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**EXPERIMENTAL STUDY OF URANIUM-SCINTILLATOR AND
IRON-SCINTILLATOR CALORIMETRY IN THE ENERGY RANGE 135-350 GeV**

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ABSTRACT

Results are reported of measurements made using a sampling hadronic calorimeter in the energy range 135–350 GeV.

The responses to hadronic showers at various energies using iron and uranium of different thicknesses as absorbers have been compared. The results obtained in iron are in substantial agreement with the existing data, while those in uranium show an unexpected overcompensation in the hadronic response.

Direct measurement of the e/π ratio is in agreement with this statement.

1. INTRODUCTION

Sampling calorimeters, comprising inert material layers interspaced with active detectors (scintillators, liquid argon, etc.), are playing an increasing role in particle-physics instrumentation.

It is customary to distinguish between 'electromagnetic' calorimeters, specially designed to measure the energy of electrons, photons, and π^0 's, and 'hadronic' calorimeters, for measuring the energy of hadrons. The responses of a calorimeter to electromagnetic and to hadronic showers are fundamentally different. In the electromagnetic case, the limit to energy resolution is related to the fluctuation in the track length of secondary electrons and positrons sampled in the active material. In the hadronic case, the main contribution to the energy resolution comes from the intrinsic fluctuations in the development of the hadronic shower. In this case the fraction of the total energy released in 'electromagnetic' form (mainly π^0 's) produces a response which fluctuates as for purely electromagnetic showers, but the interactions between hadrons and the nuclei of the absorber release energy that is only partially detectable, some energy going into nuclear fragments, slow neutrons and protons, etc.

The average response of a calorimeter is thus, in principle, lower for hadrons than for electrons and the resolution is worse, being dominated by an 'intrinsic' term, independent of the sampling thickness, due to the fluctuation of the content of electromagnetic energy in the shower. One of the main problems to be investigated in hadron calorimetry is then the correlation between energy resolution and the relative response to electrons and to hadrons [1].

It has been shown [2] that a substantial improvement in the resolution can be obtained by using as absorber ^{238}U , in which the energy released in the neutron-induced fission processes tends to compensate the nuclear losses. An intrinsic resolution of $\sigma/E \approx 0.22/\sqrt{E}$ has been inferred from data, compared to $\sigma/E \approx 0.45/\sqrt{E}$ for conventional calorimeters. Correspondingly, a nearly identical response to electrons and to pions was found, in the energy range 5–50 GeV.

Other authors [3, 4] have shown that the effect of non-compensation on the energy resolution in non-fissionable materials can be reduced by weighting techniques, using information on the longitudinal shower development. In fact, electromagnetic showers, whose scale parameter is the radiation length X_0 , tend to be shorter than hadronic showers, whose scale parameter is the interaction length λ . The fraction of electromagnetic energy in a hadronic shower is thus related to its longitudinal shape.

In this paper we present results obtained from a hadronic calorimeter with uranium absorbers of various thicknesses (0.5, 1.0, 1.5 cm) in the energy range 135–350 GeV, and compare them with the response obtained using iron layers 2.5 cm thick. The calorimeter was developed for the WA78 experiment at the CERN SPS, mainly devoted to the search for hadro-production of $B\bar{B}$ pairs. It was specially designed to work in high-rate condition (up to $\sim 5 \times 10^6$ particles per second interacting in it) with negligible variation of the energy resolution.

The description of the experiment, as well as the problems related to high rate are given elsewhere [5]. Here we discuss the results obtained in some tests made with a relatively low beam rate ($\sim 10^5$ particles per second) by changing the nature and thickness of the absorber layers in the calorimeter.

The results show that there is 'overcompensation' in the hadronic response using ^{238}U absorbers. This fact emerges both from a study of the longitudinal energy deposition in hadronic showers and from a direct measurement of the ratio of the responses for hadrons and for electrons. The results obtained with iron absorbers are in good agreement with existing data. We show that an improvement in resolution is achieved by using appropriate weighting techniques. The resolutions reported have been obtained using for both ^{238}U and Fe the algorithm previously reported in ref. [4].

We also compare the response of uranium and iron to electron showers. Finally, a measurement of the time distribution of the energy deposition in the detector shows that pulses from hadronic showers display a longer decay time in uranium than in iron.

2. DESCRIPTION OF THE CALORIMETER

The hadron calorimeter was designed and built to match the requirements of the WA78 experiment. Its main features are:

- a) capability of working in high-rate conditions,
- b) changeable absorbers,
- c) variable density.

The calorimeter (figs. 1, 2) is divided in two sections along its length. The upstream part (section A), which collects the bulk of the energy released by the incoming particles, is mechanically designed in such a way as to permit easy changing of the absorbers and variation of density. The downstream section (section B), used to achieve full containment of the showers, has a much less flexible structure which does not permit easy modifications.

In section A, each element ($60 \times 60 \text{ cm}^2$ cross-section) comprises an absorber and a scintillator sheet mounted inside a U-shaped steel frame, carried by two small carriages which can move longitudinally along two rails on the calorimeter support. The scintillator, 0.5 cm thick, is NE110, by Nuclear Enterprises. This type of scintillator was found [6] to be one of the least sensitive to radiation-damage effects, an important feature in view of the high dose to be absorbed by the calorimeter during the experiment. The light is collected through 200 optical fibres (DUPONT Crofon OE-1060, diameter 1.5 mm) held in a linear array by clamping bars screwed to the steel U-shaped frame, in such a way that the light-guides can be easily removed or replaced in contact with the lateral edge of the scintillator. Each photomultiplier collects the light from four scintillator slabs and is held by a support which allows it to follow the longitudinal movements of the four connected elements. Each group, a 'module', can be displaced along the support (3.8 m long) independently of the others. Additionally, the distance between the two adjacent elements of the same module can be varied from zero to $\sim 15 \text{ cm}$, owing to the flexibility of the light-guide. This feature permits the calorimeter to operate at different densities, and was used to evaluate the non-prompt muon background in the WA78 experiment. Moreover, the absorber plates can be easily dismantled and replaced without interference with the scintillator light-guide system.

Section A is composed of a total of 52 elements, grouped in 13 modules, each viewed by one photomultiplier. The absorber used in these tests was either iron slabs 2.5 cm thick, or uranium plates of different thicknesses. The arrangements used (Fe25, U5, U10, U15) are summarized in table 1. For easy handling and for safety reasons each uranium plate was enclosed in a steel box (with walls 1 mm thick).

Section B consists of 48 iron-scintillator sandwiches, grouped in 12 modules through light-guides identical to those of section A. Each absorber plate is $60 \times 60 \times 2.5 \text{ cm}^3$, and the scintillator sheets are the same as used in section A.

The total light collected by the photomultipliers from typical hadronic showers was shown to be sufficient to avoid deterioration of the energy resolution due to fluctuation in the number of photoelectrons (~ 100 photoelectrons per GeV in configuration Fe25).

In order to handle the high rate of incident particles foreseen in the experiment, the calorimeter was equipped with specially designed, low-gain photomultipliers [7] (Thorn EMI D254A, bialkali cathode, circular focusing, seven Sb-Cs dynodes, gain $\sim 10^3$) followed by amplifiers (current gain ~ 40), built with LeCroy VV100 BTB. To improve performance, the high voltage of the photomultipliers was set to have a greater gain in the downstream modules where high rate problems are less severe. The 25 signals were collected by LeCroy FERA 4300 ADCs (2048 channels, 0.25 pC/ch.). Each signal was split and sent to two ADCs with different gates (typically 75 and 100 ns) and the difference between the two recorded signals was used to evaluate the noise on an event-by-event basis.

The data acquisition was triggered by a beam hodoscope ($\sim 3 \text{ m}$ upstream), equipped with large anticoincidence halo counters. An iron wall shielded these counters on the calorimeter side to avoid anticoincidences due to back-scattering.

The beam signal was also sent to a multi-hit TDC (LeCroy 4208), which recorded the presence of other beam particles in a time window of ± 400 ns around the triggering particle. This was used to reject events with possible pile-up. The back-scattering (albedo) was sensed by a counter ($60 \times 60 \times 2.5$ cm³) placed just before the first module of the calorimeter.

3. CALIBRATION AND MONITORING

The dynamic range covered by the low-gain photomultipliers does not permit a minimum ionizing particle signal to be separated from noise. It was not possible, therefore, to use muons to equalize the module responses and we were obliged to use a different technique.

First the responses of individual modules were roughly equalized (at 10–20% level), using a radioactive source. At this stage care was also taken to ensure the equalization of the responses of individual scintillators belonging to the same module, particularly for the first few modules. To obtain an equal response, to within 3–5%, some fibres were darkened to lower the light output where necessary.

The final calibration was obtained by using the fact that the longitudinal energy distribution of hadronic showers must, on the average, be independent of the position of the shower vertex.

A sample of $\sim 10^5$ showers (at 210 GeV, in configuration Fe25), was divided into subsamples according to the vertex position, defined by requiring that a minimum energy be deposited in two adjacent modules. Denoting A_j^i the average energy deposited in the j -th module, from the sample with the vertex in the i -th module, we obtain a set of equalities:

$$\alpha_1 A_1^1 = \alpha_2 A_2^2 = \alpha_3 A_3^3 = \dots$$

$$\alpha_2 A_2^1 = \alpha_3 A_3^2 = \alpha_4 A_4^3 = \dots$$

.....

where α are the calibration constants. This technique leads to an overdetermination of the α_i 's, which can be found using a fitting procedure. In practice, this analysis can be restricted to the first few equalities. Particular care had to be taken to avoid systematic effects in the determination of the first constant α_1 , due to upstream interactions and to back-scattering.

Having applied this procedure, an equalization within a few per cent was obtained. This was checked by comparing the final average longitudinal energy distributions of the different subsamples. This method does not give an absolute energy scale but this can be obtained from, and continuously monitored by, the nominal energy of the monochromatic beam (momentum bite $\sim 1\%$).

The stability in time of the module responses was monitored using a light-emitting diode (LED) system. Fifty LEDs were connected by optical fibres to a plexiglas cylinder, acting as a light mixer. This common light source is viewed by all photomultipliers through individual optical fibres. During the data taking LED 'events' were registered on tape, and the variation in the relative responses of the modules were used to correct the calibration constants. However, for the data presented in this paper (taken during one month), these corrections turned out to be negligible, showing an excellent stability of the system.

Finally, to convert from ADC channels to energy, one should, in principle, weight each output with the energy loss in the corresponding absorbers. For homogeneous configurations this leads to a trivial scale factor (we put this factor at 1 for configuration Fe25). But, for configurations U5, U10 and U15, we had to take into account the non-uniformity of the calorimeter (the absorbers were of different nature and thickness). For these samples, we normalize each output as

$$E_i = A_i \{ [(dE/dx)_{\text{abs}} \Delta x_{\text{abs}} + (dE/dx)_{\text{scint}} \Delta x_{\text{scint}}]_i / [(dE/dx)_{\text{Fe}} \Delta x_{\text{Fe}} + (dE/dx)_{\text{scint}} \Delta x_{\text{scint}}] \}, \quad (1)$$

where A_i are the ADC outputs after calibration. In this way the responses (channels) for all configurations are directly comparable.

4. RESULTS FOR HADRONS

Data were taken with a proton beam at energies of 135, 210, 300, and 350 GeV, in the configurations Fe25, U5, U10, and U15 described in table 1.

4.1 Iron calorimeter

Firstly, we discuss the results obtained with the iron calorimeter (configuration Fe25), which can be compared with existing data, in particular with those obtained by the CDHS Collaboration in a very similar configuration [3].

In order to avoid accidental superposition of two showers, we have rejected events where the triggering beam particle was not clearly isolated in time. This was obtained by looking at the signal amplitude in the beam hodoscope, and at the TDC output. We have further restricted the analysis to showers with the vertex in the first four modules (40 cm of iron), thus obtaining events which are longitudinally well contained, even at the higher energy.

At 135 GeV the beam contained a large fraction of electrons giving rise to electromagnetic showers. In order to remove them from the analysis of hadronic showers, a significant fraction of the energy was required to be deposited after the first four modules from the vertex (~ 22 radiation lengths). As demonstrated in the next Section, this criterion is sufficient to separate electron-induced showers from the others. The residual contamination of electrons in the reported hadron sample of 135 GeV data is $\sim 1\%$. A more stringent cut could, however, reduce it further, at the price of losing only a few per cent of hadrons.

Figure 3 shows the energy distributions obtained at different beam energies, after all cuts have been applied (solid curves).

In fig. 4 the scatter plot of the total shower energy, $E_{\text{tot}} = \sum_i E_i$, versus the maximum energy deposited in any single counter, A_{max} , is shown. The high-energy tail is correlated with a larger energy at the maximum of the shower, i.e. showers with a large localized energy deposit have a greater response in the calorimeter (with a narrower energy distribution). As already mentioned, this effect can be interpreted as due to the fluctuation of the electromagnetic component in the shower development combined with a lower average response of the calorimeter for hadrons than for electrons. This correlation can be used to reduce the variance of the energy distributions, and various weighting algorithms have been studied to exploit this feature of the data. As concluded by the authors of ref. [4], the best result is obtained with the formula

$$E'_{\text{tot}} = E_{\text{tot}} - c' \times \sum_i A_i^2.$$

A suitable form for the parameter c' turns out to be

$$c' = c/\sqrt{E_{\text{tot}}},$$

where the value of c is selected by optimizing the resolution. The best value is practically the same throughout our energy range ($c \simeq 0.01 \text{ ch.}^{-1/2}$). The dashed curves in fig. 3 show the weighted energy distributions (nearly Gaussians) while fig. 5 shows the scatter plot of E'_{tot} versus A_{max} . The effect of the correction algorithm is evident.

Figure 6 shows the linearity of response of the calorimeter, for unweighted and weighted energies.

The dependence of the resolution on beam energy can be parametrized in the form

$$(\sigma/E)^2 = (c_1)^2 + (c_2/\sqrt{E})^2,$$

where E is the mean value of E_{tot} (E'_{tot}); for the weighted resolution it is seen that our data are consistent with such a parametrization with

$$c_1 = 0.017$$

$$c_2 = 0.55 \text{ (E in GeV)}.$$

In fig. 7 our results are compared with those from refs. [3] and [4]. There is a good agreement in the weighted results of the three experiments, but not for the unweighted resolutions. A possible explanation of these differences could be related to the intrinsic responses of the scintillators used (NE 110 in our case, Plexipop 1922 in CDHS). A different saturation in the response to low- β particles may give a change in the ratio between electromagnetic and hadronic responses, and therefore differentiate the unweighted energy resolutions.

4.2 Uranium calorimeter

Figure 8 shows the energy distributions obtained at three different beam energies in configuration U10 (solid curves). The selection criteria used here are the same as for the iron case, except that the analysis has been restricted to showers having the vertex in the first three modules (12 cm U) in order to exploit the performance given by the 10 mm absorbers.

Figure 9 shows the correlation E_{tot} versus A_{max} . In this case the correlation has the opposite sign to that shown by the iron calorimeter: shorter showers give rise to a smaller response in the calorimeter. The hadron response of the device seems, therefore, to be higher than the electron response. The same phenomenon is seen in configuration U5 (only 135 GeV available) and U15 (350 GeV). The most likely explanation of this fact is that the uranium absorbers 'overcompensate' the unseen energy of the hadronic interactions via the measurable energy released in the neutron-induced fission processes. The difference from the results reported in ref. [2], which show an almost perfect compensation, may be due to the different energy range explored (5–50 GeV instead of 135–350 GeV), to the different sampling thickness (larger in our case), and to the different response of scintillator (more sensitive in our case to low- β particles produced in the shower).

The weighting procedure to optimize the resolution can also be applied to the uranium data (even if with opposite sign). From the expression

$$E'_{\text{tot}} = E_{\text{tot}} + c' \times \sum_i A_i^2,$$

with

$$c' = c/\sqrt{E_{\text{tot}}},$$

we obtain

$$c = 0.005 \text{ ch.}^{-1/2} \text{ for configuration U5 ,}$$

$$c = 0.010 \text{ ch.}^{-1/2} \text{ for configuration U10 ,}$$

$$c = 0.013 \text{ ch.}^{-1/2} \text{ for configuration U15 .}$$

Note that the c values obtained are not directly comparable because of the non-uniformity of the calorimeter.

Figure 10 shows the scatter plot E'_{tot} versus A_{max} , for weighted data from configuration U10, while the weighted energy distributions are shown as the dashed curves in fig. 8.

We note that there is no reason why the best algorithm for uranium will be the same as for iron; preliminary results, however, seem to indicate that no substantial improvement can be obtained by using different algorithms.

Figure 11 shows the linearity of the response of the calorimeter in configuration U10 for weighted and unweighted results.

The parametrization of the resolution as

$$(\sigma/E)^2 = (c_1)^2 + (c_2/\sqrt{E})^2$$

can be studied as for iron. For weighted results we can estimate

$$c_1 = 0.026$$

$$c_2 = 0.52 \text{ (E in GeV)} .$$

The results for all the configurations are summarized in table 2, for both iron and uranium. It should be noted that in configurations U5 and U10 only the first 20 elements have a thickness of 5 and 10 mm. This is particularly relevant for configuration U5 in which a substantial part of the shower energy is sampled with a 15 mm absorber. Nevertheless for such a configuration the resolution is better than that obtained in iron despite the overcompensation effect in uranium.

5. RESULTS WITH ELECTRONS

As already anticipated, our 135 GeV beam contained a large fraction of electrons, which has permitted a study of the performance of the calorimeter for electromagnetic showers, both with uranium and iron absorbers.

Figure 12 compares the distribution of shower vertices for configuration Fe25, at the three beam energies. At 135 GeV a large excess of events is seen with the vertex in the first module. Figure 13d shows the energy distribution, at 135 GeV, for events with the vertex after the first module, while fig. 13a shows the same for events with the vertex in the first module. The double peak in the latter figure reflects the presence of a large number of electrons. In order to separate them from hadrons, we exploit the fact that electron-induced showers are much shorter than those induced by hadrons. Figure 14a shows the unweighted energy deposited after four modules from the vertex of the shower ($E_4 = \sum_{i=5}^{25} E_i$) for events with the vertex in the first module, while fig. 14b shows the same for events with the vertex after the first module. The sharp peak around zero in fig. 14a is due to electrons (the width of this peak reflects the noise summed over the downstream modules). A cut at $E_4 = 30$ ch. can be used to separate electrons from hadrons. The hadron contamination in the electron sample is $\approx 0.5\%$; and the electron contamination in the hadron sample (vertex in any of the first four modules) is also $\approx 0.5\%$. The effect of the cut is shown in figs. 13b and 13c.

As expected from the results obtained for hadronic showers, the electron peak is at higher energy. Using the same technique, it was also possible to isolate the few electrons present in the beam at 210 GeV. In this case, however, the contamination from hadrons left in the electron sample was not negligible (20–40%).

It is interesting to study the scatter plot E_{tot} versus A_{max} for events with the vertex in the first module and with no cut on E_4 (fig. 15), comparing it with that for pure hadronic samples (fig. 4). The electrons are all concentrated at high A_{max} and are well-aligned with the hadrons. This behaviour supports the interpretation that this correlation is connected with the ‘non-compensation’ between hadronic and electromagnetic responses.

Figures 16 and 17 show the results of the same analysis performed on the uranium data (configuration U10). In this case the electron peak is at a lower energy than the corresponding hadronic peak, and the correlation E_{tot} versus A_{max} behaves correspondingly. This result agrees with the behaviour found for hadrons: the response for electrons is lower than that for hadrons.

Table 3 summarizes the results for electrons obtained in configurations Fe25, U5, and U10. Although the calorimeter was not designed to measure electron showers, at 135 GeV the energy resolutions for configurations Fe25 and U5, after unfolding the beam momentum spread and the noise contribution, are roughly in agreement with the values expected for fine sampling. This is not true for configuration U10 because of the coarse sampling. Owing to poor statistics and to hadron contamination, the resolutions found at 210 GeV are not very significant and are quoted in parentheses only for completeness.

The last column of table 3 reports the ‘ e/π ’ ratio, i.e. the electron response divided by the unweighted hadron response. These ratios are reported in fig. 18 together with other existing results from a compilation of Fabjan and Ludlam [2]. The results for iron are compatible with existing data at lower energy and confirm a decrease of the e/π ratio with the energy.

The e/π ratio in uranium in our calorimeter is less than 1 and is slightly dependent on the sampling thickness. The systematic uncertainties in this ratio tend to cancel out, except for errors in the calibration constants of the first modules which would be reflected strongly in the electron energy measurement. We estimate that this uncertainty affects the result by no more than a few per cent.

As stated in Section 3, the total energy is expressed in channels; uranium configurations have been normalized to the iron one according to expression (1). Furthermore, since we were unable to calibrate with muons, we cannot set an absolute scale of the deposited energy. However, we can compare the responses of iron and uranium to electromagnetic showers. From data given in table 3, we find

$$R = (E_{\text{tot}})_{\text{U}} / (E_{\text{tot}})_{\text{Fe}} \approx 0.68$$

for both uranium samplings and for both energies.

A similar behaviour has already been observed [1], but no simple explanation has been given for it. The effect indicates that, even for electromagnetic showers, not all the energy is visible. As a consequence, it is correct to use expression (1) to compute the energy for different thicknesses of the same material but not for absorbers of a different nature. In our case, since the transition from uranium to iron occurs in the tail of the hadronic shower, our results are only affected to a negligible extent, but more careful corrections could be necessary in other configurations.

6. TIME DISTRIBUTION OF THE DEPOSITED ENERGY

If fission processes play an important role in the behaviour of uranium calorimeters, the fission-induced energy deposited in the detector will have a characteristic delay time of a few tens of nanoseconds [8]. To investigate this effect, energy measurements have been made using different gate lengths on the ADCs (50, 75, 85, 100, 160, 200 ns), for configurations Fe25 and U10 in order to obtain the time distribution of the deposited energy. The absolute shape of this distribution is affected only slightly by the time constants of the electronic chain, but any difference between uranium and iron data must reflect a different physical behaviour.

Figure 19 clearly shows, for hadron showers, a slower rise-time of the pulse in the uranium data, which is consistent with the hypothesis that part of the energy is released after a time delay. No difference is seen between uranium and iron for electrons, as shown in fig. 20, for a sample at 135 GeV.

7. CONCLUSIONS

We have reported results obtained from a sampling hadronic calorimeter, characterized by a flexible mechanical design, permitting easy change of absorbers.

The response to hadronic showers obtained with iron and with uranium of different thicknesses has been compared at various beam energies. The results in iron are in substantial agreement with the existing data. The results obtained in uranium, however, show an unexpected overcompensation of the hadronic response. Direct measurement of the e/π ratio is in agreement with this conclusion. With our calorimeter in the energy range explored, the e/π ratio is ≈ 1.1 for iron and between 0.8 and 0.9 for uranium, depending on the sampling. Nevertheless our results show that it is possible to get a better resolution in uranium than in iron by reducing the sampling thickness (even if only in the first few elements of the calorimeter). It is also worth while remarking the substantial improvement in resolution obtained both in uranium and iron by using appropriate weighting techniques. It is true, however, that the response and resolution of a uranium calorimeter are due to a combination of several physical and technical effects (dependence on energy of fission and fission-induced processes, type of scintillator and thicknesses used, etc.). Therefore any simple parametrization of the behaviour of the energy resolution in terms only of the sampling thickness is inadequate. On the other hand, the dependence of the response upon several parameters could be exploited to improve performance in specific cases.

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Table 1
Summary of the different calorimeter configurations

Configuration	Fe25	U5	U10	U15
Section A	25 mm Fe ($\times 52$)	5 mm U ($\times 20$) 15 mm U ($\times 32$)	10 mm U ($\times 20$) 15 mm U ($\times 32$)	15 mm U ($\times 52$)
Section B	25 mm Fe ($\times 48$)	25 mm Fe ($\times 48$)	25 mm Fe ($\times 48$)	25 mm Fe ($\times 48$)

Table 2
Summary of results for hadronic showers. The statistical error
on the mean value E of E_{tot} (E'_{tot}) is negligible;
the systematic error is of the order of 1% (mainly due to calibration).

Configuration	Beam energy (GeV)	E (channels)	σ/E (%)	E (channels)	σ/E (%)
		unweighted		weighted	
Fe25	135	1113	5.5	1032	5.0
	210	1741	4.7	1628	4.2
	300	2488	3.7	2369	3.6
U5	135	960	4.9	1030	4.6
U10	135	1044	6.0	1114	5.1
	210	1601	5.1	1722	4.4
	300	2259	4.6	2447	4.0
U15	350	2793	5.6	3105	4.2

Table 3

Summary of results for electron showers. The quoted errors for 210 GeV data are only statistical (negligible for 135 GeV data). The systematic uncertainties are estimated to be less than 3%, both for E and for e/π .

Configuration	Beam energy	E	σ/E	e/π
Fe25	135	1235	2.4	1.11
	210	1878 ± 5	(3.2)	1.07
U5	135	841	2.0	0.88
U10	135	835	3.4	0.80
	210	1270 ± 6	(2.6)	0.79

Figure captions

- Fig. 1: Top view of the calorimeter. The downstream section (modules 14 to 25) is only partially shown. H_1 , H_2 , A , B_1 , B_2 , and F are the counters used to define the beam; AC is the albedo counter.
- Fig. 2: Artist's view of one module, showing the four elements and the light-guide system. On the left, the exploded view of one single element.
- Fig. 3: Unweighted (solid curve) and weighted (dashed curve) energy distributions for configuration Fe25 at three beam energies (135, 210, and 300 GeV).
- Fig. 4: E_{tot} versus A_{max} for configuration Fe25 at three beam energies (135, 210, and 300 GeV).
- Fig. 5: E'_{tot} (weighted) versus A_{max} for configuration Fe25 at three beam energies (135, 210, and 300 GeV).
- Fig. 6: Mean value of E_{tot} and E'_{tot} as a function of beam energy for configuration Fe25.
- Fig. 7: Comparison of the unweighted (open symbols) and weighted (full symbols) resolutions from this experiment, from Dishaw et al. [3] and from the CDHS test calorimeter [4].
- Fig. 8: Unweighted (solid curve) and weighted (dashed curve) energy distributions for configuration U10 at three beam energies (135, 210, and 300 GeV).
- Fig. 9: E_{tot} versus A_{max} for configuration U10 at three beam energies (135, 210, and 300 GeV).
- Fig. 10: E'_{tot} (weighted) versus A_{max} for configuration U10 at three beam energies (135, 210, and 300 GeV).
- Fig. 11: Mean value of E_{tot} and E'_{tot} as a function of beam energy for configuration U10.
- Fig. 12: Distributions of the shower vertex position for configuration Fe25.
- Fig. 13: Energy distributions for 135 GeV data in configuration Fe25: a) vertex in the first module; b) vertex in the first module, with $E_4 < 30$ ch.; c) vertex in the first module with $E_4 > 30$ ch.; d) vertex after the first module.
- Fig. 14: E_4 distributions at 135 GeV for configuration Fe25: a) vertex in the first module; b) vertex after the first module.
- Fig. 15: E_{tot} versus A_{max} for 135 and 210 GeV, vertex in the first module, for configuration Fe25; hadrons and electrons.
- Fig. 16: Energy distributions in 135 GeV data for configuration U10: a) vertex in the first module; b) vertex in the first module, with $E_3 < 24$ ch.; c) vertex in the first module with $E_3 > 24$ ch.; d) vertex after the first module.
- Fig. 17: E_{tot} versus A_{max} for 135 and 210 GeV, vertex in the first module, for configuration U10; hadrons and electrons.
- Fig. 18: Ratio of electron to hadron response. Our results are reported together with previous experimental results from a compilation of Fabjan and Ludlam [2]. The errors on our results are discussed in the text.
- Fig. 19: Mean energy versus gate length for hadrons in uranium and iron at various energies: a) 135 GeV ; b) 210 GeV ; c) 300 GeV.
- Fig. 20: Mean energy versus gate length for electrons in uranium and iron at 135 GeV.

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