CHARGE COMPOSITION OF GALACTIC COSMIC RADIATION

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Abstract

Experimental results from the balloon borne ionization spectrometer flown in November 1970 have enabled the extension of the measurement of the energy spectra of cosmic rays to 10^{12} eV. The exposure factor for this flight was 1825 m^2-sr-sec and approximately 10,000 nuclei with $Z \geq 3$ have been observed. For nuclei with $Z \sim 6$, charges could be resolved to $\pm$ 0.2 units. The technique used for the measurement of energies of complex nuclei using an ionization spectrometer will be reported. Differential spectra of individual nuclei from lithium to oxygen and groups of nuclei with Z = 10-14, 15-19, 20-23, and 24-30 energy range $2\text{x}10^{10}$eV to 10^{12}eV could be described in a power law representation with an exponent -2.6. The results indicate that the composition of galactic cosmic rays remain similar to that observed at lower energies. These results from direct measurements, provide evidence for the processes of source acceleration, and interstellar propagation remaining essentially energy independent up to 10^{12}eV.

1. Introduction

The charge composition of cosmic rays between 10^{10} and 10^{13} eV was measured with an ionization spectrometer flown on a balloon which was launched on 14 November 1970, the balloon floated at a ceiling altitude of 6 gm/cm^2 for 14 hours and provided an exposure factor of $\sim$ 1825 m^2ster.sec. More than 10,000 nuclei with $Z > 2$ were studied and provide measurements of the detailed charge composition to approximately 2000 GeV total energy.

2. Experimental Details

Figure 1 shows a diagram of the instrument flown.

It consists of three major components, a charge measuring module, a spark chamber for determining particle trajectories, and an ionization spectrometer for measuring total energy. The charge of an incoming particle was determined using two plastic scintillators, the Lucite Cerenkov counter and the CsI mosaic. As each detector has a large sensitive area of 50 cm x 50 cm, the spark chamber was used to apply corrections to eliminate the dispersion caused by the variation of response over the area of the detector and also due to the angle of incidence of the particles. These corrections are discussed in some detail in the paper by Ormes and Balasubrahmanyan (1969).

When using the spark chamber to correct for these geometric effects it is necessary to determine the track of the incident particle unambiguously. The spark chamber has four perpendicularly oriented wire planes

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each with 200 wires spanning 50 cm. For each particle four (X,Y) measurements are available. As the experiment had as its objective, the study of singly charged particles such as protons and electrons and also Fe nuclei ($Z = 26$), the tracks of the incident particle had to be determined over an ionization range of 1 to 676. With the knock-on probability increasing as Z^2, heavier nuclei were invariably accompanied by knock-on electrons which cause confusion in determining the track of the incident heavy nucleus. A computer algorithm was developed to detect the tracks of heavy nuclei efficiently. For charges above Z=10 some error in angle may be caused by the knockons but the efficiency of finding a track is > 95% even at iron. Charge resolution obtained in this experiment is shown in Figure 2.

The charge-module was followed by the electron cascade section consisting of 12 tungsten plates of 6.13 gm/cm^2 (.04 mfp for protons and $\sim$ 1 radiation unit for electrons) and plastic scintillators of .63 gm/cm^2 (.01 mfp for protons). In this section, electrons developed electro-magnetic cascades whereas protons had only a small probability of simulating electrons. The details of separating electrons from the copious background of protons is discussed in detail in a subsequent paper (Silverberg et al. 1971). The electron cascade sections were followed by a nuclear cascade section consisting of 7 modules of Fe each 1/2 mfp for protons. Each module had three plastic scintillators distributed inside the iron viewed by a single photo tube. Since a sample of the number of particles in the cascade is taken every 1.5 radiation lengths, the fluctuations due to low energy electron cascades are decreased.

3. Energy Measurement

Most of the heavy nuclei interact in the tungsten modules or the first iron module allowing the whole spectrometer to absorb their energy. However using the whole spectrometer greatly reduces the available geometry. In order to "calibrate" the spectrometer response at various thicknesses the following procedure was followed. First the energy normalization was obtained using the energy loss of a sea level muon. Carbon nuclei selected from the spark chamber tracks such that they go through the entire spectrometer were calculated using 3,4,5,6, and 7 Fe modules. In Figure (3), the correlation of the energy of a particle determined with 3,4,5, and 6 modules with the energy determined using all 7 modules is shown. It can be seen that there is a good correlation between the energies determined by a subset of modules to that obtained using the entire spectrometer. However, as we go from 6 to 3 modules, the dispersion in the energy correlation increases. This gives an estimate of the error in determining the energy depending upon the "thickness" of the spectrometer as determined by the particle trajectory.

Figure (4) shows the estimated energy as a function of spectrometer depth. These curves represent average integral growth curves. These curves from 100 to 700 GeV show a tendency to saturate at the higher module numbers and can be approximately expressed on the form

$$E_i = E_A[1 - \exp(-\frac{N_i}{N})] \qquad (1)$$

Where E_i is the energy estimated using N_i modules, E_A the asymptotic energy and N is the number of modules required to absorb .73 of the energy. N varies slowly with energy. This equation is consistent with a model where the energy is absorbed exponentially in a thick block of matter. Using expression (1), the asymptotic energy E_A can be estimated. For the results presented in this paper, energy was determined for particles which passed through at least the first three iron modules.

4. Results and Discussions

Figure (5) shows the results on the differential energy spectrum of Li, Be, B, C, N, and O nuclei are shown. The intensity of the different components have been corrected for spallation in the atmosphere and the detector and have been extrapolated to the top of the atmosphere. The spectra are all consistent within errors to a power law in total energy with an exponent ~ -2.7 and extend to ~ 150 GeV/nucleon. The flattening at the lowest energy end of the spectrum is due to geomagnetic cutoff. (During the flight the balloon drifted from a geomagnetic cutoff of 5 GV to one of 3.5 GV).

Figure (6) shows the results on energy spectrum of L, M, LH, MH, VH groups of nuclei and all these nuclei have similar power law energy spectra in total energy with the exponent $\sim 2.7 \pm 0.1$. The errors shown in Figures (5) and (6) are statistical.

Von Rosenvinge et al. (1967) made measurements on composition up to 25 GeV/nucleon using the geomagentic cutoff at different locations, and, at the highest energy, a gas Cerenkov counter at different pressures as a threshold device. Our spectra and intensity are reasonable in agreement with these results. The intensities at 1.5 GeV/nucleon are about .10% below those of Von Rosenvinge (1969) which were obtained in 1966. The direction of the difference in intensities between the two experiments is consistent with an increasing solar modulation or it could be due to systematic effects.

Table (1) shows the results on the ratios of individual elements of light and medium groups and is in general agreement with the results of Lezniak et al. (1969), Dayton et al., O'Dell et al. (1969), and Webber & Ormes (1969).

Our results have shown that the charge composition at around 100 GeV/nucleon is essentially similar to that at low energies (Garcia-Munoz & Simpson, 1969; Teegarden et al., 1969). The implications of this on the photodisintegration phenomena in the immediate vicinity of a pulsar is discussed in a paper presented in this conference (Balasubrahmanyan, et al.).

TABLE 1

CHARGE RESOLUTION IN THE MEDIUM NUCLEI REGION

$\Delta Z = \pm 0.2$
$L/M = 0.29$ AT 7 gm/cm^2

No. of Boron Nuclei	1570
No. of Beryllium Nuelci	251
No. of Lithium Nuclei	496
No. of Carbon Nuclei	3505
No. of Nitrogen Nuclei	1281
No. of Oxygen Nuclei	3165

Li, Be, B = 1.98:1:6.25
C : N : O = 1.11:0.40:1

5. References

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O'Dell, F. W., Shapiro, M. M., Silberberg, R., Stiller, B., Tsao, C. H., Durgaprasad, N., Fichtel, C. E., Guss, D. E., and Reames, D. V., 1969. Proc. 11th International Conf. Cosmic Rays, 1, 457.

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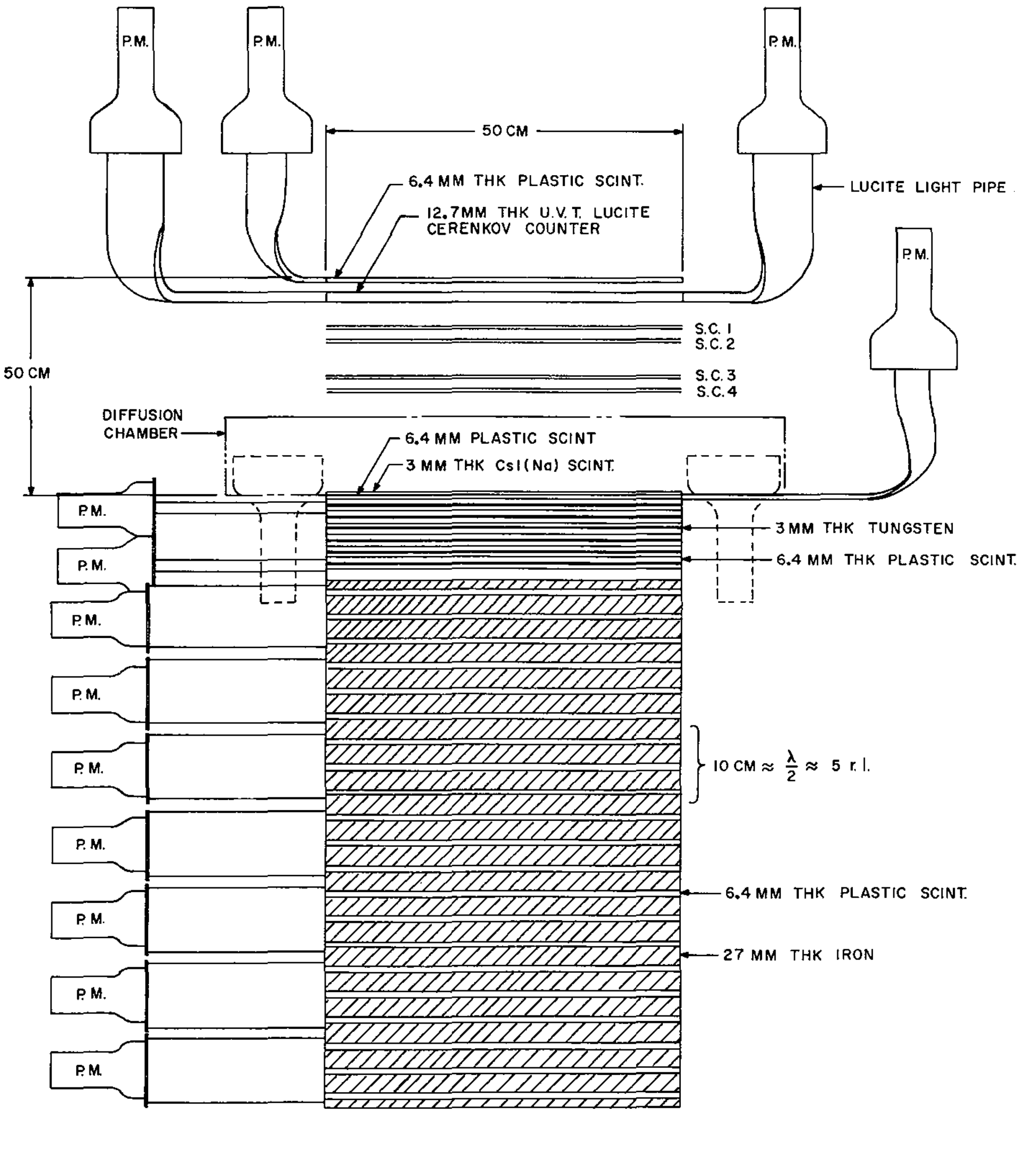
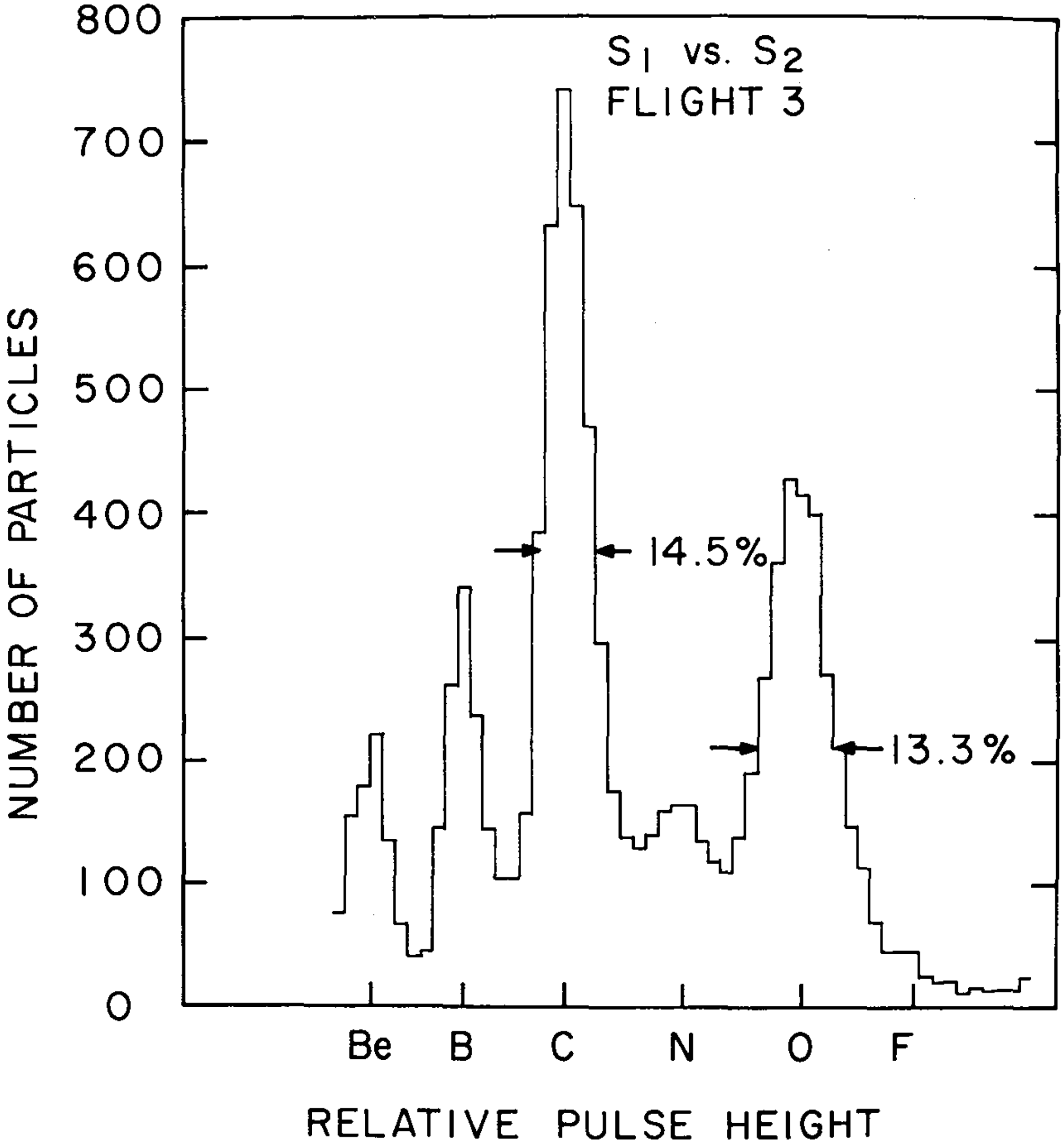


IONIZATION SPECTROMETER

FIGURE 1



800
700
600
500
400
300
200
100
0
NUMBER OF PARTICLES
S1 vs. S2
FLIGHT 3
14.5%
13.3%
Be
B
C
N
O
F
RELATIVE PULSE HEIGHT

FIGURE 2

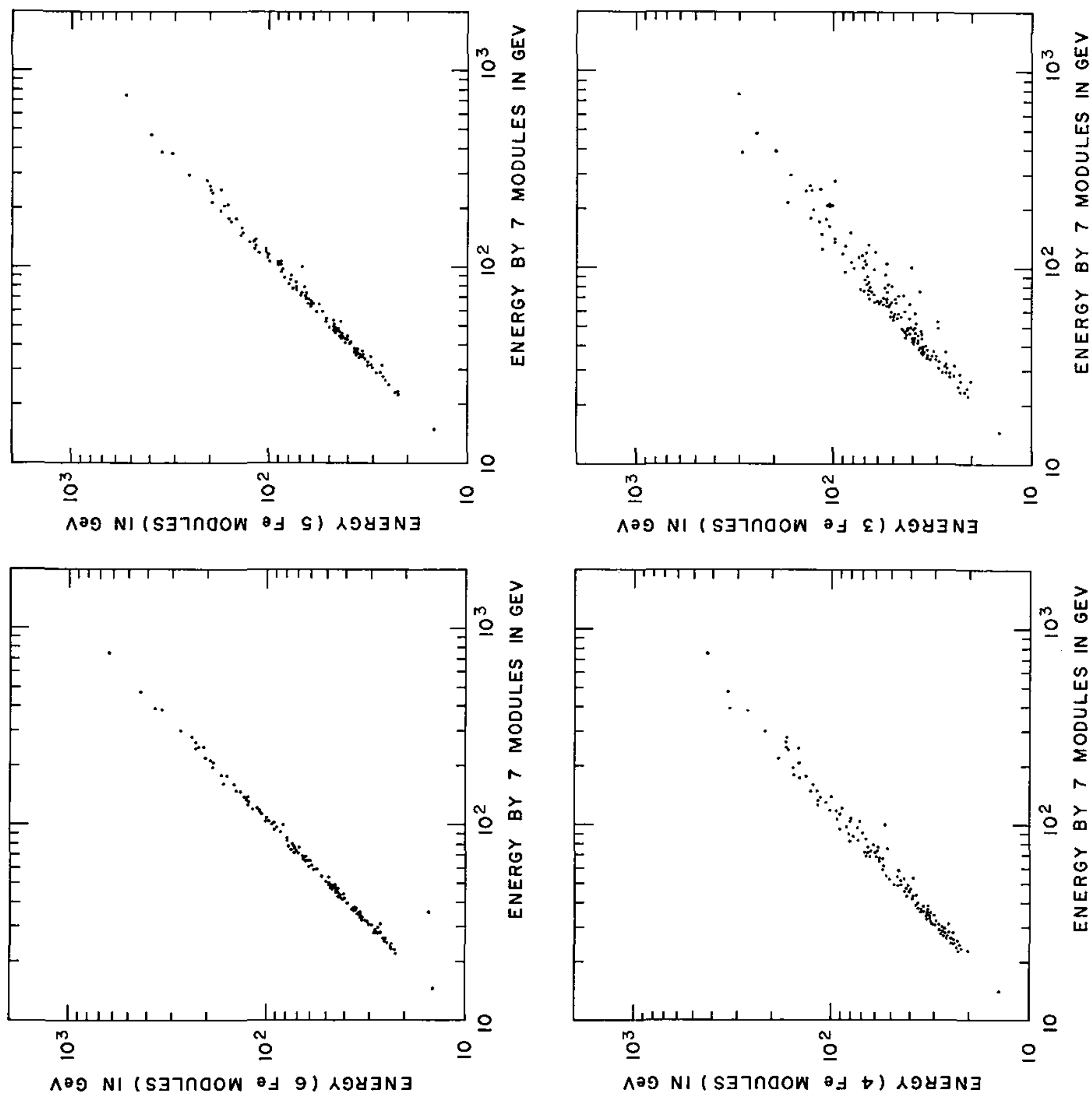

ENERGY BY 7 MODULES IN GEV
ENERGY (5 Fe MODULES) IN GeV
ENERGY (3 Fe MODULES) IN GeV
ENERGY (6 Fe MODULES) IN GeV
ENERGY (4 Fe MODULES) IN GeV
10
10^2
10^3

FIGURE 3

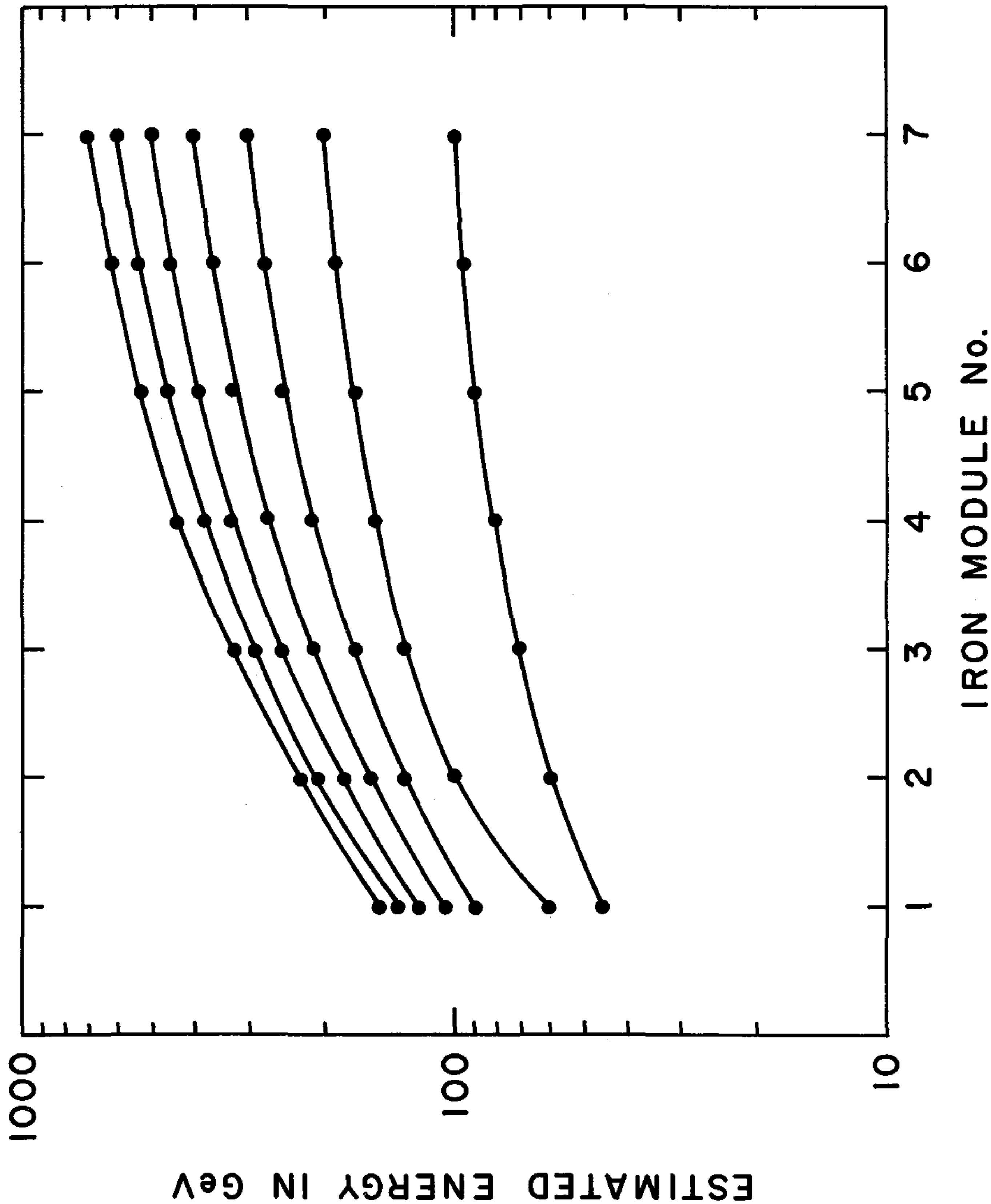


FIGURE 4

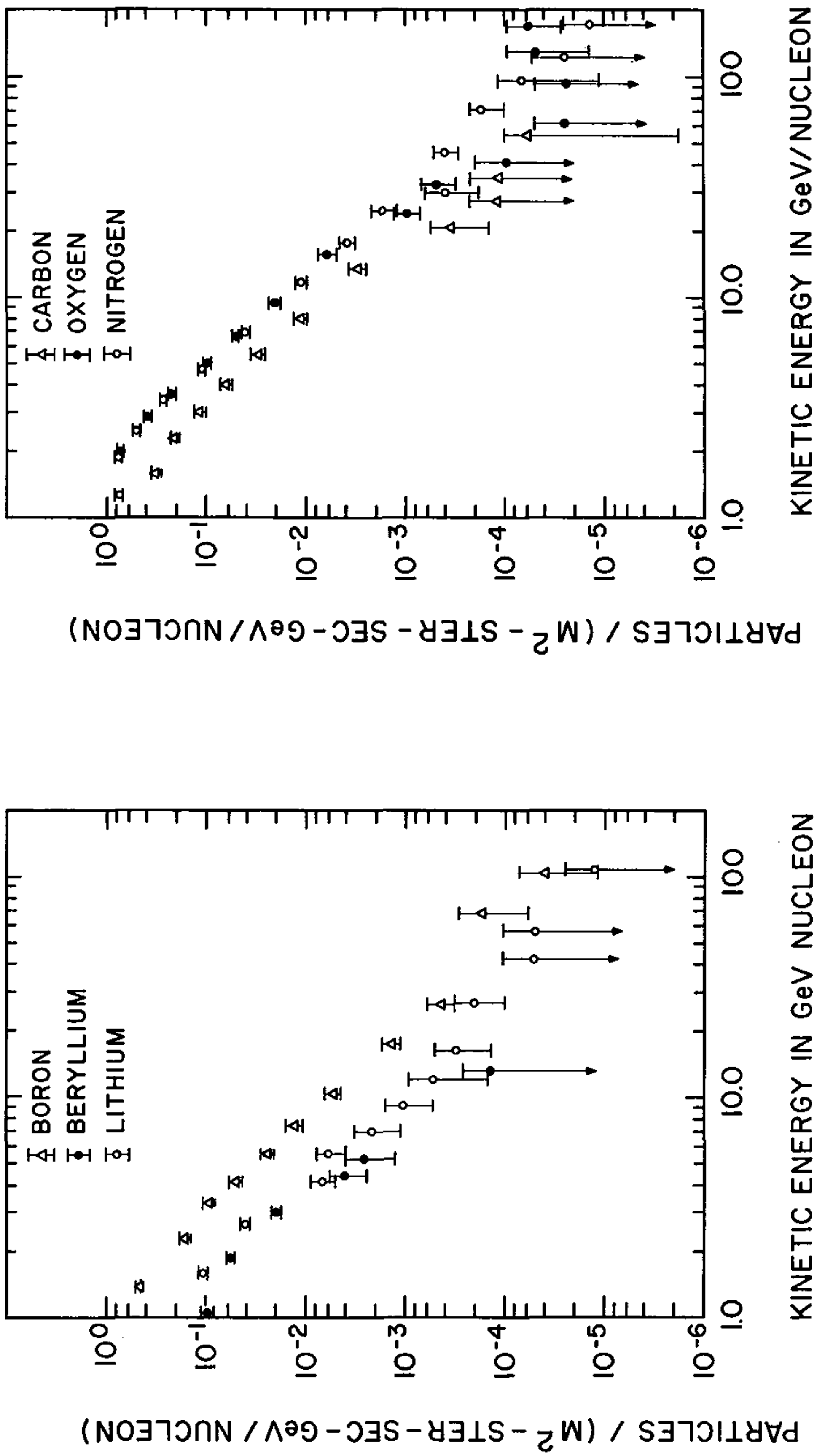

CARBON
OXYGEN
NITROGEN
PARTICLES / (M2 - STER - SEC - GeV / NUCLEON)
KINETIC ENERGY IN GeV/NUCLEON
BORON
BERYLLIUM
LITHIUM
PARTICLES / (M2 - STER - SEC - GeV / NUCLEON)
KINETIC ENERGY IN GeV NUCLEON

FIGURE 5

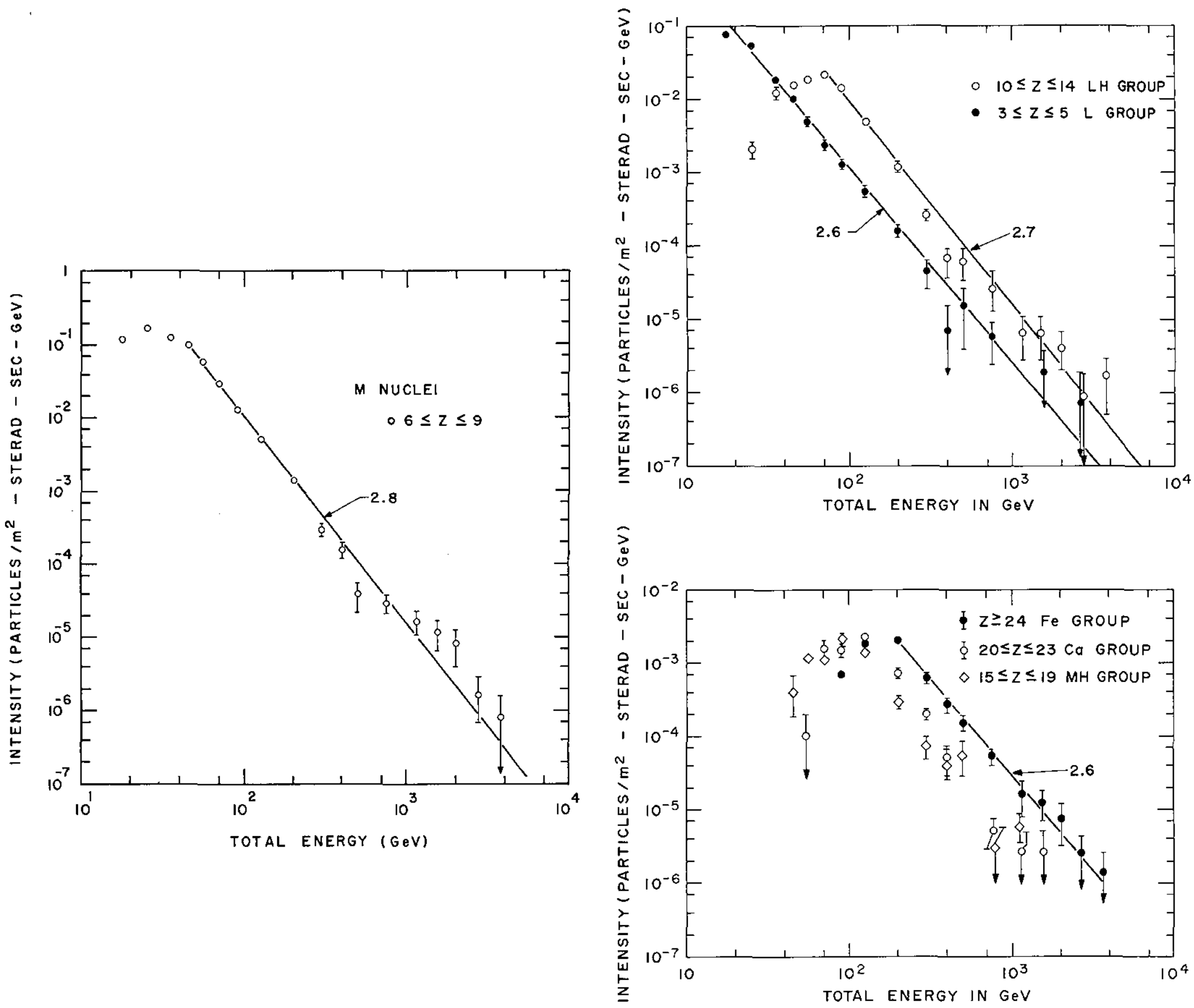

M NUCLEI
○ 6 ≤ Z ≤ 9
2.8
INTENSITY (PARTICLES/m² – STERAD – SEC – GeV)
TOTAL ENERGY (GeV)
○ 10 ≤ Z ≤ 14 LH GROUP
● 3 ≤ Z ≤ 5 L GROUP
2.6
2.7
TOTAL ENERGY IN GeV
Z ≥ 24 Fe GROUP
20 ≤ Z ≤ 23 Ca GROUP
◇ 15 ≤ Z ≤ 19 MH GROUP

FIGURE 6