**EXPERIMENTAL RESULTS OBTAINED FROM A LOW-Z,
FINE-GRAINED ELECTROMAGNETIC CALORIMETER**

(CHARM II Collaboration)

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ABSTRACT

We report on experimental results obtained with the neutrino target calorimeter of the CHARM II detector. The experiment is being performed at CERN and its aim is to measure $\sin^2 \theta_w$, the electroweak mixing parameter, via the study of neutrino-electron scattering. The detector, installed on the SPS neutrino wide-band beam line, consists of a glass calorimeter instrumented with plastic streamer tubes and scintillation counters, and of a muon spectrometer.

The performance of the calorimeter has been explored during a test run with electron and pion beams. Results concerning the detector response, the energy and angular resolution, and the e/π separation are presented here.

1. INTRODUCTION

The principal aim of the CHARM II experiment [1], which is described in detail elsewhere [2], is the precision measurement of $\sin^2 \theta_w$ with an error $\Delta \sin^2 \theta_w = 0.005$. This can be accomplished by the measurement of the ratio of the cross-sections of neutrino and antineutrino scattering on electrons:

$$R = \sigma(\nu_\mu e \rightarrow \nu_\mu e) / \sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = f(\sin^2 \theta_w). \quad (1)$$

This experiment will not suffer from theoretical uncertainties, the processes involved being purely leptonic. However, in contrast to this appealing feature, there is the experimental problem of extracting the signal of the muon-neutrino-electron neutral-current (NC) interactions out of an overwhelming background of neutrino-hadron interactions:

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) / \sigma(\nu_\mu N \rightarrow X) \approx 10^{-4}. \quad (2)$$

Because of the low value of the neutrino-electron scattering cross-section, the previous world statistics amounts to some 200 events. The precision aimed at in this experiment implies the collection of about 2000 events in each of the channels ($\nu_\mu e$ and $\bar{\nu}_\mu e$) together with a 2% precision in the measurement of the relative energy weighted flux of neutrinos to antineutrinos.

After the rejection of neutrino-hadron interactions, the procedure used to reject semileptonic neutrino reactions is based on the kinematics of the neutrino-electron scattering. The invariant $E\Theta^2$, where E is the energy and Θ the angle of the recoiling electron, is limited to the range of two electron masses:

$$E\Theta^2 < 2m_e. \quad (3)$$

This permits the rejection of most of the background due to ν_e -nucleon quasielastic scattering and coherent π^0 production by $\nu_\mu(\bar{\nu}_\mu)$ NC interactions on nuclei [1], which extend to much higher values of $E\Theta^2$.

In the following sections we shall present the detector design and its performance as obtained in test beam runs.

2. THE STRUCTURE OF THE CALORIMETER

The past experience of the CHARM Collaboration [3] in the study of neutrino-induced charged-current (CC) and NC interactions has motivated the use of a fine-grained, low- Z and high-mass neutrino target calorimeter, which acts as the neutrino target and the detector of the reaction products.

The signal we are looking for is an electromagnetic (e.m.) shower with $E\Theta^2 < 2m_e$, indicating the occurrence of the $\nu_\mu e$ scattering. It has to be discriminated against NC processes on nuclei producing hadronic showers, and CC processes on nuclei producing a hadronic shower plus a muon track. The most serious background is due to coherent π^0 production and ν_e quasielastic scattering producing an e.m. shower only.

The large target mass of the calorimeter (692 t) is required in order to have a reasonable interaction rate. Glass was chosen as the absorber material because of its low- Z number (≈ 11). Indeed, the limiting accuracy on the shower angle measurement (the direction of the scattered electron) is proportional to Z :

$$\sigma(\Theta) \propto Z/\sqrt{E}. \quad (4)$$

The above relation leads to the value of $\simeq 18 \text{ mrad}/\sqrt{E(\text{GeV})}$ as the lowest achievable resolution with the CHARM II calorimeter.

The shower angle is determined experimentally by the vertex position and by measurement of the shower profile. The main limitations for these measurements come from the sampling frequency, the target plate thickness, and the width of the detector elements used to sample the lateral shower profile.

The above considerations led us to adopt the following detector structure. The calorimeter is made of 420 modules of $3.7 \times 3.7 \text{ m}^2$ active area, grouped into 21 racks. Each module consists of a glass plate (48 mm thick, 0.5 radiation length) followed by a plane of 352 plastic streamer tubes, with $\simeq 1 \text{ cm}$ spacing. The high voltage is applied to the resistive graphite layer of the tubes. Outside the plastic envelope of the tubes, a plane of 176 pick-up strips (18 mm width and 3 mm pitch) is glued orthogonally to the wires; the pulse height on the strips is used to determine the coordinate orthogonal to the wire. Consecutive modules have wire (and strip) directions rotated by 90° (see Fig. 1). Other details regarding the construction and performance of the streamer tube can be found in Ref. [4].

A set of five modules is followed by a plane of 3 cm thick scintillators with a smaller sensitive area ($3 \times 3 \text{ m}^2$). The main purpose of the scintillator system is the separation and the relative normalization of the two kinds of e.m. backgrounds by measuring the fractions of events initiated by a single electron ($\nu_e N \rightarrow e^- N$) or by two photons ($\nu_\mu A \rightarrow \pi^0 \nu_\mu A$).

The calorimeter has a total length of 35.7 m; the number of streamer tubes is 154560, the number of strips is 73920, and there are 1540 scintillators (Fig. 2).

3. THE STREAMER TUBE SYSTEM

The large number of detector planes and the requirement of fine granularity has motivated the use of plastic streamer tubes as the active component. The large amount of charge collected on the wire and on the pick-up strips allows for relatively inexpensive front-end electronics. The tubes operate at a voltage of 4.3 kV, with a plateau length of 400 V, in a gas mixture of 73% isobutane in argon with 0.5% of water vapour.

The HV applied on the graphite layer permits the direct readout of the wire signal without decoupling capacitors. Two tube planes (i.e. 704 wires) are connected to one single HV channel. The average current load is about $1.5 \mu\text{A}$ per channel under normal working conditions. Up to now, after more than two years of continuous operation, only $\simeq 100$ wires out of $\simeq 155000$ exhibited an abnormal current value ($> 50 \mu\text{A}$). These so-called ‘hot wires’ were disconnected from the HV so as not to introduce noise at the trigger level.

The front-end digital electronics for the wire signals is modular for each tube plane (Fig. 3). Thirty-two wires are served by one shaper card; this is repeated eleven times on a plane. A memory card stores the wire pattern, serially shifted upon occurrence of a trigger.

The strips have analog readout — since one of their tasks is the measurement of the total induced charge — proportional to the shower energy. In order to limit the number of electronic channels (ADCs), eight strips spaced $\simeq 46 \text{ cm}$ in a plane are connected together to a single analog channel. This permits the number of analog channels to be reduced to 9240, without introducing any inefficiency, since 95% of the shower energy is contained laterally in $\pm 10 \text{ cm}$. A block scheme of the front-end analog electronics is shown in Fig. 3.

The different trigger signals of the experiment are constructed from the digital information of the streamer tubes. A detailed description of the trigger system can be found in Ref. [2].

4. GENERAL FEATURES OF ELECTROMAGNETIC SHOWERS

Whilst the CC events can be identified at the trigger level, the dominant (hadronic) NC background is heavily affecting the $\nu_\mu e$ signal. The separation has therefore to be done off-line and is accomplished by means of computer algorithms which distinguish between hadronic and e.m. showers on the basis of the event topology. Moreover, the actual angular and energy resolutions for e.m. showers have to be determined to evaluate the smearing of the signal peak in the $E\Theta^2$ histogram.

Mainly for these reasons, we performed a test run with pion and electron beams with momenta from 3 to 40 GeV/c, where the bulk of our data is expected to be.

Figure 4 shows a plot of the shower development in both the longitudinal and the transverse direction for 15 GeV electrons, as seen by the streamer-tube hit pattern. In Fig. 5, a similar plot shows the ‘energy flow’ of the shower, obtained by measuring the charge collected on the pick-up strips. If one looks at the projection of the shower onto the longitudinal axis (Fig. 6) as a function of the energy of the incident electrons, one can parametrize the energy dependence of the shower maximum and length with the following relations (Fig. 7):

$$\begin{aligned} \text{Shower length (in units of } X_0) &= 1.95 \times \ln E(\text{GeV}) + 8.15 \\ &(\text{containing } 95\% \text{ of the energy}) \end{aligned}$$

$$\text{Position of the shower maximum (in units of } X_0) = 1.25 \times \ln E(\text{GeV}) + 2.9 .$$

5. ENERGY RESPONSE AND CALIBRATION

We have performed the calibration of the energy response of the calorimeter to electrons and pions using estimators based on different detector elements. The main tool for the energy measurement is the analog response of the individual pick-up strips. The charges collected by these strips, in the shower region as defined by the tube hits, are summed. A correction is applied, to take into account the spread in the response of the different analog channels.

The mean value A of the energy response (i.e. the total charge) and the r.m.s. deviation R_A of the distribution at each beam energy were computed from a Gaussian fit to the data. The mean values of the energy dependence of the strip response to electrons can be parametrized as:

$$A = 40.5 \times E^{0.95} . \quad (5)$$

In Fig. 8 the quantity A is plotted as a function of E_{beam} and fitted with expression (5). One can see the almost linear behaviour of the strip response versus the energy. The resolution obtained with the strips is presented in Fig. 9, where R_A is plotted as a function of the energy, together with the parametrization:

$$R_A = 3.0\% + 27.5\%/\sqrt{E} . \quad (6)$$

Another estimator of the shower energy is the total number of streamer-tube hits H . This calibration involved recording the average number of hits at each beam energy, as well as the r.m.s. spread of the distributions. The streamer-tube hit response saturates at quite low energy, in particular for e.m. showers. This effect can be seen in Fig. 10, showing the energy dependence of H/E_{beam} , the number of hits per GeV for electrons. The experimental points are fitted with the following formula:

$$H = 52.2 \times E^{0.59} - 34.4 . \quad (7)$$

The energy resolution R_H for the tube hits is parametrized as follows:

$$R_H = 12.4\% + 6.1\%/\sqrt{E} - 0.058\% \times E. \quad (8)$$

The energy response and the calibration have also been determined for pions. The results are summarized by the following relations:

$$A(\text{pions}) = 32.3 \times E - 48.3, \quad (9)$$

$$R_A(\text{pions}) = 7\% + 40\%/\sqrt{E}, \quad (10)$$

$$H(\text{pions}) = 36.9 \times E^{0.78} - 39.7, \quad (11)$$

$$R_H(\text{pions}) = 8.4\% + 23.3\%/\sqrt{E}. \quad (12)$$

In Fig. 11 the ratio e/π of the response of the strip system, as determined by relations (5) and (9), is plotted against the beam energy.

6. ELECTRON-PION SEPARATION

The target material (glass) has a nuclear absorption length Λ of about four radiation lengths, leading to about equal length of e.m. and hadronic showers. Figure 12 shows, on a logarithmic scale, the longitudinal behaviour of showers induced by 40 GeV electrons and pions. A separation of e.m. and hadronic showers on the basis of their length is therefore difficult.

However, these two kinds of showers differ appreciably in track density and in the width of their lateral profile. In hadronic interactions, the transverse momentum of secondary particles produces showers characterized by low track density and wide lateral spread. On the contrary, e.m. showers, developing predominantly through bremsstrahlung and pair production, are more concentrated around the shower axis. Their transverse dimensions are such that 95% of the total energy is contained in a cylinder with a radius of two Molière units. Therefore, methods for discriminating between e.m. and hadronic showers have to be based on this peculiar difference between their lateral profiles. Figure 13 illustrates the above considerations, showing the hit pattern for two (typical) events induced by an electron and a pion of 15 GeV.

As an example of the algorithms used to perform the e/π separation, we mention here a method based on the difference in the lateral width of the showers. For this purpose, in both projections a 'road' of 4 cm half width along the shower axis is defined. For the digital system, the fraction of hits within the road is computed. The number of planes considered (in each projection) is a function of the shower energy (length). The same algorithm is applied to the charge collected on the pick-up strips. The distributions of these fractions are shown in Fig. 14 for equivalent samples of 15 GeV electrons and pions. By choosing appropriate cuts, one can achieve an efficiency for selecting electrons of 99% and 95% for the digital and the analog separator, respectively, the hadron contamination being 1% and 5%.

We have developed another powerful separator, based on the method of the Minimal Spanning Tree. It is discussed in detail in a different paper, submitted to this Seminar [5].

7. ANGULAR RESOLUTION

As stated above, a good angular resolution is essential for separating the signal of $\nu_\mu e$ scattering from the e.m. background, for which a wider range in $E\Theta^2$ is allowed. For this purpose, several algorithms have been developed to determine the interaction vertex and the direction of the shower induced by the recoiling electron.

The results presented here are based on the definition of the shower axis, in each projection, as the line which divides the shower energy equally. This method needs as an input the longitudinal and the lateral vertex position of the shower in both projections. In one projection this vertex is found with the help of the digital information, whilst in the other projection it is found using the information coming from the analog strips.

The shower axis is determined separately with the digital and analog information of the streamer tubes, and the results are then combined in an optimized way. Using the result of both projections, one can calculate the space angle:

$$\Theta = \sqrt{(\Theta_y^2 + \Theta_z^2)} . \quad (13)$$

With this method we achieve a preliminary angular resolution of $\simeq 20 \text{ mrad}/\sqrt{E}$ (Fig. 15), neglecting the $\simeq 2 \text{ mrad}$ beam divergence. In Fig. 16 we see how such a resolution smears the zero-angle calibration electrons of 15 GeV in the $E\Theta^2$ histogram.

8. CONCLUSIONS

The performance of the CHARM II calorimeter has been explored by means of a test beam run with electrons and pions from 3 to 40 GeV/c. The first experimental results presented here refer to a preliminary analysis of that run. They concern the general features of e.m. and hadronic showers in the calorimeter and, more specifically, the energy response, the energy resolution, the e/π separation efficiency, and the angular resolution. All these quantities have to be well known in order to extract the signal of $\nu_\mu e$ scattering out of the different kinds of background.

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Figure captions

- Fig. 1 Details of five consecutive calorimeter modules.
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THE LAST 5 MODULES OF ONE RACK

CALORIMETER MODULES

Fig. 1

CHARM II - DETECTOR

Fig. 2

DIGITAL ELECTRONICS

FRONT-END ELECTRONICS

PLANE READ-OUT (EACH SHAPER CARD READS 32 WIRES)

ANALOGUE ELECTRONICS

Fig. 3

Shower development (Tube hits)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

15 GeV electrons and pions

Fig. 14

Fig. 15

Fig. 16