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Modeling of the stacked gamma-ray detectors

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Abstract: A didactic approach has been presented for the understanding of operation of the stacked or series combination of gamma-ray detectors. Assuming isotropic scattering of gamma-rays, we have obtained expressions for the addback factor in terms of only one probability. Using the experimental data of the HHS spectrometer, we have predicted the addback factor for various stacked detectors. This generalised technique could be used to predict the performance parameters of a stacked detector with any number of elements. Other than simulation studies, we present an intuitive way of understanding the operation of series detectors.

Keywords: Gamma detectors (scintillators, CZT, HPGe, HgI etc); Spectrometers

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1 Introduction

The use of composite detectors [1, 2] present a way of obtaining high detection efficiency without deteriorating the energy resolution and timing characteristics during nuclear spectroscopic studies. Such detectors are composed of standard high purity germanium (HPGe) crystals arranged in a compact way resembling parallel combination of detectors. Two simple examples are the clover and cluster detectors. The clover detector [2] consists of four closely packed high purity germanium (HPGe) crystals (having tapered square structure) inside the same cryostat, while the cluster detector [1] consists of seven closely packed hexagonal encapsulated HPGe detectors inside the same cryostat.

When a γ-ray interacts with a general parallel or series detector, its energy could be deposited completely in a single detector module (corresponding to single detector event (SE) or there is partial deposition of gamma energy in several detector modules corresponding to multiple detector event (ME). As a result, the composite detector could be operated in the single detector mode and the addback mode.The later mode corresponds to events where the full gamma-ray energy is deposited by single and multiple hits. The addback mode allows to recover the signals of the crystal(s) lost in the single detector mode. The addback contribution not only enhances the full energy peak (FEP) efficiency but also reduces the unwanted Compton background and the escape peaks, thereby increasing the peak-to-total ratio. There have been numerous studies of both clover and cluster detectors via experiments and simulation [3–6].

Recently, based on probabilistic understanding of gamma interaction process, a series of papers has been published by one of the authors [7–13] for understanding the operation of the composite detector and predict the response for high energy γ-rays. Instead of using an empirical method or simulation, these works present the first unified approach to calculate the peak-to-total ratio using experimental data as input and presents another way of understanding the operation of composite detectors. In [7, 8], we showed that using the experimental data of cluster detector at 1.3 MeV, the formalism could be used to predict the peak-to-total ratio as a function of number of detector modules. Similar approaches for modeling the clover detector are presented in two recent papers [9, 10]. Remarkable agreement between experimental data and analysis results has been observed for composite detectors like TIGRESS clover detector and SPI spectrometer at 1.3 MeV [8, 9]. We have also been successful in modeling of pyramidal shaped composite detector [14]. In the present work, we will apply our formalism to series combination of detectors comprising of 3–5 detector modules as well as a stacked detector with very large number of modules, while considering isotropic scattering of gamma-rays upto fourth interaction. Using the experimental data of the HHS spectrometer [15] which is two element stacked detector, we have predicted the addback factor for various stacked detectors.

2 Single parameter probabilistic approach

Let N_0 be the total flux of monoenergetic γ-rays (of energy E_γ) incident on a K element stacked or series detector and N be the portion of the total flux that interact with any one detector module, such that a total of $KN\gamma$-rays interact with the composite detector comprising of K elements. We assume that at a time a single γ-ray interacts with one of the detector modules [7–12]. After interaction, we have the following possibilities:

- Some of the gamma-rays are fully absorbed in a single detector module. Let the probability of FEP absorption after single detector module interaction be x, then the total number of absorbed gamma-rays after single module interaction is Nx. Note that $0 \leq x \leq 1$.
- Rest of the gamma-rays escape the single detector module after partial energy deposition. Since the probability of scattering out from a single detector module is $(1-x)$, so the total number of such gamma-rays $= N(1-x)$.
- After scattering out from the single module, some gamma-rays are fully absorbed after interaction with the second detector module. Let the probability of FEP absorption after multiple detector interaction be α.
- Some gamma-rays could escape the composite detector after interaction with one or more detector module(s). The events corresponding to these gamma-rays will contribute to background. Let the probability of scattering away from the detector be β.

As a result, we have $N(1-x) = N\alpha + N\beta$, so that

$$x + \alpha + \beta = 1 \tag{2.1}$$

where, x, α and β are probabilities integrated over energies and angles of scattered gamma-rays. For the addback mode, the total counts (T), full energy peak counts (P) and background counts (B) are respectively given by

$$T = KN \tag{2.2}$$

$$P = KNx + KN\alpha \tag{2.3}$$

$$B = KN\beta \tag{2.4}$$

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A measure of the improvement in addback mode over single detector mode is given by the addback factor (f) which is the ratio of FEP efficiency in addback mode to that in single detector mode, given by

$$f = \frac{KNx + KN\alpha}{KNx} = 1 + \frac{\alpha}{x} \tag{2.5}$$

In the absorption process of an incident gamma-ray in a detector, the role played by photoelectric effect is an important one [16]. The probability of absorption by photoelectric effect $\propto E_\gamma^{-3.5}$ (E_γ being energy of gamma-ray), so a high value of x could correspond to low energy of a gamma-ray. Note that x depends on the shape, size and volume of an individual detector module. So, for various composite detectors made of same type of detector modules, the difference between the addback factor will be decided by the value of α.

3 An isotropic scattering model

In general, the angular distribution of scattered gamma-rays due to Compton scattering and pair annihilation is anisotropic, depending on the incident gamma ray energy [16]. If we consider low energy gamma-rays, then the angular distribution could be considered isotropic. If we consider each crystal of a detector module to be a cube, then for isotropic scattering, since there are six faces of the detector, each face scatters $\frac{1}{6}$ th part. As an illustration, in figure 1, we have shown the incident gamma-ray (represented by black arrow) interacting with the first module of a two element stacked detector. The scattered gamma-rays [total probability being $(1 - x)$] emitted from each face is shown by yellow arrow. We could directly link each arrow to the branch probability of $\frac{1}{6}(1 - x)$. Figure 1(c) shows that for the simplicity of both illustration and calculations, we will use the two dimensional block diagram of the module where the arrows at ± 45 deg corresponding to the out-of-plane faces such that the total number of arrows directly corresponds to the probability branches. In the following subsections, we will try to analyse the various gamma-rays interactions inside various stacked detectors assuming the isotropic scattering of gamma-rays, and that the individual modules are cubical in shape.[1]

3.1 Three element stacked detector

Consider a stacked detector with three modules or elements — A, B and C. Let us assume that the incident gamma ray first interacts with the module A. The interacting and scattered gamma-rays up to fourth interaction are shown in figure 2.[2] After schematically mentioning the various possible interactions through the flowchart type diagram in figure 2, its inset further shows the decomposition of events in two dimensional block diagram. The detailed calculations (not shown in the figure) are given below.

[1]It will be later shown in section 3.5 that the energy range where this method is expected to be valid is 0 – 1 MeV.

[2]From the experimental fold distribution of the clover detector [17] and the cluster detector [1], it has been observed that the triple fold events contribute ≈ 15 – 17% to FEP events for gamma energies up to 10 MeV. The contribution from four and higher fold events is found to be negligible. Still, for the sake of completeness, we will consider up to fourth gamma-ray interactions.

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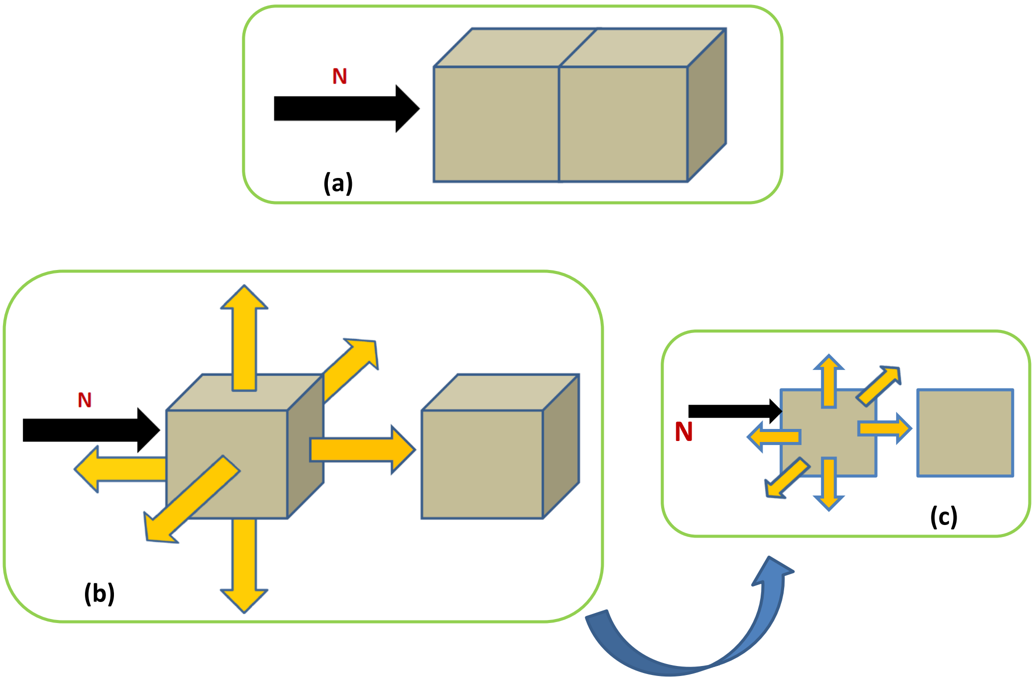

Figure 1. Schematic diagram of a gamma-ray incident (represented by black arrow) on a two element stacked detector is shown in figure (a). After interaction with the first module, scattered gamma-rays are emitted from each face shown by yellow arrows of figure (b). The two dimensional schematic representation of the module is shown in figure (c).

After first interaction, the gamma-rays:

- Absorbed in A = Total interacting gamma-rays × Absorption probability = Nx
- Scattered from A = Total interacting gamma-rays × Scattering probability = $N(1-x)$
- Scattered to B = $\frac{1}{6}\times$ total gamma-rays scattered from A= $\frac{1}{6}N(1-x)$
- Scattered outside the detector = Gamma-rays other than those scattered from A to B = $\frac{5}{6}N(1-x)$

After second interaction, the gamma-rays:

- Absorbed in B = Gamma-rays scattered from A to B × Absorption probability = $\frac{1}{6}N(1-x)x$
- Scattered from B = Gamma-rays scattered from A to B × Scattering probability =$\frac{1}{6}N(1-x)(1-x)$
- Scattered to A= $\frac{1}{6}$ × total gamma-rays scattered from B=$\frac{1}{6}\frac{1}{6}N(1-x)(1-x)$
- Scattered to C= $\frac{1}{6}\times$ total gamma-rays scattered from B=$\frac{1}{6}\frac{1}{6}N(1-x)(1-x)$
- Scattered outside the detector = Gamma-rays other than those scattered from B to A and C = $\frac{4}{6}\frac{1}{6}N(1-x)(1-x)$

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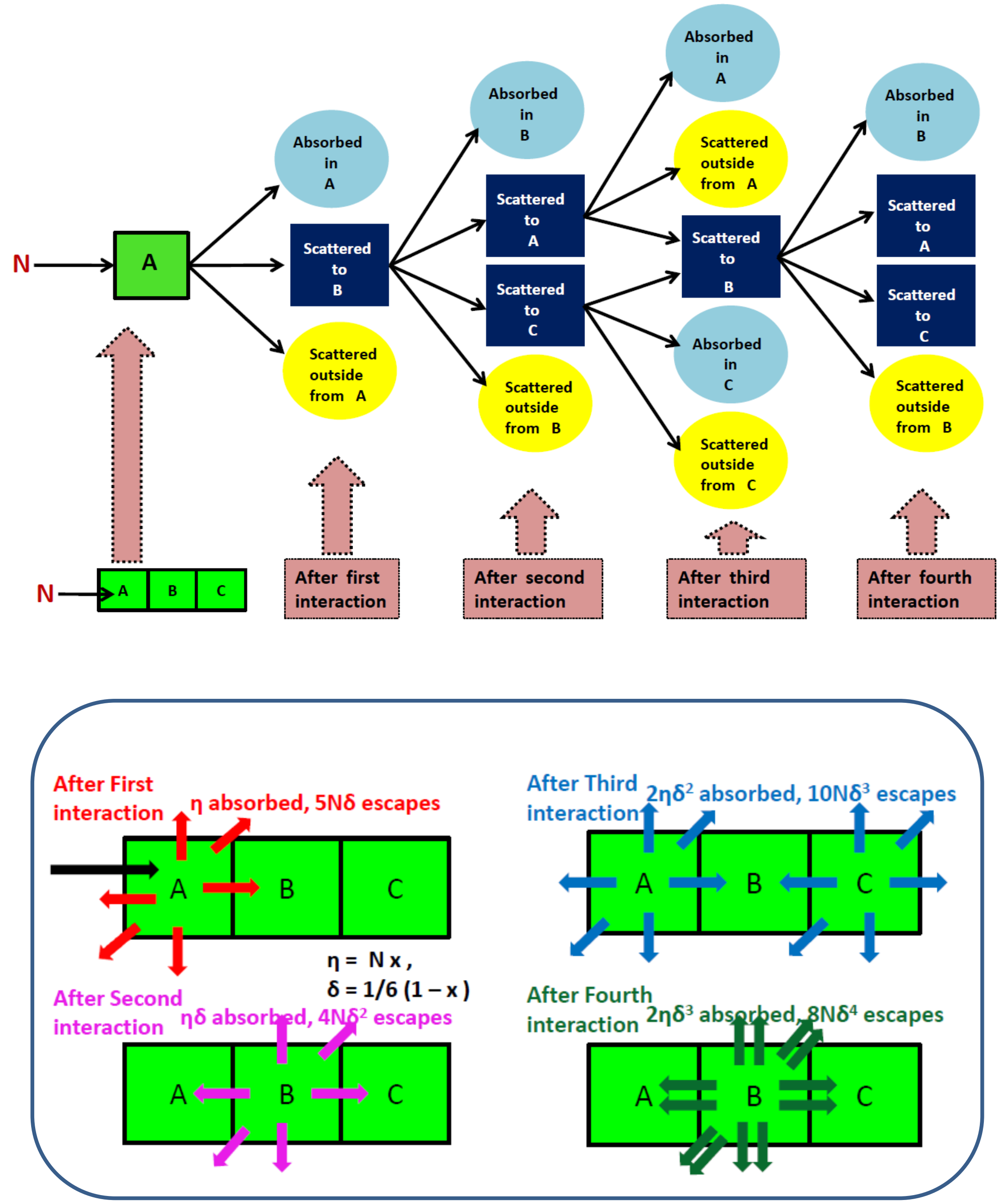

Figure 2. Block diagram of gamma-ray interactions with the first module A of the three element stacked detector is shown. The inset further explains the scenario through two dimensional block diagram.

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For third interaction, the gamma-rays:

- Absorbed in A = Gamma-rays scattered from B to A during second interaction × Absorption probability = $\frac{1}{6}\frac{1}{6}N(1-x)(1-x)x$
- Scattered from A = Gamma-rays scattered from B to A during second interaction × Scattering probability = $\frac{1}{6}\frac{1}{6}N(1-x)(1-x)(1-x)$
- Absorbed in C = Gamma-rays scattered from B to C during second interaction × Absorption probability = $\frac{1}{6}\frac{1}{6}N(1-x)(1-x)x$
- Scattered from C = Gamma-rays scattered from B to C during second interaction × Scattering probability = $\frac{1}{6}\frac{1}{6}N(1-x)(1-x)(1-x)$
- Total scattered to B =$\frac{1}{6}$ × total gamma-rays scattered from A + $\frac{1}{6}$ × total gamma-rays scattered from C

$$\begin{aligned}
&= \frac{1}{6}\frac{1}{6}\frac{1}{6}N(1-x)(1-x)(1-x) \;+ \frac{1}{6}\frac{1}{6}\frac{1}{6}N(1-x)(1-x)(1-x) \\
&= 2 \times \frac{1}{6}\frac{1}{6}\frac{1}{6}N(1-x)(1-x)(1-x) \\
&= 2 \times \frac{1}{6^3}N(1-x)^3
\end{aligned}$$

- Scattered outside the detector = Gamma-rays other than those scattered from A and C to B = $10 \times \frac{1}{6^3}N(1-x)^3$

For fourth interaction, the gamma-rays:

- Absorbed in B = Gamma-rays scattered from A and C to B during the third interaction × Absorption probability = $2 \times \frac{1}{6^3}N(1-x)^3 x$
- Scattered from B = Gamma-rays scattered from A and C to B during the third interaction × Scattering probability = $2 \times \frac{1}{6^3}N(1-x)^3(1-x)$
- Scattered to A = $\frac{2}{12}$ × total gamma-rays scattered from B=$2 \times \frac{1}{6^4}N(1-x)^3(1-x)$
- Scattered to C = $\frac{2}{12}$ × total gamma-rays scattered from B=$2 \times \frac{1}{6^4}N(1-x)^3(1-x)$
- Scattered outside the detector = Gamma-rays other than those scattered from B to A and C = $8 \times \frac{1}{6^4}N(1-x)^3(1-x)$

As we are considering isotropic scattering in all directions, so these results will be same for module C. This could also be observed from the comparison of the results related to absorption and scattering in figures 2 and 3. Let us now consider the interaction of gamma-ray with module B as shown in figure 3.

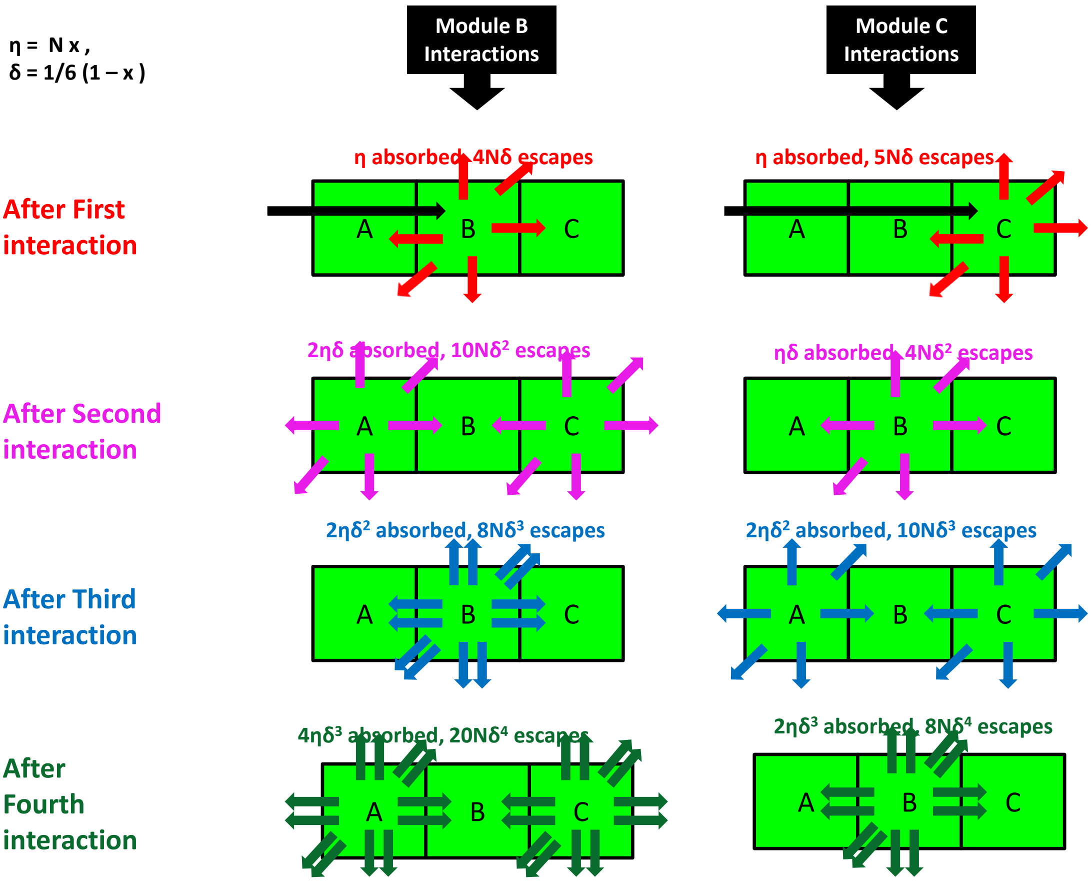

Figure 3. Schematic diagrams of gamma-ray interactions with the modules B and C of the three element stacked detector are shown.

For first interaction, the gamma-rays:

- Absorbed in B = Nx
- Scattered from B = $N(1-x)$
- Scattered to A = $\frac{1}{6}N(1-x)$
- Scattered to C = $\frac{1}{6}N(1-x)$
- Scattered outside the detector = $\frac{4}{6}N(1-x)$

For second interaction, the gamma-rays:

- Absorbed in A = $\frac{1}{6}N(1-x)x$
- Scattered from A = $\frac{1}{6}N(1-x)(1-x)$
- Absorbed in C = $\frac{1}{6}N(1-x)x$
- Scattered from C = $\frac{1}{6}N(1-x)(1-x)$

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- Total scattered to B = $2 \times \frac{1}{6^2} N(1-x)^2$
- Scattered outside the detector = $10 \times \frac{1}{6^2} N(1-x)^2$

For third interaction, the gamma-rays:

- Absorbed in B = $2 \times \frac{1}{6^2} N(1-x)^2 x$
- Scattered from B = $2 \times \frac{1}{6^2} N(1-x)^2(1-x)$
- Total scattered to A = $2 \times \frac{1}{6^3} N(1-x)^3$
- Total scattered to C = $2 \times \frac{1}{6^3} N(1-x)^3$
- Scattered outside the detector = $8 \times \frac{1}{6^3} N(1-x)^3$

For fourth interaction, the gamma-rays:

- Absorbed in A = $2 \times \frac{1}{6^3} N(1-x)^3 x$
- Scattered from A = $2 \times \frac{1}{6^3} N(1-x)^3(1-x)$
- Absorbed in C = $2 \times \frac{1}{6^3} N(1-x)^3 x$
- Scattered from C = $2 \times \frac{1}{6^3} N(1-x)^3(1-x)$
- Total scattered to B = $4 \times \frac{1}{6^4} N(1-x)^4$
- Scattered outside the detector = $20 \times \frac{1}{6^4} N(1-x)^4$

Thus, total absorbed counts

$$
\begin{aligned}
&= \left[3 \times \ Nx \ + 4 \times \frac{1}{6} N(1-x)x + 6 \times \frac{1}{6^2} N(1-x)^2 x + 8 \times \frac{1}{6^3} N(1-x)^3 x\right] \\
&= 3Nx + 4Nx\delta + 6Nx\delta^2 + 8Nx\delta^3 \\
&= 3N(x+\alpha)
\end{aligned}
$$

where $\delta = \frac{1}{6}(1-x)$, $\alpha = x\delta[\frac{4}{3} + 2\delta + \frac{8}{3}\delta^2]$.

Total scattered counts

$$
\begin{aligned}
&= 2N\delta\left[5 + 4\delta + 10\delta^2 + 8\delta^3\right] + 2N\delta\left[2 + 5\delta + 4\delta^2 + 10\delta^3\right] \\
&= 2N\delta\left[7 + 9\delta + 14\delta^2 + 18\delta^3\right] \\
&= 3N\beta
\end{aligned}
$$

where $\beta = \delta[\frac{14}{3} + 6\delta + \frac{28}{3}\delta^2 + 12\delta^3]$.

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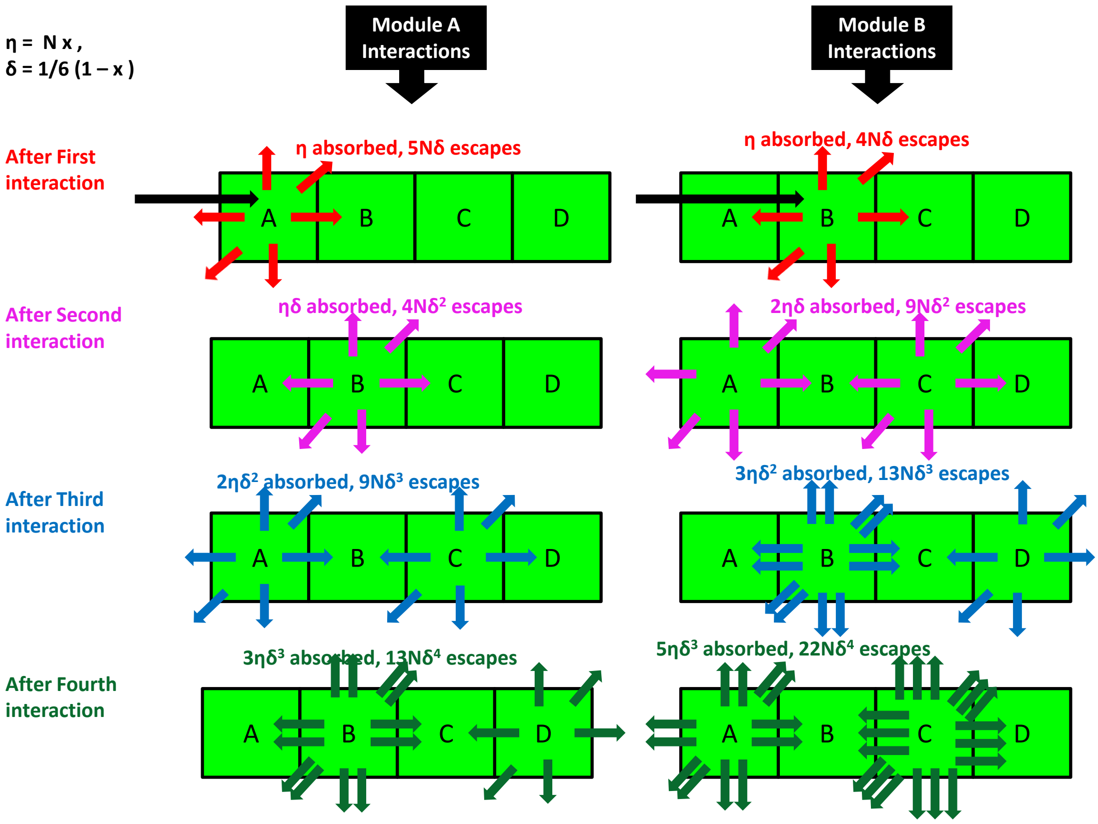

Figure 4. Schematic diagram of gamma-ray interactions with the four element stacked detector is shown.

3.2 Four element stacked detector

Let us consider the four element stacked detector consisting of modules A, B, C and D. The various possible gamma-ray interactions with module A and B are schematically shown in figure 4. Instead of the full calculations (like that of the three element stacked detector), here we will perform diagrammatic calculations using figure 2. As observed in the previous section, owing to the symmetry and isotropic scattering condition, the results for modules A and D will be identical, similar to that of module B and C. If $\eta = Nx$ and $\delta = \frac{1}{6}(1-x)$, then

Total absorbed counts

$$
\begin{aligned}
&= 2 \times [\text{Absorbed counts when incident gamma-ray interacts with module A} \\
&\qquad + \text{Absorbed counts when incident gamma-ray interacts with module B}] \\
&= 2[(\eta + \eta\delta + 2\eta\delta^2 + 3\eta\delta^3) + (\eta + 2\eta\delta + 3\eta\delta^2 + 5\eta\delta^3)] \\
&= 4N(x+\alpha)
\end{aligned}
$$

where $\alpha = x\delta\left[\frac{3}{2} + \frac{5}{2}\delta + 4\delta^2\right]$.

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Similarly, total scattered counts

$$
\begin{aligned}
&= 2 \times [\text{Escaping counts when incident gamma-ray interacts with module A} \\
&\qquad + \text{Escaping counts when incident gamma-ray interacts with module B}] \\
&= 2[(5N\delta + 4N\delta^2 + 9N\delta^3 + 13N\delta^4) + (4N\delta + 9N\delta^2 + 13N\delta^3 + 22N\delta^4)] \\
&= 4N\beta
\end{aligned}
$$

where $\beta = \delta\left[\frac{9}{2} + \frac{13}{2}\delta + 11\delta^2 + \frac{35}{2}\delta^3\right]$.

3.3 A stacked detector with large number of elements

Let us now consider a stacked detector with very large number (seemingly infinite) of detector modules, which has been shown schematically in figure 5. We will consider interaction with an inner module and neglect the effects of scattering with modules near the two ends of the stacked detector, since the number of modules is very large so the effect of former will be dominating if we consider up to 4th order interactions. If $\eta = Nx$ and $\delta = \frac{1}{6}(1-x)$, then

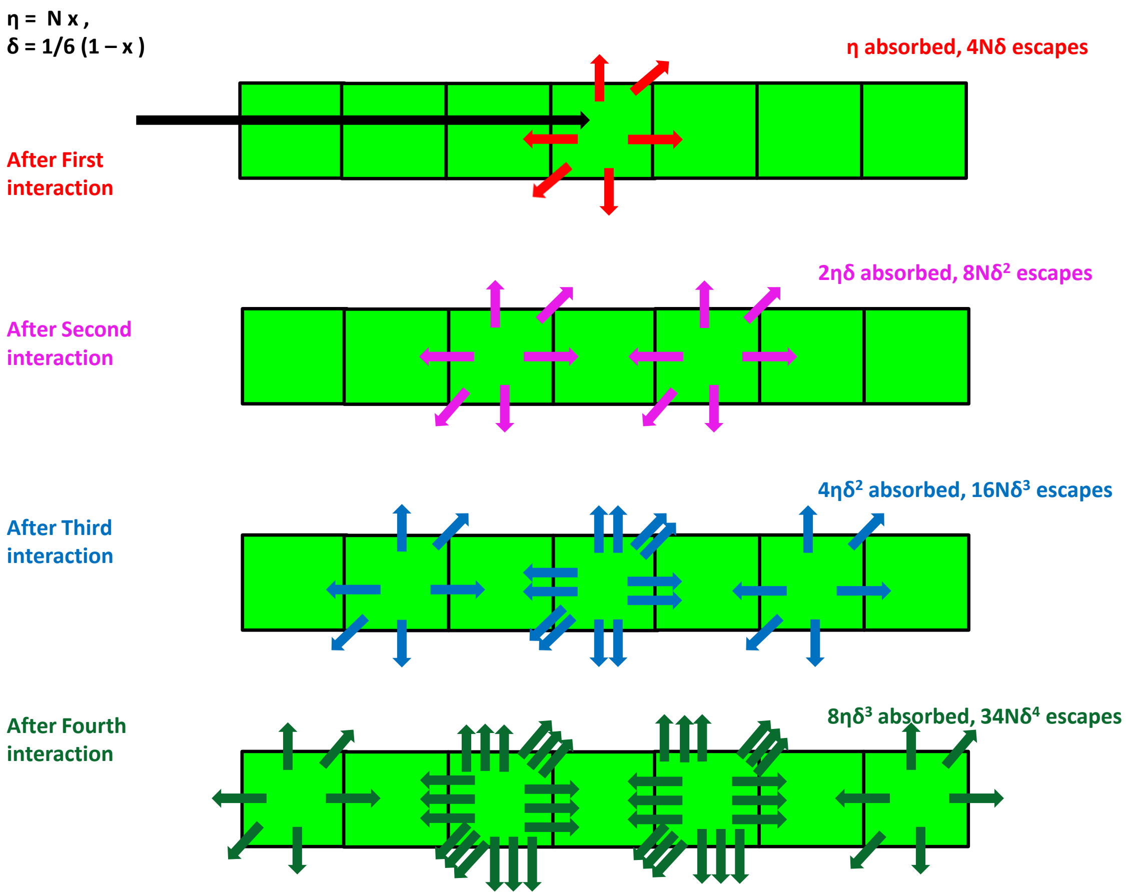

Figure 5. Schematic diagram of gamma-ray interactions with a stacked detector with large number of elements is shown.

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Total absorbed counts

$$
\begin{aligned}
&= \eta + 2\eta\delta + 4\eta\delta^2 + 8\eta\delta^3 \\
&= N(x + \alpha)
\end{aligned}
$$

where $\alpha \approx x\delta \left[2 + 4\delta + 8\delta^2\right]$.

Similarly, total scattered counts

$$
\begin{aligned}
&= 4N\delta + 8N\delta^2 + 16N\delta^3 + 34N\delta^4 \\
&= N\beta
\end{aligned}
$$

where $\beta \approx \delta \left[4 + 8\delta + 16\delta^2 + 34\delta^3\right]$.

3.4 Structure of α and β

From the above calculations, the obtained expressions for α and β are shown in table 1.

Table 1. Structure of α and β for various stacked detector.

No of detector elements	alpha	beta
3	$x\delta\left[\frac{4}{3} + 2\delta + \frac{8}{3}\delta^2\right]$	$\delta\left[\frac{14}{3} + 6\delta + \frac{28}{3}\delta^2 + 12\delta^3\right]$
4	$x\delta\left[\frac{3}{2} + \frac{5}{2}\delta + 4\delta^2\right]$	$\delta\left[\frac{9}{2} + \frac{13}{2}\delta + 11\delta^2 + \frac{35}{2}\delta^3\right]$
5	$x\delta\left[\frac{8}{5} + \frac{14}{5}\delta + \frac{24}{5}\delta^2\right]$	$\delta\left[\frac{22}{5} + \frac{34}{5}\delta + 12\delta^2 + \frac{102}{5}\delta^3\right]$
very large	$\approx x\delta\left[2 + 4\delta + 8\delta^2\right]$	$\approx \delta\left[4 + 8\delta + 16\delta^2 + 34\delta^3\right]$

We can write the generalised expressions for α and β as

$$
\begin{aligned}
\alpha &= x\delta\left[a_2 + a_3\delta + a_4\delta^2\right] \\
\beta &= \delta\left[b_1 + b_2\delta + b_3\delta^2 + b_4\delta^3\right]
\end{aligned}
$$

The variation of the various coefficients $a_2, \ldots, b_4$ as a function of the number of stacked detector elements are shown in figures 6 and 7. The coefficients a_2, a_3, a_4 show an increasing trend with increasing number of elements of stacked detector. This is due to the increase in the possible scattering and full energy peak absorption s in the various elements, which has been seen previously for various composite detectors [1, 2, 7, 11] as well. Apart from b_1, all the other b coefficients show an increasing trend indicating the increase in lost events as the number of detector modules increase.

3.5 Predictions for the addback factor

Let us consider the HHS detector [15] which is two element stacked HPGe detector. Using a similar procedure as discussed above, we can calculate the addback factor of two element stacked detector which is given by

$$
f = 1 + \delta + \delta^2 + \delta^3 \tag{3.1}
$$

It is experimentally observed that the value of addback factor for the HHS detector increases with increasing gamma-ray energy, starting from 1.0 at very low energies, reaching values greater

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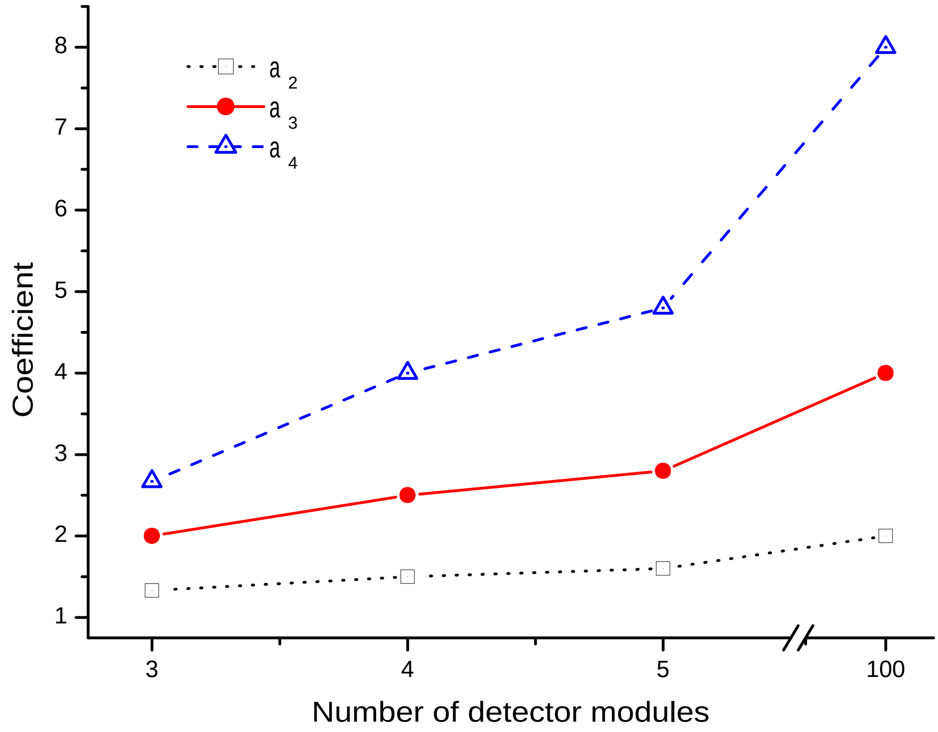

Figure 6. Variation of the coefficients of α as a function of no. of detector modules.

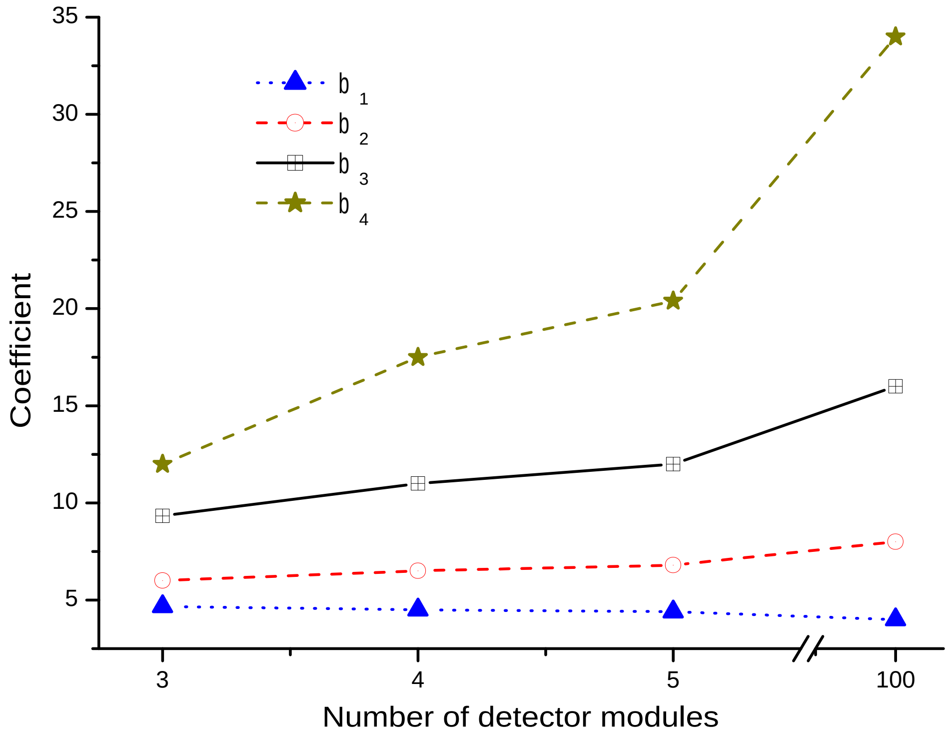

Figure 7. Variation of the coefficients of β as a function of the number of detector modules.

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than 2.0 at 20 MeV [15]. From equation (3.1), we observe that the minimum value of f is 1.0, obtained for $x = 1.0$. Our model predicts an upper limit for the addback factor - 1.2, obtained for $x = 0$, which corresponds to the maximum possible energy in our model where the isotropic scattering will be valid. This discrepancy with observed experimental data of HHS detector is due to the assumption of isotropic scattering, which is correct for low energy gamma-rays. Note that increasing incident gamma-ray energy, the angular distribution of scattered gamma-rays due to Compton scattering and pair annihilation becomes highly anisotropic [16].[3]

Using equation (3.1) and the simulation data for the addback factor (f) for HHS detector at various gamma-ray energies, given in figure 6 of ref. [15], we can get a relation between the absorption probability (x) and gamma-ray energy (E_γ). The plot between x and E_γ is shown in figure 8. The addback factor reaches its maximum value in our model at $x = 0$, which corresponds to ≈ 1 MeV as observed from figure 8. This indicated that the upper limit of gamma-ray energy for our model is ≈ 1 MeV. From the fitting of data in figure 6, we obtain a relation between x and E_γ, given by $x \approx -0.0013 \times E_\gamma + 1.2422$.

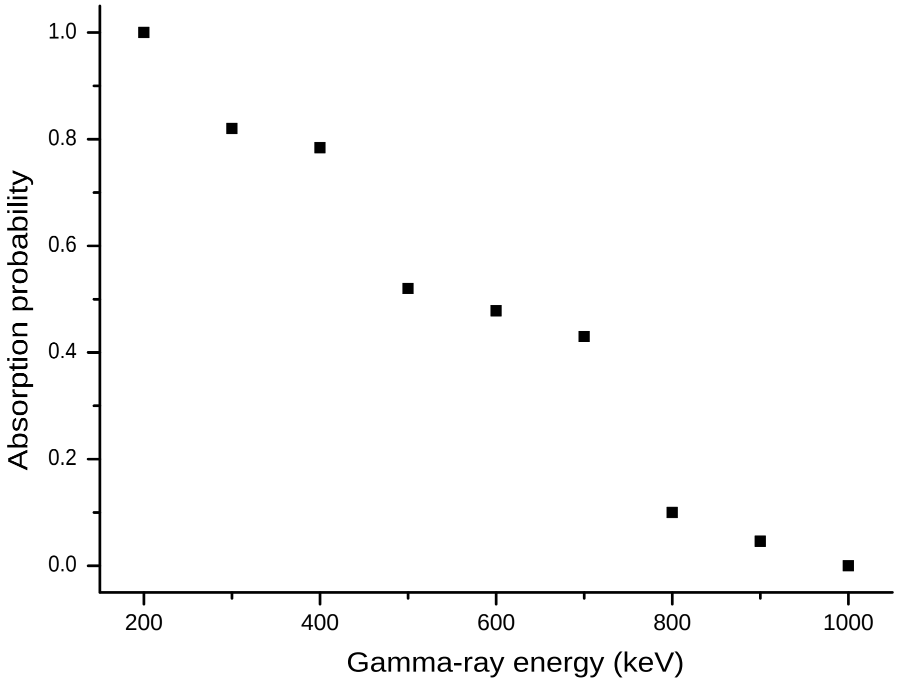

Figure 8. Variation of the absorption probability (x) as a function of the gamma-ray energy (E_γ) for the HHS detector [15].

[3]While the original motivation for the HHS detector is the detection of gamma-rays in the 10–30 MeV range [15], we are trying to analyse the various gamma-rays interactions inside similar stacked detectors assuming the isotropic scattering of gamma-rays, which is not valid for high energy gamma-rays. As a result, it could appear that the assumption of isotropic scattering is not suitable for the analysis of stacked detector geometry. However, even low energy gamma-rays contribute to the addback process, as also evidenced from our model which predict values of addback factor > 1, showing that the model could be used to understand multiple module interactions inside the stacked detector even if the incident gamma-ray energy is not very high.

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For a general stacked detector, if we consider the individual detector module to be the single detector module of the HHS detector, then we can use the relation between x and E_γ (figure 8) for that detector. Using equation (2.5) and α of table 1, we have calculated the addback factor as a function of E_γ for the various stacked detectors in figure 9. The figure shows a general increasing trend similar to the ones for the composite detectors [1, 2]. The comparative improvement due to the adding back of escaping events to the full energy peak is always more with more number of detector elements. So, we expect higher values of f for stacked detector with larger number of elements. This has been observed in figure 9 if we compare the values of addback factor for the various stacked detectors.

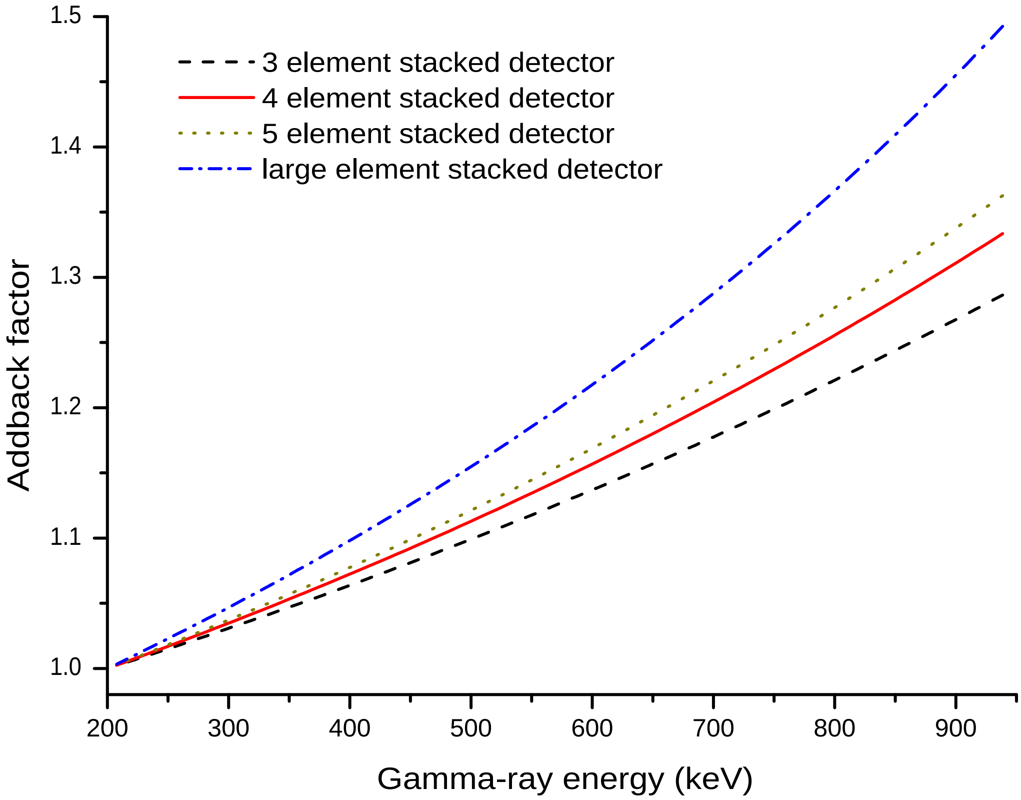

Figure 9. Variation of the addback factor (f) as a function of gamma-ray energy (E_γ) for various stacked detectors.

4 Summary and conclusion

A simple model based on isotropic scattering of gamma-rays has been presented for understanding the operation of a general stacked detectors in addback mode. If we consider the full energy peak counts from single and multiple detector module interactions, and the decomposition of background counts to counts corresponding to the escaping γ-rays and counts for γ-rays which could be recovered in addback mode, it is observed that the addback factor of stacked detectors in addback mode could be expressed in terms of only one probability. Our model predictions, based on the absorption probability, could be directly translated to gamma energy. We have predicted values of the addback factor for various stacked detectors.

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References

[1] M. Wilhelm et al., *The response of the Euroball Cluster detector to γ-radiation up to 10 MeV*, Nucl. Instrum. Meth. **A 381** (1996) 462.

[2] G. Duchene et al., *The Clover: a new generation of composite Ge detectors*, Nucl. Instrum. Meth. **A 432** (1999) 90.

[3] P. Reiter et al., *The MINIBALL array*, Nucl. Phys. **A 701** (2002) 209.

[4] A.Y. Deo et al., *Structure of dipole bands in In-106*, Phys. Rev. **C 79** (2009) 067304.

[5] M.A. Schumaker and C.E. Svensson, *Compton-suppression and add-back techniques for the highly segmented TIGRESS HPGe clover detector array*, Nucl. Instrum. Meth. **A 575** (2007) 421.

[6] D. Smalley et al., *Two-neutron transfer reaction mechanisms in $^{12}C(^{6}He,^{4}He)^{14}C$ using a realistic three-body ^{6}He model*, Phys. Rev. **C 89** (2014) 024602 [arXiv:1312.1196].

[7] R. Kshetri, *Modeling an array of encapsulated germanium detectors*, 2012 *JINST* **7** P04008 [arXiv:1203.4039].

[8] R. Kshetri, *A first principle approach for encapsulated type composite detectors*, 2012 *JINST* **7** P07006.

[9] R. Kshetri, *Modeling of clover detector in addback mode*, 2012 *JINST* **7** P07008.

[10] R. Kshetri, *A first principle approach for clover detector*, 2012 *JINST* **7** P08015.

[11] R. Kshetri, *From a single encapsulated detector to the spectrometer for INTEGRAL satellite: predicting the peak-to-total ratio at high gamma-energies*, 2012 *JINST* **7** 12007 [arXiv:1211.0839].

[12] R. Kshetri, *A novel approach for predicting the response of the spectrometer for INTEGRAL satellite*, Appl. Radiat. Isot. **75** (2013) 30.

[13] R. Kshetri and P. Bhattacharya, *A novel approach for modeling the cluster detector and the SPI spectrometer*, Pramana **83** (2014) 817.

[14] A. Samui and R. Kshetri, *Understanding the operation of gamma-ray detectors arranged in the shape of a pyramid*, 2019 *JINST* **14** T09008.

[15] Y. Shigetome and H. Harada, *Development of twin Ge detector and its performance*, Nucl. Instrum. Meth. **A 469** (2001) 185.

[16] R.D. Evans, *The Atomic Nucleus*, McGraw-Hill, (1955).

[17] M. Saha Sarkar et al., *Characterisation of a Compton suppressed Clover detector for high energy gamma rays $\leq$ 11 MeV*, Nucl. Instrum. Meth. **A 556** (2006) 266.

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