Simulation Study of Sn bolometer for $0\nu\beta\beta$

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Introduction
Search for Neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most interesting problems in the present era. Presently, it is perhaps the only experiment that will tell us the true nature of neutrino (Majorana or Dirac) and its absolute effective mass. A feasibility study of $0\nu\beta\beta$ in $^{124}$Sn using a cryogenic bolometer has been initiated [1]. The constancy of sum energy of two emitted electrons is the signature the $0\nu\beta\beta$ process and good energy resolution is of extreme importance. Low specific heat of Tin in sub-Kelvin range enables its use as a bolometer. However, for rare events like $0\nu\beta\beta$ the bolometer size needs to be very large and an array of several small crystals is essential [2]. The sensitivity of detector is critically dependent on the reduction of background. The cosmogenic background is significantly reduced in underground laboratories, but the decay of radioactive trace impurities present in the detector and in surrounding material also contributes to the background. It is essential to discriminate these background gamma-ray events from electron events of interest. Unlike electrons, photons would typically interact with more than one detector element. Hence, by using the multiplicity information from a segmented array the $e-\gamma$ discrimination can be achieved, in a limited manner. We have therefore carried out the simulations to study the background resulting from gamma ray interactions for different crystal configurations.

Bolometer Crystal Size
The size of an individual bolometer crystal needs to be optimized for a measurable temperature rise ($\Delta T$). The $\Delta T$ depends on specific heat of the material, which varies strongly with temperature. At low temperatures (< 50 mK) the specific heat of material is very small allowing for greater $\Delta T$ per unit mass. In order to achieve an energy resolution ~ 0.2%, it is desirable to have $\Delta T \geq 100 \mu K$ for 1 MeV energy deposition. Corresponding values for maximum permissible volume of a Tin crystal at different base temperatures are listed in Table 1.

<table>
<thead>
<tr>
<th>Base Temp. (mK)</th>
<th>Volume (in cc)</th>
<th>Approx. size (a) of cubic crystal (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>106</td>
<td>4.7 x 4.7 x 4.7</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>3.1 x 3.1 x 3.1</td>
</tr>
<tr>
<td>25</td>
<td>7</td>
<td>1.9 x 1.9 x 1.9</td>
</tr>
</tbody>
</table>

Simulation using GEANT4:
The simulations were performed using GEANT4 [3]. Photons of different energies ($E_\gamma = 511, 1460, 2615$ keV) were randomly generated on a spherical surface enclosing a 3D array of 27 uniform cubic tin crystals of different sizes ($a = 2, 3, 5$ cm). The radius of the sphere was kept much larger than crystal size to ensure uniform illumination of the array. The spacing between the individual crystals within the array was also varied between 2 to 10 mm. The photon energies considered cover the range of interest for natural background radiations.

If the multiplicity of an event is denoted by $M$, then total events detected in the array can be written as

$$N_{\text{total}} = (N_p + N_b)_{M=1} + (N_p + N_b)_{M>1}$$

where $N_p$ and $N_b$ are photopeak and background events respectively. As mentioned earlier, $M > 1$ events are expected to predominantly arise from photons. The photopeak events ($N_{p,M=1}$) also can be clearly identified even with $M=1$. Therefore, difficulty arises for identification and rejection of $M=1$ background events ($N_{b,M=1}$) only. It is thus essential to choose an array configuration where $N_{b,M=1}$ is minimized.
Figure 1 (a) shows the ratio $N_{b,M=1}/N_{total}$ (open symbols) and $N_{p,M=1}/N_{total}$ (filled symbols) as a function of energy for different crystal sizes but for same inter-detector spacing (2 mm). The ratios $N_{b,M=1}/N_{total}$ and $N_{p,M=1}/N_{total}$ for events with higher fold (M>1) are shown in panel (b). The background and photo peak efficiency ratios for M=1 events for the central crystal of the array are shown in panel (c). This is an indication of shielding effects of surrounding elements. The effect of inter-detector spacing on M=1 events for 3x3x3 cm$^3$ crystal is shown in panel (d). It is evident that $N_{b,M=1}/N_{total}$ is minimum and photopeak efficiency is maximum for larger crystal size, while the $N_{p,M=1}/N_{total}$ is only weakly dependent on the crystal size. As expected the background also increases with inter-detector spacing.

The present results indicate that the 3x3x3 cm$^3$ crystals with a minimum inter-detector spacing would be preferable for the prototype module, to operate in the temperature range of 10–15 mK.

References


![Fig. 1: Plots of variation of $N_b/N_{total}$ (open symbols) and $N_p/N_{total}$ (filled symbols) with crystal volume for the whole array (a) with M = 1, (b) with M > 1; (c) $N_{b,M=1}/N_{total}$ and $N_{p,M=1}/N_{total}$ for the central detector and (d) Effect of inter-detector spacing for a given crystal volume (3x3x3 cm$^3$).]