An experimental examination of low energy cosmic ray heavy nuclei

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Abstract. In sounding rocket experiments flown from Fort Churchill in September 1963 and July 1964, finite fluxes of cosmic ray heavy nuclei were detected at energies below the experimental energy cut-off of balloon-borne experiments. The particles were examined by extending large sheets of nuclear emulsions from the sides of the rocket during its period outside the atmosphere. The flux of medium nuclei ($6 \leq Z \leq 9$; Z = nuclear charge) in the energy range from 30 to 150 MeV/nucleon was 0.67 ± 0.13 particles/m^2 sterad sec in September 1963 and 1.17 ± 0.16 particles/m^2 sterad sec in July 1964. The abundances of medium and ($10 \leq Z \leq 19$) nuclei relative to helium nuclei in the same energy intervals were found to be less than the relative abundances previously determined at high energies. This type of change in the relative abundances with energy/nucleon is expected if the nuclei have the same source spectral shape and then pass through a small amount of interstellar matter. Finite fluxes of light nuclei ($3 \leq Z \leq 5$) and very heavy nuclei ($20 \leq Z \leq 28$) were also seen in the 30 to 100 MeV/nucleon and the 60 to 295 MeV/nucleon region respectively.

1. Introduction

In an effort to increase our general experimental knowledge of the cosmic radiation and at the same time obtain some new insight into some particular questions related to cosmic rays, an experiment was undertaken to examine the intensity of the heavy nuclei in the cosmic radiation in the region below about 0.2 GeV/nucleon. The first question to be answered was whether or not there are any medium or heavier nuclei in this low energy region. Secondly, if particles are present, the measurement of their properties can provide some restraints on the combined questions of the interstellar travel of cosmic rays and the spectra at the origin.

To measure the intensity, low energy heavy nuclei were exposed to the cosmic radiation above the Earth's atmosphere on Aerobee 150 sounding rockets at Fort Churchill, Canada, in September 1963, July 1964 and June 1965. To overcome the principal difficulty associated with the sounding rocket exposure—namely, having only a short exposure time available—large areas of emulsion were extended from the sides of the payload during the portion of the flights when the rockets were above the atmosphere. The rockets were fired from Fort Churchill, Canada, so that the particles of interest could reach the extended detector at full intensity without having been excluded by the Earth's magnetic field.

2. Experimental procedure

The nuclear emulsion detectors used in this experiment were 600 μm thick Ilford G-5 emulsions which were assembled in three trays, each with an effective exposure area of about 300 cm^2. The trays were kept inside of the payload until the sounding rocket had left the atmosphere, at which time extension of the trays was begun. The exposure period lasted about 350 seconds after which time the trays had to be retracted before re-entry into the atmosphere. Extension and retraction each took about 7 seconds.

Table 1 gives the launch dates of the rockets from which the data of this report were obtained, along with the Mt. Washington neutron monitor rate.

Table 1

Firing Time and Date	Mt. Washington Neutron Monitor Rate
1311 U.T., 4 Sep. 1963	2318
1843 U.T., 23 Jul. 1964	2396

A complete area scan was made under a microscope of the top emulsions, and a partial rescan was made to check scanning efficiency. The accepted tracks were analysed to separate the slow proton and helium tracks from particles with charges greater than 2. All tracks which were within a specified angle (20° in 1963 and 25° in 1964) with respect to the perpendicular to the emulsion were rejected. The charge, energy and solid angle analysis is essentially the same as that used previously in other work and described in detail by Biswas et al. (1962), and therefore, will not be repeated here.

The major correction to the raw data is the one which accounts for the background tracks formed during ascent before the trays are extended and during descent after the trays are retracted. In the more recent versions of this experiment flown in July 1964 and thereafter, this correction was eliminated by including a sliding plate mechanism which permitted separation of the tracks formed during the period that the emulsion trays were extended from those tracks made at other times. The correction which had to be made to the 1963 data is discussed in the paper by Fichtel et al. (1965).

3. Results and discussion

Table 2

Charge Interval	Energy Interval (MeV/nucleon)	Flux (Particle/m^2 sterad sec MeV/nucleon) September 1963	July 1964
3-5	30-95	—	0.35 ± 0.16
6-9	30-150	0.67 ± 0.13	1.17 ± 0.16
10-19	40-195	0.31 ± 0.09	0.35 ± 0.08
20-28	60-295	0.16 ± 0.08	0.21 ± 0.06

After completion of the analysis outlined in the previous section, the results shown in table 2 and figures 1, 2 and 3 were obtained. The first point to be made is obvious: namely, that these fluxes are quite clearly significantly different from zero. Finite fluxes of cosmic ray light, medium and ($Z \geq 10$) nuclei in an energy range as low as 40 to 95 MeV/nucleon have been observed in the vicinity of the Earth.

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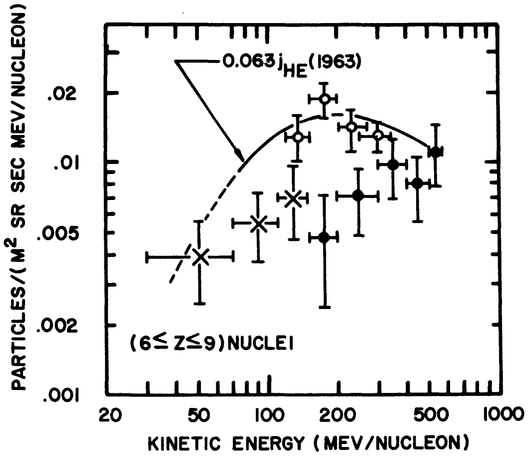

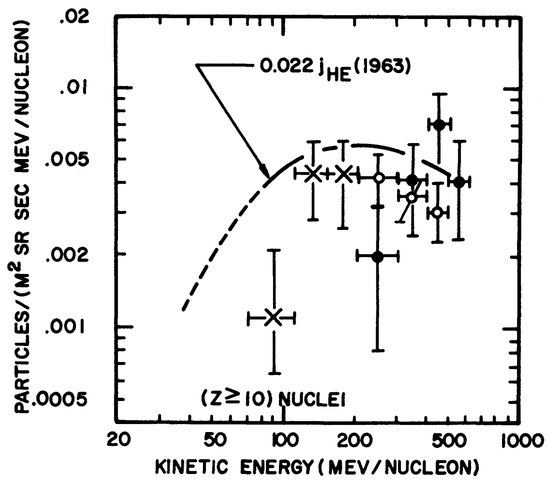

Fig. 1 Differential flux of medium nuclei in September 1963 plotted together with the results of other experimentalists in 1963 at higher energies when the Mt. Washington neutron monitor rate differed by less than 1% from that during the exposure of this work. Open circles, Lim and Fukui 1965; closed circles, Anand et al. 1965, private communication; crosses, this work.

Fig. 2 As for figure 1, but for Z ⩾ 10 nuclei.

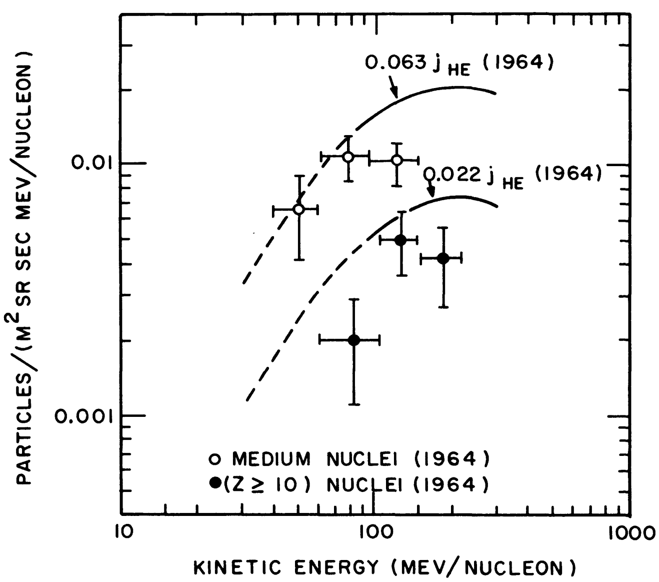

Fig. 3 The differential flux values of medium and (Z ⩾ 10) nuclei in July 1964.

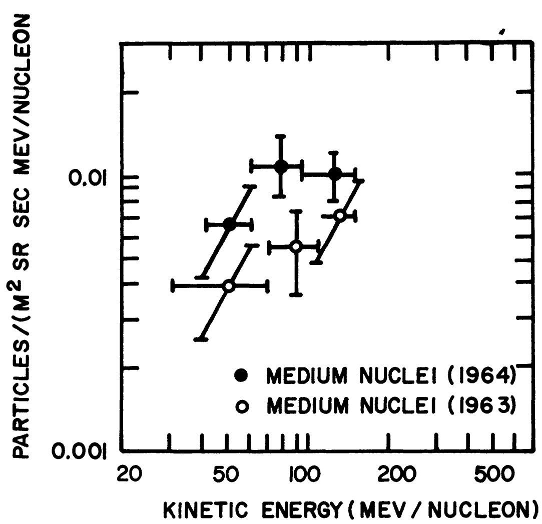

Fig. 4 A comparison of the September 1963 and the July 1964 medium nuclei differential spectra.

The flux values are consistent with a general increase from 1963 to 1964. The differential flux values for medium nuclei, the ones for which the best statistical accuracy exists, are shown in figure 4 for 1963 and 1964. Table 3 then shows the ratios for various charge groups obtained from the 1964 data. It is seen that within the statistical uncertainty, which is fairly large in some cases, the relative abundances of the heavy nuclei seem to be about the same as those observed at high energies. (See the review article of Waddington 1960, O'Dell et al. 1962.) The L/M ratio, which is smaller than the value of about 0.4 to 0.5 observed at intermediate energies of 200 to 400 MeV/nucleon (see, for example, the review article by Webber 1964, University of Minnesota, Tech. Rep. CR-76) indicates that the L/M ratio does not continue to increase strongly at low energies.

Table 3

Charge Groups	Energy Interval (MeV/nucl.)	Ratio	High Energy Ratio*
L/M	30-95	0.20 ± 0.11	0.24 ± 0.04
(10 ⩽ Z ⩽ 19)/M	40-195	0.26 ± 0.07	0.27 ± 0.05
(20 ⩽ Z ⩽ 28)/M	60-195	0.10 ± 0.04	0.09 ± 0.02

* Review article of Waddington (1960) and O'Dell et al. (1962).

The next subject of interest is the comparison of the differential energy spectra obtained in this experiment with the differential spectra at higher energies and with the spectrum of helium nuclei. The existing data at higher energies indicate that the medium and heavy nuclei have energy spectra similar to that of the helium nuclei only reduced in intensity as indicated by Webber (1962). The medium nuclei group, for example, is 0.063 times the helium particle intensity; the charge group (10 ⩽ Z ⩽ 28) is 0.022 times the helium particle intensity. There are two known measurements in 1963 of the medium and heavy nuclei in the energy range from about 150 MeV per nucleon to 600 MeV/nucleon which were obtained at a time when the neutron monitor was within 1% of the value at the time of the rocket firing. These are the results of Lim and

Fukui (1965, Preprint, Air Force Cambridge Laboratories) and Anand et al. (1965, private communication), which are shown in figures 1 and 2 for comparison. It has been shown (Webber 1962) that the particle spectrum is a smoothly varying function of energy and that for this period in the solar cycle a 1% variation in a high latitude neutron monitor rate, which gives an estimate of the higher energy particle intensity, corresponds to about a 10% variation in the helium particle differential flux at 200 MeV/nucleon, and the medium and heavy nuclei appear to behave in a similar way to the helium nuclei with respect to solar modulation.

The authors know of four helium spectra in the energy region from about 80 to 600 MeV/nucleon that were obtained during the summer of 1963 which were made at a time when the neutron monitor was within 1% of the value at the time of the rocket firing (Balasubrahmanyan and McDonald 1964, Durgaprasad et al. 1965, Ormes and Webber 1964, Freier and Waddington 1964). An average of these spectra was used as the basis for the curve in figures 1 and 2. In addition, Fan et al. (1965) and Ludwig and McDonald (1964) have obtained a helium energy spectrum in the 30 to 80 MeV/nucleon region on Explorer XVIII during the period January through March 1964, when the neutron monitor rate was typically from 1 to 2% higher than the rate at the time of the measurement of this experiment. To compensate for a systematic change in intensity in this region, the curve in figures 1 and 2 was extended below 80 MeV/nucleon by a smooth connection to the data at 80 MeV/nucleon, keeping the shape of the 30 to 80 MeV/nucleon data, but reducing the intensity appropriately. This procedure could, at most, introduce a noticeable error only in the lowest medium nuclei energy interval.

In 1964, the results of Durgaprasad et al. (1965) were used together with the Explorer XVIII data to obtain the helium particle spectra. The helium particle curves were multiplied by the ratios mentioned above at high energies for comparison with the data on the higher charges.

The results displayed in figures 1, 2 and 3 indicate that the low energy spectrum of the medium nuclei observed in the vicinity of the Earth falls below that of the helium nuclei multiplied by 0.063. Similarly, the $(10 \leq Z \leq 28)$ nuclei curve falls below the corresponding one for helium nuclei multiplied by 0.022. Hence, the abundance of helium nuclei relative to these higher charge groups apparently increases in the low energy region until it is above the fairly constant value which it has from above 400 MeV/nucleon to very high energies.

The spectra which are observed at the Earth represent the source spectra after they have passed through interstellar matter and have been modulated within the solar system. Whereas the solar system modulation affects only the intensity of the increment of flux in a given energy interval, interstellar space contains enough material along the path of the particle to change appreciably the particle energy as well as the intensity. In the latter case, it normally is assumed that the intensity is changed significantly only by fragmentation in interactions and not by the complicated time dependent magnetic effects which cause the intensity variation in the solar system.

Making these assumptions it is possible to calculate the ratios of the various particle groups. The outline for this calculation is contained in the paper by Fichtel et al. (1965) and further details will be given in the final publication of this work. There is not space to present the details here, but the results suggest that if the source spectra are the same the amount of interstellar material cannot be more than a few g cm^{-2}. The exact amount of material depends somewhat on the exact shape of the source spectrum.

4. Summary

Finite fluxes of light, medium, $(Z \geq 10)$ nuclei exist in an energy range as low as 40 to 95 MeV/nucleon. The relative abundances of light, medium, $(10 \leq Z \leq 19)$, and $(Z \geq 20)$ nuclei in the low energy regions seem to be similar to the high energy values. The relative abundance of helium nuclei relative to the heavier nuclei seems to be slightly enhanced at the lowest energies. If the source spectra of helium and heavier nuclei are similar, the particles have probably not passed through more than a few g cm^{-2} of material.

Acknowledgments

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References

Balasubrahmanyan, V. K., and McDonald, F. B., 1964, J. Geophys. Res., **69**, 3289.

Biswas, S., Fichtel, C. E., and Guss, D. E., 1962, Phys. Rev., **128**, 2756.

Durgaprasad, N., Fichtel, C. E., Guss, D. E., 1965, this Conference, Chap. 4, SPEC 19.

Fan, C. Y., Gloeckler, G., and Simpson, J. A., 1965, J. Geophys. Res., **70**, 3515.

Fichtel, C. E., Guss, D. E., and Neelakantan, K. A., 1965, Phys. Rev., **138**, B732.

Freier, P. S., and Waddington, C. J., 1964, Phys. Rev. Letters, **13**, 108.

Ludwig, G. H., and McDonald, F. B., 1964, Phys. Rev. Letters, **13**, 783.

O'Dell, F. W., Shapiro, M. M., and Stiller, B., 1962, J. Phys. Soc. Japan, (Suppl. A-III), **17**, 23.

Ormes, J., and Webber, W. R., 1964, Phys. Rev. Letters, **13**, 106.

Waddington, C. J., 1960, Progr. Nucl. Phys., **8**, 3.

Webber, W. R., 1962, Progress in Elementary Particle and Cosmic Ray Physics, Vol. 6 (Amsterdam: North Holland), p. 77.

Discussion

S. BISWAS. When you compare the heavy nuclei with alpha particles, have you seen what the spectrum of the low energy nuclei will look like if the ionization loss of heavy nuclei is taken into account ?

C. E. FICHTEL. Yes, this problem was examined in the earlier paper by Guss et al. (1965, see references above), and the results are given therein. In general, there is a suppression of the heavier nuclei relative to the helium nuclei at low energies; however, the results also depend on the shape of the source spectra chosen. We intend to examine this problem in still more detail in the final publication of this work.

M. V. K. APPARAO. It seems from the results presented in this paper and the other papers presented at this conference that the L/M ratio is about 0.20 at energies less than 100 MeV/nucleon, about 0.45 at energies $200 < E/n < 700$ and again about 0.20 at energies greater than 1 GeV/nucleon. This can be understood if the amount of matter traversed is inversely proportional to the energy and the cross sections for production of light elements from spallation of heavier nuclei is increasing with energy up to energies of about 1 GeV (Aly and Apparao, Nuovo Cim.; Badhwar et al., Progr. Theor. Phys., Japan). A product of the two will give a maximum in the medium energy region as is observed.

C. E. FICHTEL. Yes, this is correct, except possibly the peak is at a somewhat higher energy than one would expect on the basis of the best estimates of the variation of cross section with energy. There are also other effects which play a role, such as the fact that the charge to mass ratios of the light nuclei differ from those of the medium nuclei, and therefore they are modulated in a different way.