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A HODOSCOPE CALORIMETER FOR HIGH ENERGY HADRONS

THEP-IISN-LAPP collaboration

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ABSTRACT

A total absorption hodoscope calorimeter is described. It allows to measure at the same time the energy of the incident hadrons as well as their coordinates with a precision of 1 cm for hadron energies of tens of GeV and higher. The behaviour of the calorimeter with incident pions, kaons, antiprotons and electrons is studied.

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1. INTRODUCTION

The use of calorimeters as detectors in particle physics experiments is gaining importance with the rise of particle beam energy. Calorimeters are primarily intended for the energy determination of electrons, photons or hadrons. Nevertheless it has been shown in the case of electromagnetic showers that a calorimeter with an hodoscope structure which is sampling the profile of the shower may also be used to measure the impact coordinates of the electrons or the photon generating the shower [1]. The precision of about 1 mm in localisation which has been achieved is an order of magnitude smaller than the width of the electromagnetic shower and than the width of the hodoscope cell [1,2]. In this way, such hodoscope calorimeters become autonomous apparatus for the simultaneous detection of many electrons and photons and as such have effectively been used as spectrometers for particles decaying into photons [3,4].

Although hadronic showers are characterised by a wider shower profile and by more important fluctuations in the number of shower particles, the same ideas may be applied to hadron calorimetry.

Section 2 of the present paper describes a hadron calorimeter with a hodoscope structure which has been used in charge-exchange experiments at the IHEP 70 GeV proton synchrotron [5].

Section 3 shows that its energy resolution, being similar to that of conventional calorimeters, is not impaired by the hodoscope segmentation.

Section 4 describes the coordinate measurement technique and the way to optimise the hodoscope cell width.

The potential role of hadron hodoscope calorimeters in experiments in the multiTeV range of accelerators energy is considered in the conclusion.

2. HODOSCOPE CALORIMETER

2.1 Description of the set-up

The calorimeter is a sandwich detector in which 1 cm thick scintillator hodoscope planes are interleaved with 2.5 cm thick steel converter plates (fig. 1). Its total thickness of 76 cm steel and 30 cm of scintillator is equivalent to about five interaction lengths depending on the nature of the hadron. Its lateral dimensions are $70 \times 70 \text{ cm}^2$.

It is made of three identical modules which are placed immediately behind each other along the mean particle direction. Each module includes ten steel plates separated by ten scintillator planes which consist each of fourteen 5 cm wide hodoscope strips. Successive planes of scintillators are alternatively made of horizontal and vertical channels.

The light outputs of all five successive strips which have the same x or y coordinate in a module are fed to a unique photomultiplier by curved light guides. In this way there are 84 counters for 420 scintillator strips in the calorimeter.

In order to compensate for the difference in light losses through the light guides because of their varied lengths and forms, the longer ones are wrapped in highly reflecting aluminised mylar and the shorter ones in white paper.

The counters are made of NE-114 scintillator. The attenuation of the scintillation light is 50% over the length of a 70 cm hodoscope strip without reflecting wrapping. Combinations of variable step spiral wrappings with aluminised mylar, white paper and black paper allow to compensate for the difference of attenuation of the light emitted by particles crossing a hodoscope strip at different places along its length. These combinations have been empirically determined through measurements in particle beams and with radioactive sources. A light collection uniformity of a few percent is obtained in this way (fig. 2).

The calorimeter total weight is four tons, it has been installed on a platform which may be moved along the beam.

2.2 Photomultipliers and Electronics

FEU 84-3 photomultipliers with 12 dynodes and a 24 mm diameter S-20 photocathodes have been adopted. Measurements have shown that the use of a small photomultiplier which collects one fifth of the scintillator light only does not alter the calorimeter energy resolution by more than 10% because the latter is not determined by photoelectron statistics but mainly by hadron shower fluctuations [6].

High voltage dividers are optimised to get a linear output current to better than 1% over a 10^4 dynamical range [7]. The five last dynodes are fed with high current booster supplies for operations at rates up to 10^6 particles/sec.

The signals are fed in 12-bit ADC's [8] through 60 ns linear gates. The calorimeter electronics which are connected on line to a HP 2100 computer have been described previously [9].

2.3 Calibration of the calorimeter

In hodoscope calorimeters, the total amount of light output from the scintillators is collected on a relatively large number of photomultipliers (84 in the actual case) compared to ordinary total absorption counters [10]. As a consequence photomultiplier instabilities as well as calibration inaccuracies have a larger influence on the resolution of the detector and must be minimised.

A single set of light emitting diodes (LED) is used first to precalibrate the calorimeter, i.e. to preset photomultiplier working voltages, before switching the beam on, and second to control the calorimeter stability, i.e. to check the performance of each counter during measurements. The light is distributed to each counter through optical fiber light-guides. The LEDs are triggered after each accelerator pulse during the runs.

The calibration itself is made with a muon beam covering the whole aperture of the calorimeter. For each channel the mean value of the muon pulse amplitude $\langle A_\mu \rangle$ is determined, as well as the width of their distribution ($\sigma_\mu / \langle A_\mu \rangle \simeq 15\%$). These numbers and the mean amplitudes of the LED signals are stored. Their ratios are used in the process of normalising the hadron signals.

The whole calibration procedure, including the measurement of the light attenuation along each of the 84 counters (fig. 2) and the positioning of the calorimeter relative to the beam axis with a one mm precision, takes three hours.

During running periods, the LED control system may detect and correct counter instabilities at a level of 1%. Control muon calibrations are repeated at weekly intervals.

The absolute precision of the muon calibration is about 3%. This number takes into account the uncertainty due to the large dynamical factor between hadrons and muons: 40 GeV hadron signals are 30 times larger than $\langle A_\mu \rangle$.

3. PARTICLE ENERGY MEASUREMENTS

The properties of the hodoscope calorimeter as an instrument to measure hadron energy have been studied with negative particle beams at 25, 30 and 40 GeV/c. Pions, kaons, antiprotons and electrons were identified with threshold Cerenkov counters [11]. The beam divergence was less than 3 mrad. The impact coordinates of the particles on the calorimeter were determined with a precision of 1.5 mm using scintillator hodoscopes.

The modular construction of the calorimeter allows to get some information on the longitudinal development of the hadron shower. The three amplitudes corresponding to the three modules are shown on fig. 3 after normalisation to the total amplitude: $\alpha_i = A_i / A_{\text{tot}}$. A_i is the sum of the signals of all 28 counters in i -th module ($i = 1, 2, 3$) and $A_{\text{tot}} = \sum_{i=1}^3 A_i$ is the total signal from the calorimeter.

The narrow peak (fig. 3) in the region of small α_1 amplitudes is due to particles going through the first module without interaction. The number of these allows to estimate an effective absorption length λ_{eff} for the particles in the scintillator steel sandwich. The thickness of one module is equivalent to $(1.8 \pm 0.1) \lambda_{\text{eff}}$ for antiprotons, $(1.4 \pm 0.1) \lambda_{\text{eff}}$ for negative pions and $(1.3 \pm 0.1) \lambda_{\text{eff}}$ for negative kaons at 25 GeV/c, in general agreement with known cross sections.

Total amplitude spectra for 25 GeV and 40 GeV antiprotons are shown on fig. 4. Their shape is nearly gaussian with a tail towards small amplitudes corresponding to a leakage of shower particles [12]. When an energy release of at least 20% is required in the first module ($\alpha_1 > 0.2$; 75% of the total number of antiprotons), the leakage is becoming negligible and the peak width shrinks by 10%.

The mean total amplitude depends linearly on the particle energy to better than 1% (fig. 5).

The calorimeter energy resolution is $\sigma_E/E = 9.6\%$ for 40 GeV antiprotons ($\alpha_1 > 0.2$). It decreases somewhat less slowly than $E^{-1/2}$ when E is increasing between 25 and 40 GeV (fig. 6). This is due to increasing shower particle leakage at high energies. If the sample of antiprotons is restricted to those which release more than 50 % of energy in the first module, the resolution drops to 8.5 % at 40 GeV (fig. 6).

The energy resolution for pions and kaons is 10% larger than for antiprotons, because the total thickness of the calorimeter is only four effective lengths for these particles.

Adding the signals from either X or Y scintillator planes only is equivalent to multiply by two the converter plate thickness t . The resolution then deteriorates by about 25% in agreement with a $t^{1/3}$ dependence [12].

The lateral uniformity of the calorimeter sensitivity has been tested with 30 GeV/c antiproton over its entire surface. The plot of $\langle A_{\text{tot}} \rangle$ as a function of the impact coordinate is fitted by a curve calculated from

data on the shower profile (see sect. 4) (fig. 7(a)). The agreement simultaneously confirms that the procedure for calibrating individual counters warrants a 2 to 3% accuracy. In the central region ($-20 \text{ cm} < y < 20 \text{ cm}$) the lateral shower leakage is negligible. It becomes significant and the energy resolution is quickly worsening with particle impact at a distance less than 10 cm to the sides (fig. 7(b)).

Incidentally, the behaviour of this calorimeter as an electromagnetic shower detector [2,10] has been studied with photons from the decay of 30 GeV π^0 's. The whole shower is practically absorbed in the first module which is equivalent to about 15 radiation lengths. The energy resolution σ_E/E is 5%. The mean total amplitude $\langle A_{\text{tot}} \rangle$ is 25% larger than for antiprotons of the same energy.

In conclusion, the present calorimeter has energy measuring characteristics very similar to those of other total absorption hadron counters [12]. It has been extensively used to measure $\bar{n}$ (fig. 8) and K_L^0 in charge exchange experiments at IHEP [5] since 1978.

4. COORDINATE MEASUREMENTS

As for electromagnetic showers [13], the method for the localisation of hadron impacts with hodoscope calorimeters is based on the comparison of the energy deposited in a few hodoscope channels surrounding the shower axis.

4.1 Profile of hadron shower

Fig. 9 shows the profile of centered 25 GeV/c antiproton showers measured with the present calorimeter.

These measurements and others made with particles incoming at different coordinates across the channel allow to determine the differential of the mean projected profile (fig. 10). As in the case of electromagnetic showers [12] this curve is well described by the sum of two exponentials.

$$\langle a(y) \rangle = a_1 e^{-|y|/b} + a_2 e^{-|y|/b_2} \quad (1)$$

The hadron shower is composed of a relatively narrow core with $b_1 \approx 2.2$ cm and a non negligible peripheral contribution with $b_2 \approx 7$ cm ($a_1 \sim 2/3$ and $a_2 \sim 1/3$).

The channel width of the actual calorimeter $2 \Delta = 5$ cm is such that

$$\Delta \lesssim b_1$$

so that a still significant part of the central core leaks into nearby channels.

4.2 Coordinate measurements

The evaluation of the center of gravity of the shower with data from either X or Y hodoscopes provides a simple but biased estimate [1] of the corresponding incident particle coordinate

$$y_0(\text{or } x_0) = 2 \Delta \frac{\sum_j A(j)}{\sum_j A(j)} \quad (2)$$

where index j is either X or Y hodoscope channel number.

With the present detector ($\Delta \lesssim b_1$), the deviation between true and mean evaluated coordinates is always less than 6 mm. It is illustrated by fig. 11(a) where the mean coordinates of 25 GeV/c $\bar{p}$ as determined by using formula (3) are plotted as a function of the true coordinate measured with the scintillator hodoscopes. Five channels from the central zone of the shower only are used in the summation (2). The spatial resolution deteriorates when the small signals of further cells are included in the sum because of the electronic noise.

The bias introduced by relation (2) is removed by using a smoothed correction curve traced through the experimental points of fig. 11(a). The resulting mean coordinates $\bar{y}_f$ are shown by fig. 11(b). The residual fluctuations are then less than 1-2 mm, much less than the space resolution which can be achieved.

The best coordinate precision is obtained when only the data from the module in which the shower has deposited the largest fraction of its energy (largest α_1) are used. Figs 12(a) shows the lateral development of the shower through the three modules of the calorimeter. The lateral development of the shower increases fast as a function of its longitudinal development. This is still better illustrated by fig. 12(b) in which data are plotted for showers which started to develop in the first module only ($\alpha_1 > 0.2$). FWHM goes from 3.5 cm in the first module to 17 cm in the last one.

The resolution at 40 GeV/c is

$$\sigma_{x,y} = 8.5 \text{ mm}$$

when the module with maximum α_1 is used (fig. 13). It increases by 0.8 mm when the sum of all three modules is used.

$\sigma_{x,y}$ is somewhat larger at lower energies. It is 9.6 mm at 30 GeV/c and 10.2 mm at 25 GeV/c. These numbers are about the same for $\bar{p}$, π^- and K^- .

The space resolution is constant over the whole aperture of the detector, except for borderline zones, i.e. as long as two hodoscope channels are available on both sides of the channel with maximum amplitude (fig. 14). It should also be underlined that the precision on the measurement of the two coordinates are completely uncorrelated, i.e. σ_x does not depend on y and vice versa.

Space and energy resolutions are rather independant. The error on $\bar{y}_f$ resulting from a 10% variation of the amplitude in one hodoscope channel is shown to be less than 1 mm. This means that even a rough energy calibration of the hodoscope counters does not affect space resolution significantly.

The possibility to measure the coordinates as well as the energy of two hadrons generating neighbouring showers depends on the distance between both impacts and on the depth at which the hadrons start their conversion.

Two showers practically do not overlap at a distance of 25 cm (fig. 10). The known lateral development of a hadron shower in the three modules (fig. 12(b)) generally allows to disentangle the coordinates of two showers separated by

$$\ell > 15 \text{ cm} .$$

This calorimeter may be used to measure coordinates of electromagnetic showers also. The precision is 4 mm for 30 GeV electrons (to be compared with 1.2 mm in NICE [2]). The method which has been developed for photon calorimeters may be applied here to distinguish hadron and electromagnetic showers [14]. The modular structure allows a selection of α_i and the examination of the lateral development of the shower. A rejection factor of 500 may be achieved between hadrons and electrons or photons.

4.3 Choice of hodoscope channel width

The space resolution has been measured as a function of the hodoscope channel width 2Δ in three other configurations by adding the signals from 2, 3 and 4 neighbouring scintillators to simulate $2\Delta = 10$ cm, 15 cm and 20 cm width (figs 13 and 15).

When the ratio Δ/b_1 increases, the bias introduced by the evaluation of the center of gravity (2) is quickly increasing [1] but notwithstanding larger uncertainties it may still be corrected as explained above [13].

$\sigma_{x,y}$ is rather well parametrised by the relation

$$\sigma_{x,y} = \sigma_0 e^{\Delta/\Delta_0} \quad (3)$$

except for narrow channel widths ($2\Delta < 5$ cm). In this case, σ_{xy} is experimentally found to depend very little on Δ . A simple relation like (3) does not take into account the high correlation of the fluctuations between the energy deposits in neighbouring hodoscope counters [13].

The curve of fig. 15 shows that a choice of 2Δ up to seven cm would have meant no significant loss in space resolution for the hodoscope calorimeter which has been described.

CONCLUSION

A hodoscope calorimeter for the simultaneous measurement of the coordinates and energy of high energy hadrons (charged and neutral) has been tested and utilised in experiments with particles of a few tens of GeV. This kind of apparatus is quite simple to build and reliable in use. It has the essential property of measuring many hadrons simultaneously.

It is also particularly promising for experiments to be done in the TeV region, which might be obtained at accelerators in a not too distant future. Above 1 TeV it is becoming a precision instrument which should measure particle energy to better than 3% and coordinates to better than 2 mm, and evaluate the mass of an unstable particle through its decay products to better than 2%.

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FIGURE CAPTIONS

Fig. 1 Schematic drawing of the hodoscope calorimeter. Five counters only are shown in the x and y planes.

1. 2.5 cm thick steel converter plates.
2. Scintillators.
3. Light guides.
4. Fiber optics for light calibration.
5. Photomultiplier.

The last plate of each module is a 0.5 cm thick steel plate which is used to keep the "sandwich" together.

Fig. 2 Variation of the muon signal amplitude as a function of the particle impact along a scintillator strip. Full line: x plane; dotted line: y plane.

Fig. 3 Spectrum of the signal amplitudes in each of the three modules, normalised to the total amplitude in the whole calorimeter A_{tot} , measured with 25 GeV/c antiprotons.

Fig. 4 Spectra of total amplitudes for 25 GeV/c and 40 GeV/c antiprotons. Amplitudes are normalised to the mean muon signal $\langle A_{\mu} \rangle$. The wide 40 GeV curve represents all events. The more narrow one represents events with $\alpha_1 > 0.2$.

Fig. 5 Mean total amplitude as a function of the total energy. Negative pions Negative kaons: Antiprotons: o (E includes the annihilation of a nucleon).

Fig. 6 Energy resolution of the calorimeter. Antiprotons: o, all events; , events with $\alpha_1 > 0.2$; *, events with $\alpha_1 > 0.5$. Pions: $\alpha_1 > 0.2$. Kaons: , $\alpha_1 > 0.2$. The curve is $\sim 1/\sqrt{E}$.

Fig. 7(a) Mean total amplitude for 30 GeV antiproton signals as a function of the impact coordinate y.

FIGURE CAPTIONS (Cont'd)

Fig. 7(b) Energy resolution as a function of y .

Fig. 8 Energy spectrum of 25 GeV antineutrons produced in the charge exchange reaction $\bar{p}p \rightarrow \bar{n}n$.

Fig. 9 Mean shower profile of 25 GeV antiprotons.

Fig. 10 Mean differential shower profile (25 GeV antiprotons).

Fig. 11(a) Dependence of the mean position $\bar{y}_0$ of the center of gravity of the shower as a function of the true shower coordinate y_c
(b) Residual fluctuations after correction. The error bars show the space resolution.

Fig. 12 Mean shower profile in each of the three calorimeter modules.

(a) all events

(b) events with $\alpha_1 > 0.2$.

Fig. 13 Distribution of measured coordinates for two hodoscope channel widths (40 GeV antiprotons) Dotted curves are normal distributions.

Fig. 14 Space resolution as a function of the particle impact through the calorimeter aperture.

Fig. 15 Space resolution as a function of the width of the hodoscope channel.

$E = 25 \text{ GeV}$: 0

$E = 40 \text{ GeV}$: 0

The curves represent the function (5) with $\Delta_0 = 5 \text{ cm}$ and $\sigma_0 = 5.3 \text{ mm}$ and 6 mm respectively.

fig. 1

fig. 2

fig. 3

fig. 4

fig. 5

fig. 6

fig. 7

fig. 8

fig. 9

fig. 10

fig. 11

fig. 12

Fig. 13

fig. 14

fig. 15

17 100

1

1

30.