THE COSMIC RAY PROTON AND HELIUM SPECTRA ABOVE 50 GeV

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Abstract

The primary cosmic ray proton and He spectra from 50 GeV to 2000 GeV have been measured by an ionization spectrometer flown on a balloon at an altitude of 6 gm cm^{-2} for 16 hours. The geometrical factor of the instrument was 300 cm^2 sterad and more than 5,000 events were observed. At low energies, the energies of individual events can be determined to within $\pm 30\%$. At higher energies, the cascade is not fully contained within the four mean free path thick spectrometer and the problems of estimating the energies of these events will be discussed. The proton spectrum continues with constant exponent $= -2.7 \pm 0.1$ up to energies greater than 1,000 GeV. This spectrum is in agreement with the results of Pinkau et al. (1969) at the low energies. However, there is no evidence for the spectral break at about 1,000 GeV as reported by Grigorov et al. (1969).

1. Introduction

In this paper we report measurements of the proton and helium energy spectra obtained at balloon altitudes using an ionization spectrometer of depth 4 m.f.p. and 2,500 cm^2 cross sectional area. An outline of the arrangement of the detectors is shown in Fig. 1. The major part of the spectrometer is the 7 iron modules each 0.5 proton m.f.p. (5 radiation lengths) thick. Notice that there are 3 plastic scintillators in each module so that an observed detector output of N particles is actually an average of the three sampling scintillators. This averaging helps to reduce fluctuations of the nuclear cascades but allowances must be made for this averaging when reconstructing shower curves in regions of rapid development.

Above the iron section are 12 tungsten modules each 1 radiation length thick, making a total of 0.48 proton m.f.p. of tungsten. An incident primary particle is identified in the charge module section which contains 2 plastic scintillators, a Cerenkov counter and a CsI scintillator. A wire grid spark chamber containing 4 X-Y planes defines the particle trajectory and is helpful in rejecting background events.

All detector outputs are normalized to a single particle output defined as the mean energy loss of a single muon which passes through the entire spectrometer. In the proton mode the spectrometer is triggered by an energy release $>$ 50 GeV in the first five iron modules. Fig. 2 shows 4 events obtained during the balloon flight. The frequent independent sampling of this spectrometer allows a good estimate of the first interaction point of the incoming particles. For protons an interaction is defined to have occurred in the first detector whose output is greater than 3 particles provided that the following 2 detectors have outputs greater than 5 particles. For He nuclei the corresponding particle numbers are 7, 10, and 10. Basically the definition requires that a neutral pion of energy $>$ 0.5 GeV be produced at that point.

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The ability to specify the first interaction point removes a major source of fluctuation in shower development, but the remaining fluctuations in nuclear disintegration energy and in cascade development limit the estimation of the energy of individual events to ±25%. A more serious problem is that for large energy primaries the nuclear cascade is not contained within the 4 m.f.p. depth of the spectrometer and some energy escapes out the bottom as suggested by curves 2 and 4 of Fig. 2.

2. Calibration and Energy Estimation

The spectrometer was calibrated with 10, 15 and 20 GeV protons from A.G.S. at the Brookhaven National Laboratory. The total calorimeter output formed by summing the seven iron modules was found to be directly proportional to the incident proton energy. The excellent energy resolution obtainable with this type of instrument is shown in Fig. 3. The observed output implies that at these low energies 60% of the incident energy is being sampled by the scintillators. However, these energies are lower than those of the cosmic rays of interest and so a similar instrument will be calibrated at the National Accelerator Laboratory later this year. This should provide accurate calibration up to proton energies of 500 GeV. Theoretical and Monte Carlo calculations (1), (2) show that the total output of an infinitely deep absorber will be directly proportional to the incident energy up to energies of at least 10^4 GeV. To estimate the energy escaping out the bottom of our finite depth instrument we have extrapolated the mean shower curves shown in Fig. 4.

The lowest curve is that obtained with 17.6 GeV/c protons at Brookhaven. The flight data curves are constructed for events which interacted in the first iron module and penetrated the bottom of the spectrometer. They are grouped according to the sum over seven modules. The extrapolated curves indicate that the fraction of energy escaping increases from 3% at 40 GeV to 22% at 40 GeV. The correction for high energy events has been estimated from

$$C = 8.3 \ln E_7 - 28 \qquad (1)$$

where E_7 is the energy obtained by summing over all 7 modules.

In order to increase the effective geometry factor, we have also used those events which exited after 5 iron modules i.e., 3 m.f.p. To estimate the energies of these events we have used a weighted mean of modules 4 and 5 and extrapolated assuming that the showers are exponentially absorbed with an attenuation length of 240 gm cm^{-2}(3). A cross check of this method has been made using those events which exited beyond the 7th module, and it is found that the energy estimates using 5 and 7 modules are in good agreement.

We have also investigated using the number of particles at shower maximum as an energy estimator but the dispersion within groups of events is much larger. The number at maximum increases as $E^{0.8}$. Similar corrections have been estimated for He at the same energy/nucleon.

4. Energy Spectra

Using the corrections outlined above, we obtain the primary energy spectra shown in Fig. 5. We have included data from 12 hours of flight at an altitude of 6 gm cm^{-2}. The sensitive live time was 68% and the geometrical factor was

330 cm^2 ster. The fluxes shown have been corrected to the top of the atmosphere (x 1.15), for particles which interact beyond module 3 (x 1.30) for spark chamber inefficiency (x 1.2) and for backscattering (x 1.25). These corrections will be discussed in detail in a paper to be published.

The spectra show that the ratio of protons to the nuclei remains constant up to total energies of 3,000 GeV. We have checked the influence of backscatter (< 25% at 17.6 GeV/c) on our spectra by observing that the spectrum has the same slope for the groups of events which interact in the first, second, and third modules. The loss of events due to backscattering of multiple particles into the charge module from a depth of 1.5 m.f.p. should be small due to the large thicknesses of material and the small solid angle (.60 sterad) into which high energy products would have to be backscattered.

Our measurements do not give any evidence for the change in slope of the proton spectrum observed by Grigorov in the region of 1,000 GeV. If the proton spectrum continues with constant exponent to above 10^{13} eV then the observed spectra at mountain altitudes suggest that there is a change in the proton air nuclei cross section at those energies. It is hoped that these discrepancies will be resolved by the spectrometer similar to the one described above, which is being designed for the High Energy Astronomy Satellite.

5. References

Grigorov, N.L., V.E. Nestorov, I.D. Rapoport, I.A. Savenko, G.A. Skuridin, 1969, Proc. XI Int. Conf. on Cosmic Rays, 1, 518.

Jones, W.V., 1969, Phys. Rev. 187, 1868.

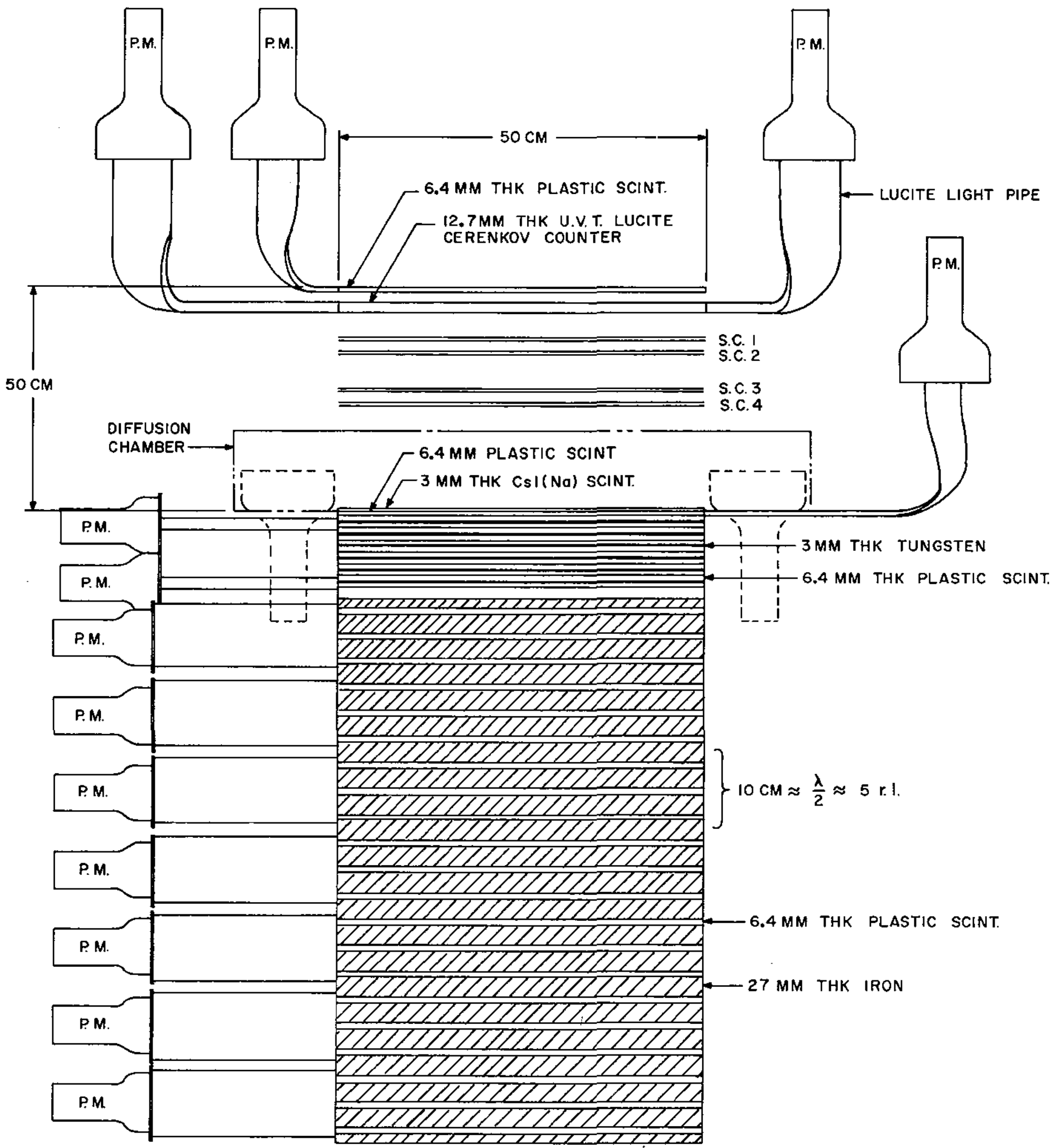
Jones, W.V., 1969, Proc. XIth Int. Conf. on Cosmic Rays.

Jones, L.W., et al., 1970, "Properties of Proton-Proton Interactions between 70 to 600 GeV", Proceedings of the XI Interamerican Seminar on Cosmic Rays, La Paz, Bolivia (to be published).

Kamata, K., et al., 1969, Proc. XIth Int. Conf. on Cosmic Rays, 3, 49.

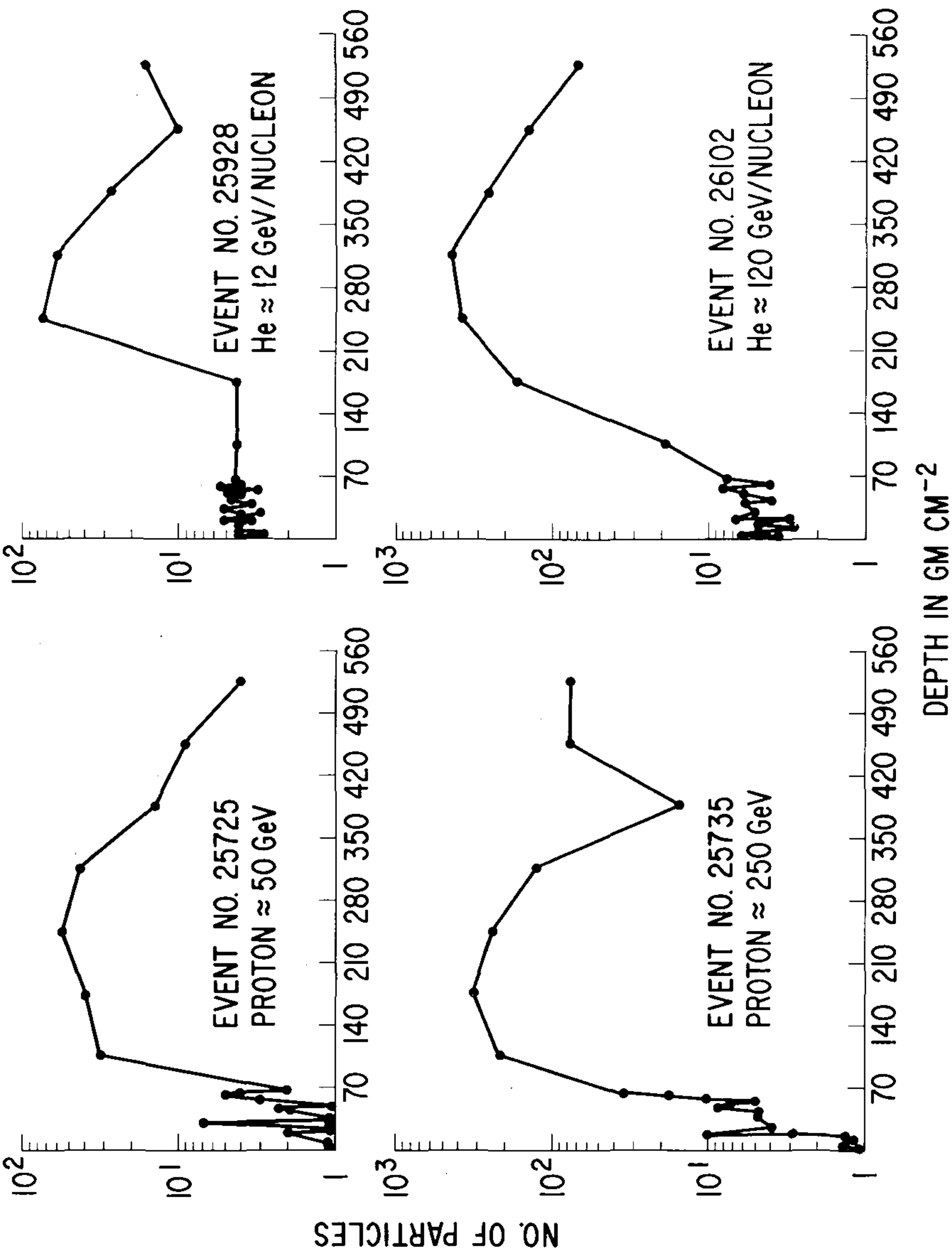
Murzin, V.S., 1967, Progress in Elementary Particles and Cosmic Ray Physics, 9, North Holland Publishing Co., Amsterdam.

Pinkau, K., U. Pollvogt, W.K.H. Schmidt and R.W. Huggett, 1969, Proc. XIth Conf. on Cosmic Rays, 3, 291.



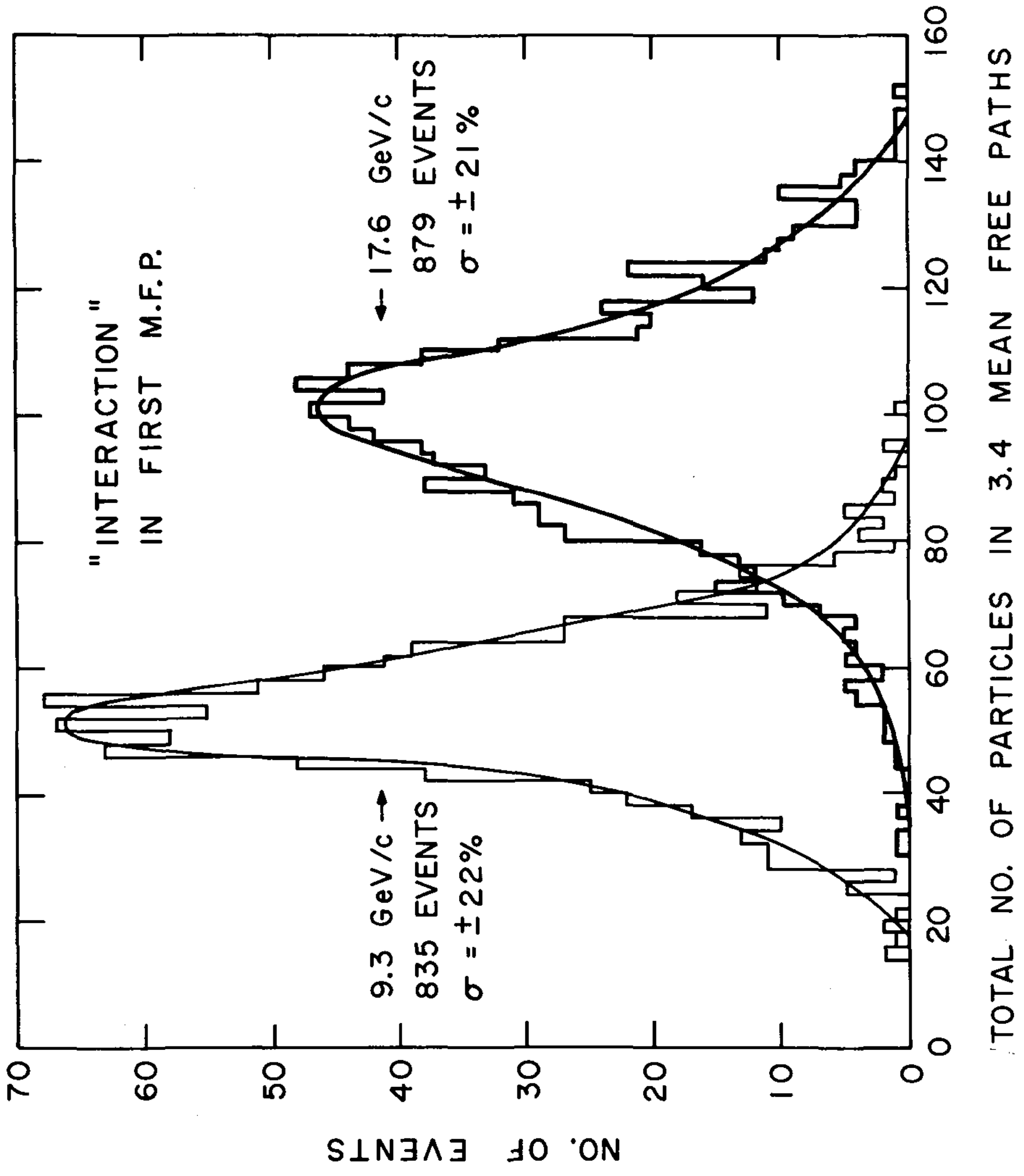
IONIZATION SPECTROMETER

Figure 1



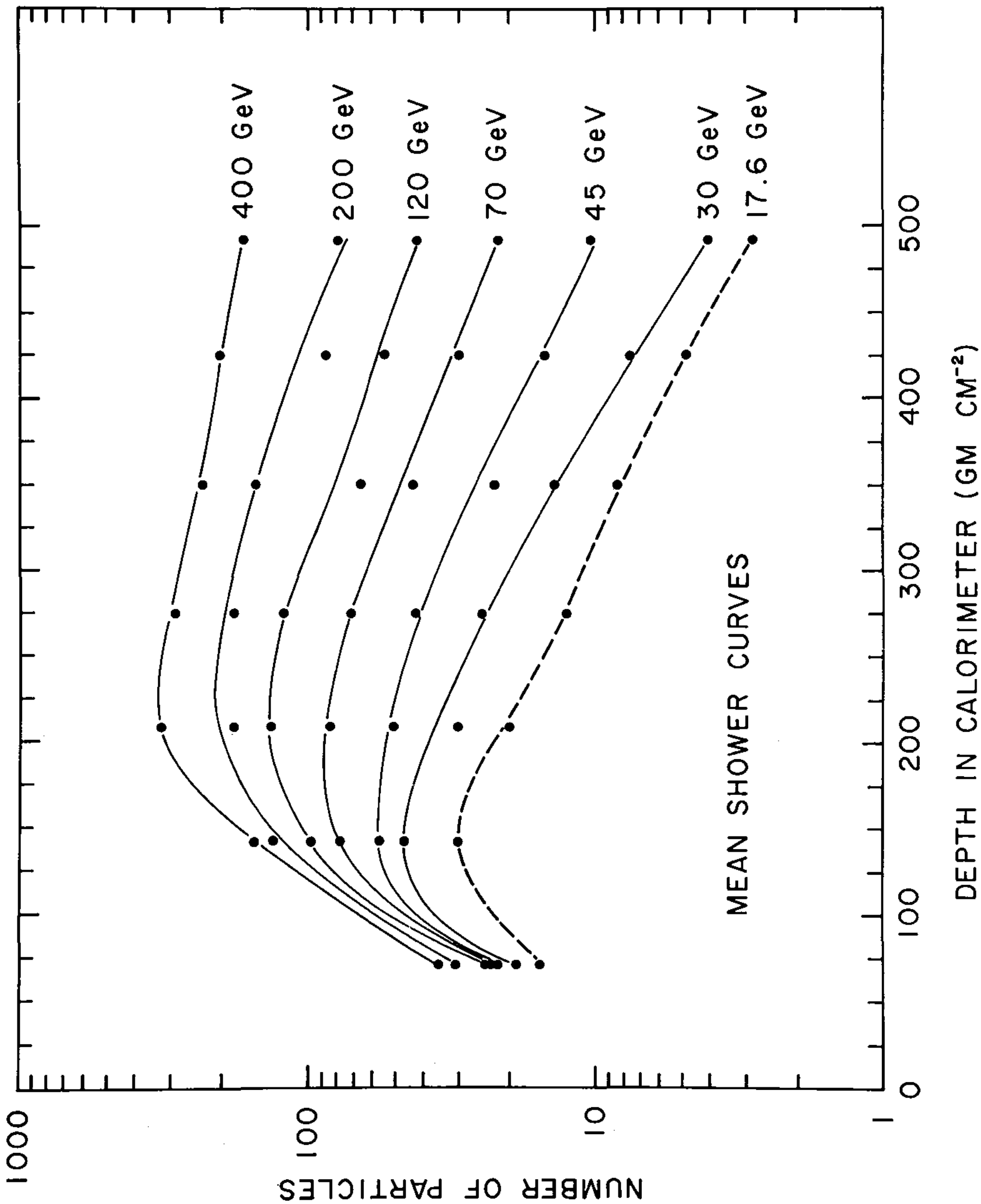
EVENT NO. 25725
PROTON ≈ 50 GeV
EVENT NO. 25735
PROTON ≈ 250 GeV
EVENT NO. 25928
He ≈ 12 GeV/NUCLEON
EVENT NO. 26102
He ≈ 120 GeV/NUCLEON
NO. OF PARTICLES
DEPTH IN GM CM⁻²
70 140 210 280 350 420 490 560
1 10¹ 10² 10³

Figure 2



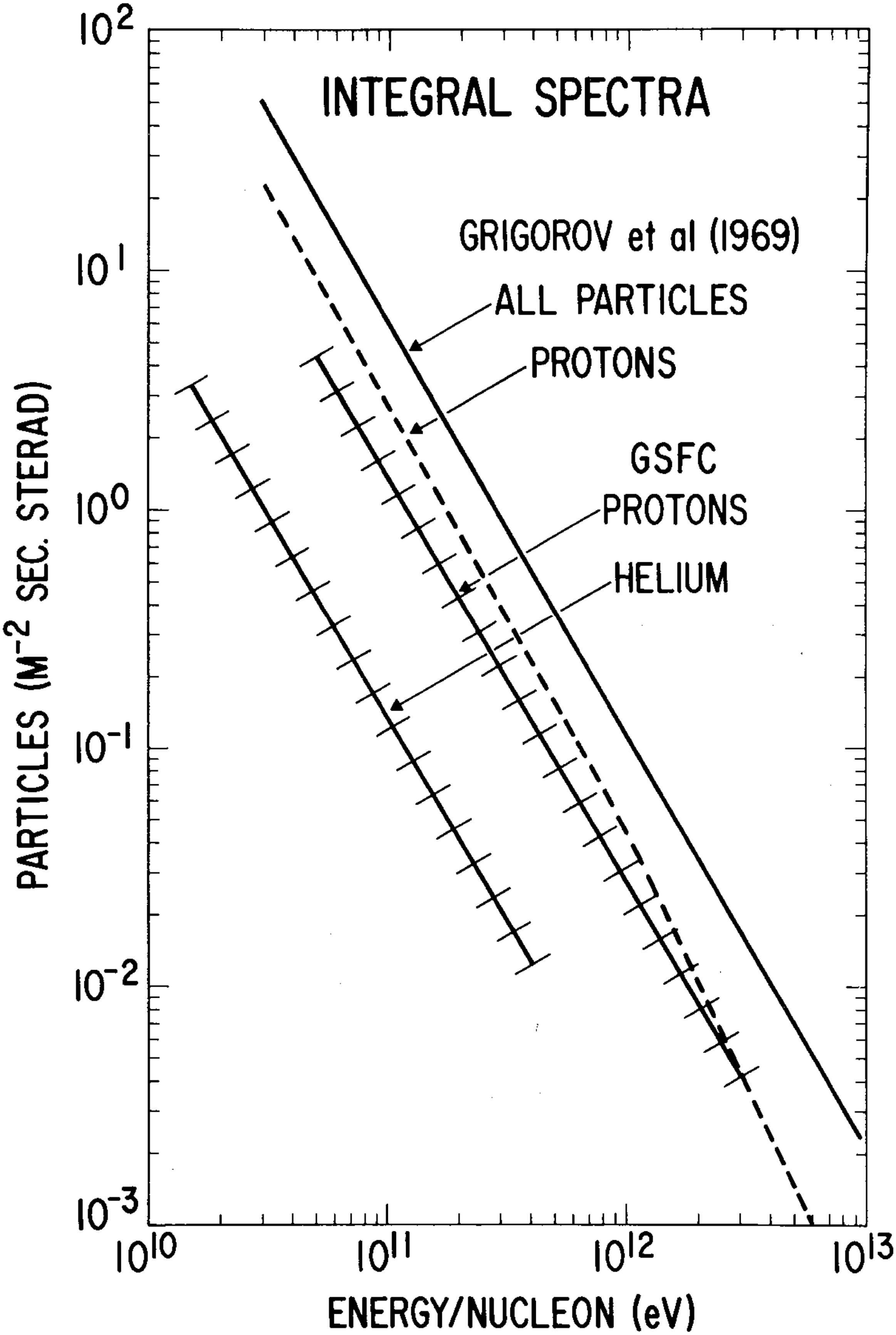
"INTERACTION"
IN FIRST M.F.P.
9.3 GeV/c →
835 EVENTS
σ = ± 22%
← 17.6 GeV/c
879 EVENTS
σ = ± 21%
NO. OF EVENTS
0
10
20
30
40
50
60
70
TOTAL NO. OF PARTICLES IN 3.4 MEAN FREE PATHS
0
20
40
60
80
100
120
140
160

Figure 3



400 GeV
200 GeV
120 GeV
70 GeV
45 GeV
30 GeV
17.6 GeV
MEAN SHOWER CURVES
DEPTH IN CALORIMETER (GM CM^{-2})
NUMBER OF PARTICLES
0
100
200
300
400
500
1
10
100
1000

Figure 4



INTEGRAL SPECTRA
GRIGOROV et al (1969)
ALL PARTICLES
PROTONS
GSFC
PROTONS
HELIUM
PARTICLES (M^{-2} SEC. STERAD)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{10}
10^{11}
10^{12}
10^{13}
ENERGY/NUCLEON (eV)

Figure 5