Properties of an Ionization Spectrometer Exposed to 10, 20.5, and 28 GeV/c Machine Accelerated Protons.+

W.V. Jones, K. Pinkau, U. Pollvogt, W.K.H. Schmidt
Max-Planck-Institut für Physik und Astrophysik
Institut für Extraterrestrische Physik
8046 Garching bei München, Germany

and

R.W. Huggett
Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803, U S A

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Abstract :

An ionization spectrometer has been employed in several successful balloon flights in combination with spark chambers and different target materials to study high energy cosmic rays. The same spectrometer was exposed to 10, 20.5, and 28 GeV/c protons from the Alternating Gradient Synchrotron (AGS) at Brookhaven, in order to study its response and be able to calibrate it at these energies. Some results of these calibration measurements are reported here. These include the accuracy of energy measurement, the inelastic interaction cross section for protons in iron, and the inelasticity of the interactions of protons with carbon, iron , and lead nuclei.

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I. Introduction

Ionization spectrometers of the type described in this paper have been in use to determine the energy oi ultra high energy particles since 1957[1].

The ionization spectrometer discussed here had a depth of only three interaction lengths, because the weight that could be carried by balloons appeared to be limited at the time of conception of the experiment. Theoretical calculations showed that an ionization spectrometer of limited depth should be still useful for energy determination, since it appeared that, on average, the maximum of the cascade development would occur within a depth of three interaction lengths[2].

It was expected that basic knowledge on the behaviour of the cascade development in the spectrometer could be obtained by exposing the apparatus to particles of known energy from an accelerator. This report is devoted to a description of the studies that have been carried out at the Brookhaven Alternating Gradient Synchrotron (AGS).

II. Experimental Procedure

A brief description of the apparatus has already been given in Ref. 3). The ionization spectrometer (see Fig.1) consisted of 6 slabs of iron, each of depth 7 cm (i.e. 55 g/cm^2), and a cross sectional area of 18 x 18 cm^2. In between these slabs and below the lowest there were 1 cm thick plastic scintillators inserted to sample the ionization loss of the cascades. Above the spectrometer there were two spark chambers of 4 and 12 gaps, respectively, and in between them a target space of dimensions

18 x 18 x 18 cm^3. Above the upper spark chamber and below the target there were two beam defining scintillators of cross sectionsl areas of 15 x 15 cm^2.

For triggering purposes each scintillator was viewed by one photomultiplier. The outputs of the PM tubes were connected to various threshold discriminators. If a pulse exceeded a threshold, a light bulb was turned on and photographed by two Bolex 16 mm movie cameras along with the spark chambers and the display of three multi-channel analyzers described below. The threshold discriminators of counter T8 were set to show more than 4 times, 9 times, and 16 times minimum ionization (corrected for non linear light output of plastic scintillators for heavily ionizing particles). In T7 the passage of 2 or more minimum ionizing particles was registered. In counters T1 to T6 the passage of two or more and 13 or more particles was registered. Counter 0 was used in anticoincidence to exclude side showers from being registered. For measuring ionization loss, three photomultipliers (MI to MIII) were employed which looked at a pair of scintillators each. The output pulses of these tubes were analysed in three 128 channel analysers of logarithmic response.

During balloon flights the apparatus was triggered whenever counters T7 and T8 registered at least 1 times minimum ionization and at the same time each scintillator of either one of the pairs A, B, or C registered at least 13 times minimum ionization. Thus the coincidence requirement for balloon flights was $(A + B + C)\ T7\ T8\ \overline{0} = 1$.

For triggering during the AGS exposure, only one particle was required to traverse T7, T8, and 2 more beam defining counters in front of the apparatus. Because of the registry of pulses exceeding thresholds as mentioned above, from all AGS events, those events could be selected which would have triggered the apparatus under balloon flight conditions. Thus it was possible to derive the change of triggering efficiency of the apparatus with incident energy.

During the AGS exposure there was on average one proton incident on the apparatus during each AGS pulse. Multiple incidence could be recognized by scanning the spark chamber pictures. The spark chambers had a very good multiple track efficiency. The number of events where two protons followed each other closely in time while only one of them was registered by the spark chambers and the other one possibly distorted the pulse height measurement was found to be negligible, mainly due to linear gates which were sensitive for less than 0.5 μsec for the pulses to be measured after the apparatus had been triggered.

Three different energies of incident protons were selected: 10, 20.5, and 28 GeV. At each energy about 5,000 events were recorded for each of two different targets in the provided space: a lead target of 86,5 g/cm^2 and a carbon target of 33,5 g/cm^2. The same targets had been used in balloon flights before. In addition, at 28 GeV, a data set was recorded with the target space empty.

III. Results

For the results described in this and the following sections, only those events were used in which the primary proton was incident on a cross sectional area of 8 x 8 cm^2 about the center of the cross sectional area of the iron absorber, i.e. the cascade axes were at least 5 cm away from the side of the absorber. Besides the target and spark chambers, the incident protons had to traverse a total of 330 g/cm^2 of iron , i.e. three geometrical interaction lengths or 24 radiation lengths. By means of the spark chamber pictures one could distinguish between particles which suffered their first interaction in the target and those which did not. Further, by means of the above mentioned threshold discriminators, one could localize approximately the depth in which the first interaction of an event took place in the iron absorber.

A) Energy Calibration

Fig. 2 and 3 show some of our results. In Fig. 2 the measured average ionization energy is plotted versus the total energy of the incident proton. ΣNi means N1 + N2 + N3, where N1, N2, and N3 are the average particle numbers of the two scintillators or each of the three measuring units as recorded by MI, MII, and MIII, respectively. "One particle" is by our definition a pulse height at the output of the PM tube corresponding to 1.15 times the most probable pulse height generated by a single minimum ionizing cosmic ray muon traversing the apparatus at sea level. One can see from the graph that within the statistical error the dependence of the average measured value of ΣNi on primary energy is linear if the primary particle did not interact above the spectrometer, but is not linear if only events are selected which show an interaction in one of the targets. Moreover, there seems to be a much larger fraction of energy unsampled in the latter case.

Fig. 3 shows for the same groups of selected events the relative standard deviation of the distribution of the measured parameter. One can see that target interactions exhibit rather large fluctuations, changing with primary energy, while the group of events with first interactions between iron slabs a and e, inclusively, exhibits relative standard deviations rather insensitive to any change in primary energy. This can also be said of the shapes of the corresponding distributions which are not shown here.

If one plots one of the sets of experimental points of Fig. 2 and takes one standard deviation of the corresponding distribution up and down from that point as the limit of error and connects the ends of the error bars, then reading the graph with the ordinate as base line instead of the abscissa yields an estimate of the error expected in measuring the unknown primary energy of an incident particle. This procedure yields approximate errors for group (a) of Fig. 2 of +60% and -30% at about 10 GeV incident energy, +50% and -30% at about 20 GeV, and +50% and -25% at about 28 GeV. The respective values for group (b) of Fig. 2 are +80% and -35%, +65% and -30%, and +60% and -30%.

B) Interaction Length of Protons in Iron

Although with some error, it was possible to locate the first interaction of an incident particle in one of the iron blocks of the spectrometer. This was done by means of the "two particle threshold", the lower threshold of T1 to T6 mentioned above. There are several possibilities for mislocation of the first interaction of an event. Apart from the overlap of the one-particle-distribution of pulse heights over the threshold, there can occur backscattering of particles from fast developing cascades and also low multiplicity interactions which do not yield two or more ionizing particles in the following scintillator. While for the overlap of the distribution can be corrected, the magnitude of the other two effects is rather unknown. However, if in all cases of the latter two effects the first interaction is misplaced by a constant number of iron blocks, it can easily be shown that the slope of the distribution of beginning points of cascades is not distorted if one retreats sufficiently far from the upper and lower boundaries of the spectrometer.

In the present case it appeared that retreating one iron slab from the upper and lower boundaries was sufficient at 20.5 and 28 GeV/c. At 10 GeV/c the remaining points of the distribution of beginning points of cascades did not appear to justify a straight line fit on a semi-logarithmic diagram, and therefore the interaction length for protons in iron reported here is derived from the data at 20.5 and 28 GeV/c only. An average of all values of the slopes of the distribution of beginning points at 20.5 and 28 GeV/c incident protons yielded for the interaction length of protons in iron $L_{p-Fe} = 139^{+5}_{-9}$ g/cm^2 corresponding to an interaction cross section of $\sigma_{p-Fe} = 666^{+44}_{-22}$ mb.

C) Inelasticity

Although the distributions of inelasticities at different energies and for different materials could not be determined, we estimated mean values of the inelasticity for the three materials carbon, iron, and lead[4].

Our results are shown in Fig. 4. The curve drawn is the function

$$(1) \qquad \bar{K}(A) = 1 - (1 - \bar{K}_{n-n})^{\alpha} \; ; \; \alpha = A^{1/3}$$

where $\bar{K}$ is the mean inelasticity and A the Atomic Mass Number. This equation was first put forward during the Jaipur conference on cosmic rays[5]. The curve was normalized to our value for carbon. We could not find a significant energy dependence in the range between 10 and 28 GeV primary energy. So the reported values are averaged over the three energies in the case of iron and carbon and over 20.5 and 28 GeV for lead. For lead at 10 GeV the inelasticity could not be determined.

IV. Discussion

Our results of this experiment indicate that in principle it is possible to measure the energy, although with a rather large error, of a primary proton with an ionization spectrometer only 3 geometrical interaction lengths in depth. Also it was possible to estimate the inelasticity of nuclear interactions and the cross section for interactions with subsequent cascade development. To get an estimate of the latter two entities during balloon flights will not be possible with such a shallow spectrometer since these are the entities which determine the energy measurement of the event.

The most significant result is probably the knowledge of the distributions of the parameter ΣNi and their insensitivity against change in primary energy. Since the largest contributions to the width of the distributions are expected to be the poisson distribution of the number of interactions in the spectrometer and the inelasticity distribution, which from present knowledge are not supposed to change rapidly with energy, we expect that these distributions do not change significantly in width and shape for at least one more order of magnitude in primary energy. Thus by finding a reasonable extrapolation for the energy dependence of the mean values of ΣNi, it is possible to measure the spectrum of cosmic rays even with a shallow spectrometer like the one described here, although the energy measurement of individual events cannot be done very accurately.

Acknowledgement

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Figure Captions

Fig. 1 : Schematic diagram of the apparatus described here.

Fig. 2 : The mean energy loss measured in units of ΣNi as a function of the primary total energy for various groups of events: (a) first interaction in Fe(a); (b) first interaction in Fe(a) to Fe(e); (c) all events without target interactions; (d) first interaction in C-target; (e) first interaction in Pb-target. The size of the symbols represents the errors of $\overline{\Sigma \mathrm{Ni}}$.

Fig. 3 : Relative standard deviations $\sigma / \overline{\Sigma \mathrm{Ni}}$ as functions of the primary total energy for the same groups of events as in Fig. 5.

Fig. 4 : Comparison of experimental values for the average total inelasticity $\overline{K}$ with the relation (1) of the text. The dashed error bars represent 15% errors arbitrarily attached to the values for which no errors were quoted by the original authors. The value of $\overline{K}$ determined by this experiment, as well as for some of the other quoted results, is taken to be $3\,\overline{K}_{\pi^0}$. The curve is normalized to the value $\overline{K} = 0.45$ obtained in this experiment for the carbon target.

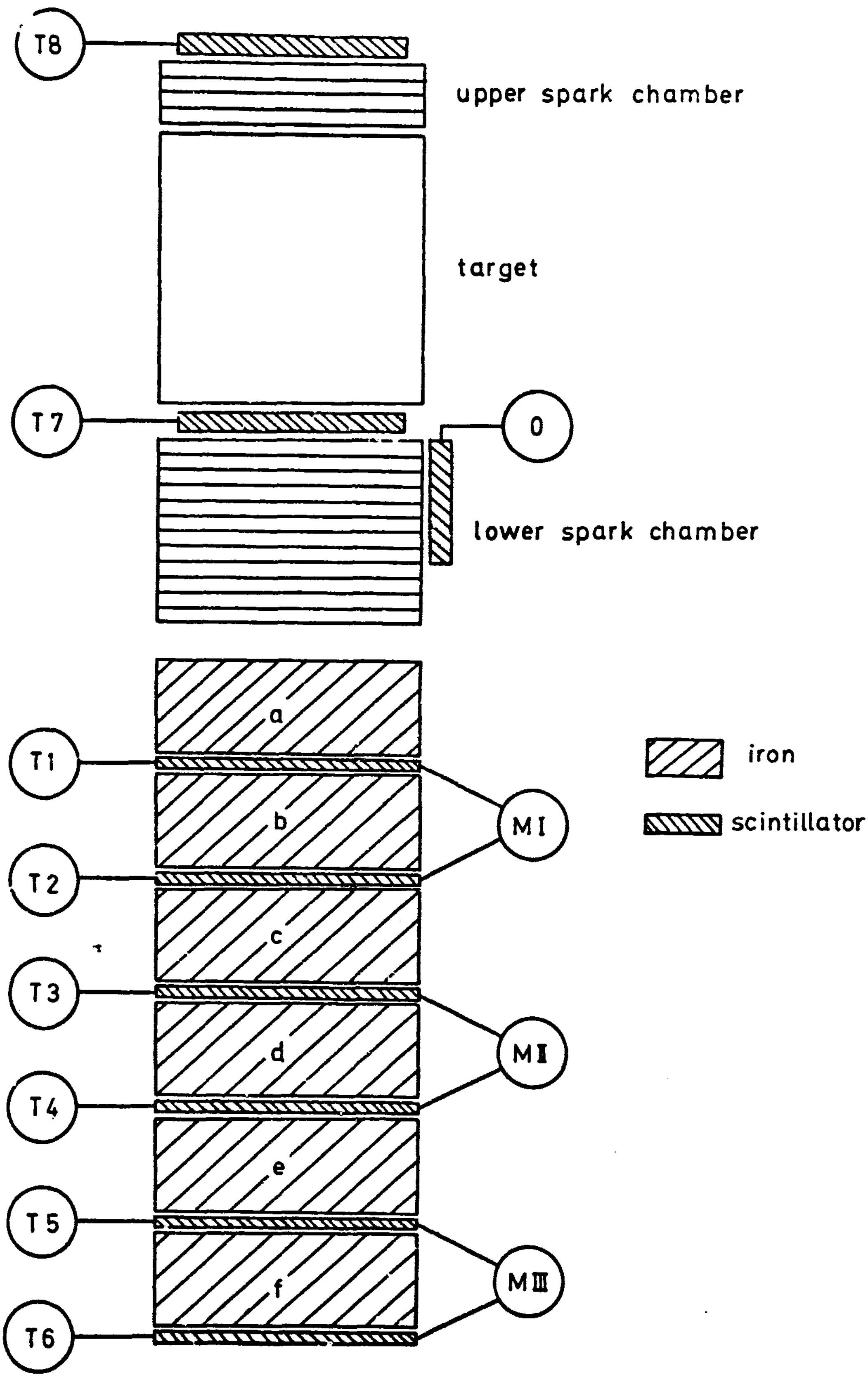
T8
upper spark chamber
target
T7
0
lower spark chamber
a
T1
b
T2
c
T3
d
T4
e
T5
f
T6
M I
M II
M III
iron
scintillator

Fig.1

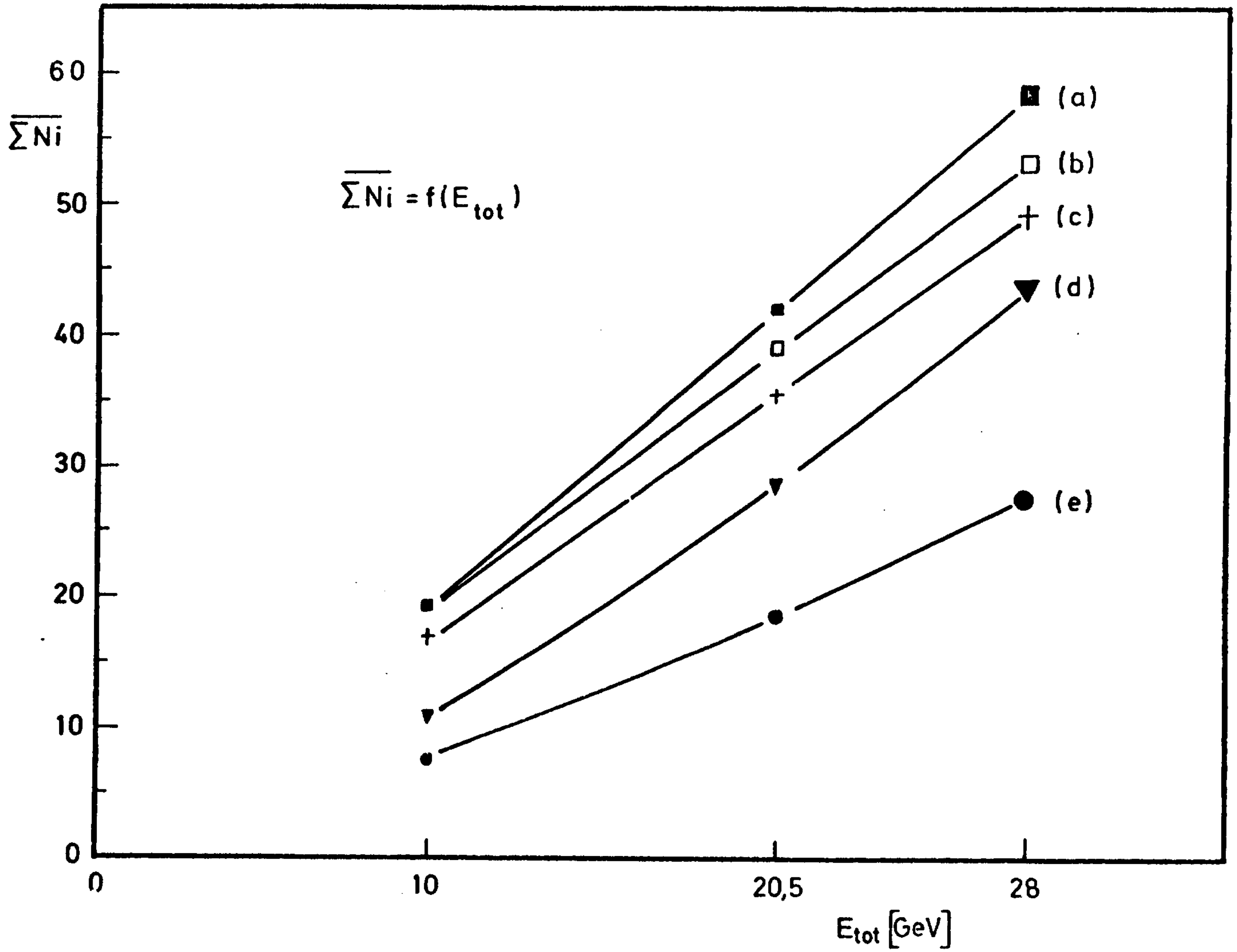
60
50
40
30
20
10
0
$\overline{\sum Ni}$
$\overline{\sum Ni} = f(E_{tot})$
(a)
(b)
(c)
(d)
(e)
0
10
20,5
28
E_{tot} [GeV]

Fig. 2

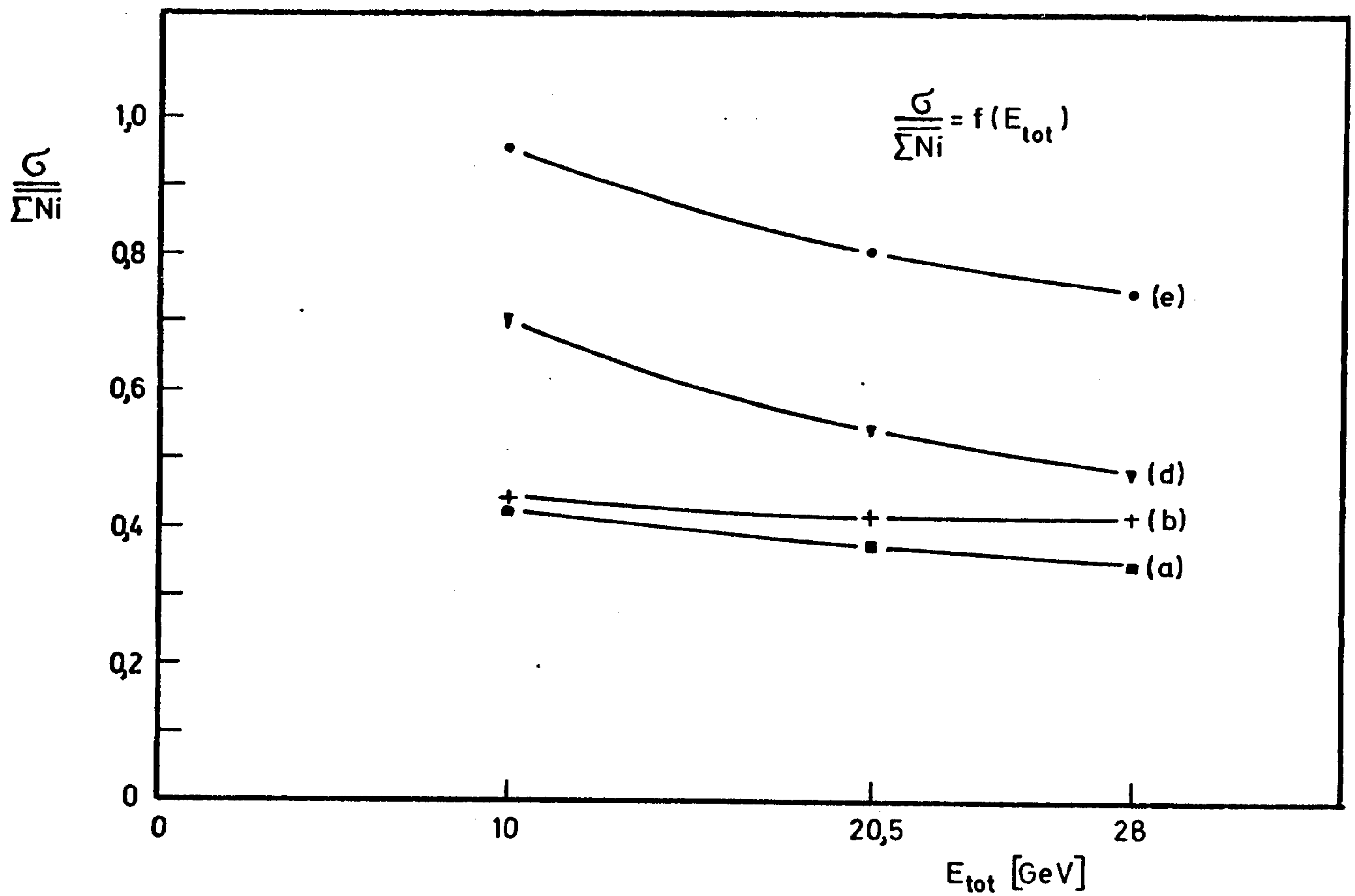

Fig. 3

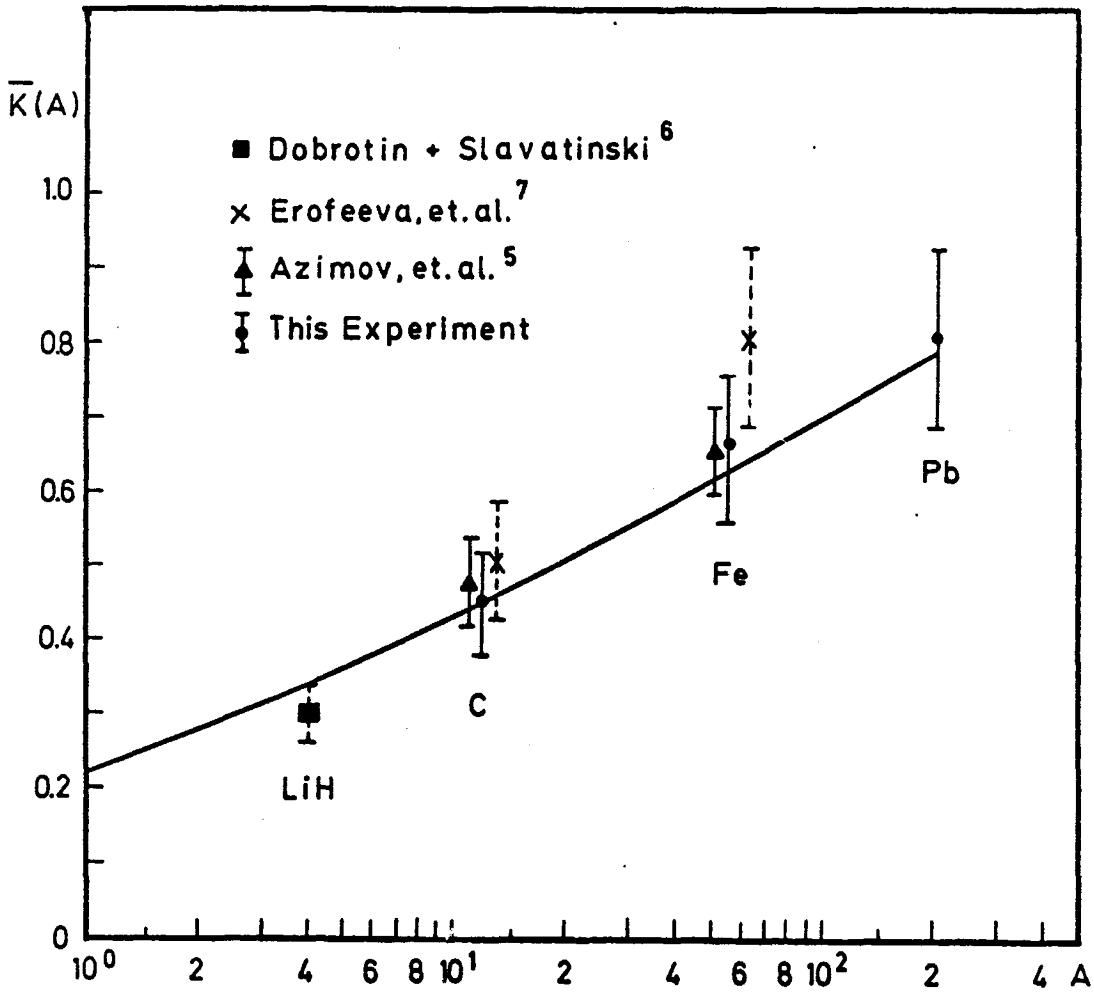
$\overline{K}(A)$
Dobrotin + Slavatinski [6]
Erofeeva, et. al. [7]
Azimov, et. al. [5]
This Experiment
1.0
0.8
0.6
0.4
0.2
0
LiH
C
Fe
Pb
10^0
2
4
6
8
10^1
2
4
6
8
10^2
2
4
A

Fig.4