X-611-66-366

NASA TM X-55602

THE ENERGY SPECTRUM OF COSMIC RAY HEAVY NUCLEI OF CHARGE Z > 10 DURING A SOLAR QUIET TIME IN JULY 1961

AUGUST 1966

NASA

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

THE ENERGY SPECTRUM OF COSMIC RAY HEAVY NUCLEI OF CHARGE Z≥10

DURING A SOLAR QUIET TIME IN JULY 1961

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ABSTRACT

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The energy spectrum of heavy nuclei (charge Z≥10) has been determined, in the energy interval from 200-700 MeV/nucleon, using a stack of nuclear emulsions, exposed on 8th July 1961 at a mean altitude of ~2.4 g/cm^2 of residual atmospheric depth on a balloon flown from Fort Churchill, Manitoba. The flight was preceded by a period of three months of low solar and geophysical activity. The charge and energy spectra were obtained principally from tracks of particles that ended in the detector by a combination of range and δ-ray density measurements. A second charge estimation for particles which stop in the emulsion was made from integral δ-ray counts as a function of range. The energy spectrum was extended up to 700 MeV/nucleon by taking into consideration also the tracks that pass through or interact within the stack using a combination of δ-ray

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density and multiple scattering measurements that determine the charge and energy of the nuclei. This energy spectrum was combined with the spectra measured for protons and helium nuclei in the same flight and with similar data obtained during 1963 with a view of arriving at a better understanding on the propagation of cosmic ray nuclei in source regions, instellar space and solar system.

Author

INTRODUCTION

The energy spectra of low energy cosmic ray nuclei observed at the earth depend on a) the energy spectrum of the nuclei at the source, b) the propagation of these nuclei in interstellar space (diffusion and acceleration) and c) the modulation of the energy spectrum in the vicinity of the solar system. These three effects may be studied by making systematic simultaneous observations of the energy spectra and intensity of various components of the cosmic radiation as a function of time. Such systematic studies of the differential energy (kinetic energy, ϵ, in the 100-600 MeV/nucleon region) spectra for protons and helium nuclei were begun in 1956 by McDonald (See Webber, 1962 for a summary); these studies were extended to the low energy regions (down to $\sim$50 MeV/nucleon) in 1961 by Fichtel et al. (1964). The energy spectrum ($\epsilon \leq 600$ MeV/nucleon) of the heavy nuclei (charge $Z \geq 10$) component was best studied for the year 1963, by Lim and Fukui (1965) and Fichtel et al. (1965A) using emulsions flown in satellites and rockets. The spectrum for the year 1961 in the energy region about 200-700 MeV/nucleon, is reported in this paper. A nuclear emulsion detector is used for this purpose.

The results obtained here have been combined with the spectra of protons and helium nuclei ($\epsilon \leq 600$ MeV/nucleon) measured in the same stack by Fichtel et al. (1964) and with the spectra obtained during 1963 for heavy nuclei, α-particles and protons with a view to draw inferences on the aspects of the propagation of cosmic ray nuclei in the source regions, in the interstellar space and in the solar system. We describe below the experimental procedures adopted and the results obtained. The implications of these results will be discussed in a separate paper.

EXPERIMENTAL DETAILS

I. Stack and Exposure: The stack of emulsions used in the present work consisted of 118 plates of 20 cmx10cmx600μ thick Ilford emulsions of various sensitivities exposed for a period of about 10 hours, at a mean altitude of 2.4 g/cm^2 of residual atmosphere in a balloon flight from Fort Churchill on 8th July 1961. The first 20 pellicles of the stack were G5 emulsions and the remaining were arranged in units of ten, each unit consisting of pellicles arranged in the following order: G0, G5, G2, G5, G2, G5, G2, G5, G2 and G5 respectively. The stack was rotated through 180° at the ceiling altitude. The time-altitude curve for the flight has been given previously by Fichtel et al. (1964).

The exposure was made at a time of low solar activity, preceded by three months during which no prominent Forbush decreases or solar cap absorption events were observed. The Mt. Washington neutron monitor counting rate on the day of the flight was 2148.

II. Scanning: The central G5 emulsions in this stack were scanned along a line parallel to the top edge and 5mm inside the stack. The scanline had a length of 5 cm. and was at least 1 cm. away from the processed edges. Tracks having a projected zenith angle $\theta p \leq 50^{\circ}$, dip angle $\alpha \leq 29^{\circ}$ and an ionization $I \geq 64$ times the minimum of ionization were accepted. These tracks were followed through the stack until they ended, or interacted within the stack or left the stack.

III. Charge identification of the nuclei and the measurement of their energies: The charge and energy of these nuclei were determined by a combination of δ-ray counting, range and multiple scattering measurements. The general experimental procedures adopted and the errors involved in the measurements were described in the literature in detail (see, for example, Aizu et al., 1960). Therefore, we shall simply state here the methods used and describe them only briefly.

Stopping Tracks: For tracks ending in emulsion, the energy and charge of each nucleus can be estimated fairly accurately, up to a few per cent of its value, from a measurement of the δ-ray density and range in the emulsion. The δ-ray density was measured, in the present analysis, by counting δ-rays in G-5 emulsions close to a point where the tracks crossed the scan line. Two procedures of δ-ray counting were used; "short δ-ray counting", in which δ-rays containing 4 or more grains were counted and "long δ-ray counting", in which δ-rays having a projected length greater than 3.2μ from the track on either side were counted. Standard checks for consistency in the counting and corrections for the dip angle of the tracks were made.

Since the δ-ray density is dependent on the sensitivity of the emulsion, it becomes necessary to determine the variation of sensitivity of emulsion with depth and from plate to plate. This variation was found to be, from measurements of grain density, less than 5 per cent, the percentage error in the grain counting. We consider below for further analysis, first the tracks that ended in the G5 emulsions, since the calibration curves were obtained from these tracks.

A) Tracks that ended in G5 emulsions: On all tracks that stopped in G5 emulsions, an integral δ-ray count was performed on the track length available in the emulsion, up to a distance of 2000μ. Both types of counting procedures were used, but the results presented here are mainly from the long δ-ray counting; the other method of counting was used only as an additional measurement to separate charges 8 and 10. The number of δ-rays counted by the long δ-ray method, N_δ (R), varies with the range R, by a similarity law (see for example, Aizu et al., 1960).

$$N_\delta \ (R) = A \ . \ F(Z^2R/A)$$

where Z and A are the charge and mass of the nucleus and $F(Z^2R/A)$ is a certain function of the product (Z^2R/A). On a plot of N_δ (R) vs range R, both on a logarithmic scale, the data of every track, irrespective of the charge, will fall on the same curve expressing the function $F\ (Z^2R/A)$, after applying a translation along the -45^o line and making a correction to the range R for the range extension, due to the capture and loss of electrons by a heavy nucleus near the end of the range. Thus, if a relationship is established for a particle of known charge, the relation can be obtained for the other nuclei. The standard relationship was obtained as follows: We selected a stack of nuclear emulsions that existed at this laboratory, in which charge values of heavier nuclei were determined previously (Fichtel et al., 1965A) and which had the same ionization characteristics as the present stack. The minimum of ionization in the G5 emulsions used for counting were found to be the same within the errors of the counting, 18.7±0.9 grains vs 17.9±0.9 grains per 100μm. The value of the background δ-ray density also was found to be the same, in the two stacks, within the errors of determination; this value is normally a small quantity and becomes negligible compared to the density for tracks of particles with high charge ($Z \geq 10$). Thus nuclei, whose charge values were well-determined in the previously analysed stack, could be used for the calibration purposes. The two types of counts, short δ-ray counts and the long δ-ray counts, were made by the same observer on the following tracks, each having at least a length of 2mm. in the 600μm emulsion.

a) Two well-identified carbon nuclei

b) Two well-identified oxygen nuclei

c) One nucleus of charge Z=12

and d) One nucleus of charge Z=26

Making use of this data, the similarity law and the correction for the range extension, the calibration curve, $N_\delta(R)$ vs range R was constructed. This curve was used to determine the charge values of the tracks that have at least a length of 0.8 mm in the G5 emulsion. Twenty nuclei satisfy this criterion, and the charges of these nuclei thus determined constitute one estimate of the charge value.

The kinetic energies per nucleon, near the scan line, of all stopping particles in G-5 emulsions were estimated using the range-energy relation given by Barkas (1963) and the relation,

$$R_P = \left(\frac{Z^2 \quad R_H}{A} \right) - R_{ext}$$

where R_H is the range of the nucleus of charge Z and mass A, in units of proton mass, R_P is the equivalent proton range and R_{ext} is the well-known range extension discussed above (Barkas, 1963).

In order to obtain the charge values a) for nuclei that stop in G5 emulsions and have lengths less than 0.8 mm in that emulsion and b) also for nuclei that stop in G2 and G0 emulsions, we had obtained an additional calibration curve, δ-ray density vs energy of the nucleus for various charge values from the information deduced above, namely, the charge and the kinetic energy of the nuclei stopping in the G-5 emulsions. On all these tracks, additional measurements of range and δ-ray density using both types of counts were made near the scan line. The calibration curves of (N_δ) vs the velocity of the nucleus for various Z-values have been obtained, making use of the relation $N_\delta = (aZ^2/\beta^2) + b$ where a and b are constants. These curves were used to determine the charges of <u>all</u> nuclei that stopped in the G-5 emulsion; thus a second estimate of the charge value is obtained for the twenty nuclei that stopped in G-5 emulsions described before. These two values are plotted in Figure 1; they agree within the errors of the determination. We cite this as one argument for justifying the validity of the calibration procedure adopted here; a further discussion will be made at the end of the section.

The charge values of <u>all</u> nuclei thus determined are plotted in Figure 2. The energies of these nuclei were estimated from the ranges as described above; these values extrapolated (See section "IV Corrections") to the top of the stack are given in Figure 3.

B) Tracks that ended in G2 and G0 emulsions: On every track that ended in a G2 or a G0 emulsion, the two types of counts, long δ-ray counts and short δ-ray counts, wherever possible, were made near the scan line and their respective densities, $(N_\delta)_l$ and $(N_\delta)_s$ were computed. The charge values and energies of these nuclei were determined as described before from this information, the measured values of residual ranges and the calibration curves of $(N_\delta)_1$ and $(N_\delta)_s$ vs range obtained in the previous section. The charge values thus determined are shown in Figure 2 and the corresponding energy values, extrapolated (See section "IV Corrections") to the top of the stack are given in Figure 3.

C) Errors in the charge and energy determination: Since we have used the range-energy relation to determine the energy per nucleon of the various particles, the error in the energy per nucleon ΔE arises mainly from the error, in the charge determination, ΔZ. In most cases, the error ΔZ is given by $0.03 x Z$ and rarely exceeds one unit of charge value. The corresponding error in energy per nucleon ΔE, is given by $(\Delta E/E) = 2\alpha(\Delta Z/Z)$ where α is the range-energy exponent in emulsion and has a value ~ 0.6. An error of one unit of charge will introduce an error in the energy of ~12% for Neon and ~5% for Iron-nucleus. Thus the error on the energy estimates, on the average, is about 4 to 5 per cent. Most of the tracks for which the energy spectrum has been measured in this work stopped in the emulsion.

Tracks leaving the stack or interacting: Tracks leaving the stack or interacting in emulsion, provide information on the high energy part of the spectrum. However, the charge and energy measurements for these nuclei becomes worse compared to those for ending tracks. Hence, we made use, wherever possible, of three parameters, in order to ensure the reliability of the data. These are i) δ-ray density of the primary track near the scan line ii) δ-ray density of the primary track close to the point of exit or close to the point of interaction (both short and long δ-rays, at least 200 in number were counted) and iii) multiple scattering measurements on favourable flat tracks (at least 5mm. in length in 600μ emulsion). The calibration curves given in "section, Stopping tracks" were used and were extended to higher energies by utilizing the relation, $N_\delta = (aZ^2/\beta^2) + b$ described above. The energy was estimated either from a change in the δ-ray density with range or from multiple scattering measurements; for some tracks both methods were used. For scattering measurements, a basic cell size of 250μ was employed and the method of overlapping cells was adopted to eliminate the noise. In Table 1 are given the energy values of the five nuclei determined by both the methods. The agreement is satisfactory.

It was found that $_{13}$ and $_{11}$ nuclei having charge values $Z \geq 10$ and energy values corresponding to ϵ = 300-900 MeV/nucleon at the top of the stack pass through and interact within the stack. Since the error estimates on the energy for $\epsilon \geq 700$ MeV/nucleon become larger than 14%, the energy spectrum has been limited to energies below 700 MeV/nucleon at the top of the atmosphere. Thus only 9 tracks (four tracks interacting and five tracks passing through the stack) were included in the final sample, together with the stopping tracks discussed above. In the case of these 9 tracks, integral charge values have been assigned for every such track; these are shown separately by dashed and shaded squares in the plot of the charge spectrum. (Figure 2).

The combined charge spectrum of all nuclei thus obtained is shown in Figure 2 and the combined energy spectrum extrapolated (See section IV "Corrections") to the top of the stack is given in Figure 3.

Since we have used, for calibration purposes, well-identified nuclei from a different stack, the ionization characteristics of which we have shown, with great care to be very nearly the same as the present stack, we may remark here, that the validity of the calibration procedure used here is justified from the facts: a) a consistent assignment of charge values were arrived at by the two methods of charge determination employed as discussed previously (Figure 1) and b) the energy values determined by two methods agree within the errors of observation (See Table 1). We may further add that the gross features of the cosmic ray charge spectrum reported by other observers is well exhibited here; a) preponderance of even nuclei over odd nuclei (even/odd ratio ~2.2 as compared to value of ~3.2 reported by Aizu et al., 1960) indicating no wrong assignment of charge values by one unit in the region of Z = 10-19, and b) the paucity of elements around Z = 16-19 exists as is observed by others (See section "RESULTS- Charge Ratios").

IV. Corrections: Every track was followed backwards to the top edge of the stack and an energy spectrum of particles at the top of the stack was constructed, after allowing for the change in energy of each nucleus due to ionization loss in traversal through emulsion from scan line to the processed edge. This correction has been made for each nucleus, from the data of the actual track length measured in emulsion and using the range-energy curves in emulsions given by Barkas (1963). Further, three types of corrections were applied: a). For loss of particles due to inefficiency in scanning; the efficiency has been estimated to be 96% for nuclei of charge $Z \geq 10$ by two independent observers. b)For loss of particles due to interaction between the scan line and processed edge; this loss has been estimated as 4.9% and 6.6% for $H_{2,3}$ (Z = 10-19) and H_1 - nuclei ($Z \geq 20$) respectively from the measured values of the actual track length in emulsion and the interaction mean free paths in emulsion (Daniel and Durgaprasad, 1962) and finally c) for loss of particles, in the energy region between 160 MeV/nucleon and the minimum energy a nucleus is required to have at the top of the atmosphere so that it gets recorded at the scan line of the detector. We call this as the "minimum cut-off energy of observation". This energy depends mainly on the ionization losses of the nucleus in the air and in the emulsion between top edge and the scan line. This last correction was applied together with the extrapolation correction, discussed in the next section, to the final energy spectrum obtained at the top of the atmosphere.

V. Extrapolation to the top of the atmosphere: The procedure adopted for extrapolating the observed spectrum to the top of the atmosphere is that of Aizu et al. (1960). The effective mean vertical atmospheric depth is 2.4 g/cm^2 in the present flight; in view of this low value, it is assumed that all the fragmentation has occurred at the top of the atmosphere. The error introduced, by making this approximation, is less than two per cent for the mean depth and the charge value considered. Thus the energy of <u>each</u> nucleus was first corrected for the ionization loss in air. The range-energy relation given by Barkas and Berger (1964) was used to correct for this ionization loss. The flux values thus computed for every energy interval from this data were later corrected for loss due to the fragmentation, using the diffusion equations (Kaplon and Noon, 1955) and the following parameters;

$$J_{H_1}(x) = J_{H_1}(o) \exp(-x/\Lambda_{H_1})$$

$$J_{H_{2,3}}(x) = J_{H_{2,3}}(o) \exp(-x/\Lambda_{H_{2,3}})$$

$$+ J_{H_1}(o) \frac{P_{H_1 H_{2,3}}}{\lambda_{H_1}} \left[\exp\left(\frac{-x}{\Lambda_{H_{2,3}}}\right) - \exp\left(\frac{-x}{\Lambda_{H_1}}\right) \right]$$

where $J_{H_1}(x)$ and $J_{H_{2,3}}(x)$ are the fluxes of the H_1 ($Z \geq 20$) and $H_{2,3}$ ($Z=10-19$) nuclei measured at the depth x and the other parameters have the following values: $\lambda_{H_1} = 12.9$ g/cm^2, $\lambda_{H_{2,3}} = 16.5$ g/cm^2, $P_{H_{2,3} H_{2,3}} = 0.33 \pm 0.15$, $P_{H_1 H_1} = 0.28 \pm 0.28$

$$P_{H_{2,3} H_{2,3}} = 0.15 \pm 0.15 \text{ and } \Lambda i = \lambda i/(1-P_{ii})$$

Now we discuss the correction mentioned in the last section, for the loss of particles in the energy region between 160 MeV/nucleon and the minimum cut-off energy of observation at the scan line. This cut-off energy varies with the charge of the nucleus; for vertical traversal, these energies are 156 MeV/nucleon, 235 MeV/nucleon and 265 MeV/nucleon for charge values Z=10, Z=20 and Z=26 respectively. It is assumed, in applying this correction that the charge ratios of H_1 ($Z \geq 20$), H_2(Z=16-19) and H_3 (Z=10-15) groups of nuclei observed in the energy region, 400-600 MeV/nucleon are maintained in the low energy intervals, 160-275 and 275-400 MeV/nucleon as well. The observed abundances of H_1 and H_2 - groups of nuclei in the low energy intervals were corrected proportionately for this loss.

RESULTS

I. Energy Spectrum: The differential energy spectrum of H-nuclei ($Z \geq 10$) obtained for the top of the atmosphere is given in Table 2 and is plotted in Figure 4. The energy spectra of protons (in the energy region 68-250 MeV) and helium nuclei (in the energy region 80-600 MeV/nucleon) as was measured by Fichtel et al. (1964) in the same stack, has also been plotted in Figure 4. Thus we have the spectra of the three components for purposes of comparison, in some overlapping energy interval.

The energy spectrum of protons and helium nuclei have been best studied for the year 1963 from the low energy region (~70 MeV/nucleon) to a few GeV(~2) per nucleon. (Balasubrahmanyan and McDonald, 1964, Frier and Waddington, 1965, Fichtel et al., 1965B, and Ormes and Webber, 1964). The dates of flights and the corresponding Mt. Washington neutron monitor rates, given in brackets, are the following: 24th July 1963(2325), 28th July 1963(2325), 15th June 1963(2330), and 15th August 1963(2293) respectively. The neutron monitor rates, in the first two flights are the same, in the third and the fourth flights they vary by 0.22 and 1.59 per cent respectively.

The question naturally arises as to whether we will be justified in combining the data obtained by different observers and different times to construct a single spectrum. It is assumed here that the biases introduced by different observers in the measurements are negligible. Further

Webber (1964) has compiled the data on the intensities of protons and helium nuclei, in the energy range 100-830 MeV/nucleon, as a function of the Mt. Washington neutron monitor rates. Using this work, the maximum error introduced in combining the data presented above is estimated as 9.6%, 7.0% and 5.2% for the energy intervals 100-200, 200-430 and 430-830 MeV/nucleon respectively. These errors are less than the statistical and systematic errors of observation.

The energy spectrum of heavy nuclei in the energy range 50-1000 MeV/nucleon and for the year 1963, has been obtained from the data of Lim and Fukui (1965), Fichtel et al. (1964) and Evans (1963). The Mt. Washington neutron monitor counting rates corresponding to the three flights are 2300, 2318 and 2297 respectively. Assuming that the temporal variations in intensity of α-particles and heavy nuclei for a particular energy interval, are the same to a first approximation (See section "Charge Ratios"), the error introduced in combining the data of the three observations to form a single spectrum has been estimated as less than a few percent, using the work of Webber (1964) mentioned above.

Thus, we have the energy spectra of the three components for the year 1963 in the corresponding energy intervals. These are plotted in Figure 4. The energy spectra of heavy nuclei in the energy interval 250-650 MeV/nucleon and of α-particles in the 60-320 MeV/nucleon were obtained by Koshiba et al. (1963) during a period close to solar maximum (4th September 1959) in a high altitude balloon flight ($\sim$2 g/cm^2 of residual atmosphere); the spectrum of heavy nuclei is shown in Figure 4 for purposes of comparison. No reliable data, with appropriate corrections for secondary production in the atmosphere, exists for the proton component during this period.

From a comparison of all the spectra presented in Figure 4, a general observation can be made that there is a decrease in intensity of all the components as solar activity increases. Whilst an attempt to understand the shapes of these spectra and the magnitude of the decrease as a function of energy is being made elsewhere, we now proceed to study the variation with energy of the charge ratios of the nuclei, measured in the present investigation. We restrict this comparison for nuclei having energies $\epsilon \geq 200$ MeV/nucleon.

II. Charge ratios: Ratio $\Gamma_{H_1, H_{2,3}}$ - The charge ratio, $\Gamma_{H_1 H_{2,3}}$ of H_1-nuclei to $H_{2,3}$-nuclei, has been computed for the energy interval 400-700 MeV/nucleon. This value is $\Gamma_{H_1,H_{2,3}} = 0.38 \pm 0.12$ and can be compared with the values 0.31 ± 0.02 and 0.37 ± 0.08 obtained by Daniel and Durgaprasad (1962) and Waddington (1963) for nuclei of $E \geq 1.5$ GeV/nucleon and the value 0.41 ± 0.14 obtained for nuclei in the energy interval 200-700 MeV/nucleon by Aizu et al. (1960).

Ratio $\Gamma_{H_2 H_3}$ - The ratio $\Gamma_{H_2 H_3}$, has been computed for the energy interval 400-700 MeV/nucleon in the present work as $\Gamma_{H_2 H_3} = 0.11 \pm 0.08$. This value can be compared with the value 0.20 ± 0.07 by Aizu et al. (1960) for nuclei in the interval 200-700 MeV/nucleon and 0.08 ± 0.08 quoted by Daniel and Durgaprasad (1962) for nuclei of $E \geq 1.5$ GeV/nucleon.

Thus, within the experimental uncertainties, there is no energy dependence of these charge ratios in the energy intervals considered here. This information could be used to determine the energy dependence of the average path length traversed by the radiation, by making certain assumptions regarding the nature of the source spectrum and the model of diffusion of these nuclei in the interstellar space.

Ratio $\Gamma_{H\alpha}$ - The differential intensity of H-nuclei, in the energy range 200-600 MeV/nucleon, has been measured in the present work as 0.00291 ± 0.00037 particles/m^2 sec. sr. MeV per nucleon. Combining this data with the intensity of α-particles quoted by Fichtel et al. (1964) in the same flight and in the same energy region, the ratio, $\Gamma_{H\alpha}$, has been computed as 0.025 ± 0.004. This value and the corresponding Mt. Washington neutron monitor rate are plotted in Figure 5. The reliable values of $\Gamma_{H\alpha}$, obtained by other observers using balloons flown to altitudes less than $\leq 7 g/cm^2$ of residual atmosphere, are also shown in this Figure 5. These results seem to suggest a gradual decrease of the ratio with increasing neutron monitor counting rate; however, they are not inconsistent with a constant mean value of .022 and also with the value of 0.022 ± 0.003 (Waddington 1963) obtained for nuclei of relativistic energies ($\epsilon \geq 1.5$ GeV/nucleon). Many modulation mechanisms suggested in literature (Parker 1963, Ehmert 1960 a,b) predict the constancy of the ratio, $\Gamma_{H\alpha}$, with time since the particles involved have approximately, the same charge to mass ratio.

It may further be added here that this ratio, computed from the data given in Figure 4, decreases with decreasing energy for energies $\epsilon \leq 200$ MeV/nucleon. As mentioned earlier, this information could also be used to determine the energy dependence of the path length traversed by the radiation.

ACKNOWLEDGMENTS

I am thankful to Dr. F. B. McDonald for encouragement in carrying out this work and to Dr. C. E. Fichtel for critical comments and discussions during the various phases of the work and for going through the manuscript.

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TABLE 1: Comparison of Ene· values estimated by two methods

Charge of the Nucleus	Energy value measured from	
	Multiple scattering measurements (MeV/nucleon)	Change in ionization with range (MeV/nucleon)
14	315 ± 47	335 ±31
14	600 ± 53	670 ± 73
15	773 ± 35	840 ± 92
18	720 ± 90	750 ± 83
18	800 ± 60	840 ± 126

TABLE 2

Differential intensities of heavy nuclei ($Z \geq 10$)

Kinetic energy (MeV/n) ϵ	Flux (dJ/dE) Particles/m^2 sec. sr. MeV
160 - 275	0.0027 ± 0.0007
275 - 400	0.0035 ± 0.0008
400-- 600	0.0026 ± 0.0005
600 - 700	0.0019 ± 0.0006

Caption for figures:

Figure 1 - A cross plot of the two charge values Z_1 and Z_2 assigned to the same nucleus by the two methods employed from measurements made at the scan line and the stopping end respectively. These values were determined for the 20 nuclei that ended in G5 emulsions and had a length of at least 0.8mm in the emulsion in which the track ended.

Figure 2 - The charge spectrum of all nuclei of charge $Z \geq 10$ recorded in this stack. Some oxygen nuclei were also recorded, but the estimated efficiency is 96 per cent for all nuclei of $Z \geq 10$. The error in charge estimation for stopping particles, in most cases is $0.03 \times Z$. In the case of tracks that interact and pass through, shown in the figure by dotted and shaded squares, the error could vary by 1 or 2 units of charge value. Integral charge values were assigned to these tracks.

Figure 3 - Energy spectrum of heavy nuclei ($Z \geq 10$) observed at the top of the stack. The numbers indicated in the box refer to the measured charge of the nucleus.

Figure 4 - Differential intensities of protons, helium and heavy nuclei measured in 1963, 1961 and 1959 as a function of kinetic energy (MeV/nucleon). The data shown here refer to: Fichtel et al. (1965B) O Protons, 1963, ● Helium nuclei, 1963; Frier and Waddington (1965) □ Protons 1963, ▩ helium nuclei, 1963; Balasubrahmanyan and McDonald (1964) ◇ Protons, 1963, ◈ Helium nuclei, 1963; Ormes and Webber (1964), △ Protons, 1963. ▲ Helium nuclei, 1963; Fichtel et al. (1964) ▽ Protons, 1961, ▼ Helium nuclei, 1961; Fichtel al. (1965A) ⊗ heavy nuclei, 1963; Lim and Fukui (1965) ⚠ heavy nuclei, 1963; Evans (1963) ☒ heavy nuclei, 1956;

Koshiba et al. (1963) heavy nuclei, 1959, Present work, heavy nuclei, 1961.

Figure 5 - Ratio of intensities of heavy nuclei to alpha particles plotted as a function of Mr. Washington neutron monitor counting rate. The data shown refer to:

A: Aizu et al. (1960), kinetic energy ϵ = 200-700 MeV/nucleon, M: McDonald and Webber (1962), $\epsilon \geq 400$ MeV/nucleon, Ev: Evans (1963), ϵ = 200-600 MeV/nucleon, and Biswas (1965), ϵ = 200-600 MeV/nucleon.

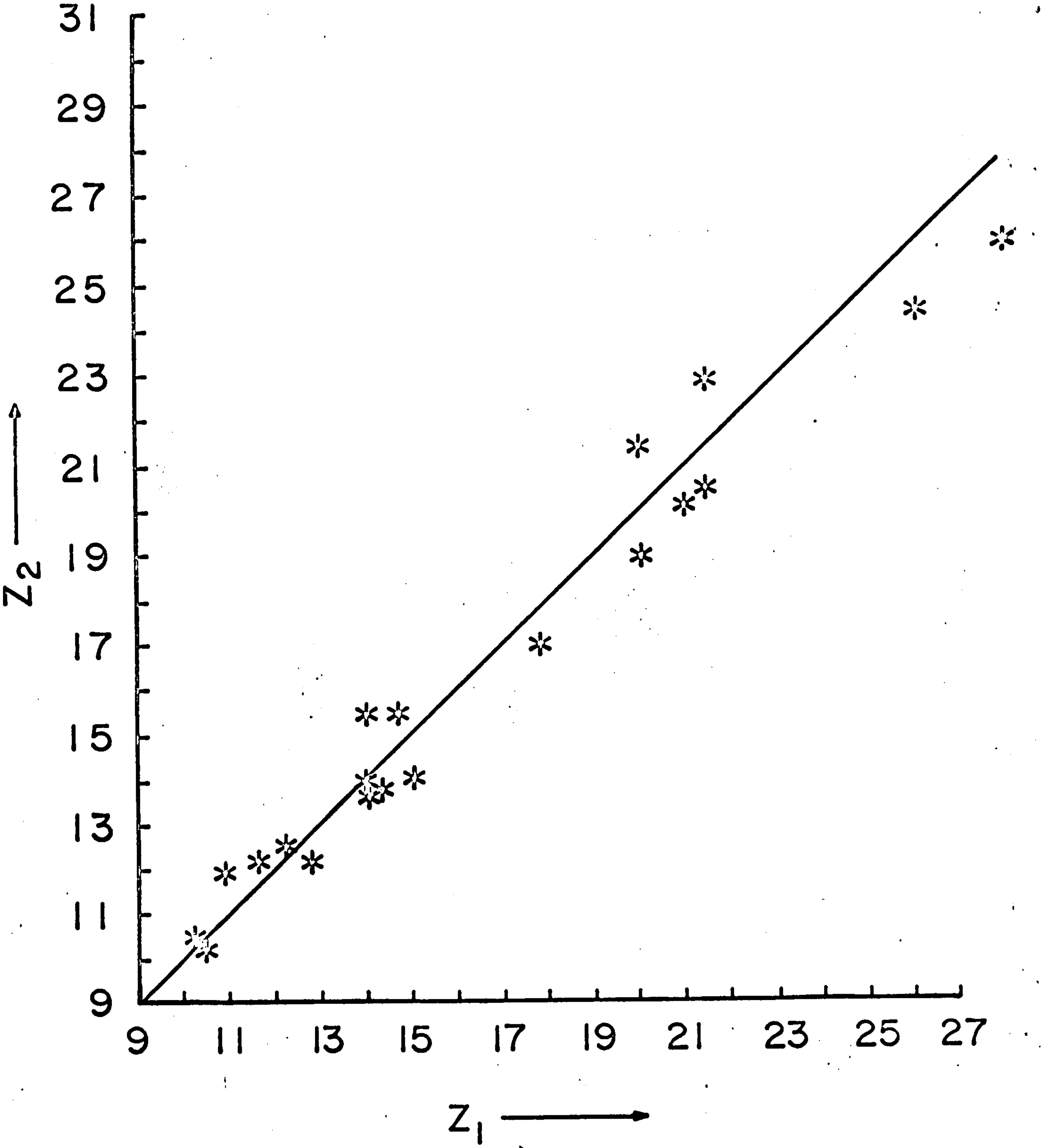
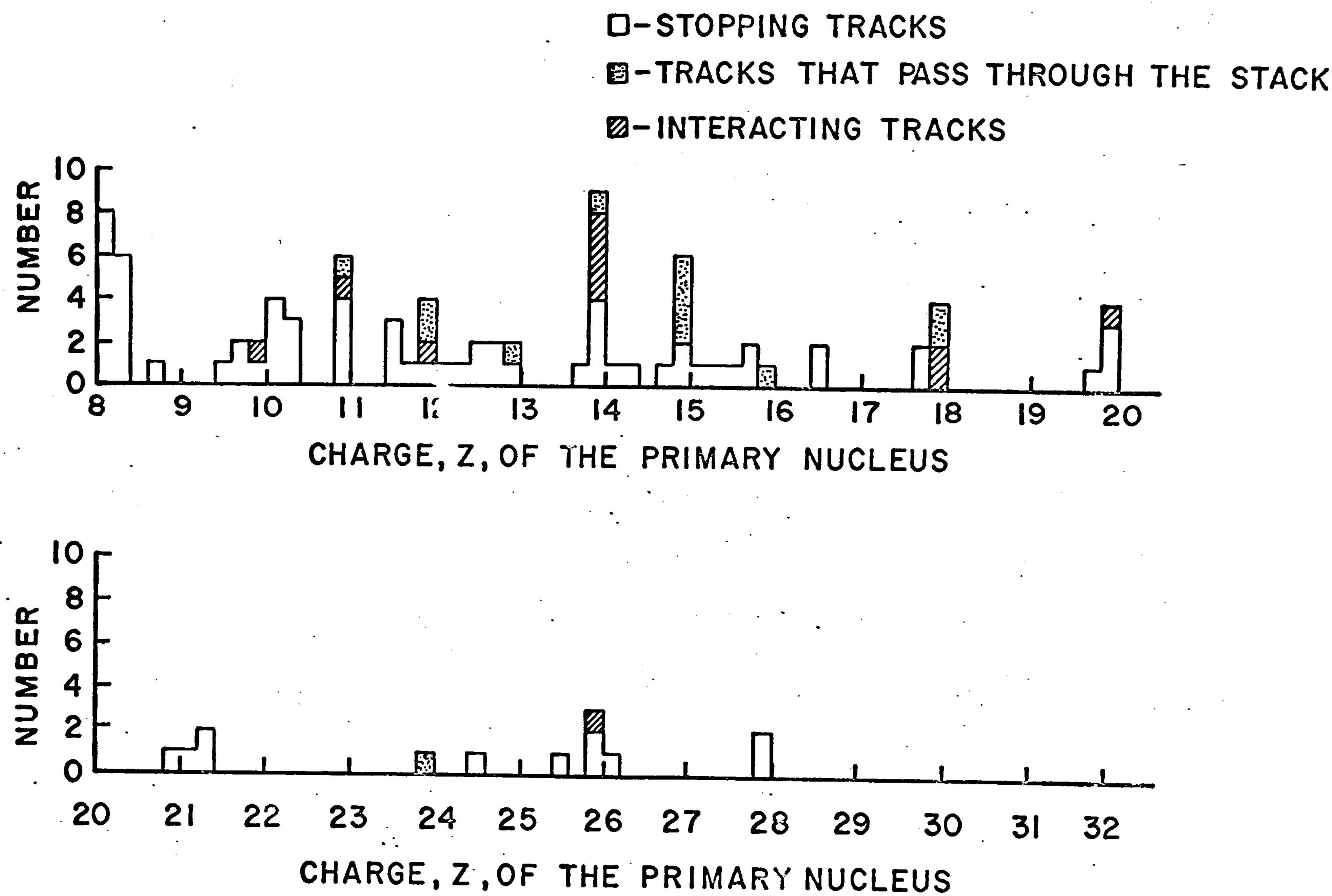


Figure 1



□-STOPPING TRACKS
▨-TRACKS THAT PASS THROUGH THE STACK
▨-INTERACTING TRACKS
NUMBER
0
2
4
6
8
10
8
9
10
11
12
13
14
15
16
17
18
19
20
CHARGE, Z, OF THE PRIMARY NUCLEUS
NUMBER
0
2
4
6
8
10
20
21
22
23
24
25
26
27
28
29
30
31
32
CHARGE, Z, OF THE PRIMARY NUCLEUS

Figure 2

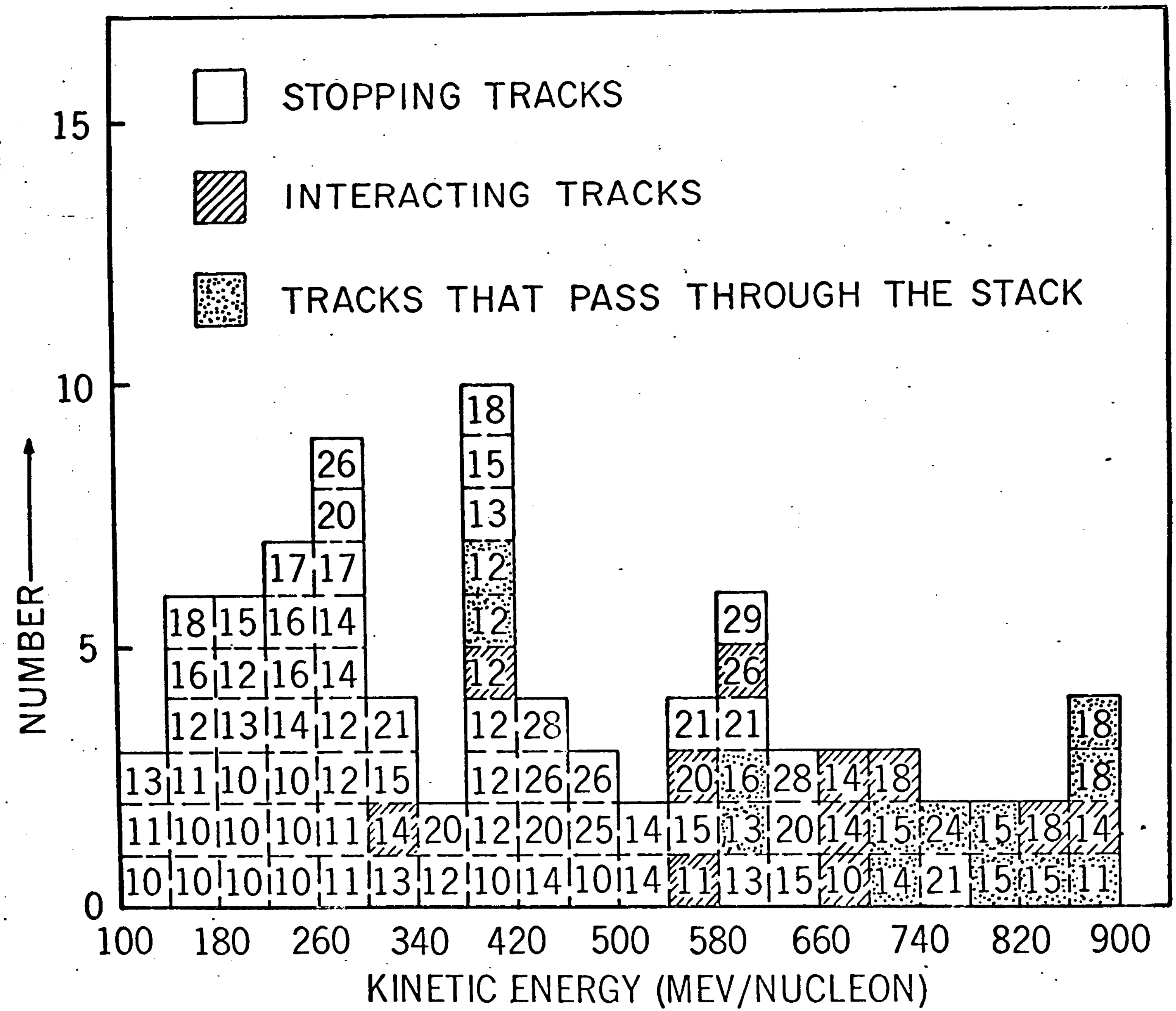
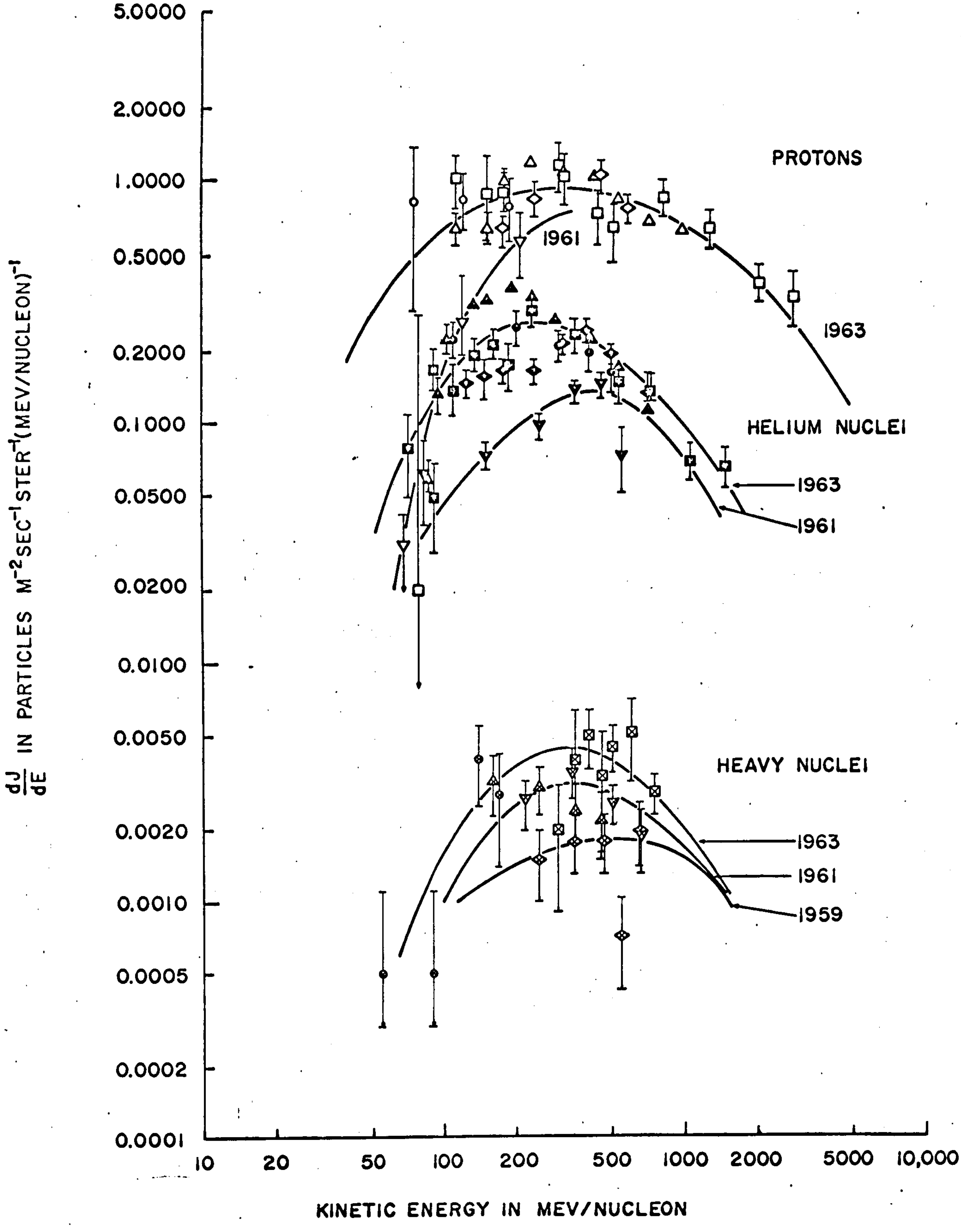

STOPPING TRACKS
INTERACTING TRACKS
TRACKS THAT PASS THROUGH THE STACK
NUMBER
0
5
10
15
100
180
260
340
420
500
580
660
740
820
900
KINETIC ENERGY (MEV/NUCLEON)

Figure 3



5.0000
2.0000
1.0000
0.5000
0.2000
0.1000
0.0500
0.0200
0.0100
0.0050
0.0020
0.0010
0.0005
0.0002
0.0001
$\frac{dJ}{dE}$ IN PARTICLES $M^{-2}SEC^{-1}STER^{-1}(MEV/NUCLEON)^{-1}$
PROTONS
1961
1963
HELIUM NUCLEI
1963
1961
HEAVY NUCLEI
1963
1961
1959
10
20
50
100
200
500
1000
2000
5000
10,000
KINETIC ENERGY IN MEV/NUCLEON

Figure 4

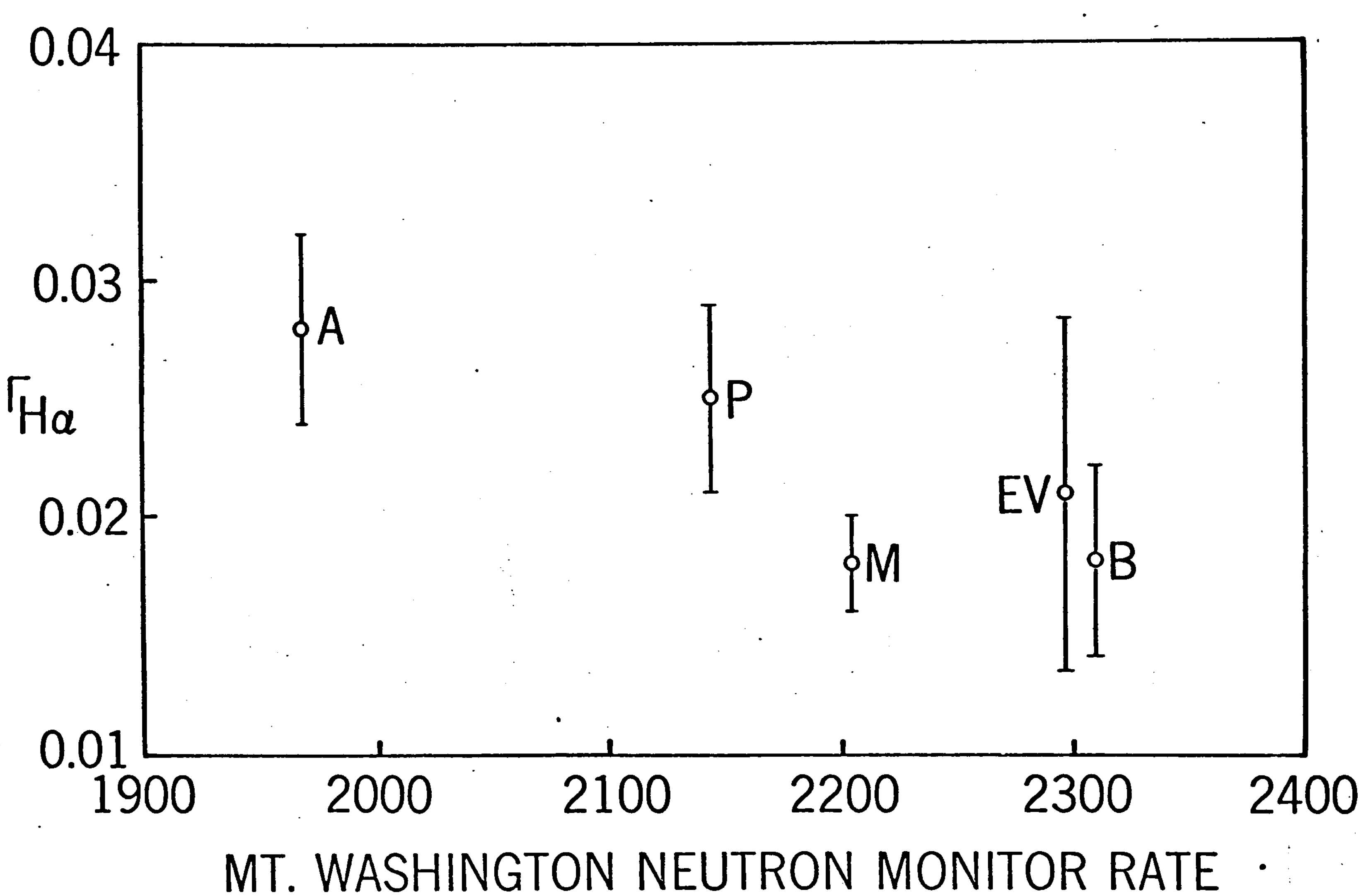

0.04
0.03
0.02
0.01
$\Gamma_{H\alpha}$
A
P
M
EV
B
1900
2000
2100
2200
2300
2400
MT. WASHINGTON NEUTRON MONITOR RATE

Figure 5