HEAVY NUCLEI IN SOLAR COSMIC RAYS

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This Letter concerns the first successful attempt to detect heavy nuclei in a solar cosmic-ray event. The analysis to be reported here was made in a set of nuclear emulsions flown at 1408 U.T. on September 3, 1960, from Fort Churchill, Manitoba, Canada, in a Nike-Cajun research rocket payload during a solar particle event. A short description of the solar cosmic-ray event, the rocket, and the solar beam program is given in a preceding paper,[1] and will not be repeated here.

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 five-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 the latter group, seventeen tracks were found in the September 3 flight; this number corresponds to about $(80 \pm 21)\,\%$ of the expected cosmic-ray background of approximately 18 particles/(m^2 sr sec) seen at balloon altitudes at this time in the solar cycle. The 80% figure is reasonable because of the limited statistics and the low scanning efficiency for relativistic Li, Be, and B particles.

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 this group of particles represents the normal cosmic-ray low-energy heavy spectrum or that of this solar cosmic-ray event. 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 β was found to agree well with Mott's formula,

$$N_\delta = C\frac{Z^2}{\beta^2}\left\{\frac{m}{E_m} - \frac{1-\beta^2}{2\beta^2} - (1-\beta^2)\ln\left[\frac{m}{E_m}\left(\frac{2\beta^2}{1-\beta^2}\right)\right]\right\}, \tag{1}$$

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.[2,3] A graph showing the curves for N_δ as a function of range and the experimental points for the thirty-five low-energy heavy nuclei is shown in Fig. 1. The spread in points is approximately as expected for the limited statistics, due to the short ranges in most cases and the general limitations of charge resolution. For a discussion of further details of charge identification, charge calibration, and the expected distributions due to errors, see Aizu et al.[3] and Fichtel.[4]

Knowing the charge, range, and, thereby, the rigidity of each particle, a comparison can be made to the proton flux in a given rigidity range. The particles of medium charge, $6 \leq Z \leq 8$, have been chosen for this purpose because they are

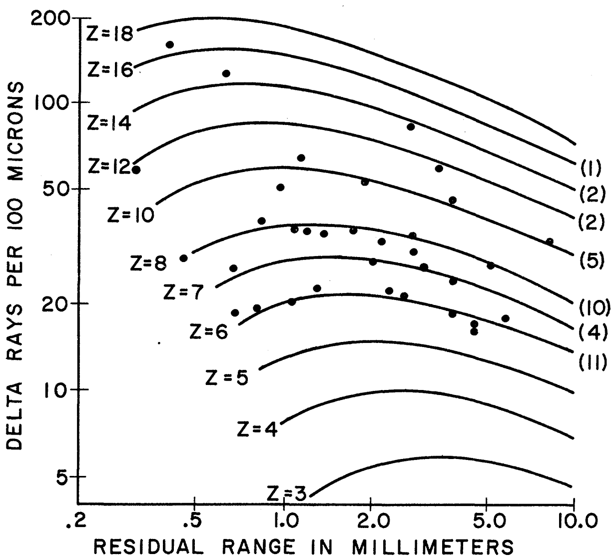

FIG. 1. Charge distribution of heavy solar cosmic rays detected in the nuclear emulsions flown on the Nike-Cajun rocket fired at 1408 U.T., September 3, 1960, at Fort Churchill, Canada. A brief discussion of the equation used for the curves giving N_δ as a function of Z and R is given in the text.

the most abundant and they are not widely separated in charge. After determining the rigidity of each particle from its range and the estimate of its charge, there were found to be 24 particles in the medium group with rigidities greater than 570 Mev/c corresponding to a flux of 20 ± 4 particles/(m^2 sr sec). The 570-Mev/c lower limit was set so that, under the given amount of material and within the given solid angle, all particles in the accepted group would have a residual observable path in the the emulsion of at least five-hundred microns. Due to the separation of tracks on a basis of range, there is an implied upper limit of approximately 1000 Mev/c. From the nuclear emulsion work presented in the previous Letter,[1] the flux of protons with rigidities greater than 570 Mev/c is $(2.5\pm0.7)\times10^4$ particles/(m^2 sr sec). The following ratio can then be obtained:

$$\frac{F(6\leq Z\leq 8,\ R>570\ \mathrm{Mev}/c)}{F(Z=1,\ R>570\ \mathrm{Mev}/c)}=(0.8\pm0.3)\times10^{-3}. \quad (2)$$

For the same energy per nucleon or the same energy per charge, the medium to proton ratio is appreciably smaller.

The ratio given by Eq. (2) can be compared to the cosmic-ray ratio of medium particles to protons of $(9.3\pm0.7)\times10^{-3}$ for the same rigidity cutoff.[5] In the sun, the medium to proton ratio has been estimated to be in the range of 1.0×10^{-3} to 2.1×10^{-3}, with one of the more recent determinations being 1.5×10^{-3}.[6] Within the uncertainties, then, the medium to proton ratio observed above a given rigidity cutoff in this sample of solar cosmic rays is slightly smaller than that observed in the sun, but an order of magnitude smaller than the galactic cosmic-ray ratio.

Although the statistics are poor, a little more detailed examination of the charge distribution to observe the more general features is justifiable. The fact that C and O nuclei occur in nearly equal numbers is consistent with their relative abundances in the sun. Due to the limitations on the charge determination, the number of nuclei classified as N should only be taken as an upper limit. Further, the observed absence of Li, Be, and B is reasonable on the basis of the abundances of these elements in the sun, where it is estimated that, as a group, they are less abundant than hydrogen by a factor of 10^{-9}, or more.[6] There is no spectral evidence to indicate what the abundance of Ne in the sun should be; however, on the basis of stellar models there is no reason to expect the abundance of Ne relative to C, N, and O to be very different from the cosmic abundance[7]; hence, the number of Ne nuclei observed, namely five, is reasonable. Nuclei with charges greater than ten were detected, and the number found is not too surprising on the basis of their relative abundance in the sun; however, one must remember that the acceleration process for the larger charges may differ appreciably from that of the medium group.

Sufficient statistics are not available in the September 3 event to permit a quantitative determination of the rigidity spectrum of the heavy particles; however, qualitatively it is not inconsistent with the proton rigidity spectrum in the same region. Some of the more probable acceleration mechanisms suggested for solar cosmic rays would lead to either the same rigidity dependence, the same energy per nucleon spectrum, or the same energy per charge relationship. However, there are also other considerations, such as favorable or unfavorable acceleration of heavies, partial ionization of the heavies during acceleration, and variations between events, such as those observed for the He to proton ratio.[8] Thus, although the bare medium to proton ratio found in this experiment may appear to give some support to theories suggesting that ordinary stars cannot be the sole primary source of cosmic rays, the considerations mentioned above demand that the question of the origin of cosmic rays be left open at this time.

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LOW-ENERGY PION-PION S-WAVE PHASE SHIFTS*

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Evidence for a P-wave $\pi\pi$ resonance has recently been found by Anderson et al. in an experiment on peripheral π^-p collisions[1]; the resonance position and width are in rough accord with predictions based on nucleon electromagnetic structure.[2] It now becomes possible to make certain assertions about the S-wave $\pi\pi$ phase shifts on the basis of the crossing relations developed by Chew and Mandelstam.[3,4] Recently it has been suggested by Truong[5] that the anomalous peak in the double-pion production in $p+d$ collisions—$p+d \rightarrow He^3+\pi^+ +\pi^-$—observed by Abashian et al.[6] may perhaps be due to the large enhancement brought about by the interaction of the S-wave pions in the $I=0$ state, I being the isotopic spin. In this connection, therefore, it is of interest to see whether we can obtain from our solutions large $I=0$ S-wave amplitudes.

Crossing symmetry gives relations between the derivatives of the S- and P-wave amplitudes at the symmetry point, which are exact if we consider all higher partial waves to be small.[3,4] At this symmetry point, where $\nu=\nu_0=-2/3$ (ν being the square of the c.m. momentum of a pion), the two S amplitudes are given in terms of the pion-pion coupling constant, λ, and the first derivatives of the S amplitudes are given by the value of the P amplitude. In addition, there is a single relation connecting the second derivatives of the S waves to the first P-wave derivative. A two-parameter form for the P resonance has been given by Frazer and Fulco, the parameters being ν_R and Γ, which are related to the position and the width of the resonance.[2] To fit the experiment of reference 1, we need $\nu_R=3.5$ and $\Gamma=0.3$. Such a two-parameter form should be sufficient, we believe, to give a rough first approximation to the P amplitude and its first derivative at ν_0 if the contribution from the left cut is no larger than estimated by Chew and Mandelstam.[4,7] The above crossing relations then largely determine the S-wave amplitudes at low energies in terms of the three parameters λ, ν_R, and Γ.

The crossing relations at ν_0 are[4,8]

$$a_0 = \tfrac{5}{2} a_2 = -5\lambda, \tag{1}$$

$$a_0' = -2a_2' = 6a_1, \tag{2}$$

and

$$a_0'' - \tfrac{5}{2} a_2'' = -12a_1', \tag{3}$$

where a_0 and a_2 are the S amplitudes at ν_0 for isotopic spin 0 and 2, respectively, and a_1 is the P amplitude. The primes indicate derivatives at ν_0. A correction for the D waves has already been made in the second-derivative relation, (3), given above.

If we indicate by $A_0^I(\nu)$ the S amplitude at an energy ν for a given isotopic spin I (= 0 or 2), we can write it in the familiar form,[3]

$$A_0^I(\nu) = N_0^I(\nu)/D_0^I(\nu), \tag{4}$$

where $N_0^I(\nu)$ and $D_0^I(\nu)$ are the numerator and