IONIZATION LOSS IN BGO

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Abstract: We report on a precise measurement of the energy loss through ionization by pions in bismuth germanate performed at several values of the incident particles momentum with a prototype of the L3 electromagnetic calorimeter. The experimental results are in good agreement with theoretical predictions showing the relativistic rise modified by density effect.

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1. INTRODUCTION

This work is motivated by the fact that the ionization loss in bismuth germanate ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) has not yet been accurately measured. The knowledge of the ionization loss is also relevant to the project of monitoring the stability of crystal calibration constants using cosmic muons, once the L3 electromagnetic calorimeter will operate in its final position.

In Section 2 a short description of the experimental set-up is given. Section 3 is devoted to the discussion of some relations that are necessary in order to obtain the mean ionization loss per unit length and to explain how the analysis is performed. In Section 4 the final results are presented and compared with theoretical predictions.

2. EXPERIMENTAL SET-UP

A prototype of the L3 electromagnetic calorimeter, composed of a matrix of 100 BGO crystals, was tested in the X3 beam spectrometer of the CERN Super Proton Synchrotron (SPS) during the summer of 1986. This test was meant to define a calibration procedure for the final detector. In addition, the possibility of using a pion beam gave us the opportunity to measure, over a wide momentum range, the energy loss due to ionization in BGO. The relative pion content of the beam was enriched by interposing a 5 mm lead absorber after the momentum slit in order to remove electrons produced in the upstream target.

Particles were identified by a set of scintillators and two threshold Cherenkov counters; track reconstruction was made possible by a series of wire chambers positioned both in front of and behind the matrix (fig. 1).

The test matrix was mounted on a rotating support, permitting azimuthal and polar movements in the beam line; this facility allowed the alignment of the longitudinal axis of each crystal with the beam. In the following, the aligned crystal will be called the 'central' crystal. The matrix was housed in a temperature-regulated box and was also equipped with temperature sensors to record residual variations.

The tapered BGO crystals are 24 cm long and measure $2 \times 2 \text{ cm}^2$ at the front and 3×3

cm² at the rear. All crystals are equipped with two photodiodes (Hamamatsu S2662), each of which has an active surface of 1.5 cm². Each crystal is wrapped in aluminized Mylar and inserted in a carbon-fibre cell with 0.2 mm thick walls. The readout electronics and data-acquisition system are described in detail in Ref. [1].

3. ENERGY LOSS DETERMINATION

3.1 Generalities

The mean value of the ionization loss of a charged ($Z = 1$) massive ($M \gg m_e$) spin-zero particle of energy E is given by the Bethe-Bloch formula [2]

$$\frac{dE}{dx} = \frac{2Cm_e}{\beta^2} \left(\ln \left(\frac{2m_e\beta^2\gamma^2 E_{max}}{I^2} \right) - 2\beta^2 - \delta \right), \quad (3.1)$$

where I is the mean excitation potential, Z and A the atomic number and atomic weight of the traversed medium,

$$C = \pi N_A \frac{Z}{A} r_e^2, \quad (3.2)$$

N_A is the Avogadro constant, r_e is the classical radius of the electron, and

$$E_{max} = \frac{2m_e\beta^2\gamma^2}{1 + 2\gamma \frac{m_e}{M} + \left(\frac{m_e}{M}\right)^2} \quad (3.3)$$

is the maximum energy transferable in a single collision. The term δ represents the density effect.

The fluctuations of the energy loss in thin absorbers ($2Cm_e\rho\Delta x/\beta^2 E_{max} \leq 10$, as is the case for the 24 cm BGO crystals at the energies considered in this analysis) follow a Landau distribution [3] or its generalization, the so-called Vavilov distribution [4].

The strong interacting nature of pions makes the measurement of the mean ionization loss somewhat more complicated than in the case of muons. To avoid energy depositions due to pions that undergo strong interactions, some selection criteria based on the energy deposited in the crystals surrounding the central one must be applied. Such selection eliminates also 'good' events with ionization losses in the tail of the Landau distribution; these events correspond to collisions where the energy transfer is sufficient to extract from BGO molecules the electrons (so-called 'knock-on electrons') which leave part of

their energy outside the central crystal. Therefore, in this case it is the selection criteria rather than the kinematics that determine the maximum value of energy transfer to be used in the argument of the logarithm in formula (3.1), and the average energy loss is systematically lower than the one in that formula.

The strategy adopted is therefore the following: first determine from the data the most probable energy loss [2] $E_p(\Delta x)$ (Δx being the thickness traversed), since it does not depend on the maximum energy transfer

$$E_p(\Delta x) = \frac{2Cm_e}{\beta^2} \Delta x \left[\ln \left(\frac{4Cm_e^2 \gamma^2 \Delta x}{I^2} \right) - \beta^2 - \delta + j \right] , \quad (3.4)$$

then, calculate the average energy loss $E_a(\Delta x)$ from the most probable energy loss through the relation

$$E_a(\Delta x) = E_p(\Delta x) + \frac{2Cm_e}{\beta^2} \Delta x \left(\ln \frac{\beta^2 E_{max}}{2Cm_e \Delta x} - \beta^2 - j \right) . \quad (3.5)$$

Note that $E_p(\Delta x)/\Delta x$ still depends logarithmically on the thickness traversed. The constant $j = 1 - \Gamma + \lambda_p$ contains Euler's constant $\Gamma = 0.577$ and the value at which the universal Landau distribution has its maximum, $\lambda_p = -0.223$ [5]. The relation between the most probable energy loss in 1 cm and the one in Δx cm is given by

$$E_p(1cm) = \frac{E_p(\Delta x)}{\Delta x} - \frac{2Cm_e \rho}{\beta^2} \ln \Delta x . \quad (3.6)$$

3.2 Data selection

Data were collected with a negative beam at five different momenta: 2, 4, 10, 20, 50 GeV/c, and on seven different (central) crystals. Incident pions were selected by requiring the presence of a track in the upstream drift chambers and the absence of a signal in the two Cherenkov counters. The last requirement was relaxed at 50 GeV/c. Moreover to eliminate events escaping the 3×3 matrix around the central crystal, only events for which the track coordinates were within a 3×3 cm² area centred on the central crystal itself were accepted. After this first selection, the signal observed in a crystal during a typical run at 4 GeV/c is as shown in fig. 2.

In order to select non-interacting pions traversing the central crystal only, a hit was required in the chamber situated after the matrix, and the signal in each of the eight crystals surrounding the central one had to be compatible, within 3σ , with a pedestal signal (roughly corresponding to 6 MeV). The pedestal evaluation profited from the exhaustive study performed for the electron calibration analysis [6]. The distribution shown in fig. 2 reduces to the one in fig. 3.

A nice confirmation that the selected events are not due to strongly interacting pions is shown in fig. 4. Here the distribution of the absolute value of the difference between the y_5 and y_6 coordinates measured in a 4 GeV/c run on the chamber in front of and behind the matrix, respectively, is compared with the distribution expected from the effect of multiple scattering.

3.3 Peak determination

The peak value A_p (μV) of a distribution of the energy deposited by events that survive the selection criteria discussed above was determined either empirically, comparing histograms with different binning, or by performing a local fit around the maximum of the distribution using a Gaussian plus a power tail towards high energies to reproduce the asymmetric Landau shape. The two different determinations agree well within errors.

Once the peak value of a distribution is determined, a correction must be applied to take into account the energy loss in the 100 μm silicon layer of each photodiode which produces an additional signal. This effect was evaluated using a Monte Carlo simulation, assuming that the energy loss in 100 μm of silicon [7] follows a Landau distribution with an average energy loss of 39 keV, a most probable energy loss of 26 keV, and a FWHM of ~ 10 keV, and taking the mean energy required to produce an electron-hole pair to be 3.6 eV. The percentage of tracks traversing the active area of the photodiodes was estimated for each momentum, taking into account the beam shape, the geometrical layout and the effect of multiple scattering in BGO. The shift in the energy loss distribution in BGO, induced by this effect, was computed as a function of the percentage of the events traversing the photodiodes (fig. 5). This percentage is estimated to be around

45%, corresponding to a value

$$\Delta A_p = 200 \pm 25 \text{ } \mu V$$

to be subtracted from the measured position of the peak of the energy loss distributions.

4. RESULTS

To convert the peak values A_p , as determined in the previous section, to energy units, the calibration constants $C^e(T_0)$ obtained from 10 GeV electrons at the reference temperature $T_0 = 20.0^\circ C$ [6] were used. These calibration constants were properly rescaled to the actual temperature using the coefficient $dC^e/dT = 1.55\%/^\circ C$ [6].

Given the fact that the light collection efficiency in a crystal is not uniform, a further correction to C^e must be applied to account for the different ways in which pions (considered here as muon-like particles) and electrons release their energy in the crystal. The digitized energy yield is given by

$$A^\mu = k \int L(x) \frac{dE}{dx} dx \quad (3.7)$$

for the muons, and

$$A^e = k \int L(x) S(x) dx \quad (3.8)$$

for the electrons, where k is a proportionality factor, $L(x)^{*)}$ represents the light response of the crystal and $S(x)$ is a parametrization of the longitudinal shower profile of the form [9]

$$S(x) = B t^\alpha e^{-\beta t} \text{ ,} \quad (3.9)$$

with

$$\begin{aligned} B &= -46.9 + 16.2 \ln E \text{ ,} \\ \alpha &= -2.56 + 0.571 \ln E \text{ ,} \\ \beta &= 0.183 + 0.027 \ln E \text{ ,} \end{aligned} \quad (3.10)$$

*) For $L(x)$ we use a parametrization of the data obtained from cosmic-ray measurements on each crystal, made by the L3 Lyon group [8].

where t is the depth measured in unit of radiation lengths and the energy of the electron E is in MeV. The corresponding calibration constants are

$$C^\mu = \frac{(dE/dx)\Delta x}{A^\mu} , \quad (3.11)$$

and

$$C^e = \frac{\int S(x)dx}{A^e} . \quad (3.12)$$

Combining eqs. (3.7) to (3.8) with eqs. (3.11) to (3.12) it then follows that

$$C^\mu = \frac{\Delta x \int L(x)S(x)dx}{\int S(x)dx \int L(x)dx} C^e . \quad (3.13)$$

For the BGO crystals in the matrix the size of this correction varies from 0 to 1.5%.

The final results obtained at various beam momenta are listed in table 1, where the error is purely statistical. A systematic error of $\pm 2\%$ was estimated to come from the uncertainty on the absolute value of beam momentum in the determination of the electron calibration constant.

For each beam momentum, data were collected on several crystals. For example, measurements of the most probable energy loss at 4 GeV/c were performed on six different crystals. In fig. 6 we show for each crystal the inverse of the calibration constant C^μ as a function of the digitized energy. The solid line represents the result of a fit to a straight line. At each beam momentum we use this method to combine the measurements on different crystals and to produce the final values for the most probable energy loss listed in table 1.

In fig. 7 the most probable energy loss in 1 cm of BGO is shown as a function of the particle momentum; also shown is the corresponding mean energy loss per unit length, which is derived from the most probable value using eq. (3.6) and assuming that $Z/A = 0.4207$, $\rho = 7.10$ g/cm³, and $I = 534$ eV [7]. The parametrization of the density effect, and the parameters appropriate for BGO, were taken from [10]:

$$\delta(X) = 4.6052X + a(X_1 - X)^m + D , \quad X_0 \leq X < X_1 ,$$

$$\delta(X) = 4.6052X + D , \quad X \geq X_1 ,$$

where $X = \log_{10}(\beta\gamma)$, $D = -5.741$, $X_0 = 0.046$, $X_1 = 3.382$, $a = 0.096$, and $m = 3.078$. The solid lines represent the theoretical predictions obtained using relations (3.1) and (3.2) and the aforementioned values for material parameters and δ .

4. CONCLUSIONS

A precise measurement of the most probable energy loss through ionization by pions in BGO was performed in the momentum range 2-50 GeV/c. The corresponding average energy loss is derived from these measurements. Its relativistic rise is clearly observed, and the results agree with theoretical predictions within the error of measurement, which is generally $\leq 0.5\%$ statistically, with an overall systematic error of $\pm 2\%$.

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FIGURE CAPTIONS

- Fig. 1 Layout of the L3-X3 beam line where Q refers to quadrupoles, B to bending magnets, DWC to wire chambers, S to scintillators, and C to Cherenkov counters.
- Fig. 2 Distribution of the pulse heights (μV) in the central crystal obtained in a typical 4 GeV/c run.
- Fig. 3 Distribution of the signals in the central crystal of fig. 2 for events that survive the selection criteria.
- Fig. 4 The distribution, for a beam momentum of 4 GeV/c, of the absolute value of the difference between the coordinates y_5 measured on the chamber DWC5 and y_6 measured on DWC6 is compared with the one (full dots) expected from the effect of multiple scattering in 24 cm of BGO.
- Fig. 5 Shift of the peak position (μV) of the selected distributions as a function of the percentage of events traversing the active region of the photodiodes.
- Fig. 6 The inverse of the calibration constant as a function of the peak position A_p measured for six different crystals (open circles). The solid line is the result of a straight line fit.
- Fig. 7 The mean energy loss per unit length (open circles) and the most probable energy loss in 1 cm (open triangles) as measured in BGO at five different values of beam momentum; the error bars are purely statistical. The solid lines represent theoretical predictions.

Tab. 1

p (GeV/c)	$E_p(24\text{cm})$ (MeV)	dE/dx (MeV/cm)	$E_p(1\text{cm})$ (MeV)
2	224 ± 5	10.09 ± 0.21	7.87 ± 0.21
4	232.5 ± 0.8	11.04 ± 0.03	8.22 ± 0.03
10	239.8 ± 1.2	12.08 ± 0.05	8.53 ± 0.05
20	245.1 ± 1.3	12.80 ± 0.05	8.75 ± 0.05
50	248.9 ± 2.3	13.53 ± 0.10	8.91 ± 0.10

FIG. 1

Fig. 2

Fig. 3

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Fig. 6

Fig. 7