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Evidence for a Forbush Type of Decrease in the Intensity of Heavy Nuclei of the Primary Cosmic Radiation

S. Biswas,* P. J. Lavakare,† K. A. Neelakantan, and P. G. Shukla
Tata Institute of Fundamental Research, Bombay, India
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In an emulsion stack flown on March 13, 1956 from Iowa, the flux of heavy nuclei with $Z\geq 6$ in the primary cosmic radiation was measured as 15.8 ± 1.0 and 3.7 ± 0.6 particles/m^2 sec sr for particles of kinetic energy ≥ 0.23 and ≥ 1.55 Bev/nucleon, respectively. The measured flux of energy ≥ 1.55 Bev/nucleon was $57\pm 11\%$ lower than the normal flux. It is shown that almost the entire part of the reduction must be attributed to a large Forbush decrease of the cosmic radiation that occurred at the same time. The exponent of the integral energy spectrum of heavy nuclei ($Z\geq 6$) was measured as 1.78 ± 0.24 in the energy interval 0.23 to 9 Bev/nucleon. As this value is not significantly different from its normally measured value, it appears that the large reduction in the primary flux was not accompanied by any significant change in the energy spectrum.

We have recently measured the energy spectrum of the heavy nuclei ($Z\geqslant 6$) of the primary cosmic radiation, in the energy range 0.23 to 9 Bev/nucleon, using a stack of emulsions which was flown from Iowa on March 13, 1956. In our experiment, 206 particles of charge $Z\geqslant 6$ were obtained. Energy measurements in most of the cases were made by the "knock-on electron method"; in this method the energies and angles of emission are measured of electrons knocked out by the primary particle in elastic collisions along its trajectory; from the kinematics of elastic collisions the energy of the primary particle is then derived. Details of this experiment are published elsewhere.[1] The exponents of the integral energy spectra of the M ($6\leqslant Z\leqslant 9$) and H ($Z\geqslant 10$) groups of nuclei were obtained as 1.65 ± 0.27 and 1.82 ± 0.59, respectively, and for the S nuclei ($Z\geqslant 6$) as 1.78 ± 0.24.

The vertical flux of primary S nuclei as obtained in our experiment is shown in Table I; three different values are shown, corresponding to particles with energies $\geqslant 230$ Mev/nucleon, $\geqslant 550$ Mev/nucleon and $\geqslant 1.55$ Bev/nucleon. About 60% of the total area of 223 cm^2 was rescanned and the scanning efficiency for these particles found to be 95%. The flux of S nuclei of energy $\geqslant 1.55$ Bev/nucleon obtained by this experiment may be compared with the values obtained by the following two experiments:

1. Waddington[2] has measured the flux of primary S nuclei of energy $\geqslant 1.55\pm 0.05$ Bev/nucleon at $\lambda=46°$N, using emulsions exposed on a balloon flight over Northern Italy on September 14, 1954.

2. The flux of primary S nuclei of energy $\geqslant 1.5\pm 0.1$ Bev/nucleon (which is the experimentally deduced[3] geomagnetic cutoff energy over Texas, $\lambda=41°$N) was measured by Appa Rao *et al.*[4] using emulsions exposed on a balloon flight from Texas on February 6, 1956.

The flux values obtained in these two experiments are also shown in Table I. Absorption mean free paths of 33 g/cm^2 and 29 g/cm^2 have been used for the M and H groups of nuclei, respectively, to obtain the flux values at the top of the atmosphere in the present experiment and that of Appa Rao *et al.*, so that a strict comparison can be made with the experiment of Waddington, wherein these values have been employed. It may be seen from Table I that:

(a) There is no significant difference in the values of flux for September 14, 1954 (Waddington) and February 6, 1956 (Appa Rao *et al.*). This indicates that long term variations (normally due to the 11-year solar cycle), in the flux of S nuclei were absent or small between 1954 and 1956.

(b) On the other hand, there is a reduction of $57\pm 11\%$ and $59\pm 11\%$ in the flux of S nuclei on March 13, 1956 (this experiment) compared to that on

Table I. Flux values of S nuclei ($Z\geqslant 6$).

Author and date of flight	Flux of S-Nuclei (in particles/m^2 sec sr) of energy $\geqslant 0.23$ Bev/n	$\geqslant 0.55$ Bev/n	$\geqslant 1.55$ Bev/n
Present work (March 13, 1956)	15.8 ± 1.0	12.1 ± 1.0	3.7 ± 0.6
Appa Rao *et al.*[4] (February 6, 1956)			9.1 ± 0.7[a]
Waddington[2] (September 14, 1954)			8.6 ± 0.6[b]
Kaplon *et al.*[7] (September 24, 1950)		15.8 ± 1.6	

[a] Flux calculated from tracks with zenith angle $\leqslant 30°$.
[b] The author has used tracks up to 60°. According to geomagnetic theory,[8] at $\lambda=46°$, the cutoff energy, averaged over all azimuths, increases for particles with zenith angle $>45°$.

* Now at the University of Minnesota, Minneapolis, Minnesota.
† Now at the University of Rochester, Rochester, New York.
[1] S. Biswas, P. J. Lavakare, K. A. Neelakantan, and P. G. Shukla, Nuovo cimento (to be published).
[2] C. J. Waddington, Phil. Mag. 2, 1059 (1957).
[3] P. S. Freier, E. P. Ney, and C. J. Waddington, Phys. Rev. **114**, 365 (1959).
[4] M. V. K. Appa Rao, S. Biswas, R. R. Daniel, K. A. Neelakantan, and B. Peters, Phys. Rev. **110**, 751 (1958).

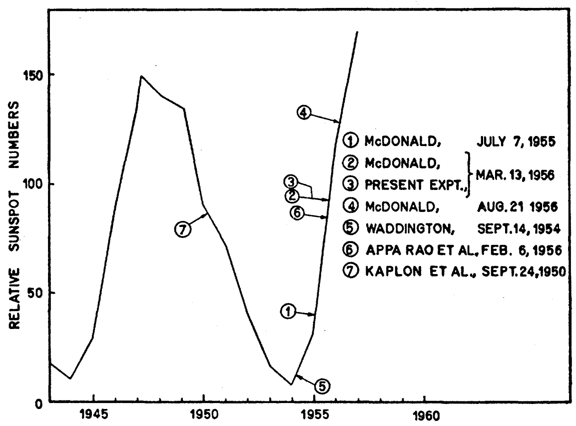

FIG. 1. The Zurich sunspot number vs year showing the 11-year cycle of solar activity. The levels of solar activity arising from the 11-year cycle for the periods of different experiments are indicated.

September 14, 1954 (Waddington) and February 6, 1956 (Appa Rao *et al.*, respectively. This decrease must be attributed almost entirely to a short term effect, i.e., a Forbush type of decrease.

In a recent publication, McDonald[5] has shown that the flux, at the top of the atmosphere, of α particles with energies $\geqslant 280$ Mev/nucleon was lower by 30 $\pm 14\%$ on March 13, 1956 and by $12\pm 14\%$ on August 21, 1956 when compared to the flux on July 7, 1955 in the same range of energies. The counter telescope with which McDonald measured the α-particle flux, and the emulsions used in the present experiment for measurement of the flux of S nuclei were both on the same flight on March 13, 1956. The reduction in the flux of α particles on August 21, 1956, i.e., $(12\pm 14)\%$—which has to be taken as a trend rather than a statistically significant reduction—has been ascribed to increased solar activity as part of the 11 year cycle.[6] On the other hand, a large part of the decrease of $(30\pm 14)\%$ in the flux of α particles on March 13, 1956, was attributed to a Forbush decrease since neutron monitors at $\lambda = 56°$N (Fig. 9 of reference 5) also showed a large Forbush decrease at the same time; it would be difficult otherwise to explain the difference between the flux values for March 13 and August 21, 1956, which are not very different periods in terms of the 11-year cycle.

It thus appears that on March 13, 1956 a Forbush type of decrease took place as recorded by neutron monitors, and there was simultaneously a reduction $[\sim(30\pm 14)\%]$ in the flux of α particles of energy $\geqslant 280$ Mev/nucleon and a reduction $(\sim 57\pm 11\%)$ in the flux of S nuclei of energy $\geqslant 1.55$ Bev/nucleon.

In Fig. 1 is shown a plot of the relative sun-spot number vs year for the period 1943–1957. It may be seen that the two Bombay experiments (that of Appa Rao *et al.* on February 6, 1956 and this experiment on March 13, 1956) were conducted at a time of increased solar activity but very close together in terms of the 11-year cycle, while the experiment of Waddington was near the solar minimum. The dates of the other experiments considered in this paper are also marked in Fig. 1.

We have shown above that a decrease occurred in the flux of S nuclei of energy $\geqslant 1.55$ Bev/nucleon. It is of interest, however, to ascertain whether the decrease was the same or different for different energy ranges of the spectrum. For this, we have tried to estimate in our experiment the reduction in the flux of particles with energies $\geqslant 550$ Mev/nucleon (a region of energy covered by an earlier experiment of Kaplon *et al.*[7]). We find that our value for the flux of S nuclei of energy $\geqslant 550$ Mev/nucleon is lower by $(23\pm 12)\%$ compared to that of Kaplon *et al.* who have determined it as J_S^0 $(E \geqslant 550$ Mev/nucleon$) = 15.8\pm 1.6$ particles/m^2 sec sr at $\lambda = 55°$N on September 24th, 1950. It may be noted (Fig. 1) that the sun-spot numbers were similar during the year 1950 and in 1956 (when the emulsion stack used in the present experiment was exposed). Therefore, if a comparison is made with the vertical flux of particles during the solar minimum of 1954, the reduction is likely to be greater than the above mentioned value of $(23\pm 12)\%$ for the following reasons:

1. The experiment of Kaplon *et al.* was conducted when solar activity was fairly high and not during the solar minimum of 1954; this effect appears to be small ($\sim$few percent).
2. Tracks at large zenith angles were included by Kaplon *et al.* for flux determination; according to geomagnetic theory,[8] at $\lambda = 55°$, the cutoff energy averaged over all azimuths increases for particles with zenith angle $>45°$; these effects are, at the moment, greatly unknown quantities. We would also like to mention that the exposure in the experiment of Kaplon *et al.* was made at a fairly large atmospheric depth, ($\sim$20 g/cm^2), rendering the extrapolation to the top of the atmosphere uncertain; there are also some doubts about the reliability of charge identification and charge resolution in that experiment.

In these circumstances, all that can be said from the above comparison is the following. Though the decrease in the flux of particles of energy $\geqslant 550$ Mev/nucleon and that of particles of energies $\geqslant 1.55$ Bev/nucleon in the present experiment appears to be not very different, one cannot say anything definite as to whether the decrease is the same or different for the different energy intervals.

A further point is that the large change observed in the primary flux is not accompanied by any significant

[5] F. B. McDonald, Phys. Rev. **107**, 1386 (1957).
[6] F. B. McDonald and W. R. Webber, Phys. Rev. **115**, 194 (1959).
[7] M. F. Kaplon, B. Peters, H. L. Reynolds, and D. M. Ritson, Phys. Rev. **85**, 295 (1952).
[8] R. A. Alpher, J. Geophys. Research **55**, 437 (1950).

change in the energy spectrum. The exponent of the integral energy spectrum of S nuclei, obtained in this experiment, over the range of energies from 0.23 to 9 Bev/nucleon is 1.78 ± 0.24; this is, within limits of experimental error, consistent with the values 1.54 ±0.16[9] and 1.60 ± 0.15[10] obtained in other experiments for energy intervals above 1.5 Bev/nucleon. Similarly, in the experiments of McDonald,[5,11] for α particles of energy between 0.28 and 0.9 Bev/nucleon, the exponent in the integral energy spectrum is 1.5 (as calculated by us from his data) for the March 13, 1956 flight and 1.4 ± 0.2 for the July 7, 1955 flight.

We conclude, therefore, that there is evidence for a large Forbush type of decrease in the intensity of the heavy nuclei ($Z\geqslant6$) of the primary cosmic radiation; unfortunately, one can say very little about the energy dependence of the decrease.

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[9] R. Cester, A. Debenedetti, C. M. Garelli, B. Quassiati, L. Tallone, and M. Vigone, Nuovo cimento 7, 371 (1958).
[10] P. L. Jain, E. Lohrmann, and M. W. Teucher, Phys. Rev. **115**, 654 (1959).
[11] F. B. McDonald, Phys. Rev. **104**, 1723 (1956).

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Relativistic Pion-Hyperon Dispersion Relations*†

RICHARD H. CAPPS AND MICHAEL NAUENBERG
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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Relativistic, fixed momentum-transfer dispersion relations are derived (but not proved) for pion scattering from Σ and Λ particles and the processes $\pi+\Lambda\leftrightarrows\pi+\Sigma$. Separate equations for the S- and P-wave amplitudes are obtained under the assumptions that high-energy processes and baryon recoil may be neglected. The P-wave equations are identical to those derived from Chew-Low theory for these processes. A brief discussion is given of the behavior of the P-wave amplitudes under the assumption of global symmetry. It is pointed out that the production of $K-N$ pairs may play an important role in both the S- and P-wave equations.

I. INTRODUCTION

IN recent years relativistic dispersion relations have become a useful tool in the theoretical investigation of the pion-nucleon interaction. Dispersion relations have also been applied to K meson-nucleon scattering,[1] and there is every reason to believe that the dispersion approach to the strong interactions involving strange particles will become more and more useful as the experimental data concerning these interactions becomes more and more abundant.

We consider here the possible usefulness of the dispersion approach to the following three types of interactions involving systems of strangeness minus one:

$$\pi+Y\rightarrow\pi+Y, \qquad (1a)$$

$$\bar{K}+N\rightarrow\pi+Y, \qquad (1b)$$

$$\bar{K}+N\rightarrow\bar{K}+N, \qquad (1c)$$

where the symbol Y denotes either a Σ or a Λ hyperon. There is much evidence that the $K-N-Y$ interaction is somewhat weaker than the pion-nucleon interaction. On the other hand, the binding of Λ particles in nuclei is most easily explained by the hypothesis that the $\pi-\Sigma-\Lambda$ interaction is comparable to the pion-nucleon interaction. Hence it is probable that the pion-hyperon interactions are somewhat stronger than the $K-Y-N$ interactions. Thus the relationships among the three processes, (1a) through (1c), are analogous to those among the following three processes: (a) pion-nucleon scattering, (b) photopion production from nucleons, and (c) photon-nucleon scattering. However, there are two important points of difference between the (K,π) processes [Eq. (1)] and the corresponding (γ,π) processes mentioned above (besides the obvious differences in mass, charge, and spin). First, the K interactions are not really weak as are the electromagnetic interactions. This nonweakness complicates the relations between the amplitudes for the three processes. For example, the $\pi-Y$ scattering amplitudes may be affected appreciably by the $K-Y-N$ interactions.[2] The second point of difference is that in the reactions of Eq. (1) the total rest mass of the particles

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† Part of this work was done while one of the authors (M.N.) was at the Lawrence Radiation Laboratory, Berkeley, California.
[1] See, for example, P. T. Matthews and Abdus Salam, Phys. Rev. **110**, 565 and 569 (1958).

[2] R. H. Dalitz and S. F. Tuan, Phys. Rev. Letters **2**, 425 (1959).