Energy Spectrum of Heavy Nuclei of the Primary Cosmic Radiation during Solar Maximum

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The energy spectrum of nuclei with $Z \geqslant 13$ has been determined using the knock-on electron method in a stack of nuclear emulsions flown on 4 February 1959 from Texas, U.S.A. ($\lambda = 41°$N). In the interval of kinetic energy from 1.5 to 10 GeV/nucleon, the exponents of the integral energy spectra for nuclei with charge $Z \geqslant 13$, $13 \leqslant Z \leqslant 16$ and for those with $Z \geqslant 17$ have been determined to be 1.70 ± 0.30, $1.85_{-0.20}^{+0.23}$, and $1.55_{-0.30}^{+0.20}$, respectively. From this and other similar experiments it is surmised that within the experimental uncertainties the observations are consistent with the assumption that the energy spectra of all the components of the primary cosmic radiation have the same exponent; also the exponent seems to be the same during solar minimum and during solar maximum. The flux of nuclei with $Z \geqslant 10$ has been obtained as 1.26 ± 0.09 particles/m^2 sec sr and that of nuclei with $Z \geqslant 20$ as 0.39 ± 0.06 particle/m^2 sec sr. These values are $\sim 50\%$ lower than those determined over Texas during solar minimum.

1. INTRODUCTION

THE energy spectra of multiply charged nuclei of the primary cosmic radiation have been determined in the past by using a number of techniques: from the vertical flux values at the top of the atmosphere at different geomagnetic latitudes as deduced from observations made at balloon altitudes[1]; by directly determining the energies of individual nuclei from measurements of multiple Coulomb scattering on the tracks produced by them in nuclear emulsions[2]; and from the characteristics of the disintegrations produced by the heavy nuclei.[3–5] In a previous paper, Biswas *et al.*[6] have discussed the limitations of the above procedures and reported a different method in which the energies of multiply charged nuclei were obtained by measuring the angles and energies of electrons which they "knock on" in elastic collisions in traversing nuclear emulsion. In that investigation, the conditions under which the primary energy could be estimated reliably by the knock-on electron technique were described. The validity of this method has been further demonstrated in an investigation by Jain.[7] Using this technique Biswas *et al.* obtained for the exponent m of the integral energy spectrum $[N(\geqslant E) = C/(1+E)^m$, where E is the kinetic energy per nucleon in GeV$]$ a value of 1.65 ± 0.27 for the M nuclei ($6 \leq Z \leq 9$) in the energy range 0.23 to 9.0 GeV/nucleon, and 1.82 ± 0.59 for the H nuclei ($Z \geqslant 10$) in the energy range 0.41 to 9.0 GeV/nucleon. They concluded that in the above energy interval, the form of the energy spectra for the different groups of multiply charged nuclei of the primary cosmic radiation could be considered to be the same within experimental errors.

From an analysis of the flux data available at the beginning of 1957, Singer[1] suggested that the energy spectra of the various primary components are not all the same and that the exponent was a function of charge, increasing with increasing Z. He obtained values of m as 1.15 for protons, 1.6 for α particles and M nuclei, and 2.0 for H nuclei.

In the previous investigation reported from this laboratory[6] the number of tracks due to H nuclei on which measurements were carried out was not sufficient to determine whether there was any detectable difference between the spectra of the M and H nuclei as suggested by Singer. Hence, it was felt that it would be worthwhile to study the energy distribution of H nuclei with greater statistical weight. Further, it was considered that it would be of interest to investigate whether there is any modulation of the energy spectrum of the primary cosmic radiation due to increased solar activity at solar maximum. It is now well known that the largest modulation effects occur at the lowest energies, below 1 GeV/nucleon. It is of importance, however, to determine the behavior of the modulation at higher energies to extract information which may be useful for any proposed model of the modulating mechanism.

In this paper, we describe measurements made on 178 tracks of nuclei with $Z \geqslant 10$ to determine their charge and energy spectra at a time near solar maximum. The energy spectrum of these nuclei has been determined in the energy range 1.5 to 10 GeV/nucleon.

2. EXPERIMENTAL PROCEDURE

2.1 Emulsion Stack Used

The experiment was carried out using an emulsion stack which consisted of 58 Ilford G5 pellicles flanked on either side by 1 K0, 1 G5, and 1 C2 pellicle. Each of

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[1] S. F. Singer, *Progress in Elementary Particles and Cosmic-Ray Physics* (North-Holland Publishing Company, Amsterdam, 1958), Vol. IV, p. 203–335.

[2] C. J. Waddington, Nuovo Cimento **5**, 737 (1957).

[3] M. F. Kaplon, B. Peters, H. L. Reynolds, and D. M. Ritson, Phys. Rev. **85**, 295 (1952).

[4] R. Cester, A. Debenedetti, C. M. Garelli, B. Quassiati, L. Tallone, and M. Vigone, Nuovo Cimento **7**, 843 (1958).

[5] P. L. Jain, E. Lohrmann, and M. W. Teucher, Phys. Rev. **115**, 654 (1959).

[6] S. Biswas, P. J. Lavakare, K. A. Neelakantan, and P. G. Shukla, Nuovo Cimento **16**, 644 (1960).

[7] P. L. Jain, Phys. Rev. **120**, 292 (1960).

the pellicles had dimensions, 15 cm$\times$20 cm$\times$600 μ. This stack was flown from Texas ($\lambda=41°$N) on 4 February 1959, and it floated under 5.3 g/cm^2 of residual air for 6 h and 35 min. At launch the plane of the emulsions was horizontal but 15 min after the balloon reached ceiling altitude it was turned such that the 20-cm side was vertical.

The time-altitude curve is shown in Fig. 1.

The emulsions were developed by the usual temperature cycle method. After development it was found that the K0 and C2 emulsions were not useful for measurements owing to excessive fogging. Hence, only the central 58 G5 emulsions were used in this experiment.

2.2 Selection Criteria for Tracks

The central regions of the two outside emulsions ($\gtrsim 1$ cm from the processed edges) were scanned for tracks of heavy nuclei which satisfied the following criteria: (a) ionization greater than that of a relativistic beryllium nucleus; (b) projected track length $\geqslant 1.0$ mm/plate; (c) zenith angle $\leq 90°$.

Tracks satisfying the above conditions were followed through successive emulsions, till they interacted or passed out of the stack. In the case of interactions, if any of the fragment products of the incoming nucleus had an ionization greater than that of a relativistic boron nucleus, it was followed further until it interacted or left the stack.

Charge determination was then made on those tracks with (a_1) ionization greater than or equal to that of a relativistic fluorine nucleus; (b_1) projected track length $\geqslant 1.1$ mm/plate; (c_1) zenith angle $\leq 45°$.

Of the tracks satisfying conditions (a_1), (b_1), and (c_1) those obeying the following additional criteria were selected for energy determination: (i) ionization greater than or equal to that of a nucleus with $Z \geqslant 13$; (ii) available track length for measurements, before the particle interacted or left the stack was $\geqslant 1$ cm.

In addition, three lines were scanned, one along the top edge and one each along the two vertical edges of each pellicle for tracks of heavy nuclei which satisfied the following criteria: (a_2) ionization greater than or equal to that of a relativistic fluorine nucleus; (b_2) projected track length $\geqslant 1.1$ mm/plate; (c_2) zenith angle $\leq 60°$.

The tracks obtained in the additional area were used for the determination of the energy spectrum; these scans were made at a distance of 5 mm from the processed edges.

The scanning efficiency was checked by a second observer rescanning 89.48 cm^2 of the area originally scanned. It was found that for tracks satisfying the conditions (a_1), (b_1), and (c_1) mentioned above, the efficiency was 92% while for tracks with $Z \geqslant 20$ it was 100%.

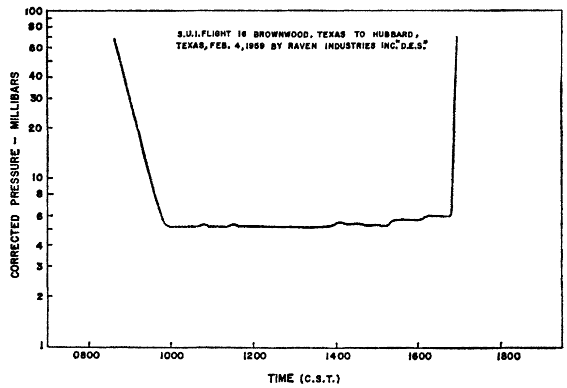

FIG. 1. Time-altitude curve.

2.3 Estimation of Charge

The effective vertical geomagnetic cutoff energy at the flight latitude ($\lambda=41°$N) has been deduced to be 1.5 ± 0.1 GeV/nucleon by Freier *et al.*[8] Hence all primary particles entering the stack can be considered to be relativistic. Since ionization due to these particles is directly proportional to Z^2, the charge of each particle was obtained by counting "long δ rays" on its track. In this convention, all δ rays which projected outside two parallel straight lines 2.5 μ on either side of the primary track were counted. A minimum of 200 such δ rays was counted on each track with $Z \geqslant 10$. The consistency in counting was better than 4%; this was checked frequently by measurements on standard tracks. The charge of each particle was obtained from the relation $N_\delta = aZ^2+b$, where N_δ is the number of "long δ rays" per 100 μ and a and b are constants. Initially, a charge calibration curve for the standard convention of counting δ rays, (i.e., δ rays with 4 or more grains) was obtained by using relativistic α particles and suitable "charge indicating interactions" caused by nuclei with charges 5, 7, and 9 (interactions in which $N_h=0$ and no mesons are produced). This calibration curve was used to build up a calibration curve for "long δ rays" using additional interactions caused by nuclei with charge 14, 15, and 19. The calibration curve for the "long δ rays" convention yields $a=0.0307$ and $b=0.045$. This curve was, then, extrapolated up to $Z=26$. Considering that the minimum number of δ rays counted on each track was only 200 and the fact that in the δ-ray density obtained for a single charge at $\lambda=41°$N there is a spread of $\sim$20%,[9] the charges assigned by us here could be in error by at most one unit of charge for Z up to 20. In the absence of suitable calibration events, the charges assigned to particles with $Z>20$, could be in error by one or even two units of charge.

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[8] P. S. Freier, E. P. Ney, and C. J. Waddington, Phys. Rev. **114**, 365 (1959).

[9] M. V. K. Appa Rao, S. Biswas, R. R. Daniel, K. A. Neelakantan, and B. Peters, Phys. Rev. **110**, 751 (1959).

2.4 Estimation of Energy

The energy per nucleon of nuclei traversing the whole stack or interacting in the stack after a distance of 1 cm, was obtained by the "knock-on electron" technique. In a previous investigation,[6] the conditions under which the primary energy can be estimated reliably by this technique have been established. The method of scanning for knock-on electrons, criteria for their acceptance and the procedure for calculation of error on the primary energy have been discussed in detail in this paper. The same procedures were adopted in the present experiment.

The energy per nucleon of a primary nucleus can be determined from measurements of the angle of emission and the energy of the knock-on electron by using the relation:

$$\gamma_p=\left(\frac{\gamma_e+1}{2-(\gamma_e-1)\tan^2\omega}\right)^{1/2}, \tag{1}$$

where γ_p = total energy per nucleon of the primary nucleus in units of nucleon rest mass, γ_e = the total energy of the knock-on electron in units of electron rest mass and ω = angle of emission of the knock-on electron with respect to the direction of the primary particle.

A minimum of two knock-on electrons was measured on each primary track and from each of these the primary energy γ_p was evaluated. If these two values of the primary energy were not consistent with each other within two standard deviations, measurements were made on a third knock-on electron, and the value of the primary energy was again calculated. Thus (except in a few cases where measurement on a fourth knock-on electron was necessary), there were at least two values of the primary energy which were consistent with each other within two standard deviations. This was done to avoid some sources of uncertainty which could lead to wrong values for the primary energy; these have been discussed in detail earlier by De Marco *et al.*[10] and Biswas *et al.*[6] The final value of the primary energy was obtained from the mean of two or more estimated values which were consistent with each other.

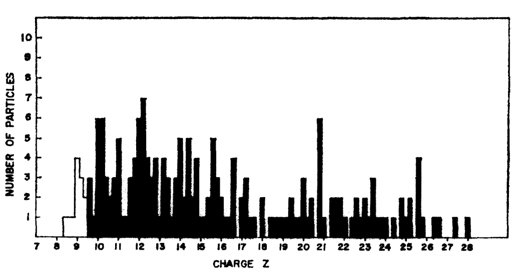

FIG. 2. Charge spectrum of heavy nuclei.

[10] A. DeMarco, A. Milone, and M. Reinharz, Nuovo Cimento 1, 1041 (1955).

3. RESULTS AND DISCUSSION

3.1 Charge Spectrum

In an area of 490 cm², 178 tracks due to nuclei with $Z \geqslant 10$ were found to satisfy the conditions (b_1) and (c_1) mentioned in Sec. 2.2. The charge spectrum of these nuclei is plotted in Fig. 2. Up to $Z=20$, the resolution is fairly good; there seems to be an excess of nuclei with even charge over those with odd charge up to $Z=16$, as has been observed in previous experiments.[11–16] Further, as observed by earlier workers,[13,15,16] nuclei with charges 17, 18, and 19 seem to have a low abundance; this aspect has been particularly demonstrated and discussed in the report of a recent investigation completed in this laboratory.[17] The charge spectrum seems to be unaffected by the increase in solar activity.

3.2 Energy Spectrum

It is seen from Fig. 2 that there are 123 tracks with $Z \geqslant 13.0$. From the additional area scanned we obtained

TABLE I. Energy Distribution of Nuclei with $Z \geq 13$.

Kinetic energy interval GeV/nucleon	No of tracks measured	Corrected number of particles
<1.0	2	2.42
1.2–1.5	18	21.75
1.5–2.0	21	25.39
2.0–2.5	19	22.95
2.5–3.0	18	21.75
3.0–4.0	13	15.71
4.0–6.0	15	18.12
6.0–∞	14	16.91
Total	120	145.00

27 more tracks of particles with $Z \geqslant 13$, thus making a total of 150; 13 of these particles interacted or left the stack before traversing 1 cm inside the stack and hence no energy measurement was done on these. In addition, it was established that 5 tracks were due to nuclei which entered the stack during the ascent of the balloon (the direction of motion of each of these particles was determined from the direction of emission of the knock-on electrons produced by them). The remaining tracks were scanned for knock-on electrons according to the criteria mentioned in the paper by Biswas *et al.*[6] There were 5 tracks which did not have any useful knock-on

[11] H. L. Bradt and B. Peters, Phys. Rev. 80, 943 (1950).
[12] A. D. Dainton, P. H. Fowler, and D. W. Kent, Phil. Mag. 43, 729 (1952).
[13] R. R. Hillier and V. Y. Rajopadhye, Suppl. Nuovo Cimento 8, 520 (1958).
[14] M. Koshiba, G. Schultz, and M. Schein, Nuovo Cimento 9, 1 (1958).
[15] V. Bisi, R. Cester, C. M. Garelli, and L. Tallone, Nuovo Cimento 10, 881 (1959).
[16] K. Kristiansson, O. Mathiesen, and B. Waldeskog, Arkiv Fysik 17, 455 (1960).
[17] R. R. Daniel and N. Durgaprasad, Suppl. Nuovo Cimento 23, 82 (1962).

electron tracks along the entire available length; in addition, there were 7 tracks each of which had only one useful knock-on electron track. Thus, a reliable value of the primary energy based on at least two knock-on electrons, as mentioned in Sec. 2.4 could be obtained only for 120 tracks.

From the measured energy of the particle inside the stack its energy at the entrance point was obtained using the range-energy relation in emulsion for the most abundant isotope of each element with charge Z from 10 to 26. These curves were calculated from the range-energy relation for protons in G5 emulsion given by Barkas.[18] In extrapolating the energy up to the entrance

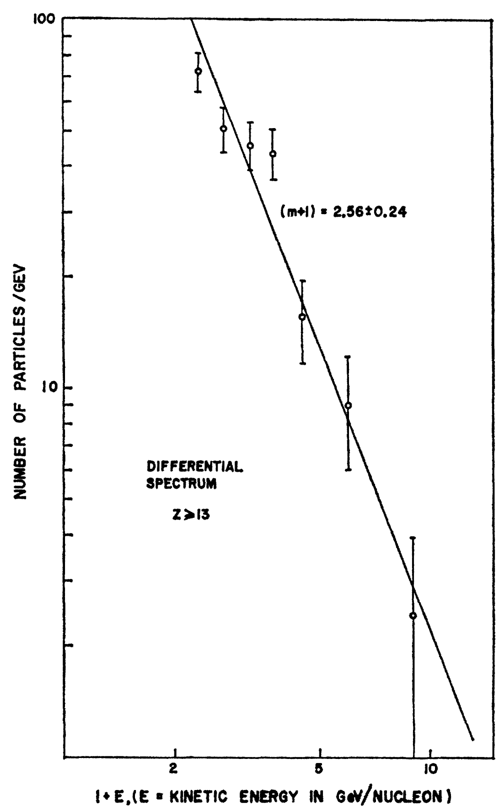

FIG. 3. Differential energy spectrum for nuclei with $Z\geqslant 13$.

point in the stack, account was taken of the three outside emulsions which were not used in this experiment. Then, using the range-energy relation in air and the amount of air (and packing material) traversed before entering the stack, the energy of each particle at the top of the atmosphere was obtained. (Since the packing material traversed was small and was composed of light material, it was directly added to the amount of air traversed by the particle.) In extrapolating the energy of a particle to the top of the atmosphere, it was assumed that no loss of charge occurred in the air above the stack. That this assumption is reasonable can be

[18] W. H. Barkas, Nuovo Cimento 8, 201 (1958).

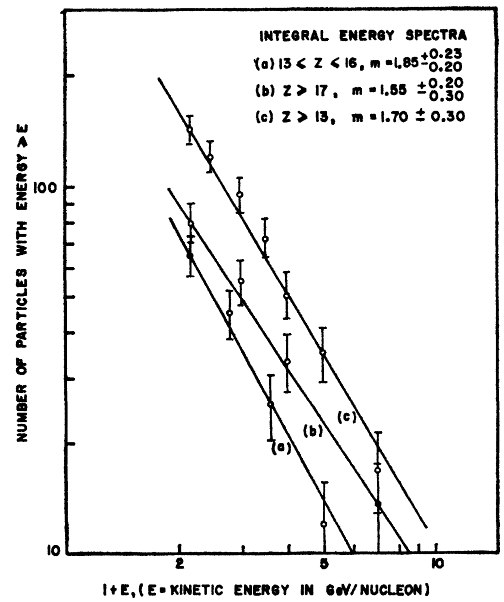

FIG. 4. Integral energy spectra: (a) for nuclei with $13\leq Z\leq 16$; (b) for nuclei with $Z\geq 17$; (c) for nuclei with $Z\geq 13$.

seen from the fact that even if we take an extreme case of an iron nucleus with an energy of 1.5 GeV/nucleon at the top of the atmosphere giving rise to a nucleus of $Z=10$ just above the emulsion stack, the error in the energy estimated is not more than 50 MeV/nucleon.

The numbers of particles observed in the various energy intervals are shown in Table I. It was stated earlier in this section that due to paucity of suitable knock-on electrons and due to selectrion criteria, energy measurements could not be made on 25 particles with $Z\geqslant 13$. These 25 particles have been distributed in the ratio of the measured number in various energy intervals. The corrected numbers are shown in column 3 of Table I.

Figure 3 shows the differential energy spectrum of nuclei with $Z\geqslant 13$ over the kinetic energy interval 1.2 to 10 GeV/nucleon. The differential spectrum can be represented by the relation:

$$dN/dE=C(1+E)^{-(m+1)}, \tag{2}$$

where dN is the number of particles in the energy interval E to $E+dE$, $E=$ the kinetic energy in GeV/nucleon, and $C=$ a constant. A line fitted to the points plotted in Fig. 3 using the method of least squares gives the exponent $(m+1)$ as 2.56 ± 0.24; the error quoted is the standard deviation. The integral energy spectrum of nuclei with $Z\geqslant 13$ is shown in Fig. 4. To obtain the best value of $\langle m\rangle$ and its error in the integral spectrum we have made use of the maximum likelihood method. A plot of the likelihood function in arbitrary units is shown in Fig. 5. This is approximately a Gaussian and we obtain for the best value of $\langle m\rangle$ and its error the value 1.70 ± 0.30. The error quoted here is the probable

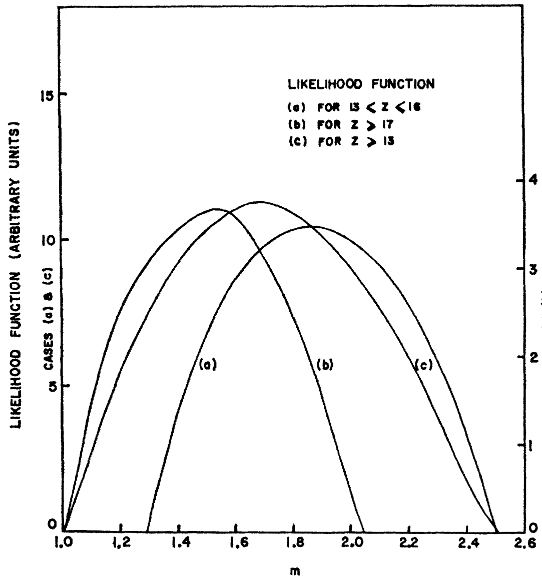

FIG. 5. Plots of likelihood function for the exponents of energy spectra: (a) for nuclei with $13 \leq Z \leq 16$; (b) for nuclei with $Z \geq 17$; (c) for nuclei with $Z \geq 13$.

error. It should be mentioned here that the value of $(m+1)$ in a differential plot varies according to the manner in which the particles are grouped into various energy intervals though always within the limits of the statistical error. But the maximum likelihood value remains the same whatever be the differential grouping. Hence, we consider the value 1.70 ± 0.30 to be a better representation of the value of the exponent in the integral energy spectrum of nuclei with $Z \geqslant 13$.

A similar treatment has been carried out in the case of the integral energy spectra of nuclei with $13 \leq Z \leq 16$ and those with $Z \geqslant 17$. (About half the number of tracks with $Z \geqslant 13$ which were suitable for energy measurement have $Z \geqslant 17$). In Figs. 4 and 5 are also included the integral energy spectra and the plots of the likelihood function for nuclei with $13 \leq Z \leq 16$ and for those with $Z \geqslant 17$; we obtain for $\langle m \rangle$ for these nuclei the values $1.85_{-0.20}^{+0.23}$ and $1.55_{-0.30}^{+0.20}$, respectively, where the errors quoted are the probable errors.

Since nuclei with $Z \geqslant 13$ constitute about 70% of nuclei $Z \geqslant 10$, the value $m = 1.70 \pm 0.30$ will be regarded in all further discussions as representing the exponent of the integral energy spectrum of H nuclei ($Z \geqslant 10$). Similarly, due to the low abundance of elements $17 \leq Z \leq 19$ (Sec. 3.1), the value $m = 1.55_{-0.30}^{+0.20}$ will be regarded as representing the exponent of the integral energy spectrum of VH nuclei ($Z \geqslant 20$).

The value for the exponent of energy spectrum of heavy nuclei, obtained in this investigation, refers to the period of solar maximum and is, within limits of statistical errors, unchanged when compared with similar values obtained in other experiments[3–5] at different periods of solar activity. Further, in an earlier investigation from this laboratory it has been shown[19] that there is no significant change in the primary energy spectra during a large Forbush decrease observed on 13 March 1956. These results indicate that for kinetic energy >1.5 GeV/nucleon, the exponent of energy spectrum for heavy nuclei is not affected either by the long-term variations of solar activity with the eleven-year cycle or by large Forbush-type decreases.

A similar observation has been made by Guss,[20] who measured the energy spectrum of α particles over Texas on 8 February 1959, during solar maximum. His value $m = 1.48_{-0.14}^{+0.17}$ in the kinetic energy range 1.5–7.5 GeV/nucleon is consistent with the value obtained by Fowler and Waddington[21] in a period of nearly minimum solar activity. However, this result, of Guss, is in disagreement with the experiment of Freier *et al.*[8] who have obtained the energy spectrum of α particles using a stack of emulsions exposed over Texas on 19 October 1957, and another one exposed over Minnesota on 31 August 1957. They found a value $m = 1.17 \pm 0.14$ in the range of kinetic energies between 200 MeV/nucleon and 3 GeV/nucleon. However, the low value of m in their experiment is most likely due to the fact that the Minnesota flight took place during the time of a large Forbush decrease and the points for low energy in the spectrum were obtained from this flight. Thus, from the above considerations, it seems that for kinetic energy >1.5 GeV/nucleon, the exponent of energy spectrum for α particles remains unaffected by the increase of solar activity.

On the basis of the foregoing it is meaningful to make a comparative study of the energy spectra of the different components of the primary cosmic radiation, determined during different periods of solar activity. Our values for the exponent $\langle m \rangle$ of H and VH nuclei are, within statistical errors consistent with each other; they are also consistent with similar determinations made for α particles and M nuclei in various investigations in the past, by direct energy determinations.[2–6,21,22] Our spectra for nuclei with $13 \leq Z \leq 16$ and for those with $Z \geqslant 17$, seem to indicate a trend opposite to what would be expected according to Singer's[1] hypothesis. However, we can only say that, within the limits of statistical errors, the present data are not inconsistent with the customary assumption that all the multiply charged nuclei of the primary cosmic radiation have the same energy spectra.

The conclusions arrived at above imply that the exponent of energy spectrum is not subject to such large scale variation as was reported by Pomerantz and Witten[23] at the Kyoto meeting. In their Explorer VII

[19] S. Biswas, P. J. Lavakare, K. A. Neelakantan, and P. G. Shukla, Phys. Rev. **118**, 591 (1960).
[20] D. E. Guss (to be published).
[21] P. H. Fowler and C. J. Waddington, Phil. Mag. **1**, 637 (1956).
[22] F. B. McDonald, Phys. Rev. **104**, 1723 (1956).
[23] M. A. Pomerantz and L. Witten, in *Proceedings of the International Conference on Cosmic Rays and the Earth Storm, Kyoto, 1961* [J. Phys. Soc. Japan **17**, Suppl. AIII, 40 (1962)].

experiment they determined the flux of nuclei of charge $Z \geqslant 6$, at different geomagnetic latitudes, using an ionization chamber. Assigning cosmic-ray cutoff rigidities on the basis of centered dipole field approximation, they obtained average values for the exponent over fortnightly periods; these values have considerable variation with time in the first several months for which the results were presented. If these results are confirmed by other workers in this field, our ideas about the modulation of energy spectrum will have to be revised.

3.3 Flux Values

As mentioned in Sec. 3.1, in an area of 490 cm², 178 tracks of particles with charge $Z \geqslant 10$ were found satisfying the selection criteria. This corresponds to a figure of 193.5 after scanning efficiency is taken into account. In the scanning of the central area, it was observed that out of 123 tracks of particles with $Z \geqslant 13$, 4 entered the stack during the ascent of the balloon. This corresponds to an ascent correction of 6.3 particles (of $Z \geqslant 10$) to the total of 193. 5. The flux at the top of the atmosphere was obtained using the diffusion equation:

$$\frac{dN_H(x)}{dx} = (-1/\Lambda_H)N_H(x), \tag{3}$$

where $N_H(x)$ is the number of particles observed at depth x and Λ_H is the absorption mean free path of H nuclei in air. We used the value of 27.6 g/cm² for Λ_H, as given by Wassington.[24] We, thus, obtain for the flux of H nuclei the value:

$$(J_H)_0 = 1.26 \pm 0.09 \text{ particles/m}^2 \text{ sec sr.}$$

We have 50 tracks due to particles with $Z \geqslant 20$. After correcting for particles which entered the stack during the ascent of the balloon and using $\Lambda_{VH} = 17.2$ g/cm²,[24] we obtain for the flux of VH nuclei:

$$(J_{VH})_0 = 0.39 \pm 0.06 \text{ particles/m}^2 \text{ sec sr.}$$

Our flux values and those from other investigations are summarized in Table II.

Our flux values for H and VH nuclei at a time near solar maximum are $(51\pm9)\%$ and $(44\pm27)\%$ lower than the corresponding values during the period of minimum solar activity quoted in the fifth row of Table II from Waddington's review[24] article. (The day of our experiment, apart from being in a period of increased solar activity due to the eleven-year solar cycle, was a quiet day, as judged from the neutron monitor data from Climax.) Such an effect has been observed by previous investigators also. Freier *et al.*[25] observed in the case of a balloon flight made on 19 October 1957, that their value of the flux of H nuclei was lower than that at solar minimum period by $(34\pm14)\%$. Further, Van Heerden and Judek[26] have obtained a value $(J_H)_0 = 1.11\pm0.11$ particles/m² sec sr for the flux of H nuclei in a flight made on 9 March 1958.

In contradiction with our observation, Young *et al.*[27] have come to the conclusion that the flux of H nuclei has no long-term variation associated with the eleven-year solar cycle. Their data, unfortunately, do not include the important part of the cycle from 1957 to 1959. Also, in each flight they have made observations in single emulsions only and have included for analysis steeply dipping tracks; this renders the estimation of the charge of the tracks unreliable.

Thus, we conclude that the H component of the primary cosmic radiation of energy >1.5 GeV/nucleon, undergoes a large reduction in flux during the period of solar maximum. It is of interest to note that in the period from 19 October 1957 to 4 February 1959, the neutron monitor data show that the flux of the protons was increasing. Also as can be seen in Table III, the flux of He nuclei is on the increase during this period. On the other hand, the flux of H nuclei shows a decrease in this experiment as also in that of Van Heerden and Judek.[26]

TABLE II. Comparison of flux during solar maximum with that during solar minimum.

Authors	Date	Flux (particles/m² sec sr) (for particles with kinetic energy ≥1.5 GeV/nucleon) $(J_H)_0$	$(J_{VH})_0$
Present work	4 February 1959	1.26±0.09	0.39±0.06
Van Heerden and Judek[a]	9 March 1958[b]	1.11±0.11	···
Freier *et al.*[c]	19 October 1957	1.70±0.30	···
Daniel and Durgaprasad[d]	6 February 1956	2.07±0.28	0.71±0.23
Waddington[e]	Solar minimum[f]	2.50±0.20	0.69±0.16

[a] See reference 26.
[b] There is a little uncertainty in the total time of flight in this experiment as the last 1½ h of the time-altitude curve was obtained by extrapolation [F. W. O'Dell, M. M. Shapiro, and B. Stiller, *Proceedings of the Moscow Cosmic Ray Conference* (Moscow, 1960), Vol. III, p. 118]. This extrapolation, however, seems to be reasonable and it cannot make any appreciable change in the flux value quoted here. Even if one were to assume that the flight terminated one and a half hours before its extrapolated end, the corresponding increase in the flux would be about 20% which would still be about as low as our value.
[c] See reference 25.
[d] See reference 17.
[e] See reference 24.
[f] These are mean values of fluxes observed by different observers during the period when solar activity was nearly minimum.

3.4 Comparison of the Fluxes of α Particles and Heavy Nuclei During Solar Maximum with Those During Solar Minimum

Table III gives relevant data about the fluxes of α particles and H nuclei at $\lambda = 41\,^\circ$N, when simultaneous measurements of the flux of the α particles and H nuclei were made on the same day.

[24] C. J. Waddington, in *Progress in Nuclear Physics* (Butterworths Scientific Publication, Ltd., London, 1960), Vol 8.
[25] P. S. Freier, E. P. Ney, and C. J. Waddington, Phys. Rev. **113**, 921 (1959).
[26] I. V. Van Heerden and B. Judek, Can. J. Phys. **38**, 964 (1960).
[27] O. B. Young, T. P. Wang, and P. C. Hsieh, Nuovo Cimento **23**, 101 (1962).

TABLE III. Simultaneous measurements of the Flux of α particles and H nuclei at $\lambda=41°$N.

Author	Date of flight	Flux (particles/m² sec sr) $(J_\alpha)_0$	$(J_H)_0$	Flux ratio $(J_\alpha)_0/(J_H)_0$	Method
Waddington[a,b]	14 September 1954	89±8	2.5±0.3	35.6±5.3	Emulsion
Freier *et al.*[c,d]	19 October 1957	68±4	1.7±0.3	40.0±7.4	Emulsion
Present work	4 February 1959	...	1.26±0.09	58.7±6.3	Emulsion
F. B. McDonald[e]	4 February 1959	74±6	...		Čerenkov scintillator
(also) D. E. Guss[f]	8 February 1959	76±4	...		Emulsion

[a] See reference 28. [b] See reference 29. [c] See reference 8. [d] See reference 25. [e] See reference 30. [f] See reference 20.

In Table III, the measurements of Waddington[28,29] refer to flux values at solar minimum period while all other values refer to the active period of solar cycle. The fluxes of He nuclei and H nuclei on 19 October 1957 (shown in row II of Table III) are seen to be (24±11)% and (32±17)% lower than the corresponding values for 14 September 1954 (in row I of Table III). Within experimental errors this reduction in flux seems to be closely similar for He nuclei and H nuclei. In rows III and IV of Table III, observations made from the same balloon flight on 4 Februry 1959 are given. (The value given in row V, of the flux of He nuclei observed on 8 February 1959 by Guss,[20] confirms the observation of McDonald[30] on 4 February 1959.) These values of the fluxes of He nuclei and H nuclei on 4 February 1959 are reduced by (17±11)% and (50±14)% as compared to the corresponding values in row I.

Thus, while on 19 October 1957, the flux of He nuclei and H nuclei seem to be lower than those for 14 September 1954 by about the same amount, on 4 February 1959 the H nuclei show a reduction $\sim$3 times greater than that of the He nuclei. The observation does not seem to be due merely to statistical errors as can be seen by comparing the flux ratios, shown in column 5 of Table III.

Such a differential reduction in the fluxes of α and H components, cannot be understood on the basis of the existing modulation mechanisms which do not distinguish between the two components of the same rigidity. The present observation, thus, presents an anomaly to be accounted for by any proposed modulation mechanism.

[28] C. J. Waddington, Phil. Mag. **2**, 1059 (1957).
[29] C. J. Waddington, Nuovo Cimento **6**, 748 (1957).
[30] F. B. McDonald, Bulletin SVI-59-11, State University of Iowa, 1959 (unpublished).

4. CONCLUSIONS

The results obtained in the present investigation can be summarized as follows:

(1.) The exponents of the integral energy spectra of the H and VH nuclei of the primary cosmic radiation are found to be 1.70±0.30 and $1.55_{-0.30}^{+0.20}$, respectively. These values are consistent with the assumption that all multiply charged nuclei of the primary cosmic radiation in the energy region 1.5–10 GeV/nucleon have the same exponent of energy spectrum within experimental errors.

(2.) The exponent of the energy spectrum appears to remain unaltered during the eleven year solar cycle as well as during Forbush decreases.

(3.) The fluxes of H and VH nuclei of the primary cosmic radiation are reduced by a factor of $\sim$2 during the period of solar maximum compared to the corresponding values at solar minimum.

(4.) On 4 February 1959, the percentage reduction in the flux of H nuclei is $\sim$3 times greater than that in the flux of the He nuclei ,when compared with the fluxes of H and He nuclei, respectively, on 14 September 1954 at solar minimum.

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