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A detector system including parallel-plate pulse ionization chambers and a Lucite Cerenkov counter, having geometry factor 0.92 m^2 ster, was operated during a series of balloon flights near 4.5 g/cm^2 atmospheric depth at geomagnetic cutoffs near 4.5 GV and 1.6 GV. Charge spectra and flux ratios are presented. The VH results are consistent with a cosmic-ray source having $J(21 \leq Z \leq 24) = 0$, and $J(20)/J(26) = .12 \pm .06$. The VVH results are consistent with the dominant mode of nucleosynthesis for these nuclei being rapid neutron capture (r-process).

1. Introduction. We are reporting preliminary results of a series of high-altitude balloon flights to measure the charge spectrum of cosmic rays in the Very-Heavy (VH) region, i.e., nuclei of charge (Z) 20 to 30, and in the Very-Very-Heavy (VVH) region, i.e., nuclei of $Z > 30$. Our detector system identifies the charge of the particles by measuring energy-loss in parallel-plate pulse ionization chambers and measuring intensity of Cerenkov light emitted in a sheet of Lucite. The detectors have active area nearly 1 m^2, and the geometry factor of the system is 0.92 m^2ster. The instrument was flown from the Southern USA near geomagnetic cutoff 4.5 GV in three flights in January and May, 1970. It was also flown in September 1970 from Sioux Falls, S.D., where the geomagnetic cutoff is below the Cerenkov counter threshold. In all flights the balloon float altitude was near 4.5 g/cm^2. Float data was recorded for 28 hours near 4.5 GV and for 18 hours in the flight at low cutoff.

2. Detector system.

Figure 1 shows the cross-section of the detector used in the first three flights. The principal components of the system are the two parallel-plate pulse ionization counters and the Lucite Cerenkov counter. The pulse height from each of these three detectors is recorded for each heavily charged particle that penetrates the system. The trajectory of the particle is given by a hodoscope consisting of two crossed layers of scintillator strips above the other counters and two crossed layers below. The hodoscope also serves to define the acceptance cone of the system.

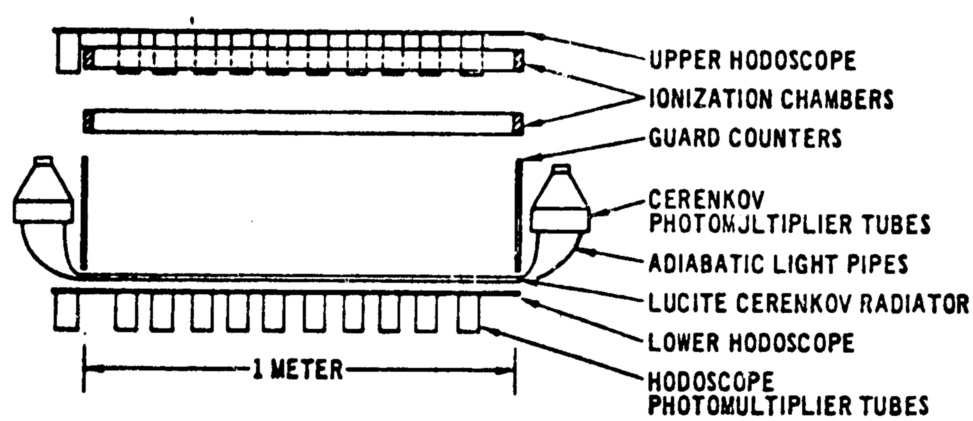

Fig. 1

The ionization chamber plates are separated by 5 cm of gas, 90% Argon and 10% Methane at one atmosphere. Ionization chambers are used for the energy-loss measurement because they are easily constructed in the large areas required and they do not show the non-linearity at large energy-loss which is characteristic of plastic scintillators. These chambers have been described more fully by Epstein et al (1971). The Cerenkov counter is a sheet of ultraviolet-transmitting Lucite 0.63 cm thick viewed on the edges by four 12 cm diameter photomultipliers through adiabatic light pipes. For the last flight of the series, the one at low cutoff, this total internal reflection counter was replaced by one using diffuse reflection for more uniform light collection. This latter counter has the Lucite radiator placed inside a white box, viewed by eight photomultipliers around the sides.

Figure 2 illustrates the familiar response of such an energy-loss-Cerenkov detector system. Both energy-loss and Cerenkov radiation vary directly with the square of the nuclear charge, but their dependence upon the energy of the particle is different. Thus particles of different charge and energy fall along a series of curves. This plot illustrates two problems of interpretation of our data.

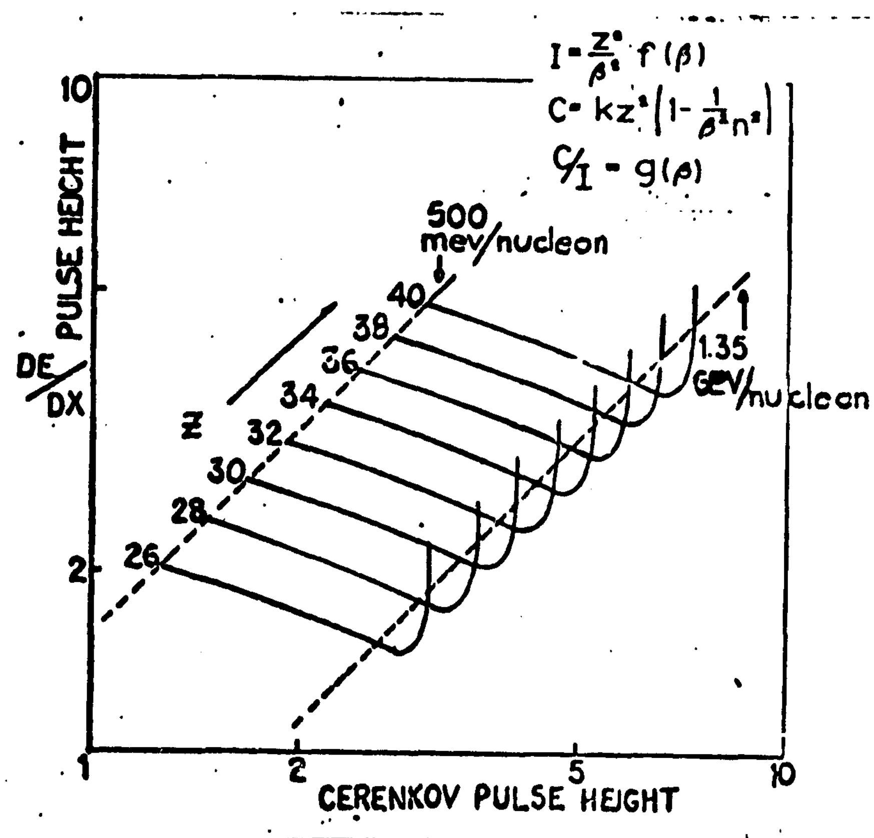

Fig. 2

First, the relativistic rise of energy-loss results in a region of ambiguity where, for example, an iron nucleus (Z=26) with energy near 10 GeV/nucleon gives the same energy-loss and Cerenkov-light as a nickel (Z=28) nucleus near 2 GeV/nucleon. Because of the steepness of the cosmic ray energy spectrum, this ambiguity seriously affects the charge spectrum only where the lower charged particle is very much more abundant than the higher charged particle. Since the cosmic-ray charge spectrum has a large peak at iron and very low abundances at higher charge, the results we present for cosmic rays of charge 28 through 31 will be confined to the lower energies outside this region of ambiguity.

The second source of ambiguity in interpretation of our results is peculiar to our detector and is significant for measurement of the lower energy nuclei with charge below 26. Incident nuclei which penetrate the ionization chambers and then suffer a nuclear interaction somewhere inside the Lucite Cerenkov radiator will register an improperly low Cerenkov signal. Thus, for example, an iron nucleus of 2 GeV/nucleon interacting in the Cerenkov counter will be displaced to the left in this plot and may be incorrectly identified as a 600 MeV/nucleon particle of charge 23. The Lucite thickness is 7% of an interaction length for iron and the low energy nuclei whose measurement is affected are much less abundant than the relativistic iron. As a result our observations of nuclei with charge below 26 and energy below about 1 GeV/nucleon must be taken as upper limits to the true flux. To eliminate this source of ambibuity in future flights, a third ionization chamber, below the Cerenkov counter, has been added to our system. Requiring agreement between the energy-loss in the chambers above the counter and the energy-loss in the chamber below the counter will eliminate most events in which a particle interacts in the Cerenkov counter.

3. Results.

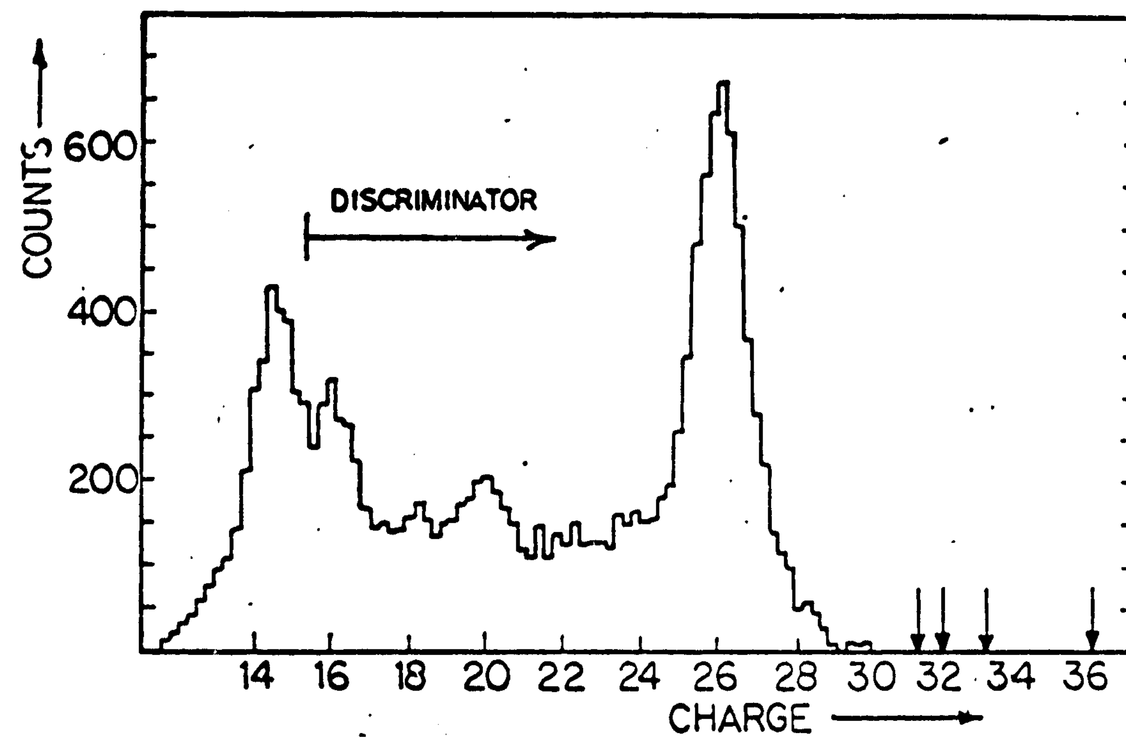

Fig. 3

Figure 3 is a charge histogram for 16,000 events observed near 4.5 GV cutoff. The charge is determined by taking the mean of the two ionization chamber signals and correcting for the velocity of the particle as determined with the Cerenkov counter. For particles above 4.5 GV, the ionization is very nearly constant with energy and the Cerenkov correction has only a small effect on the charge resolution, although it is extremely useful in verifying that the particles are actually relativistic. In addition to the prominent peak at iron, we also observe peaks at charge 14, 16, 18, and 20. The peaks at 14 and 16 are distorted by the ionization chamber discriminator and so are not representative of the true flux of these nuclei. The charges between calcium and iron are not resolved but their fluxes are low compared to iron. For example, the flux of chromium (charge 24) is not more than 25% that of iron. In general, our results in the VH region agree with other recent counter measurements (Lezniak et al, 1969; Dayton, et al, 1969). We have better statistics but poorer charge resolution.

The normalization of the charge scale is based on the assumption that the center of the prominent peak is exactly at charge 26. However, we have an independent verification that this peak is in fact iron. Each ionization chamber has a built-in radioactive source of 5.5 MeV alpha particles. The ionization chamber signal due to these alpha particles is measured periodically throughout the flight. Calculations show that the mean signal due to these alphas in our chamber should have the same pulse height as a vertically incident cosmic-ray nucleus of 2.5 GeV/nucleon with charge 21.5 $\pm$ 0.4. (The uncertainty in this number is a conservative estimate, principally due to uncertainty in the distribution of energy-loss along the path of the stopping alpha-particle.) Using this in-flight calibration, the peak in the cosmic-ray charge spectrum is at charge 26.1 ± 0.5. The width of the peak (approximately 1.5 charge units, fwhm) implies that it consists mostly of particles of one nuclear charge. We therefore have direct evidence that this peak consists of iron nuclei.

The arrows in Figure 3 represent particles we have observed with charges greater than 30. In the case of these relativistic particles, the charge assignment agrees in all three counters, and so we are quite confident that they are actual VVH particles and not fluctuations from the iron peak.

It is always necessary to extrapolate observed data to the top of the atmosphere. With our very large geometrical factor, we can use the data gathered during the balloon ascent to measure directly the atmospheric attenuation of these nuclei. We find an attenuation mean free path for iron nuclei of 15.6 ± 2.2 g/cm^2; and for the VH group, 19.7 ± 1.8 g/cm^2.

Figure 4 shows the charge spectrum for 6200 particles whose energy at the top of the atmosphere was 0.6 to 1.3 GeV/nucleon, as measured in the flight at low geomagnetic cutoff. As mentioned before, the fluxes below iron in this energy range must be treated as upper limits; however the fluxes above iron are reliable because there is no ambiguity due to relativistic rise of energy loss in this energy interval. Note the clump of particles near charge 28 which gives us confidence that we are really observing particles of this charge and not just a tail on the iron distribution.

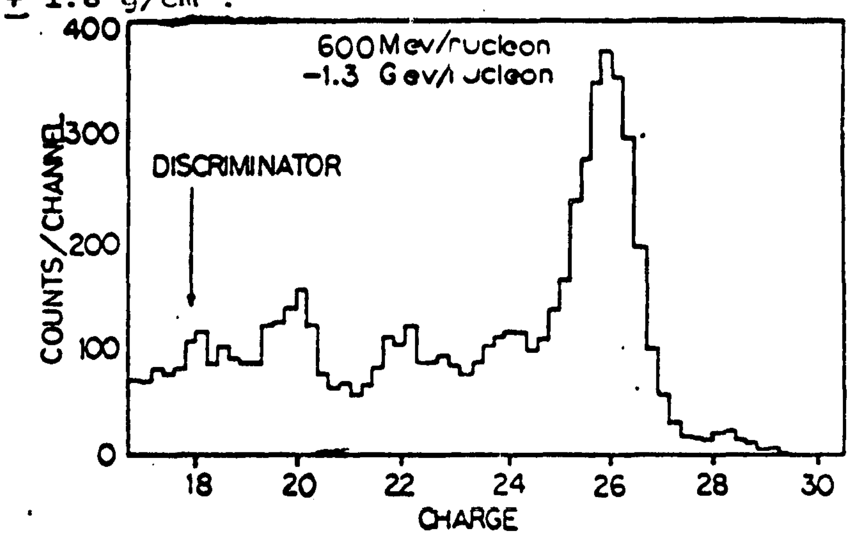

Fig. 4

4. Discussion. The following table summarizes flux ratios for the VH nuclei above 4.5 GV:

	$\frac{J(21 \leq Z \leq 24)}{J(25 \leq Z \leq 30)}$	$\frac{J(Ca)}{J(Fe)}$
Observed at detector	.42 ± .04	.27 ± .04
Extrapolation to top of the atmosphere	.35 ± .06	.21 ± .05
Source: slab model	assume zero	.12 ± .06
steady state model	assume zero	.11 ± .06
Solar system (Cameron, 1967)	.02	.08

Calculating with simple models of the galactic propagation, we can account for all the observed nuclei in the charge 21 through 24 interval as fragmentation products. In a slab model this requires a slab thickness of 2 g/cm^2. In a steady state leaky box model a leakage length of about 5 g/cm^2 is required, consistent with that derived from the ratio of light to medium cosmic rays;

however, in this model the losses of VH nuclei are due mainly to interactions, and the relative fluxes are not very sensitive to the leakage length. In either of these models we find that about half of the observed calcium has resulted from fragmentation, implying that the excess calcium was originally present at the source. The resulting calcium to iron ratio at the source is consistent with the solar system abundances.

In the energy interval of 0.6 to 0.9 GeV/nucleon the ratio $J(21 \leq Z \leq 24)/J(25 \leq Z \leq 30)$ is observed to be $0.67 \pm .05$. This is an upper limit to the correct ratio, as previously noted, but it is still consistent with all nuclei in the 21 through 24 interval being fragments of heavier nuclei because of the greater probability that an interacting iron will fragment into this group at these lower energies. (Waddington, 1969, gives the probability of fragmentation of iron into this charge group as 0.41 for energies greater than 2.1 GeV/nucleon, and 0.60 at 0.7 GeV/nucleon.)

The following table summarizes our results for nuclei heavier than iron. The results are expressed as a ratio of flux in the given interval to flux in the "iron peak" $(25 \leq Z \leq 27)$. For charges 28 through 31 the results are for the energy interval 0.6 to 1.3 GeV/nucleon. For higher charges the results are for all events observed with energy greater than 0.6 GeV/nucleon. (2.9×10^4 such particles were observed in the iron peak.)

Z	this experiment	solar system (Cameron, 1967)	emulsions & plastics
28 - 29	$.035 \pm .005$	.05	
30 - 31	$.0015 \pm .001$	.002	
≥ 33	$(8 \pm 2) \times 10^{-4}$	3×10^{-4}	1.3×10^{-4} *
≥ 40	$(2 \pm 1) \times 10^{-4}$	$.5 \times 10^{-4}$	$.7 \times 10^{-4}$ **

*Blanford et al (1969)
**Fowler et al (1969)

Our results are in rough agreement with the solar system abundances. The disagreement with the emulsions and plastics above charge 33 may be due to an error in determination of the charge threshold for the plastics.

Finally, an important aim of the study of VVH cosmic rays is to obtain information on the nature of the cosmic ray sources. Supernova explosions are likely candidates and it is believed that nucleosynthesis by the rapid neutron capture process (r-process) occurs in such explosions. In the charge interval between 34 and 40, the charge spectrum expected from an r-process is quite different from that of slow neutron capture, (the s-process). We have calculated the expected value of the ratio $J(34 \leq Z \leq 36)/J(37 \leq Z \leq 40)$ in cosmic rays using galactic propagation in a steady-state leaky box model and fragmentation cross-sections from Shapiro & Silberberg (1970). Taking r-process source abundances (Seeger et al, 1965), we find a ratio of 7 or 8; with s-process source, the ratio is between 1.1 and 1.4. We observe the ratio 11/2=5.5. Within its rather poor statistics, this observation favors the r-process over the s -process.

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