Charge and Energy Spectrum of Heavy Nuclei during the Solar Minimum, 1965

N. DURGAPRASAD* AND D. V. REAMES
National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
(Received 5 June 1967)

The differential energy spectra of H_1 ($Z\geq 20$) and H ($Z\geq 10$) nuclei were measured in a balloon flight at a time close to the solar minimum using a nuclear emulsion stack flown at an altitude of 2.7 g/cm² from Fort Churchill, Manitoba, Canada on 30 June 1965. δ-ray density and residual range measurements on tracks, and measurements of change of δ-ray density with track length, were used to determine the charge and energy of the nuclei. The measured differential fluxes of H_1 ($Z\geq 20$) and H ($Z\geq 10$) nuclei are 0.0013 ± 0.0006 and 0.0045 ± 0.0010 particles/(m² sr sec MeV per nucleon) in the energy range 300–500 MeV per nucleon and 0.0011 ± 0.0004 and 0.0049 ± 0.0008 particles/(m² sr sec MeV per nucleon) in the energy range 500–800 MeV per nucleon. These results are in agreement with satellite and rocket measurements made in the similiar energy range, and, when compared with low-energy measurements, indicate an energy spectrum of nucle that is flatter than those observed during earlier years.

1. INTRODUCTION

A KNOWLEDGE of the detailed relative abundances and energy spectra of cosmic-ray nuclei can be used to draw some important inferences on the origin of the cosmic radiation. Very recently during the near solar minimum such studies of this composition in the low-energy region (20–300 MeV per nucleon) have been made using the data obtained from satellites[1,2] and sounding rockets.[3] Since the charge and energy spectra of these nuclei during solar minimum are of great interest for the study of phenomena of solar modulation as well, we made measurements of the energy spectra of nuclei of charge $Z\geq 10$ that extend into the energy range 200–800 MeV per nucleon using a nuclear emulsion detector flown in a balloon at Fort Churchill, Manitoba, Canada. Similar attempts to study the different components during a period close to solar minimum 1964, have been reported in literature.[4,5] We first describe our results and combine them with the available data from the same period and then compare them with measurements made at other times in similar charge and energy intervals.

2. EXPERIMENTAL DETAILS

The stack of emulsions used in the present work consisted of 296 pellicles of 20-cm×10-cm×600-μ thick Ilford emulsions of various sensitivities. The types used were alternate G5 and G2 pellicles; every ninth pellicle used was G0 emulsion. The stack was exposed in a balloon flight flown from Fort Churchill, Canada for 10.1 h on 30 June 1965 at a mean altitude of 2.7 g/cm² of residual atmospheric depth. This stack was rotated through 180° at the ceiling altitude, to allow discrimination between particles collected during ascent and those recorded during the flight.

The central G5 emulsions in this stack were scanned along a line parallel to and 5 mm below the top edge of the stack. The scan line was 8 cm long, and began and ended at least 6 cm away from the sides of the stack. Tracks were accepted that had a projected length greater than or equal to 2.0 mm per plate, a projected zenith angle $\leq 30°$ (in the emulsion plane), and an ionization $I\geq 64I_0$, where I_0 is the proton minimum ionization in the stack. The selection of ionization was made from δ-ray density measurements as discussed below. The tracks selected were followed through the stack until they ended or interacted within the stack or left the stack. Tracks were also followed backwards to the top of the stack; those that came from an interaction were rejected.

The charge and energy of the nuclei were determined by a combination of δ-ray counting and residual range techniques. These methods have been described in detail in the literature[6–8] before. δ-ray density measurements were made near the point of exit, interaction or ending; at least 200 δ rays were counted at each point. For all tracks which stopped in G5 emulsion, an integral δ-ray count versus range was performed for a distance of 2 mm or the track length available in the G5 emulsion. Two procedures of δ-ray counting were used; "short δ-ray counting" in which δ rays containing four or more grains were counted and "long δ-ray counting" in which δ rays having a projected length greater than 3.2 μ from the

* NAS–NASA Resident Research Associate, on leave from Tata Institute of Fundamental Research, Bombay, India.
[1] V. K. Balasubrahmanyan, D. E. Hagge, G. H. Ludwig, and F. B. McDonald, J. Geophys. Res. **71**, 1771 (1966).
[2] G. M. Comstock, C. Y. Fan, and J. A. Simpson, Astrophys. J. **146**, 51 (1966).
[3] D. V. Reames and C. E. Fichtel, preceding paper, Phys. Rev. **162**, 1291 (1967).
[4] P. S. Freier, J. S. Rno, and C. J. Waddington, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and The Physical Society, London, 1966), Vol. 1, p. 387.
[5] W. R. Webber, J. F. Ormes, and J. Von Rosenvinge, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and The Physical Society, London, 1966), Vol. 1, p. 407.
[6] H. Aizu, Y. Fujimoto, S. Hasegawa, M. Koshiba, I. Mito, J. Nishimura, and Y. Yokoi, Progr. Theoret. Phys. (Kyoto) Suppl. **16**, 54 (1960).
[7] N. Durgaprasad, J. Geophys. Res. **71**, 5625 (1966).
[8] D. V. Reames and C. E. Fichtel, Phys. Rev. **149**, 991 (1966).

track were counted. The results presented here are mainly from the long δ-ray counting; the other method was used only as an additional measurement to separate charges 8 and 10.

A calibration of the integral counting technique was obtained using a sample of well-identified stopping helium nuclei that made small dip angles with the emulsion surface. The charge values of *two* long, flat stopping particles, were then determined relative to the helium nuclei so that they could be used as calibration tracks for subsequent δ-ray counting. Their kinetic energies in MeV per nucleon, were determined using the range-energy relationship given by Barkas.[9] Using these calibration tracks, both types of δ-ray counts were made near the scan line and at different points along the track. The calibration curves of (N_δ) versus the velocity of the nucleus β, were made for different particle charges Z using the relation

$$N_\delta = a(Z^2/\beta^2)+b\,, \qquad (1)$$

where a and b are constants determined from the calibration tracks. These curves were then used to determine the charge and energy values of all nuclei that either stopped, left the stack or interacted. In the case of tracks that stopped in the emulsion, only the δ-ray density at the scan line and residual range were used; for other tracks the two δ-ray counts and the distance between them were used. Multiple scattering measurements were made on favorable flat tracks to check the accuracy of the energy (and charge) determined from δ-ray counts. A basic cell length of 250 μ was employed for this purpose. The energies thus estimated by two methods are summarized in Table I. It may be added here that the variation of sensitivity of emulsion with depth and from plate to plate was studied from measurements of grain density. This variation was found to be less than 5% (the percentage error in the grain counting), when these measurements were confined to the central 70% of the emulsion thickness. All measurements were made within this central region.

A sample of the tracks were δ-ray counted by two different observers. A scatter plot of the charge values determined for these particles is shown in Fig. 1. A histogram of the charges of all the 108 particles of charge $Z\geq 9$ found in this experiment is shown in Fig. 2.

TABLE I. Scattering measurements on flat tracks.

Charge Z of the nucleus	Energy measured in MeV per nucleon from δ-ray density measurements	from multiple scattering measurements
10	569±40	535±113
12	451±29	469±75
11	548±33	560±93
13	776±36	810±228
10	451±17	431±100
26	818±75	740±150

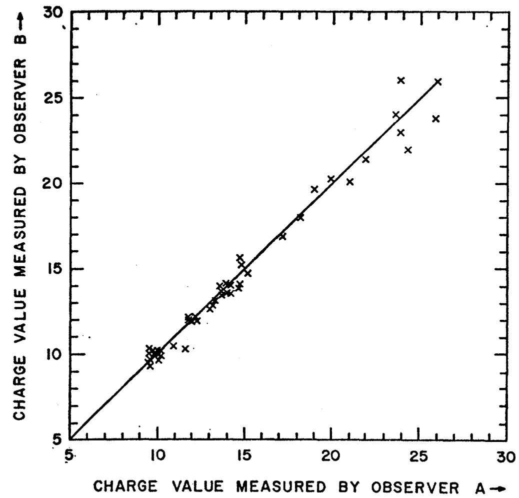

FIG. 1. A cross-plot of the two charge values (Z) assigned to the same nucleus by two different observers. The points of equal charge value should lie on the 45° line.

Scanning efficiency here was determined by a rescan of 71% of the 31.0 cm² total area. This efficiency was found to be 97.7% for H nuclei (of charge $Z\geq 10$) and 100% for H_1 nuclei (of charge $Z\geq 20$).

The energy of each track at the top of the atmosphere was determined by using the range-energy relation of Barkas and Berger[10] and the path length appropriate for the zenith angle of the particle. Using these energies, the flux values in various energy intervals were calculated. These fluxes were then corrected for fragmentation of the nuclei in air and emulsion using the param-

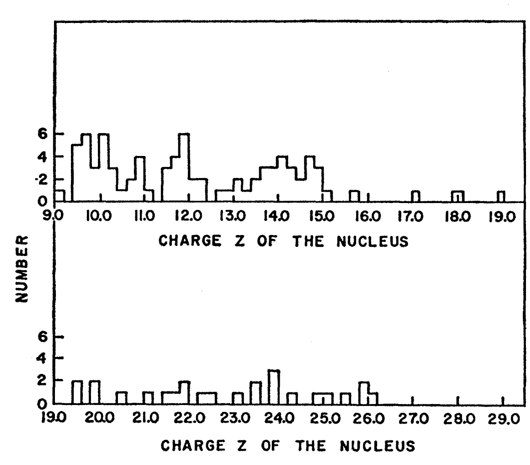

FIG. 2. The charge spectrum of all nuclei of charge $Z\geq 10$ recorded in the stack.

[9] W. H. Barkas, *Nuclear Research Emulsions* (Academic Press Inc., New York, 1963), Vol. 1.

[10] W. H. Barkas and M. J. Berger, Nat. Acad. Sci.—Nat. Res. Council, Publ. 3013, 1 (1964).

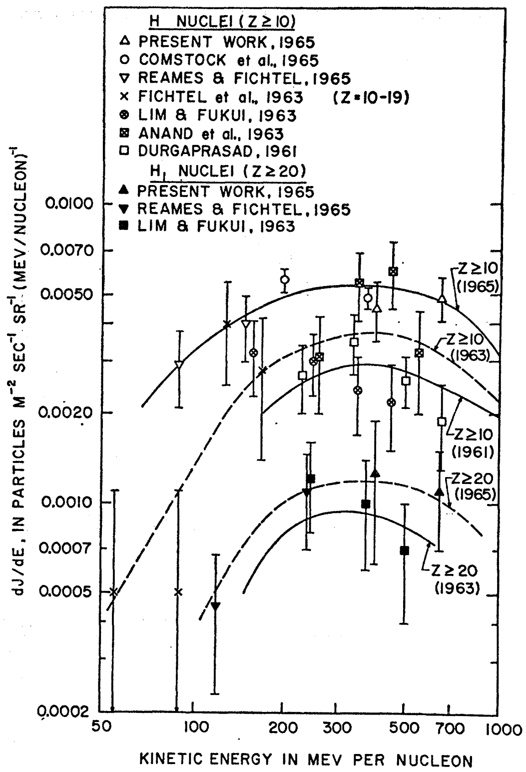

FIG. 3. The differential energy spectra of nuclei of charges $Z \geq 10$ and $Z \geq 20$, measured in the present work and by others during periods of 1965, 1963, and 1961. It may be noted that the work of Fichtel *et al.* (Ref. 12) refers to the charge group $Z = 10$–19. ○, Comstock *et al.*, 1965 (Ref. 2); ▽, Reames and Fichtel, 1965 (Ref. 3); ×, Fichtel *et al.*, 1963 (Ref. 12); ⊗, Lim and Fukui, 1963 (Ref. 13); ⊠, Anand *et al.*, 1963, [K. C. Anand, S. Biswas, P. J. Lavakare, S. Ramadurai, N. Sreenivasen, V. S. Bahatia, V. S. Cohen, and S. D. Pabbi, J. Geophys. Res. **71**, 4687 (1966)]; □, Durgaprasad, 1961 (Ref. 7); ▼, Reames and Fichtel, 1965 (Ref. 3); ■, Lim and Fukui, 1963 (Ref. 13).

eters given by Daniel and Durgaprasad[11] and adopting the procedure given by Durgaprasad.[7] The energy and fragmentation correction, when applied separately would introduce an error into the flux extrapolated to the top of the atmosphere. However, since the fragmentation corrections made here were only about 6% and 12% for emulsion and air, respectively, we feel that this approximation is justified.

3. RESULTS AND DISCUSSION

The differential energy spectra of H nuclei ($Z \geq 10$) and H_1 nuclei ($Z \geq 20$) obtained for the top of the atmosphere are given in Table II and are plotted[12,13] in Fig. 3. The integral particle flux values measured during this period for energies $E \geq 700$ MeV/nucleon for H_1 $H_{2,3}$, and H nuclei are 0.53 ± 0.15, 1.48 ± 0.24, 2.01 ± 0.28 particles/m^2-sr-sec, respectively. Near the same time, the differential energy spectra of H nuclei and H_1 nuclei in the energy range 30–300 MeV per nucleon were measured by Reames and Fichtel[3] using nuclear emulsion stacks flown in Aerobee rockets on 17 and 23 June 1965. The data obtained by these authors are shown in Fig. 3. Similar measurements of the energy spectra of H nuclei in the same energy range (50–800 MeV per nucleon) were available for H nuclei and have been summarized by Durgaprasad.[7] These data are also included in Fig. 3. One striking feature of the spectrum obtained near solar minimum is the relative flatness of the spectrum at low energies as compared to the spectrum obtained during earlier years. Also during the time close to the solar minimum, the energy spectra of helium, light ($Z = 3$–5) and medium ($Z = 6$–9) nuclei as well as of protons in the low-energy range, were measured by Balasubrahmanyan *et al.*[1] in OGO-I and IMP-III satellites. Comstock *et al.*,[2] in addition, have measured the spectra of Ne, Mg, Si, $Z = 15$–25, Fe-Ni elements. They also have reported flat spectra in the low-energy region when compared with the helium spectrum. The energy spectrum of H nuclei given in Fig. 3 has been derived from the quoted Fe-Ni energy spectrum and the charge abundances reported by them. Our results are in agreement with their findings.

TABLE II. Differential energy spectra of $H_{2,3}$($Z = 10$–19), H_1($Z = 20$–28), and H($Z \geq 10$) nuclei.

Energy in MeV/nucleon	Particle flux in particles/(m^2 sec sr MeV per nucleon) $Z = 10$–19	$Z = 20$–28	$Z = 10$–28
200–300	0.0017 ± 0.0009	...	...
300–500	0.0032 ± 0.0008	0.0013 ± 0.0006	0.0045 ± 0.0010
500–800	0.0038 ± 0.0007	0.0011 ± 0.0004	0.0049 ± 0.0008

ACKNOWLEDGMENT

We are happy to acknowledge the helpful comments of Dr. C. E. Fichtel.

[11] R. R. Daniel and N. Durgaprasad, Nuovo Cimento Suppl. **23**, 82 (1962).

[12] C. E. Fichtel, D. E. Guss, and K. A. Neelakantan, Phys. Rev. **138**, 732 (1965).

[13] Y. K. Lim and K. Fukui, Nuovo Cimento **40**, 102 (1965).