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HIGH ENERGY COSMIC MUONS AND THE CALIBRATION OF THE L3 ELECTROMAGNETIC CALORIMETER

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Abstract : A method to calibrate the L3 electromagnetic calorimeter with cosmic muons has been tested on a matrix of 100 tapered BGO crystals. Calibration constants in the energy range of 20-30 MeV were measured at the 2% level collecting about 200 muons per crystal. The results are in agreement with the calibration constant determined using a 10 GeV electron beam.

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1. Introduction

The central part of the L3 electromagnetic calorimeter consists of 7680 BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) crystals mounted on a barrel-shaped carbon fiber structure. The detector is expected to have an energy resolution better than 1% in a wide energy range (from 2 GeV up to 50 GeV) [1]. To reach such a performance a very accurate determination of the calibration constant of each crystal is needed. This quantity, defined as the ratio between the energy, E , released into a crystal and the corresponding measured electric signal, A , is

$$C = \frac{E}{A} [\text{MeV}/\text{mV}], \quad (1)$$

and can be determined experimentally in several ways. As we will see in section 2 the calibration constant measured with different particles does not necessarily take on the same value.

Before installation in the experimental hall, the calibration constants are determined in the GeV range by exposing the crystals to an electron beam of energies 2, 10 and 50 GeV, and in the 20-30 MeV range by cosmic muons.

The calibration of the L3 e.m. calorimeter during its operation at LEP will be provided mainly by physical processes like

$$e^+e^- \rightarrow e^+e^-$$

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and high energy cosmic muons. Among these methods only cosmic muons allow a measurement of the variation of light produced along the crystal length and collected by photodiodes. In the following we will use the term "light response function" for this effect. Furthermore, a stability monitor will be provided by illuminating each crystal with light from xenon lamps.

We report on an experiment performed with a 10×10 BGO crystal matrix to define a calibration procedure with high energy cosmic muons to be applied to the e.m. calorimeter both before the installation and inside the L3 hall.

In section 2 the definitions of calibration constants for muons and electrons are given. In section 3 the relevant parameters for the calibration of the e.m. calorimeter in the L3 hall at LEP are quoted. Section 4 describes the experimental set-up used in this test. In section 5 results are given and section 6 contains conclusions of this experiment.

2. Definitions

2.1) Calibration constants A charged particle passing through a BGO crystal generates light by an intrinsic scintillation process. The corresponding signal, integrated over the whole crystal length, can be written as:

$$A = gq \int_0^{x_L} dx L(x) S(x, E_o) \quad (2)$$

where A is the signal, $S(x, E_o)$ is the particle energy loss along its trajectory, $L(x)$ parametrizes the light response function, q depends on the ratio between the released energy and the number of emitted photons, and g is an overall constant which accounts for the intrinsic features of the system (photodiode quantum efficiency and read-out electronics gain).

The total released energy is

$$E = \int_0^{x_L} dx S(x, E_o) \quad (3)$$

so that the calibration constant is:

$$C = \frac{\int_0^{x_L} dx S(x, E_o)}{gq \int_0^{x_L} dx L(x) S(x, E_o)} \quad (4)$$

By eq. (4) the electron calibration constant can be written explicitly as:

$$C^e = \frac{\int_0^{x_L} dx S(x, E_o)}{gq \int_0^{x_L} dx L(x) S(x, E_o)} \quad (5)$$

where $S(x, E_o)$ here and following describe the electromagnetic shower transition curve.

Note that in this case the crystal response does not depend linearly on the incident energy because of the x dependence of the light response function and other effects like rear leakage.

For cosmic muons crossing a crystal perpendicular to its main axis, the induced signal can be written as:

$$A^T(x_o) = gq t k(E_o) L(x_o) \quad (6)$$

where x_o is the longitudinal coordinate of the closest approach point to the crystal axis, t is the path length inside the crystal and $k(E_o)$ is the ionization loss in BGO.

Applying a normalization factor due to light response we define a new quantity

$$A^\mu = \frac{A^T(x_o)}{L(x_o)} \frac{\int_0^{x_L} dx L(x)}{x_L} \quad (7)$$

that we use to define the C^μ as:

$$C^\mu = \frac{E}{A^\mu} = \frac{x_L}{g \int_0^{x_L} dx L(x)} \quad (8)$$

which no longer depends on x_o , and is equal to the expression obtained for muons crossing a crystal longitudinally, assuming a constant energy loss by ionization. Therefore, this is the quantity to be compared with the expression (5) of the C^e .

Because of the x dependence of $S(x, E_o)$ in the C^e definition, C^μ and C^e are not expected to be equal. The relation between the two constants is:

$$C^e = C^\mu \times f^{e\mu}(E_o) \quad (9)$$

where

$$f^{e\mu}(E_o) = \frac{\int_0^{x_L} dx L(x)}{x_L} \frac{\int_0^{x_L} dx S(x, E_o)}{\int_0^{x_L} dx L(x) S(x, E_o)} \quad (10)$$

2.2) Light uniformity measurements The light response function (see fig. 1) can be parametrized as a polynomial of the form:

$$L(x) = ax^3 + bx^2 + cx + d \quad (11)$$

The values of the parameters are measured [2] for each crystal before its installation in the barrel. Long term changes in their values can be due to radiation damage, while apparent short-term deviations from (11) can be induced by a temperature gradient along the crystal axis.¹

Cosmic muons are the only tool to measure and monitor the stability of the light response function during the experiment life. Muons that cross a crystal perpendicularly to its main axis, allow the study of the crystal response to signals generated at different distances from the photodiode (see eq. (6)), and therefore a fit of $L(x)$ is possible.

¹ The temperature dependence of the light yield is approximately $-1.55\%/C^o$ [3].

3. E.m. calorimeter calibration with high energy cosmic muons

To perform the muon calibration, a tracking device is needed to reconstruct the muon trajectory inside the e.m. calorimeter. This task will be possible in the L3 detector [4] using as muon spectrometer the combined information given by Time Expansion Chambers (internal to the barrel with a radius of $r = 50 \text{ cm}$) and by the large muon chambers, both immersed in a 0.5 T magnetic field. Muon chambers are separated from the barrel by the hadron calorimeter of total thickness ~ 6 interaction lengths.

The main contribution to the uncertainty in the reconstruction of the muon impact point on the BGO crystal surface comes from multiple scattering in the hadronic calorimeter. For a path length of $\sim 130 \text{ cm}$ inside the hadron detector, the error due to multiple scattering is:

$$\sigma \simeq \frac{10}{p} \text{ cm.}$$

where p is the muon momentum in GeV/c . Therefore a cut on p at the level of 10 GeV will reduce the uncertainty in the muon position at the surface of the barrel to $\leq 1 \text{ cm}$.

To evaluate the expected event rate we use Dar's parametrization [5] of the cosmic muon flux (fig. 2). Taking into account the shield effect of the rocks surrounding the experimental hall and applying the zenith angle cut, $|\theta_z| \leq 45^\circ$, to ensure the complete containment of the track into the muon spectrometer, the expected muon flux with momentum larger than $10 \text{ GeV}/c$ is:

$$\frac{d^2 n_\mu}{ds dt} = 0.5 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$$

Since the active area of the e.m. calorimeter, as seen by muons, is $\sim 2 \times 10^4 \text{ cm}^2$, the rate for the whole detector is:

$$\Phi_\mu \simeq 10 \text{ sec}^{-1}$$

On the average a muon crosses 20 crystals and therefore the expected rate per day per crystal is:

$$N = 1400 \mu/\text{crystal} \times \text{day}$$

To minimize the uncertainty on the reconstructed track length, some constraint on events topology can be applied. Two classes of crystal crossing can be identified: a track crossing two opposite

lateral faces (or "face to face" crossing) and tracks crossing two contiguous lateral faces. With the face-to-face crossing, the track length depends mainly upon x_o , defined above, and two angles (see fig. 3a). For crossing of two contiguous faces, however, a precise determination of the entry and exit point coordinates is needed.

The accuracy of the geometrical reconstruction is intrinsically limited by multiple scattering effect, so that in the second case the track length determination depends critically on the accuracy of p_{in} , p_{out} as it is illustrated in fig. 3b.

With the face-to-face constraint the track length can be reconstructed with a precision of $\sim 3\%$, but the accepted event rate is reduced to the level of:

$$N_h \simeq 500 \mu/day \times crystal$$

for horizontal crystals, and

$$N_v \simeq 200 \mu/day \times crystal$$

for the vertical ones.

The main source of fluctuations in the measured signals are : errors in the track length reconstruction ($\sim 3\%$), Landau fluctuations ($\sim 8\%$), electronic noise in the read-out chain ($\sim 6\%$) and the intrinsic BGO resolution ($\sim 3\%$). Combining these values one gets

$$\frac{\sigma_E}{E} \simeq 11\%$$

A calibration at the 1% level is then possible with 100 events corresponding to a data-taking time of less than one day, while one week is sufficient to reach the 0.3% level accuracy needed to match the detector performance [3].

4. Test experiment with a prototype BGO matrix

4.1) Experimental set-up The 10×10 crystal matrix used in this test reproduces a small fraction of the barrel. The tapered crystals are 24 cm long with a cross section $\sim 2 \times 2 \text{ cm}^2$ at the front and $\sim 3 \times 3 \text{ cm}^2$ at the rear face. The rear side is equipped with two photodiodes of 1.5 cm^2 active surface each. A detailed description of the read-out electronics and data acquisition system can be found in [1].

To reconstruct the track of incoming muons, a streamer tube telescope was assembled (see fig. 4). Two pairs of orthogonal planes measure the (x, y) position of the incoming muon. The distance between the two pairs is 1 m and the lower pair is 1.2 m from the top of the matrix.

Each plane contains 128 tubes, 1.5 m long, with a $1 \times 1 \text{ cm}^2$ square section. The active surface of each pair is $128 \times 128 \text{ cm}^2$. Below the matrix, a 40 cm-thick iron absorber selects muons with momentum above 0.6 GeV/c. A triple coincidence from a $50 \times 50 \text{ cm}^2$ plastic scintillator triggers the data acquisition system.

A third pair of smaller streamer chambers, $45 \times 45 \text{ cm}^2$, was installed under the iron absorber to measure the multiple scattering produced by BGO and iron.

Streamer tubes were read digitally. This set-up ensures a 1 cm resolution on the muon position at the surface of the matrix which corresponds to about the expected accuracy at the barrel surface in the L3 detector.

4.2 Data taking and event selection In January 1987 about 3×10^4 muon events were collected in 7 days of effective data taking. The trigger rate was $\sim 430 \mu/\text{hour}$ in agreement with Monte Carlo prediction. The data acquisition rate was reduced by a factor of 2 due to the dead time in the BGO read-out chain. Furthermore, about 2.4×10^5 pedestals per crystal were recorded at 0.3 Hz rate.

A sample of events was selected by requiring a fully efficient track reconstruction in the upper telescope.

A study of pedestal fluctuations showed that, on the average, the r.m.s. of the distribution is $\sigma_n \simeq 60 \mu V$, which is equivalent to $\sim 1.5 \text{ MeV}$. The minimum expected signal amplitude for muon crossing is of the order of $\sim 800 \mu V$. Then a crystal was defined as 'fired' if the signal amplitude was greater than $3\sigma_n$.

An algorithm to identify the face-to-face crossing was developed by examining event by event the pattern of fired crystal in the matrix, as shown in fig. 5. A face-to-face crossing occurs in the n -th crystal of the i -th row, $c_{i,n}$, when the two adjacent crystals of the same row are off, and at least one of the remaining adjacent crystals is fired.

With this algorithm 90% of the events are found to be "face-to-face", as expected from Monte Carlo simulation.

5. Results

5.1 Data analysis The muon track fit provides a measurement of x_o and of the angles α and β . Using those quantities, the muon path length in a crystal is:

$$t = h(x_o) \sqrt{1 + \tan^2 \alpha + \tan^2 \beta}$$

where $h(x_o)$ is the crystal thickness at x_o .

Signals were converted according to expression (7) using the parametrization of $L(x)$ available from cosmic ray measurement [2].

The quantity

$$T^\mu = \left\langle \frac{t}{A^\mu} \right\rangle (cm/mV) \quad (12)$$

proportional to the calibration constant, were evaluated for each crystal and each track.

5.2 Muon calibration constants Fig. 6 shows the T^μ distribution of a crystal; the mean value is $\simeq 3 cm/mV$ with a dispersion of the order of 25%. About 200 events per crystal were collected and the error on the mean value is expected to be at the 2.5% level. Fig. 7 shows the distribution of the error on T^μ for the selected crystal sample; the bulk of the entries are centered around 2%; the highest values are due to the inefficiency of the face-to-face procedure when fired crystal is adjacent to dead crystal.

The r.m.s. of the T^μ distribution measured in this test experiment can be explained taking into account the following contributions:

Landau fluctuation: Landau fluctuation can be evaluated from the knowledge of the muon spectrum and the $k(E_o)$ dependence on energy. For this purpose the range of the energy spectrum extends from 700 MeV to 50 GeV, and the contribution above 50 GeV can be neglected, being less than 1% of the total flux. The mean value of $k(E_o)$ has been evaluated by convoluting the muon spectrum $\Phi(E_o)$ with the reduced form of the Landau distribution [6]:

$$\overline{k(E_o)} \Big|_{E_{cut}} = \frac{\int_0^\infty dE_o \Phi(E_o) \int_{\zeta_{min}}^{\zeta_{max}} d\zeta L_R(E_o, \zeta, E_{cut}) \zeta}{\int_0^\infty dE_o \Phi(E_o)} \quad (13)$$

where L_R is the probability density for a muon of energy E_o to lose an energy ζ (MeV/cm) in the range $\zeta_{min} < \zeta < \zeta_{max}$. The parameter E_{cut} set an upper limit to the maximum energy transferred by a muon in a single atomic collision.

With $E_{cut} \simeq 6 \text{ MeV}$ we get:

$$\bar{k} \simeq 10 \text{ MeV/cm}$$

but it must be noticed that it is sensitive ¹ to the value of E_{cut} , which cannot be estimated with great accuracy. The convolution of the reduced Landau distribution with the cosmic muon spectrum evaluated at $E_{cut} = 6 \text{ MeV}$ is shown in fig. 8. The r.m.s. width of the distribution depends only weakly on E_{cut} and is:

$$\frac{\sigma_{\bar{k}}}{\bar{k}} \simeq 18\%$$

Track length: The expected accuracy in the track length measurement has been studied through a Monte Carlo simulation, looking, for each fired crystal, at the quantity:

$$\Delta t = t_r - t_t$$

where t_r indicates the track length deduced from the telescope information and t_t is the true path length. In fig. 9 the resulting distribution for a face-to-face selected sample is compared with that obtained without cuts. Taking the r.m.s. value of the Δt distribution as an estimation of the error on t_r , we get for this experiment:

$$\frac{\delta t_r}{t_r} \simeq 7.3\%$$

while without the face-to-face selection

$$\frac{\delta t_r}{t_r} \simeq 8.2\%$$

This difference is rather small because of the particular geometry of the set-up that favours face-to-face topologies.

Without multiple scattering the spread of the Δt distribution is due only to the intrinsic resolution of the telescope: the resulting value of $\frac{\delta t_r}{t_r}$ is about 2%, which proves the dominance of multiple scattering in the error on the estimation of t_r . Taking into account the survey uncertainties of the telescope and matrix position, we get

$$\frac{\sigma_t}{t} \sim 10\%$$

¹ A change of 1 Mev in E_{cut} induces a variation of $\sim 0.1 \text{ MeV/cm}$ in the determination of $\bar{k}$.

Electronic noise: This contribution is expressed by the r.m.s. of the pedestal distribution, σ_n , so that:

$$\frac{\sigma_n}{A} \simeq 6\%$$

Crystal intrinsic resolution: It depends on the fluctuation in the number of photons emitted by the ionizing particle; the resolution of BGO at low energies was measured in the laboratory and is [7]:

$$\frac{\sigma_{int}}{E} \simeq \frac{0.3\%}{\sqrt{E(\text{GeV})}}$$

assuming that the mean energy deposited by a muon is $\simeq 25 \text{ MeV}$ we get

$$\frac{\sigma_A}{A} \simeq \frac{0.3\%}{\sqrt{0.025}} \simeq 2\%$$

Temperature : BGO is an intrinsic scintillator whose characteristics strongly depend on temperature. Around 20°C , the variation of the light yield with temperature is, on the average, $-1.55\%/^\circ\text{C}$. During the data-taking period the temperature was monitored, and its long term variation was kept below $\delta T \simeq 2^\circ\text{C}$. This induces an error on the calibration constants of:

$$\frac{\sigma_{temp}}{C^\mu} \simeq 3\%$$

Light response function: The correction for the non uniformity of the light response function is at the level of 2% and therefore the resulting error is smaller than 1%.

Combining all these contributions the expected r.m.s. of the T^μ distribution is

$$\frac{\sigma_{T^\mu}}{T^\mu} \sim 22\%$$

compatible with the measured value.

To compare the T^μ with the C^e , the conversion factor (10) was evaluated, at the electron energy of 10 GeV, parametrizing the longitudinal development of an e.m. shower as [8]:

$$S(x, E_o) = \alpha \left(\frac{x}{X_0}\right)^\beta e^{-\gamma \frac{x}{X_0}}$$

where the radiation length in BGO is $X_0 = 1.12 \text{ cm}$ and

$$\alpha = -46.9 + 16.2 \ln(E_o)$$

$$\beta = -2.56 + 0.571 \ln(E_o)$$

$$\gamma = 0.183 + 0.027 \ln(E_o)$$

with E_o in MeV.

A comparison between T^μ and the C^e measured by our collaboration [3] at an electron energy of 10 GeV is reported in fig. 10, which shows a strong correlation between the two sets of constants. The best linear fit to the data is of the form:

$$C^e = \bar{k} f^{e\mu} T^\mu \quad (14)$$

where $\bar{k} = 9.5 \text{ MeV/cm}$ can be interpreted as the mean value of the muon energy loss in BGO. A dedicated experiment [9] to measure L_R and $\bar{k}$ was performed by our collaboration, obtaining a result in perfect agreement with the theory giving a confirmation to the interpretation of the $\bar{k}$ parameter.

The normalized distribution of the difference between $\bar{k} f^{e\mu} T^\mu$ and C^e :

$$\delta_c = \frac{\bar{k} f^{e\mu} T^\mu - C^e}{C^e}$$

is shown in fig. 11; the r.m.s. is about 2.2%, in good agreement with the statistical error of the T^μ determination.

6. Conclusion

Low energy (20-30 MeV) calibration constants were measured at the 2% precision level by collecting about 200 muons per crystal in 7 days of data taking; an algorithm to minimize the uncertainty on the track length determination was developed and tested, which proved the feasibility of the cosmic muon calibration of the L3 e.m. calorimeter.

Since with this measurement we proved that the track length inside the crystal can be determined with the necessary accuracy, we conclude that this method can be used to measure the light response of each crystal and its variation along the major axis by light collection or light transmission or else light yield variation with temperature.

In the L3 apparatus the cosmic ray data, if supplemented with the muon momentum measurement, will provide a set of absolute calibration constants in the energy range of 20 MeV

by eq. (9). In addition, cosmic ray data taken during the electron beam calibration without the knowledge of the muon momentum, will give a set of intercalibration values through the ratios of the T^μ constants.

The stability of these ratios will insure the stability, with the same proportionality, of the electron calibration values. The absolute scale can be fixed, once the calorimeter is installed, by $e^+ e^-$ physical processes.

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Fig. 1.

Fig. 2.

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Fig. 7

Fig. 8.

Fig. 10

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