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Energy Resolution of a Prototype EM Calorimeter with BSO Crystals

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A new high resolution electro-magnetic (EM) calorimeter with a large solid angle is planned for the precise study of nucleon resonances via π^0 and η photo-production. A BSO crystal is a candidate of modules which comprise the EM calorimeter. The performance of a prototype EM calorimeter made up with 4 BSO crystals has been studied by using positron beams with energies ranging from 100 to 800 MeV. The energy resolution for 1 GeV positron corresponds to 1.75%. The decay time is roughly estimated to be 136 ns from a pulse shape taken with an oscilloscope. The energy resolution for the 0.662 MeV photons from ^{137}Cs has also been measured, and it is found to be 16.6%±0.2%.

§1. A New Large Solid Angle EM Calorimeter

A new EM calorimeter complex FOREST with a solid angle of about 4π in total has been constructed in the GeV-γ experimental hall [1] to study nucleon resonances via π^0 and η photo-production. It consists of three calorimeters: a forward one with CsI crystals, a middle one with lead scintillating fiber (Lead/SciFi) modules, and a backward one with lead glass Čerenkov counters. The π^0 and η mesons are identified as a peak in the $\gamma\gamma$ invariant mass distribution. Thanks to the large solid angle of FOREST, a background due to wrong combinations of γ's is strongly suppressed, which do not form a peak of π^0 nor η in the mass distribution. The resolutions of the EM calorimeters with Lead/SciFi and lead glass modules are 7.2% [2] and 4.9% [3] for 1 GeV positrons, respectively. The resolution of each calorimeter is poorer than that of nominal inorganic scintillator crystals. A high resolution EM calorimeter with a large solid angle is desired for the further precise study of nucleon resonances.

Since photons with an energy of several hundred MeV are mainly produced, inorganic scintillator crystals with a good energy resolution in this energy region are required. A fast response is also required to suppress pile-up events, and a short radiation length and no hygroscopicity are preferable. A BSO crystal [5] is a candidate which satisfies the requirements among the available crystals. The BSO is a bismuth silicate $Bi_4Si_3O_{12}$, produced by replacing Ge in BGO with Si.

§2. Experimental Setup

The performance measurement of a prototype BSO EM calorimeter was carried out by using positron beams for testing detectors at LNS. The prototype EM calorimeter was constructed with a 2×2 array of BSO crystals. Each crystal was 210 mm long with a cross section of 40×40 mm^2, and was connected to a 1-inch photo-multiplier tube (Hamamatsu H7415MOD). Semi-monochromatic positrons with energies ranging from 100 to 800 MeV were used as incident beams. To determine the incident position of the positrons, a beam profile monitor (BPM) was used. The BPM consists of two layers of scintillating fiber (SciFi) hodoscopes and 16 SciFi's with a cross section of 3×3 mm^2 were aligned in each hodoscope. The upstream and downstream layers determine x and y positions from responding fibers, respectively. Figure 1 shows the experimental setup for the energy resolution measurement of the calorimeter.

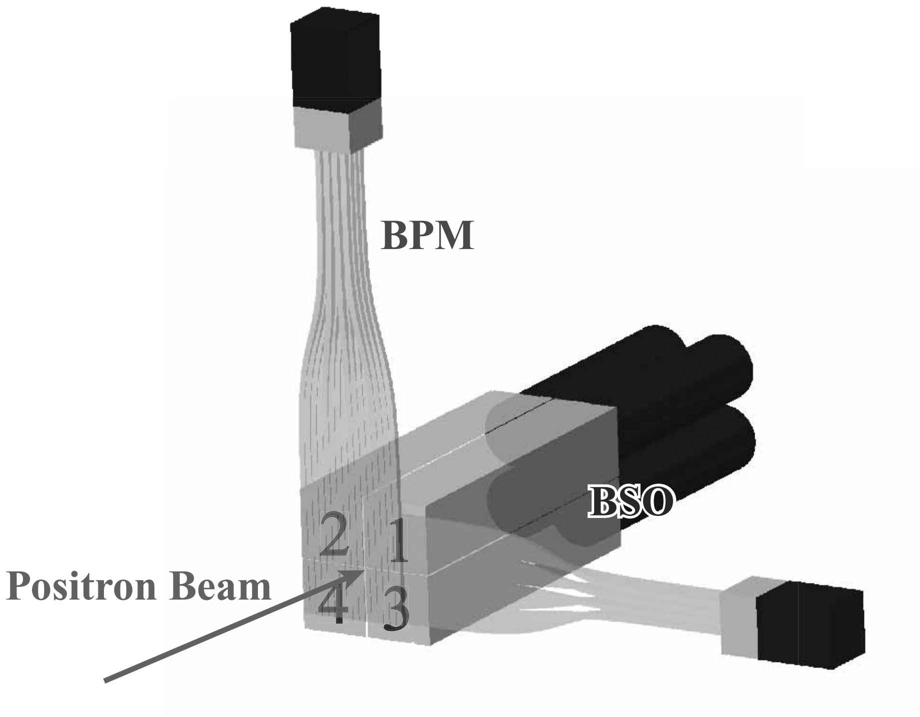

Fig.1. Experimental setup for the performance measurement of a prototype BSO EM calorimeter. The 16×16 scintillating fiber hodoscopes are placed in front of the calorimeter to determine incident positions of positrons.

The trigger condition of the data taking system was described as

$$[x \text{ fiber OR}] \otimes [y \text{ fiber OR}], \tag{1}$$

where $\otimes$ stands for the coincidence of signals. The maximum trigger rate was 3 kHz and a fraction of accidental coincidence events was negligibly small. The energy calibration for the BSO modules was made by using 300, 460, 590, and 750 MeV positrons injected onto the central region (3×3 mm^2) of each crystal one by one, and the gain of each crystal was adjusted so that peak positions for the same incident energy should be the same.

§3. Energy Resolution

The energy of the calorimeter was reconstructed by the sum of 4 crystal energies as

$$E = \sum_{i=1}^{4} E_i. \tag{2}$$

The events that positrons were injected onto the central region (3×3 mm^2) of the EM calorimeter were selected to suppress the energy leakage in the lateral direction. Figure 2 shows energy distributions for all the incident positron energies.

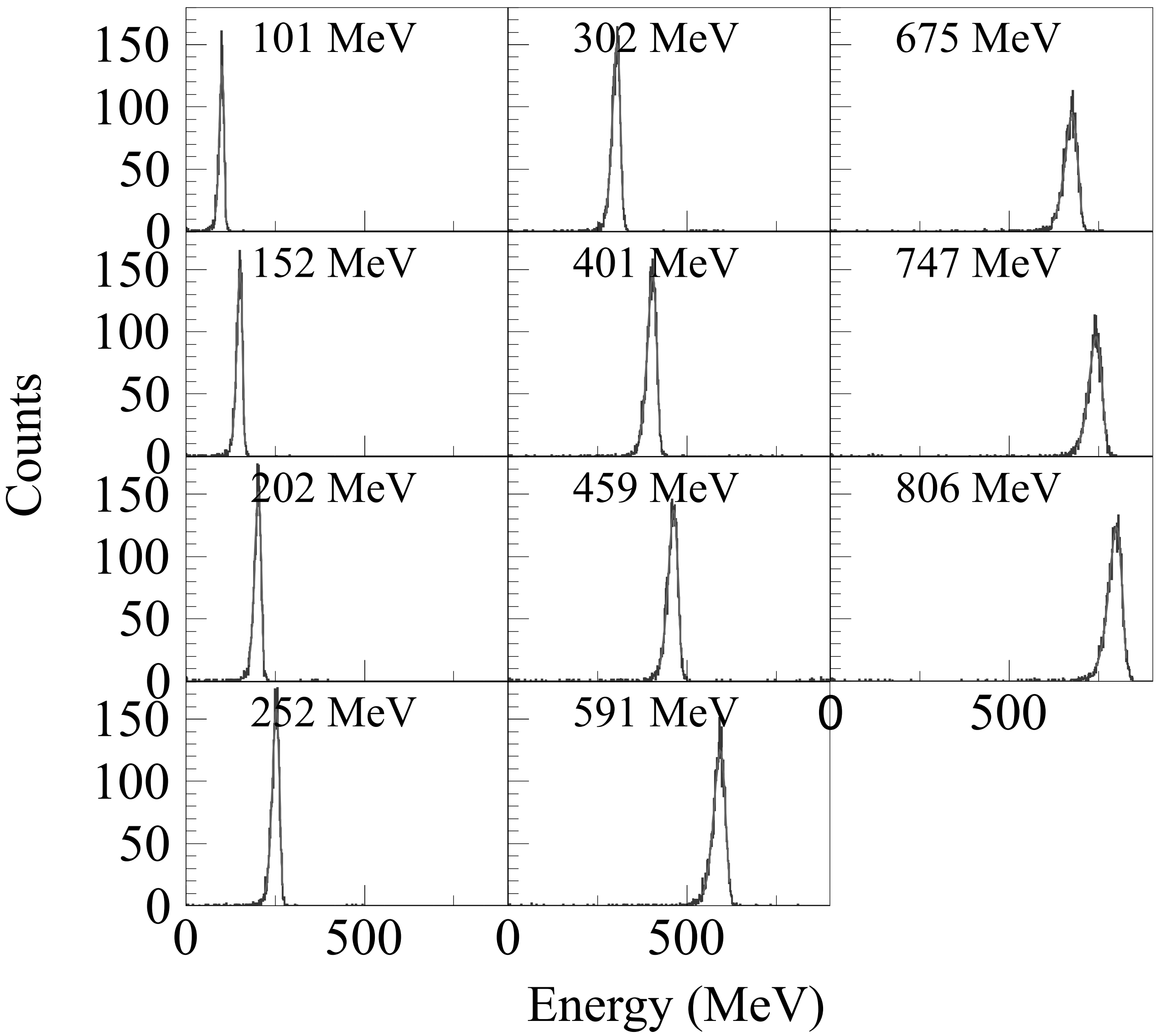

Fig.2. Energy distributions for all the incident positron energies together with the fitted function (3).

The energy distributions were fitted with a logarithmic Gaussian [3]

$$F(x) = N \exp\left[-\frac{1}{2\sigma_0^2}\left\{\log\left(1 - \frac{x-\mu}{\sigma}\eta\right)\right\}^2 - \frac{\sigma_0^2}{2}\right], \tag{3}$$

where σ_0 is described with a constant $\xi = 2\sqrt{\log 4}$ as

$$\sigma_0 = \frac{2}{\xi}\sinh^{-1}\frac{\eta\xi}{2}. \tag{4}$$

The parameters μ, σ, and η show a mean, a width, and an asymmetry, respectively. One gets a nominal Gaussian function taking the limit of Eq. (3) as η becomes infinitely small.

The linearity of the energy response was checked by the ratio of the reconstructed energy to the incident positron energy. Figure 3a) shows the ratio as a function of the incident energy. The normalization of the reconstructed energy is arbitrary. The non linearity of the energy response was less than 2% for all the incident beam energies. The asymmetry parameter as a function of the incident energy was also checked, and it was a constant within errors. Figure 3b) shows the asymmetry as a function of the incident energy.

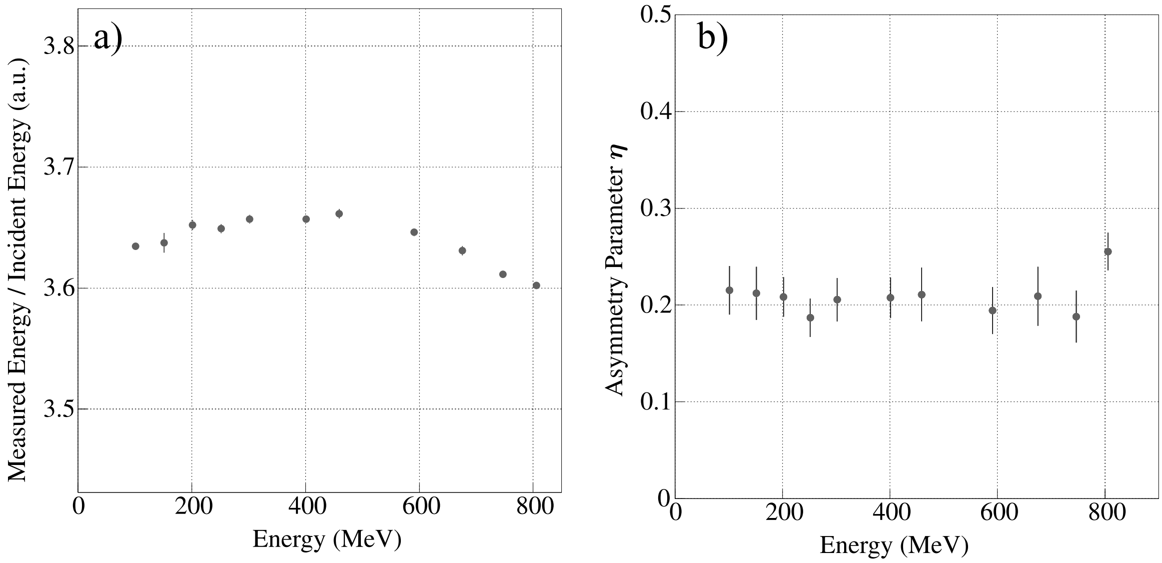

Fig.3. The energy response as a function of the incident positron energy. a) The ratio of the reconstructed energy to the incident energy. The normalization factor is arbitrary. b) The asymmetry parameter. Both the values are almost constant for all the incident energies.

The energy resolution σ_E/E was estimated from the mean μ and width σ of the reconstructed energy distribution, the beam energy spread σ_b/μ_b [4], and the width σ_p of the pedestal distribution as

$$\frac{\sigma_E}{E} = \left\{ \left(\frac{\sigma}{\mu}\right)^2 - \left(\frac{\sigma_b}{\mu_b}\right)^2 - \left(\frac{\sigma_p}{\mu}\right)^2 \right\}^{1/2}. \tag{5}$$

Figure 4 shows the energy resolution as a function of the incident energy. The energy resolution σ_E/E as a function of the incident energy E_i was fitted with

$$\frac{\sigma_E}{E}(E_i) = \left\{ \left(\frac{0.000 \pm 0.233}{E_i}\right)^2 + \left(\frac{1.466 \pm 0.032}{\sqrt{E_i}}\right)^2 + (0.977 \pm 0.115)^2 \right\}^{1/2}, \tag{6}$$

where the units of the resolution and E_i were % and GeV, respectively. The energy resolution is much higher than that measured for an EM calorimeter consists of nine BSO crystals, $22 \times 22 \times 180$ mm^3 [5]:

$$\frac{\sigma_E}{E}(E_i) = \left\{ \left(\frac{2.3 \pm 0.3}{\sqrt{E_i}}\right)^2 + (1.7 \pm 0.2)^2 \right\}^{1/2}. \tag{7}$$

The energy resolution for 1 GeV positron corresponds to 1.74%, and it is extremely high. The details of the analysis for the energy resolution are described elsewhere [7, 8].

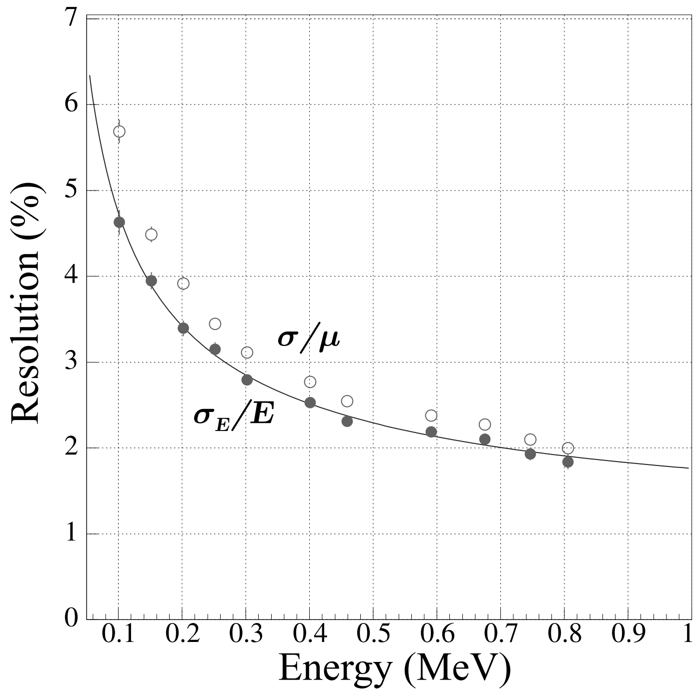

Fig.4. The energy resolution as a function of the incident positron energy. The open circles show σ/μ and the filled ones show σ_E/E. The data points for σ_E/E are fitted with the parametrization $\sqrt{(0.000/E_i)^2 + \left(1.466/\sqrt{E_i}\right)^2 + (0.977)^2}$.

§4. Decay Time

The decay time of the BSO crystal has been estimated from pulse shapes taken with a digital phosphor oscilloscope (Tektronix DPO4104: 5 GHz sampling and 1 GHz bandwidth). The trigger for taking pulse shapes is a coincidence signal of the central x and y BPM fibers to select the positrons which inject onto the central region (3×3 mm^2) of the crystal. Figure 5 shows the pulse shapes for some positron energies.

The pulse shape from 0 to 800 nsec are fitted with an exponential function, and the obtained decay times are 133.9, 136.4, and 137.2 ns for positron energies of 800, 670, and 500 MeV, respectively. The fitting error is less than 0.1 ns, and the average value is 136 ns. The obtained decay time is longer than that of a BSO crystal with a size of $22 \times 22 \times 180$ mm^3 ($\sim$100 ns) measured by a single photo-electron method [5]. The measured value from the pulse shape depends on how the EM shower grows in the BSO crystal and where scintillation photons are produced. The details of the analysis for the decay time are described elsewhere [8].

§5. Energy Resolution for ^{137}Cs

The energy of the photons from ^{137}Cs is 0.662 MeV and is so low that electron and positron pair creation does not take place. The energy deposit of electrons generated by the photoelectric effect forms a bump in the energy distribution. The energy resolution is given by the number of detected scintillation photons.

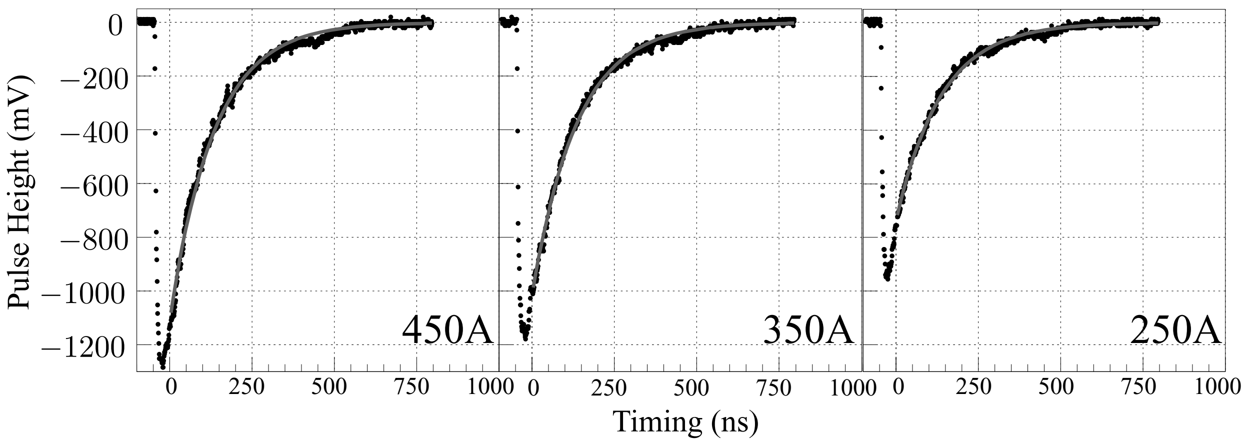

Fig.5. The pulse shape taken by an oscilloscope for positron energies of 800, 670, and 500 MeV ($\mathcal{R}$TAX currents of 450, 350, and 250 A) together with the fitted exponential functions.

The energy of ^{137}Cs photons were measured with a BSO crystal with a size of $40 \times 40 \times 210$ mm^3. A 2-inch photo-multiplier tube (Hamamatsu H6522) was connected to the crystal. Figure 6 shows the ADC distributions taken with ^{137}Cs together with a background distribution measured without the ^{137}Cs source which is normalized by a data taking time and a data taking efficiency. A net ADC distribution for the ^{137}Cs photons is obtained by subtracting the background distribution from the ADC distribution with ^{137}Cs.

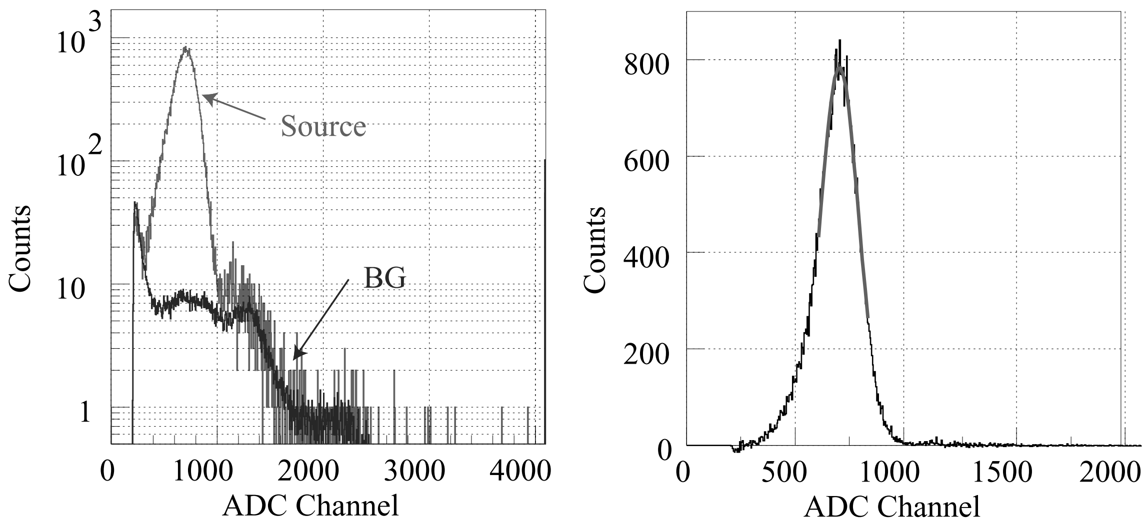

Fig.6. The measured ADC distributions. The left panel shows the ADC distributions taken with ^{137}Cs together with a background measured without the ^{137}Cs source which is normalized by a data taking time and a data taking efficiency. The right panel shows the net ADC distribution for the ^{137}Cs photons together with the fitted Gaussian.

The mean μ and width σ of the net ADC distribution was estimated by fitting with a Gaussian function. The energy resolution for the ^{137}Cs photons are estimated as

$$\frac{\sigma_E}{E} = \frac{\sigma}{\mu - \mu_p}, \tag{8}$$

where μ_p stands for the mean of the pedestal distribution. The width of the pedestal distribution is negligibly small as compared with that of the net ADC distribution. The energy resolution of 16.6%±0.2% has been obtained, which corresponds to about 40 detected photons with the photo-multiplier tube. The resolution is much higher than that of the first manufactured small BSO with a diameter of 20 mm and a thickness of 39 mm (∼32% [9]). The details of the analysis for the energy resolution for the ^{137}Cs photons are described elsewhere [10].

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