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OBSERVATION OF TRANS-IRON NUCLEI IN THE PRIMARY COSMIC RADIATION*

G. E. Blanford, Jr., M. W. Friedlander, J. Klarmann, R. M. Walker, J. P. Wefel, and W. C. Wells
Laboratory for Space Physics, Washington University, St. Louis, Missouri

and

R. L. Fleischer, G. E. Nichols, and P. B. Price
General Electric Research and Development Center, Schenectady, New York

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Interleaved layers of nuclear photographic emulsion and plastic detectors, covering a total area of 21 m^2, were exposed to the primary cosmic radiation on high-altitude balloon flights. Flux values, in particles/m^2 sr sec, have been estimated to be

$J(Z\geq 33)\geq 2.6\times 10^{-5}$,
$J(33\leq Z\leq 40)\geq 1.9\times 10^{-5}$,
$J(Z\geq 70)\gtrsim 1\times 10^{-6}$.

These values refer to the top of the atmosphere, after extrapolation through 1.5 g/cm^2 of detector and 3.5 g/cm^2 of atmosphere, for particles with magnetic rigidities above 5 GeV.

It is only recently that extremely heavy particles with $Z\geq 30$ have been identified unambiguously in the cosmic radiation. First measurements of the flux of these particles, referred to as VVH, were derived from stored nuclear tracks in crystals found in meteorites[1] and represent, therefore, a flux value that was averaged over the exposure time of the meteorites, typically 10-100 million years.[2] The presence of VVH particles in the present-day cosmic radiation was first shown by Fowler et al.,[3] using nuclear emulsions flown on a balloon at high altitudes. Where previously typical emulsion areas had been of the order of 200 cm^2, Fowler et al. used 4.5 m^2 and found nine nuclei with $Z>40$, including two inferred as having charges in the vicinity of 92. Nuclei with $26<Z<40$ were not readily identifiable because of their possible confusion with the very much larger number of slowing-down iron nuclei.

The present work, started in 1965,[4] makes use of the unique ability of plastic track detectors to record only heavily ionizing particles in the presence of much larger numbers of lightly ionizing ones. We found that the ionization threshold for the most sensitive plastic known—cellulose nitrate (CN)—lies above the ionization level of relativistic iron nuclei.[4] Based on the meteorite results, the flux of VVN particles was expected to be of the order of a few particles/m^2 h. Fortunately several methods[5] have been developed to find such widely separated etch-track holes in plastics, thus obviating the need for tedious optical scanning. Another attractive feature of the plastics which has recently emerged is that of using the rate of etching along a track as a measure of a particle's ionization rate.[6] This promises to permit precise charge identification, and so complement the traditional measures available with emulsions.

Our method employs as its basic unit a "sandwich": nuclear emulsion and plastic sheets held rigidly together. For those particles which produce detectable tracks in a plastic the corresponding tracks in the adjacent emulsions and other plastics can then be found and the particles studied in both emulsions and plastics. Since different plastics have different charge thresholds for relativistic particles, the existence of a track in a particular plastic provides an immediate indication of a lower limit to its charge. However, since the rate of ionization also depends on velocity, it is essential that the particle be known to be relativistic for this method of charge identification to be valid. Accordingly, our balloon flights with large-area detector systems (our Barndoor series) have been launched from Palestine, Texas, where the geomagnetic cutoff is around 5 GV.

Barndoor I with 7.8 m^2 of detector was flown on 23 September 1967, and floated at an average residual atmospheric pressure of 3.7 g/cm^2 for 15.0 h. For Barndoor II, the corresponding data were 13.8 m^2, 24 May 1968, 3.5 g/cm^2, and 14.0 h, respectively.

In Barndoor I, three sandwiches of emulsions and plastics were used, each composed as shown in Fig. 1. Set A was moved relative to sets B and C when the balloon reached float altitude and also shortly before descent. The different positions were separated horizontally by two inches, and the overall effect is to define, for each track in the B layer, different locations in the A layer which thus distinguish between tracks recorded

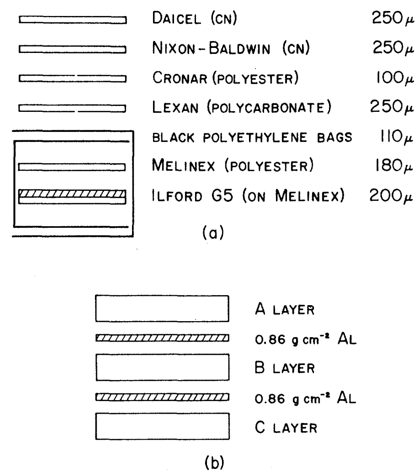


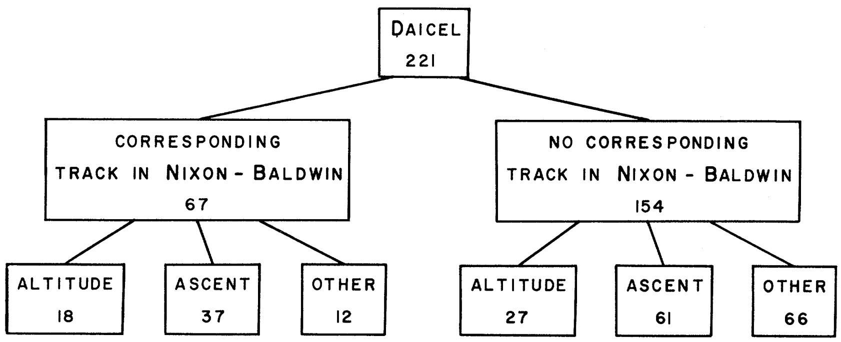
FIG. 1. (a) Composition of basic detector sandwich in Barndoor I. (b) Disposition of the three detector layers in Barndoor I.

at ceiling and those detected during the balloon ascent and descent. On the basis of earlier calibrations[5] it was expected that the order of decreasing sensitivity of the plastics would be Daicel CN, Nixon-Baldwin CN, and Lexan polycarbonate. A total of 72 units made up each of the A, B, and C layers. Part of the area of B was obscured by the aluminum framework supporting the A layer; we estimate that for 16% of the particle tracks detected in B, the extrapolated location in A will be within the aluminum frame.

After flight, the emulsions were developed by conventional methods, and the plastics were etched in 6.25N NaOH solution. The first scanning was carried out in the Daicel B layer. The B emulsions were used in the early stages to confirm the passage of a heavily ionizing particle. The next step was to follow the track to the Daicel A layer where the available positions were scanned. In addition to checking in those places adjacent to tracks in the Daicel layers, the Nixon-Baldwin and Lexan were scanned independently. It is significant that no tracks were found in this scanning that had not already been found in the Daicel. Scanning of plastics was done both optically, using a low-power stereo microscope, and by the much more rapid spark scanning technique.[5] Excellent agreement was obtained with the two methods. The results are summarized in Table I.

Classification of a track as "altitude" or "ascent" was determined by the position in Daicel A where the track with similar length and direction was found. Every unambiguous Nixon-Baldwin altitude track had a counterpart in the Daicel.

Table I. Breakdown of tracks found in plastics, according to their registration in Daicel and Nixon-Baldwin and also by classification as altitude or ascent tracks.



There were 12 tracks in the Nixon-Baldwin for which no counterpart could be found in the A layer in either the altitude or ascent positions. This number is very close to that expected (16%), considering the inactive fraction of the A layer. Similarly, for the 66 "other" tracks listed (Table I), none had a corresponding track in any available position of the Daicel A layer. We would expect about 25 tracks in such a category due to shadowing, and consider that the excess is caused by particles with $Z \leqslant 26$, which are too lightly ionizing to register in the Daicel A layer, but have slowed down enough to be detected by the Daicel B layer.

The preliminary charge identification given here rests on photometric analysis of emulsion track structure, for the lower atomic-number particles, and additionally on etching-rate measurements for the two high-Z particles that were found. At this stage, charge identifications are subject to further calibration, but there are some statements which can be made with a fair degree of certainty. All of the 18 altitude tracks recorded in the Nixon-Baldwin show tracks in emulsion that are appreciably heavier than those of iron. All tracks found by independent scanning in Nixon-Baldwin were also found in the Daicel; the charge identification in emulsion of the 18 Nixon-Baldwin tracks yields 14 with $33 \leqslant Z \leqslant 40$, and four with $Z > 40$. We therefore conclude that Nixon-Baldwin records relativisitic particles with $Z \geqslant 33$ with 100% efficiency. For particles with $27 \leqslant Z \leqslant 33$, we have not yet determined the efficiency of registration in Daicel and we make no further statements about these tracks. We accepted for analysis only those tracks within 60° of the zenith, thus defining a solid angle of π sr.

In Barndoor II, scanning has so far been confined to the Lexan and two particle tracks were found by spark scanning.[5]

Estimates of the threshold for Lexan derived from low-energy heavy-ion irradiations suggest that each of these particles must have a charge of $Z \geqslant 55$. Using the photodensitometer at the University of Bristol, the charges determined by Fowler's method[3] are 77 and 84; measurement of the rate of etching of the matching tracks in Lexan yields charge values of 74 and 80, respectively. Thus for our two tracks, the photodensitometer and track-etching methods gave similar results with the Lexan yielding slightly lower values. Standard deviations cannot yet be attached to these estimates of charge, but at present we consider the values to be uncertain by no more than ~10%. Without laying too much stress on the precise charge identifications, we wish to emphasize the basic observation: Two particles with Z appreciably heavier than 70 were found.

It must be remembered that spark scanning reveals the presence of an etched track only if the two cones being etched from the two surfaces of the plastic sheet are connected. From our knowledge of etching rates[6] and the etching conditions in this experiment we estimate that the spark scanning would have revealed tracks of nuclei having $Z > 70$ and arriving within 60° of the zenith.

Extrapolation from the intensities observed at the level of the B layer of detector to the top of the atmosphere and then further to possible cosmic-ray sources requires a knowledge of the values of the interaction mean free paths and fragmentation parameters. Data for the different charge groups are collected in Table II. Mean

Table II. Data on particle fluxes, showing extrapolation from flight observation level to the top of the atmosphere.

Charge group	Number of tracks	Flux at B layer $\left(\frac{\text{particles}}{\text{m}^2\text{ sr sec}}\right)$	Flux at A layer $\left(\frac{\text{particles}}{\text{m}^2\text{ sr sec}}\right)$	Mean free path in air (g/cm^2)	Flux at top of atmosphere $\left(\frac{\text{particles}}{\text{m}^2\text{ sr sec}}\right)$	Mean free path in hydrogen (g/cm^2)	$\frac{\text{Flux at top atm}}{\text{Flux of Fe group}}$
$33 \leq Z \leq 40$[a]	14	1.3×10^{-5}	1.4×10^{-5}	12.0	1.9×10^{-5}	2.5	5×10^{-5}
$Z \geq 33$[a]	18	1.6×10^{-5}	1.8×10^{-5}	11.0	2.6×10^{-5}	2.2	6×10^{-5}
$Z > 70$[b]	2	6×10^{-7}	6×10^{-7} [c]	7.1	1.1×10^{-6}	1.3	3×10^{-6}

[a]Barndoor I only.
[b]Barndoor I and II.
[c]No absorber between A and B layers in Barndoor II.

free paths have been calculated using a simple overlap model in the estimation of cross sections.[7] In the absence of accurate knowledge of the fragmentation parameters, we have used $P_{ii} = 0.2 \pm 0.2$ both for aluminum and for air. Even such a generous assignment of uncertainty leads to an uncertainty of only 10% in the flux at the top of the atmosphere.

Above the B layer in Barndoor I, particles incident vertically traversed 1.5 g/cm^2, consisting of plastics, emulsion, and $\frac{1}{8}$-in. aluminum.

The final flux values, at the top of the atmosphere, are then

$$J(Z \geq 33) \geq 2.6\times10^{-5} \text{ particles/m}^2 \text{ sr sec},$$

$$J(33 \leq Z \leq 40) \geq 1.9\times10^{-5} \text{ particles/m}^2 \text{ sr sec},$$

$$J(Z > 70) \gtrsim 1\times10^{-6} \text{ particles/m}^2 \text{ sr sec}.$$

For comparison, the flux of the Fe group ($20 \leq Z \leq 26$) at the same latitude, is about 0.4 particles/m^2 sr sec and the corresponding flux ratios are listed in Table II. These are comparable with those deduced from the examination of tracks recorded in meteorites representing averages over very long times.[1]

The flux values for particles with $40 < Z \leq 70$ and $Z > 70$ are lower by a factor of about 5 than values recently deduced by Fowler (private communication) from his first two large-area flights. The reason for such a large discrepancy is not yet understood. The numbers of tracks of Fe nuclei, both in our Barndoor I and in Fowler's flights, appear to be normal. Our VVH values depend on the location of tracks in the plastics and so on the efficiency of track registration. From the following argument we believe that this efficiency is 100% for particles with $Z \geq 33$. For every track in the Daicel which shows a matching emulsion track heavier than that for relativistic $Z = 33$, there is a matching Nixon-Baldwin track. There is no case where an emulsion track of apparently high Z (above 33) is not recorded in the Nixon-Baldwin. Optical scanning of one third of the area of Barndoor I emulsions has failed to yield additional tracks. Since this scanning has a high efficiency for tracks with $Z \gtrsim 40$, we are unable at present to understand the large difference between Fowler's flux values and ours, unless in terms of a severe statistical fluctuation. Conventional tests suggest this as being very unlikely, i.e., where on the basis of Fowler's flux we would expect to observe about 20 tracks, we actually see four.

Another possible effect may be introduced through our differing methods of rejecting slow or ascent particles. We have unambiguous identification through matching with altitude positions of the A and B layers, where Fowler must rely on observing changes in ionization in order to reject the slow particles. From the following evidence we consider this an unlikely explanation.

We examined a sample of tracks as though we had no external evidence with which to classify them as "altitude" or "ascent": 32 "ascent" tracks in the Nixon-Baldwin were chosen. In the B layers, 23 of these tracks are less heavy than fast particles with $Z = 38$, while the other nine appear to have $Z > 38$. For only one of these nine tracks is there negligible ionization difference between A and B layers, and we would have classified this as $Z = 39$. The other eight tracks show changes in ionization consistent with passage of slow Fe nuclei through the 1.5 g/cm^2 separating the A and B layers.

We have not yet extrapolated our fluxes to give abundances at source. In Table II, we have listed the mean free paths for heavy particles in hydrogen. With the present view that cosmic-ray particles, on the average, have passed through about 3 g/cm^2 of hydrogen, the effect on the heaviest particles is clearly large, and a far more extensive knowledge of the fragmentation parameters is needed, in addition to better experimental statistics.

Our intention, in this Letter, has been to draw attention to a powerful new technique for cosmic-ray studies and its first results. The various figures which have been given, even in the absence of reliable values of fragmentation parameters, permit us to estimate definite lower limits to the fluxes of the VVH particles, and provide, for the first time, a flux estimate for the charge region $33 \leq Z \leq 40$.

We wish to thank Professor P. H. Fowler of the University of Bristol for his willingness to receive one of us (W.C.W.) into his laboratory to perform the photometric measurements on the Barndoor-II tracks. We also wish to acknowledge the splendid support of the National Center for Atmospheric Research Scientific Balloon Flight Station, Palestine, Texas.

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POLE-EXTRAPOLATION RESULTS FROM $pp \to \Delta^{++}n$ AT 6.6 GeV/c *†

Z. Ming Ma, Gerald A. Smith, and R. J. Sprafka
Physics Department, Michigan State University, East Lansing, Michigan 48823

and

Eugene Colton and Peter E. Schlein
Physics Department, University of California, Los Angeles, California 90024
(Received 25 June 1969)

We present an experimental study of the low-momentum-transfer $\Delta^{++}n$ component of 6424 $pp \to p\pi^+n$ events at 6.6 GeV/c. The π^+p elastic cross sections in the Δ^{++} region are measured by means of several different pole-extrapolation procedures. We find that the conventional Chew-Low extrapolation procedure yields results not in satisfactory agreement with the known on-shell cross sections. We suggest a modified extrapolation procedure which in our case yields results in good agreement with the on-shell values.

The proper extraction of $\pi\pi$ and $K\pi$ scattering cross sections from πp and Kp experimental data is a subject of increasing importance in many high-energy experiments. Lack of sufficient statistics in single-momentum experiments and ambiguities in pole-extrapolation procedure provide compelling reasons to study pp reactions from which the already known πp elastic cross sections can be obtained. These pp studies would allow, for example, a determination of the minimum statistics necessary to get reliable results and a comparison with the results using several different extrapolation procedures. In short, until it can be shown that πp cross sections can be reliably extracted from pp experiments, the credibility of $\pi\pi$ and πK results will be in doubt. We present in this Letter results of a study of the $(p\pi^+)$ effective-mass and momentum-transfer dependences of the reaction

$$pp \to p\pi^+n \qquad (1)$$

at 6.6 GeV/c from which the elastic π^+p on-shell cross sections are successfully obtained in the Δ^{++} region.[1]