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NEW IDEAS IN CALORIMETRY

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ABSTRACT

The hadron calorimeter for the CERN ISR experiment R 807 is of the fission compensating type, using ^{238}U as absorber. The possibility of replacing part of the uranium by more easily accessible material without destroying the good properties of a pure uranium-scintillator calorimeter has been investigated.

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INTRODUCTION

One of the most important factors influencing the performance of a hadron calorimeter is its different response to the two components of a hadron initiated cascade:

the electromagnetic component due to neutral pions produced in the cascade and

the nuclear component consisting of charged pions, nucleons and nuclear fragments.

The difference in response is related to the fact that in the electromagnetic cascade essentially all the energy is converted into ionization by electrons and hence detected, whereas part of the energy in the nuclear cascade remains unmeasurable having been spent on disruption of nuclei (nuclear binding energy) or carried away by neutrinos or non-interacting neutrons. The relative magnitude of these two components is mainly determined in the very first interaction of the incident hadron. Hence, on an event-by-event basis, large fluctuations must be expected due to the rather low multiplicity of particles produced in this primary interaction - especially at low beam energies. These fluctuations are reflected in the energy resolution of the calorimeter.

It has been demonstrated in an experiment at CERN [1] that the fluctuations in the amount of "missing energy" in the nuclear part of a hadronic cascade can be compensated by exploiting the effects of nuclear fission in uranium. In this experiment a hadron calorimeter using depleted ^{238}U as absorber and liquid argon as active material was investigated extensively and shown to have an energy resolution superior to that of other hadronic devices ($\sim\frac{0.30}{\sqrt{E}}$). Also, the ratio of electron to pion signals was measured to be smaller than that obtained with a commonly used absorber like iron - varying with incident momentum between 1.12 at 5 GeV/c and $\sim$ 1 at 10 GeV/c, Fig. 1.

The idea of using uranium as absorber has been taken up in the experiment R807 at the CERN ISR [2]. We are presently building a 2π uranium-scintillator calorimeter for study of large transverse momentum phenomena. The expected response of this device has been investigated by means of Monte Carlo and it seems that a slight over-compensation leading to a ratio of electron to pion signals smaller than 1 cannot be excluded. Such a possibility makes it rather interesting to consider the notion of a hybrid calorimeter where uranium plates are interspersed with plates of a less exotic absorber in such proportion as to obtain a ratio of electron to pion signals close to 1. As this ratio would then be comparable to that found with the uranium - liquid argon calorimeter described above, one might hope for the energy resolutions also being not too different.

To investigate the idea of a hybrid calorimeter, tests have been made at the CERN PS:

1. Two different kinds of material have been considered as possible admixtures (second absorbers) in a hybrid uranium device - namely copper and lead. The reason for using copper rather than iron is the requirement that the final calorimeter operates in a magnetic field. Otherwise, the properties of a copper-scintillator detector are expected to be very similar to those of an iron-scintillator device with the same sampling frequency. Lead was chosen as a relatively easily available material close to uranium in atomic number ("uranium without fission").

   Total containment calorimeters with copper plates in one case and lead plates in the other have been tested in electron and pion beams and their response compared.

2. As the only uranium plates available were those used in the uranium-liquid argon experiment, the hybrid test calorimeter had to be of hexagonal shape and rather small lateral dimensions. In this test, iron was used as the second absorber and the response of a pure uranium-scintillator, a pure iron-scintillator and a hybrid calorimeter was compared.

THE SET-UP

The tests have been performed in the d_{31} beam at the CERN PS. The maximum obtainable momentum in this beam is 10 GeV/c. The maximum rates are $\sim 10^6$ (10^5) positive (negative) particles per burst (300 ms).

The electron fraction is normally below 1%, increased somewhat for the duration of the tests by means of a lead converter placed immediately after the target.

The set up is shown schematically in Fig. 2. $\check{C}_1$ (not shown) and $\check{C}_2$ are two Čerenkov counters used for tagging electrons. Beam definition was provided by the scintillation counters C_A (40 mm x 40 mm), C_B (60 mm x 60 mm) and the large counter C_V (400 mm x 400 mm). C_V had a circular hole (diameter 20 mm) in the center and was used for vetoing events with more than one particle hitting the calorimeter within the sensitive period of the system. Muons were identified using the scintillation counter C_M placed behind an 80 cm thick iron wall.

The device used for comparison of lead and copper as calorimeter absorbers is sketched in Fig. 2 (inset). It consisted of units foreseen to be part of the R807 calorimeter (Fig.3). Two sets of three units each were placed one behind the other. To minimize the distance between the two, the upstream calorimeter was mounted with its back (and the photomultiplier tubes) facing the beam. Care was taken that the beam did not directly hit the tubes.

The units consisted of alternating 5 mm thick copper plates and 2.5 mm thick acrylic scintillator plates, in total 100 cells. The distance between two consecutive copper plates was 3 mm, ensured by spacers. During part of the tests the copper plates in the central unit of the upstream calorimeter were replaced by 5 mm thick lead plates. The light collection system consisted of BBQ doped acrylic wave length shifter sheets (thickness: 2 mm) entirely covering both sides of the absorber volume, and acrylic lamella light guides glued to their back edges for directing the light towards the PM's (1.5" Phillips XP 2008 UP). The dimensions of one unit were: 214 mm width, 500 mm height, 800 mm depth (in the beam direction). Hence, the calorimeter had a lateral depth of $\geqslant$ 4 absorption lengths*and a longitudinal depth of $\geqslant$ 6.9 absorption lengths, enough to contain showers produced by 10 GeV/c hadrons incident at the center.

The calorimeter used for comparison tests of uranium, iron and mixture is sketched in Fig. 4. It consisted of hexagonal plates of absorber (width: 350 mm, height: 300 mm) interleaved with rectangular acrylic scintillator plates (350 mm x 300 mm x 3 mm). The scintillators were read-out by means of BBQ doped wave length shifter bars (width: 150 mm, thickness: 3 mm), two each side, connected to PM's (EMI 9830 KB) via acrylic light guides. Each scintillator plate was wrapped in aluminium foil with only the two edges facing the wave length shifters uncovered. The WLS bars themselves were also wrapped in aluminium foil, the sides viewing the scintillators excepted.

Three configurations with different fractions of uranium but approximately same depth in terms of absorption lengths were considered. The interleaving of uranium and iron was done uniformly throughout the total depth of the calorimeter. For comparison, tests were also made with a hexagonal lead - scintillator sandwich device. A summary of the properties of the various devices can be found in Tables 1 and 2 below.

TABLE 1

CONFIGURATION	I	II	III	IV
Number of plates	187	155	118	169
Material	U	1.7 mm U	Fe	Pb
Thickness (mm)	1.7	4 mm Fe	4	3
Fraction of Fe plates	0	0.40	1	0
Scintillator thickness (mm)	3	3	3	3
Total depth (abs.1.)	3.51	3.48	3.30	3.52
Most probable muon energy loss (MeV)	981.3	842.2	723.2	962.6

Hexagonal Calorimeters

TABLE 2

CONFIGURATION	I	II
Number of plates	100	100
Material	Cu	Pb
Thickness (mm)	5	5
Scintillator thickness (mm)	2.5	2.5
Total depth (abs. 1.)	3.76	3.09
Most probable muon energy loss (MeV)	803.1	864.6

Calorimeters for copper vs lead comparison tests
(parameters for one unit)

MUON CALIBRATION

The calibration of the calorimeter was based on single ionizing muon signals. Before each series of measurements, runs were made with 10 GeV/c muons incident at the center of each calorimeter module. The calibration of the PM's was achieved using the most probable values of the muon pulse height distributions. For the hexagonal calorimeter tests, where each side of the device was read out by two PM's, the calibration was done by varying the most probable value for each PM in such a way as to obtain the smallest FWHM to peak ratio for the normalized distribution. In all cases the normalized muon signal was determined to be 1 within 2%.

The most probable muon pulse heights have been used to define a "single ionizing pulse" in the calorimeter. All pulse height distributions presented below have been normalized in terms of an equivalent number of single ionizing particles.

The absolute energy scale for each calorimeter configuration was determined from a calculation using the Landau formula for most probable energy losses in an absorber [3]. The formula was applied in each case for the total absorber thickness. The computed values are given in Tables 1 and 2.

RESULTS OF TOTAL CONTAINMENT LEAD AND COPPER COMPARISON

Runs were made at 5,7 and 10 GeV/c with incident pions and at 5 and 7 GeV/c with incident electrons.** At 10 GeV/c the electron rate was too low to permit reasonable data taking. In all cases the beam particles were incident at a spot 50 mm below the centre of unit 2 (see Fig. 2) in order to avoid the rod which constrains mechanically the whole structure.

The response of the lead and copper calorimeters is summarized in Figs. 5 to 9. Fig. 5 shows the peak of the pulse height distribution (in terms of equivalent number of single ionizing particles) as a function of beam momentum for incident electrons and pions. In all cases the points are fitted well by straight lines going through zero. It should be noted that for both pions and electrons the measured signal is consistently lower in a lead calorimeter as compared to a copper device. Fig. 6 shows the measured pulse height distributions for 10 GeV/c pions incident on copper and on lead. The curve drawn on top of the distribution is in each case a Gaussian fit to the symmetric part of the peak. The r.m.s. width of this fit determines the resolution for pions

$$R = \frac{\sigma}{E_{PEAK}} \begin{cases} = 0.16 \text{ at } 10 \text{ GeV in lead} \\ = 0.17 \text{ at } 10 \text{ GeV in copper} \end{cases}$$

Fig. 7 shows the variation of the energy resolution with incident momentum. The difference between lead and copper is negligible (of the order of 1%). Fig. 8b displays the resolution for a device of half the total depth of the calorimeter ($\sim$3.4 absorption lengths). Again, the difference between lead and copper is small. A fit to the data in Fig. 8b gives

$$R = \frac{0.004E + 0.567}{\sqrt{E}} \quad \text{for copper}$$

$$R = \frac{0.004E + 0.522}{\sqrt{E}} \quad \text{for lead.}$$

The dependence of the resolution on $E^{+\frac{1}{2}}$ reflects the effects of non-containment.

Fig. 9 displays observed pulse height spectra for electrons at 5 GeV/c incident on copper and on lead respectively. The non-Gaussian low energy tail in the distributions is caused by the amount of material in the beam line upstream of the calorimeter, making the electrons radiate. A comparison shows that the FWHM of the two distributions are approximately equal. The curve drawn on top of the data in Fig.9a is a Gaussian with a r.m.s. width representing the resolution expected from previous tests of the copper-scintillator units [4].

RESULTS OF HEXAGONAL CALORIMETER TESTS

Data were taken at 5,7 and 10 GeV/c with pions and at 5 and 7 GeV/c with electrons. The beam was always incident at the centre of the device. The results are presented in Fig. 10 for pions and in Fig. 11 for electrons. Fig. 10 shows the pion signal (in terms of equivalent number of single ionizing particles) in the four different configurations as a function of beam momentum. One notes that the signals in configurations I and II are almost equal but consistently smaller than the signal in a pure iron calorimeter (configuration III). The signal in the lead calorimeter (configuration IV) is at all momenta smaller than any of the others. However, before drawing any conclusions from these facts it must be stressed that the data has to be considered with some caution. None of the calorimeters was large enough to contain hadron showers laterally, the degree of lateral containment depending on the absorber material. (All had the same longitudinal depth). Hence the fact that uranium and lead calorimeters yield a smaller signal than an iron calorimeter, although the denser materials are expected to contain hadron showers at least just as well as iron, must be partly ascribed to the larger nuclear losses in high-A materials, and partly due to the different dE/dx ratios of active to passive absorbers in the different configurations. Correcting for the dE/dx ratio one obtains a uranium response which, at all momenta, is larger than the iron response.

(Note: the pion signal in the lead calorimeter is too high due to rate problems. Hence, a comparison of dE/dx corrected signals for iron and lead calorimeters would show a negligible difference - although one would expect a smaller amount of "visible energy" in the lead case due to nuclear effects).

Fig. 11 shows the electron signal as a function of incident momentum as measured in the four calorimeter configurations. Again, the signal measured in the iron calorimeter is larger than any of the others whereas the response of the lead calorimeter is the smallest of all. This feature can be attributed to the increasing importance of transition effects at the metal scintillator interfaces for metals with high atomic numbers. Another way of presenting the influence of transition effects on the measured electron signal is by comparing this signal with the expected signal computed on the basis of most probable muon energy loss as given in Table 1. The results are shown in Table 3. The errors quoted are actually overestimates taking into account the bad beam conditions.

The ratios of electron to pion signals for the different configurations are found in Table 4. When comparing the different values one should remember that uranium contains better than iron, making us expect a smaller discrepancy between the two with total containment devices. The electron to pion ratio for lead (IV) should probably be corrected by a factor of 1.1 (to take into account the pion data problem mentioned above).

An estimate of the energy leakage, corrections can - in the case of uranium - be obtained from the uranium-iron-liquid argon measurements mentioned above. Assuming the leakage in the uranium-scintillator calorimeter to be the same as in the liquid argon device, it is possible to calculate the electron to pion ratio expected in a total containment uranium-scintillator detector. One then obtains at 5 GeV/c, the estimate

$$0.98 < \frac{E_e}{E_\pi} < 1.06$$

and at 10 GeV/c

$$0.84 < \frac{E_e}{E_\pi} < 0.94$$

where for the lower limit a fission amplification factor of 1.4 for uranium as compared to iron has been assumed [1], whereas the higher limit assumes no fission amplification. Comparing to the liquid argon values 1.12 at 5 GeV/c and $\sim$ 1 at 10 GeV/c, see Fig. 1, one could argue that "overcompensation" is achieved.

An estimate of the total containment electron to pion ratio for an iron-scintillator calorimeter can be obtained from the copper calorimeter measurement, considering the rather similar properties of the two absorber materials. The ratio: 1.46 at 7 GeV/c agrees with that obtained with an iron-liquid argon calorimeter above 5 GeV/c, see Fig. 1.

Finally, the total containment electron to pion ratio for lead has been measured in the tests described above, the value being 1.37 (see Table 4).

CONCLUSIONS

Pure uranium seems to give a lower electron to pion ratio than the other materials. This is due to two factors:

- the amplified pion signal due to fission
- the decreasing electron signal due to transition effects.

The magnitude of the fission amplification factor for uranium as compared to lead can be found comparing the estimated total containment uranium signal with the measured signal in lead. One gets 1.42 - 1.54 at 5 GeV/c (depending on the limit taken for $\frac{E_e}{E_\pi}$ in uranium, see above).

It appears that interleaving uranium with another metal, like iron, indeed increases the electron to pion ratio - however to determine a mixture giving exactly 1 requires more total containment tests both with pure uranium and with varying uranium - non-uranium absorber ratios. This is an ongoing project which also will give the resolution.

Use of lead as second absorber seems to provide no great advantage over copper from the physics point of view. Hence, from mechanical considerations copper is more advantageous.

Footnotes:

* p.4: Here and in the following an "absorption length" is the absorption length for nucleons as given in Particle Properties Data Booklet, 1978.

**p.6: After the tests had finished, it was found that the beam momenta had systematically been different from the assumed 5,7 and 10 GeV/c. Throughout the text (Addendum excepted) the nominal values 5,7 and 10 GeV/c should be understood as the true values: 5.61, 7.71 and 9.92 GeV/c.

TABLE 3

TYPE		MOMENTUM (GeV/c)	
		5	7
URANIUM	(I)	0.98 ± 0.05	1.04 ± 0.06
URANIUM / IRON	(II)	1.03 ± 0.06	1.08 ± 0.06
IRON	(III)	0.98 ± 0.05	0.99 ± 0.05
LEAD	(IV)	1.09 ± 0.06	1.09 ± 0.07
		a	
LEAD		1.12 ± 0.06	1.12 ± 0.06
COPPER		0.98 ± 0.06	0.98 ± 0.05

b

Ratio of theoretical to measured electron signal for the hexagonal calorimeter configurations (a) and for the lead vs copper test calorimeters (b). The theoretical electron signal is calculated on the basis of most probable muon energy loss as given in Table 1.

TABLE 4

TYPE		MOMENTUM (GeV/c)	
		5	7
URANIUM	(I)	1.35 ± 0.05	1.32 ± 0.05
URANIUM / IRON	(II)	1.50 ± 0.05	1.42 ± 0.04
IRON	(III)	1.67 ± 0.05	1.68 ± 0.04
LEAD	(IV)	1.44 ± 0.06	1.43 ± 0.06
		a	
LEAD		1.37 ± 0.03	1.38 ± 0.02
COPPER		1.47 ± 0.03	1.46 ± 0.02

b

Ratio of electron to pion signals for the hexagonal calorimeter configurations (a) and for the lead vs copper test calorimeters (b). When comparing "lead" and "copper" values in Table 4b one should bear in mind that in the lead case only the central module of the upstream calorimeter (see Fig. 2) had lead plates while all the others had copper plates. Hence, the pion signal in the "lead" case is somewhat overestimated as compared with an all lead configuration.

REFERENCES

[1] C.W. Fabjan et al., Nucl. Instr. and Meth. 141 (1979) 61.

[2] A study of large transverse momentum phenomena, Proposal
S. Almehed et al., CERN/ISRC/76-36, ISRC/P95.

[3] R.M. Sternheimer and R.F. Peierls, Phys. Rev. B3 (1971) 3681.

[4] O. Botner et al., submitted to Nucl. Instr. and Meth (1980).

FIGURE CAPTIONS

Fig. 1 Calorimeter for uranium-iron-liquid argon tests. Ratio of electron to pion signals for uranium-liquid argon and iron-liquid argon calorimeters.

Fig. 2 Schematic view of the set-up for total containment calorimeter tests. Inset: top view of the calorimeter.

Fig. 3 A copper (lead) scintillator unit for total containment tests.

Fig. 4 Hexagonal test calorimeter.

Fig. 5 Pion and electron signals as a function of beam momentum for lead and copper calorimeters in total containment test.

Fig. 6 Pulse height distribution for incident pions; (a) lead; (b) copper. Total containment tests.

Fig. 7 Energy resolution $R = \sigma/E_{peak}$ for pions as a function of beam momentum. Total containment tests.

Fig. 8 Response of a 3.5 absorption length deep copper (lead) calorimeter:
(a) signal as a function of incident momentum;
(b) resolution at 1 GeV, $(\sigma/E_{peak})\sqrt{E}$, as a function of incident momentum.

Fig. 9 Pulse height distributions for 5 GeV/c incident electrons,
(a) copper,
(b) lead.

Fig. 10 Response of hexagonal calorimeters to incident pions.

Fig. 11 Response of hexagonal calorimeters to incident electrons.

Fig. 12 Schematic view of the set-up for uranium module tests;
(a) front view
(b) top view.

Fig. 13 A uranium-scintillator module (U2),
Module U1 had only one set of six wave lengths shifter bars covering each side.

ADDENDUM

Recently (July-August 1980) tests were performed with uranium scintillator sandwich modules as a preparation for the construction of the 2π calorimeter for the R807 experiment at the CERN ISR. The tests were done in the d_{31} beam at the CERN PS in a set-up very similar to that described previously. Fig. 12 shows schematically the calorimeter configuration. Two different uranium-scintillator modules were tested:

A) U1, consisting of alternating uranium plates (dimensions: 200 mm x 1200 mm x 2 mm) and acrylic scintillator plates (200 mm x 1200 mm x 2.5 mm) - in total 160 of each. The read-out system consisted of BBQ doped wave length shifter bars (width: 198 mm, thickness: 2 mm) connected to the photomultiplier tubes via acrylic light guides. Six wave length shifter bars covered each side of the module;

B) U2, divided longitudinally into two separate read-out sections: a front section with a total depth of 6.3 radiation lengths consisting of 10 uranium-scintillator cells (uranium thickness: 2 mm) and a back section of 125 uranium-scintillator cells (uranium thickness: 3 mm), see Fig. 13. The width and length of the uranium and the dimensions of the scintillator plates were as for the U1 module.

As the total amount of uranium plates available was limited, a copper-scintillator module of the kind described previously (see Fig. 3) was placed next to each uranium module to ensure lateral shower containment. Also, as shown in Fig. 12b,copper-scintillator modules acting as energy catchers were placed downstream of the actual test calorimeter.

Runs were made with hadron and electron beams at 2, 5, 7 and 10 GeV/c. In all cases the beam was hitting at the center of "tower" 4 (see Fig. 12a) of a uranium module - viz. U1 in configuration A or U2 in configuration B. The results which should be considered as preliminary are presented in Table 5 below.

TABLE 5

Mom. (GeV/c)	CONFIGURATION A			CONFIGURATION B		
	Electrons R	Hadrons R	$\frac{E_e}{E_\pi}$	Electrons R	Hadrons R	$\frac{E_e}{E_\pi}$
2	0.164±0.002	0.32±0.01	1.088±0.004	0.162±0.002	0.32±0.02	1.095±0.004
5	0.138±0.002	0.32±0.01	1.134±0.004	0.158±0.002	0.32±0.01	1.113±0.004
7	0.139±0.002	0.34±0.01	1.146±0.004	0.159±0.002	0.34±0.01	1.120±0.004
10	0.139±0.003	0.33±0.01	1.126±0.003	0.171±0.002	0.34±0.01	1.117±0.003

Results of the uranium-scintillator calorimeter tests. R is the energy resolution at 1 GeV, $R = (\sigma/E_{peak})\sqrt{E}$. The errors cited are only statistical. The systematic errors are estimated to $\sim$2% for R and 3-4% for E_e/E_π.

Tests were also made of various hybrid modules with different mixtures of uranium and copper plates. The results of these measurements are presently being studied.

Here, it should be noted that the ratio of electron to pion signals, E_e/E_π, is consistently larger than 1 - apparently excluding overcompensation. However, the numeric values of this ratio as cited above should be considered with some caution as they depend on the fission amplification factor used for copper to make it comparable to uranium. (Here, the factor is $\sim$1.4 chosen from rather arbitrary considerations). Also in configuration B, the ratio E_e/E is influenced by the balance chosen between the front and back sections of the U2 module. Studies of the front to back balancing and the fission amplification are still continuing.

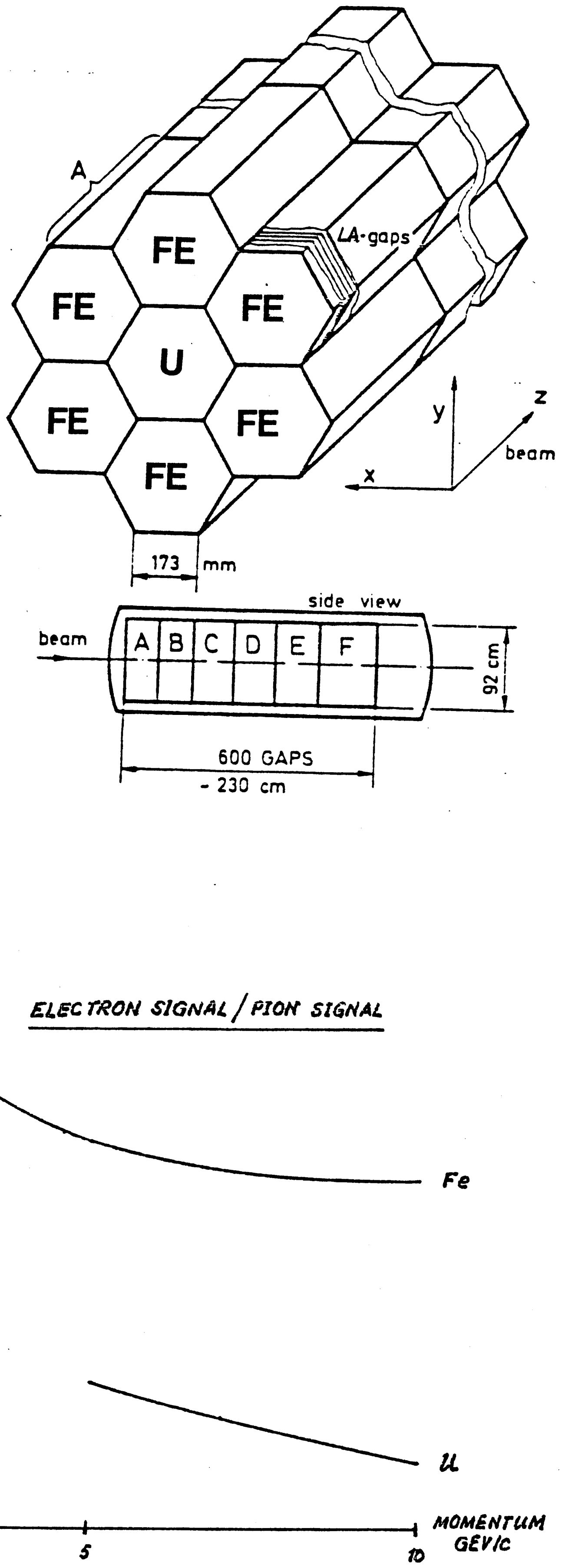
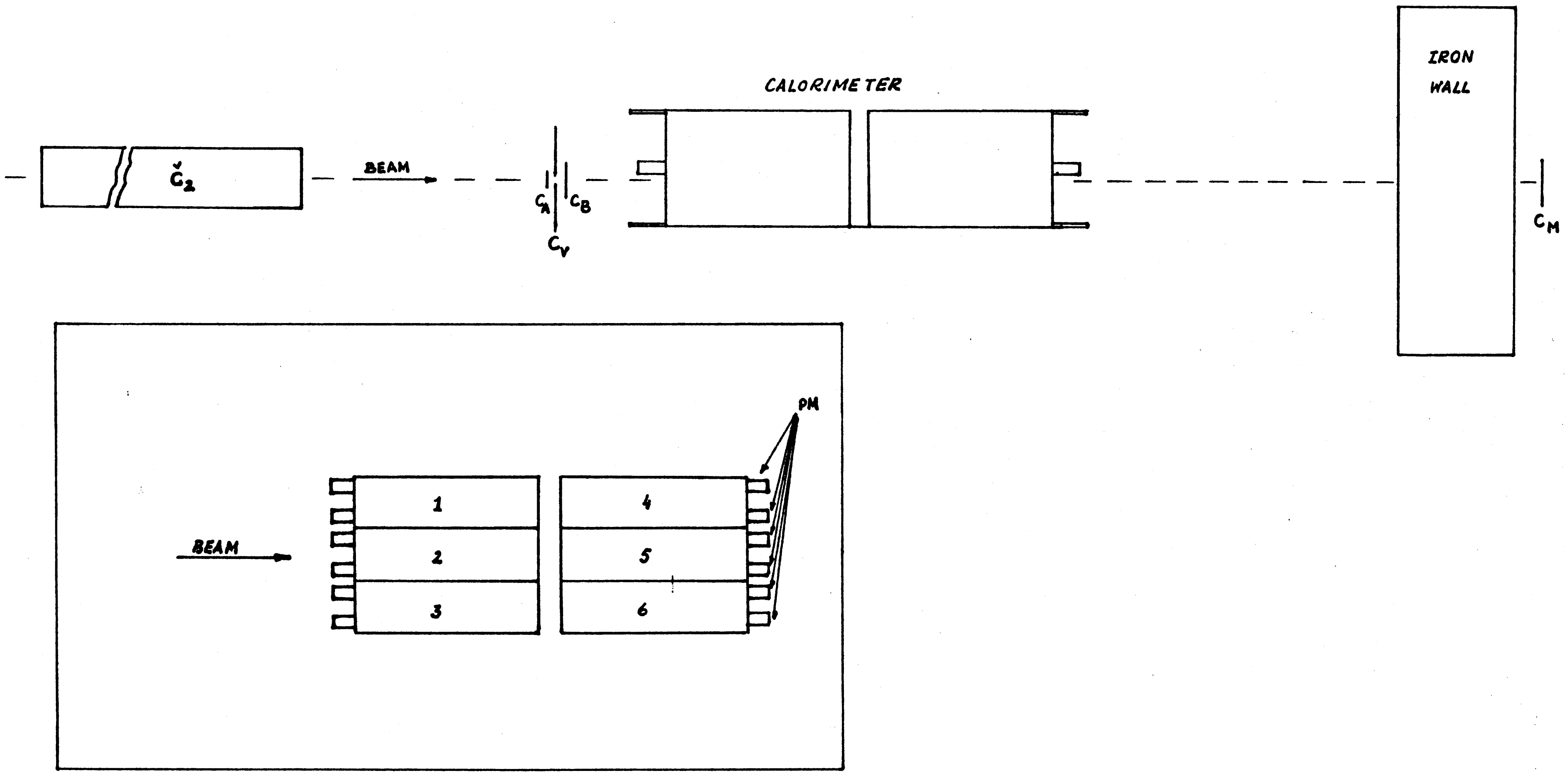

A
FE
FE
FE
U
FE
FE
FE
LA-gaps
y
z
beam
x
173 mm
side view
beam
A B C D E F
92 cm
600 GAPS
- 230 cm
ELECTRON SIGNAL / PION SIGNAL
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
Fe
U
5
10
MOMENTUM
GEV/C

FIG. 1

FIG. 2



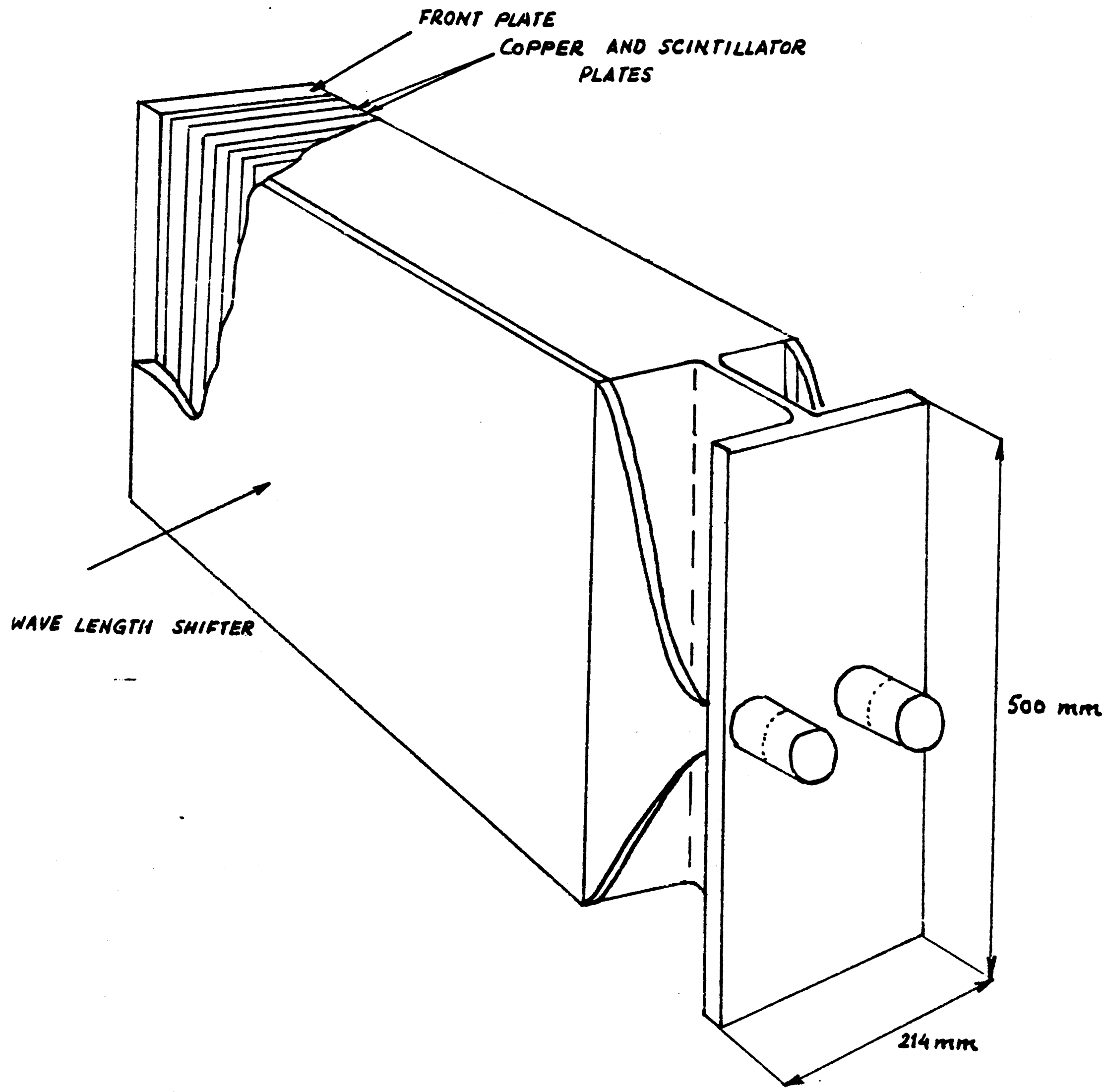

FRONT PLATE
COPPER AND SCINTILLATOR PLATES
WAVE LENGTH SHIFTER
500 mm
214 mm

FIG. 3

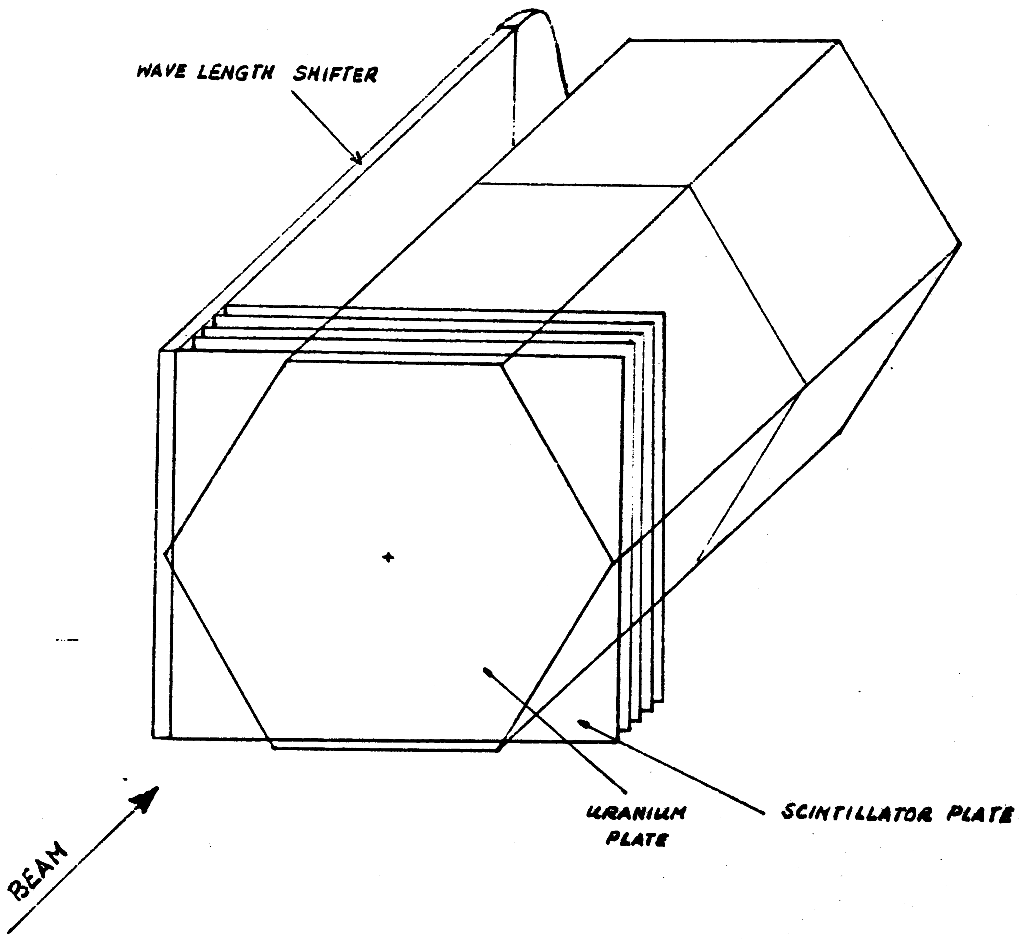

WAVE LENGTH SHIFTER
URANIUM PLATE
SCINTILLATOR PLATE
BEAM

FIG. 4

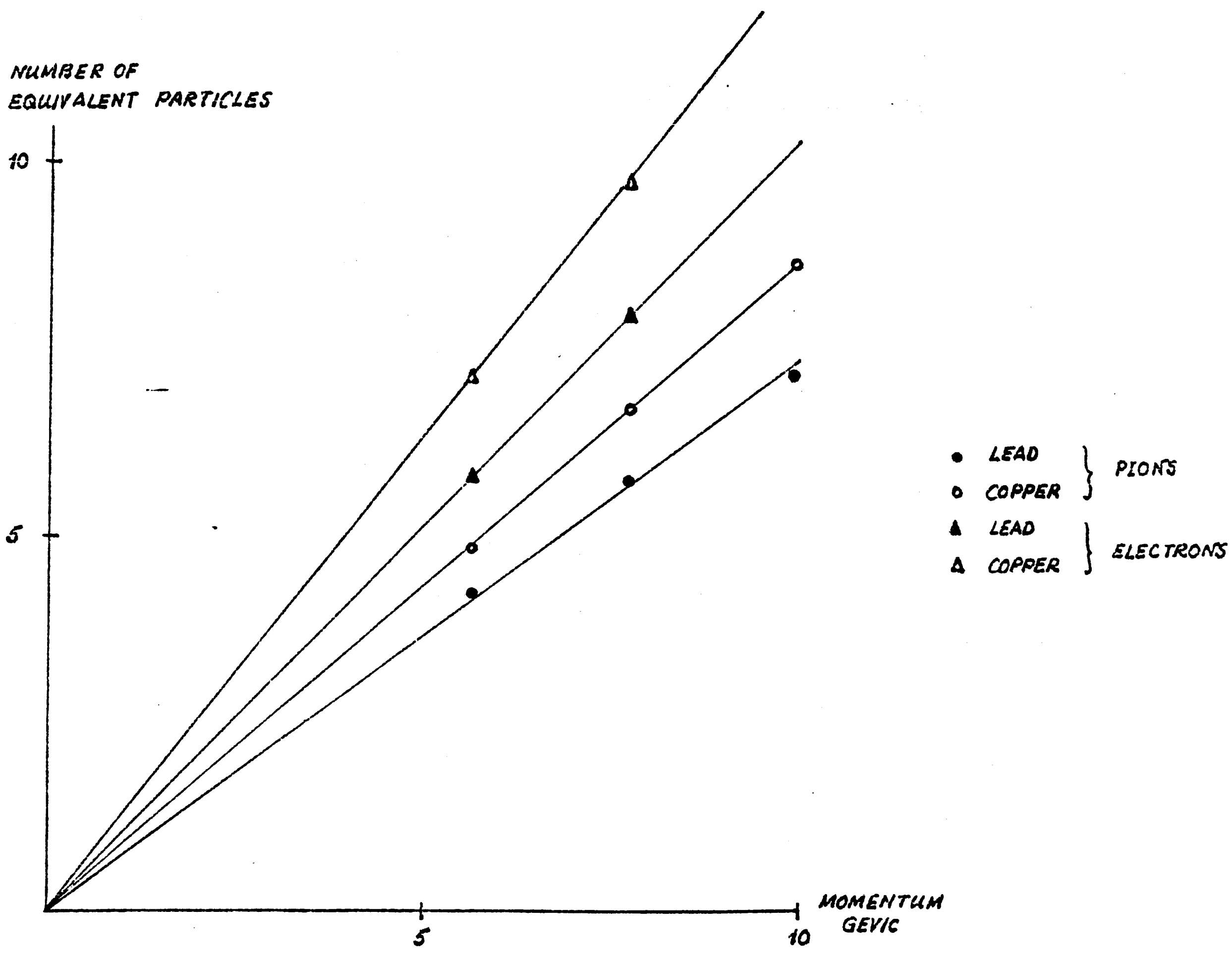

NUMBER OF
EQUIVALENT PARTICLES
10
5
5
10
MOMENTUM
GEV/C
LEAD
COPPER
PIONS
LEAD
COPPER
ELECTRONS

FIG.5

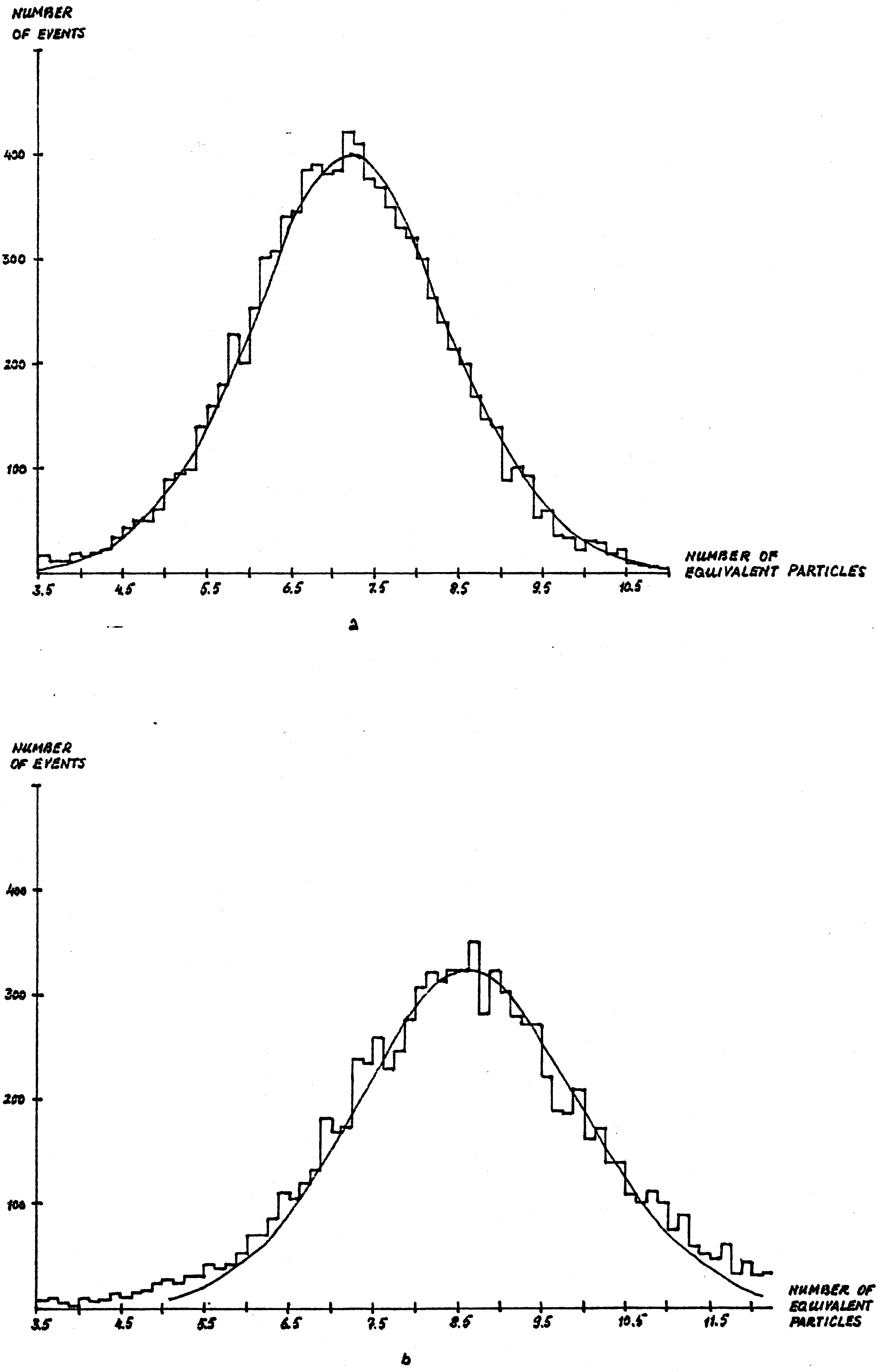

NUMBER
OF EVENTS
400
300
200
100
NUMBER OF
EQUIVALENT PARTICLES
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
a
NUMBER
OF EVENTS
400
300
200
100
NUMBER OF
EQUIVALENT
PARTICLES
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
b

FIG. 6

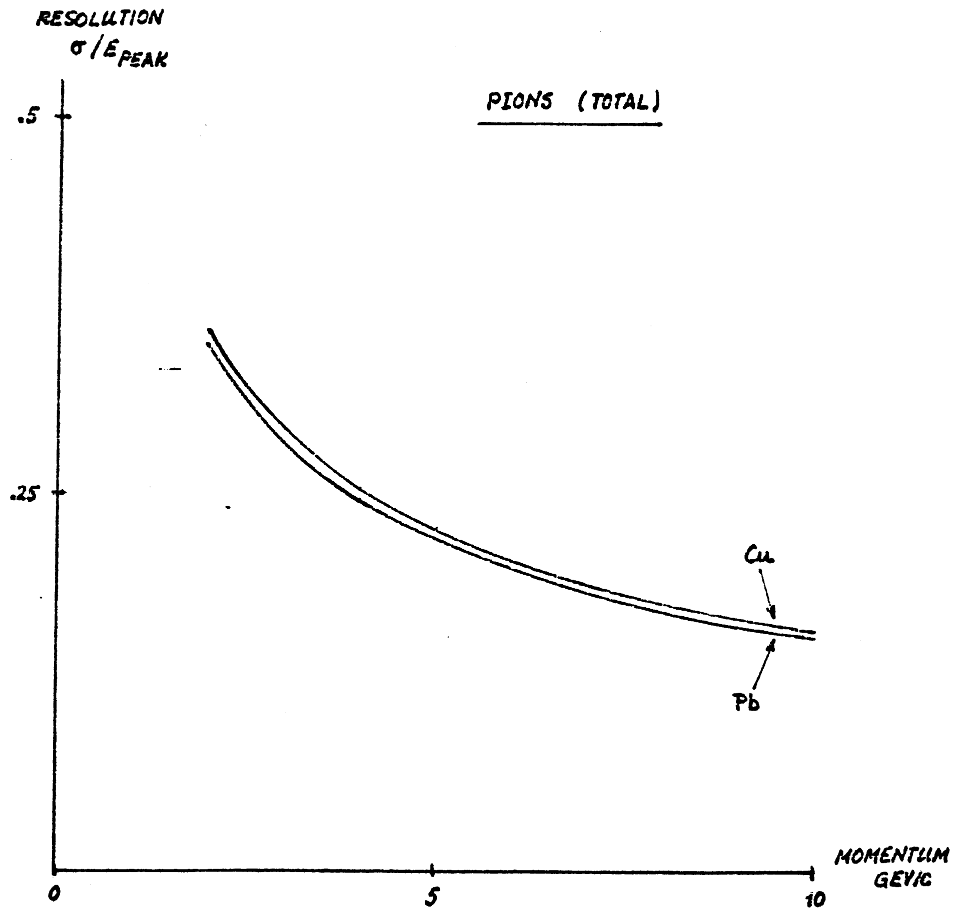


FIG. 7

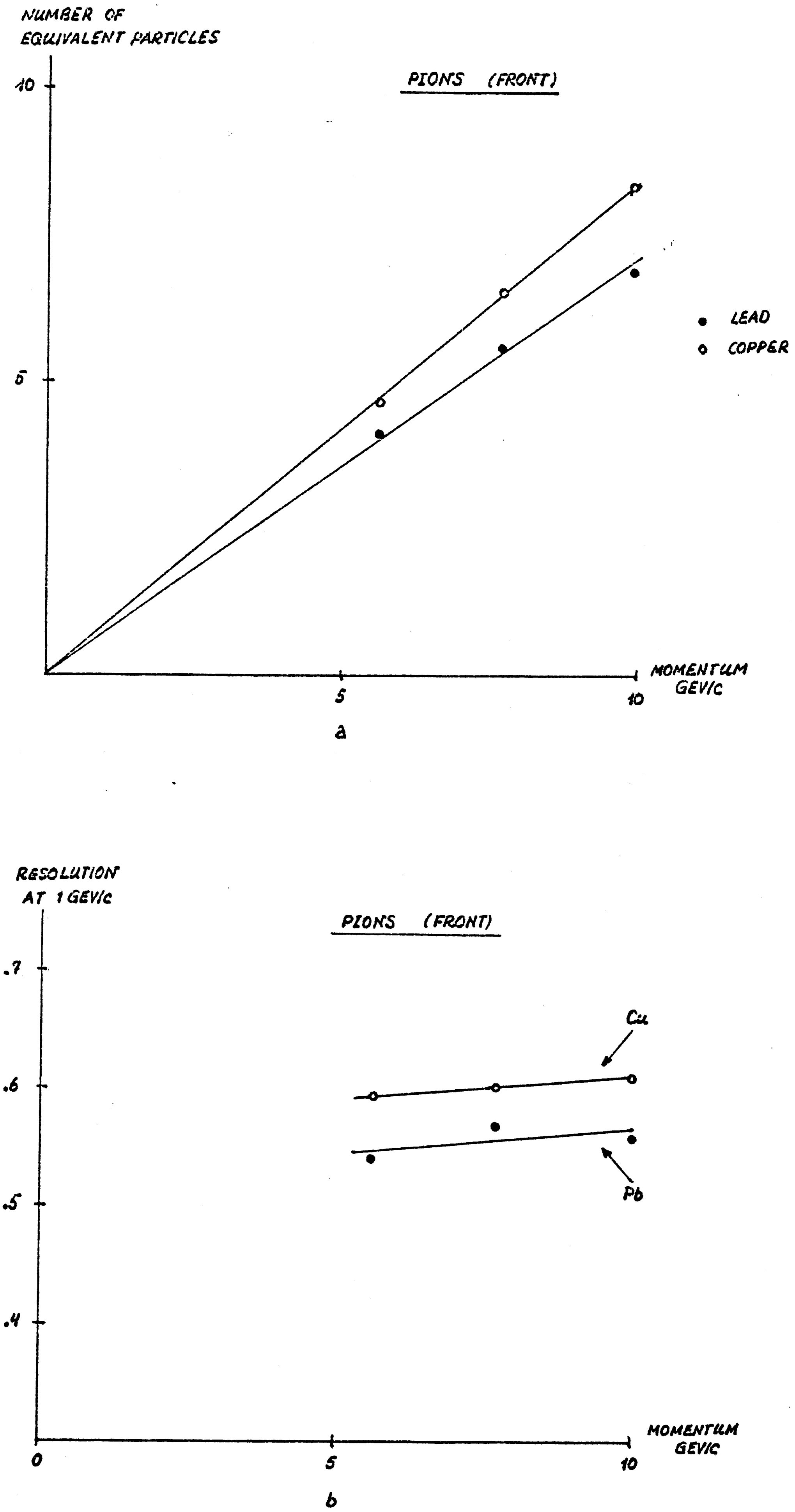
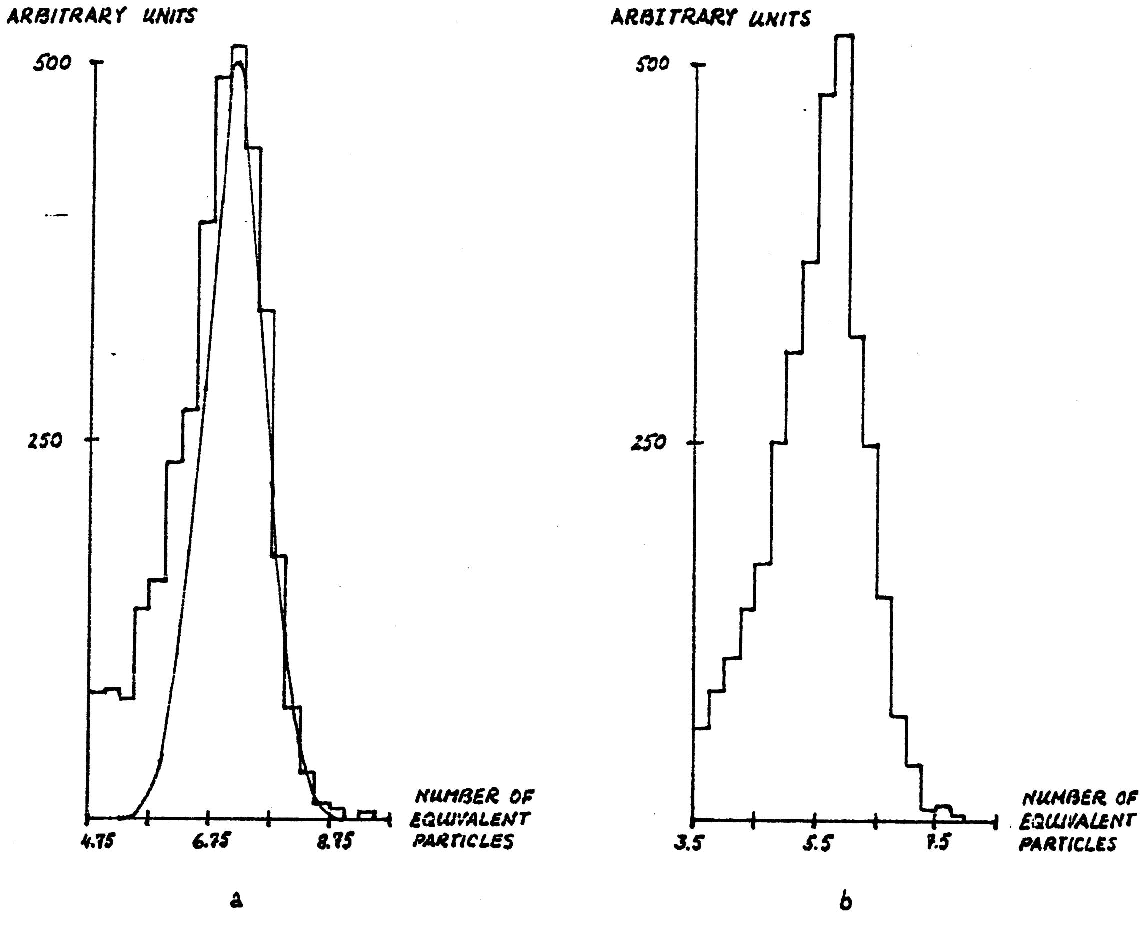

NUMBER OF EQUIVALENT PARTICLES
PIONS (FRONT)
10
5
LEAD
COPPER
MOMENTUM GEV/C
5
10
a
RESOLUTION AT 1 GEV/C
PIONS (FRONT)
.7
.6
.5
.4
Cu
Pb
MOMENTUM GEV/C
0
5
10
b

FIG. 8



ARBITRARY UNITS
500
250
4.75
6.75
8.75
NUMBER OF EQUIVALENT PARTICLES
a
ARBITRARY UNITS
500
250
3.5
5.5
7.5
NUMBER OF EQUIVALENT PARTICLES
b

FIG. 9

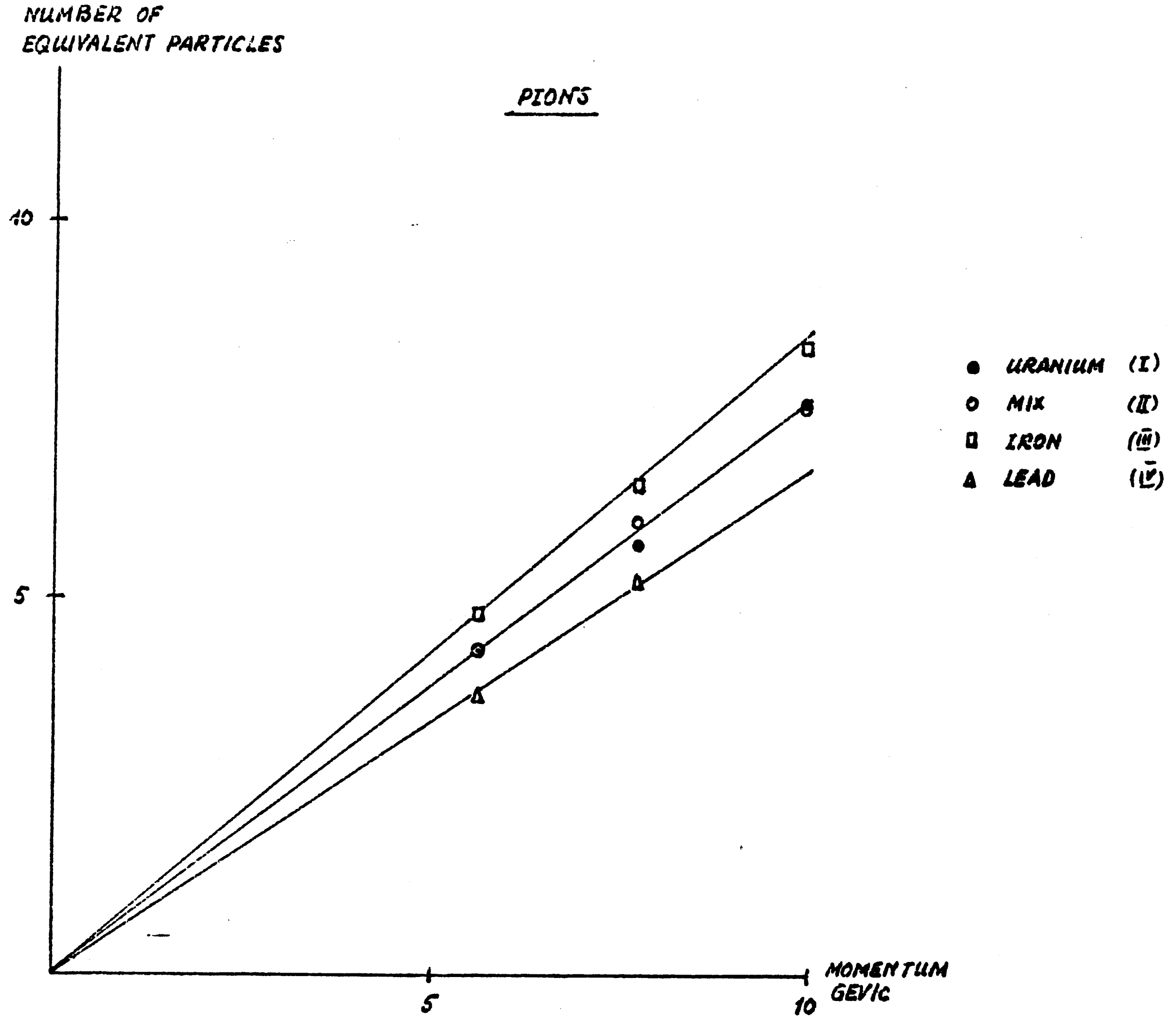

NUMBER OF
EQUIVALENT PARTICLES
PIONS
10
5
5
10
MOMENTUM
GEV/C
● URANIUM (I)
o MIX (II)
□ IRON (III)
Δ LEAD (IV)

FIG. 10

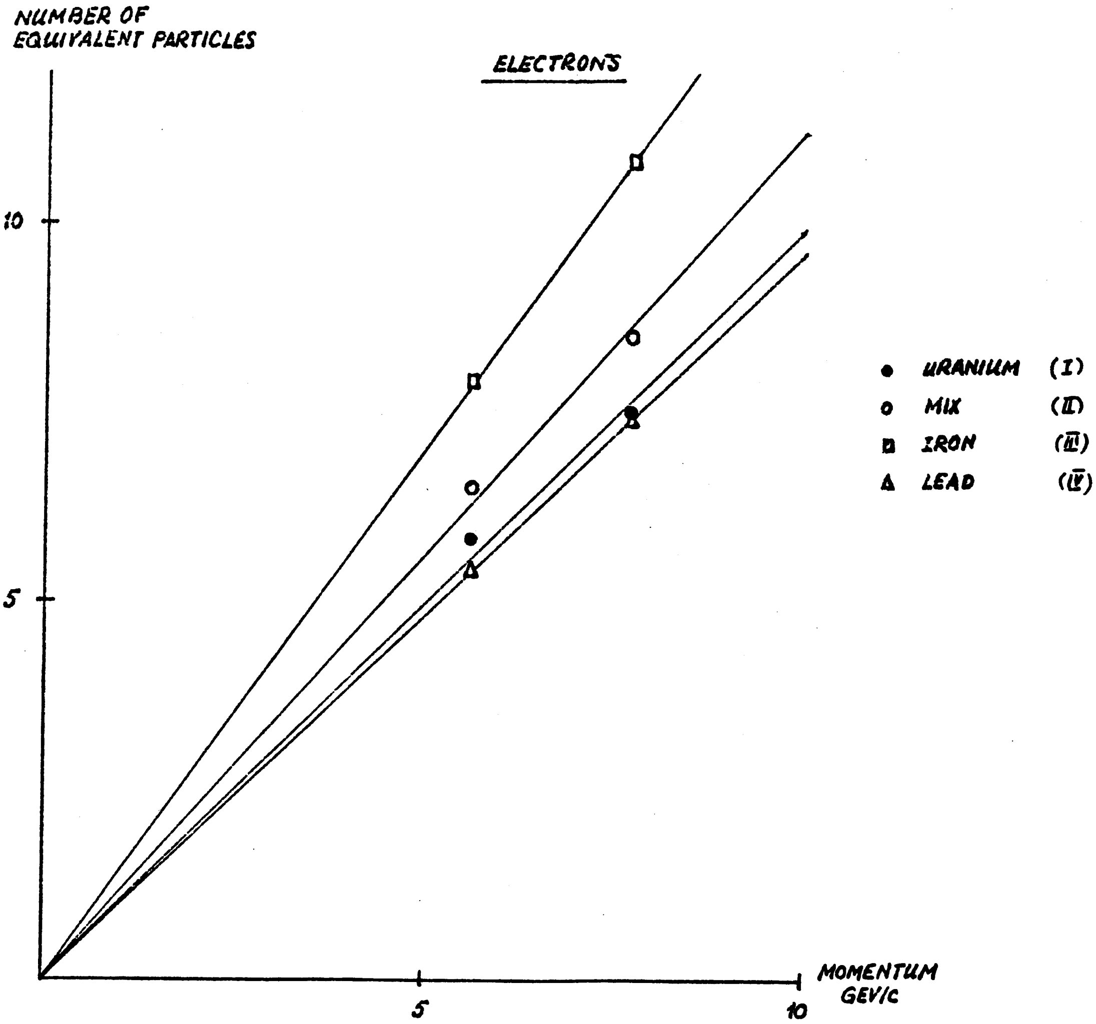
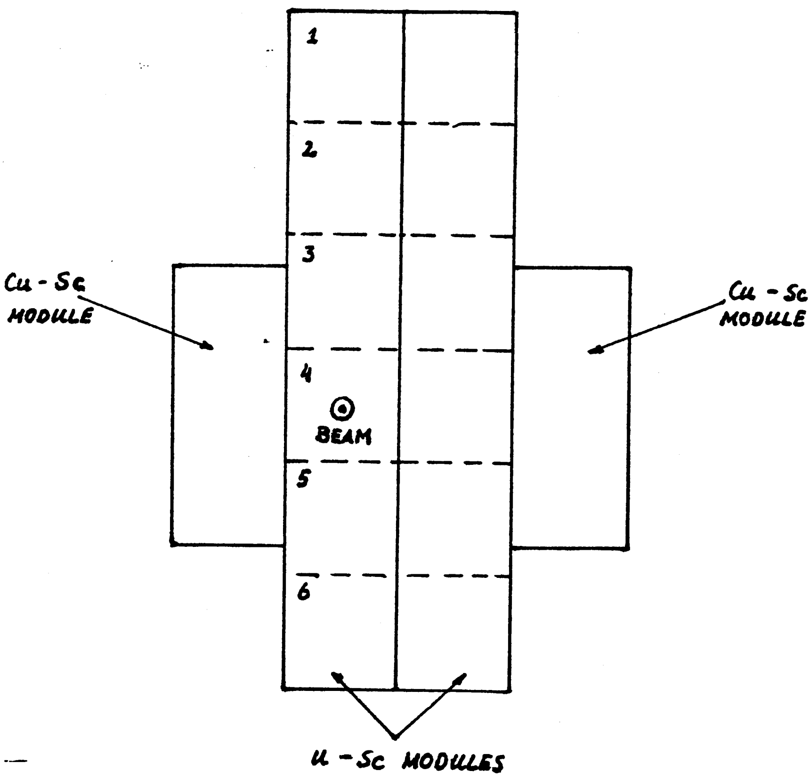
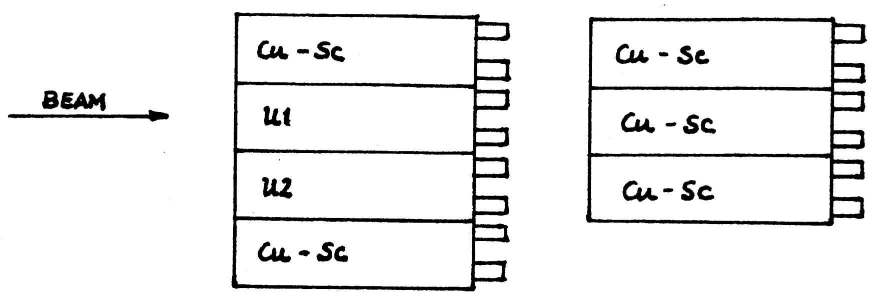

NUMBER OF
EQUIVALENT PARTICLES
ELECTRONS
10
5
5
10
MOMENTUM
GEV/C
● URANIUM (I)
o MIX (II)
□ IRON (III)
Δ LEAD (IV)

FIG. 11



1
2
3
4
5
6
Cu - Sc
MODULE
Cu - Sc
MODULE
BEAM
U - Sc MODULES

a



BEAM
Cu - Sc
U1
U2
Cu - Sc
Cu - Sc
Cu - Sc
Cu - Sc

b

FIG. 12

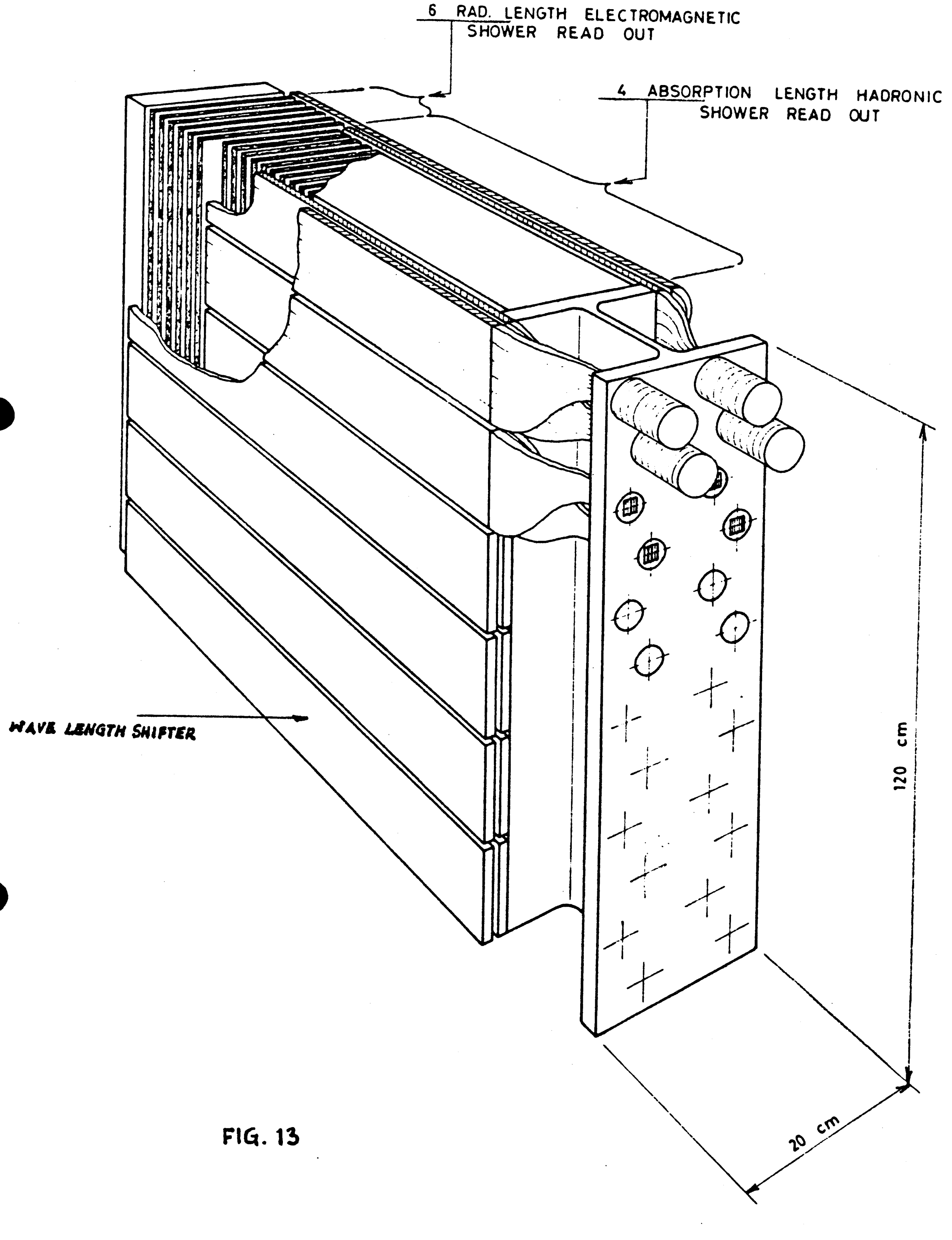

6 RAD. LENGTH ELECTROMAGNETIC SHOWER READ OUT
4 ABSORPTION LENGTH HADRONIC SHOWER READ OUT
WAVE LENGTH SHIFTER
120 cm
20 cm

FIG. 13