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MEASUREMENTS OF ENERGY FLOW DISTRIBUTIONS OF 10 GeV/c HADRONIC SHOWERS IN IRON AND IN ALUMINIUM

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ABSTRACT

The lateral distribution of energy of hadron showers initiated by 10 GeV/c π^- and protons has been measured at various depths in Fe and Al absorbers. It is found to scale with the density of the absorber. The energy flow is characterized by a cone of ±65 mrad opening angle. The direction of the energy flow can be determined by two points, the vertex of the primary interaction and the centre of gravity of the energy deposited by the shower. The fluctuation of the centre of gravity has been measured using a fine-grained calorimeter and is found to give the shower direction with an rms spread of 60 mrad.

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1. INTRODUCTION

Calorimetric methods are of increasing importance in high energy experiments$^{1)}$. The measurements described here were carried out to gain more direct experimental information on hadron shower development. This information is required for designing large total absorption calorimeters which can be used to measure the total energy and the direction of energy flow of hadron showers.

Two series of measurements with different techniques were performed. In the first series the lateral distribution of the energy flow of hadron showers was measured at several depths in iron and in aluminium. In the second series the distribution and the fluctuation of the centre of gravity of the energy flow was studied in aluminium absorber.

Previous investigations of showers are reported in the literature$^{2-7)}$, but to our knowledge there exist no measurements relevant to details of the energy flow.

2. LATERAL DISTRIBUTION OF THE ENERGY FLOW

A scintillation counter was used to scan the lateral distribution of energy flow at various depths of absorber; the pulse height at each position was averaged over 5000 showers and recorded.

A schematic side view of the experimental set-up is shown in figure 1. A beam of 10 GeV/c is incident on the absorber; it is defined by a coincidence between two scintillation counters, 1 and 2, each of them 6 cm high and 0.3 cm wide. Another scintillation counter, A, with dimensions of 30 x 30 cm^2, behind 80 cm of concrete and 50 cm of iron, served to veto muons in the primary beam.

The absorber was composed of modules of 50 x 50 cm^2 cross section and the scanning counter F was inserted in a 3 cm gap between the absorber and the end module. In this way an approximately homogeneous medium was created around the scanning counter in which also backscattering could contribute.

The scanning counter F was a plastic scintillator 0.3 cm wide and its height was limited to 5 cm to ensure constant light collection efficiency. The distribution was measured in the horizontal position with a resolution of $\pm 0.3/\sqrt{2}$ cm; integration over the vertical coordinate was performed by summing up the average pulse height for the vertical steps of 5 cm each at each horizontal position. The scanning operations were controlled on-line by a computer. At any given position a timing gate of 80 ns length was opened following each incident beam particle. The charge accumulated during this time was digitized and averaged over 5000 events. The sensitivity of the pulse height measurement was approximately one photoelectron per 10^4 beam particles or the equivalent of 10^{-5} of a minimum ionizing track. The pedestal was subtracted after each event and a correction for accidental coincidence was applied at each position.

Lateral distributions were measured at 10, 20, 30, 50 and 70 cm depth of iron absorber using a 10 GeV/c beam of negative pions and at 28, 56 and 84 cm depth of aluminium absorber using 10 GeV/c protons. The results are shown in figures 2 and 3.

The lateral distributions are characterized by a cusp-like behaviour near the incident particle position and very long tails extending beyond 100 g/cm^2 of iron. While the cusp-like behaviour near the beam axis, due to surviving beam particles and possibly also due to elastic and inelastic diffraction scattering, has been observed before, e.g. by Citron et al.$^{8)}$ who counted tracks in emulsions, observation of long tails has not been reported before, perhaps because no measurement of the distribution of energy deposition had been attempted. It must be stressed that the small amount of energy collected in these tails can be correlated with an incident particle due to precise timing. We are attributing these tails to low energy particles created in the shower by nuclear break-up and by nuclear de-excitation. A shower calculation by Monte Carlo methods including these processes indeed shows similar tails.[9)]

We note that the central part of the shower remains narrow even at considerable depth and that hence the direction of its energy flow remains closely related to the direction of the primary hadron. Figure 4 shows the shower width (full width at half maximum) as a function of absorber depth, expressed in a scale of length x density. We observe approximate scaling of the width with the density of the absorber material. A 10 GeV shower is developing in a cone of about ±65 mrad opening angle.

3. CENTRE OF GRAVITY OF THE ENERGY FLOW

We have investigated the possibility of actually determining the direction of the energy flow by two points:

- the vertex of the primary interaction;
- the centre of gravity of the energy deposition by the shower.

A schematic plan view of the experimental set-up is shown in figure 5. The vertex position was determined by two beam defining counters (1 and 2) and by a target counter, T, consisting of 5 layers of 0.8 cm scintillator and 2.5 cm aluminium. A threshold was set on the pulse height collected from the scintillator plates to select events[*] with the primary interaction at the position of the target counter; less than 3% of the events thus selected had their primary vertex at a position beyond the target.

The shower developed in aluminium plates and in a fine-grained calorimeter installed at a variable distance behind the target. The calorimeter was composed of nine vertical cells, each 5 cm wide and 50 cm high, consisting of 20 layers of 0.6 cm liquid scintillator[**] and 2 cm aluminium plates, each covered with 0.8 mm thick plexiglas reflectors,

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[*] It has been checked experimentally that the value of the threshold does not bias the shower distributions.

[**] NE 235 obtained from Nuclear Enterprises Inc.

thus totalling 121.4 g/cm^2 of material or 1.3 absorption lengths. The scintillators of each cell were optically coupled to a single photomultiplier and the pulse height Q_i of each cell was digitized using ADC techniques and read by a computer.

All information is related to the lateral cell coordinate, X_i. The data acquisition program computed on-line for each event the following four quantities:

(1) the centre of gravity: $\bar{X} = \Sigma X_i Q_i / \Sigma Q_i$.

(2) the rms width with respect to the centre of gravity:
$W = (\Sigma Q_i (\bar{X} - X_i)^2 / \Sigma Q_i)^{\frac{1}{2}}$.

(3) the mean pulse height $<Q_i>$ in each cell i, averaged over many events.

(4) the total pulse height per event, summed over all cells, $Q = \Sigma Q_i$.

These quantities were accumulated in histograms and were also written onto magnetic tape. The effective gain of all cells was carefully equalized by moving them into a muon beam, defined by a coincidence between the beam defining counters and a large scintillator A behind 80 cm of concrete and 50 cm of iron (see figure 5). Pedestal subtraction was performed on-line.

Using this set-up we have taken a large amount of data in various configurations using a 10 GeV/c beam of negative particles (98% pions). As a check on consistency we are comparing in figure 6 the lateral energy distribution measured behind 28 cm of aluminium using the single scanning counter and using the calorimeter; the agreement is good.

Examples of distributions of the centre of gravity, of the rms width with respect to it, and of the lateral energy distribution are shown in figures 7-9 for 1 m distance between the centre of the target and the centre of the calorimeter. We note that the centre of gravity is fluctuating inside the width at half maximum of the lateral energy distribution with a spread which is comparable to its width. The variance of this spread σ_W is about 40% of the width itself.

It must be stressed, however, that these results are only approximate because of the limited lateral and longitudinal dimensions of the fine-grained calorimeter which does not contain the full shower development. As a consequence the measured values, e.g. of the rms spread of the centre of gravity, tend to be too large because part of the shower energy is leaking out longitudinally and to be too small because the observable fluctuations are limited by the lateral dimensions of the calorimeter.

This second effect can be estimated with the help of figure 10, showing the pulse height profile of the shower with its axis displaced by 12.5 cm with respect to the calorimeter centre. Comparing figure 10 and figure 9 we find an increase in the rms width of the shower profile by 15% and estimate a comparable correction to be applied to the rms spread of the centre of gravity. We have not applied this correction to the summary of our results in figure 11, showing the rms spread of the centre of gravity position $\sigma_{\bar{X}}$, the mean value of the rms width of the profile with respect to the centre of gravity, $\bar{W}$, and its spread σ_W as a function of interspersed absorber thickness.

We conclude that the direction of hadron showers initiated by negative pions of 10 GeV/c can be measured with an rms spread of 60 mrad using a fine-grained calorimeter and a vertex detector.

Due to the approximate scaling of the shower width with the density of the absorber material, this result, obtained for a mean density of $\rho = 1.5$ g/cm^3 and a detector width of 5 cm, can be applied to different values of density if the width of the detector elements is scaled accordingly. Doubling the bin size did however not change the results.

A novel application of calorimetric methods to the problem of measuring the direction of the energy flow of hadrons seems therefore within reach of present technology.

ACKNOWLEDGEMENTS

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P. Stähelin, private communication.

FIGURE CAPTIONS

Figure 1 - Side view of the set-up for measuring the lateral energy distribution of hadron showers. 1 and 2 are beam defining counters, F is the scanning counter and A a muon veto counter.

Figure 2 - Lateral energy distribution of showers induced by 10 GeV/c π^-, measured at 10, 20, 30, 50 and 70 cm depth in Fe.

Figure 3 - Lateral energy distribution of showers induced by 10 GeV/c protons, measured at 28, 56 and 84 cm depth in aluminium.

Figure 4 - Shower width (FWHM) as a function of depth in absorber measured in units of length x density. There is approximate scaling with the density. The solid line indicates a cone of ±65 mrad opening angle.

Figure 5 - Schematic plan view of the experimental set-up used for the centre of gravity measurements. The vertex of the primary interaction is localized in a target counter T. A fine-grained calorimeter composed of 9 cells measures the centre of gravity of the energy flow in the horizontal projection.

Figure 6 - Comparison of the lateral energy distribution measured behind 28 cm of aluminium using the scanning counter and the calorimeter.

Figure 7 - Observed distribution of the centre of gravity, at 1 m distance from the target T, using a 10 GeV/c π^- beam.

Figure 8 - Observed distribution of rms width around the centre of gravity at 1 m distance from the target T.

Figure 9 - Observed lateral energy distribution at 1 m distance from the target, beam centred on axis.

Figure 10 - Observed lateral energy distribution at 1 m distance from the target, beam displaced by 12.5 cm.

Figure 11 - Summary of experimental results showing the spread of the centre of gravity distribution, $\sigma_{\bar{X}}$, the mean width $\bar{W}$ and its spread σ_W for different absorber depths and for 1 m distance between target and calorimeter. The direction of the energy flow can be measured with an accuracy of $\tan^{-1}(\sigma_{\bar{X}}/\text{distance}) \sim 60$ mrad.

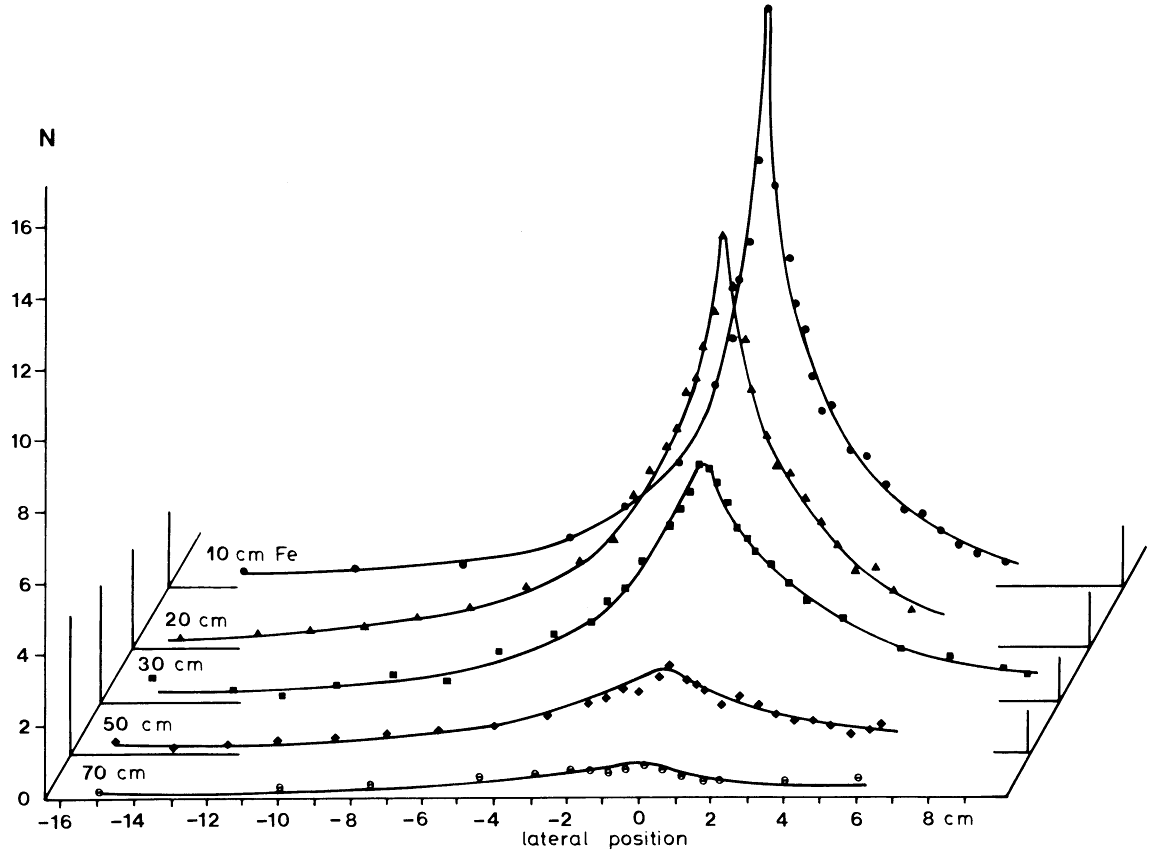

N
0
2
4
6
8
10
12
14
16
10 cm Fe
20 cm
30 cm
50 cm
70 cm
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8 cm
lateral position

Fig. 1

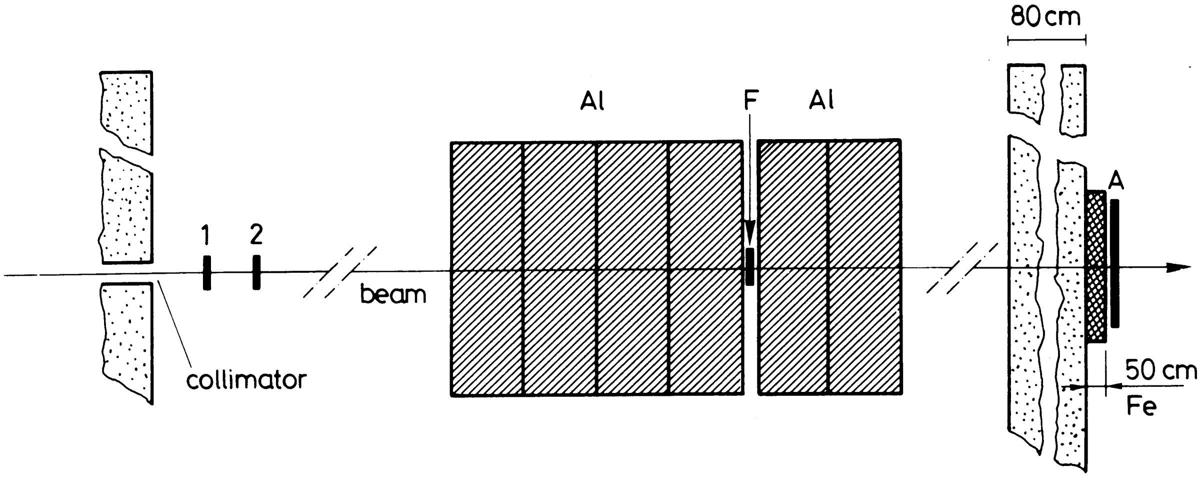

80cm
Al
F
Al
A
1
2
beam
collimator
50 cm
Fe

Fig. 2

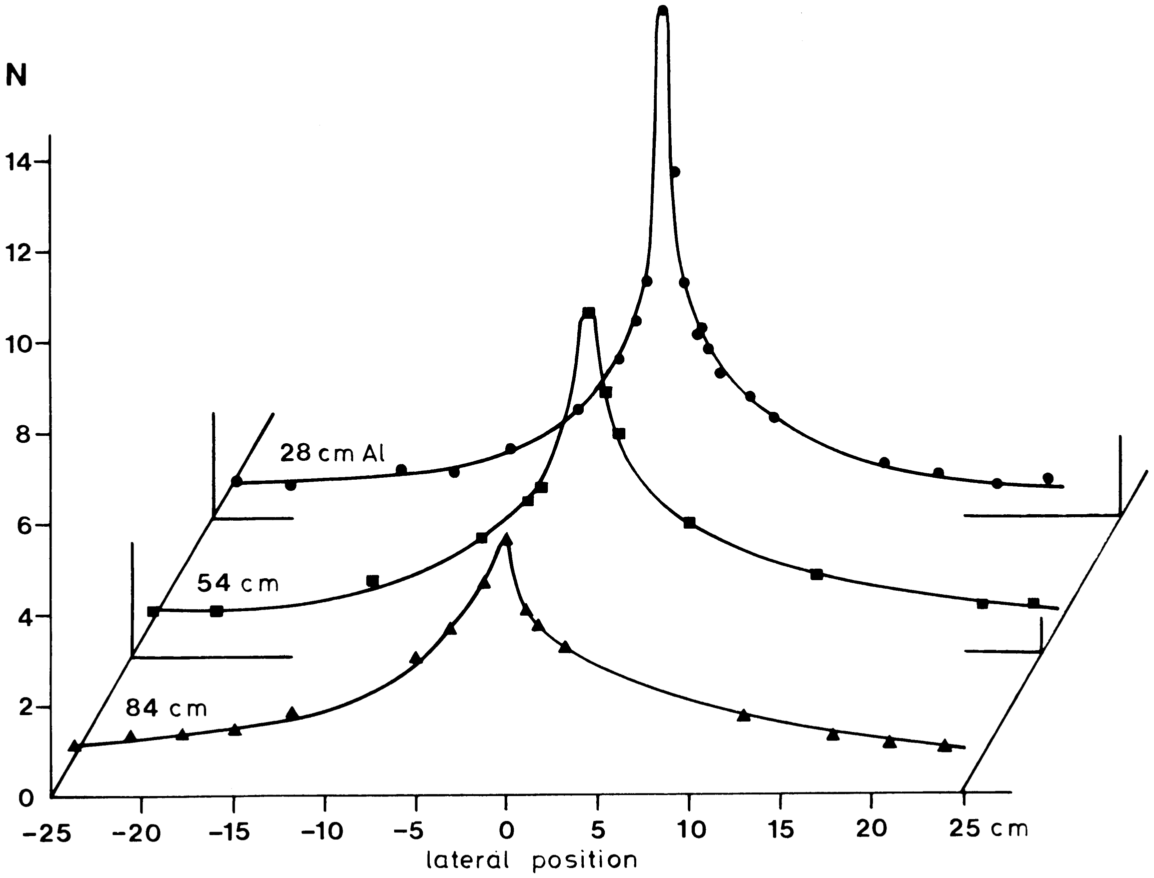

N
14
12
10
8
6
4
2
0
28 cm Al
54 cm
84 cm
−25
−20
−15
−10
−5
0
5
10
15
20
25 cm
lateral position

Fig. 3

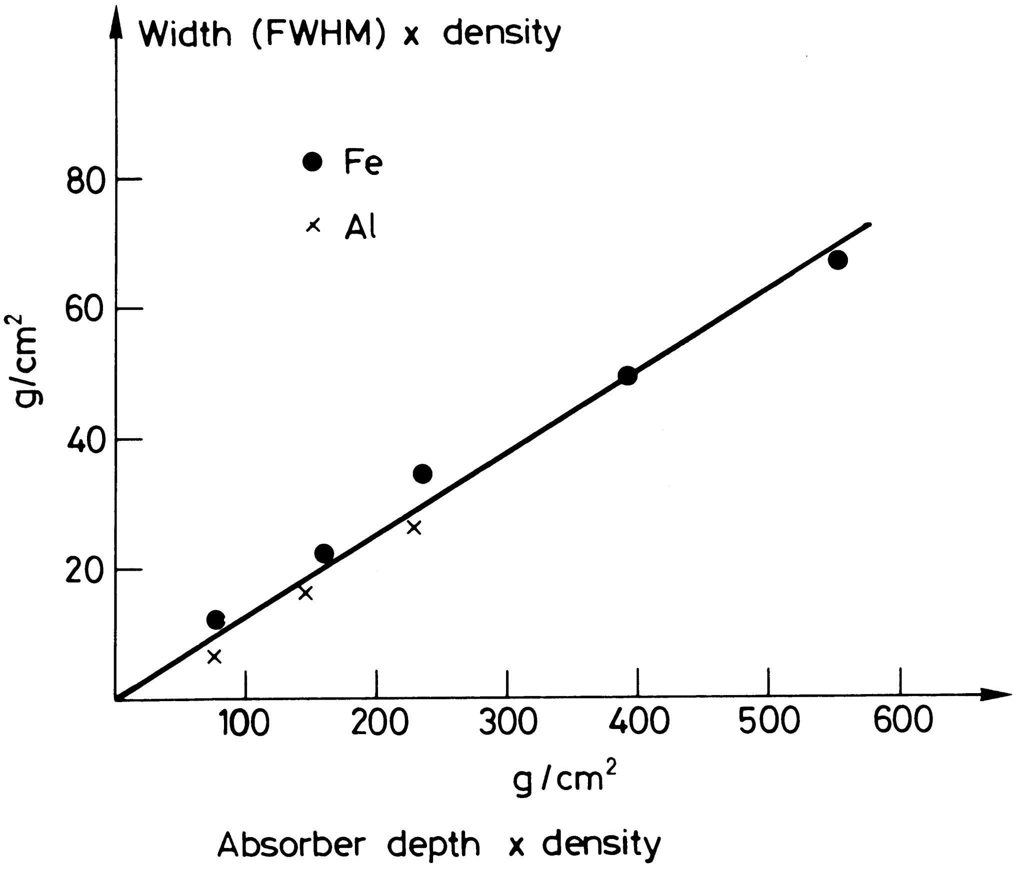

Width (FWHM) x density
● Fe
× Al
80
60
40
20
g/cm²
100
200
300
400
500
600
g / cm²
Absorber depth x density

Fig. 4

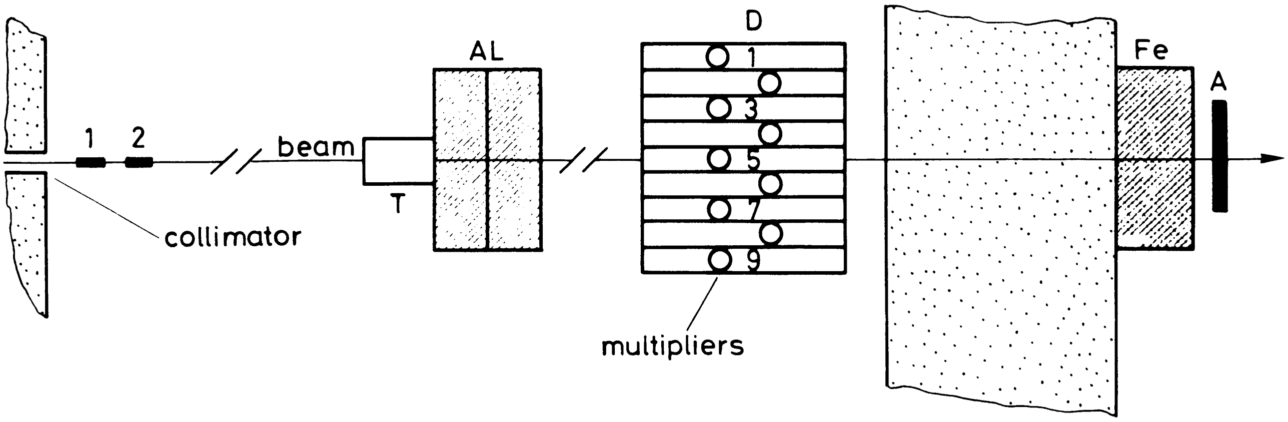

D
AL
Fe
A
1
2
beam
T
collimator
1
3
5
7
9
multipliers

Fig. 5

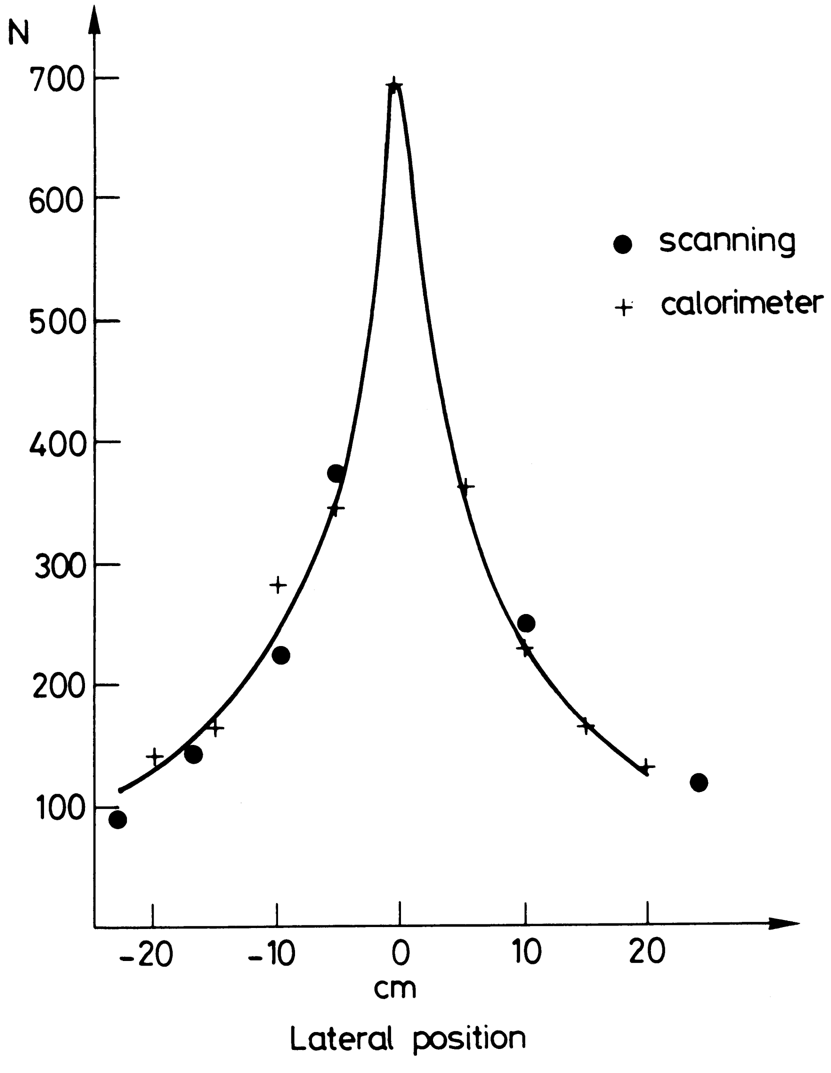

N
700
600
500
400
300
200
100
● scanning
+ calorimeter
-20
-10
0
10
20
cm
Lateral position

Fig. 6

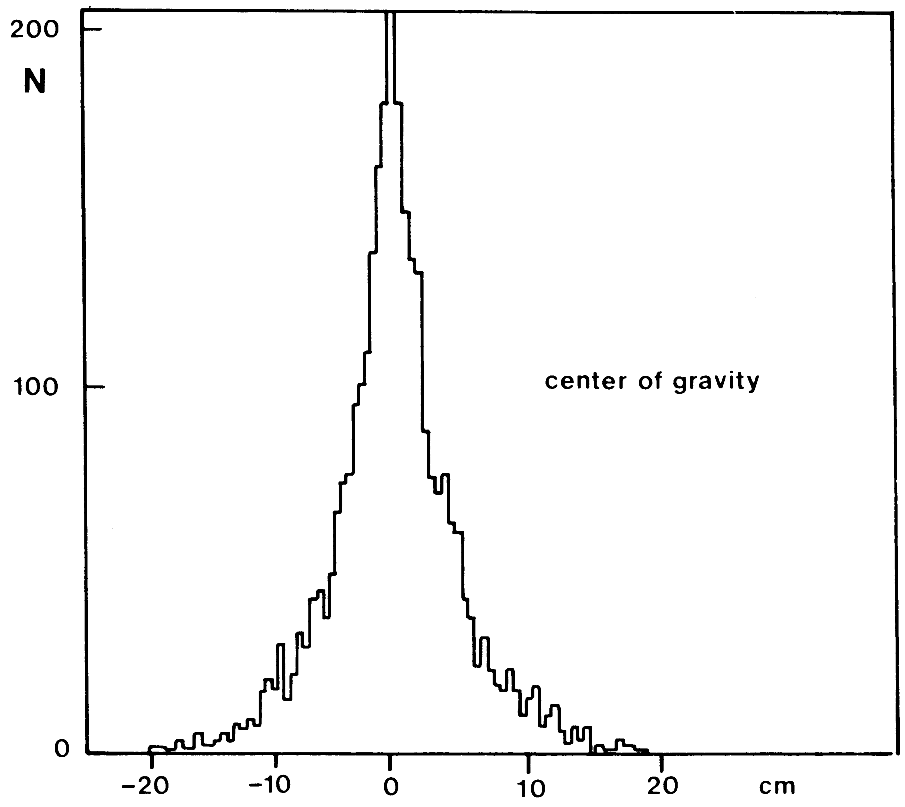

200
N
100
0
-20
-10
0
10
20
cm
center of gravity

Fig. 7

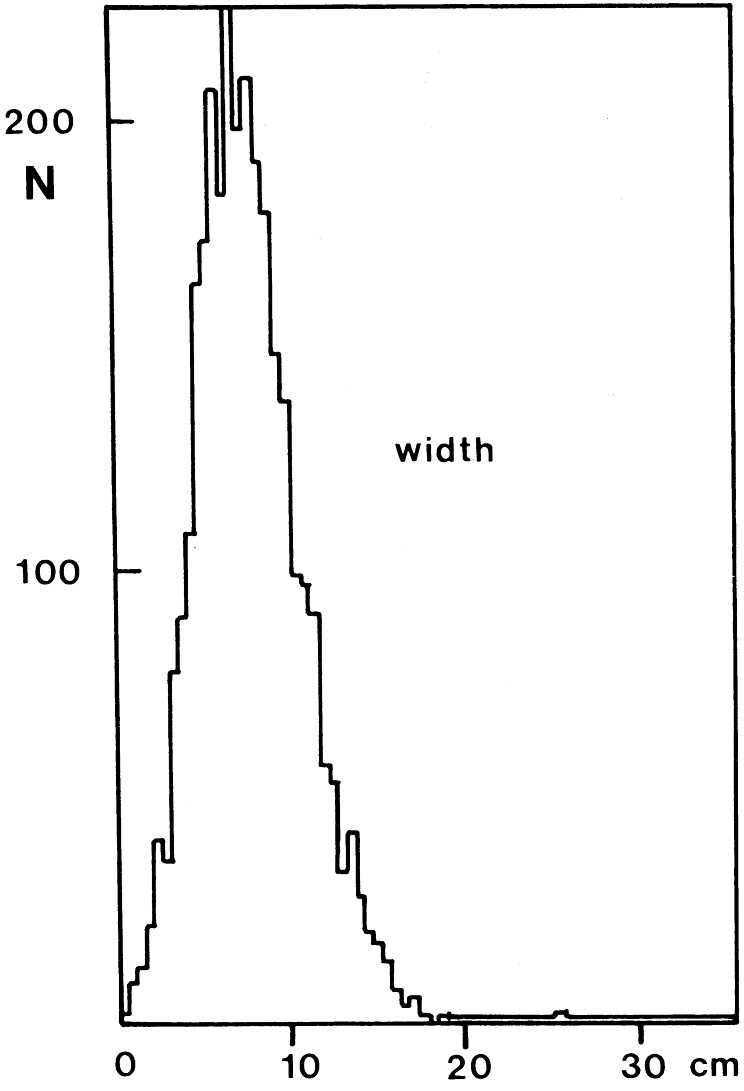
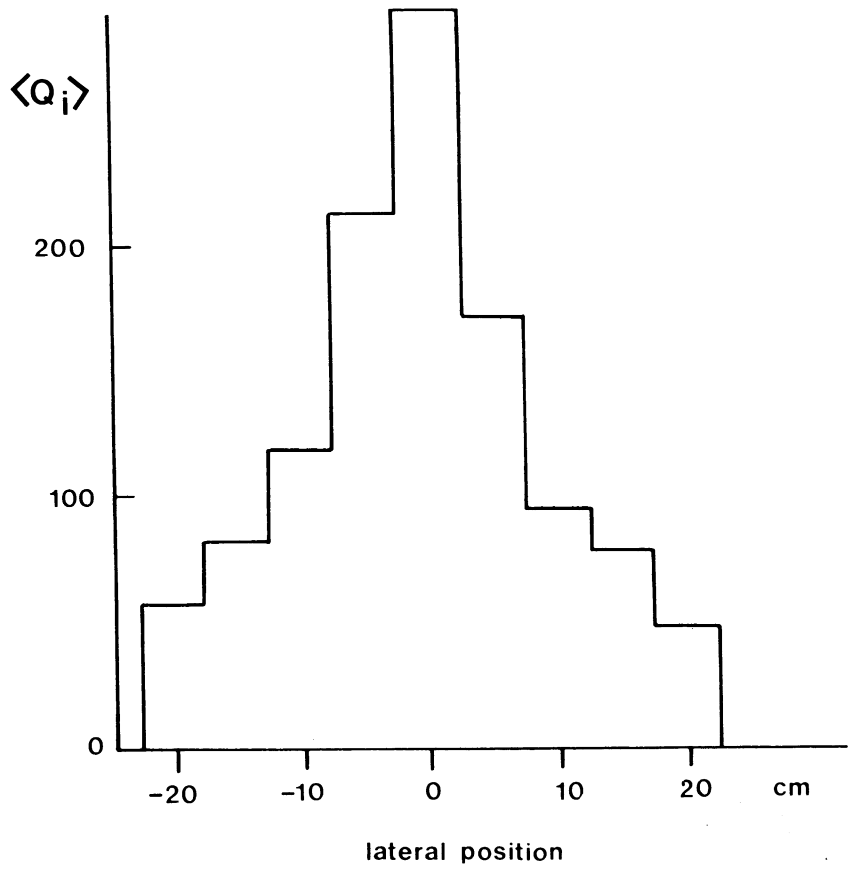
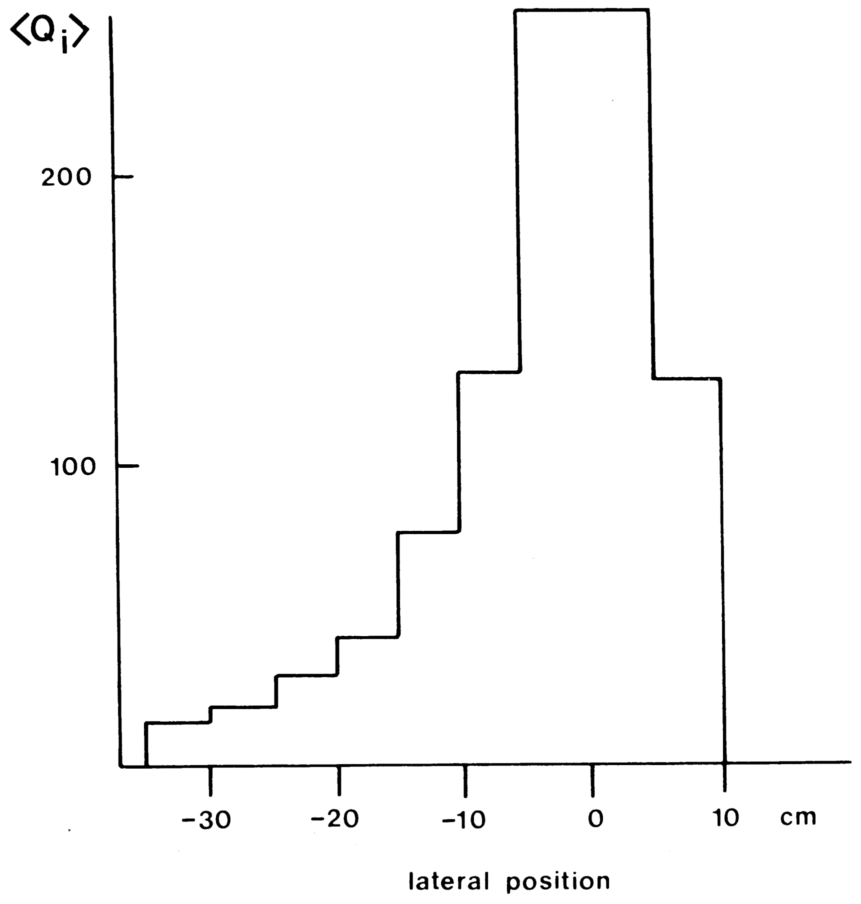

200
N
100
0
10
20
30 cm
width

Fig. 8



$\langle Q_i \rangle$
200
100
0
-20
-10
0
10
20
cm
lateral position

Fig. 9



$\langle Q_i \rangle$
200
100
-30
-20
-10
0
10
cm
lateral position

Fig. 10

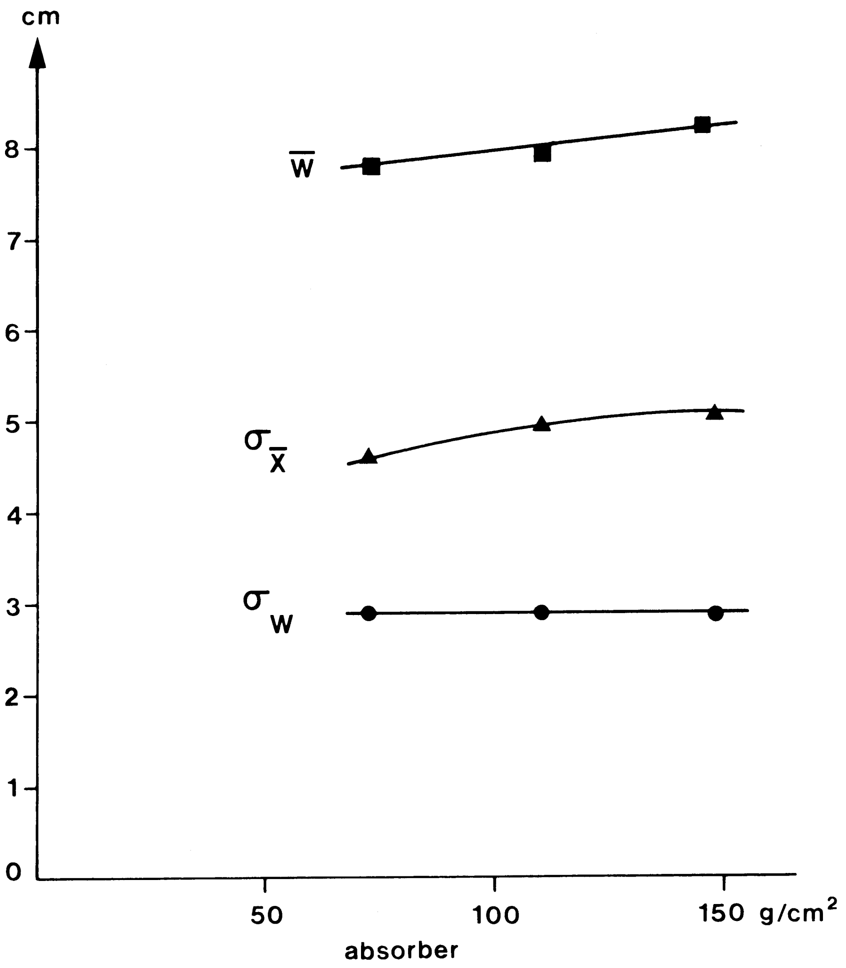

cm
8
7
6
5
4
3
2
1
0
$\bar{w}$
$\sigma_{\bar{x}}$
σ_w
50
100
150 g/cm^2
absorber

Fig. 11