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Energy calibration of plastic scintillators for low energy electrons by using Compton scatterings of γ rays

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Abstract

An energy calibration of plastic scintillators for electrons in the energy region 0.5–3 MeV is shown to be made by means of Compton scatterings of γ-rays. The shape of the Compton spectrum was analytically derived and the availability of the shape function was tested by fitting the simulated spectrum. The method to derive the energy and energy resolution at the Compton edge of the γ-ray is described. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Interest in rare beta (β) and $\beta\beta$ decays has been sharpened in view of particle and nuclear physics. Accordingly, demands for calibration methods for plastic scintillators (PL) as β-ray detectors have increased for precision studies of such rare β decays and $\beta\beta$ decays in the energy region from 0.5 to 3 MeV.

Measurements of such rare nuclear decays have to be carried out at low-background underground laboratories to reduce backgrounds from cosmic rays. Also, detectors have to be free from any radioactivities. The energy calibration of electron (β-ray) detectors face a serious problem here. Mono-energetic electron beams are not realistic. There are no radioactive sources with mono-energetic β-ray in the energy region from 0.5 to 3 MeV, except internal conversion electrons. However, internal conversion electrons suffer from the energy loss in the film covering the source and the intensity of the internal conversion electron is quite small in comparison with the γ-ray.

Plastic (PL) electron detectors are used widely for nuclear rare decays because of their large volumes and good time resolutions. Gamma-ray sources, which give mono-energetic γ-rays in the energy region of the present interest, are quite handy and thus are very adequate at underground laboratories. The energy spectrum of γ-rays for PLs are mainly due to Compton scattered electrons, because the photo-peak cross section is very small. Thus, if the shape of the Compton spectrum can be fitted by an analytically derived function with parameters of the Compton edge energy E_{max} and the energy resolution σ_{Reso}, the energy calibration of

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PL in the energy region of rare $\beta(\beta\beta)$ decays (typically 0.5–3 MeV) will be carried out satisfactorily.

The present work aims at reporting a calibration method by using the shape of the Compton spectrum with the analytically derived function by χ^2-fitting method.

2. The shape of Compton spectrum

The energy distribution of Compton scattered electrons, is known as the Klein-Nishina formula,

$$\frac{d\sigma}{dT} = \frac{\pi r_e^2}{m_e c^2 \alpha^2} \times \left(2 + \frac{s^2}{\alpha^2(1-s)^2} + \frac{s}{(1-s)}\left(s - \frac{2}{\alpha}\right)\right) \quad (1)$$

where T indicates the kinematic energy of the scattered electron, $\alpha = h\nu/m_e c^2$, and $s = T/h\nu$. Experimentally, the shape of the Compton spectrum to be fitted is obtained by introducing the Gaussian-type energy resolution. It is written as

$$\mathrm{Compton}(X) = k\int_0^{E_{max}/E_I}\left(\frac{d\sigma}{dT}\right)\exp\left(-\frac{(X-s)^2}{2\sigma_{Reso}^2}\right)ds \quad (2)$$

with the condition,

$$\left(\frac{d\sigma}{dT}\right)ds = \int_{-\infty}^{\infty} A(s)\exp\left(-\frac{(X-s)^2}{2\sigma_{Reso}^2}\right)dX \quad (3)$$

where E_I is the incident γ-ray energy, $A(s) = k/\sigma_{Reso}(d\sigma/dT)$ and k, E_{max} and σ_{Reso} are parameters of the constant, the energy of the Compton edge and the energy resolution, respectively. Here, the most typical shape of the Compton spectrum appears around the energy of the Compton edge, the energy resolution, σ_{Reso}, in Eq. (2) is included as a constant at the value of the Compton edge without taking into account the dependence on energy. The calculated spectra in Eqs. (1) and (2) with various energy resolutions are shown in Fig. 1.

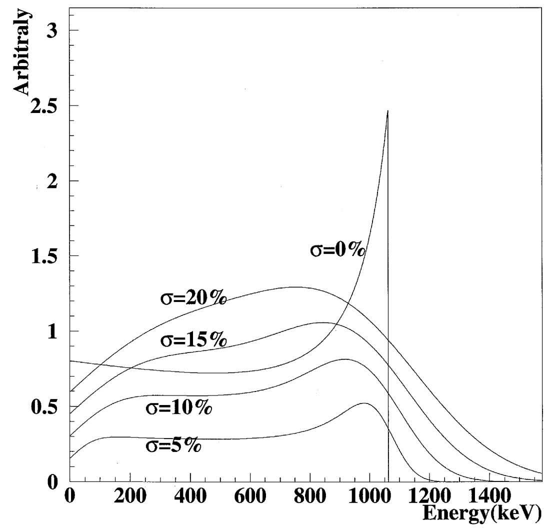

Fig. 1. The energy distribution of Compton scattered electrons. The energy of incident γ-ray is 1275 keV. The spectra are drawn without energy spread, $\sigma_{Reso} = 0\%$, as shown in Eq. (1) and with energy resolutions σ_{Reso}, $\sigma_{Reso} = 5\%, 10\%, 15\%$, and 20% as shown in Eq. (2), respectively.

3. Experimental setup and the Monte Carlo simulation

The Monte Carlo program (MC) has been developed to reproduce the Compton spectra and to test if the present fitting method with Eq. (2) can reproduce the parameters needed here. GEANT 3.21 [1] was used.

The plastic scintillator has been used to detect the β-rays from $\beta\beta$ decay in ELEGANT V. Details of ELEGANT V have been published in Ref. [2]. The experimental setup for the energy calibration of the plastic scintillators used in the ELEGANT V detector system is briefly described here. The plastic scintillator (PL) (Bicron BC408) arrays with 1000 mm × 120 mm × 15 mm are used to detect β-rays from $\beta\beta$ decays with $Q_{\beta\beta}$ value from 2 to 3 MeV. Both ends of this PL module are viewed by photomultipliers (PMT) (Hamamatsu H1161K). The energy information is acquired by Lecroy ADC2249A. The trigger condition is the coincidence of signals from both sides of PMT. During the measurement of $\beta\beta$ decays, the PLs have been calibrated by using the ^{22}Na γ-ray source with the energies 511 and 1275 keV [3] at the center of PL.

The MC has been carried out to reproduce the experimental condition as given above and to produce other conditions to test the performance of the present fitting method as follows:

1. To reproduce the experimental situation, conditions with γ-ray source of ^{22}Na and thickness of PL 15 mm were selected.
2. To make clear the characteristics of the fitting method, conditions with γ-ray energies of every 100 keV from 400 to 1300 keV were selected.
3. To investigate effects of multiple Compton scatterings, PLs with $t = 7.5$, 30 and 45 mm in thickness were selected in addition to the PL with $t = 15$ mm.

One thousand samples with the energy resolution of $\sigma_{\mathrm{Reso}}(E) = A\exp(-BE)$, where E indicates the deposited energy in PL and A and B selected to be $\sigma_{\mathrm{Reso}}(341\ \mathrm{keV}) = 5$–$20\%$, were generated to test this fitting method. The dependence on position of the pulse height was investigated as a function $\exp(a + bx)$, where x indicates the position of PL. Parameters a and b were derived from the experimental data.

4. Results

The parameters for the energy of the Compton edge were obtained by fitting the spectra generated by MC. Fig. 2 show the relation between incident γ-ray energies and differences, $\Delta E = E_{\mathrm{fit}} - E_{\mathrm{Cmp}}$, between energies of the fitted value, E_{fit}, and the Compton edge, E_{Cmp}. These differences ΔE's are considered to be arising from the multiple Compton scattering. Thus the ΔE's increase, as the thickness of PL increases. The plots with open circle in Fig. 2 were obtained by fitting the MC generated ^{22}Na spectra. This result shows that the energy of the Compton edge can be determined with an accuracy of 0.44% at 341 keV and 0.76% at 1062 keV, and that the fitted values for ^{22}Na spectra are larger than those for single γ-ray spectra around the same energy region. This is the effect of events that both 511 and 1275 keV γ-rays in the same decay scatter at least two Compton electrons.

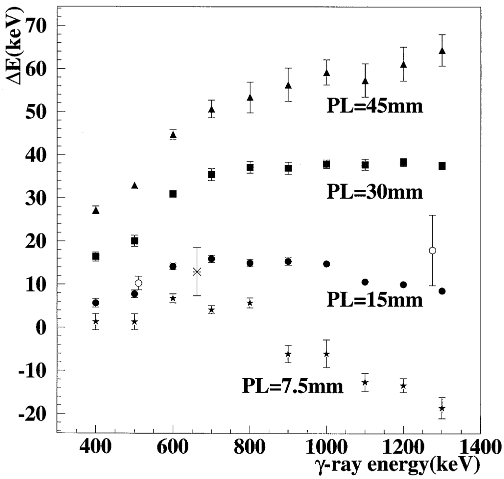

Fig. 2. The relation between the γ-ray energy and the difference ΔE for the fitted value, ΔE is given by $E_{\mathrm{fit}} - E_{\mathrm{Compton}}$, where E_{fit} is the value derived by fitting and E_{Compton} is the Compton edge energy. PLs with 7.5, 15, 30 and 45 mm in thickness were investigated. The plots with the open circle show the value derived by the MC generated ^{22}Na spectra. The plot with the asterisk (*) shows the value derived from experimental ^{137}Cs with $E_\gamma = 662$ keV spectra.

This property was checked by the experimental data. The energy calibration was carried out with ^{22}Na source by taking into account the ΔE estimated as above. Then single γ-ray emitting source was selected as ^{137}Cs, with $E_\gamma = 662$ keV [3]. The results were obtained by fitting several energy spectra with each γ-ray source. These results are plotted with the asterisk(*) in Fig. 2. They are in agreement with the estimated ΔE's in MC.

We next focus on the information on the energy resolution. Fig. 3 shows the relation between the energy resolution investigated in MC and the energy resolution obtained by fitting the MC generated ^{22}Na spectra. Here, the energy resolution in MC, σ_{MC}, was investigated as $\sigma_{\mathrm{MC}} = \sqrt{\sigma_{\mathrm{L}}^2 + \sigma_{\mathrm{R}}^2}$, where $\sigma_{\mathrm{L(R)}}$ were given by a function of energy as $\sigma_{\mathrm{L(R)}}(E) = A\exp(-BE)$. The energy resolution obtained by fitting σ_{Fit} was evaluated as follows. The energy spectra in the measurement were derived as $E = \sqrt{E_{\mathrm{L}}E_{\mathrm{R}}}$, where $E_{\mathrm{L(R)}}$ indicates the energy viewed from left (right) side of PL. Thus the energy spectra generated by MC for fitting were derived in accordance with this derivation. Although the

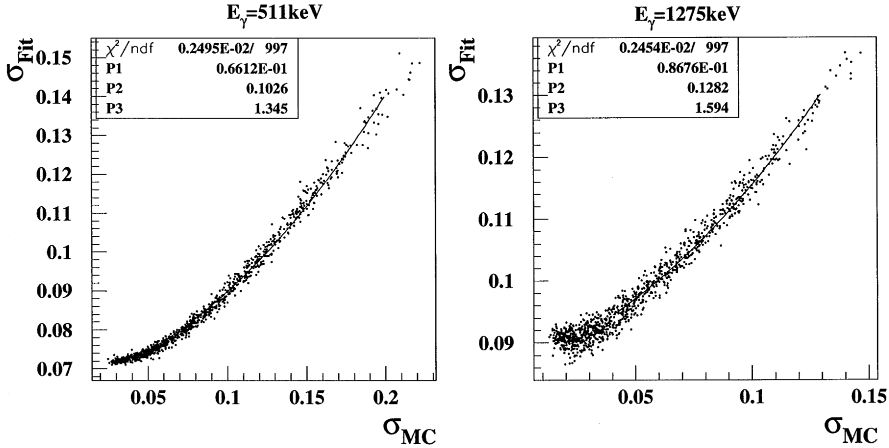

Fig. 3. The relation between the energy resolution σ_{MC} in MC and the resolution σ_{Fit} derived by fitting. σ's are the standard deviation to the corresponding energy. Functions to be fitted are selected to be a two-dimensional polynomial, $\sigma_{Fit} = P_1 + P_2 \cdot \sigma_{MC} + P_3\sigma_{MC}^2$.

energy resolution is not given directly from σ_{Fit}, it can be derived by translating the σ_{Fit} to σ_{MC} in accordance with the fitting function $\sigma_{Fit} = P_1 + P_2\sigma_{MC} + P_3\sigma_{MC}^2$ as in Fig. 3. The energy resolution is reproduced with accuracy 2.4% at the energy of 341 keV and 3.0% at 1062 keV.

5. Conclusion

A calibration method for plastic scintillators by using the Compton spectrum of γ-rays has been established. Parameters of the energy and the energy resolution for the Compton edge were obtained by the fitting function of the shape of the Compton spectrum. The accuracy of the energy of the Compton edge is 0.44% at 341 keV and 0.76% at 1062 keV and that of energy resolution is 2.4% at 341 keV and 3.0% at 1062 keV. The points to be emphasized here for this method are as follows:

1. This method can be applied for various detectors with small Z number, such as plastic scintillator, CaF_2 detector and so on, where photo-peak efficiencies are very small.
2. Energy calibrations for electrons can be made by γ-ray source, wherever measurements are carried out in the underground laboratories, where electron source is hardly obtained.
3. The energy calibration, in principle, can also be made by comparing energy spectra generated by MC. However, this method has to compare an experimental spectrum with so many samples with parameters of energy of the Compton edge and energy resolution in MC. In contrast to this method, the present method with analytically derived function directly gives these parameters.

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