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著者	Miyahara F., Hariu H., Ishikawa T., Itaya M., Iwata T., Kinoshita T., Moriya M., Nakabayashi T., Tajima Y., Hayakawa T., Yamamoto M., Yamazaki H., Yoshida H. Y., Yoshida Y., Shimizu H.
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F. Miyahara[1], H. Hariu[2], T. Ishikawa[1], M. Itaya[2], T. Iwata[2], T. Kinoshita[1],
M. Moriya[2], T. Nakabayashi[1], Y. Tajima[2], T. Hayakawa[1], M. Yamamoto[2],
H. Yamazaki[1], H.Y. Yoshida[2], Y. Yoshida[2], and H. Shimizu[1]

[1]*Laboratory of Nuclear Science, Tohoku University, Sendai 982-0826*
[2]*Department of Physics, Yamagata University, Yamagata 990-8560*

The response of an electromagnetic calorimeter of large bismuth silicate (BSO) crystals has been measured for the first time for electrons, positrons, and charged pions at the incident momentum ranging from 0.5 to 3.0 GeV/*c*. The calorimeter consists of 9 BSO crystals arranged in a 3 × 3 matrix. The size of each crystal is 22mm × 22mm × 180mm (15.6 radiation lengths). The energy resolution of $(\sigma_E/E)^2 = (0.024 \pm 0.003/\sqrt{E\,[\mathrm{GeV}]}\,)^2 + (0.018 \pm 0.002)^2$ has been obtained for incident electrons. The position information for the electrons injected onto the center crystal is given with energy deposit signals from 9 BSO crystals. The obtained position resolution is better than 5 mm in this energy range. The misidentification probability of pions to electrons is found to be $\sim 10^{-3}$ in the energy range from 1.0 to 3.0 GeV.

§ 1. Introduction

In the energy region of several hundred MeV, NaI(Tl) and CsI crystals are often used for electromagnetic (EM) calorimeters since the light outputs of these crystals are rather large so as to give a good energy resolution. However, the total volume of the NaI(Tl)/CsI calorimeter would be relatively large because their unit radiation lengths are long compared to that of other crystals. In addition to that, there is another inconvenience that the hygroscopicity of these crystals has to be taken care during experiments. Bismuth silicate $Bi_4Si_3O_{12}$ (BSO) scintillating crystals have good characteristics [1] such as a short unit radiation length and non-hygroscopicity. BSO may well replace these crystals regardless of smaller light output since the number of scintillating photons is large enough if the energy of the incident γ is in the several hundred MeV region or higher. Table 1 lists physical properties of BSO and other crystals. BSO crystals have not been used notwithstanding their good qualities for EM calorimeters because it was difficult to grow a large single crystal. Recently Ishii *et al.* succeeded in

Table 1. Properties of some scintillators. (f : fast component, s : slow component)

	Density (g/cm^3)	Radiation length (cm)	Decay constant (ns)	Peak emission (nm)	Relative output	Hygroscopicity
BSO	6.8	1.15	99	480	0.04	no
BGO	7.13	1.12	300	410	0.15	no
NaI(Tl)	3.67	2.59	250	410	1.00	very
Pure CsI	4.53	1.85	10^f, 620^s	305^f, $\sim 480^s$	0.10^f, 0.20^s	some

growing up large BSO crystals with the vertical Bridgman method [2, 3], although there seemed to be some difficulties preventing them from producing a large number of big size crystals. Employing the same method but with an additional technique we have gotten the way for mass production of large single BSO crystals in cooperation with a crystal company supervised by Ishii. We performed the first beam test of a prototype BSO calorimeter to measure the energy resolution and the position resolution for 0.5−3.0 GeV/*c* electrons and also the electron/pion separation factor.

§ 2. Experimental Setup

The measurement was made at the $\pi 2$ beamline of the proton synchrotron facility at KEK. Electron, positron and charged pion beams are produced by 12 GeV protons striking a production target located in the synchrotron ring. The produced charged particles are momentum-analyzed with the beamline magnets. The beam momenta used in the test experiment are 0.5, 1.0, 1.5, 2.0, and 3.0 GeV/*c*. The experimental setup is illustrated in Fig.1.

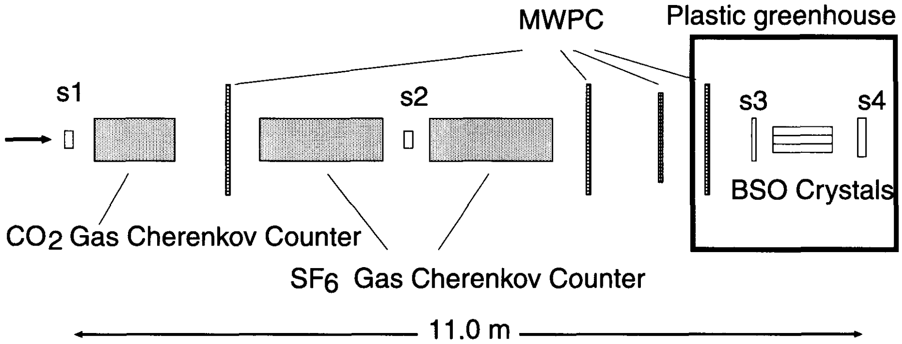

Fig.1. Plan view of experimental setup.

Three plastic scintillation counters, S1, S2 and S3, are used as trigger counters. Particle identification is made by means of time of flight (TOF). And the momentum resolution for the $\pi 2$ beam line is evaluated also with TOF spectra given by time difference between the signals from S1 and S4 plastic counters, the thickness of which is 10 mm and 30 mm, respectively. Three sets of gas Cherenkov counters(GCC) distinguish electrons/positrons from the other charged particles. The GCC1 is filled with 1.8 atm CO_2 gas, while 1 atm SF_6 gas is employed for GCC2 and GCC3. The three GCCs are used in the trigger for electrons. The trajectory of a charged particle is obtained by using four sets of multiwire proportional chambers (MWPC). Each MWPC has 2 wire planes, x and y. The wire spacing for all these planes is 2 mm. The BSO calorimeter, shown in Fig.2, consists of 9 BSO crystals giving a 3 × 3 matrix. Each crystal size is 22 mm × 22 mm × 180 mm, which corresponds to 15.6 radiation lengths along the incident beam direction. The calorimeter located at the end of the beam line is placed in a plastic greenhouse so that thermal stabilization is achieved. The temperature in the greenhouse has been monitored during the measurement and is kept to be 17 ± 1 °C.

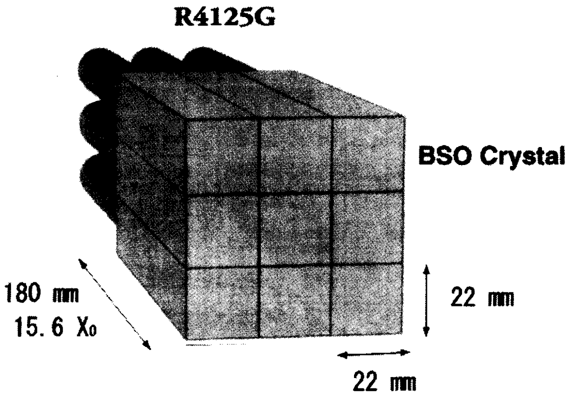

Fig.2. Schematic view of the BSO calorimeter.

§ 3. Results

3.1 Energy resolution

Figure 3 shows the energy spectra for the 0.5, 1.0, 1.5, 2.0, and 3.0 GeV/c electrons incident on the 4×4 mm^2 area of the central crystal after energy calibration is made. The deposited energy is given by

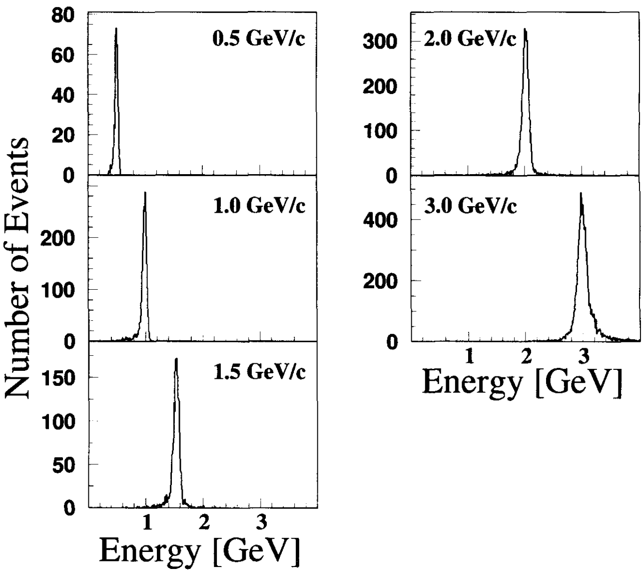

Fig.3. Response of the BSO calorimeter for 0.5, 1.0, 1.5, 2.0, and 3.0 GeV/c electrons.

summing up all the signals of the 9 crystals and normalized with 3 GeV/*c* electrons. These spectra are fitted with a Gaussian function.

Figure 4(a) shows the obtained energy resolutions σ_E/E (closed circles) and the result of Monte Carlo simulations based on the GEANT3 code (open diamonds) as a function of the incident electron energy. The energy resolution σ_E/E is deduced by subtracting the effect of the beam-momentum spread from the observed value σ_{ob}/E_{ob} which may be written as

$$\frac{\sigma_{ob}}{E_{ob}} = \sqrt{\left(\frac{\sigma_E}{E}\right)^2 + \left(\frac{\sigma_b}{E_b}\right)^2} \qquad (1)$$

Here E_b represents the beam energy and σ_b denotes the energy spread of the beam which is estimated

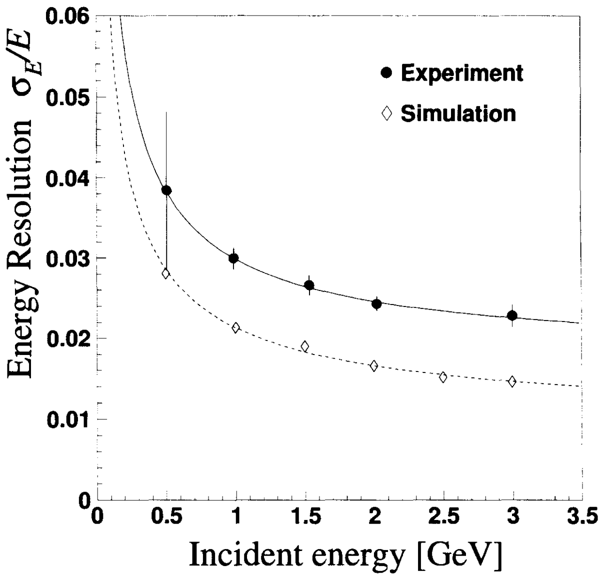

Fig.4. Energy resolution σ_E/E of a 3 × 3 BSO crystal calorimeter. The solid line indicates function(2) with parameters obtained by fitting the data. The dashed line represents a simulation result for the same detector arrangement.

from the momentum resolution of the $\pi 2$ beam line. The momentum spread for 1 GeV/*c* protons is measured with TOF and 0.7% is obtained for σ_b/E_b. The energy resolution is parameterized as

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2} \tag{2}$$

where *a* means the statistical fluctuation for the incident energy *E* given in GeV and *b* is a constant. By fitting the data of σ_E/E with Eq. (2), the coefficients are found to be $a = 0.024 \pm 0.003$, $b = 0.018 \pm 0.002$ (experiment) and $a = 0.019$, $b = 0.010$ (simulation).

Figure 5 shows a simulation result for the correlation between a crystal length and the parameters *a* and *b*. The statistical term *a* is constant through this energy range and the constant term *b* depends on the crystal length. The result indicates that the fluctuation of EM showers is almost constant in this energy region and that shower leakage from the calorimeter mostly accounts for the constant term. However, the length of our crystal (180 mm) seems long enough according to the simulation result. Discrepancy in the constant term could be related other effects such as non-uniformities in the crystal response [4].

3.2 Position resolution

Position information for the incident γ/electron is important to provide an accurate reconstructed invariant mass of a meson decaying into photons or electrons (e.g. $\eta \rightarrow 2\gamma$, $\eta \rightarrow e^+e^-\gamma$, *etc.*). The position of the center of gravity X_{cg} is given with measured energy deposits as

$$X_{cg} = \frac{\Sigma_{i=1}^{9} E_i x_i}{\Sigma_{i=1}^{9} E_i} \tag{3}$$

where E_i is the energy deposit and x_i the *x* coordinate of the center of the *i*th crystal. Comparing a X_{cg} to the MWPC reconstructed position, we obtain an energy dependent function giving the position of the incident γ/electron out of the X_{cg}. The position resolution of the BSO calorimeter is estimated with the

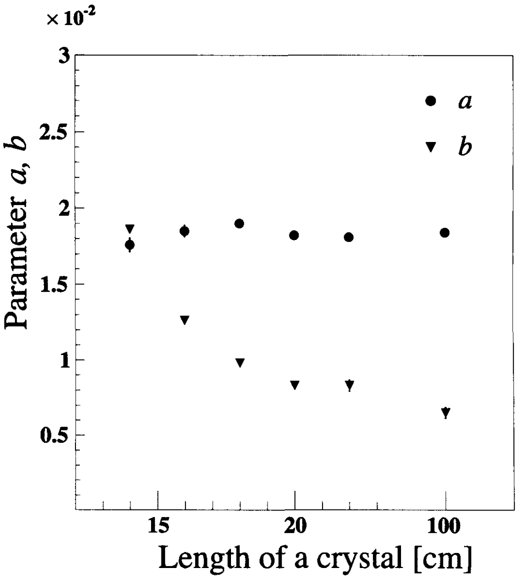

Fig.5. Correlation between a crystal length and the parameters *a*, *b*.

standard deviation of the position given by the function with the X_{cg} from the MWPC reconstructed position. The results are shown in Fig.6. The position resolution at the center of the calorimeter is better than 5 mm for incident electrons of the energy greater than 0.5 GeV.

3.3 Electron/pion separation

The e/π separation capability is one of the characteristics to be measured for EM calorimeters. Pions produced in experiments sometimes give a large energy deposit due to the nuclear reaction taking place in the calorimeter. In order to measure the e/π separation factor, first of all, pions have to be well selected on the $\pi 2$ beam line. Three GCCs are employed for this purpose. The detection efficiency of the

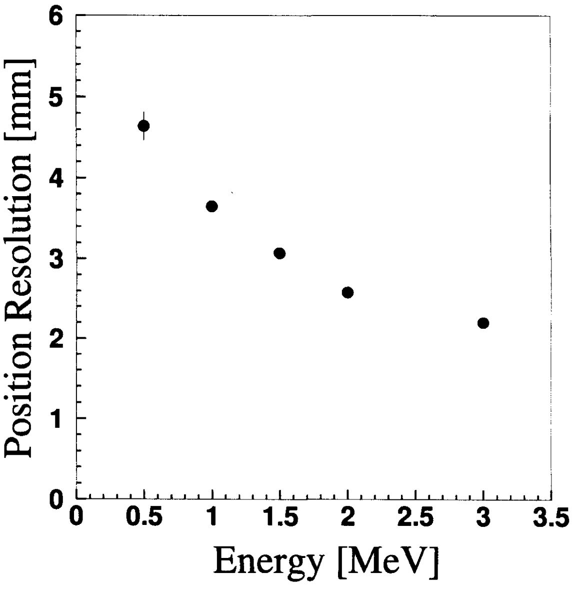

Fig.6 Position resolution at the center of the calorimeter.

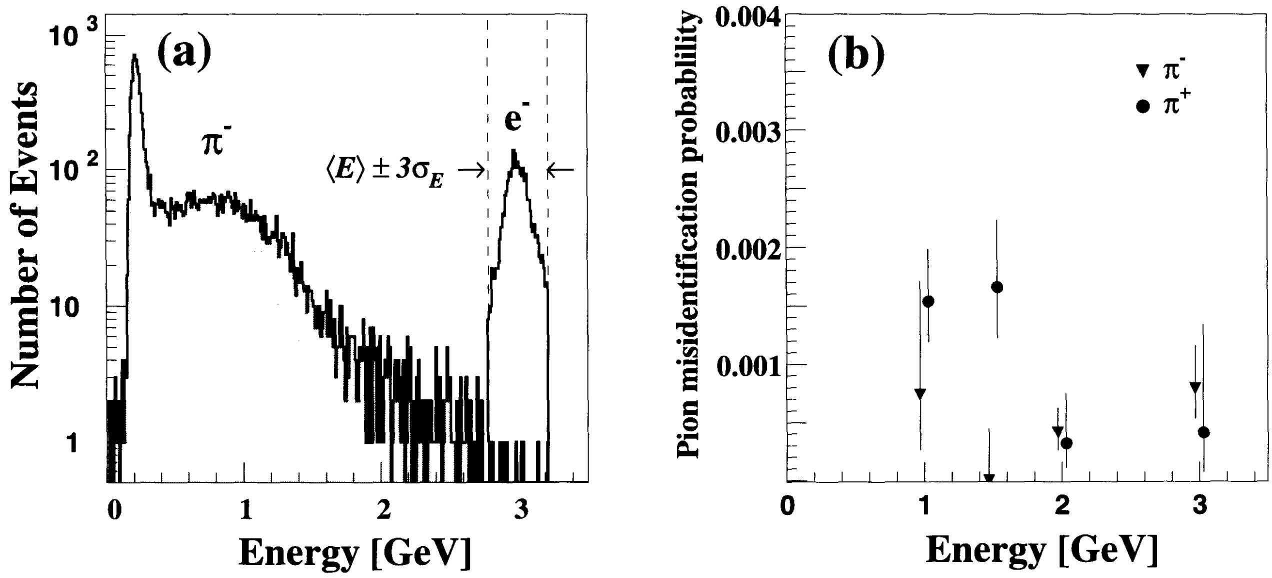

Fig.7. (a) Energy spectra for 3 GeV/c π^- together with 3 GeV/c electrons. (b) Misidentification probability of pions to electrons.

ith GCC for electrons is given by

$$\varepsilon_i = \frac{Y_{123}}{Y_{jk}} \tag{4}$$

where Y_{123} represents the number of three-fold coincidence events firing 3 GCCs simultaneously and Y_{jk} means that of two-fold coincidence events. The obtained efficiencies are $\varepsilon = 0.959$, $\varepsilon_2 = 0.996$, and $\varepsilon_3 = 0.987$, respectively. Thus the contamination ratio of electrons into the pion beam is found to be $(1-\varepsilon_1)(1-\varepsilon_2)(1-\varepsilon_3) = 2.13 \times 10^{-6}$. Figure 7(a) shows the response of the BSO calorimeter for 3.0 GeV/c π^- and electrons. The peak around 200 MeV corresponds to the minimum ionization loss of passing through pions and a broad bump up to 3.0 GeV is due to the nuclear reaction in the BSO crystals. The pion spectrum has an overlap with the electron peak slightly. Using the measured energy resolution we define the misidentification probability of pions to electrons (so called e/π separation factor) at each momentum as

$$\eta = \frac{\sum_{E=\langle E\rangle-3\sigma_E}^{E=\langle E\rangle+3\sigma_E} Y_\pi(E)}{\sum_{E=0}^{\infty} Y_\pi(E)} \tag{5}$$

where $Y_\pi(\mathrm{E})$ is the number of pions for the incident momentum E, $\langle E\rangle$, the peak energy of electrons at each momentum, and σ_E, the measured energy resolution. Figure 7(b) shows the misidentification probability of pions to electrons in the energy range from 1.0 to 3.0 GeV. There is no clear difference observed between π^+ and π^- in the present experiment. The misidentification probability is found to be about 1/1000.

§4. Conclusions

We have tested a calorimeter consisting of 3 × 3 BSO crystals using electron, positron and charged pion beams of 0.5, 1.0, 1.5, 2.0 and 3.0 GeV/c. The obtained energy resolution is $(\sigma_E/E)^2 = (0.024 \pm 0.003/\sqrt{E\,[\mathrm{GeV}]})^2 + (0.018 \pm 0.002)^2$ in this energy range. The position resolution is found to be better than 5 mm at the center of the calorimeter for 0.5−3.0 GeV/*c* electrons. The electron/pion separation factor (the misidentification probability of pions to electrons) is estimated to be approximately 10^{-3} in the energy range of 1.0−3.0 GeV.

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