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Measuring high-energy γ-rays with Ge clover detectors

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Abstract

Gamma-rays with energies up to 20.7 MeV produced by the ^{208}Pb(p, γ) capture reaction were measured with the AFRODITE germanium detector array. The measured full energy peak efficiency of the array is 1.5% at 1.3 MeV and $9(2) \times 10^{-4}$ at 15 MeV. The FWHM of capture γ-ray peaks was 50 keV up to the highest measured energies. The efficiency curve has been calculated using a Monte-Carlo simulation code GEANT. The simulation and measurements agree very well.

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Keywords: High-energy gamma-rays; Monte-Carlo simulation; AFRODITE Ge detector array

Germanium detectors are very widely used for γ-ray detection, but the gamma-ray energies are usually restricted to below 10 MeV [1]. Gamma-rays with higher energies have only been detected with good resolution pertaining to Ge detectors after the development of large volume composite detectors such as Clover and Cluster [2,3]. The main reason is that the detector volume is the decisive factor for full energy peak detection efficiency at high energies. At these energies the efficiency becomes prohibitively low in small volume detectors making the full energy peak invisible in the background of γ-rays escaping from the detector [4]. Another difficulty lies in the construction of germanium detector preamplifiers. Since they are always designed as a compromise between large dynamic range and low noise level, they do not necessarily allow for measuring high- energy γ-rays. This paper reports on high-resolution measurement of γ-rays with energies up to 20.7 MeV using the AFRODITE Ge Clover detector array. The measured and calculated efficiency curves for the array are presented.

The AFRODITE Ge detector array at iThemba LABS is mounted in a rhombicuboctahedron frame with 16 detector positions. The array normally consists of eight Clover detectors and eight low-energy photon spectrometers. For the purpose of the experiment described in this paper only the Clover detectors were used. They are similar to those of EUROBALL III [5]. Each Clover consists of four 50×70 mm HPGe crystals and the eight Clovers subtend a solid angle of 11% of 4π. These detectors are very suitable for measuring high-energy γ-rays due to their large volume. The total active Ge volume is approximately 470 cm^3. Moreover, the crystals are closely packed without any material between them, thus enabling good energy resolution for signals added from more than one crystal. The distance between the front face of the detector and the center of the AFRODITE array is 17 cm. For our experiment the target chamber was fitted with 5 mm thick Al windows. Each Clover detector is surrounded by a BGO Compton suppression shield. In front of the suppression shields 10 cm from the center of the target chamber are 3 cm thick tungsten collimators with a 3.5 cm by 3.5 cm opening for γ-rays. The opening is tapered at 9°. The collimator partially shadows the Ge crystals, but allows for

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smaller Doppler broadening of γ-ray lines. Although Clovers are made of n-type germanium, they operate with positive high voltage and their outputs are therefore positive. In order to have signals with negative polarity, an inverter is added as the last stage of the preamplifier. At the same time, the amplitude of the signals is limited to about $-2\,\mathrm{V}$ with $50\,\Omega$ impedance, which with a factory set calibration of $-200\,\mathrm{mV/MeV}$ corresponds to about 10 MeV γ-ray energy. Higher energies cannot be measured with standard settings of the clover detector preamplifiers. We overcame this problem by taking positive polarity signals from the preamplifier, therefore, avoiding the inverter that not only inverts but also amplifies the signal by about a factor of 3. This is illustrated in Fig. 1 which shows positive and negative polarity signals corresponding to a 20 MeV γ-ray from a Clover detector preamplifier operating in resistive feedback mode. The positive polarity signals were treated with standard pulse processing electronics, read out with MIDAS data acquisition system [6] and stored in list mode.

Efficiency calibration was performed with ^{152}Eu, ^{56}Co and ^{60}Co sources up to 3.5 MeV and with the ^{12}C(p, p′γ) reaction at 15 MeV γ-ray energy. The proton beam with an energy of 66 MeV was delivered by the separated sector cyclotron at iThemba LABS [7]. A cross-section of 1.0(2) mb was assumed for the calibration reaction [4]. Efficiency calibration for the eight Clover detectors of the AFRODITE array in the energy range between 0.1 and 20 MeV is shown in Fig. 2 together with the results of a simulation using the GEANT 3 Monte-Carlo simulation tool [8]. The simulation was performed in the same way as described in Ref. [5], except that the detector geometry was slightly simplified. Instead of cylindrical tapered detectors we used rectangular ones, but care was taken that their volume remained the same as specified by the manufacturer. Contrary to Ref. [5] the BGO Compton suppression detector was also put into the model. After taking care that

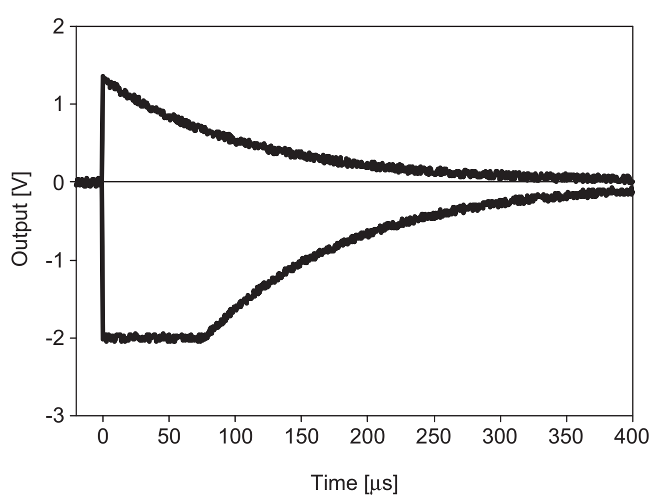

Fig. 1. Positive and negative polarity signals corresponding to a 20 MeV γ ray from a Clover detector preamplifier operating in resistive feedback mode.

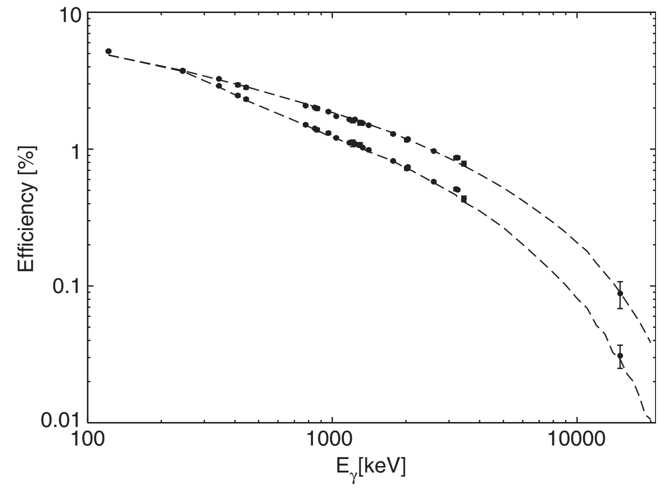

Fig. 2. Measured efficiency calibration data for the eight Clover detectors of the AFRODITE array in the energy range between 0.1 and 20 MeV (full circles), compared with the calculated results (dashed line) obtained with the GEANT package [8]. The upper curve corresponds to the add-back detection mode and the lower one to the direct mode.

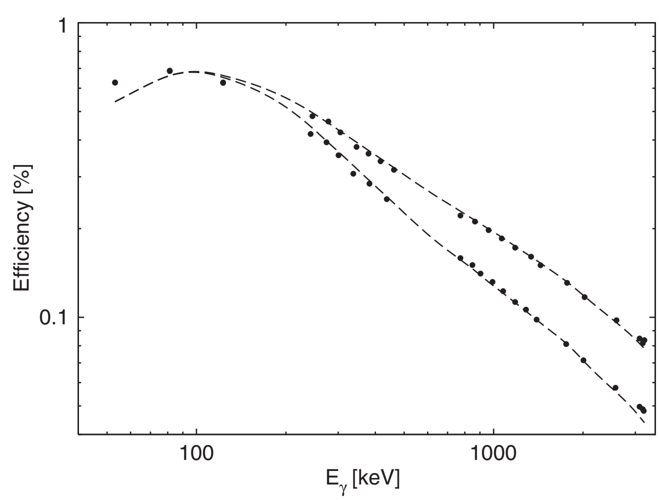

Fig. 3. Efficiency values for a single Clover detector (full circles) in the energy range between 0.1 and 3 MeV is shown, as obtained from point source measurements at a distance of 25 cm [5]. The results of a simulation using the GEANT tool [8] are shown as a dashed line for the add-back detection mode (upper curve) and the direct mode (lower curve).

the area of the front face of the Ge detectors exposed to γ-rays is as close to reality as we could determine, no normalization of the simulation results to the measured data was necessary. To verify the validity of the detector model used in the simulation we reproduced the results of efficiency measurements for a single clover detector, taken from Ref. [5] (Fig. 3).

High-energy γ-ray detection capabilities of the AFRODITE array were put to the test with the reaction ^{208}Pb(p, γ) where cross-sections for capture into different single proton states in ^{209}Bi were measured at nine different beam energies [3]. The target consisted of an enriched ^{208}Pb foil with a thickness of $1\,\mathrm{mg/cm^2}$ mounted on a $5\,\mu\mathrm{g/cm^2}$

thick carbon backing. Four clover detectors were placed at polar angle 90° and four at 135° with respect to the beam axis. Events were accepted if at least one of the 32 Ge crystals gave an energy signal higher than 3.5 MeV. Signals from all four crystals in a clover detector were added for each event during the data analysis. Data were analyzed with RADWARE software [9]. A special procedure was applied for energy calibration at high γ-ray energies.

For an accurate energy calibration of partial γ-ray spectra, we used a correlation method [10]. The method is based on simple observation that slight changes of energy calibration result in practically pure shift of the upper part of the spectrum which is of interest. From low- energy points alone the calibration lacks precision needed to align the partial spectra properly. The key point of the method is knowledge of the energies and resolution of the peaks expected to emerge from the capture experiment.

Let us denote the expected spectrum, free of uncorrelated background, by $s_t(E_\gamma)$. The position of the peaks and their widths are usually known quite well. The low-energy tails of the peaks, which are correlated with peak height, may be known to some degree as well as the relative intensities of the expected peaks. The last two pieces of information, however, are not critical for applying the method.

The measured spectrum, already energy calibrated as well as possible, is denoted as $s_e(E_\gamma)$. Here, E_γ denotes the channel of the calibrated spectrum.

Now the aim is to find slight shifts of several channels of the individual spectra, relative to a selected one, which we combine to obtain the final spectrum showing sharp peaks. Needless to say, any shift of the order of the width of the peaks or larger may smear the resulting spectrum to a degree where one sees no peaks. Since the individual peaks of the partial spectra are not seen at all, the correlation, which is sensitive to all of the peaks in the spectrum, may be helpful.

To find the relative shifts of the spectra, the correlation spectrum is determined from

$$c(\Delta E_\gamma) = \sum_R s_e(E_\gamma) s_t(E_\gamma + \Delta E_\gamma).$$

The range of the summation R should be properly chosen to avoid massive contribution from the background. The energy shift ΔE_γ is in the interval $[-\delta, \delta]$, with δ chosen to cover the expected energy shift of the spectrum, which comprises only a few channels. When the spectra s_t and s_e are carefully calibrated at low energies, the correlated spectrum shows a clear peak close to $\Delta E_\gamma \approx 0$. There are, of course, also other peaks in this spectrum but they are clearly separated from the central one so the shift $(\Delta E_\gamma)_0$ of this peak is what we need to finally align the spectra. In some cases there is an ambiguity which peak of the correlation spectrum is the proper one. Due to the background, the central peak may not be the highest one as one may expect. In such cases one has to try several possibilities and observe the features of the resulting

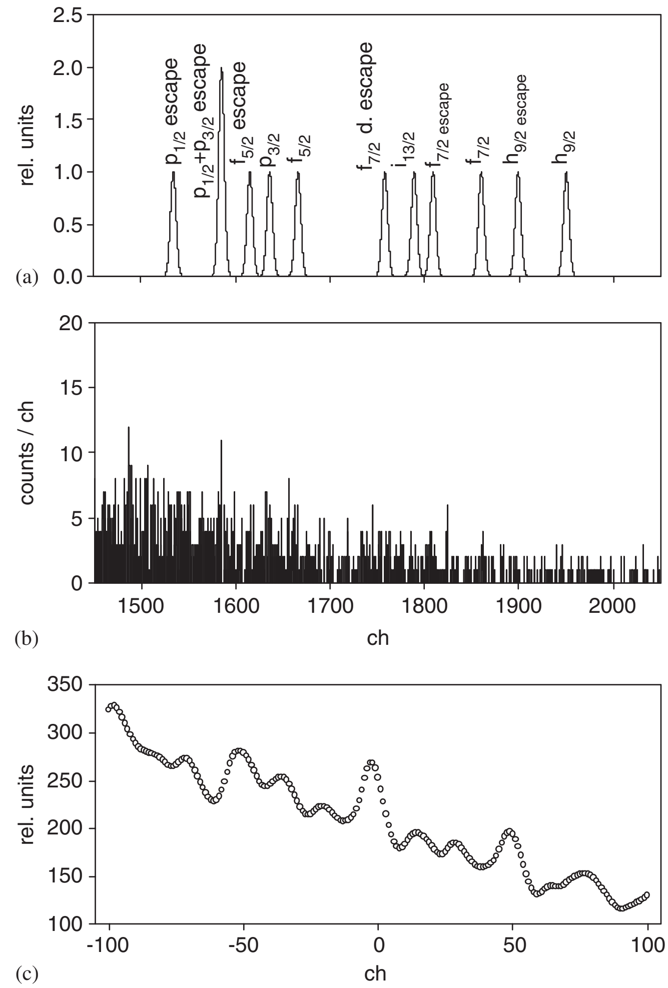

Fig. 4. Illustration of the efficiency of the correlation method described in the text is shown in this figure. (a) The expected spectrum without background, (b) the measured spectrum from a single Ge crystal and (c) the correlation spectrum, showing no shift between the spectra (a) and (b).

spectrum. Fig. 4 illustrates the point given above. The expected spectrum s_t is shown in Fig. 4a, the corresponding measured spectrum s_e in Fig. 4b, is a spectrum from a single Ge crystal. The correlation spectrum is shown in Fig. 4c, clearly showing the efficiency of the method. Since the spectrum 4b has no shift, the proper correlation peak is the one in the middle of the correlation graph at channel zero. The second peak centered at channel 51 is due to a fixed distance between full energy and escape peaks. The energy calibration of Fig. 4c is 10 keV per channel.

An example for the result of the experiment described above and the calibration procedure used is a spectrum summed from eight Clover detectors measured at 15.7 MeV proton energy (Fig. 5). Peaks in the spectrum are marked with the single particle orbit of the captured proton and escape peaks are due to missed detection of a 511 keV positron annihilation γ-ray. The FWHM of all peaks between 11 and 20 MeV due to proton capture was about 50 keV. The intrinsic Ge detector resolution is probably better than 50 keV in this energy range and most likely depends on energy. The main reason for a constant

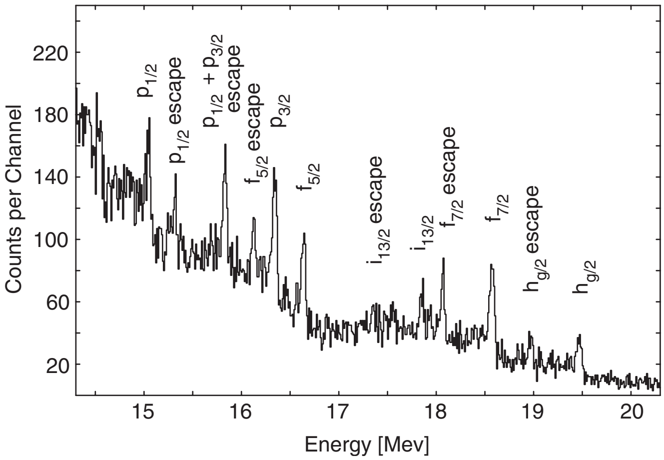

Fig. 5. Spectrum summed from eight Clover detectors measured at 15.7 MeV proton energy. Peaks in the spectrum are marked with the single particle orbit of the captured proton and escape peaks are due to missed detection of a 511 keV positron annihilation γ-ray.

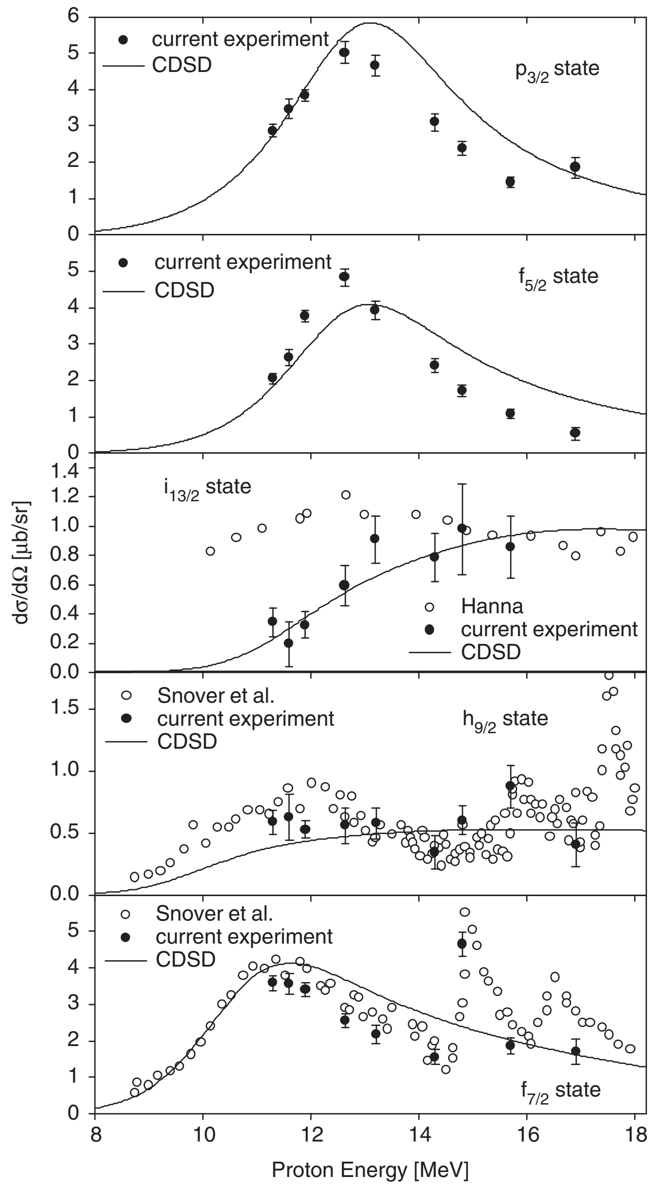

Fig. 6. Excitation functions for capture into different single proton states in ^{209}Bi. The differential cross-sections are one half of the summed cross-sections at $\theta = 135^\circ$ and $\theta = 90^\circ$. Data are from current experiment (•), from Ref. [11] (○) for the $f_{7/2}$, and $h_{9/2}$ final states and from Ref. [13] (○) for the $i_{13/2}$ state. The results of calculation with the consistent DSD model are shown with solid line.

FWHM is that it was mostly determined by the limited beam energy resolution which does not depend on γ-ray energy. In addition, the capture γ-ray peaks were broadened partly by the energy loss of the beam in the target and Doppler broadening due to the finite opening angle of the detectors. The beam loses about 15 keV in the target while the Doppler effect broadens the lines by about 4 keV at 15 MeV γ-ray energy and 90° detector angle. The energy calibration procedure may have also introduced a broadening of the peaks by less than 10 keV. Despite this limitation, an improvement in resolution by more than a factor of 10 was achieved as compared to the previous measurements [11,12].

The final result of the experiment described above are the measured excitation functions for the population of different single-proton states in ^{209}Bi, which are plotted in Fig. 6 as an example of what can be done with much improved γ-ray detection resolution at energies above 10 MeV. Captures into the $f_{5/2}$ and $p_{3/2}$ single proton states lying 294 keV apart, were separated for the first time due to the improved resolution. Also the $i_{13/2}$ peak, which was previously submerged under a much higher $f_{7/2}$ peak is now clearly separated and the excitation function for capture into this state differs considerably from the previous measurement [13]. Fig. 6 shows differential cross-sections as measured in our experiment with one half of the detectors at polar angle $\theta = 135^\circ$ and the other half at $\theta = 90^\circ$. The results of the current experiment marked with full circles are compared with previous measurements [11–13], marked with empty circles and with the results of calculations with the consistent DSD model [14]. The same normalization procedure and model parameters were used as in Ref. [3].

Another interesting aspect of the Clover detector is the add-back factor corresponding to the gain in efficiency by summing the signals from detector crystals firing simultaneously. The behavior of this factor has been discussed previously [15]. The add-back factor for the AFRODITE array is shown in Fig. 7, together with results from Ref. [15] and our Monte-Carlo simulation. Our measurement cannot be directly compared with that of Ref. [15] since it was obtained in a different geometry. The add-back factor increases almost linearly from 250 keV up to about 4 MeV γ-ray energy. Above this energy, the add-back factor increases much more rapidly than below it. The energy of the change coincides with the energy at which the pair production becomes the dominating interaction mechanism in germanium and these two facts might be

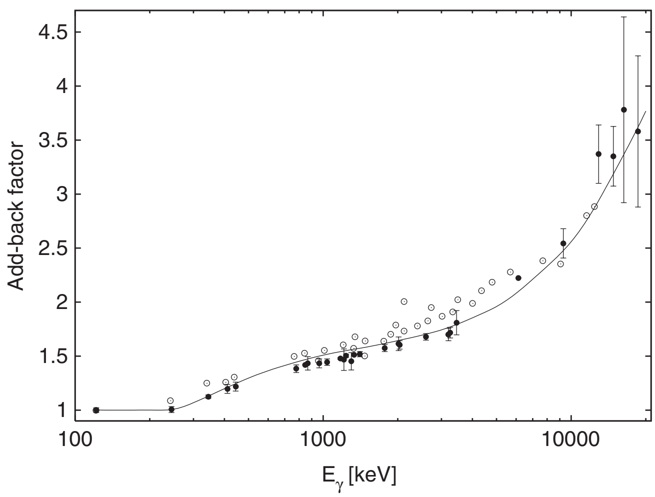

Fig. 7. Add-back factor for the AFRODITE clover detector array (full circles), compared to Ref. [15] (empty circles) and a Monte-Carlo simulation (solid line).

connected. This further illustrates the importance of large detector volume for high-energy γ-ray detection.

To conclude, large volume composite germanium detectors are very suitable for measuring high-energy γ-rays. We have measured capture γ-rays with energies between 10 and 20.7 MeV with an energy resolution about 10 times better than any previous measurement in this energy range. This opens many new possibilities for γ-ray spectroscopy and enabled us to clearly differentiate proton captures into various single particle states in ^{209}Bi.

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