HIGH-ENERGY MULTIPLE MUONS AND HEAVY PRIMARY COSMIC-RAYS

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Abstract

The three-dimensional simulations have been carried out on high-energy multiple muons. On their lateral spread, the comparison with the deep-underground observations so far indicates that the primary cosmic rays seems to include heavy nuclei of high content. The calculated results also suggest us a method to determine the average mass number of primary particles in the energy around 10^{15} eV.

1. Introduction

The cosmic-ray composition in the energy around 10^{15} eV provides us with a useful clue to clarify acceleration and propagation mechanism of cosmic rays. However, the restriction of observation limits the direct measurements to a lower energy region. On the other hand, on the informations given indirectly from the observations of very high-energy phenomena in the atmosphere, the reliability has increased, because that the characteristic feature of high-energy interactions has been clarified by the scale-up of accelerators.

According to a systematic study of gamma-ray family phenomena observed with emulsion chambers at Mt. Fuji(1),(2), which gives us one of those indirect informations, the heavy-nuclei content seems to increase in those energy region. This feature is consistent with some observations of extensive air showers(3). In order to investigate further this feature, as described in the previous report(4), we carried out the Monte Carlo simulations on high-energy multiple muons, and compared with the experimental results of deep-underground observations (5),(6). On the lateral spread of multiple muons, which is not much affected by experimental bias, the observations coincide with those calculated under the assumption of the primary cosmic rays with heavy nuclei of high content. For the purpose of the further examination, our simulation study has been continued with the same method. The results suggest us one of a method to determine the average value of mass number of cosmic rays at very high energy.

2. Simulations

The three-dimensional Monte Carlo simulations have been carried out on the high-energy multiple muons which are produced in the upper layer of the atmosphere and reach to the sea level and also to the point of great depth underground(4).

On the nature of hadron interactions in the atmosphere, it is assumed in the simulations that the Feynman scaling is held in the fragmentation region of particle production and the collision cross section increases as increasing of energy corresponding to the $\ln^2 s$ dependence. In the nucleus-nucleus collision, some of nucleons in the incident nucleus interact with the target nucleons and induce multiple productions of pions and kaons. The remaining part of the incident nucleus breaks up into lighter nuclei and nucleons according to an assumed fragmentation probability. In the above assumptions, we adopt almost the same model parameters as those used in the simulations(5),(6) by which the observed feature of gamma-ray families at Mt. Fuji was investigated. The decay probability of charged pions and kaons into muons depends on the atmospheric density. The structure of the atmosphere is determined on the basis of the US standard atmosphere. Also, the effects are taken into account of energy losses and of geomagnetic field.

3. Results and discussions

The lateral distribution of muons in the simulated phenomena was compared with the experimental results of multiple muons obtained at the great depth underground(7),(8) in the previous report(4). The comparison is shown again in Fig. 1. The parameter of lateral spread r_0 has been determined by assuming muon density $\rho(r)$ expressed as the linear exponential form $\exp(-r/r_0)$. As increasing of mass number of primary particles, the average height of muon production increases, and then the lateral spread of multiple muons broadens. The experimental results on the lateral spread prefer the hypothesis of the primary cosmic rays including heavy nuclei of high content to the proton-dominant case. This feature agrees with the information obtained from the emulsion-chamber experiment(1),(2). By using the above comparison, one may determine the average mass number of primary particles. The lateral spread, however, depends on cross section and transverse momentum of interactions. The obtained value of mass number only by the above comparison is, therefore, influenced by

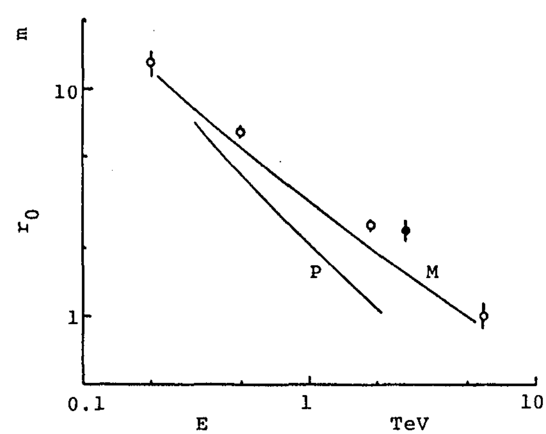

Fig. 1. Energy dependence of the parameter of lateral spread for constituent muons in the multiple-muon phenomena(4). The solid curves represent the simulation results for various values of the threshold energy of muons at sea level E. Two cases are shown of primary cosmic rays: the proton-dominant (P) and the heavy-nucleus-dominant (M) cases. The circles indicate the experimental results at the Kolar Gold Fields(7) (the open circles) and at the Homestake Gold Mine(8) (the solid circles).

their dependence on energy, and includes ambiguity in the assumptions of the calculations.

The figure of energy spectrum of constituent muons in a phenomenon also depends on the mass number of primary particles. The characteristic feature differs with distance from the center of the phenomenon. The spectrum in the case initiated by a heavy nucleus relatively steepens compared to that of a light-nucleus case. In the restricted region within a certain radius near the center, this tendency is much evident. To the contrary, in the region far from the center, the opposite tendency appears. In the intermediate region, the spectral figure does not depend of

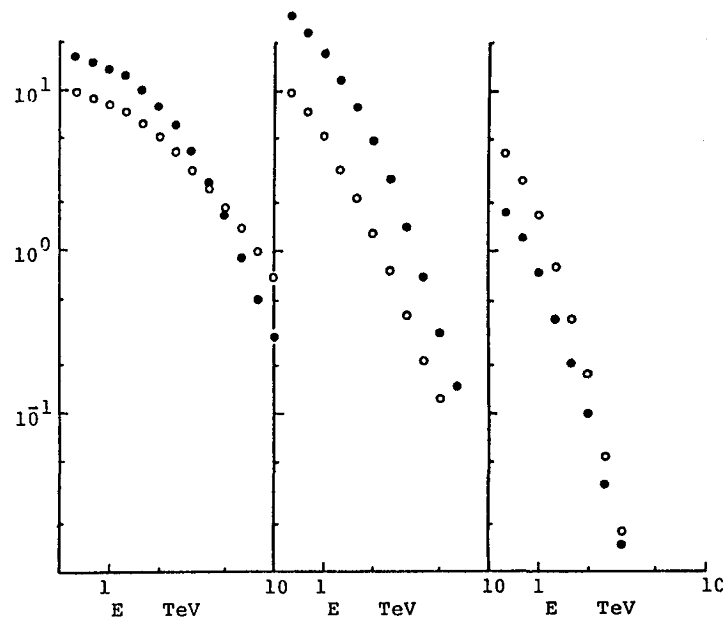

Fig. 2. Integral energy spectra of constituent muons in the multiple-muon phenomena. The circles indicate the simulation results observed at sea level in various ranges, r < 2 m (a), 2 m < r < 6 m (b) and 6 m < r < 10 m (c), for the cases initiated by protons (the open circles) and iron nuclei (the solid circles) with the energy from 10^{15} eV to 10^{16} eV.

the mass number of the primary particle. This feature is shown in Fig. 2. These characteristics allows us to devise a method for determining the average mass number of primary particles. Foe example, if one detects high-energy multiple muons associated with extensive air showers, and measures the energy of their constituent muons in the high-energy region, then he may take the spectra of those muons in various ranges as shown in Fig. 2. The reliability of the calculation and the applied assumptions would be confirmed by examining an agreement between observed and calculated values in the intermediate region where the spectral form does not depend of the mass number of primary particles. The distance of that region shifts according to the assumptions for cross-section value and average transverse momentum, and also the spectral form in that region varies according to the production spectrum in the fragmentation region of hadron interaction. If the assumptions were not appropriate. the observed results would not coincide with the calculated ones. After the above examination in the intermediate region. a comparison is made of the observed spectral form with the ones calculated for various nuclei of primary particles in the central region. Evaluating the possibility, for example, in the observation of about 3 years using a TeV-region spectrometer of about 20 m^2 in scale observing muons with an air-shower array, the average mass number of primary particles can be determined with an accuracy of about 50 % in the energy around 10^{15} eV. Considering the current situation that the direct observation is not much easy. this is one of the methods to be investigated for the measurements of composition of primary particles. We also anticipate the results on high-energy multiple muons obtained from the huge detecters of proton-decay experiments at deep underground. to be compared with our calculated results.

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