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Characteristics of a Compton suppressed Clover detector up to 5 MeV

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Abstract

The Clover detectors in their addback mode are excellent tools for detecting high-energy gamma rays ($\geqslant 2$ MeV). The characteristics of these detectors, at energies above 2 MeV, are usually determined from simulation data or from extrapolation of the empirical data. This is the first time that the characteristics of a Compton suppressed Clover germanium detector have been studied up to 5 MeV using a radioactive ^{66}Ga ($T_{1/2} = 9.41$ h) source. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Advances in nuclear spectroscopic studies are closely related to the innovations in detector technologies. The recent attempts to study nuclei under extreme conditions of spin, isospin, mass and temperature, demand many additional and improved features in the detection tools. The usefulness of a gamma spectrometer is characterised by its energy resolution, efficiency of detection and ability to discriminate gamma rays of interest against the background radiations. In heavy ion induced compound nucleus reactions, the energy resolution is affected by Doppler broadening. So, besides having large efficiency, the gamma detectors should have small opening angle to reduce this broadening. A new concept of composite detectors (Clover, Cluster) [1–3], consisting of an assembly of smaller crystals in a common cryostat, have been designed to overcome this problem and yet preserve the high efficiency. Electrical segmentation of the individual crystals of the Clover detector, a technique reported recently [4,5], lowers the opening angle and thereby

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improves the performance of these detectors further. Moreover, since the Clover detector consists of four individual crystals housed in a single cryostat, each of the individual crystals can be considered as a scatterer and the two adjacent crystals as absorbers. This makes Clover detectors sensitive to the polarisation of the gamma transitions.

Due to their high efficiency the composite detectors are very effective for detection of high-energy gamma rays ($\geqslant 2$ MeV). But suitable radioactive sources having gamma rays of energies greater than 1.5 MeV (e.g. ^{56}Co [5]), are not easily available. So the characteristics of these detectors at higher energies ($\geqslant 2$ MeV) are usually determined from simulation data [1] or from extrapolation of the empirical data to energies above 1.5 MeV. This paper reports the first direct determination of the characteristics of a Compton-suppressed normal Clover detector [2,5] up to 5 MeV using radioactive sources. For this, ^{152}Eu (13.5 yr) with gamma rays from 122 to 1408 keV and ^{66}Ga (9.41 h) with gamma rays from 833 to 4806 keV were used. The measurements of full energy peak detection efficiency, addback factor, energy resolution and hit pattern have been performed.

2. The Clover detector

2.1. The geometry

The Clover detector (from Eurisys Mesures) used in the present work has the standard geometry [2]. It consists of four co-axial N type Germanium detectors, arranged like a four leaf clover. Each crystal has a quasi-square front face with round edges obtained by tapering the two adjacent faces with an angle of 7.1° starting at about half of length, and by cutting the two other faces, parallel to the crystal axis, along the whole length. The starting dimensions of the Germanium crystals are 51 mm diameter and 71 mm length. The active volume of the Clover detector is about 470 cm^3, which is $\simeq 89\%$ of the original crystal volume. The detector is inserted in a BGO Compton suppressor from Crismatec.

2.2. Modes of detection in the Clover detector

The total full energy peak efficiency of the Clover detector with 4 crystals is given by the sum of two complimentary effects [2]. They are

- full gamma energy is deposited in any one of the individual crystals—related to the direct detection efficiency,
- the full gamma energy resulting from the partial absorption in two or more crystals—related to coincidence detection efficiency.

Direct detection efficiency $(\varepsilon_p\omega)_{\mathrm{direct}}$ of 4 crystals of the Clover detector, where their signals are treated separately, is given by the uncorrelated sum of the individual photopeak efficiency of each of these crystals, $(\varepsilon_p\omega)_{\mathrm{direct},i}$.

$$(\varepsilon_p\omega)_{\mathrm{direct}} = \sum_{i=1}^{4} (\varepsilon_p\omega)_{\mathrm{direct},i}. \quad (1)$$

The coincidence detection mode, $(\varepsilon_p\omega)_{\mathrm{addbk}}$, when two or more crystals are in temporal coincidence, is mainly due to Compton scattering from one crystal to its neighbouring ones. The energy signals of individual crystals fired simultaneously, are recorded event by event in the list mode. The coincidence detection efficiency is given by the time correlated sum (addback) of these signals.

So the total full energy peak detection efficiency of the Clover detector is

$$(\varepsilon_p\omega)_{\mathrm{total}} = (\varepsilon_p\omega)_{\mathrm{direct}} + (\varepsilon_p\omega)_{\mathrm{addbk}}. \quad (2)$$

Therefore, for a Clover detector, the addback contribution is responsible for the enhancement of the total full energy peak detection efficiency compared to the direct mode. As a measure of this enhancement, the addback factor F is defined as the ratio of the total full energy peak efficiency to the direct detection efficiency.

$$F = (\varepsilon_p\omega)_{\mathrm{total}}/(\varepsilon_p\omega)_{\mathrm{direct}}, \quad (3)$$

where, $F \geqslant 1$.

2.3. The present set-up and the ^{66}Ga source

The present work was done in the Indian National Gamma Array (INGA) [6,7] using the

BARC–TIFR Pelletron facility at TIFR, Mumbai, India, using 8 Clover detectors.

The radioactive sources were placed in the target position which was $\simeq 25$ cm from the crystal front faces of the Clover detectors. The data presented in this work are from a detector at 90° in the array. Energy and timing signals were taken from each crystal and the pulse processing was carried out using standard NIM and CAMAC modules. Spectroscopic amplifiers with Gaussian shaping and a shaping time constant of 3 μs were used. The data were recorded in the list mode.

While preparing for an experiment for studying nuclei in the $A = 40$ region, it was found that the energies of most of the gamma rays involved in the deexcitation of the nuclei populated in this region are very high ($\geqslant 2$ MeV, even up to 5 MeV) [8], necessitating efficiency data up to at least 5 MeV. To have a complete information of the efficiency and addback characteristics for the entire energy region, we prepared ^{66}Ga ($T_{1/2} = 9.49$ h) by the reaction ^{52}Cr(^{16}O$,pn$)^{66}Ga by bombarding natural Cr with 55 MeV ^{16}O, in the INGA setup. The decay of $^{66}_{31}$Ga to $^{66}_{30}$Zn gives a large number of strong gamma rays with energies ranging from 0.833 to 4.806 MeV. Substantial amount of natural Cr (^{50}Cr = 4.345%, ^{52}Cr = 83.789%, ^{53}Cr = 9.501%, ^{54}Cr = 2.365%) powder was rolled on to a 10 mg/cm^2 thick Gold foil. The dominant reaction products like ^{62}Cu ($T_{1/2} = 9.67$ m), ^{63}Cu (stable), ^{59}Ni ($T_{1/2} = 7.6 \times 10^4$ yr), ^{65}Ga ($T_{1/2} =$ 15.2 min) were either very shortlived or longlived/stable compared to the half life of ^{66}Ga. Only ^{65}Zn ($T_{1/2} = 244.26$ d) and ^{62}Zn ($T_{1/2} = 9.186$ h) could produce some interfering gamma lines. But ^{65}Zn decay contains only one intense gamma line at 1115.5 keV and ^{62}Zn with a comparable half-life, contains dominant gamma rays of relatively low energies (40.8, 507.6, 548.3, 596.6 keV, etc.) and they do not create any difficulty in the analysis of the gamma rays of interest from the decay of ^{66}Ga (Fig. 1). The target was bombarded for $\simeq 7$ h. Data were not accumulated for the next 3 h. Most of the radioactivity produced died out during this period except ^{65}Zn and ^{62}Zn, as discussed earlier, and our nucleus of interest ^{66}Ga. The data were then accumulated for 3 h.

3. Characterisation of the Clover detector with radioactive sources

A standard source of ^{152}Eu from Amersham and a freshly prepared ^{66}Ga source as described above, were used in the study of the characteristics of the Clover detector. The gamma ray spectra (both in total and direct modes) obtained after the irradiation of a sample of natural Cr with 55 MeV ^{16}O beam are shown in Fig. 1. The energies of the gamma rays from ^{66}Ga decay are shown in the figure along with their relative intensities (taking I_γ of 1039 keV = 100) within parentheses. The spectra clearly demonstrates the improved response (peak/total ratio) obtained in the total (i.e. addback) mode. Full energy peak efficiency (Fig. 2), addback factor (Fig. 3) and energy resolutions (Fig. 4) of this detector as measured in the present work are shown in Figs. 2, 3 and 4, respectively.

The performance of the Clover detector in the direct and total detection modes versus gamma-ray energy was determined in an offline analysis with the programme INGASORT [9]. The hit pattern, i.e., the relative distributions of different contributions from "single hit", "double hit" etc. of the detector crystals as a function of gamma energy have also been determined and shown in Fig. 5. In Fig. 6, part of the spectra generated from single, double, triple and quadrupole hits are shown.

3.1. *Full energy peak efficiency*

Fig. 2 shows the measured relative full energy peak efficiencies for the direct and total modes. Although these two modes show more or less similar efficiencies for gamma rays of energies below $\simeq 500$ keV, for higher energies, the total mode shows considerable increase in the efficiency due to the increase in the addback contribution.

3.2. *Addback factor*

3.2.1. *Experimental results*

The addback factor F, has been determined in the range of energies from 122 to 4800 keV. The factor at low energies starts from $\simeq 1.0$ indicating that the direct and total modes do not differ at low

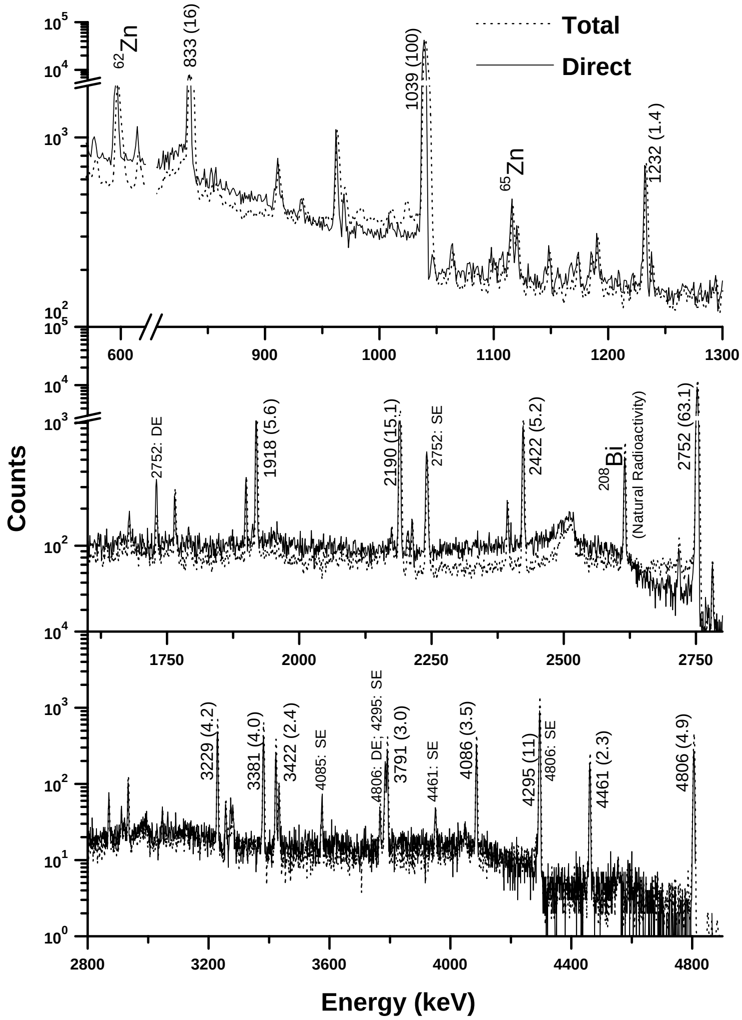

Fig. 1. The gamma ray spectra (both in total and direct modes) obtained after the irradiation of a sample of natural Cr with 55 MeV ^{16}O beam. The energies of the gamma rays from ^{66}Ga decay are indicated. The relative intensities of these gamma rays are also shown in parentheses.

gamma ray energies ($\leqslant$300 keV) since most of these gamma rays deposit their full energy in one of the crystals only. The factor then starts increasing sharply till $\simeq$2 MeV, where the add-back mode contribution comes in. Although the rate of increase is less for higher energy gamma rays, the factor continues to increase steadily for energies up to 5 MeV.

3.2.2. Simulation results

The results of the Monte-Carlo simulation program, CLOVER, [10] for estimating the response of the Clover detector for mono-energetic gamma radiations is also shown in Fig. 3. The program simulates the propagation of photons through Ge crystal, dead layers and any surrounding shield materials.

For an incident photon, the interactions of the primary photon or any secondary photon with the medium are followed until the full energy is absorbed or part of it escapes from the interaction zone. The Ge detectors are assumed to have dead layer in front, sides and back to simulate absorber materials. The energy dependence of the various

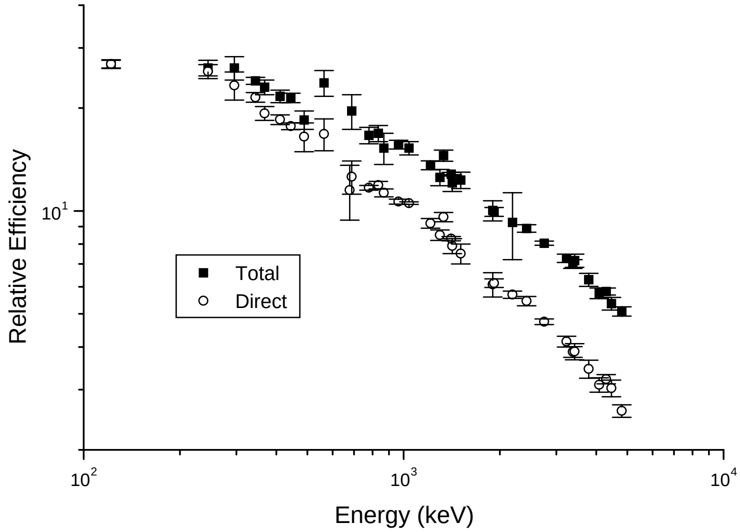

Fig. 2. Variation of relative efficiency with energy in direct and total modes.

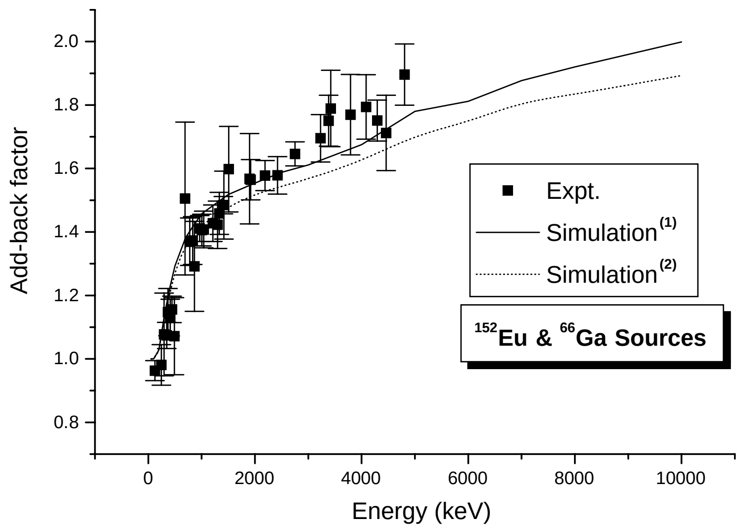

Fig. 3. Variation of addback factor with energy.

processes in Ge and BGO (or NaI) are taken from literature [11]. The Compton scattering cross sections of photons (polarised or unpolarised) are taken from Klein–Nishina formula [12,13]. For an incident flux of mono-energetic photons, the program calculates the energy deposited in individual crystals and in the surrounding anti-Compton shield. The energy deposited in the inert core or dead layer is ignored.

For the first set of results (indicated by simulation$^{(1)}$ in Fig. 3) calculations were done for a dead layer of 0.1 mm of Ge at the front, sides and at the back. The lengths of individual crystals were taken to be 7.0 cm with outer dimensions and tapers as per specification of the detector and the source-to-crystal distance was taken to be 25 cm. In the second set of results (simulation$^{(2)}$ in the figure), deadlayers were increased to 0.5 mm all

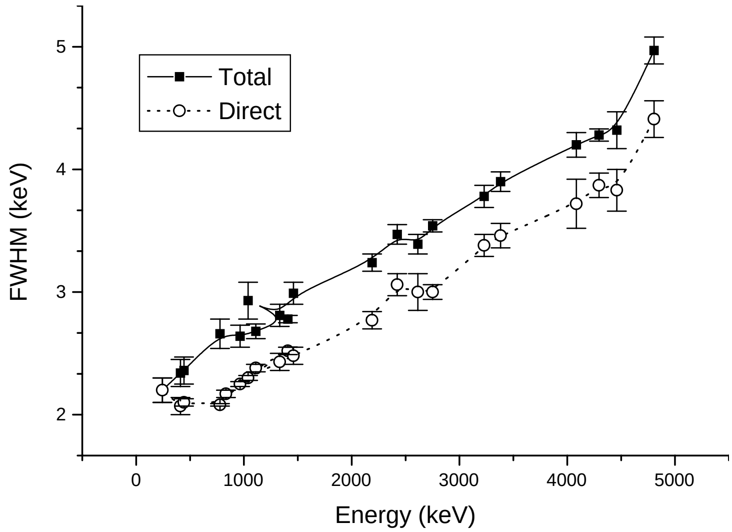

Fig. 4. Variation of FWHM of the gamma-ray peaks with energy. The lines are drawn to guide the eyes.

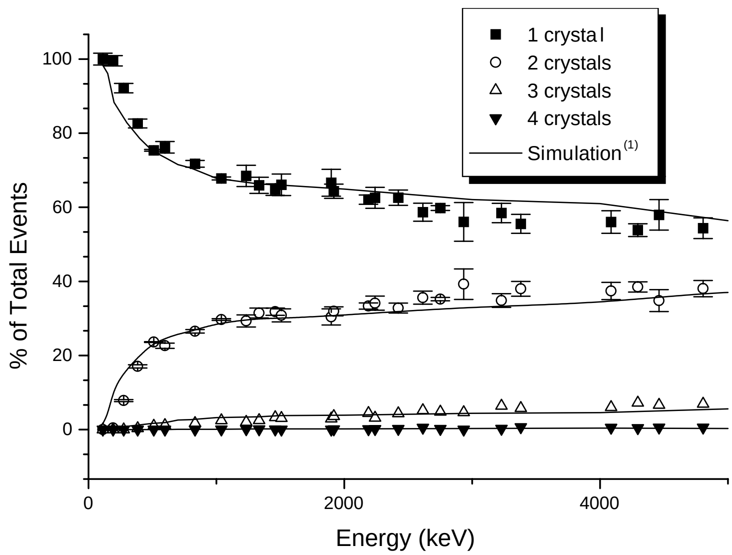

Fig. 5. Distribution of hit patterns with energy.

throughout. Reduction of the front dead layer (which simulates the effect of absorbers) would cause the efficiency curve to be flatter at low energies with the peak shifted below 100 keV. The side dead layer affects the addback factors. The back dead layer simulates the dewar material, and does not have any significant effect on the efficiency (other than reducing the effective volume of the crystal).

The two sets of simulation results, agree reasonably well with the experimental data at lower energies, but the first set fits the data better at higher energies. This shows the sensitivity of the simulation calculations on the detector parameters (dead layers, etc.) and the need for the experimental data. The simulation results for higher energies up to 10 MeV indicate that the addback factors slowly increase to $\simeq 2$. So at such high

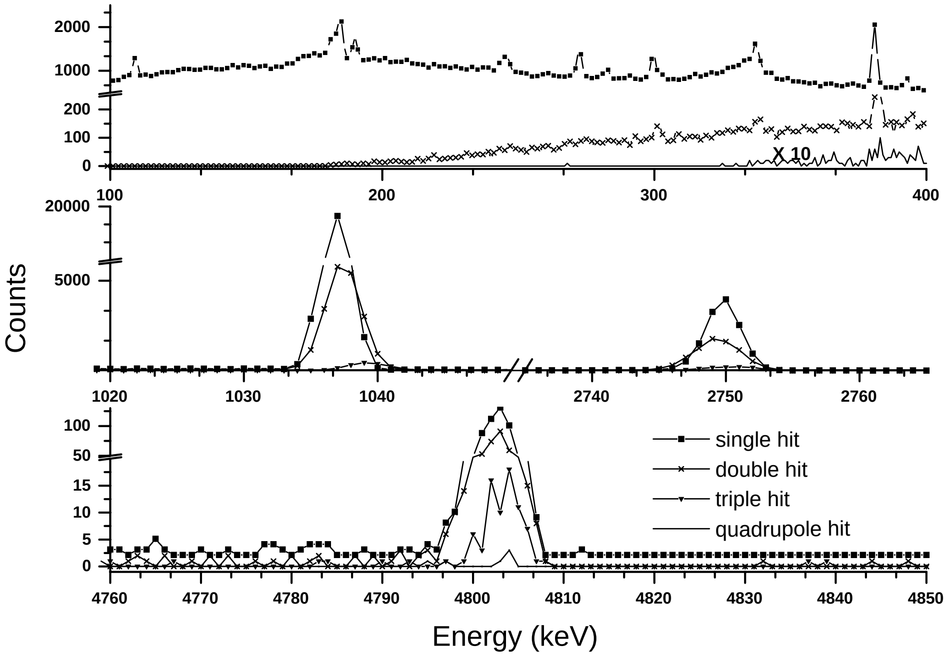

Fig. 6. Spectra generated from single, double, triple and quadrupole hits.

energies the Clover detector in its total mode including the addback effect should have a remarkably improved performance compared to the normal detectors.

3.3. Energy resolution

The energy resolutions of the detector in the direct and total modes are determined in terms of the full-width at half-maximum (FWHM) of the gamma ray peaks in the spectrum. The FWHMs in the two modes are shown in Fig. 4. For 122 keV the FWHMs are same for both the modes. At higher energies, the FWHM in the total mode is comparatively larger than that in the direct mode mainly because of the contribution of the noise from each of the crystals.

3.4. Fold distribution

The hit pattern distribution of the different crystals of the Clover detector with energy is shown in Fig. 5. The simulated results for the first set of parameters are shown by continuous lines. In Fig. 6, the single, double, triple and quadrupole hit spectra are shown.

For energies less than 200 keV, the total spectrum consists of only single hit (Fig. 6) events. Above 200 keV, the double hit probability gradually increases and reaches nearly $\simeq$20% of the total events at about 500 keV (Fig. 5). With increase in energy, the double hit probability increases significantly (to $\simeq$30%) up to 1000 keV. The single hit probability in this range gradually decreases (from $\simeq$100% at 100 keV to $\simeq$68% at 1000 keV). The triple hit starts contributing from above 300 keV (Fig. 6). At 1000 keV, its contribution, however, is only $\simeq$2.5%.

Above 1000 keV, the hit pattern more or less stabilizes up to 5 MeV (Fig. 5). It shows very slow increase in double, triple and quadrupole hit probabilities and corresponding decrease of single hit probability in this energy range. The single hit probability decreases from 68% of the total events at 1 MeV to $\simeq$54% at 5 MeV. The doubles and triples increase from 30% to 38% and 2.5% to 7.0%, respectively, in this energy domain, leading to a consistent increase in the addback factor throughout the range. But for quadrupole hit, the contribution is negligible throughout the energy range. It ranges from 0.04% at 1 MeV to 0.6% at 5 MeV. The simulation results (Fig. 5) for the single and double hits at higher energies are slightly overestimated and underestimated, respectively, compared to the experimental quantities. This difference is also manifested in the experimental and simulated addback factors (Fig. 3).

3.5. Effect of pair production

The escape peaks observed in the spectra above 2 MeV are strongly suppressed due to the anti-Compton shield (ACS) used in the experimental setup. According to the simulation calculations, the intensities of the single and double escape peaks of a 5 MeV gamma ray in the total spectrum would be reduced by factors of 3.1 and 6.7, respectively, with respect to the unsuppressed spectra. Slightly smaller suppression (2.6 and 6.0, respectively) are predicted for individual Clover segment spectra.

Table 1 shows a comparison between the experimentally observed ratios of escape to full energy peaks with the results of the simulation calculation. Considering the difficulty of exactly modelling the geometry of the ACS used, the agreement is reasonable.

There were some difficulties in the determination of the experimental ratios from the present gamma ray spectra (Fig. 1).

(1) The single escape peak of 4806 keV ($I_\gamma = 4.9$) gamma ray coincides with the 4295 keV ($I_\gamma = 11$) gamma ray. As a result, the double escape peak of the 4806 keV gamma ray coincides with the single escape peak of 4295 keV gamma ray.
(2) The double escape peak (at 3273 keV) of 4295 keV ($I_\gamma = 11$) gamma ray in the total spectrum is very weak and falls under the low-energy tail of the single escape peak of 3791 keV gamma ray ($I_\gamma = 3$).
(3) Although the single escape peaks of 4461 keV ($I_\gamma = 2.3$) and 4086 keV ($I_\gamma = 3.5$) gamma rays are clearly visible in the total and the direct spectra, the corresponding double escape peaks are barely visible in the total spectrum.
(4) Only for 2751.8 keV ($I_\gamma = 63.1$) gamma ray, both escape peaks are clearly seen in the two spectra.

While comparing the escape peak areas of the same gamma ray in the total and the direct spectra (Table 1), we find that the addback process reduces the escape peak areas in the total spectra. But this process cannot eliminate these peaks completely because of the finite probability of losing one or two annihilation gamma rays from the setup, mainly due to the exponential nature of the absorption of gamma rays.

Table 1
Comparison of the experimentally observed ratios of the areas of escape to full energy peaks with the results of simulation calculation

Photon energy (MeV)	Spectrum	SP/FP		DP/FP	
		Expt.	Simulation	Expt.	Simulation
2.752	Direct	0.068(2)	0.068	0.030(2)	0.025
	Total	0.042(1)	0.044	0.009(1)	0.008
4.086	Direct	0.213(21)	0.168	—	0.058
	Total	0.128(13)	0.101	—	0.017
4.461	Direct	0.297(37)	0.222	—	0.074
	Total	0.139(24)	0.130	—	0.022

The single escape, double escape and full energy peaks are denoted as SP, DP and FP, respectively. The errors in the last significant digits of the experimental quantities are shown within parentheses.

4. Conclusion

In the present study, the standard Clover detector with a BGO Compton suppressor has been characterised using a radioactive source up to 5 MeV. The results show that even up to 5 MeV, the detector performance is quite impressive. The simulation data (which agree reasonably well with the experimental data up to 5 MeV) indicate that even up to 10 MeV, the addback factor should show a slow but steady increase. This feature highlights the effectiveness of Clover detectors in the detection of high-energy gamma rays.

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