during the flare. They are about 100-fold more abundant than those observed in a similar emulsion block flown in polar orbit during 7 to 10 December 1960 under normal solar activity. The energy spectrum of the solar flare heavy nuclei is being investigated by measuring the ranges of the particles and the results will be presented.

References

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-3B-18. Heavy Nuclei in Solar Cosmic Rays

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Rocket borne nuclear emulsions flown into solar cosmic ray events during 1960 from Fort Churchill were examined for the presence of particles with charges greater than two. Heavy nuclei ($Z\geq3$) in excess of normal galactic cosmic ray background were detected in small numbers in the solar particle beam which began to arrive at the earth on 3 September 1960. Subsequently, they were found in much greater abundance in the larger events of 12 November 1960 and 15 November 1960. The properties of these heavy nuclei including their charge, their energy, and their flux are presented, and their significance is discussed.

§1. Introduction

Many properties of solar cosmic ray events have been studied using ground-level monitors, balloon-borne equipment, and satellites. In order to obtain more detailed information on the characteristics of the low energy portion of these phenomena, Nike-Cajun sounding rockets were used to carry nuclear emulsions and other equipment above the earth's atmosphere into several solar cosmic ray events. The rockets were launched from Fort Churchill, Manitoba, Canada, geomagnetic latitude 60.7°N, at which point the magnetic field of the earth does not prevent the entry of the low energy particles to be studied. This paper is particularly concerned with the detection of heavy nuclei in the three solar cosmic ray events studied and an examination of their properties.

§2. Experimental Procedure

In order to determine whether or not heavy particles were present in the solar particle beam under consideration, a complete scan of the periphery of the four-inch diameter nuclear emulsion disks was made for delta-ray tracks, which had residual observable ranges in the emulsion of seven-hundred microns or more and were within a specified solid angle. After the elimination of the tracks which could be identified as slow alpha particles, the remaining tracks fell into two groups; those which had a residual range of the order of several millimeters or less, and those which had ranges in the emulsion of many centimeters or more. In each case the number in the latter group was found, within statistics, to be consistent with the expected cosmic-ray back-ground of 15 to 20 particles/

(m^2. sr. sec.) seen at balloon altitudes during the same period in the solar cycle.

Since the amount of material above a normal balloon flight is equivalent in stopping power to one or two centimeters of emulsion, the heavy particles in the former group, those with ranges less than one centimeter, would not have reached balloon altitudes. Hence, it is necessary to determine whether or not a significant fraction of the particles in this group represent the normal cosmic-ray low-energy heavy spectrum. There was an identical firing on June 6, 1960, with the same Nike-Cajun payload system to obtain background data for the subsequent shots. In an equivalent scan of the nuclear emulsion plates flown on June 6, there were no heavy particles with residual ranges less than one centimeter. On the basis of finding no particles in this group, the calculated probability that the flux of heavy nuclei exceeded 3 particles/(cm^2 sr sec) in this range interval during the time of the June firing is less than approximately 0.05. Since no major decline in solar activity or increase in cosmic-ray intensity was detected during the period from June to September, 1960, the flux of galactic cosmic-ray heavy nuclei with potential ranges in nuclear emulsion of less than one centimeter during the September flight may be assumed to be essentially zero, or a few particles/(m^2 sr sec) at most.

The particles of interest, then, are those which had the short ranges, since, on the basis of the discussion of the preceding paragraph, these are the true solar particles. In order to determine the charge of the nuclei, the delta-ray method was used, since it gives a more reliable estimate of the charge than the thin-down or effective track width measurements. The variation of the delta-ray density with range was found to agree well with Mott's formula, with m/E_m equal to 13. This equation has previously been shown to be a good representation of the experimentally observed delta-ray distribution.[1,2] For a discussion of further details of charge identification, charge calibration, and the expected distributions due to errors, see Aizu *et al*[2] and Fichtel.[3]

§ 3. Results

After the charge, range, and thereby the rigidity and energy of each particle had been determined, a comparison was made to the proton flux. The particles of medium charge, $6 \leq Z \leq 9$, were chosen for this purpose because they are the most abundant and they are not widely separated in charge and mass. Table I gives the flux of solar cosmic ray medium particles at the time indicated in the event and also the ratio of these nuclei to singly charged nuclei above the same rigidity cut-off, the same energy per nucleon cut-off, and the same energy per charge cut-off. There was a lower limit on the range of the heavy nuclei of about 0.5 gm/cm^2 due to this skin of the rocket and the minimum track length accepted for inclusion in the analysis. One sees that the three medium fluxes listed in the table represent three different orders of magnitude in intensity. The medium to proton ratio is seen to vary appreciably from event to event for the same rigidity cut-off, but is found to be much more nearly the same for the same energy per

Table I. Fluxes of Medium Nuclei ($6 \leqq Z \leqq 9$) and Medium to Proton Ratios

Time of flare	0040 UT 9/3/60	1322 UT 11/12/60	0200 UT 11/15/60
Time of measurement	1408 UT 9/3/60	1840 UT 11/12/60	1951 UT 11/16/60
Medium particle flux ($E/N \geq 42.7$ Mev) part./m^2 sr. sec.	19 ± 4	1530 ± 210	258 ± 40
M/P (same rigidity interval)	$0.7 \pm 0.3 \times 10^{-3}$	$2.3 \pm 0.5 \times 10^{-3}$	$12^{+7}_{-5} \times 15^{-3}$
M/P (same E/Z interval)	$0.3 \pm 0.1 \times 10^{-3}$	$0.61 \pm 0.12 \times 10^{-3}$	$1.3 \pm 0.4 \times 10^{-3}$
M/P (same E/Z interval)	$0.17 \pm 0.05 \times 10^{-3}$	$0.25 \pm 0.05 \times 10^{-3}$	$0.42 \pm 0.13 \times 10^{-3}$

nucleon cut-off.

However, upon examining the energy and rigidity spectra of the heavy nuclei in comparison with the proton spectra in the same intervals, as shown in Figs. 1 and 2, one finds that the heavy nuclei in the three events do not have the same energy per nucleon spectrum as the protons. Although the information

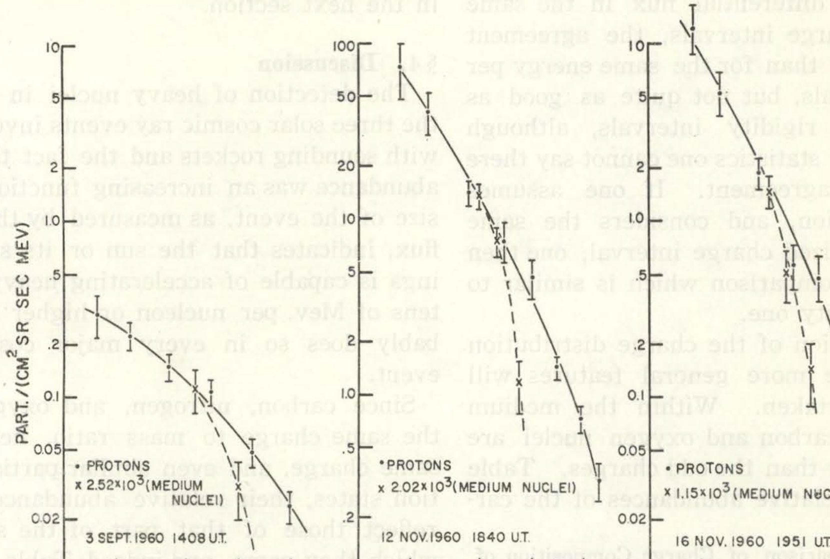

Fig. 1. Comparison of differential energy per nucleon spectra for protons and medium nuclei.

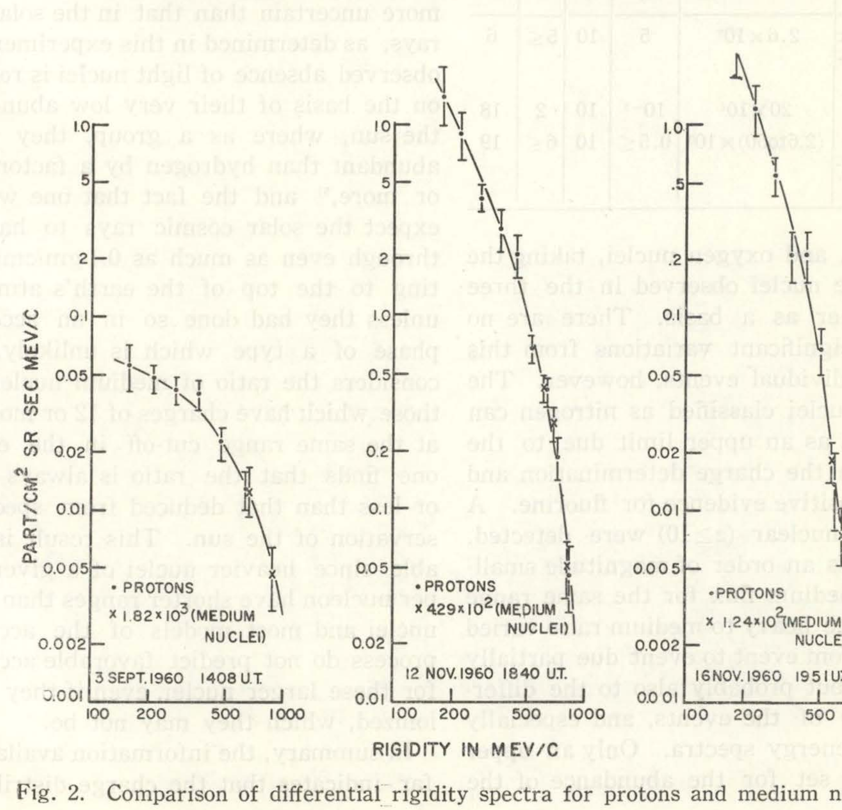

Fig. 2. Comparison of differential rigidity spectra for protons and medium nuclei.

is unfortunately limited by the necessarily poor statistics due to the short flight time, there does seem to be reasonably good agreement between the protons and the heavy nuclei defferential rigidity spectra. If one compares the differential flux in the same energy per charge intervals, the agreement is much better than for the same energy per nucleon intervals, but not quite as good as for the same rigidity intervals, although within present statistics one cannot say there is definite disagreement. If one assumes partial ionization, and considers the same energy per ionized charge interval, one then approaches a comparison which is similar to the same rigidity one.

An examination of the charge distribution to observe the more general features will now be undertaken. Within the medium nuclei group, carbon and oxygen nuclei are more abundant than the odd charges. Table II shows the relative abundances of the carbon, nitrogen, and oxygen nuclei, taking the sum of all the nuclei observed in the three events together as a basis. There are no statistically significant variations from this average in individual events, however. The number of nuclei classified as nitrogen can only be taken as an upper limit due to the limitations on the charge determination and there is no positive evidence for fluorine. A few heavier nuclear ($z \geq 10$) were detected. Their flux was an order of magnitude smaller than the medium flux for the same range cut-off, but the heavy to medium ratio varied appreciably from event to event due partially to statistics, but probably also to the different character of the events, and especially the different energy spectra. Only an upper limit can be set for the abundance of the light nuclei. This limit is given in Table II, and indicates that the heavy nuclei have gone through no more than a fraction of a gm/cm^2. before reaching the emulsion.[4] The significance of these results will be discussed in the next section.

Table II. Comparison of Charge Composition of Solar Cosmic Rays Galactic Rays, and the Sun Relative abundances

	P	Be, B	C	N	O
Galactic cosmic rays (same rigidity interval)	2.6×10^3	5	10	$5 \leq$	6
sun	20×10^3	10^{-5}	10	2	18
Solar cosmic rays (same rigidity interval)	$(2.6 \text{to} 50) \times 10^3$	$0.5 \leq$	10	$6 \leq$	19

§ 4. Discussion

The detection of heavy nuclei in each of the three solar cosmic ray events investigated with sounding rockets and the fact that their abundance was an increasing function of the size of the event, as measured by the proton flux, indicates that the sun or its surroundings is capable of accelerating heavy ions to tens of Mev. per nucleon or higher and probably does so in every major cosmic ray event.

Since carbon, nitrogen, and oxygen have the same charge to mass ratio, nearly the same charge, and even similar partial ionization states, their relative abundance should reflect those of that part of the sun from which they came, and indeed Table II shows that they do agree with spectroscopic evidence.[5] In fact, the uncertainty in the carbon to oxygen ratio in the sun is much more uncertain than that in the solar cosmic rays, as determined in this experiment. The observed absence of light nuclei is reasonable on the basis of their very low abundance in the sun, where as a group, they are less abundant than hydrogen by a factor of 10^{-9} or more,[5] and the fact that one would not expect the solar cosmic rays to have gone through even as much as 0.1 gm/cm^2 in getting to the top of the earth's atmosphere, unless they had done so in an acceleration phase of a type which is unlikely. If one considers the ratio of medium nuclei, M, to those which have charges of 12 or more,[6] $\mathscr{H}$, at the same range cut-off in the emulsion, one finds that the ratio is always equal to or less than that deduced from spectral observation of the sun. This result is reasonable since heavier nuclei of a given energy per nucleon have shorter ranges than medium nuclei and most models of the acceleration process do not predict favorable acceleration for these larger nuclei, even if they are fully ionized, which they may not be.

In summary, the information available thus far indicates that the charge distribution of the heavy nuclei is in agreement with that observed in the sun together with reasonable acceleration and transit models, but is quite different from the galactic cosmic ray spectrum in at least three ways: the light to medium ratio, the carbon to oxygen ratio which is the inverse of that observed in galactic cosmic rays, and the $\mathscr{H}/M$ ratio.

Two interesting features of the medium to proton ratios indicate that probably no simple explanation for the characteristics of the heavy component will be found which will apply to all events. These are the large variations of the medium to proton ratio from event to event and the fact that, although the differences are much smaller for the same energy per nucleon intervals, as opposed to the same rigidity intervals, the heavy nuclei seem to have the same rigidity spectrum as the protons and not the same energy per nucleon spectrum. The variations may be due either to the acceleration phase, the transit and modulation phase of the solar cosmic ray event, or both. In the acceleration phase, they may be due to favorable or unfavorable acceleration of the heavy nuclei, partial ionization, or differences in the source composition. In the second phase, several effects might cause variations. For example, one might begin with similar spectra in each event which are then acted upon by different rigidity and velocity dependent diffusion mechanisms. There is now appreciable evidence from the proton results to indicate that the transit phenomena are extremely complex and vary appreciably from event to event.

References

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2) H. Aizu, Y. Fujimoto, S. Hasegawa, M. Koshiba, I. Moto, J. Nishimura, K. Yokoi, and M. Schein, Phys. Rev. **116** (1959) 436.
3) C. E. Fichtel, PhD. thesis, Washington University, 1959 (unpublished).
4) There was 0.19 gm/cm². between the emulsion and the ambient radiation in the rocket.
5) For some of the more recent results and a summary of other data, see L. Goldberg, E. Muller, and L. Aller, Astrophys. J. Suppl. **45** Vol. V, (1960) 1.
6) The group ($Z\geq 12$) was chosen rather than ($Z\geq 10$) because there is no spectral evidence to indicate what the abundance of Ne in the sun is.

Discussion

Gold, T.: Can you say more about the time variation of the ratio of protons to medium nuclei?

Can one think that there is just an appropriate slower time sequence for heavier nuclei?

Fichtel, C.E.: Yes, If one considers that one has some types of diffusion modulation in such case with a diffusion coefficient of the form

$$\beta a(r,f)\{1+b(r,f)R\},$$

where R is rigidity and a and b are complex functions which vary from event to event, then for a given rigidity one can consider times determined by β if a and b do not vary appreciably during the time of interest. This may be the case in the Sept. 3 and Nov. 15 cases. If one analyzes the event in this way, one finds that the medium to proton ratios are more nearly the same for the same rigidity cut-off, and of special interest is the fact that this ratio is now fairly close to the Medium to proton ratio in the sun of 1.5×10^{-3}, moreover, remember, in any case, one cannot expect exact agreement due to the true complexity.

Ney, E.P.: What are the heavy to proton ratio and how do they track the α/P ratios we measure in the same events?

Fichtel: Between Sept. 3 and Nov. 15 we get an increase in μ/P from 7×10^{-3} to 12×10^{-3} where the α/P ratios are 1/25 in Sept. 3 and 1/1 in Nov. 15.