COMPOSITION OF RELATIVISTIC COSMIC RAYS DETECTED ON GEMINI XI

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We present final results on the first satellite experiment on abundances of cosmic-ray nuclei having a mean energy of several GeV per nucleon. A nuclear emulsion detector, exposed on Gemini XI in a near-equatorial orbit ranging between geographic latitudes $\pm 29°$, collected 619 high-quality tracks above the earth's atmosphere. Time resolution (within about 5 minutes) was provided by movement of a lower emulsion stack relative to an upper one. The detector was covered by only 0.07 g/cm^2 of aluminium, and was favorably oriented for 18 hours. The results on abundances, requiring no correction for secondary production in the atmosphere, are characterized by: (a) a pronounced odd-even effect, with low abundances for elements of atomic numbers 7, 9, 11 and 13, compared to those of neighboring elements with even Z; (b) approximately equal fluxes of neon, magnesium and silicon, each being about one-fourth that of oxygen; and (c) an abundance gap in the region $15 \leq Z \leq 19$. The composition is similar to that observed at ≈ 100 MeV/nucleon on satellites; however, the abundances of the "Heavy" nuclei ($Z \geq 10$) relative to oxygen are higher in this experiment by approximately one standard deviation, or $\approx 20\%$, than those at low energies.

Introduction

The composition of the heavy nuclei in the galactic cosmic radiation can shed light on the nature of cosmic-ray sources, on interactions of cosmic rays with the tenuous interstellar gas, and on the amount of material traversed before escaping the galaxy. In previous work at high energies (≥ 1 GeV/nucleon), even in good high-altitude balloon flights, one had to correct through about 0.1 or 0.2 of a mean free path of atmosphere to deduce the primary composition. These corrections involve uncertainties due to insufficient knowledge of fragmentation cross sections. Hence, an experiment above the atmosphere can help resolve certain ambiguities. The Gemini XI emulsion experiment is the first flight above the atmosphere with a sufficient time-area factor for track collection to explore some of the relative abundances of elements at energies ≥ 1 GeV/nucleon, and to verify previous assumptions regarding partial fragmentation cross sections in air. The orientation of the spacecraft, and the location of the high-altitude orbits were optimized to reduce detrimental effects of the slow Van Allen belt protons on the search for heavy primary nuclei. Even under these circumstances, detection of the lightly ionizing lithium was prohibitively difficult, and the efficiency for beryllium was low.

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Experimental details related to space flight

The experimental package was contained in a metal box 3.0 inches by 8.5 inches laterally, and 6.0 inches deep. A 250-micron thick aluminium window interposed a minimum of material between the collection face of the stack and the incident radiation consistent with a light-tight pressure seal.

The time history of arrival of the nuclei was obtained by moving a lower stack relative to an upper stack at the rate of 25 μ per minute. It was thus possible to separate the "useful" tracks due to particles from the sky – formed during the oriented portion of the flight – from those registered at other times. A time history of cutoff rigidities was also provided thereby. Fig. 1 is a schematic view of the flight package, showing the top stack and the main stack, which had a potential travel length of 2.0 inches. Movement of the lower stack of emulsions was initiated 102 minutes after launch.

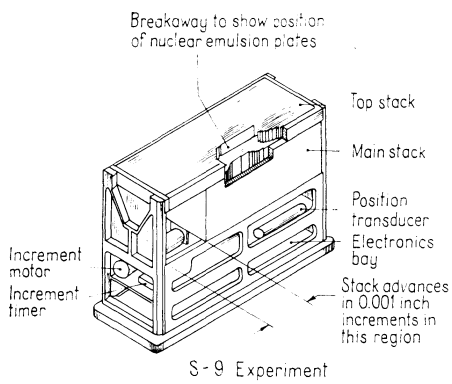

Fig. 1. Experimental flight package

To keep the emulsions within tolerable temperature limits, a coolant was circulated through the walls of the well in which the detector was placed. In addition, the upper surface of the metal box was covered with a thin thermal reflective coating. During launch, a covering hatch protected the package from atmospheric heating. Additional details of the apparatus have been published elsewhere [1].

The spacecraft was oriented so that the emulsion layers were nearly vertical for as much of the time as would be commensurate with other operational requirements during the period of data collection. To minimize the background effect of Van Allen particles accumulated in the region of the South Atlantic anomaly, the attitude of the spacecraft was maintained such that the collection face of the detector was approximately normal to the magnetic field lines in the region. In this way the mirroring particles produced tracks mainly at right angles to those of the primary nuclei sought by the scanners. About 24 hours after launch, pilot RICHARD GORDON opened the hatch for his "space walk", and extracted the package from its well. Command pilot CHARLES CONRAD then stowed the package safely inside the Gemini command module.

Data reduction

The upper stack of nuclear emulsions was $^1/_2$-inch deep and consisted of Ilford K.5 emulsions, 600 microns thick. K.5 emulsions were selected so that even minimum-ionizing tracks left by particles coming from interactions could be seen. Below this shallow stack was a 2.25-inch deep stack that could move with respect to the former. This stack consisted of emulsions (600 μ) of different sensitivities arranged in a repeating sequence of emulsion types: K.2, K.5, K.2, G.0, K.2. The variety of sensitivities helped identify the nuclei. The emulsions were chemically processed at NRL and then divided between the GSFC and NRL groups for scanning and data reduction.

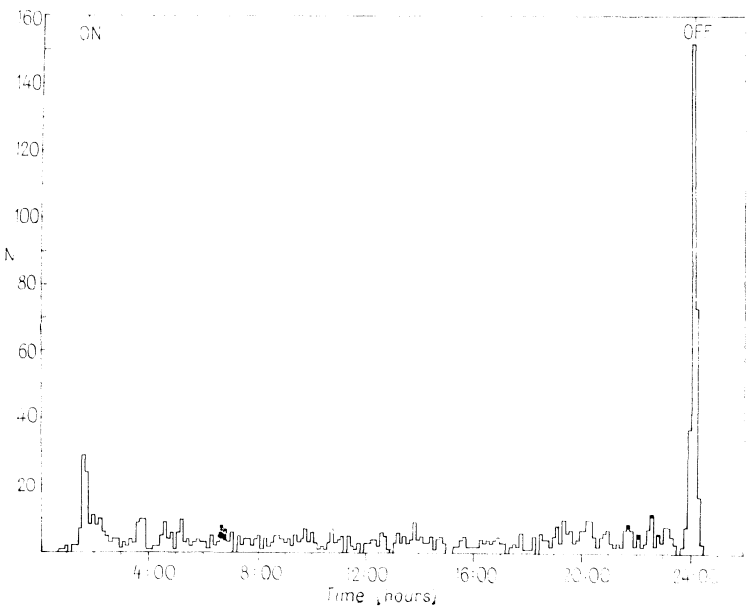

Fig. 2. Distribution of arrival times of heavy primary nuclei

The K.2 and K.5 pellicles in the lower stack were scanned along a line 5 mm below the upper edge of the stack for tracks satisfying the criteria: 1. projected track length per plate $\geq$ 2 mm, 2. projected angle with the normal to the collection edge $\leq 60°$, 3. ionization $\geq$ 9 times minimum. (With the latter criterion, most of the low-energy protons could be excluded from the initial scan.) Coordinates at 3 or more points along each track that passed through the scan plate were recorded using three-coordinate digitized microscopes.

The upper stack was scanned at 4 mm above its lower edge. Segments of tracks that passed through both upper and lower stacks were matched by means of a computer program. The displacement of a track in the lower stack from the position it would have had if the stack had not moved is a measure of the time of arrival of the particle that made the track. Fig. 2 gives a frequency distribution of track displacements, and hence of elapsed time. The small peak at the left shows tracks that arrived prior to actuation of stack motion. The more pronounced peak at the

Table 1

Charge composition

Z	4	5	6	7	8	9
$N_{observed}$	8	50	178	42	162	≤ 6
Scan efficiency	0.77	0.91	0.94	0.94	0.95	0.97
Absorption correction	1.169	1.179	1.189	1.200	1.208	1.218
N_{true}	12.1	64.8	225.2	53.6	206.0	≤ 7.5
N/N_{oxygen}	$0.06 \pm .03$	$0.31 \pm .05$	$1.09 \pm .08$	$0.26 \pm .04$	$1.00^* \pm .08$	≤ 0.04

* The error in oxygen has not been incorporated into the errors for the ratios.

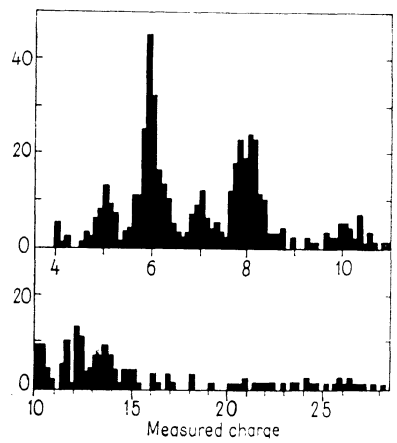

Fig. 3. Charge estimation from combination of various ionization loss measurements

right represents the tracks arriving after cessation of stack motion. From the shape of this peak we deduced that the uncertainty in arrival time of particles was $\pm$ 5 minutes.

Tracks accumulated between the two peaks in Fig. 2 were followed for their entire length in the emulsion; those which interacted above the scan line in the lower plate were rejected.

In a partial rescan, the overall scanning efficiency was found to be a function of Z. It varied from 0.77 ± 0.2 for beryllium to 0.98 for heavy nuclei.

Estimates of charge were based on delta-ray measurements in K.5 emulsion, and grain density (or blob-hole density) measurements in the less sensitive K.2 and G.0 emulsions. Two or more independent charge determinations were made for most of the tracks. The results obtained by the various techniques have been shown by O'DELL et al. [1]. The observed charge distribution in Fig. 3 displays adequate resolution up to magnesium. Fig. 3 includes only the "good"-time tracks described below.

Since the spacecraft was not always oriented so that the emulsion stack was facing upward, it was necessary to determine the arrival direction of each particle

10	11	12	13	14	15–19	≥ 20
39	≤ 5	43	≤ 10	39	15	30
0.98	0.98	0.98	0.98	0.98	0.98	0.98
1.226	1.235	1.243	1.251	1.259	1.284	1.346
48.8	≤ 6.3	54.5	≤ 12.8	50.1	19.7	41.2
0.24 ± 0.04	≤ 0.03	0.26 ± 0.04	≤ 0.06	0.24 ± 0.04	0.10 ± 0.03	0.20 ± 0.04

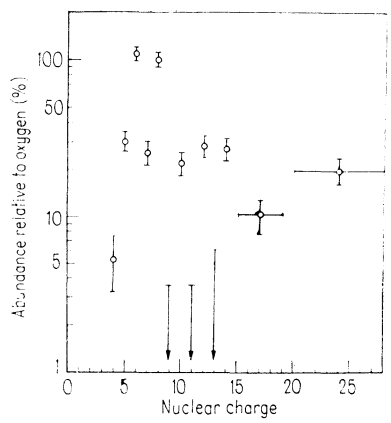

Fig. 4. Relative charge composition of cosmic ray nuclei. (Normalized relative to oxygen.) The abundances of Ne, Mg and Si shown include minor contributions from the neighboring odd-charge elements

in the earth's coordinate system. Tracks were accepted for analysis only if their arrival directions were within 73° of the local vertical. The uncertainty in the arrival time introduced a spread into the estimated arrival directions. Tracks with a probability of less than 0.7 of having arrived within 73° of the vertical were rejected. (Actually, about 80% of the accepted tracks had probabilities > 0.999 of being within 73°.)

In order to look for possible variations in charge composition with energy we determined the geomagnetic cutoff rigidity corresponding to the arrival time (hence also to the geographic position) and arrival direction of each particle.

Results

The observed cosmic ray composition between beryllium and nickel is shown in Fig. 4. The plotted values have been corrected for scanning efficiency and for fragmentation loss in the emulsion above the scan line. The maximum fragmentation correction amounts to 11% for the ratio of nuclei with $20 \leq Z \leq 28$ to oxygen.

(Since nearly all interactions above the scan line were observed, only the total interaction mean free paths had to be used rather than uncertain fragmentation parameters.) The results are characterized by: (a) a pronounced odd-even effect, with low abundances for elements of atomic numbers 7, 9, 11 and 13, compared to those of the neighboring elements with even Z; (b) approximately equal amounts of neon, magnesium and silicon, each being about one-fourth that of oxygen; and (c) an abundance gap in the region $15 \leq Z \leq 19$. The abundances obtained, normalized to oxygen as unity, are given in Table 1.

The results shown are similar to those obtained in balloon experiments at relativistic energies, and to satellite measurements [2] at a much lower energy ($E \lesssim 200$ MeV/nucleon). Any variation in composition with energy is not large. However, the relative abundances of elements heavier than oxygen are somewhat higher in the present experiment. Thus, the abundances of the group of heavy nuclei ($Z \geq 10$) relative to oxygen are higher by approximately one standard deviation ($\approx 20\%$). If the observed differences are real, the lower abundances obtained in the satellite experiments at low energies might be accounted for by the presence of greater ionization losses at these energies. In the high-energy data at balloon altitudes, the difference may stem in part from uncertainties in fragmentation parameters used in correction for passage through air.

By assigning a cutoff rigidity to each particle from its arrival time and direction, we could crudely explore the charge composition versus energy in the relativistic domain sampled in this flight. The statistical weight of the results is limited, but the B/M, H/M and VH/M ratios are consistent with constancy of the composition between rigidities of 4 and 30 GV.

References

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