A URANIUM SCINTILLATOR CALORIMETER WITH PLASTIC-FIBRE READOUT

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ABSTRACT

We have developed a method for reading out scintillator plates in a compact calorimeter using embedded wavelength-shifting fibres coupled to photomultipliers. A test calorimeter using this technique, with uranium plates as the passive medium, was placed in test beams of 1 GeV to 80 GeV. Results on resolution, uniformity, and electron-pion discrimination are presented, as well as a discussion of compensation (the near-equality of electron and hadron responses due to 'fission amplification' of the hadronic response).

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1. INTRODUCTION

Sampling calorimeters consisting of alternate layers of dense showering material (Fe, Pb, U, etc.) and active readout devices (scintillator, liquid ionization chambers, gaseous detectors, etc.) have become standard detectors for energy measurement in high-energy physics (see ref. [1] for a recent review). With the present trend towards colliding beam facilities, most experiments require a compact calorimeter (for reasons of cost and space) with full angular coverage (4π solid angle) and no cracks or insensitive regions. In addition it is generally desirable to have several depth samples to measure the longitudinal shower development, in particular to distinguish between electromagnetic (e.m.) showers and hadronic showers (e.g. for e/π discrimination). These requirements are not easily made compatible.

The development of wavelength-shifting (wls) techniques to concentrate a portion of the light from scintillator sheets was an important step, which made it possible to have large solid-angle scintillator-based calorimeters at colliding-beam machines. Normally the side of a calorimeter stack is covered with a plate of plastic doped with a wls dye, which absorbs and re-emits the scintillation light isotropically at a longer wavelength; part of the re-emitted light can then be transported to a photomultiplier (PM) by a normal light-guide [2, 3]. Limited depth subdivision can be achieved by overlapping wls plates, but at the expense of larger cracks and ‘hot-spots’ resulting from showers propagating along the wls plates.

We have developed and tested an alternative readout method using a single plastic wls optical fibre embedded in each scintillator sheet. The wls fibres are connected after a short distance to a long (5 m) clear optical fibre which transmits the light to a remote photomultiplier. This work was motivated by the need for a new calorimeter to replace the present gondolas [3] of experiment UA1. The constraints in this case were severe and could not be met by any previously used technique. The aim was to devise an optical readout technique for a calorimeter with six samplings in depth and fine lateral segmentation, whose total depth is limited to 50 cm, and which must reside in a high-field region (0.7 T) to which there is almost no external access. The complicated geometry suggested flexible fibre light-guides. Described in this paper is a test calorimeter which was built to demonstrate the feasibility of these techniques for a large 4π calorimeter.

The choice of uranium as the showering material results from its very high density—and hence the ability to have ≈ 2.6 interaction lengths in 50 cm depth—and the expectation that the hadronic energy resolution is improved by a near-equality of the response to e.m. and hadronic particles. This is believed to result from an additional signal in hadronic showers generated by neutrons and photons from the break-up of uranium nuclei, which compensates for binding energy losses (‘compensation’), as first pointed out by Fabjan and Willis [4]. A large uranium/scintillator calorimeter with wls plates has achieved a hadronic energy resolution $\sigma_E/E = 0.36/\sqrt{E}$ and a ratio of response $e/\pi \approx 1.1$ (Åkesson et al., in ref. [2]). Whilst uranium has disadvantages resulting from its radioactivity, namely machining and handling problems, increased noise, and radiation damage to the scintillator, the signal from the uranium can also be of use in maintaining a calibration for the whole calorimeter.

2. CHOICE OF LIGHT-COLLECTION SCHEME

We considered and tested several geometrical schemes for collecting the light from a 2.5 mm thick scintillator sheet into one or a few plastic fibres [5]. The most conventional scheme (fig. 1a) uses two wls bars of rectangular cross-section ($\approx 1.5 \text{ mm} \times 2.5 \text{ mm}$), on opposite faces of the scintillator, gluing to the end of each bar two clear fibres of diameter $\approx 1.2\text{--}1.5 \text{ mm}$. Whilst this scheme gives a relatively uniform response over the plate, four fibres per plate was considered excessive given the number of plates ($\approx 2 \times 10^5$) that would be required in a large 4π calorimeter. A factor of 2 reduction could be obtained using wls fibres of 1.5 mm diameter embedded in grooves machined in the scintillator, replacing the external bars (fig. 1b). This preserves the good uniformity of the

method pictured in fig. 1a, simplifies the connections (a fibre-fibre connection is simpler than fibres-bar), and increases the scintillator coverage. Schemes with a single fibre looping around a circumferential groove were found difficult to implement; however, a single diagonal fibre (fig. 1c) was found to collect adequate light, albeit with a 50% difference in output between particles near the diagonal and in the far corners. We used a polystyrene scintillator. Its relatively high index of refraction means that more light than usual is trapped in the scintillator, thus increasing the chance that light is absorbed in the embedded doped fibre. The non-uniformity can to a great extent be removed by arranging alternate plates in the tower with alternate (crossed) diagonals. In order to avoid dead space between adjacent towers it was necessary that the fibres emerged parallel to an edge of the plate; thus the final scheme adopted (fig. 1d) uses a gently curved groove. Using this technique we constructed a calorimeter and tested it in beams of 1–80 GeV at the CERN Proton Synchrotron (PS) and Super Proton Synchrotron (SPS).

3. DESCRIPTION OF THE MODULES

The basic layout of the test calorimeter set-up is shown in fig. 2. It consists of seven $20 \times 20 \text{ cm}^2$ towers. The first three towers constructed were modules 1, 4, and 7, of which number 4 had $10 \times 10 \text{ cm}^2$ subdivision for the e.m. samples. The remaining four towers (5, 6, 8, 9) had improved fibre connectors, improved clear fibres [polymethyl methacrylate (PMMA) rather than polystyrene, with reduced attenuation and more flexibility], and better photomultipliers (our final choice was the Philips XP2072). The results we present are based on the $40 \times 40 \text{ cm}^2$ block of towers 5, 6, 8, and 9, with towers 1, 4, and 7 used only for the study on lateral containment of hadronic showers.

Each tower has six independently read out depth samples. The first four samples, of 3.2, 6.7, 8.8, and 6.6 radiation lengths (X_0), are the ‘e.m. section’ and have 2 mm thick uranium plates, with 2.5 mm thick scintillator plates in a 3 mm gap. (See table 1 for parameters.) The last two samples, for hadronic energy, are each ≈ 1 interaction length (λ) of 2.5 mm scintillator plates alternated with 4 and 6 mm uranium plates (5 mm thick uranium plates were not available). The scintillator plates (whose precise dimensions were $19.4 \text{ cm} \times 20.0 \text{ cm} \times 2.5 \text{ mm}$) were of KSTI 430 extruded polystyrene (KSH, Belgium). Each plate had a machined diagonal groove of 1.8 mm depth, curved for tangential exit of the fibre (fig. 1d). A 30 cm long wls fibre [1.5 mm diameter polystyrene doped with 400 mg/l K27 (supplied by Hoechst) wavelength-shifter] was warmed (for bending) and glued into the groove with vinyl acetate, the same material as that used for the fibre cladding (refractive index $n \approx 1.4$; cf. $n \approx 1.6$ for the fibre core). K27 was chosen because its absorption and emission spectra match well with those of the chosen scintillator and PM (see fig. 3). A reflective aluminium layer was deposited under vacuum on the embedded end of the fibre. The edges of the scintillator sheets were covered with adhesive reflecting foil, and the scintillator sheets were separated from the uranium plates with a sheet of reflective Mylar. For each tower, approximately 70 of these uranium/scintillator layers were stacked up and held together by external tie rods with special ‘washers’ to ensure the uranium plate spacings. Alternate scintillator plates were inverted so that alternate fibres formed a cross to improve uniformity.

After assembly of the stacks, the protruding doped-fibre ends were connected to clear fibres of 5 m length and 1.5 mm diameter. Clear fibres were necessary because of the short attenuation length of the doped fibres. Despite its good reputed radiation resistance, initial trials with polystyrene clear fibre were discontinued because of its lack of flexibility (even a bending radius $\approx 10 \text{ cm}$ without heating caused light loss), its brittle nature (it crazed and broke easily), and the short attenuation length of available samples (typically $\approx 1 \text{ m}$). The final four towers used commercially available PMMA fibres (ESKA CK60, Mitsubishi), which had a transmission $\approx 80\%$ over 5 m, and were also much more flexible. A still better fibre exists (ESKA Extra, Mitsubishi), but is at present available

with only 1 mm diameter. The radiation resistance of PMMA fibres was checked [6] and found to be adequate for our purposes. The Saclay-designed fibre-fibre connectors were simple Teflon sleeves with an outer metal sleeve crimped over. This cheap connector gave $\approx 80\%$ transmission. The clear fibres from one sampling were bundled together in a light-tight sleeve up to the phototube, where they were glued in a cylindrical plastic tube with a spring-pressure contact on the PM window. The PMs were in one fixed box, whilst the calorimeter was enclosed in a separate, movable (for scanning), light-tight box. An additional clear fibre in each bundle came from a diffuser box containing a light-emitting diode (LED) which could be pulsed, for setting up and calibrating the PMs.

The photomultipliers were chosen after consultation and tendering action with all companies capable of producing several thousand tubes on an acceptable time scale, and after extensive testing of sample tubes. The specification included quantum efficiency, linearity, single-photoelectron resolution, stability, cathode size, and noise. Two models, both $1\frac{1}{2}$ inch diameter head-on tubes, met our specifications, the EMI9902 (10 stages) and the Philips XP2072, an 8-stage tube developed with our requirements in mind. The latter shows particularly good single-photoelectron resolution and green-light quantum efficiency for an inexpensive tube; we used these tubes for the four towers 5, 6, 8, and 9. We ran the tubes at low gain ($\sim 5 \times 10^4$) followed by two amplifier stages ($\times 25$ and then $\times 30$), with parallel LeCroy 2282 ADCs after the first and second stages. The low-gain channel is mainly used for high-energy showers, and the high-gain channel for muons, uranium radioactivity signal, and low-energy particles. A third electronic channel carried out a (6.6 ms time constant) integration of the signal, providing a d.c. level proportional to the uranium signal read out with a voltage-sensing ADC. This acted as a gain stability monitor, and in principle could be used for calibration.

4. TEST-BEAM LAYOUT

The calorimeter was installed successively in two test beams at CERN, providing particles from 1 GeV to 10 GeV at the PS and from 10 GeV to 80 GeV at the SPS. The layout (fig. 4) included beam-defining trigger counters, two Cherenkov counters used normally for e/hadron discrimination, and wire chambers to define the position of the beam particles (to ≤ 0.5 mm). Behind the prototype calorimeter an iron/scintillator calorimeter with two depth segments, each with two PMs, simulated the C- and I-modules in the UA1 experiment [7]. This was followed by further scintillators and an iron wall, which enabled us to trigger on penetrating particles (muons). The prototype calorimeter itself was mounted on a stand, enabling horizontal and vertical motion as well as rotations about a vertical axis for scanning the response. Data were taken with electrons, hadrons, and muons. The Cherenkov counters were used to ensure that the contamination of electron and pion samples was negligible. Above 5 GeV muon identification was essentially 100% efficient. Position and angle scans were done with 40 GeV electrons, and a position scan with 40 GeV hadrons.

5. CALIBRATION PROCEDURES

All the photomultipliers could be excited simultaneously by a pulse from a LED via an optical fibre (1 per PM tube). Measuring the approximately Gaussian pulse-height spectrum for several LED intensities enables one to determine the number of photoelectrons per ADC channel, by comparing the mean pulse height ($\propto n_{pe}$) with the width ($\propto \sqrt{n_{pe}}$), given that the pulse-to-pulse variation of the LED pulse is negligible. We then used penetrating muons and adjusted the PM voltages so that the muon signal (after pedestal subtraction) in each of the six depth samplings was proportional to the amount of scintillator traversed (number of sheets per sample). In practice the PM gains were adjusted approximately with this method before data-taking: off-line, we found coefficients to correct the measured ADC signal so that it was proportional to the number of scintillator sheets.

Using the LED calibration, the muon data gave the average number of photoelectrons per scintillator plate for minimum-ionizing particles, $N_{\mu,p}$. Figure 5 shows the distribution for 17 of the 24 samples (the other samples were not well calibrated with the LEDs). Each measurement is the average over all the scintillator sheets in a sample. The mean is $N_{\mu,p} = 1.2$. The spread is partly due to the accuracy of this method (estimated $\approx 20\%$), and partly genuine owing to plate-plate and fibre-fibre variations. In order that energy resolution of the calorimeter is not dominated by photoelectron statistics, it is generally required that there be at least one photoelectron per sheet, and this was a benchmark for these tests. The decrease with respect to the single-plate tests, where we found ≈ 3 photoelectrons from a β -source (implying ≈ 2.6 photoelectrons from a muon), is attributed to the fibre-fibre connector (transmission typically 80%), the 5 m of clear fibre, and losses in the coupling to the photomultiplier. This result has been cross-checked by a test with cosmic-ray muons [8]. The resolution of the calorimeter also depends on the equality of response between all the scintillator plates, and it is important to control any variations, as far as is practical.

We developed a method using a xenon flashlamp to calibrate individual fibres and check the linearity of the PMs. This was in the nature of a special test rather than an overall calibration, as we were concerned with possible differences between individual clear fibres and their connectors, and with the light coupling to the PM. It was possible to run the PM tubes with a very low gain (600 V, gain $\sim 10^4$) even with the light-tight calorimeter box removed and the doped-fibre tails exposed. Illuminating the exposed doped fibre with an ultraviolet xenon flashlamp collimated to a small spot, we measured the wavelength-shifted light on the PM, using a QVT pulse-height analyser. With this method it was possible to check for variations from fibre to fibre within a bundle. An example is given in fig. 6, which shows an $\approx 10\%$ variation (standard deviation). In constructing a large calorimeter, such a check could be made automatic on all connectors/clear fibres. The linearity of the PMs was also checked using calibrated grey filters in the xenon flashlamp.

The muon data can also be used to set an energy scale, if one knows the mean energy loss of muons in the calorimeter. However, it is known [9] that this energy scale is not correct for electrons and hadrons; calorimeters have a ratio $\mu:e \neq 1.0$. It is thus essential to derive energy scales also from e's and hadrons.

The use of uranium plates as the passive material provides an evenly distributed radioactive source throughout the detector. The uranium signal, which can be read out continuously, provides a stability monitor of the complete chain (scintillator, fibres and connectors, PM gain variations, etc.). In these measurements the uranium signal (time averaged over 6.6 ms) for every PM was read out in a voltage ADC. By averaging over a few hundred consecutive measurements, drifts of $\sim 10^{-3}$ relative gain can be measured. In these tests the observed time variations (typically a few per cent in a day) were dominated by the temperature and humidity dependence of the electronic chain. By reducing these electronic instabilities to below the level of PM tube gain fluctuation, a system could be used to monitor and correct for the latter. Such a system also allows one to monitor and correct for any long-term changes in the scintillator-fibre-PM tube system, e.g. scintillator ageing, certainly at a level $\leq 0.5\%$.

6. RESULTS

6.1 Muons

Muon data at 40 GeV were taken in all four towers as part of the above calibration procedure. We also took data with 80 GeV muons in one tower, and observed a significant increase in the mean pulse height of $(7.8 \pm 2.3)\%$ (see fig. 7). This can be compared with an expected increase [10] of 6% for the dE/dx rise in polystyrene.

These muon data were used for determining $N_{\mu/p} = 1.2$ as described above. Having a significant muon signal for all six depth samples is valuable in an experimental situation, both for identification of muons and for an additional *in situ* calibration with cosmic-ray muons.

6.2 Electrons

In order to measure the calorimeter response and energy resolution for electrons, the beam was centred on the tower to be studied, so as to ensure that there was no transverse leakage into neighbouring towers. For electrons, the contribution to the total pulse height from samplings beyond the fourth one was negligible; that is, the showers were fully contained within the e.m. section. For all electron results presented here a summation is made over only the first four layers of one tower (tower 5). The resolution is worse if the sum extends over the entire calorimeter, owing to uranium and electronic noise. This point is returned to in the next subsection.

Initial calibration constants of the samplings were determined off-line by equalizing the average pulse height per scintillator plate for penetrating muons, as previously described. After this equalization, energy-independent coefficients for the first four samplings were used as parameters in a fitting program which finds the best fit to a form

$$(\sigma/\mu)^2 = (A/\sqrt{E})^2 + K^2 ,$$

where μ and σ , the mean and r.m.s. of the pulse-height distributions at each energy, were obtained from Gaussian fits to the distributions, which always gave good fits. A typical distribution is shown in fig. 8 with the Gaussian fit superimposed. The resulting coefficients for the four samplings are 1.10, 1.00, 0.97, and 1.00. These coefficients are close to 1, as expected. The corresponding expression obtained for the energy resolution, from 1 to 80 GeV, is

$$(\sigma/\mu)^2 = (17.6\%/ \sqrt{E})^2 + (2.1\%)^2 ,$$

as illustrated in fig. 9. This result includes the 1.4% momentum spread of the beam.

Other types of fits to the resolution were also tried. None gave coefficients appreciably different from 1 or better overall resolution, and in all cases the resolution was better than $18.5\%/\sqrt{E}$.

The electromagnetic gamma shower (EGS) [11] simulation code was run using a geometry exactly simulating the prototype. The resolution found was $14\%/\sqrt{E}$, assuming perfect light collection. Including the contribution due to photoelectron statistics for one photoelectron per plate, the result is $16\%/\sqrt{E}$. Finally, the effect of plate-to-plate variations was included in the simulation. Here, the response of each scintillator plate is allowed to vary in a Gaussian way about the mean response. The width of the Gaussian chosen was 20%, which is consistent with our measurements of the plate-to-plate fluctuations. The result is $18\%/\sqrt{E}$. Thus the experimental result of $17.6\%/\sqrt{E}$ is believed to be understood in terms of the contributions of these three sources. This point is more fully discussed in ref. [8].

The response of the calorimeter to electrons is linear over the range tested (fig. 10). The development of the shower in depth is illustrated in fig. 11 for several energies. Above 5 GeV the profile changes only slightly with energy. For 5 GeV and below the fractional energy in the first sampling is much higher.

We used a 40 GeV electron beam (shower r.m.s. width at shower maximum $\approx 2-3$ cm) to scan the device for uniformity. The position of each track was measured with proportional chambers. Figure 12 shows the result of two horizontal scans, across the centre of tower 5 (i.e. across the point where all fibres cross) and across a higher point where the fibres with the two orientations occur at different x-values. The fibres are visible as an $\approx 10\%$ (5%) increase in response for two (one)

fibre-crossing positions. The fall-off towards the tower edge is largely due to side-leakage. The resolution also is degraded somewhat (from $\approx 3.4\%$ to $\approx 4\%$ at 40 GeV/c) when the shower crosses all fibres. We have checked that the response remains Gaussian at all positions, and there is no increase in the fraction of events $> 4\sigma$ above the mean when the shower crosses a fibre. We believe this (peak-to-peak) non-uniformity for electron showers could be largely, if not totally, eliminated by printing a mask on the paper sheet covering the scintillator so as to reduce a little the response over the region of the fibres. A position detector for e.m. showers at $\approx 6X_0$ would also allow one to correct any remaining non-uniformities.

6.3 Hadrons

For the hadron data presented here, the beam was directed on a point 5 cm in x and y from the corner of tower 5 in order to ensure as nearly full containment of the hadronic shower as possible, but to avoid the effects of cracks and edges (see fig. 2).

For hadronic showers, the e.m. section, the hadronic section, and the 'leakage' section will in general each contain a significant portion of the total energy. Because the ratio of active to passive material is different for these three sections, relative normalization constants are necessary in order to put the signals from these sections on the same scale. If one assumes that the true energy of a hadronic shower deposited in each medium is proportional to the mean dE/dx in that medium, one arrives at the following relative coefficients:

$$\text{e.m. section : hadronic section : leakage section} = 1 : 2.34 : 3.25 .$$

In practice, these values were used as starting values for a fitting program which varied the coefficients of each of the eight layers (four e.m., two hadronic, and two leakage, the samplings from all four towers being summed at each depth), until the best fit to a form

$$(\sigma/\mu)^2 = (A/\sqrt{E})^2 + K^2$$

is achieved. Within each section, the coefficients should be nearly identical, but we have allowed them to vary separately. The final coefficients found were

$$(1.04, 1.00, 1.02, 1.00) : (2.44, 2.30) : (4.20, 2.71) ,$$

which are near the calculated values, as expected. In other words, we choose here a set of relative coefficients which optimizes the hadronic energy resolution. The resulting expression for the resolution, valid from 10 to 80 GeV, is

$$(\sigma/\mu)^2 = (55.4\%/\sqrt{E})^2 + (6\%)^2 ,$$

as shown in fig. 13. The rather large constant term of 6% is thought to be due to the non-uniformity of the calorimeter response (see fig. 12); that is, certain regions of the hadronic shower will experience local variations of response up to 10%. The lack of full containment of hadronic showers, discussed below, may also contribute to this term. With the masking suggested in subsection 6.2, this constant term should be markedly reduced.

Other types of fits to the resolution were also tried, none of which gave statistically significant differences from $1/\sqrt{E}$ behaviour, nor a smaller value of the resolution parameter A.

In all cases, the resolutions quoted are based on Gaussian fits to the experimental distributions, which always gave good fits. A typical pulse-height distribution is shown in fig. 14 (40 GeV) with a superimposed Gaussian fit. The hadron resolution is only presented for 10 GeV and above, since the resolutions for data taken at the PS, i.e. 1, 2, and 5 GeV, were found to be dominated by electronic noise when the entire calorimeter was summed. For electrons, where only four samples are summed, the noise is much less important.

Using the coefficients from the fitting program the calorimeter response is linear above 20 GeV, but deviates slightly from linearity below 20 GeV, as shown in fig. 15. The 5 GeV point is some 8% lower than the others, and this is not understood.

For 5 GeV and below, it was possible, using time-of-flight measurements, to isolate samples of pure pions (i.e. no proton contamination). Results for these energies, then, are for these pion samples. At 2 GeV it was possible to isolate a sample of pure protons as well. The protons gave a response consistent with that of pions of the same *kinetic energy*.

The PM gains for the leakage section were inadvertently set too high; consequently, the ADCs for these tubes sometimes gave overflows at 60 and 80 GeV for those instances in which the incident particle passed through the uranium sections and only began to shower in the leakage section itself. In order to be able to treat the data sets identically at all energies, all events in which the hadron passed through the 2.62λ uranium scintillator sections and interacted only in the leakage section were removed from the data sample. This will henceforth be referred to as the 'punch-through cut'. Application of this cut eliminated less than 10% of the events in all cases, which is in qualitative agreement with the 7.3% obtained by calculating $\exp(-2.62)$. The events eliminated are simply those in which all of the particles' energy is deposited in the leakage section. To study the effects of this cut, the results at 40 GeV and below, where the overflows never occurred, can be examined with and without the cut. For these data sets, the removal of the punch-through cut caused the resolution to worsen slightly, from $55\%/\sqrt{E}$ to about $58\%/\sqrt{E}$, but did not significantly affect the energy dependences of the resolution. This cut also slightly affects the depth profiles and e/π ratios, as discussed later.

Figure 16 shows the average fractions of total energy in each sampling, divided by the number of interaction lengths in that sampling, i.e. the average longitudinal depth profiles of the showers. The depth of the shower maximum is seen to increase with energy, with the most striking changes taking place between 1 and 5 GeV. The effect of removing the punch-through cut is shown by the dashed curve in figure 16e: the main effect is to increase the mean energy in the leakage section, since the cut events have all the energy there.

Compensation is important, especially for jet physics, in order to avoid effects of fluctuations in the neutral-to-charged composition. To minimize the systematic errors, the electron and pion runs used for our compensation study were taken together in time and with the same impact point (i.e. electrons and hadrons were both taken at 5 cm in x and y from the centre of the prototype, as in fig. 2). Electron and pion analyses were done with the same programs, using identical coefficients and, in each case, summing over all uranium and iron samplings. It is interesting to note that at 10 GeV the electron resolution, using this method, was 40% worse than that obtained by summing over only the e.m. samplings of the struck tower. The results are shown in figs. 17 and 18, superimposed upon a compilation of results from other experiments. For the low-energy PS data, the systematic error bars are much larger owing to electronics problems and the smallness of the signals.

The mean value of e/π above 10 GeV is 1.10. It was found possible to make the mean e/π ratio exactly 1.0, by varying the relative coefficients of the uranium and leakage sections, but with $e/\pi = 1.0$ the best resolution obtainable was $61\%/\sqrt{E}$. Thus, we have chosen here the coefficients which give the best resolution, without regard to the value of e/π , but this is somewhat arbitrary: a perfect e/π ratio can be had at the price of only slightly worse resolution. Removing the punch-through cut has the effect of increasing the e/π values by about 0.01.

The lateral containment of hadronic showers was studied using hadron position scans. Based on these scans, the amount of transverse leakage was estimated to be of the order of a few per cent. The longitudinal containment is essentially total, see fig. 16. The e/π ratios quoted here are thus upper limits, since undetected hadronic energy will decrease e/π . The average lateral extent of a 20 GeV hadronic shower, in the four $20 \times 20 \text{ cm}^2$ towers, is shown in fig. 19. Containment of hadronic showers is discussed again in the following section.

The lack of uniformity of the calorimeter response to electrons (see fig. 12) also introduces an uncertainty in the e/π ratios, since hadrons presumably do not experience the same degree of non-uniformity versus position (a premise supported by the hadron position scans). This effect is estimated to contribute an overall 5% uncertainty to the scale of the e/π values quoted, i.e. this uncertainty is applicable to all e/π values simultaneously.

6.4 Comparison with hadron shower Monte Carlo simulations

The GHEISHA code [12], as implemented within GEANT 3.10, was run at 2, 5, 10, 20, and 40 GeV, using a geometry exactly simulating that of the prototype, including lateral size. The punch-through cut, described earlier, was also applied to the Monte Carlo data. With these, just as with the real data, it is necessary to assign relative coefficients to the sections of different composition. The optimum coefficients found for the Monte Carlo were

$$\text{e.m. : hadronic : leakage} = 1.0 : 2.1 : 2.8 ,$$

which, again, are in reasonable agreement with those expected from dE/dx . The resolutions and e/π values found with GHEISHA appear in table 2. The resolution values also appear in fig. 13 and the e/π values in fig. 17. The agreement with the experimental results is good.

Within the Monte Carlo, it is necessary to specify the degree of saturation of the response of the scintillator to ionizing particles. The standard procedure, following Birks [13], is to replace dE/dx by $dE/dx \cdot [1 + K_B \cdot dE/dx]^{-1}$. The value chosen for K_B , the so-called ‘Birks’ constant’, was that of anthracene, i.e. $K_B = 0.0146 (\text{g/cm}^2) \cdot \text{MeV}^{-1}$ [14], as K_B for KSTI 430 has not been measured. In table 2 and in fig. 17, the e/π values are also shown for $K_B = 0$.

The containment of hadronic showers within the prototype has also been studied with the Monte Carlo. The longitudinal leakage increased with energy but was always less than 1%. The transverse leakage remained essentially constant at about 3% except at 2 GeV, where it was only 1.5%.

6.5 Electron-pion discrimination

We studied e/π separation for single particles with energy between 5 and 40 GeV using the matrix method of Engelmann et al. [15]. The method compares the energy deposit in the eight depth layers (six-fold longitudinal readout for the uranium calorimeter and two-fold readout for the classical hadronic iron calorimeter) of a given shower with average showers from electrons and hadrons. In this analysis, we did not use the difference in lateral development between electronic and hadronic showers.

For a sample of N electrons (or N hadrons) we construct an 8×8 matrix M , ‘the covariance matrix’ whose elements are given by:

$$M_{ij} = (1/N) \sum_{n=1}^N (E_i^{(n)} - \bar{E}_i) \times (E_j^{(n)} - \bar{E}_j) ,$$

where $E_i^{(n)}$, $E_j^{(n)}$ is the energy observed in the i^{th} , j^{th} element of our calorimeter for the n^{th} electron (or hadron) event, and $\bar{E}_i$ is the mean energy deposited in that layer.

The inverse matrix $H \equiv (M)^{-1}$ can be used to define a single variable ζ_m for each event m :

$$\zeta_m = \sum_{i,j=1}^8 (E_i^{(m)} - \bar{E}_i) (H)_{ij} (E_j^{(m)} - \bar{E}_j) .$$

The deviations from the standard shower in the energy deposition in the different layers are correlated with each other. Two single variables ζ_{electron} and ζ_{hadron} are formed. Experimentally, at 40 GeV for example, ζ_{electron} behaves for electrons like a χ^2 distribution with 5 degrees of freedom but takes very large values for pions; ζ_{hadron} behaves for pions like a χ^2 distribution with 5 degrees of freedom but takes very large values for electrons. This behaviour is also apparent in the Monte Carlo simulations. The different behaviour of ζ_{electron} and ζ_{hadron} for electrons and pions is used to separate electrons from pions, always comparing at the same energy.

Consider the scatter plots $\log(\zeta_{\text{electron}} + 1)$ versus ζ_{hadron} obtained from electron and hadron data. We can see in figs. 20a and 20b such plots drawn respectively for electrons and hadrons at 20 GeV. If we compare fig. 20a and fig. 20b we see that, as expected, electrons are all concentrated at low ζ_{electron} and are well separated from hadrons. In fig. 20b, we find hadrons with low ζ_{electron} which simulate electrons. It is possible now to calculate hadron and electron rejection factors.

We determine an electron region and a hadron region using a cut (a simple straight line) in the scatter plots shown in fig. 20a and fig. 20b, respectively. Two different cuts are chosen: the first cut adjusted in fig. 20a [or fig. 20b] keeps 90% of electrons (e) [or 90% of hadrons (h)]; another cut was set in order to keep 97% of electrons (or 97% of hadrons). Then we can read off the hadron contamination (or the electron contamination) in the electron region (or hadron region).

The resulting hadron rejection factor for 90% and 97% electron efficiency are shown in fig. 21. The e/π separation improves with increasing energy. For 90% electron efficiency, it is $\approx 3\%$ at 5 GeV, $\approx 0.25\%$ at 15 GeV, and $\approx 0.1\%$ at 40 GeV.

The resulting electron rejection factor for 90% and 97% pion efficiency are shown in fig. 22. The π/e separation improves with increasing energy. For 90% pion efficiency, it is $\approx 5\%$ at 5 GeV, $\approx 0.1\%$ at 15 GeV, and not measurable above 20 GeV.

The uncertainty in these results is mainly caused by event statistics and the impurity of the electron and pion beams.

6.6 Measurement of albedo

During some of the low-energy runs the probability of finding particles scattered back into the forward hemisphere was measured. This was done using a scintillation counter, measuring $0.2 \text{ m} \times 0.2 \text{ m} \times 0.01 \text{ m}$, which subtended a solid angle of $\approx 0.1 \text{ sr}$ located at an angle of 50° to the incident beam direction. The pulse height and timing of this counter were recorded, having been previously calibrated by placing the counter in a beam of minimum-ionizing particles. Empirical cuts were made on the time of flight to exclude early particles (beam halo) and very late particles (possibly accidentals), and on the pulse height to exclude signals significantly below those expected from minimum-ionizing particles. Suitable cuts were also imposed on the positions in the beam-defining chambers, the Cherenkov counter, and the muon counter, and on rear hadron samplings and the 'C' hadron calorimeter (to exclude hadron contamination of the electron data), according to the type of particle under investigation. The results given are qualitatively insensitive to these cuts. We define albedo as the ratio of the number of events in which some signal was observed in the albedo counter, to the total number of events giving a beam trigger. Thus our definition is different from the more common one, in which albedo is taken to mean the fraction of shower energy which is scattered backward. A certain amount of caution must be taken against trying to find the total albedo by

scaling up by the solid angle, since there is evidence that at least some of the events produce a large number of particles in the backward direction.

The results show that muons give a very low albedo (fig. 23), compatible with zero, since the value given relies on a single event which, as it arrives rather late, could be an accidental. This gives us confidence in the higher values seen for other particles.

Hadrons show an albedo rising from about 10^{-2} at 1 GeV to about 2.5×10^{-2} at 5 GeV (fig. 23) and remaining about the same at 10 GeV. Positive and negative hadrons are compatible, but there is a significant difference between π/K mesons and protons at the energies where they could be separated by time of flight. When the hadron events giving an albedo signal are examined, it is found that they have a very slight tendency to be events with a shallower mean depth of energy deposition, but this is not very significant.

In contrast, the electrons (see fig. 23) (both positive and negative) have an albedo which falls from a value of about 5×10^{-2} at 1 GeV to a value similar to that of hadrons at 5 GeV. These events show characteristics of early shower development, with most of their energy appearing in sample 1, rather than in sample 2 as for the majority of events, and the total energy deposited in the calorimeter is noticeably deficient, suggesting that there are events in which a significant part of the energy left the calorimeter near its front surface.

6.7 Conclusions

The conclusions of these calorimeter tests can be summarized as follows:

- i) The device performs successfully as a calorimeter, proving that single fibres can be used for reading out individual scintillator plates over distances of 5 m to remote PMs (10 m with ESKA extra fibres). This method, although rather labour intensive in its present form, solves the problem of extracting light from a complex and closed geometry.
- ii) The energy resolutions for electrons and hadrons are in agreement with expectations from Monte Carlo studies when plate-to-plate fluctuations are included. For electrons, the resolution is $(17.6\%/\sqrt{E})^2 + (2.1\%)^2$; for hadrons, $(55.4\%/\sqrt{E})^2 + (6\%)^2$. These could be improved by more automated manufacture including good quality control.
- iii) The device is uniform at the $\approx 10\%$ (max-min) level. This worsens the energy resolution for hadrons. The uniformity, and hence the resolution, can probably be improved by using masking techniques.
- iv) The ratio of response $\langle e/\pi \rangle$ is close to 1, i.e. compensation is observed.
- v) Methods exist for calibrating the detector, and the signal from the uranium radioactivity can be used to accurately maintain the calibration.

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Table 1

Parameters of prototype calorimeter towers

	Sampling number	Plate thickness (mm ^{238}U)	Number of layers		Radiation lengths	Interaction lengths
			U	Scint.		
Uranium sections	1	2	5	6	3.2	0.13
	e.m. 2	2	10	11	6.7	0.28
	3	2	14	14	8.8	0.31
	4	2	10	10	6.6	0.26
	had. 5	4 and 6	8 each	17	25.5	0.82
	6	4 and 6	8 each	17	25.5	0.82
	Total	238	71	75	76.4	2.62
Leakage sections	1	$8 \times (5 \text{ cm Fe} + 1 \text{ cm scint.})$				2.50
	2	$7 \times (5 \text{ cm Fe} + 1 \text{ cm scint.})$				2.19
	Total					4.69

Table 2

GHEISHA results

Energy (GeV)	Resolution ($\%/\sqrt{E}$)	e/π $K_B = 0.0146$	e/π $K_B = 0$
2	42	1.12	1.08
5	53	1.16	1.12
10	58	1.14	1.10
20	66	1.09	1.04
40	64	1.08	1.04

Figure captions

- Fig. 1 : Geometry of various schemes for reading out a scintillator plate with fibres. (a) Bar coupling; (b) two embedded edge fibres; (c) single embedded diagonal fibre; (d) selected geometry.
- Fig. 2 : Layout of test calorimeter modules, consisting of seven uranium scintillator towers of $20 \times 20 \text{ cm}^2$. The 'C-module' behind is an iron-scintillator leakage calorimeter. The cross shows the impact point used for e/π and hadron resolution measurements.
- Fig. 3 : Emission and absorption spectra of K27 wavelength shifter.
- Fig. 4 : Layout of elements in test beam. S1-S10 are scintillation counters, and W.C. is a wire chamber.
- Fig. 5 : Distribution of the mean number of photoelectrons per scintillator for muons, for 17 samples (each sample is 6-17 plates, see table 1).
- Fig. 6 : Spread in optical transmissions for wavelength-shifting fibre to photocathode, including connector, clear fibre and PM contact.
- Fig. 7 : (a) Pulse height spectrum for 40 GeV muons in one tower, after pedestal subtraction (b) As (a), for 80 GeV muons.
- Fig. 8 : Spectrum of pulse heights from 40 GeV electrons in first four samplings, with Gaussian fit superimposed.
- Fig. 9 : Dependence of energy resolution for electrons on the beam energy. The ordinate is $(\sigma/\text{mean})^2$, with σ obtained from Gaussian fits.
- Fig. 10 : Deviations from linearity for electrons, shown as ADC counts/energy from 1 to 80 GeV.
- Fig. 11 : Depth profiles of electron-induced showers in the four e.m. samplings, expressed as the fraction of the total energy per radiation length, for five energies.
- Fig. 12 : Variation of response with beam position, for 40 GeV electrons, showing the enhanced response near the wls fibres and the fall-off towards the tower edge.
- Fig. 13 : Dependence of energy resolution for hadrons on the beam energy. The ordinate is $(\sigma/\text{mean})^2$ with σ obtained from Gaussian fits.
- Fig. 14 : Pulse-height spectrum for 40 GeV hadrons, in the full calorimeter (including the Fe leakage calorimeter), with a Gaussian fit.
- Fig. 15 : Deviations from linearity for hadrons, shown as ADC counts/energy, from 1 to 80 GeV.
- Fig. 16 : Average depth profiles of hadron-induced showers in the eight samplings (six of the prototype, two of the Fe leakage calorimeter), expressed as the fraction of the total energy per interaction length, for six energies. The dashed curve in (e) shows the effect of removing the 'punch-through' cut described in the text.
- Fig. 17 : Ratio of response to electrons and pions including comparison with Monte Carlo for two values of Birks' constant K_B .
- Fig. 18 : Ratio of response to electrons and pions, superimposed on a compilation of data from other calorimeters.
- Fig. 19 : Sharing of energy between the four towers for 20 GeV hadrons incident at point indicated. CMOD is the iron leakage section.
- Fig. 20 : Scatter plot of covariance parameter ξ_{hadron} against $\log(\xi_{\text{electron}} + 1)$ (a) from electron data and (b) from pion data. Lines indicate 90% efficiency for electrons (e) and hadrons (h).
- Fig. 21 : Probability for a hadron to simulate an electron as a function of the beam energy. The error bars (statistical fluctuations only) are calculated by Monte Carlo (GEANT 3.10).

- Fig. 22 : Probability for an electron to simulate a hadron as a function of the beam energy.
- Fig. 23 : Albedo, defined as the fraction of events with measurable energy in a counter in front of the calorimeter, versus momentum for electrons, hadrons, and muons.

Fig. 1

Fig. 2

Fig. 3

S1...S10 : TRIGGER COUNTERS
W.C : WIRE CHAMBER

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

TRANSVERSE ENERGY DISTRIBUTION (20 GeV/c)

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23