COMPOSITION OF PRIMARY COSMIC RAYS NEAR THE BEND FROM A STUDY OF HADRONS IN AIR SHOWERS AT SEA LEVEL

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ABSTRACT

Data on hadrons in air showers arriving at sea level in College Park, Maryland have been studied to find sensitivity to primary cosmic ray composition. The rate of showers which satisfy minimum shower density and hadron energy requirements as well as the rate of showers containing hadrons delayed with respect to the electron shower front are compared to Monte Carlo simulations. The data on the rate of total triggers and delayed hadrons are compared to predicted rates for two models of primary composition. The data are consistent with models which require an increasing heavy nuclei fraction near 10^{15} eV. The spectra which are consistent with the observed rate are also compared to the observed shower size spectrum at sea level and mountain level.

1. Introduction. In this paper we present analysis of a two year run of the Delayed Hadron Experiment at sea level in College Park, Maryland. Four segmented ionization calorimeters (Figure 1), each of area ~1.5m^2 were used to study the energy and arrival time distribution of hadrons near the core of

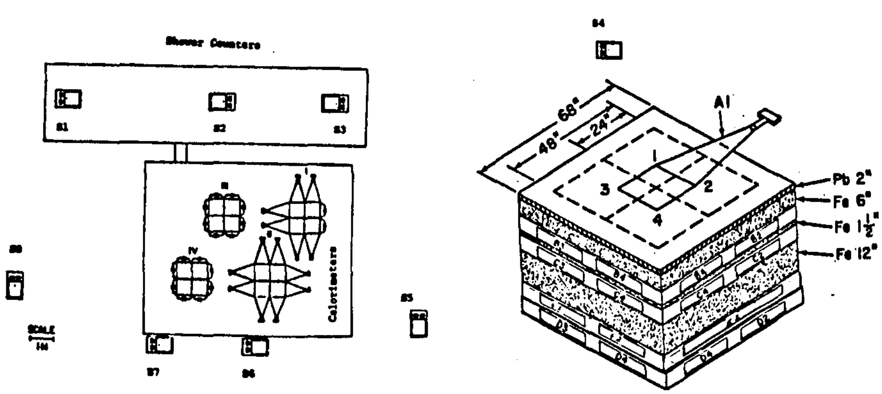


Figure 1: Experimental layout Calorimeter profile

extensive air showers. A small air shower array of 12 scintillation counters located near the calorimeters were used to record the density and arrival time of the electromagnetic component of the air shower. The details of the design of this experiment have been presented elsewhere.[1]

2. The Experiment. Events were required to pass the following offline cuts in order to be included in our data sample: 1) A signal greater than 75 equivalent particles must be recorded in the top layers of at least one hadron calorimeter. 2) The average shower density in the four counters "A" directly above the calorimeters must have an average density of greater than 13.5 ptls/m^2 and at least two of the four counters must equal or exceed this density. 3) All four A counters must have fired a timing discriminator set at 0.1 particle and shown a timing signal consistent with the other shower counters.

Signals were recorded at four depths in each of four quadrants in all calorimeters. The arrival time of a signal > 3 equivalent particles was recorded for three of these counters within each quadrant. Data from the B layers (located under 150 gm/cm^2) are displayed in Figure 2 as a scatter plot of B signal against arrival time relative to the A counter above it. Events in which the hadronic counter signal is large are consistent with a resolution of 2.5 ns. The data show several events with large signal and delay (these are described in detail in paper HE 6.2-7 of this conference) as well as a significant tail of low signal delayed events.

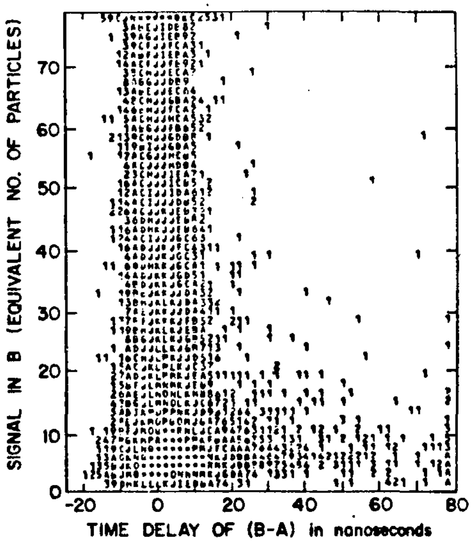


Figure 2

The rate of events passing all offline cuts is 3.15 ± .04 events per hour. The rate of events which contain at least one calorimeter counter delayed by greater than 20 ns and having a signal greater than 20 equivalent particles is 0.050 ± 0.004 events per hour. These two event rates are compared to simulations for various compositions in the next section.

3. Simulation of the Experiment. In order to interpret the data taken in this experiment it is necessary to compare it to a Monte Carlo calculation which simulates the interaction of cosmic rays in the atmosphere and the response of our detector to these particles. The details of the air shower simulation used have been given elsewhere.[2] In this paper we shall give a brief description of the simulation.

The program generates air showers in energy intervals from E_0 to $2E_0$ on a spectrum with a slope of $E^{-2.6}$. The data from each of these intervals may then be combined in different proportions to produce different spectra. Over the range of spectral indecies investigated in this work this method produces a smooth spectrum. Nuclei of atomic number A are simulated using a superposition model where A nucleons are generated at the same angle and energy. The simulation uses a cross section which increases with energy for nucleon air interactions.

Interactions are simulated using a modified scaling model in which the rise in central rapidity density seen at the SPS collider is included by steepening the X distribution of produced secondaries in an energy dependent manner. The Monte Carlo includes production of nucleon anti-nucleon pairs as well as pions and kaons. Leading particle effects are included for various projectiles and the effect of nuclear targets is simulated. All hadrons are followed from their production until they either reach detector level, interact, decay or drop below 2 GeV. The electromagnetic shower is calculated by accumulating each gamma ray produced in a meson decay. The gamma rays are then projected to detector level using approximation B[3] and the lateral spread of their showers is computed using a modified NKG[4] lateral distribution function. The information on both the hadrons and electromagnetic shower are written out on to tape where they are fed into our detector simulation program.

For each hadron which reaches detector level in our simulation we store its energy, position, particle type, momentum, arrival time, and local shower density. The response of our detector to each incident hadron and its accompanying electromagnetic shower is simulated. The number and distribution of triggers and delayed events are computed by applying offline cuts to the simulated data. We then compute an efficiency for triggering for each primary species and energy interval. The simulation of detector response is accomplished by comparison with direct calibration and Monte Carlo calculation.[5]

4. Comparison of Data and Simulation. This experiment provides a set of experimentally measured quantities which may be compared with simulations to test various composition models. It does not measure primary composition directly. Those models which predict rates which are inconsistent with our measured rates can be ruled out within the context of the high energy physics model used. It is important to note that by the use of models which predict significant deviations from observed interaction properties above measured energies different results may be obtained. In this paper, we compare our data to a high energy model which requires a minimum extrapolation from observed data. We also attempt to use models for primary spectra which are consistent with extensive air shower data.

The two models which we consider here represent divergent theories of cosmic ray propagation. In the first (model Md), the spectrum of the light and medium nuclei are assumed to be that given by the JACEE Experiment[6] while the spectra of the heavy nuclei (Si and Fe) are chosen to be somewhat flatter up to a rigidity dependent steeping, resulting in an increasing fraction of heavy nuclei. In the second model (model L), we follow the proposal of Linsley[8] in choosing a proton dominant composition which contains a flattening of the proton spectrum at 10^{14} eV. In Table 1 we list the parameters of each of these models. In Table 2 we present the predicted rates for this experiment for each model.

5. Results. The results of the comparison between our experimental data and our Monte Carlo simulation show that model Md of primary composition which has a significant enrichment of heavy nuclei near the break fits both our trigger rate and delayed event rate. Model L would produce a trigger rate 60 percent above the observed value while producing only 50 percent of the fraction of delayed events observed.

Model Md has been shown to be in agreement with our predicted rates for trigger rate and for delayed event rate. It has also been shown elsewhere to be consistent with measured muon distributions. This model is used to compute the expected flux of air showers at sea level and mountain level. Figure 3 shows these results. The discrepency between the simulation and the reported data[8,9] is consistent with the spread between various measurements.

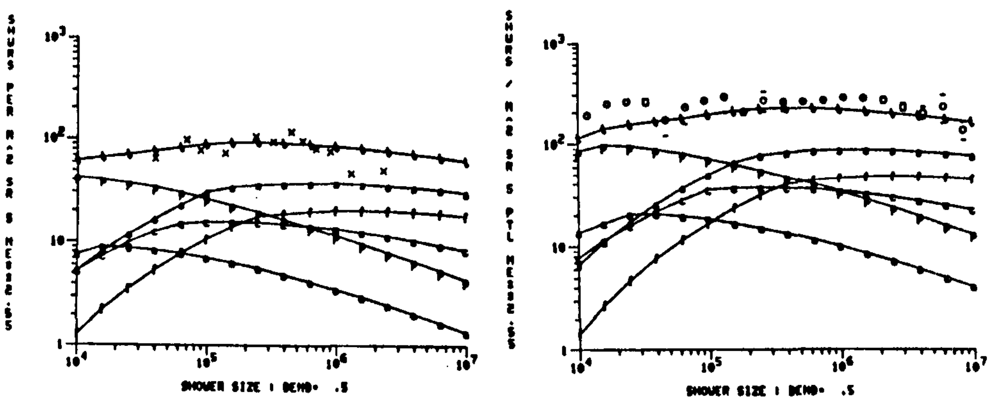
Table 1
Composition Models

	Slope (below break)	Break rigidity	Slope (above break)
Model Md			
Protons	-2.75	200 TV	-3.3
Alphas	-2.78	200 TV	-3.3
C-N-O	-2.6	200 TV	-3.2
Silicon	-2.55	200 TV	-3.1
Iron	-2.55	200 TV	-3.1
Model L			
Protons	-2.7	100 TV	-2.5 up to 10,000 TV then -3.1
Alphas	-2.7	500 TV	-3.1
C-N-O	-2.7	500 TV	-3.1
Silicon	-2.75	500 TV	-3.1
Iron	-2.75	500 TV	-3.1

Table 2
Rate Predictions

Model	Event Rate (per hour)	Delayed Event Rate (per hour)	Fraction Delayed
Data	3.15 ± .04	0.050 ± 0.004	0.016
Md	3.2	0.05	0.015 *
L	5.1	0.04	0.008

* The Md model was chosen to give the best fit to this data.



Sea level Mountain level

Figure 3: Vertical shower flux: x = sea level data, 0 = mountain level data, t = sum of simulated species

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