ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-86/63

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Estratto da:
Nucl. Instr. Meth. A247, 438 (1986).

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

Nuclear Instruments and Methods in Physics Research A247 (1986) 438–444
North-Holland, Amsterdam

PERFORMANCE OF A LIMITED STREAMER TUBE HADRON CALORIMETER

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Received 13 November 1985

The energy response and the resolution of a hadron calorimeter test module prepared by the ALEPH collaboration at LEP have been studied between 5 and 50 GeV. The energy resolution for pions follows a $0.78/\sqrt{E}$ law for orthogonally incident particles. Effects of different incident polar angles ($\theta = 90°, 60°, 50°$) are studied. The wire readout and the trigger capability are also discussed.

1. Introduction

The ALEPH hadron calorimeter [1] represents an integrated system for hadron and muon detection at LEP.

The detector consists of a sandwich of iron slabs and plastic streamer tubes [2] with external readout electrodes: pads and longitudinal strips (parallel to the wires). The measurement of shower energy is performed by collecting the charge induced on the pads which is linearly related to the number of sampled tracks and, therefore, to the energy of the primary particle. Longitudinal strips give the spatial pattern of tracks inside the calorimeter.

Hadron calorimeters using plastic streamer tubes [3,4] have shown a good energy resolution, comparable with that obtained with plastic scintillator calorimeters. In addition, the tracking capability gives a good pion/muon separation.

It must be noticed that the relationship between energy and collected charge deviates from linearity at high energies, where saturation effects are initiated when a particle crosses the dead region caused by the streamer due to another nearby track.

At low energies (< 10 GeV) digital readout can be used for calorimetric purposes, by simply counting the fired strips. This method can be largely used at LEP due to the presence of a relevant number of low energy pions.

The large signal/noise ratio of the tower information allows triggering on low energy deposits. Similar and complementary triggers can be built from the digital information (triggers on single muon, muons in jets, etc.).

2. The test module

The test module (figs. 1a and 1b) is made of 23 iron plates (100×100 cm^2), the first 0.5 cm and all the others 5 cm thick, 2.2 cm apart, interleaved with 23 layers of plastic streamer tubes. The total depth is about 6.5 interaction lengths, while the average distributed interaction length is about 29 cm. Each plane is equipped with pads and longitudinal strips (one per wire and 4 mm wide) and contains 96 streamer tubes, each with a 9×9 mm^2 active cell, a separation wall of 1 mm and a 100 μm anode wire.

The streamer tubes used are coverless [5], i.e. have three plastic walls coated with graphite, while the plastic cover is uncoated. When a voltage is applied to the anode wire, positive ions produced by the streamer process drift towards the insulated top side (fig. 2), which is quickly charged. As the charge increases, the

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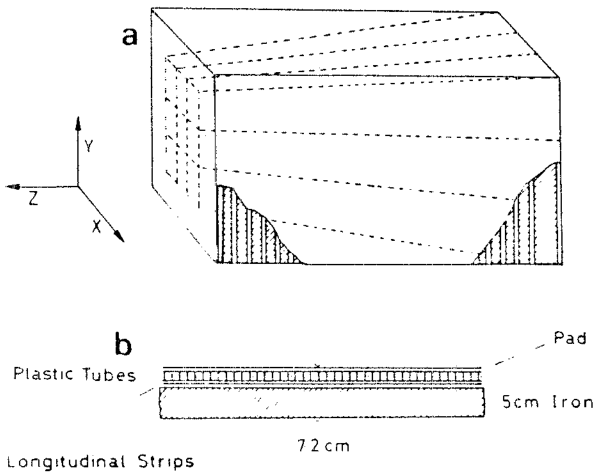

Fig. 1. Geometry of the complete test module (a) and of a sampling layer (b).

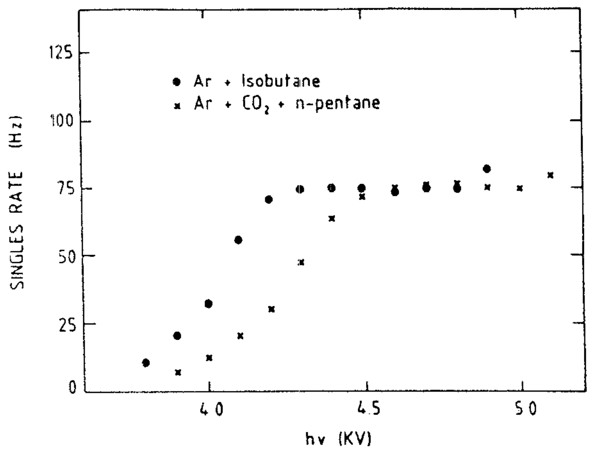

Fig. 3. Single counting rate vs hv.

field lines are reshaped until each of them falls on the graphite cathodes. At this point, no more ions can be deposited on the uncoated surface. The only difference with respect to the standard configuration (i.e. with four graphite-coated walls) is a 150 V shift to higher voltage in the coverless tube plateau curve. The dependence of the streamer charge on the voltage shows the same behaviour. Due to the large amount of ionic charge produced in the streamer process, the charge-up time is negligible. On the other hand, the discharge time of the ionic charge is some hours. Several tests, with and without beam, have shown that the charge-up time is below a few seconds, at least at the ground level. Easy extrapolations show that the system is also completely safe in the underground cave.

Besides the standard gas mixture, Ar + isobutane (25% + 75%), the calorimeter has been operated with Ar + CO_2 + n-pentane (15% + 60% + 25%). The use of n-pentane [6], which is liquid at room temperature, instead of isobutane, is dictated by safety reasons, in order to reduce the quantity of hydrocarbons in the detector. Tests with this gas mixture have shown the possibility to achieve working conditions and performance equivalent to those obtained with Ar + isobutane: the plateau (fig. 3) is wide (> 500 V) showing uncritical and noiseless operation; the charge fluctuations of the single streamer (fig. 4) are, within 20%, equal to those obtained with the standard gas mixture.

The calorimeter was operated with Ar + isobutane at 4.35 kV (single streamer charge ~ 14 pC) and with Ar + CO_2 + n-pentane at 4.5 kV (single streamer charge ~ 18 pC). Both values of hv set the working point at the beginning of the efficiency plateau, since this working condition gives the best energy resolution.

The analog readout was performed by a 3 × 3 matrix of pads drawn on one face of a printed circuit board. The other face, unsegmented, acts as ground electrode. The pads were arranged in projective towers with dimensions increasing from 20×20 cm^2, on the first plane, up to 33×33 cm^2 at the end of the calorimeter. In order to have a longitudinal segmentation, the sum of the first 11 pads in a tower and that of the remaining 12 have been kept separate. Tower signals, after proper attenuation, were digitized by standard ADCs. The pulse

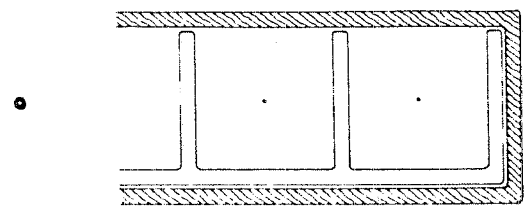

Fig. 2. Basic structure of the coverless streamer tubes together with the field line for the tube element.

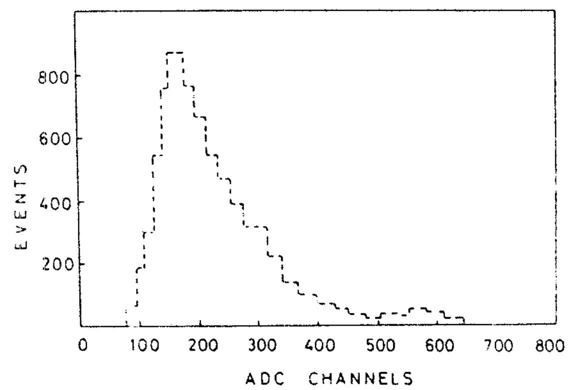

Fig. 4. Streamer charge distribution for isotropic cosmic rays (Ar + CO_2 + n-pentane).

shape on pads (fig. 5a) is determined by their capacitance (about 3.5 nF, for 30 × 30 cm^2 pads), discharging through 50 Ω termination with a 175 ns time constant. The charge collected on towers for a single muon passing orthogonally through the pads was about 0.33 nC (about 60 mV pulse height on 50 Ω).

Pulses on the strips and on the wires have very similar triangular shapes, with 5 ns rise time and 50 ns base width (figs. 5b,c). The strips are connected to a digital readout system (amplifier, discriminator, one-shot chain) with a threshold of about 3 mV on 50 Ω.

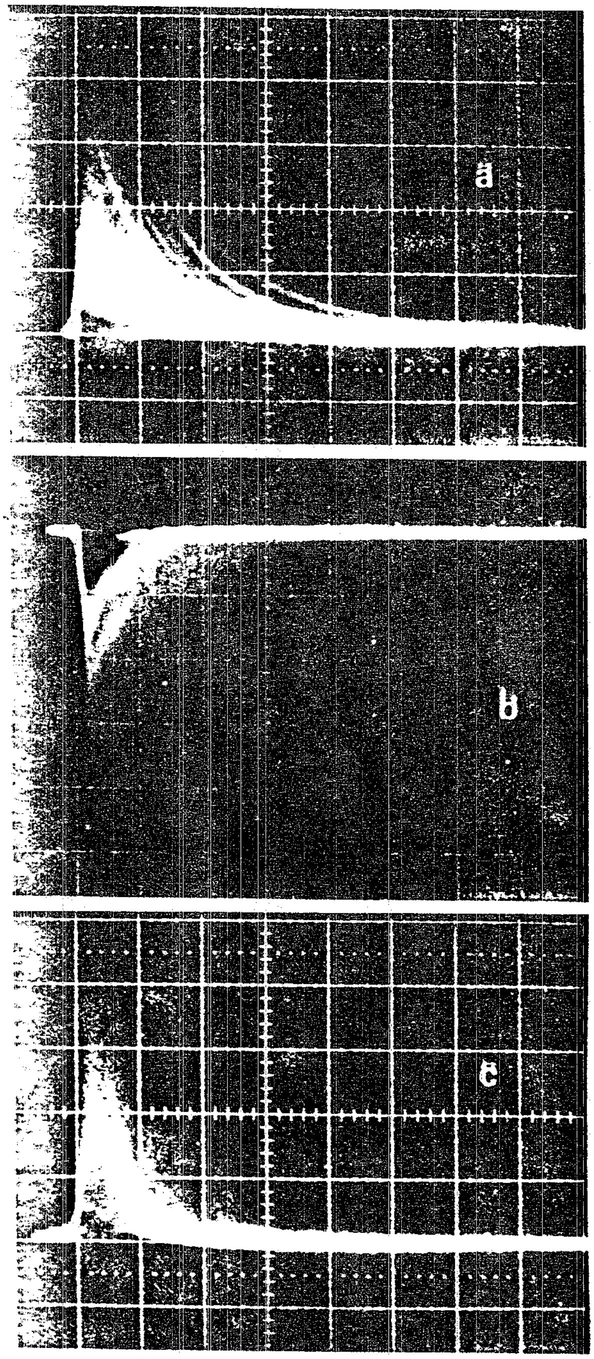

Fig. 5. Typical streamer pulses on a pad (a), on a wire (b) and on a strip (c). (5 mV/div vert., 200 ns/div hor.)

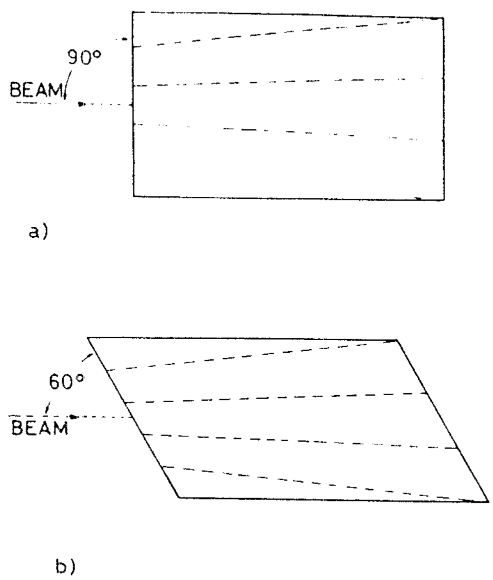

Fig. 6. Calorimeter arrangements. (a) $\theta = 90°$, (b) $\theta = 60°$.

The test module was exposed to the X7 CERN-SPS test beam of pions, muons and electrons of energies ranging from 5 to 50 GeV, at orthogonal incidence. In addition to this, we have rearranged the calorimeter to simulate towers sitting at $\theta = 60°$ (fig. 6) and $\theta = 50°$ in order to study the performance of the projective towers of the ALEPH calorimeter.

3. Analog readout

Signals from the towers, after pedestal subtraction, are summed to define the total charge seen by the calorimeter. Typical muon and pion charge distributions at 20 GeV, for $\theta = 90°$, are shown in fig. 7. In order to evaluate the energy resolution these data have been fitted with a Gaussian distribution cutting out the noise outside the peak.

At $\theta = 90°$, a muon crossing a tower produces an analog signal equivalent to a 2.7 GeV pion with a resolution (standard deviation) of 23% for both gas mixtures. With the assumption that only one streamer per plane * has been produced, a calibration value of about 120 MeV/streamer (i.e. 8.3 streamer/GeV) is obtained. At $\theta = 60°$ (50°), muons produce an analog

* In fact a more precise estimate taking into account delta-ray effects and geometrical inefficiency could give an average of 1.15 streamer/plane.

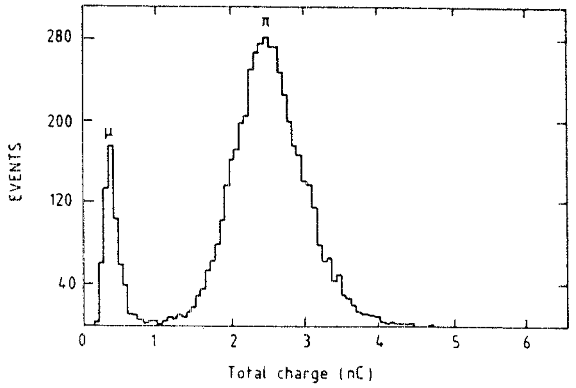

Fig. 7. Charge distribution for 20 GeV pions and muons. ($\theta = 90°$, Ar + isobutane.)

signal equivalent to a 4.1 (5.9) GeV pion with a resolution of 17% (13%). The increase of the signal is due to the fact that the average number of streamers produced in the tubes depends on the crossing angle, more than one streamer (i.e. more charge) being produced for angles different from 90°. A mean value of 1.5 and 2.1 streamer/plane has been observed at $\theta = 60°$ and $\theta = 50°$, respectively.

Calibration curves and energy resolution for pions in the case of Ar + isobutane, for all measured incident polar angles, are shown in fig. 8.

At $\theta = 90°$, the analog response is found to be linear up to 40 GeV, with a nonlinearity of 4% at 50 GeV. In the range 0–40 GeV, a calibration value of (120 ± 1) pC/GeV and a resolution consistent with a parametrization $\sigma/E = (78 \pm 1)\%/\sqrt{E}$ are obtained.

Projective towers at polar angles smaller than 90° show a larger iron thickness to crossing particles, worsening therefore the shower sampling. In addition, at such angles, the number of streamers per plane increases. The results for hadrons give, at low energy, an overall charge increase of about 16% (32%) at $\theta = 60°$ (50°), showing a prevalence of the streamer number increase over the sampling effect, both depending on θ. Moreover, the increase of the number of streamers per track makes saturation effects already evident around 30 GeV for $\theta = 60°$, and around 20 GeV for $\theta = 50°$. The resolution (fig. 8) becomes worse, $(82 \pm 1)\%/\sqrt{E}$ at $\theta = 60°$, consistent, within the errors, with what is expected from coarser sampling.

Calibration curves and energy resolution for pions in the case of Ar + CO_2 + n-pentane, for $\theta = 60°$, are shown in fig. 9. The analog response is similar to that for Ar + isobutane at the same polar angle. In the range 0–20 GeV, a calibration factor of (155 ± 2) pC/GeV is obtained and the resolution can be parametrized as $\sigma/E = (84 \pm 4)\%/\sqrt{E}$.

The resolutions obtained are in good agreement with

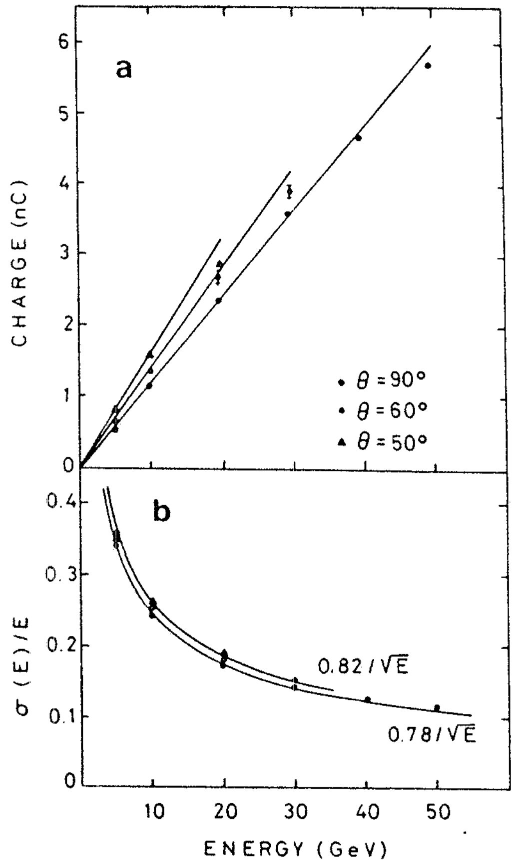

Fig. 8. Charge response (a) and energy resolution (b) for pions. (Ar + isobutane.)

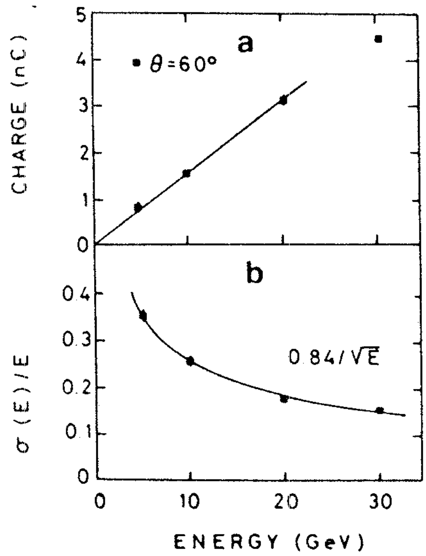

Fig. 9. Charge response (a) and energy resolution (b) for pions. (Ar + CO_2 + n-pentane.)

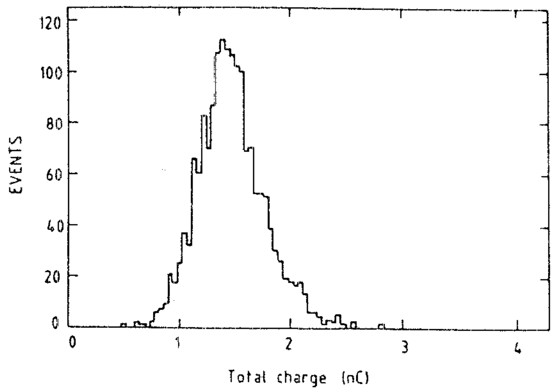

Fig. 10. Charge distribution for 10 GeV electrons. ($\theta = 90°$, Ar + isobutane.)

that of the previous test calorimeter [3,4], built with tubes having all the four walls coated with graphite.

The dependence of the analog response on the impact point was studied. This test was performed at $\theta = 90°$ with Ar + isobutane. The central tower has been scanned by moving the calorimeter across the beam. The total analog signal and the energy resolution do not show any dependence on the x coordinate as expected.

The dependence of the calorimeter response on high voltage variation around the operating value was studied with 20 GeV pions and muons. This test was performed at $\theta = 60°$ with Ar + CO_2 + n-pentane. The variation of the mean charge q versus high voltage was observed to be consistent with

$$\Delta q/q = 12\ \Delta V/V.$$

The calorimeter response for incident electrons was studied at $\theta = 90°$ with Ar + isobutane. A typical electron charge distribution at 10 GeV is shown in fig. 10. The calibration curve and energy resolution are plotted in fig. 11. Electrons show a deviation from linearity above 10 GeV, the density of streamers in electromagnetic showers being higher than in hadronic showers of the same energy. A calibration value of (160 ± 5) pC/GeV is found and in this range (up to 10 GeV) the resolution can be parametrized as $\sigma/E = (55 \pm 1)\%/\sqrt{E}$.

By comparing this figure with the calibration constant for hadrons we obtain a ratio $E_{vis}(e\ )/E_{vis}(\pi) = 1.33 \pm 0.04$, as expected for an iron calorimeter in this energy range [7].

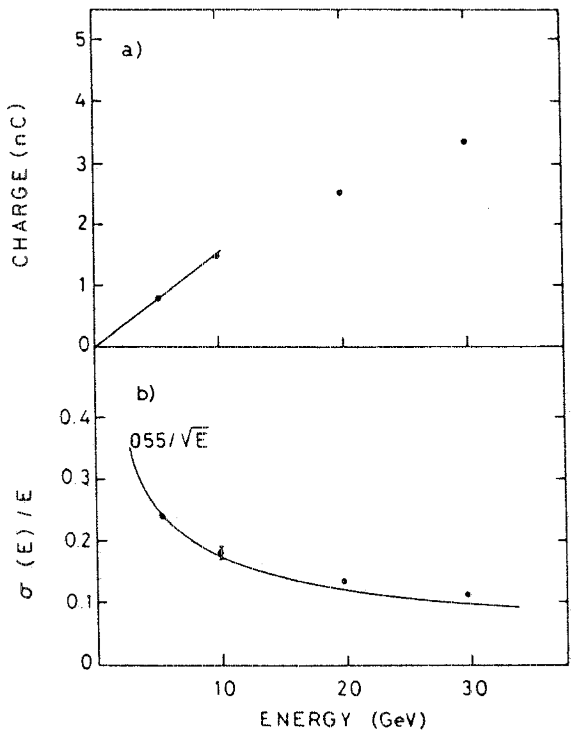

Fig. 11. Charge response (a) and energy resolution (b) for electrons. ($\theta = 90°$, Ar + isobutane.)

4. Digital readout

The strip digital readout of the calorimeter produces the pattern of fired wires inside one event. Typical patterns of a showering pion, of a traversing muon and of an electron are shown in figs. 12a, b and c respectively. These figures show that the calorimeter acts as a tracking device and gives a detailed picture of a muon which can be useful for pion/muon discrimination.

The mean multiplicity (i.e. the number of strips fired per plane) for an orthogonally crossing muon is 1.6 in the planes where at least one wire has fired, while the total number of hits is 32 on average. This multiplicity

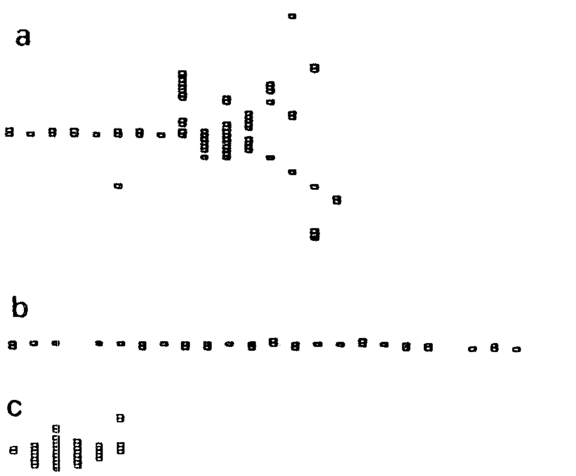

Fig. 12. Typical digital pattern of a 10 GeV pion (a), a muon (b) and an electron (c).

is partially due to purely electronic effects, since a streamer in a tube fired a strip on an adjacent tube in 20% of the cases. In addition, delta-ray production, giving a relatively high number of hits in a single plane, causes the observed mean multiplicity. With muons at 60° (50°) incidence angle, a mean multiplicity of 1.8 (2.0) and a mean number of hits of 36 (40) are obtained. These values are the same for both gas mixtures.

The mean number of hits produced by pions as a function of the energy is given in fig. 13 for different angles in the case of Ar + isobutane. The figure shows a saturation effect in the calorimeter response as the energy increases. This is due to the fact that the probability of two or more shower tracks crossing the same tube increases with the shower track density (i.e. shower energy). The digital response, before saturation occurs, is independent of the gas mixture and it is not affected by the geometrical configuration. However, hit saturation occurs at lower energy for θ smaller than 90° as a consequence of the larger mean multiplicity per plane.

At low energy, a calibration value of (5.5 ± 0.8) hits/GeV is obtained and the measurement of the

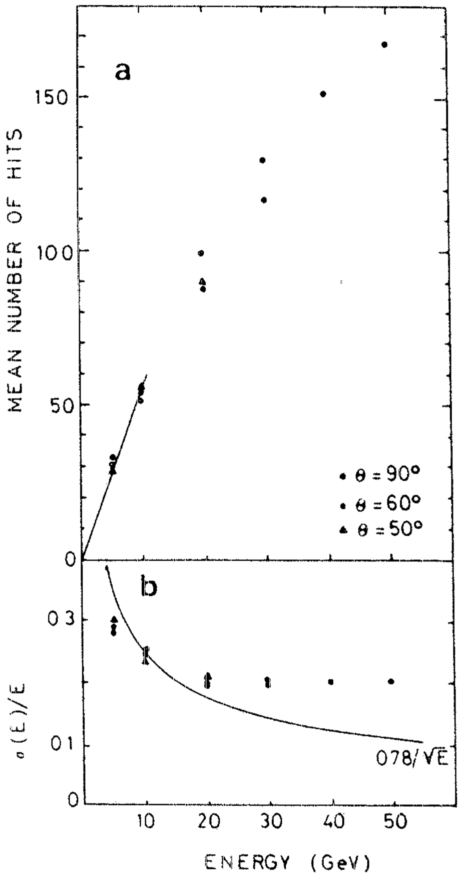

Fig. 13. Digital response (a) and energy resolution (b) for pions. (Ar + isobutane.)

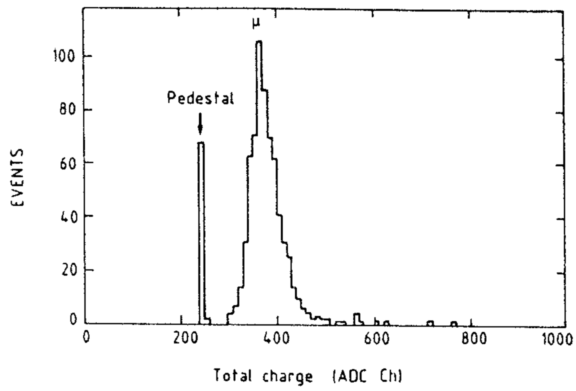

Fig. 14. Charge distribution for muons in a single tower (24 dB attenuation, $\theta = 90°$, Ar + isobutane). The pedestal peak is also shown for reference

shower energy can be performed by hit counting. The resolution obtained is shown in fig. 13. Due to saturation effects the resolution cannot be parametrized as const./$\sqrt{E}$. At low energies the resolution obtained by hit counting ($\sigma/E = 28\%$ at 5 GeV, $\theta = 90°$) is better than that given by the analog response. This can be understood by observing that at low energies the track density is low and gives a negligible probability for more than one track in the same tube. Consequently, simple hit counting gives a good measurement of the shower energy if compared to the analog signal which, below 5 GeV, still reflects the single streamer charge fluctuation. The effect is opposite when the energy increases.

Due to the higher track density in an electromagnetic shower, the digital response to electrons also saturates at low energy (< 5 GeV) so that the hit counting method cannot be used for energy measurement of electromagnetic particles.

5. Trigger capability

Typical tower signals have a rise time of 50 ns and a decay time of 200 ns. Signals from individual streamers come at different times due to a few millimeter difference in the drift distance between the place of the primary ionization and the wire. However, due to the large number of streamers, the time response of the calorimeter to high energy hadrons is fast, with a time resolution of few ns. Muons and low energy hadrons, characterized by a smaller number of streamers, show a resolution of about 20 ns [4]. The tower signal is well separated from noise also for minimum ionizing particles as shown in fig. 14 where the pulse height distribution for muons in a single tower is plotted together with the pedestal peak.

These features allow the use of the calorimeter sig-

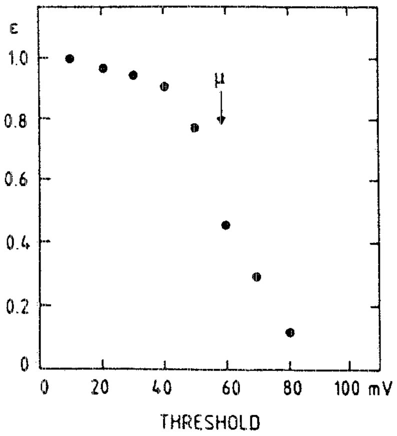

Fig. 15. Efficiency curve for muons. ($\theta = 90°$, Ar + isobutane.)

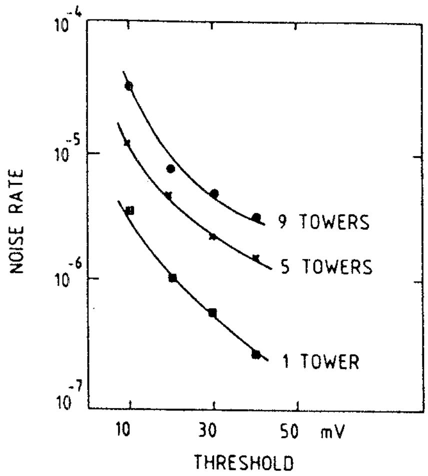

Fig. 16. Noise rate vs threshold.

nals for triggering the experiment on hadrons and muons. In particular for muons, trigger efficiency and noise level have been investigated at $\theta = 90°$ with Ar + isobutane. Setting the threshold on the sum of all towers at a voltage corresponding to 1/3 of the energy release of a minimum ionizing particle, the resulting efficiency is 97% (fig. 15)

The noise level has been studied by reading out the calorimeter, in the absence of the beam, when a coincidence between a clock and a discriminated tower signal occurred. After reconstruction, the cosmic ray background has been eliminated and the counting rates for a single tower, for five towers summed together, and for the full nonet, have been obtained (fig. 16). The rate increases almost linearly with the number of towers, indicating that the background is not uncorrelated. Indeed, a scanning of the events shows that the main source of random triggers (~ 80%) is due to a group of adjacent tubes simultaneously fired in a single plane. This rate can be reduced by requiring the coincidence of two or more fired planes, since this condition is satisfied only by a real particle crossing the calorimeter.

Acknowledgement

It is a pleasure to acknowledge the continuous and useful discussions with E. Iarocci and the contributions of the engineers and technicians at the collaborating institutions. We thank in particular A. Bechini, F. Ceglie, G. Corradi, U. Denni, R. Ferorelli, A. Masciullo and G. Mazzenga for their help in preparing and running the test.

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