Studies on angular correlation of gamma rays using GEANT4

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Introduction

Radioactive sources that emit gamma rays in two-step cascade are widely used in gamma spectrometry for the purpose of energy calibration. This type of sources are also widely used for the purpose of efficiency calibration as very few mono-energetic gamma sources are available in the laboratory. However, if the time difference between these two gamma rays is small compared to the resolving time of detector, then the deposition of energy of two gamma rays results in a sum peak in the energy spectrum. Consequently, the counts from individual full energy peaks are lost in sum-peak. It is well known that if counts in sum-peak are large enough then the efficiency calibration done using individual full energy peaks will not be accurate. Therefore, the coincidence summing effect needs to be corrected in order to obtain accurate efficiency calibration of the detector. In addition, in double gamma emitters, two gamma rays are angularly correlated i.e. emission of second gamma ray is not isotropic. For example, in case of \textsuperscript{60}Co, the probability that the second gamma ray emitted in the same direction, parallel or anti-parallel, as first gamma ray is about 17\% higher than emitted at an angle of 90\°.

In order to understand the extent to which coincidence summing and angular correlation effects the number of counts under individual gamma ray peaks and sum peak, it is necessary to carry out Monte Carlo simulations. Many theoretical and experimental studies have been done on this phenomenon [1, 2]. Courtine \textit{et al.}, [3] have studied the angular correlation between gamma rays emitted from \textsuperscript{60}Co for well type HPGe detector and reported that the sum peak is not biased by the angular correlation for a source inserted in a well inside the detector crystal. On the other hand, when the source is placed outside, near the detector, the sum peak is significantly affected by the angular correlation and this effect is enhanced with increasing distance. Not many groups have reported studies using simulations that can provide new information about this phenomenon with scintillation detectors. In the present work, we aim to study the effect of coincidence summing and angular correlation between gamma rays by Monte Carlo simulations using using LaBr\textsubscript{3}:Ce.

Simulations

Monte Carlo simulations were carried out using GEANT4 toolkit [4] in order to understand whether the angular correlation would result in peak areas different from those obtained by considering random emissions of coincident gamma rays. For this purpose, we have used decay schemes of different double gamma emitters, namely, \textsuperscript{60}Co, \textsuperscript{46}Sc and \textsuperscript{94}Nb. The detector used was a cylindrical 3.56\" × 6\" LaBr\textsubscript{3}:Ce detector. In the simulations, we have considered standard electromagnetic package for physics process class. The range cut was selected in such a way that when the energy of the particle is less than 100 eV, the particle has been considered to be entirely absorbed within the active volume of the detector. The number of events was selected to be \textsuperscript{10\textsuperscript{7}} in order to neglect the statistical uncertainties associated with counts in photo-peaks and sum-peak due to the Monte Carlo nature of the simulations. Simulations

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were also carried out using individual mono-
energetic gamma rays, for comparison.

TABLE I: Corrected photo-peak efficiencies with
and without angular correlation

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Single Energy Source</th>
<th>Without angular correlation</th>
<th>With angular correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.129</td>
<td>0.128</td>
<td>0.122</td>
</tr>
<tr>
<td></td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.099</td>
<td>0.099</td>
<td>0.094</td>
</tr>
<tr>
<td></td>
<td>0.093</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.074</td>
<td>0.073</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>0.069</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.051</td>
<td>0.051</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>0.047</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effect of angular correlation was incor-
porated in the simulations as follows. Two
coincident gamma rays were generated using
particlegun class. The first gamma was as-
sumed to be emitted randomly and the second
gamma was emitted with correlation relation:

\[ W(\theta) = 1 + acos^2 \theta + bcos^4 \theta \]

where \( \theta \) is the angle between directions of
gamma rays. It can be verified that \( W(0^\circ) = W(180^\circ) = 1 \), whereas \( W(90^\circ) = W(270^\circ) = 1.17 \). As GEANT4 toolkit does not have the
functionality to take into account the effect of
angular correlation, the probability of both
gamma rays being emitted at a certain angle
with respect to right angle was incorporated
into the code. An array of angles was made
with frequency of a particular angle stored in
it being governed by the probability of that
angle. That probability was determined by
the above given formula. During the simu-
lation, a random angle was chosen from this
array. Simulations were done for a source lo-
cated on the detector front surface and also
for different values of source-detector separa-
tion. The correction for coincidence summing
was done by the method explained in Ref. [5].

Results and Discussion

Table-I shows the simulated absolute photo-
peak efficiencies of LaBr₃:Ce detector consid-
ering ⁶⁰Co source and after correcting for co-
incidence summing. In each cell of the table,
two efficiency values correspond to gamma en-
ergies of 1173 keV and 1332 keV. The efficien-
cies were simulated with and without incorpo-
rating the effect of angular correlation. The
corrected efficiencies are compared with those
obtained using monoenergetic gamma sources.
Clearly, with increase in source-detector sep-
aration, the efficiencies obtained using angu-
lar correlation are better agreement with those
obtained using monoenergetic gamma rays of
similar energies. Experimental measurements
are in progress for validating the simulated re-
results.

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