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Cosmic Rays and Particle Physics--1978
(Bartol Conference)

Edited by
T.K. Gaisser

American Institute of Physics

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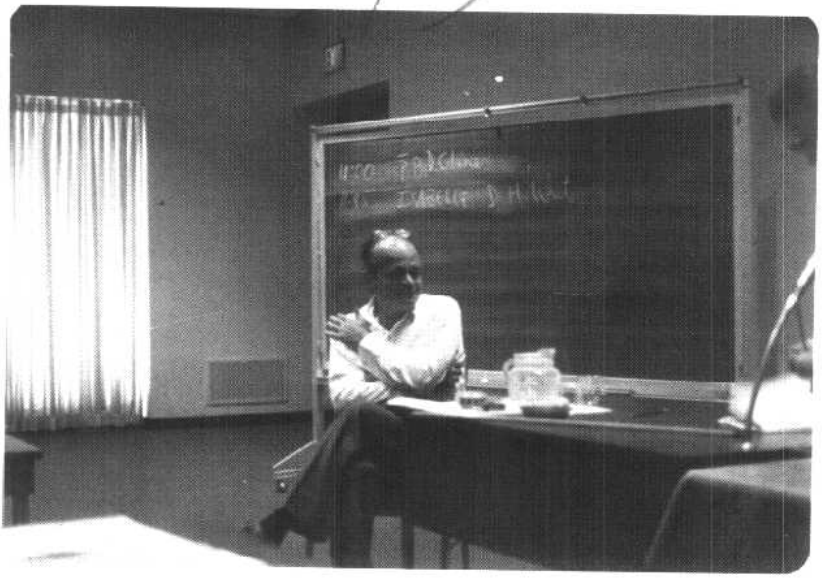

C. M. G. Lattes chairing the session on new accelerators

Carlo Rubbia summarizing the Conference

FOREWORD

About 100 physicists attended the meeting at the Bartol Research Foundation, University of Delaware, Newark, Delaware, 16-21 October 1976. Participants were roughly equally divided between the fields of particle physics and cosmic rays. The theme of the meeting was the interaction between these fields, with emphasis on particle interactions above 10 TeV. The problem of cosmic ray composition above 10^{13} eV was also discussed, and plans for new cosmic ray and accelerator experimental facilities were presented. The schedule of the meeting had three parts: 16-18 October, detailed discussions and talks on emulsion chamber experiments and extensive air showers; 19 October, Workshop on Charm Particle Production and Lifetimes; 20-21 October, Topical Conference on Cosmic Rays and Particle Physics.

Primary support for the meeting was provided by the U.S-Japan Cooperative Science Program of the National Science Foundation and by the Japan Society for the Promotion of Science under a bi-national agreement. A delegation of 13 cosmic ray physicists from Japan and 12 U.S. participants attended the meeting under this program. Publication of the proceedings is supported by the U.S. Department of Energy, which also provided some supplementary funds for the Topical Conference. The meeting was sponsored and also partially supported by the Bartol Research Foundation and by the Physics Department of the University of Delaware through funds from the UNIDEL Foundation.

It is a pleasure to acknowledge the advice and assistance of the advisory committee, the local committee and the session chairmen (all listed on the preceding page) in many aspects of organizing and running the meeting. I am particularly grateful to Professor T. Yuda, the Japanese coordinator, to Professor S. Miyake for a memorable after-dinner toast and to Gaurang Yodh, who, in addition to advising on the program, acted variously as photographer, projectionist and chauffeur. I am also grateful to Mr. David Bartley of the Clayton Hall Conference Management for arrangements during the meeting, and I am especially grateful to Helen Kryka for valuable assistance in editing these Proceedings. Finally, I would like to thank Martin A. Pomerantz for his apt welcoming remarks which opened the meeting and Carlo Rubbia for his valuable summary which ended it.

T. K. Gaisser

January, 1979

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A subset of participants

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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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ABSTRACT

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 of 730 $g.cm^{-2}$. Monte Carlo simulations of the expermental observations have shown that these observations are sensitive to the composition of primary cosmic rays of energies $10^{13}-10^{15}$ eV. The energy spectra of primary protons and iron group nuclei required to understand these observations are

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

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

respectively, where E is energy per nucleon, indicating that iron group nuclei are the dominant component of primary cosmic rays at air shower energies of $10^{14} - 10^{16}$ eV.

INTRODUCTION

Recent measurements[1-6] of flux and energy spectra of protons and various nuclei in primary cosmic rays for total energies of 100 to 5000 Gev suggest that the iron group nuclei have an energy spectrum considerably flatter than protons and other lighter nuclei. The index of the power law energy spectrum has been measured to be about −2.3 for iron group nuclei, compared to −2.75 for protons. These observations have far reaching significance[7] for theories of origin and propagation of cosmic rays. These results also have interesting implications for interpretations of many air shower observations since they indicate that iron group nuclei dominate

This work constituted in part the Ph.D. thesis of J. A. Goodman, University of Maryland, August 1978
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the primary cosmic ray flux at air shower energies of 10^{15} - 10^{16} eV. Experimental observations such as rapid longitudinal development of air showers[8], high muon to electron ratio[9], and paucity of high energy hadrons[10] in air showers have been interpreted to indicate significant violation of scaling characteristics in high energy interactions[11], implying the onset of some new phenomenon at very high energies. Similar remarks apply to observations of multiple muons[12] and muon charge ratio[13] at high energies. However, these analyses have usually assumed protons to be the dominant component at these energies. Therefore any experimental confirmation of continuation of relative spectral differences between protons and iron group nuclei at air shower energies would be very significant and would lead to better understanding of high energy interactions at these high energies.[11] Direct observations in satellite borne experiments, though desirable, are difficult due to limitations imposed by the size and weight of the instrumentation required.

We present results obtained from a study of arrival time distributions of hadrons in air showers which suggest that the composition of primary cosmic rays is continuing to change with energy above 10^{13} eV. We show that a best fit to the experimental data requires the energy spectrum of iron group nuclei to have a power law exponent of 2.36 ± 0.06 compared to an exponent of 2.71 ± 0.06 for protons in the energy range of 10^{13} - 10^{15} eV.

APPARATUS

The experiment was carried out at the Sacramento Ridge Cosmic Ray Laboratory of the University of Maryland located at Sunspot (2900 meters or 730 $g.cm^{-2}$ altitude) in New Mexico during the period April 1975 to May 1976. The experimental arrangement is shown in figure 1 and has been discussed in detail elsewhere[14]. The apparatus basically consists of an ionization calorimeter of area 4 m^2 and depth of 940 $g.cm^{-2}$ of iron absorber. The hadron cascades are sampled by seven layers of liquid scintillation detectors. There are four shower particle detectors. Two of them, T1E and T1W, are placed above the calorimeter and have a total area of 3.2 m^2. The other two shower detectors, TSE and TSW, are located at about 3 meters from the center of the calorimeter on opposite corners. The detectors T1 measure the shower particles density above the calorimeter and time the arrival of shower particles.

A plastic scintillation detector T3 of area 0.55 m^2 and thickness 1 cm viewed by a 56AVP photomultiplier through an air light guide samples the hadron cascades traversing the central area of the calorimeter. The detector T3 is placed under 15.7 radiation length (220 $g.cm^{-2}$ of iron) inside the calorimeter and is thus well shielded from shower particles. This detector is also unaffected by side showers due to its small size relative to the calorimeter area. This detector measures the arrival time of the hadron relative to shower particles as detected by the T1 detector. In cases where two or more hadron cascades traverse the detector T3 in the same air shower, arrival time of the earliest hadron only is measured.

All the calorimeter detectors, T1's, TS's, and T3, are calibrated using near vertical relativistic muons. Their pulse amplitudes are digitized and recorded for selected triggered events.

Four wide gap spark chambers SCB, SC1, SC2, and SC3 placed above and inside the calorimeter provide valuable visual information about hadron cascades in the calorimeter. A transition radiation detector consisting of a 24 layer sandwich of styrofoam radiators and proportional chambers, each of 1 m^2 area, was located above the spark chamber SCB, but was not used in the present experiment and is not shown in figure 1.

DATA

The experimental data was collected basically in two groups with different selection criteria. The group I data selected all showers with particle density Δ_e above the calorimeter greater than 18 m^{-2} which also had 5 or more particles traversing the detector T3. The particle density threshold was lowered to 4 m^{-2} for data group II, but a higher pulse amplitude corresponding to traversal by 25 or more particles was required from T3 for selection. For both data groups a minimum of about 50 Gev energy release in the calorimeter was required. A total of 21,500 events were collected for group I with an exposure area factor of 1.35×10^7 m^2 sr sec. The group II data had 9150 events collected with an exposure area factor of 8.44×10^6 m^2 sr sec.

The observed arrival time distribution for hadrons of data group I is shown in figure 2 as a diplot of arrival delay versus the signal amplitude of the detector T3. It is of interest to note that there are no events on the negative delay (tachyon) side, indicating the absence accidental events. This is as expected from calculations using observed detector rates. This time distribution shows a long delay tail with 0.55 ± 0.05 percent of the events having delays larger than 15 ns and pulse amplitude in T3 greater than 5 particles. A similar distribution for events of data group II shows no delayed tail, primarily due to the T3 detector threshold being as high as 25 particles. However, there are 3 events with large delay (~15 ns) and large pulse amplitude (~35 particles) in data group II which are discussed elsewhere[14]. A detailed examination[14] of various electronic and physical effects (like evaporation neutrons, nuclear fragments, stopping antinucleons, etc.) has indicated the background which could generate a delayed event to be negligible (2×10^{-5} per event). These delay distributions are very similar to those observed in earlier experiments[15,16], but an exact comparison is not possible due to different selection requirements in different experiments.

MONTE CARLO SIMULATION

For interpretation of experimental results, a detailed simulation of the experiment was carried out using the Monte Carlo method. This 4-dimensional simulation generates atmospheric air showers from primary high energy protons and various nuclei. For generating showers due to primary nuclei (atomic no. A), the superposition model (A nucleons of energy E/A each) is assumed. Hadron-air nuclei interaction cross-sections are considered to be increasing with energy[17]. Hadron-nuclei interactions are assumed to be essentially hadron-nucleon interactions and effects due to intranuclear cascading are ignored. Hadron-nucleon interactions are generated using the independent particle scaling model incorporating various results obtained in accelerator experiments at Fermilab and ISR. The inclusive production cross-section is assumed to have a factorizable form as

$$E \frac{d^3\sigma}{d p^3} \propto e^{-bx} \cdot e^{-ap_t}$$

where x is the Feynman variable ($= 2p_\parallel/\sqrt{s}$), $p_\parallel$ and p_t are the cm longitudinal and transverse momenta, and s is the square of the cm energy. The values for the parameter b 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 11, 2.5, and 3.4 respectively. For the leading nucleons, the x value is picked from a flat distribution between 0 and x_{max}, with negative value assigned 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 as suggested by observations in Fermilab experiments. Energy and momentum are conserved on the average. Secondaries are produced in the ratio $\pi : K = 0.90 : 0.10$, while baryon (p, $\bar{p}$, n, $\bar{n}$) production is assumed to increase with energy as $0.0164 \ln(1 + 0.015\, E_{lab})$, where E_{lab} is the energy of the interacting particle in Gev. This form of increase is indicated by accelerator[19] and cosmic ray experiments[10,16]. All hadrons are followed down to 3 Gev unless they decay. For each photon resulting from the decay of a π^0, the contribution to shower size at observational level (730 g.cm^{-2}) is calculated using expressions given by approximation B of cascade calculations. The shower particle density at the location of each hadron at the observational level is calculated using a modified NKG lateral distribution function[20].

To simulate the experiment as closely as possible, each hadron arriving at the observational level is assuumed to be incident on a calorimeter. Its contribution, in terms of number of particles, is computed for a fictitious detector, 'T3', similarly placed as T3. Fluctuations in cascade development in the calorimeter, as observed experimentally[21], are taken into account in this computation. The arrival delay of the hadron relative to super-relativistic particles, as given by the simulation, is also fluctuated according to the observed instrumental time resolution[14].

The energies of all the hadrons incident over a 4 m^2 area around the hadron incident on T3 are summed together. As in the experiment, in case of two or more hadrons incident over the T3 area, the arrival time of only the earliest hadron is considered.

Thus, the simulation gives the number of particles in 'T3', the shower density at the 'T3' location, and the total energy in 4 m^2 area around 'T3' for each hadron arriving at the observational level. This set of computed values allows selection of simulated hadrons with the same criteria as used in the experiment. 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, A. The variation of N with primary energy for group I type hadrons is shown in figure 3 for various primary nuclei. It should be noted from this figure that at an energy of 20 Tev/n showers initiated by iron nuclei are almost 1600 times more efficient in producing a hadron of group I type than showers initiated by protons. This factor is only 250 for group II type hadrons due to the requirement of higher energy for this group.

Combining these calculated factors, N(E,A), for various energies and various nuclei with extrapolation of measured[2] energy spectral slopes and fluxes normalized at an energy of 1 Tev/n, contributions to the observed number of events by each component have been computed. These calculations show that observed hadrons are generated by primary protons of energies 10 - 100 Tev and by primary iron nuclei of energies 2 - 40 Tev/n for both data groups. The energy range for other nuclei like the CNO group lies between the values for protons and iron nuclei. The energy spectra for α-particles, CNO nuclei, and medium heavy nuclei have been assumed to have the same spectral index as protons, since direct measurements[2-6] have not shown any significant spectral difference between these components at lower energies (10 - 100 Gev/n).

Similar computations have been carried out for various different assumed values of the power law indices assigned to the energy spectra of protons and iron nuclei, again with flux values normalized at an energy of 1 Tev/n to values observed directly or extrapolated from lower energies.

The simulations show that group I contains an appreciable contribution from iron primaries, while events of group II are generated preferentially by proton primaries. However, the relative contributions depend on the values of spectral indices assumed for the energy spectra of proton (and lighter nuclei) and iron nuclei.

In figure 4 is shown the spectral index contour curve for allowed values of spectral indices which are consistant with the observed flux of events of group I. This curve shows, for example, that the observed flux requires the spectral index of iron nuclei to be -2.36 if the proton spectral index is -2.71. A similar curve has also been obtained for events of group II type and predictions from the two data groups agree with each other within a value of 0.05 for the spectral indices.

DELAYED EVENTS

The preceding discussion shows that the observed flux of events of group I or II can only restrict the values of the spectral indices of the two components in primary cosmic rays to the allowed values which parameterize the curve in figure 4. However, an extimate of the spectral indices can be obtained by comparing the observed and expected time delay distributions for hadrons of group I. As mentioned earlier, the observations show 0.55 $\pm$ 0.05 % ov the events with $>$ 5 particles in T3 to be delayed by 15 ns or more. The simulations show that the proton-initiated showers generate a negligible number of events with these delay and energy characteristics. On the other hand, the iron-nuclei-initiated showers give 1.25 $\pm$ 0.4 % of hadrons with these characteristics. Showers initiated by α -particles, CNO group, and medium heavy nuclei contribute relatively a much smaller proportion of delayed hadrons. Using these values for the fraction of delayed events and earlier computations of N and flux for air showers initiated by various nuclei, it is estimated that the iron group nuclei contribute $.40^{+0.2}_{-.1}$ of the observed flux of hadrons in data group I. This value is then used to obtain from the curve in figure 4 the spectral indices for protons (as well as α and CNO) and iron group nuclei to be -2.71 ± 0.06 and -2.36 ± 0.06, respectively. Note that figure 4 implies lower bounds to proton and iron spectral indices of 2.55 and 2.25, respectively, purely from rate considerations.

CONCLUSION

We find that the relative proportion of iron group nuclei in primary cosmic rays at energies above 10 Tev continues to increase with increasing energy. Our observations on the flux of hadrons associated with air showers at mountain altitude and their arrival time distribution when comapred with Monte Carlo simulation strongly suggest that the flux and energy spectra for protons and iron nuclei are well represented by the following expressions:

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

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

for energies of $13^{13} - 10^{15}$ eV, 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 %. An increasing iron component is necessary for scaling to remain valid for high energy interactions in the fragmentation region up to about 10^{16} Ev. These results would also provide reasonable understanding of observations on muon charge ratio and multiple muons.