ENERGY DEPENDENCE OF CROSS SECTIONS OF COSMIC RAY NUCLEI IN TUNGSTEN

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Abstract

An ionization spectrometer consisting of 12 layers of tungsten each 6.13 gm cm^{-2} thick and 7 iron modules each 70 gm cm^{-2} thick was flown in a balloon on November 14, 1970 at an altitude of 6 gm cm^{-2} for 16 hours. The distributions of the first interaction points are used to determine the mean free path of the incident particles. At energies of 20 GeV the proton m.f.p. of 140 gm cm^{-2} is in agreement with that of other workers. The m.f.p.'s of heavynuclei have been determined as a function of energy up to a total energy of 1,000 GeV. These results are compared with the overlap model of nucleus-nucleus collisions of Brandt and Peters. For C nuclei interacting with W the overlap parameter is -2.6×10^{-13} cms. The energy dependence of this parameter will be discussed.

1. Introduction

Nucleus-nucleus collisions at relativistic energies have been studied using the cosmic ray beam. This is the only available source of these particles because machines for accelerating heavy nuclei to high energies are not yet available. In this paper, the dependence of the collision mean free path of carbon and oxygen nuclei incident on alternate layers of tungsten and plastic scintillator are studied in the energy range 2 GeV/nuc. to 15 GeV/nucleon.

2. Experimental Details

The results were obtained from a balloon-borne ionization spectrometer used to determine the charge spectrum of cosmic rays in the energy range 10^{10} to 10^{13} eV (Ormes, et al. 1970). The instrument had a geometric factor of ~ 450 cm^2 ster and collected data at 6.0 gm/cm^2 for 14 hours. Energy measurements were performed on a total of ~ 1800 carbon and ~ 1700 oxygen nuclei. The identity of the incident particles was determined in a charge module consisting of two plastic scintillators, a lucite Cerenkov counter, a CsI scintillator mosaic, and a four module wire spark chamber. All the detectors had a sensitive area of 50 cm x 50 cm.

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The charge module was followed by an electron cascade section with 12 tungsten plates, each followed by a plastic scintillator. The tungsten plates were 6.13 gm/cm^2 thick (0.03 proton mean free paths) and the plastic scintillators were .63 gm/cm^2 thick (0.01 m.f.p.). The purpose of this section was to discriminate electrons from protons utilizing the rapid development of electromagnetic cascades in tungsten. This section was followed by a nuclear cascade section with 7 iron modules each 1/2 m.f.p. thick and was used to determine the energy of protons and other nuclear particles in cosmic rays. Using the electron cascade section, it was possible to study the passage of carbon and oxygen nuclei and to detect when they suffered nuclear interactions.

The C and O nuclei studied in this paper were selected using their consistent signatures in the multi-element charge module and in Figure (1) the charge resolution attained in the experiment is shown for the medium group of nuclei. The peak to valley ratio and charge resolution is quite good so that C and O nuclei could be selected unambiguously.

Figure (2) shows the pulse height resolution for the oxygen nuclei (as selected by the charge module) in some of the tungsten modules. Of the 12 detectors, all except the 5th module (called T-5) had resolution $\approx$ 15% FWHM with a pronounced peak due to the oxygen nuclei. Note that the peak of oxygen is becoming less abundant relative to the background with increasing depth in the tungsten. Results with carbon nuclei had similar resolution. The energy measurement is described in detail in an accompanying paper and will be published elsewhere (Ormes, et al., 1971). An incident nucleus is said to have interacted according to the following criteria: A_i is the mean pulse height for a given charge and W_i the full width at half maximum, where i represents the tungsten module. If a particle in the (i + 1), (i + 2), and (i + 3) detectors has its pulse heights such that $\frac{Pi}{A_i} > (1 + W_i)$ or $< (1 - W_i)$ in all the three successive detectors, then it is supposed to have interacted in the i detector. The probability of this occurring by a chance fluctuation was < .1%. Reducing the criteria for nuclear interactions to two successive detectors instead did not affect the results.

Figure (3) and Figure (4) show the exponential absorption of carbon and oxygen nuclei in the tungsten and plastic scintillators. It can be seen from the figures that as the energy increases from 1.5 GeV to 9 GeV/nuc., the particles are absorbed more quickly.

Figure (5) shows the mean free paths for carbon and oxygen nuclei as a function of energy. The mean free paths were calculated using the relation

$$\lambda_i = {}^{X}/(\Delta N_i/N_i)$$

where X is the absorber in gm/cm^2, N_i is the number of incident nuclei in a module and ΔN_i the number of interactions in the i^{th} module. (For the purposes of this calculation, data from detector T5 and all the other detectors which depended on T5 for definition of nuclear interaction were ignored.) The implied increase in cross section can be related on Bradt & Peter's (1950) phenomenological model for nucleus-nucleus collisions to the changes in the overlap parameter b in the formula

$$\sigma = \pi r_o^2 \; (A_1^{\;1/3} + A_2^{\;1/3} - b)^2$$ where A_1 and A_2 are the mass numbers of the incident and target nuclei, $r_o = 1.1 \times 10^{-13}$ cms. The value b from these measurements varies from $-(2.6 \pm 0.5) \times 10^{-13}$ cms at 2 GeV/nuc. and $-(11.9 \pm 2.4) \times 10^{-13}$ cm at 15 GeV/nucleon. (From figure (5), one can see that the mean free path decreases as a function of energy for both carbon and oxygen nuclei.)

3. Discussion

The mean free paths of both carbon and oxygen nuclei are approximately equal and decrease by roughly a factor of 2.5 over the energy range 2 to 15 GeV/nucleon.

Aizu et al. (1960), for collisions with nuclei of nuclear emulsions, observed that the mean free path decreased from 16.2 $\pm$1.3 cm to 13.2 $\pm$0.7 cm when energy changes from 0.7 GeV/nuc. to 3 GeV/nuc. Data at higher energies are not available for comparison.

The change in b could be due to the relativistic deformation of the incident nucleus. At higher velocities, as seen from the reference frame of the target nucleus, the projectile will be disc shaped. This distortion might result in a higher effective b in the Bradt and Peters' model or alternatively, the distorted nucleus may be more prone to break-up resulting in a decreased mean free path at higher energies.

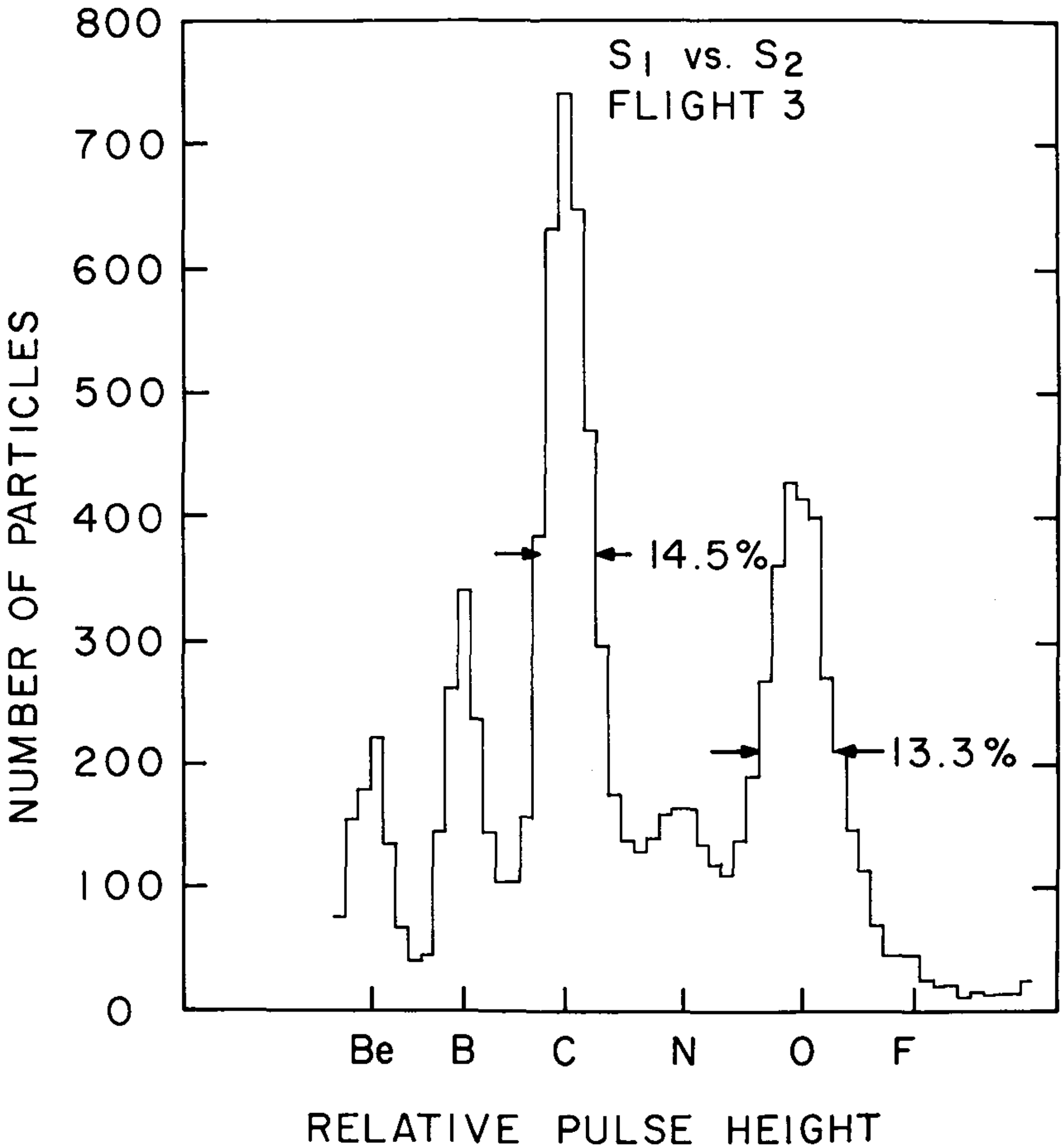
4. References

Aizu, H., et al. 1960, Prog. Theo. Phys., Suppl. No. 6, 54.

Bradt, H. L., and Peters, B., 1950, Phys. Rev. 77, 54.

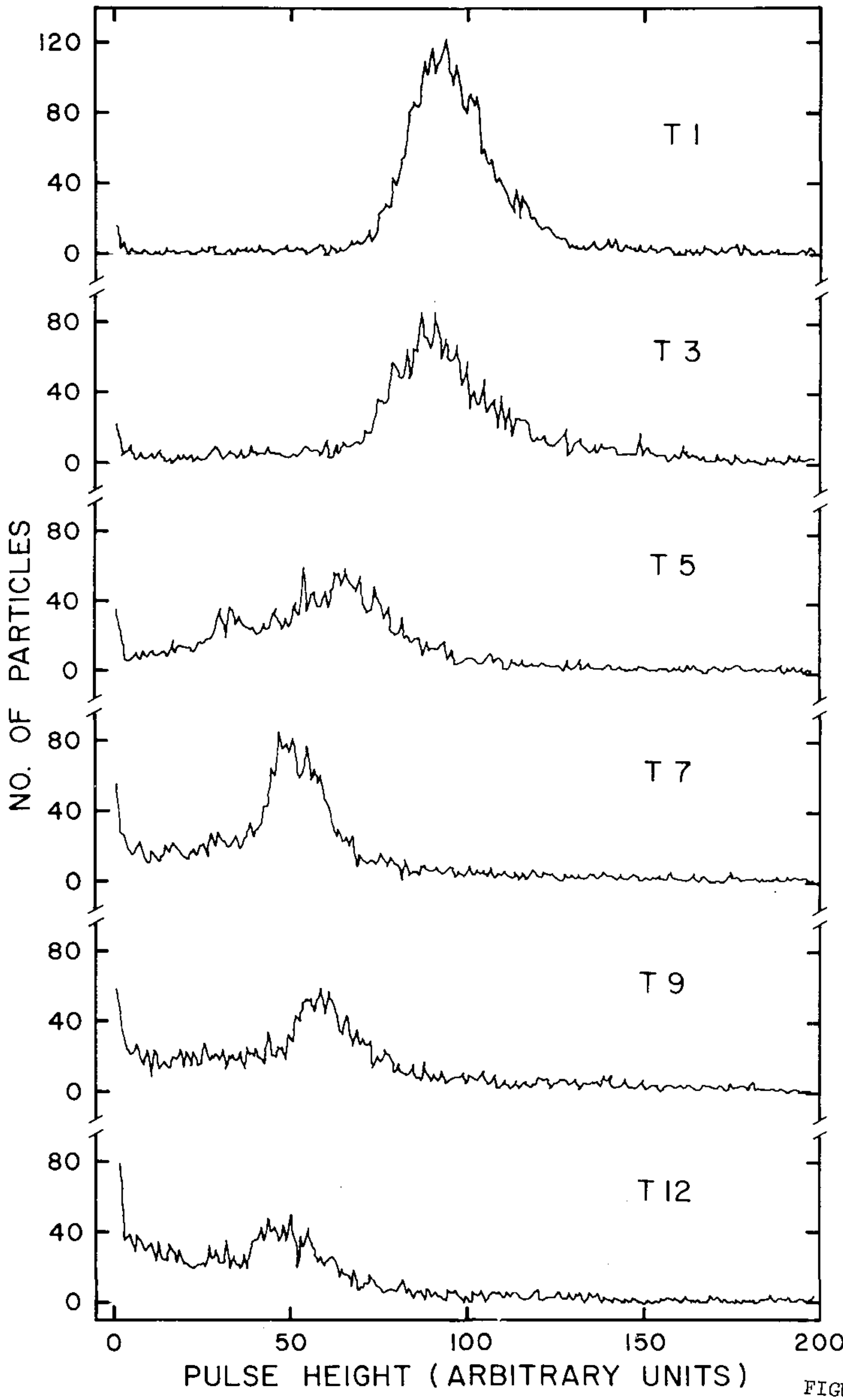
Ormes, J. F., Balasubrahmanyan, V. K., McDonald, F. B., and Price, R. D., IEEE Trans. on Nuc. Sci., Vol. NS-15, 3, 566, 1968.

Ormes, J. F., Balasubrahmanyan, V. K., and Ryan, M. J. (paper presented at this conference in the O.G. session, to be published).



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 1



120
80
40
0
T 1
80
40
0
T 3
80
40
0
T 5
80
40
0
T 7
80
40
0
T 9
80
40
0
T 12
NO. OF PARTICLES
0
50
100
150
200
PULSE HEIGHT (ARBITRARY UNITS)

FIGURE 2

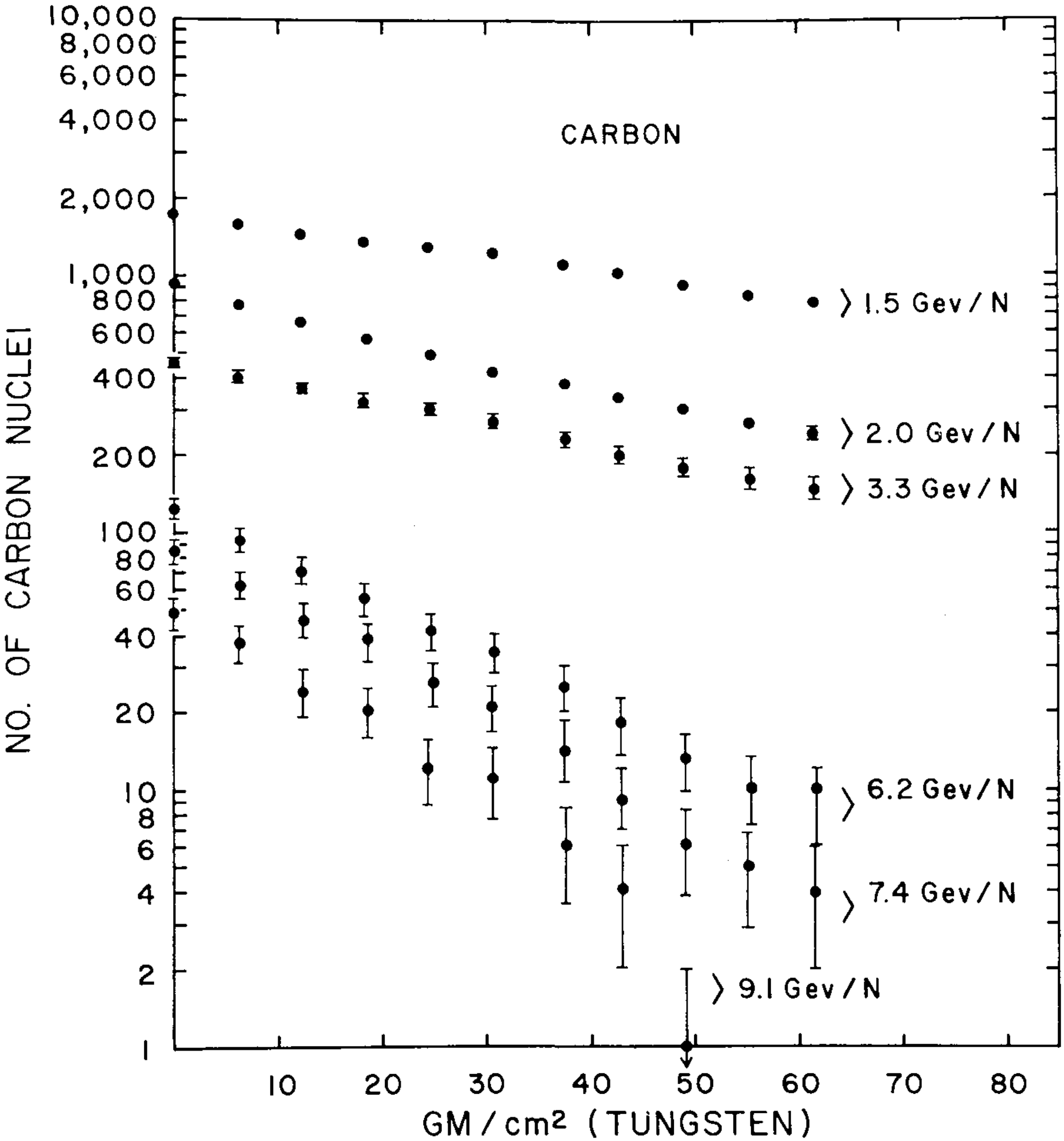

CARBON
NO. OF CARBON NUCLEI
10,000
8,000
6,000
4,000
2,000
1,000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
1.5 Gev / N
2.0 Gev / N
3.3 Gev / N
6.2 Gev / N
7.4 Gev / N
9.1 Gev / N
10
20
30
40
50
60
70
80
GM / cm2 (TUNGSTEN)

FIGURE 3

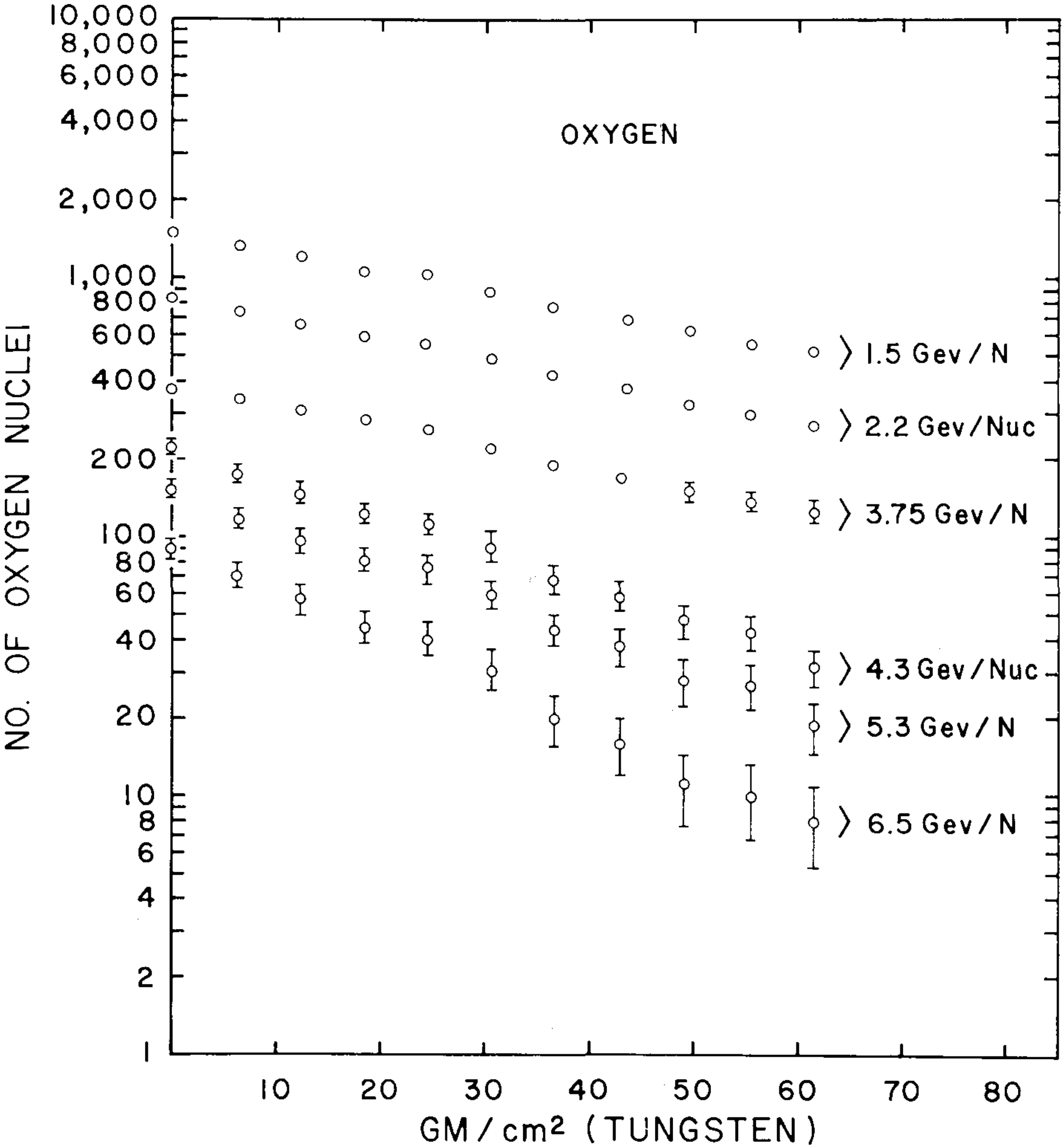

OXYGEN
NO. OF OXYGEN NUCLEI
10,000
8,000
6,000
4,000
2,000
1,000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
10
20
30
40
50
60
70
80
GM / cm2 (TUNGSTEN)
1.5 Gev / N
2.2 Gev/Nuc
3.75 Gev / N
4.3 Gev/Nuc
5.3 Gev / N
6.5 Gev / N

FIGURE 4

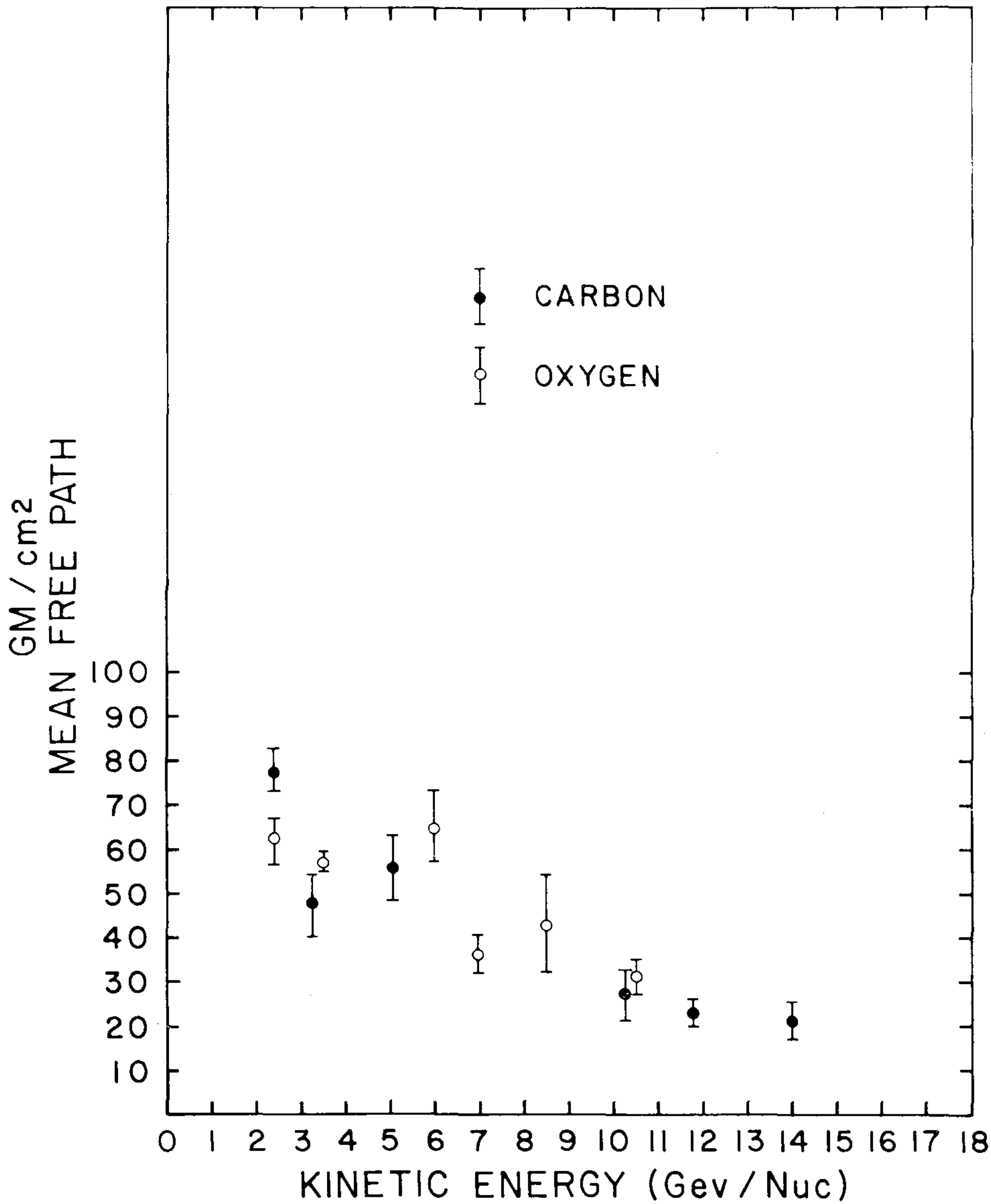

CARBON
OXYGEN
MEAN FREE PATH
GM / cm2
100
90
80
70
60
50
40
30
20
10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
KINETIC ENERGY (Gev / Nuc)

FIGURE 5