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Very heavy low energy cosmic ray nuclei*

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Abstract A stack of nuclear emulsions having a surface area of 900 cm^2 and mounted in a pressure activated emulsion 'camera' was exposed during 1964 at a residual pressure of 2.1 mb over Fort Churchill. These emulsions are being used to measure the intensity of all nuclei having charges of 20 or greater and the differential energy spectrum of these $Z \geq 20$ nuclei between 240 MeV/nucleon and 650 MeV/nucleon. This range of energies covers the region where nuclei of different charges might be expected to show the greatest spectral changes due to propagation or other causes. Provisional results are reported on the energy spectrum and intensities of these nuclei. These results show that, if acceleration processes are neglected, the mean amount of interstellar or source material traversed by these nuclei does not exceed 2 g cm^{-2}.

1. Introduction

Experimental examination of cosmic ray particles with dissimilar charge-to-mass ratios provides a valuable means of investigating the solar modulation process, while a similar examination of those particles having low cosmic abundances gives an indication of the nuclear fragmentations produced during propagation and thus indicates the mean amount of material traversed since the initial acceleration process. In an analogous manner, an examination of those cosmic ray particles having very high charges might be expected to provide information on the ionization effects occurring while the particles are propagating. Since such effects will be proportional to the square of the nuclear charge, clearly the highest charged particles will afford the most sensitive indicators of these effects. This report describes provisional observations on the energy spectrum and absolute abundances of the cosmic ray nuclei which have nuclear charges between those of calcium and nickel nuclei, $20 \leq Z \leq 28$, VH nuclei. Less than 20% of the available data have been analysed thus far, and consequently the final results and conclusions may differ from those quoted here.

2. Experimental procedure

Because of the extremely low absolute intensity of VH nuclei, any experiment which hopes to detect a reasonable number of these nuclei must have a large area-solid angle exposure time factor. In this experiment, the particles were detected in a stack of Ilford G5 600μ stripped emulsions made up of 400 12 in. by 2 in. pellicles and 50 12 in. by 6 in. pellicles. These emulsions were mounted in a vertical plane with the 12 in. edge horizontal so that the total collecting area of the stack was about 900 cm^2. Placed over this collecting area and acting as 'shutters' were two glass backed emulsions mounted in a mechanical frame so that they could be swung out of the way. This emulsion 'camera' was mounted in a pressure-tight sphere and the shutters connected to the logic circuits of an alphatron pressure measuring device so that they would open when the pressure fell to some predetermined value and then close again after the pressure increased to some other predetermined value.

This device was flown from Fort Churchill on the 22nd of July 1964 and floated for approximately 11 hours at a mean residual pressure of 2.1 mb. Due to a malfunction, only one of the two shutters opened at the preselected pressure of 3 mb. It had originally been intended that this flight be simultaneous with a rocket shot by Fichtel of the NASA group to study still lower energy nuclei. Adverse winds delayed the rocket shot by several days, but all indications are that these two experiments can be directly compared.

The processed emulsions have been scanned along a line 2 mm below the top edge for tracks as heavy as those produced by fast nuclei having $Z = 18$. All such tracks having a mean projected length greater than 2 mm and with zenith angles of less than 35° were recorded. Thus far, all the scanning has been done in the area covered by the shutter that did work, but as yet no attempt has been made to identify those particles which entered while the shutter was closed. Once this has been done, it will be possible to remove individually those particles whose energies have been incorrectly calculated because they entered while the stack was under appreciably more matter than at ceiling.

Every particle found in this manner was traced through the emulsions until it came to rest, made a nuclear interaction, or passed out of the bottom of the stack. With the stack thickness employed here and for this exposure VH nuclei will end in the emulsions, and thus reveal their energies very accurately, in the approximate energy interval 240-650 MeV per nucleon. The greatest uncertainty in these energy estimates arises from the uncertainty in the charge determination. If, for example, the uncertainty in the charge of a VH nucleus is ± 2 units of charge, then the energy estimate has an uncertainty of less than ± 7%.

Charge determinations thus far have been based on the measurement of delta rays having a lateral range greater than 4.5 μ. Assignments of charge, based on a scale built up from nuclei of small charge, such as helium and carbon, using different range delta rays for $Z \leq 8$, lead to a peak of iron nuclei and a subsidiary peak at calcium. Furthermore, there is a clear absence of particles between the assigned charges of 20 and 16. These features all resemble those observed at higher energies and give confidence to the general correctness of the charge assignments. Nuclei which did not come to rest in the emulsion were examined for changes in ionization by making delta-ray counts at each end of the track. These measurements allowed the velocities of VH nuclei to be reasonably determined up to the region where the ionization becomes essentially independent of velocity, and consequently, allowed charges to be assigned to these faster nuclei. In the case of nuclei making interactions, the velocity could in every case be determined either by ionization change, or from a study of the fragmentation products.

3. Results

From the measurements outlined in the previous section, it was possible to determine the differential energy spectra of VH nuclei between 240 and 650 MeV/nucleon, the integral intensity of VH nuclei above 240 MeV/nucleon and a differential intensity of nuclei with $16 \geq Z \geq 14$ between 210 and 350 MeV/nucleon.

The differential energy spectrum of the VH nuclei is shown in figure 1 and is based on the observation of 93 nuclei. These data have been corrected to the top of the atmosphere by using

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a simple absorption mean free path of VH nuclei in air of 15 g cm^{-2}, which for an extreme altitude flight such as this only results in an approximately 20% correction. Figure 1 shows the results of smaller statistical weight reported by Lim and Fukui (1965, for VH nuclei observed in emulsions flown on a recoverable satellite at a time when the sea level neutron monitor counting rate was 3.4% less than that prevailing during this experiment.

By analogy with observations on helium nuclei (Waddington and Freier 1965), these satellite results would be expected to be not more than 20% lower than those of this experiment due to solar modulation. In fact, figure 1 shows qualitative agreement.

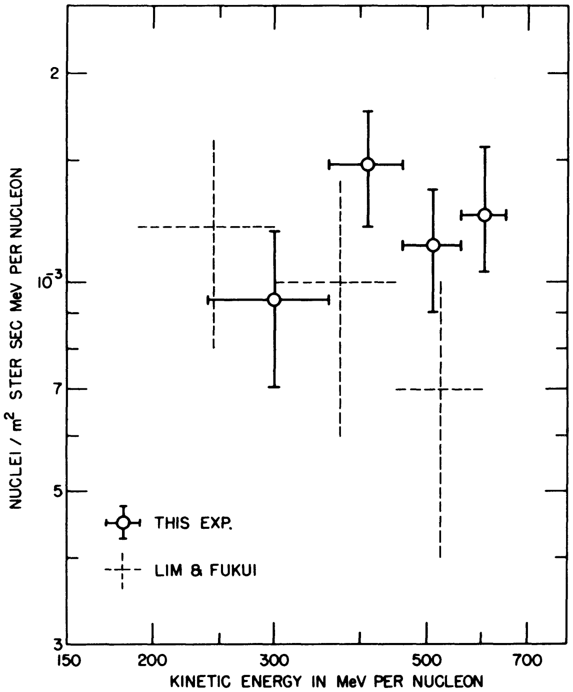

Fig. 1 The differential energy spectrum of VH nuclei as measured in this experiment and compared with the data of Lim and Fukui (1965).

The integral intensity of VH nuclei having E ⩾ 240 MeV/nucleon, after correction to the top of the atmosphere, was:

J_{VH} (E ⩾ 240 MeV/nucleon) = 1.40 ± 0.10 nuclei per m^2 sterad sec.

This value, taken together with the comparable intensity of helium nuclei measured in a flight made four days earlier, when the neutron monitor counting rate was 0.7% less, of J_{He} (E ⩾ 240 MeV/nucleon) = 266 ± 17 nuclei/m^2 sterad sec (Waddington and Freier 1965), leads to a ratio of VH to helium nuclei of $(5.27 \pm 0.50) \times 10^{-3}$. This can be compared with the value of 5.9×10^{-3} previously measured for high energy, E ⩾ 1.5 GeV/nucleon, nuclei (Waddington 1962).

Finally, it is possible to calculate a single differential intensity value for those nuclei having $16 \geqslant Z \geqslant 14$ between 210 and 350 MeV/nucleon. This value is: $dJ/dE = (11.5 \pm 2.4) \times 10^{-4}$ nuclei m^2 sterad sec MeV/nucleon.

4. Discussion

The differential energy spectrum of the VH nuclei can be compared directly with that observed for the helium nuclei four days earlier, (Waddington and Freier 1965). If ionization effects are unimportant, then the spectrum of the VH nuclei should be given by that for the helium nuclei when this latter spectrum is reduced by the relative abundance of VH nuclei to helium nuclei. Figure 2 shows the helium spectrum and the resulting predicted VH spectrum. It should be noted that very little difference would be made if instead of using the VH nuclei to helium nuclei ratio for E ⩾ 240 MeV/nucleon given above, the ratio for E ⩾ 650 MeV/nucleon were used, $(5.5 \pm 0.6) \times 10^{-3}$.

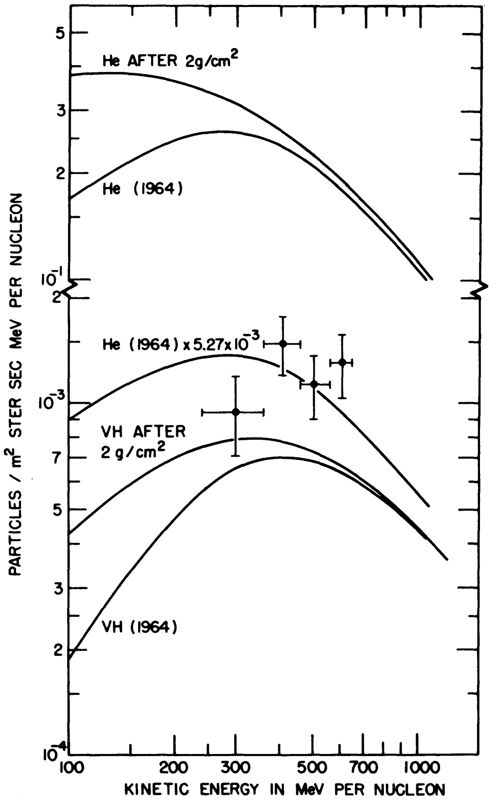

Fig. 2 Differential energy spectra of helium and VH nuclei for various assumptions and models (see text).

Examination of figure 2 shows that, with the possible exception of the lowest energy point, the data are in reasonable agreement with the predicted curve, which implies essentially no measurable effect due to ionization losses. An indication of the expected effect of passage through as little as 2 g cm^{-2} of interstellar matter, neglecting fragmentation, which would further reduce the predicted spectra, can be obtained in the following manner. If it is assumed that the source spectrum of these nuclei is a power law in total energy per nucleon, so that $dJ/dE = K_i\,(E + m_0c^2)^{-2.5}$, then it is simple to calculate the shape of the unmodulated helium and VH nuclei spectra resulting from the passage through 2 g cm^{-2} of interstellar hydrogen. This unmodulated spectrum of helium nuclei can be normalized to the observed modulated spectrum by assuming an arbitrary value for the integral intensity at some energy. Figure 2, for example, shows the resultant spectrum when J_{He} (E > 240 MeV nuc^{-1}) is assumed to be 300 nuclei m^{-2} $ster^{-1}$ sec^{-1} MeV^{-1} per nucleon. The differences between this spectrum and that experimentally observed represent the modulation functions at every energy. The unmodulated spectrum of the VH nuclei, after passage through 2 g cm^{-2} can now be similarly normalized, using the VH to helium nuclei ratio. This ratio should be that of the unmodulated spectra, but since it is being implicitly assumed that both these groups of nuclei are similarly modulated, the ratio should be unaffected. The resulting unmodulated spectrum is shown in figure 2, together with the spectrum produced when this unmodulated spectrum is operated on by the modulation functions found from the spectra of the helium nuclei. Because of this feature of operating on the theoretical spectrum with the deduced modulation function, it is apparent that the resultant predicted spectrum is largely independent of the original $J(\geqslant E)$ intensity value chosen to normalize the theoretical spectrum. Furthermore, since the modulation is presumably a Z dependent function, while ionization loss is Z^2 dependent the predicted spectra will be still further depressed if it is assumed that the mean amount of matter traversed is greater than 2 g cm^{-2}.

Examination of figure 2 shows that the observed intensities are about a factor of two higher than those predicted after traversal through 2 g cm^{-2}, but in reasonable agreement with those expected if ionization plays no appreciable role during propagation. In view of the provisional nature of these data, and the uncertain assumptions underlying the analysis given above, it is presumably just possible to reconcile these data with the passage of 2 g cm^{-2} of interstellar matter, but this must surely be an upper limit. If this result is incompatible with path lengths derived from the composition, then it will be necessary to conclude that some acceleration processes take place during the majority of the time while the particles traverse the matter so as to overcome the influence of the de-accelerative ionization losses.

References

Lim, Y. K., and Fukui, K., 1965, J. Geophys. Res., **70**, 4965.

Waddington, C. J., 1962, Enrico Fermi International School of Physics Course XIX (New York: Academic Press).

Waddington, C. J., and Freier, P. S., 1965, this Conference, Chap. 4, SPEC 10.

Discussion

E. N. PARKER. What is the justification of a power law spectrum before passage of the particles through 2 g cm^{-2}?

C. J. WADDINGTON. The use of a source spectrum having the form of a power law in total energy per nucleon is somewhat arbitrary, although convenient for calculation. However, whatever form is chosen for the source spectrum, the effect of ionization loss must be to depress the observed spectrum for VH nuclei below the equivalent He spectrum unless one assumes that these two components have different source spectra. The experimental observation that the VH nuclei have a similar spectrum to that of the He nuclei must imply either that ionization loss does not play a significant role in shaping the spectra or that the source spectra have just the correct difference to bring the observed spectra into agreement.