approximately 5 percent, is reproduced in the simulation requiring the two interactions to occur at positions differing in their distance to the anode by at least 3 mm. For events where a 212 keV photon reaches the HPGe detector, a considerably smaller fraction of events undergo consecutive scattering in the CdTe crystal. In simulations with the same requirements as above, the fraction of events in the tail in this case is 0.4 percent, a value consistent with observations.

Considering the scatter plot for the singles mode (Fig. 9) it is obvious that the pulse-height correction algorithm developed for the small planar CdTe detector is not applicable. An unambiguous relationship between the rise time (deviation from the diagonal) and the pulse-height deficit cannot be defined because of the occurrence of two distinct tails. However, sampling the pulse shape it would be possible to distinguish between the different types of events and correct for the amplitude deficit. A simpler alternative is to use the information in the scatter plot for rise-time discrimination of the recorded pulse-height distribution excluding any data outside of the region along the diagonal. This way it is possible to improve the peak-to-valley ratio and the resolution at a certain loss of efficiency. We return to this point below.

4.2.1. Improvements by cooling

Studies have shown that the noise can be considerably reduced by cooling the CdTe detector. Chirco et al. [13] investigated the temperature dependence of different noise sources in CdTe detectors. They found that above 10 °C the leakage current is the dominant source of noise. Below 5 °C they reported the noise to be essentially independent of temperature. Other studies suggest different optimal values for the temperature of operation. A study by Khusainov [14] indicates temperatures between −10 and −40 °C, whereas a study by Redus et al. [15] suggests an optimal temperature of approximately 0 °C. Lower temperatures, it is concluded, may lead to significantly larger detrapping times of charge carriers, hence degrading the detector performance due to polarization effects.

In order to investigate how cooling affects the pulse-height distribution, a Peltier element with water cooling was attached to the rear side of the detector housing, making it possible to reach a temperature of approximately −7.5 °C after covering the detector housing and Peltier element with foam insulation. The detector response to the lower temperature could be directly monitored by the decreasing leakage current. Below 0 °C the leakage current in the hemispheric detector was less than 0.5 nA as compared to 100 nA at room temperature. Cooling the detector improved the energy resolution, but below approximately 0 °C no further improvement was observed.

In the case of the large planar detector the improvement in resolution was comparatively small. However, for the hemispheric detector the effect was larger. Spectra recorded with the hemispheric detector at room temperature and at −7.5 °C and applying rise-time discrimination are shown in Fig. 11. The results are summarized in Table 1. Rise-time discrimination is done by means of cuts in the ratio of the equivalent energy as measured by the pulse height from the amplifier with 0.1 μs shaping time, $E_{0.1\,\mu s}$, to that from the amplifier with 2 μs shaping time, $E_{2.0\,\mu s}$. The peak-to-valley ratio is defined as the ratio of the height of the full-energy peak (662 keV) to the average height in the valley between 550 and 570 keV. The peak-to-Compton ratio is calculated for the average height of the Compton distribution in the region between 340 and 370 keV. In order to quantify the efficiency loss due to rise-time discrimination the summed total number of counts in the region between 615 and 700 keV is compared. A relative peak efficiency of 100 percent at room temperature (−7.5 °C) corresponds to 2.2 ± 0.1 (3.0 ± 0.1) percent of all photons entering the

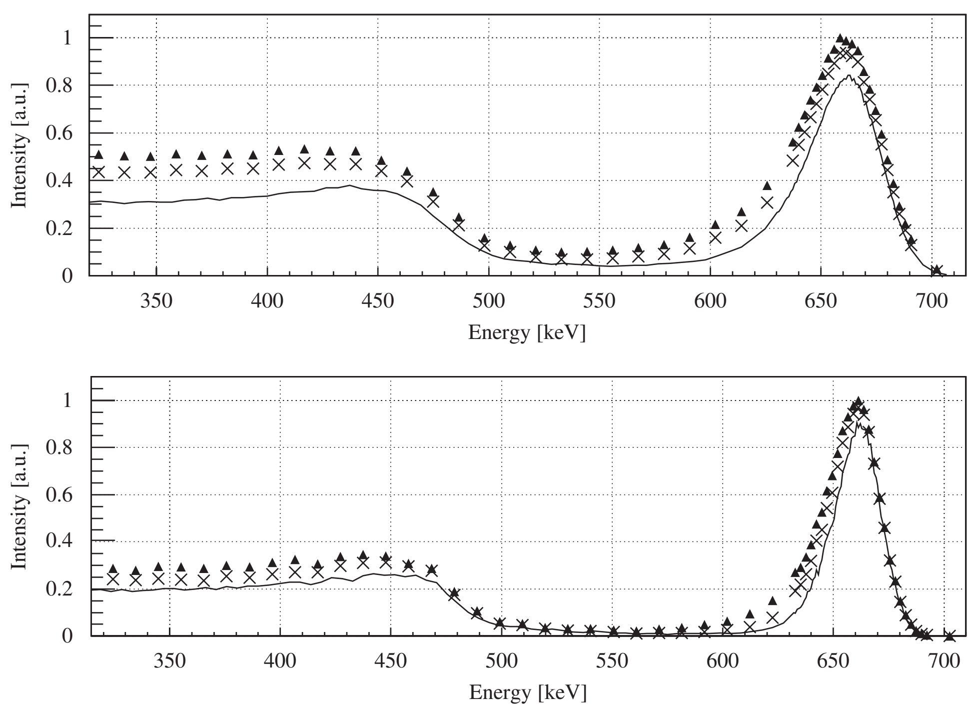

Fig. 11. Effects of rise-time discrimination on pulse-height distributions for ^{137}Cs from the hemispheric CdTe detector at 20 °C (upper) and cooled to −7.5 °C (lower): accepting all events (triangles), retaining 90 percent (crosses) and retaining 75 percent (line). Applied high voltage was 1000 V.

Table 1
The effects of rise-time discrimination and cooling on the properties of the pulse-height distribution for the hemispheric CdTe detector (cf. text)

Temperature (°C)	Applied high voltage (V)	Requirement $E_{0.1\,\mu s}/E_{2.0\,\mu s}$	Resolution (FWHM) at 662 keV (keV)	Peak-to-valley ratio	Peak-to-Compton ratio	Relative peak efficiency (%)
20	1000	–	46	10	2.0	100
20	1000	> 0.914	43	14	2.1	90
20	1000	> 0.962	40	19	2.6	75
−7.5	1000	–	29	37	3.1	100
−7.5	1000	> 0.977	27	74	3.3	90
−7.5	1000	> 0.988	25	92	3.5	75

detector, giving rise to an event in the full-energy peak. For a NaI(Tl) scintillation detector 12.5 mm in diameter and 12.5 mm in height was used for comparison and the corresponding figure was 4.9 ± 0.2 percent.

5. Summary of the results and conclusions

As part of a program investigating means to improve gamma-ray spectra obtained with CdTe detectors, we report results obtained with two $10 \times 10 \times 5\,mm^3$ CdTe detectors, one of planar geometry and the other of quasi-hemispheric geometry. The planar detector we find unsuited for spectroscopic applications. For the quasi-hemispheric detector the results are more promising. Applying a combination of cooling and pulse rise-time discrimination the peak-to-valley ratio may be improved by more than a factor of nine and the resolution by almost a factor of two, resulting in a resolution of approximately 4 percent at 662 keV, at a loss of approximately 25 percent of the counts in the full-energy region. Although the resolution is twice that obtained in an earlier investigation of the properties of a small planar detector, the peak-to-valley ratio, 92, obtained in the present study is excellent. It renders the detector an interesting candidate for applications to in-situ investigations of the distribution of radionuclides in the environment. The required cooling to below $0\,^{\circ}C$ is, however, a definite drawback.

Acknowledgment

This work was supported in part by the Swedish Radiation Protection Institute.

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