Composition of Primary Cosmic Rays above 10^{13} eV from the Study of Time Distributions of Energetic Hadrons near Air-Shower Cores

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An experimental study of the distribution of arrival time of energetic hadrons relative to associated air-shower particles has been made at a mountain altitude, under 730 g cm^{-2}. Monte Carlo simulations have shown that these observations are sensitive to the composition of primary cosmic rays of energies 10^4–10^6 GeV. The energy spectra dN/dE of primary protons and iron-group nuclei required to understand these observations are $1.5\times10^4E^{-2.71\pm0.06}$ and $1.27E^{-2.36\pm0.06}$ m^{-2} sr^{-1} sec^{-1} $(GeV/N)^{-1}$, respectively, where E is the energy per nucleon.

Recent measurements[1-6] of the energy spectra of primary cosmic-ray nuclei for energy per nucleus from 100 to 5000 GeV indicate a spectrum for iron group nuclei which is flatter than those of protons and other nuclei. This observation has great significance not only for theories of the origin, acceleration, and propagation of cosmic rays,[7] but also for particle physics. If the spectra were to extend to higher energies without a change of spectral indices, iron-group nuclei would become dominant at air-shower energies of 10^6 GeV, and would significantly affect conclusions derived from air showers regarding particle physics. Interpretations of air-shower observations such as rapid longitudinal development,[8] high muon to electron ratio,[9] fluctuations in the number of muons for fixed shower size,[10] and paucity of high-energy hadrons[11] would not require dramatic violations of scaling in the fragmentation region at these energies. A changing composition, in which the role of the heavier nuclei is increasing with energy, would provide a natural explanation of muon charge ratio[12] and multiple muons.[13]

This paper reports results obtained from a study of arrival-time distributions of energetic hadrons near air-shower cores. The study shows that the experimental data imply a continuation of the spectral indices obtained at lower energies into the energy range 10^4 to 10^6 GeV.

The experiment was carried out at the Sacramento Ridge Cosmic Ray Laboratory of the University of Maryland, located at Sunspot, New Mexico (730 g cm^{-2}), during the period April 1975 to May 1976. The experimental arrangement,[14] shown in Fig. 1, consists of an ionization calorimeter of area 4 m^2 and depth of 940 g cm^{-2} of iron absorber. There are four scintillators which measure the shower-particle density. Two are placed directly above the calorimeter, and have a total area of 3.2 m^2; these are also used for timing. The other two are located about 3 m from the center of the calorimeter.

A plastic scintillation detector, $T3$, of area 0.55 m^2 and thickness 12.7 mm, samples the hadron cascades traversing the central area of the calorimeter. The detector $T3$ is placed inside the calorimeter under 15.7 radiation lengths of iron, and is thus well shielded from shower particles and side showers.

All the detectors are calibrated using near vertical relativistic muons. Their output charges are digitized and recorded for triggered events.

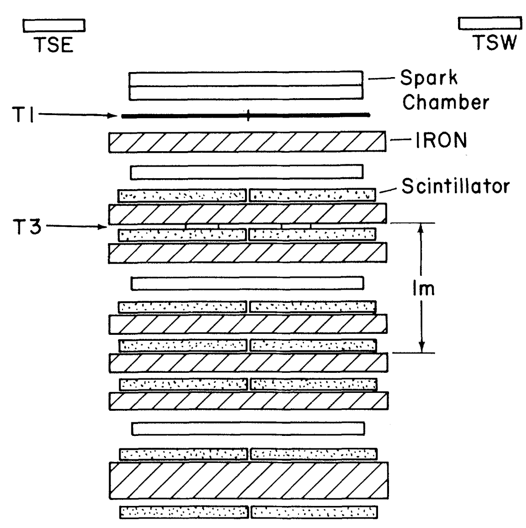

FIG. 1. Schematic diagram of the experimental apparatus. The detector $T3$ is 2 ft×3 ft, its width (length) being indicated on the diagram by the inner (outer) two vertical lines. Detector $T1$ measures shower density and relative arrival time. Detectors TSE and TSW record shower density only.

The relative timing of the leading edges of discriminator pulses from $T3$ and two of the shower detectors are measured for each event. Thus the electronics records the earliest hadron in $T3$. The time resolution of the timing system was determined to be < 9 nsec (full width at half maximum) using single high-energy hadrons traversing these counters. Four wide-gap spark chambers SCB, SC1, SC2, and SC3 placed above and inside the calorimeter provide visual information about hadron cascades in the calorimeter. All counters, photomultipliers, and cables were shielded to eliminate noise from the spark chambers.

The trigger requirement for events accepted for analysis was threefold: (1) shower-particle density greater than a minimum number of particles per square meter, d_m; (2) pulse height in $T3$ exceeding a minimum number of particles, N_m; and (3) energy deposited in the calorimeter greater than 50 GeV. The energy requirement combined with the density requirement selects showers with cores near the detector.

Data were collected in two groups: Group I, corresponding to $d_m = 4$ particles/m^2 and $N_m = 25$ particles; and Group II, requiring $d_m = 18$ particles/m^2 and $N_m = 3$ particles. The number of events collected in Groups I and II were 9135 and 21 477, respectively, with exposure factors corresponding to 7.65×10^6 and 1.16×10^7 m^2 sr sec.

The observed arrival-time distribution for Group II is shown in Fig. 2 as a plot of delay versus particle number in $T3$. We note the absence of events with negative delays (right-hand side) outside of the resolution and a delay distribution extending up to about 80 nsec with pulse heights between 5 and 20 particles. The number of events with delay greater than 15 nsec and pulse height above 5 particles was found to be 118 corresponding to $(0.55 \pm 0.05)\%$. No delayed events are seen with pulse heights greater than 25 particles. In Group I (not shown), because of the higher (> 25 particles) $T3$ threshold we do not observe the delayed tail except for 3 anomalous events with large delay and large pulse height, which are discussed elsewhere.[14] A detailed examination and estimation of the contribution of electronic and other physical (e.g., local production of neutons, antinucleons, pions, and nuclear fragments) background has shown them to be negligible ($< 2\times10^{-5}$ per event).[14] Delayed hadrons have been observed in previous experiments.[15,16]

To interpret these results, it is necessary to determine the relative effectiveness of different species of primary cosmic-ray nuclei in generating an event trigger and the fraction of events with delayed hadrons for each species. A four-dimensional Monte Carlo calculation of the cascade through the atmosphere was made and the experimental detection simulated. The Monte Carlo computations assumed a scaling model for hadron production in hadron-nucleus collisions based on CERN Intersecting Storage Rings and Fermilab results for inclusive cross sections,[17] increasing hadronic cross sections,[18] and a superposition model to generate cascades due to nuclei (they were considered as A-independent nucleons with energy E/A).[19] The inclusive production cross section is assumed to have a form, $e^{-bx}e^{-ap_t}$, where x is the Feynman variable. The values for the b parameter have been chosen as 11 for baryons, 4.5 for π^+ and K^+, and 5.5 for π^- and K^- for nucleon interactions. The corresponding values for pion and kaon interactions are taken as 11, 2.5, and 3.4, respectively. For leading nucleons, the x value is picked from a flat distribution between 0 and $x_{\max}$, with negative values given to the target nucleon. The x values for the leading pions and kaons are picked from a step distribution with an average x of 0.28. Baryon-antibaryon production is assumed to increase with energy as $0.0164 \ln(1 + 0.015E_{\text{lab}})$, where E_{lab} is in GeV.[10,16,19] All hadrons are followed down to 3 GeV unless they decay. The contribution of each photon to

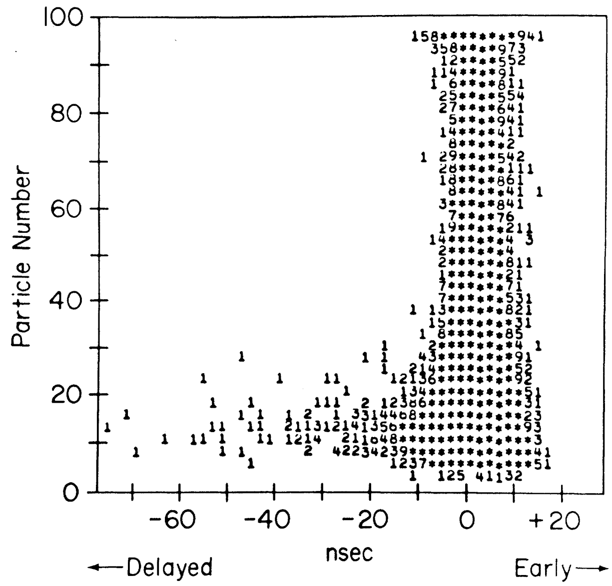

FIG. 2. A plot of hadron time delay (the difference between times recorded by $T1$ and $T3$) vs equivalent number of minimum-ionizing particles in $T3$. The total number of events in the plot is 21 477.

the shower size is calculated in Approximation B,[20] and the contribution of each photon to the shower density at the location of each hadron is calculated using a modified Nishimura-Kamata-Greisen lateral distribution.[21]

The number, $N(E,A)$, of hadrons per air shower satisfying the selection requirements of either Group-I– or Group-II–type hadrons is then determined separately for various primary energies, E, and different primary nuclei with A nucleons. The results show that at the same energy per nucleon showers initiated by iron nuclei are almost 1600 times more efficient in producing event triggers of Group II than showers initiated by protons. In simulating the actual experimental trigger, experimental time resolution is imposed and hadron energy is converted to $T3$ particle number using experimental observations for cascade fluctuation.[22]

The results are used to calculate the contribution to the trigger rate from each primary species, for varying spectral indices. The absolute value of the fluxes are obtained from experimental measurements at lower energies. These energies correspond to a total energy per nucleus of 500 GeV for protons, 2000 GeV for α's, 1500 GeV for CNO, and 1200 GeV for iron. Since the low-energy data show no statistically significant difference between the spectral indices of protons, α's, and CNO, they have been assumed to be the same. The calculations showed that the observed hadrons are generated by primary protons with energies between 10^4 and 10^5 GeV and by iron nuclei with total energies between 10^5 and 10^6 GeV.

The results of the Monte Carlo simulations show that proton-initiated showers produce a negligible number of hadrons with delays greater than 15 nsec and pulse heights larger than 5 particles. On the other hand, under Group-II trigger conditions $(1.25 \pm 0.4)\%$ of the hadrons detected in showers produced by iron primaries are delayed. Showers initiated by α and CNO-group nuclei contribute a much smaller fraction of delayed hadrons than do iron-initiated showers. Therefore, iron-group nuclei must contribute $0.4^{+0.2}_{-0.1}$ of the observed flux in Group II to account for the 0.55% delayed events observed.

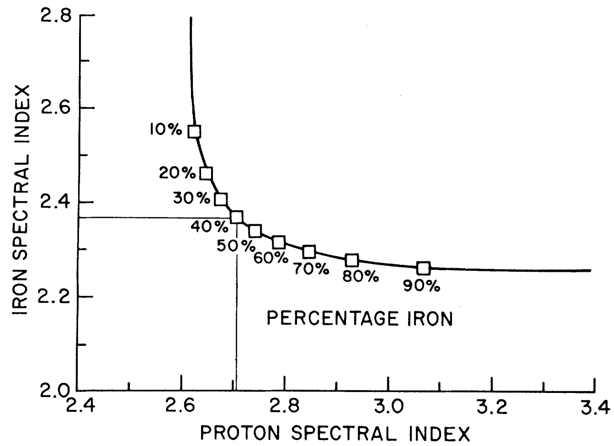

FIG. 3. Iron spectral index vs the spectral index for protons and others. Lines indicate indices implied by time-delay data.

The simulation results for total trigger rate can be summarized by calculating the spectral-index contour for allowed values of spectral indices for protons (and others) and iron group which are consistent with the total observed rate of Group-II triggers. This is shown in Fig. 3. A point on this curve simultaneously specifies an iron spectral index, the index for protons and others, and the fraction of observed triggers which came from iron primaries. Note that Fig. 3 implies lower bounds on the proton and iron indices of 2.55 and 2.25, respectively, purely from rate considerations.

Finally, combining the requirement imposed by the fraction of delayed hadrons with the rate contour in Fig. 3 we find the spectral indices for protons, α's, and CNO to be -2.71 ± 0.06 and for the iron group to be -2.36 ± 0.06. By using these indices, we can also predict the trigger rate for Group-I events; this prediction is consistent with our data. The smallness of the errors in the indices is a consequence of the large energy span between the highest primary energies measured directly and the primary energies which produce our detected hadrons.

The results of this analysis are the following fluxes:

$$(dN/dE)_{\text{protons}} = 1.5 \times 10^4 E^{-2.71 \pm 0.06}\ \text{m}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}\ \text{GeV}^{-1},$$

$$(dN/dE)_{\text{Fe group}} = 1.27 E^{-2.36 \pm 0.06}\ \text{m}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}\ (\text{GeV}/N)^{-1},$$

for energies of 10^4–10^6 GeV, E being the energy per nucleon in GeV. If these spectra were extended up to 10^{16} eV, the percentage of iron nuclei in primary cosmic rays would be greater than 90%.

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