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**INFLUENCE OF THE ELECTRIC FIELD ON COMPENSATION
IN A URANIUM/TETRAMETHYLPENTANE HADRONIC CALORIMETER**

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ABSTRACT

A uranium tetramethylpentane hadronic calorimeter has been tested using electrons and pions of 7 GeV/c momentum with electric fields varying from 0.8 to 16.0 kV/cm; the e/π charge collection ratio has been measured as a function of the electric field within this range. It is observed that the e/π ratio can be tuned acting on the electric field without spoiling the energy resolution for electrons. At the same time the energy resolution for pions is improved. The effect was cross-checked using a second module and 40 GeV/c electron and pion beams.

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1. INTRODUCTION

The major improvement of the UA1 detector intended for the Antiproton Collector (ACOL) was the replacement of the old lead/scintillator calorimeters by other units consisting of depleted uranium plates as absorber and ionization chambers filled with a room-temperature non-polar liquid: 2-2-4-4 tetramethylpentane (TMP) as active medium [1].

General details about the upgraded forward calorimetry for UA1 have already been published [2]. In the present paper we report on the results obtained when exposing a very forward (VFW) module to a beam coming from the CERN Proton Synchrotron. Electrons and pions of 7 GeV/c momentum were used and the electric field in TMP was varied between 0.8 and 16 kV/cm.

The paper is organized as follows: section 2 contains the technical details concerning the module and the description of the set-up. The performance of the electronics and the study of the uranium noise is given in section 3. Section 4 is devoted to the presentation of the results and some conclusions are drawn in section 5.

2. EXPERIMENTAL

2.1 The module

The module consists of 29 depleted uranium plates, each 10 mm thick, sandwiched between 30 ionization chambers filled with TMP at room temperature. Two end plates of steel, each 22 mm thick, hold together the U/TMP sandwich through four tensioning pieces and straps. Figure 1 is a sketch of the module, which has a thickness of about 3 absorption lengths. Each 10 mm plate makes about 3 radiation lengths.

Tetramethylpentane is contained in chambers (fig. 2) made of stainless steel. The skins, each 0.15 mm thick, are welded on a frame of cross-section $3 \times 3 \text{ mm}^2$. The electrodes are 0.5 mm thick and are held in the middle of the chamber by ceramic spacers so that there is a liquid gap of 1.25 mm on either side of the electrode. Eight electrodes are placed in each chamber and the high voltage and signal connection to the outside is made via one feedthrough per electrode. The dimensions of each chamber are $551 \times 324 \text{ mm}^2$. A central bar, with holes, divides the chamber in two halves and provides additional rigidity. All welds are done with YAG lasers. The chambers are filled with TMP via two tubes of 2.2 mm external diameter.

The module contains a total of 240 electrodes. It is subdivided laterally into 8 towers of 30 electrodes each. A tower is then divided in depth in 6 samplings consisting of 5 electrodes each. Every sampling, a channel, is read out by one amplifier connected to the 5 electrodes by separated blocking capacitors. The complete readout consists thus of a total of 48 channels from the eight towers.

2.2 The beam layout

The beam layout is shown in fig. 3; S0, S1 and S2 are beam-defining scintillation counters and V is a scintillator to veto beam halo. The beam position is given by a multiwire proportional chamber (MWPC) allowing an improvement of the spatial resolution. The Cherenkov counters C1 and C2 are used in the trigger to select electrons. M1 and M2 are two scintillation counters used for triggering on muons. The module was placed on a movable platform in order to change its position with respect to the beam in both the horizontal and vertical directions. Placed behind the U/TMP module is an iron/scintillator calorimeter used in the UA1 experiment ('C-module') having 4.5 interaction lengths. It is followed by a 1.6 m long iron block used as a muon filter. The trigger logic for e, π , and μ is also given in fig. 3.

3. ELECTRONICS

The electronics to read out the 48 channels of the VFW module is the same as that used in the rest of the UA1 U/TMP calorimeter [3, 4] except for a modification of the feedback time constant on the integrating amplifiers, with the purpose of reducing pile-up effects, since the detector was going to be installed in the very forward region of the experiment [2]. Owing to this modification the noise level is slightly increased and ranges from $8600 e^-$ at 0 kV/cm to $9900 e^-$ at 16 kV/cm.

The noise increases with the high voltage owing to the natural radioactivity of the uranium plates. This contribution can be measured by the difference between the squares of the width of the pedestals with high voltage on and off. The noise due to uranium increases from $1900 e^-$ at 1.6 kV/cm to $4500 e^-$ at 16 kV/cm as shown in fig. 4; a linear fit

$$\text{ENC(uranium)} = a + b \cdot E \quad (E \text{ in kV/cm})$$

gives a slope to intercept ratio $\alpha = b/a$ of $0.08 \pm 0.01 \text{ cm/kV}$, to be compared with predictions based on the Onsager theory [5], which leads to $\alpha = 0.057 \text{ cm/kV}$ (see below).

The cross-talk between channels was of the order of 1%.

To measure the signal of minimum ionizing particles, the module was exposed to a 7 GeV/c muon beam. The collected charge expected per electrode for a minimum ionizing particle crossing a TMP chamber is, according to the Onsager theory, 0.27 fC at 3.2 kV/cm and 0.36 fC at 13.6 kV/cm. The measured values are $0.29 \pm 0.03 \text{ fC}$ and $0.34 \pm 0.04 \text{ fC}$ respectively. Defining the signal-to-noise ratio S/N as the difference between the most probable value of the collected charge and pedestal distributions, divided by the pedestal half-width for one tower, we get $S/N = 1.4 \pm 0.1$ at 3.2 kV/cm and 2.0 ± 0.1 at 13.6 kV/cm. Figures 5a and b give the signal and noise distributions for 3.2 and 13.6 kV/cm respectively.

4. RESULTS

4.1 The data

A 7 GeV/c electron and pion beam was incident on tower 4 as indicated by letter B in fig. 1. Data were taken at field strengths which varied from 0.8 kV/cm to 16 kV/cm. For each voltage 5000 electron and 10000 pion events were recorded.

In fig. 6 we display the charge collected as a function of electric field, for electrons and pions.

In order to interpret the data, three independent effects must be considered:

- i) How the electric field strength E affects the number of electron-ion pairs that initially escape recombination. This influences the charge collected at the anode.
- ii) The fact that some of the secondary electrons produced in the liquid, which initially escape electron-ion recombination, may later (during their transit across the gap) be converted into negative ions due to attachment to electronegative impurities present in the liquid. Negative ions have a mobility which is several orders of magnitude smaller than that of a free electron; consequently, the contribution to the electronic signal read by the charge-sensitive amplifier (CSA) is lost upon an electron attachment reaction. If the concentration $[A]$ of electronegative impurities of type A is much larger than the concentration of quasi-free electrons n_e , then, at a given time t , n_e can be described as $n_e(t) = n_e(0) \exp(-t/\tau)$, where $\tau = 1/k[A]$ is the electron lifetime, and k is the rate constant characterizing the attachment reaction.
- iii) How the pulse read by the analog-to-digital converter (ADC) depends on the structure in time of the signal collected in the chamber when the electric field is varied.

Concerning the first two effects listed above, under the conditions of uniform ionization (which are certainly appropriate when the module is exposed to e and π beams with momentum in the GeV/c range), the charge read by the CSA can be written [6, 7] as

$$Q(E, \tau) = Q(E) \left\{ (\tau/t_d) [(\tau/t_d)(e^{-t_d/\tau} - 1) + 1] \right\}. \quad (1)$$

In eq. (1) the effect (i) of the electric field strength E on the free ion yield is represented by the field-dependent function $Q(E)$; the effect (ii) of electron loss due to impurities via electron attachment is represented by the term in braces. Waveform analysis of charge collection [6] for incident electrons of 7 GeV/c in three chambers leads to $\tau \sim 8.5 \mu\text{s}$.

Concerning the last of these effects, a correction has to be applied because the amplified and shaped signals depend on two time scales: one of them is set by the charge collection time in the chamber, the other is set by the shaping time of the filtering network. The former time scale is determined by $t_d = d/\mu E$, where $d = 1.25 \text{ mm}$ is the drift gap, $\mu = 30 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is the electron mobility in TMP, and E is the electric field strength; the latter time scale is determined by the time constant $\tau_0 \sim 1 \mu\text{s}$ chosen for the integrator-differentiator circuit used as shaper [4]. At high fields (e.g. $E > 10 \text{ kV/cm}$) $t_d < 380 \text{ ns}$ and the response of the filter to the signal read by the CSA is very nearly independent of E ; hence, no corrections are needed. However, for fields $E < 3 \text{ kV/cm}$ ($t_d > 1 \mu\text{s}$), the charge collection time in the chamber becomes larger than τ_0 . Consequently, the height of the shaped pulse emerging from the filter becomes progressively smaller as the field strength E is decreased, and the number of counts read by the ADC needs to be corrected.

The electronic effect can be calculated in a standard fashion: let $G(t)$ be the Green's function describing the response of the electronic chain to a delta-function current. The current produced in the chamber by ionizing particles is

$$i(t) = \begin{cases} 0 & \text{for } t < 0 \\ [Q(E)/t_d](1 - t/t_d)e^{-t/\tau} & \text{for } 0 < t < t_d \\ 0 & \text{for } t > t_d \end{cases}$$

The response of the electronics to this current pulse is given by

$$R(t) = \int_0^t G(t - t') i(t') dt' . \quad (2)$$

4.2 Electron showers

4.2.1 The Onsager theory

The free electron yield, for minimum ionizing particles, $Q(E)$ can be calculated using the Onsager theory [5],

$$Q(E) = Q_0(1 + \alpha E) , \quad (3a)$$

where Q_0 is the number of secondary electrons escaping recombination at zero field, and α is a constant given by

$$\alpha = e^3 / 8\pi\epsilon\epsilon_0(kT)^2 , \quad (3b)$$

where T is the absolute temperature, ϵ is the dielectric constant (1.98 for TMP), ϵ_0 is the permittivity of vacuum, k is the Boltzmann constant, and e is the electron charge. For TMP at room temperature, $\alpha = 0.057 \text{ cm/kV}$.

4.2.2 Analysis of the data

We have fitted eq. (3a) to the electron data, taking into account the electronic correction given by eq. (2), and derived the free electron charge $Q(E)$ for each value of the electric field strength E . The result is shown in fig. 7a. The fit (full line) gives:

$$Q_0 = 32.2 \pm 0.5 \text{ fC} .$$

The deviation in slope of data points from the theoretical 0.057 cm/kV value may be interpreted as indicating that electron showers cannot be considered as pure convolution of minimum ionizing particles, or that powers of the electric field strength E , of order higher than linear in the expansion [8] of the Onsager theory, should be considered.

Since the goal of this paper is to report the observation of the Q_e/Q_π variation as function of the electric field we leave this discrepancy as an open question for a forthcoming work.

4.3 Pion showers

4.3.1 Introduction

Figure 7b shows the resulting free electron charges from incident pions as a function of the electric field after correction for the electronic response and the finite electron lifetime. The data are not corrected for shower leakage.

The charge collected from pions results from various processes. The pions produce showers containing:

- i) a pure electromagnetic component, mainly through the production of π^0 's and η^0 's whose decay γ 's produce in turn electromagnetic cascades,
- ii) a non-detectable component as ν 's from π and K decays and
- iii) a pure hadronic component.

In the case of uranium absorber, the hadronic component of the cascade partially leads to the production of low-energy spallation and fission neutrons. In TMP (C_9H_{20}), very rich in hydrogen, these neutrons produce slow, highly ionizing, recoil protons.

4.3.2 Mechanisms affecting the charge collection

The field dependence of the collected charge arising from these heavily ionizing particles is expected to be different from that due to minimum ionizing particles. The number of electrons arriving at the anode will depend on the interplay between diffusion, recombination, and the local electric field seen by each electron.

In the case of minimum ionizing particles, when ionization events in the liquid are separated, on the average, by a distance which is large compared with the Onsager escape radius r_c , the local electric field seen by each electron is, to a good approximation, the Coulomb field between the electron and the parent ion, plus the field applied externally. Here, r_c represents the distance at which an isolated electron-ion pair in the liquid has an electrostatic energy, arising from the Coulomb field, equal to the thermal energy kT . It is given by

$$r_c = q^2/4\pi\epsilon_0\epsilon_1 kT \approx 288 \text{ \AA} , \quad \text{at } 20^\circ \text{C} .$$

Under these conditions, the description of the Brownian motion performed by the excess electrons after thermalization, provided by the Onsager theory, seems appropriate. In the limit of zero applied field, the electrons that escape recombination are roughly those that thermalize at a distance larger than the Onsager radius r_c . As the applied field increases, the external field pulls out more electrons from the region of influence of their parent ions, leading to an increase in the escape probability given by eq. (3a). In TMP the expected increase in the charge collected, when the applied field is increased from 2 to 16 kV/cm, is $\sim 70\%$.

On the contrary, in the case of electrons arising from heavily ionizing particles such as the recoil protons, where ionization events are, on the average, separated by a distance small compared with r_c , the local field seen by the secondary electrons is the superposition of the internal field due to the dense positive ion core left along the track and the less dense electron cloud that surrounds it, plus the external field applied between the electrodes. In this context, at zero field the number of electrons

escaping recombination is expected to be small; these are mainly electrons produced at the ends of the ionizing track, or electrons produced by δ -rays along the track. Indeed, current theories of columnar recombination [9, 10] predict a probability of escape which is zero when the applied field is zero. As the external field increases, electrons are pulled out of the ionizing track. The electrons that escape recombination are expected to be mainly those located in a region where the strength of the applied field exceeds that of the internal field, and where these two fields exhibit opposite directions. Such a situation leads to a steeper field dependence of the collected charge upon the applied field. As an example, in TMP irradiated by α particles, when the external field is increased from 2 to 16 kV/cm, the collected charge increases by 220% [11].

4.3.3 Analysis of the data

A phenomenological description of the data can be obtained by using a power law dependence. Following ref. [11], we have written:

$$Q_\pi = A + b E^n \quad (4)$$

where Q_π is expressed in fC and E in kV/cm.

The fit (full line in fig. 7b) agrees well with the data points, with the following parameters:

$$\begin{aligned} A &= 9.1 \pm 3.8 \text{ fC} \\ b &= 12.6 \pm 3.4 \\ n &= 0.46 \pm 0.07 . \end{aligned}$$

4.4 The ratio Q_e/Q_π

A desirable property of calorimeters is that the charge collected from electromagnetic and hadronic showers of identical energy should be the same. This is usually referred to as compensation.

In fig. 8a the ratio Q_e/Q_π is shown as a function of E ; Q_π is the collected charge for pion showers without any leakage correction. The ratio decreases from 1.77 ± 0.07 at 0.8 kV/cm to 1.05 ± 0.04 at 16 kV/cm. Taking into account that the pion leakage in the module (lateral and longitudinal) was of the order of 20% we observe that $Q_e/Q_\pi = 1$ in the region of field strengths between 8 and 10 kV/cm.

Furthermore, the energy resolution, defined as the ratio between the r.m.s. of the charge distribution and its mean value, improves with increasing electric field both for incident electrons and pions (see fig. 8b). The improvement for pions is larger than for electrons.

To cross check the observations reported here, a second VFW U/TMP module was exposed to a beam from the CERN SPS, using electrons and pions of 40 GeV/c; the electric field was varied between 0.6 and 11.2 kV/cm. The beam was incident to the center of Tower 4 (see fig. 1).

The Q_e/Q_π data is displayed in fig. 9a. The difference in absolute values, between the 7 GeV/c and 40 GeV/c data, are due to a higher leakage in the SPS exercise.

The energy resolutions for the 40 GeV/c electrons and pions, shown in fig. 9b, agree with those shown in fig. 8b for the 7 GeV/c beams momenta. Electrons reach a plateau as from 4–6 kV/cm, while pions continue improving until about 8 kV/cm.

5. CONCLUSIONS

In a U/TMP calorimeter, with 10 mm U plates and 2.5 mm TMP gaps, tested at the CERN PS beams, we have observed that the ratio of the collected charge from electron showers to that from pion showers decreases with increasing electric field strength. After allowing for hadronic shower leakage, a ratio $Q_e/Q_\pi \sim 1$ is achieved at a modest electric field of ~ 8 –10 kV/cm. The electric field strength can thus be used to ‘tune’ the compensation.

This effect can be qualitatively understood as being due to a different electric field dependence of the collected charge expected from heavily ionizing recoil protons, when compared with that of minimum ionizing particles.

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Figure captions

- Fig. 1 Sketch of the U/TMP very forward calorimeter module; the 8 towers are indicated.
- Fig. 2 Design of a TMP ionization chamber showing its components: the stainless-steel frame with the intermediate bar (1,7,9), the eight electrodes (3,5), HV feedthroughs (6), TMP filling tubes (8), and the ceramic spacers(2,4).
- Fig. 3 The experimental set-up at the CERN PS.
- Fig. 4 Uranium noise as a function of the electric field.
- Fig. 5 Muon signal (shadowed) and noise distributions: a) for 3.2 kV/cm, b) for 13.6 kV/cm.
- Fig. 6 Collected charge in fC as a function of the electric field for: a) electrons, b) pions.
- Fig. 7 Collected charge in fC, corrected for the response of the electronic chain, as a function of the electric field for: a) electrons and b) pions. c) Applied correction (in %).
- Fig. 8 Q_e/Q_π as a function of E.
- Fig. 9 Electromagnetic and hadronic resolutions as functions of the electric field.

Fig. 1

Fig. 2

TEST BEAM LAYOUT

TRIGGERS

$$\begin{aligned}
 e: & S0 \cdot S1 \cdot S2 \cdot \bar{V} \cdot C1 \cdot C2 \cdot \bar{M1} \\
 \pi: & S0 \cdot S1 \cdot S2 \cdot \bar{V} \cdot C1 \cdot C2 \cdot (M1 \cdot M2) \\
 \mu: & S0 \cdot S1 \cdot S2 \cdot \bar{V} \cdot M1 \cdot M2
 \end{aligned}$$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9