Proceedings of the 30th International Cosmic Ray Conference
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Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 39–42

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

The chemical composition of primary cosmic rays in the energy range $\sim 10^{15}$ eV from muon energy spectrum with the Okayama muon telescope

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Abstract: The energy spectrum of muons associated with extensive air shower (EAS) is studied by the synchronized observations with the EAS array and the solid iron spectrometer for muons, in the primary energy range of about 50 TeV - 5 PeV. We have determined muon momentum in EAS for 344 events. As the result, the median energy of spectrum lies on about 10 GeV and its FWHM is 2 to 70 GeV. And the obtained muon energy spectrum is compared with the simulated results. As follows from AIRES air shower simulation program with SIBYLL/HSA for hadronic interaction models assuming both proton and iron+proton for primary cosmic ray compositions, the muon energy spectrum below 20 GeV is well explained in case of the proton dominant composition. Above 20 GeV, the obtained spectrum indicates no significant difference between primary compositions.

Introduction

Studying the properties of EAS particles such as the EAS size, the lateral distribution, the compositions of electrons and muons, and the energy spectrum can provide the information on the hadronic interaction model, the primary energy and the mass composition number of a primary cosmic ray. Therefore, measuring the muon energy spectrum in EAS is one of the tools to explore cosmic ray composition.

In order to determine the chemical composition of primaries, we focus on muon energy spectrum obtained with the solid iron spectrometer in EAS events.

Apparatuses

The EAS array is placed on the roof of the building in Okayama University [1, 2]. It consists of 8 scintillation counters. Each counter is equipped with a scintillator disk, of which size and thickness are 50 cm $\times$ 50 cm $\times$ 5 cm, and a fast photomultiplier. The scintillation counters are set within about 30 m $\times$ 20 m in area (figure 1).

The Okayama muon telescope is installed in the building of the floor just below the EAS array (figure 1). The telescope is a momentum spectrometer and a momentum of incident particle is calculated by the trajectory registered in this detector [3]. It can determine muon momenta ranging from 0.9 to 150 GeV/c and has 1 mrad angular resolution. The acceptance is 24.4 cm^{2}sr. The detail of the arrangement and properties of the detector are shown in reference [4].

For coincidence observation of muons and EAS, the EAS array provides the telescope with the arrival information of EAS particles by on-line. If there is an event in EAS array within 1 μsec from the event observed in the telescope, the event is registered as EAS events by the telescope.

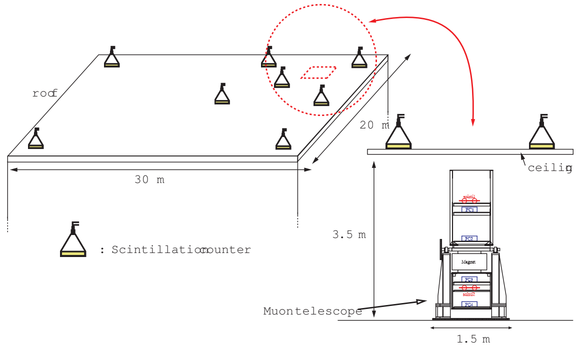

Figure 1: Arrangement of the EAS array (quarter view) and the muon telescope (sectional view).

Data analysis

We used the data from 1/February/2004 to 11/January/2007, the total observational time is 968 days and 7.8×10^5 events are obtained.
To determine each muon momentum, we select observed events with the following criteria.

- All drift chambers register information of an incident particle.
- Trajectories calculated from registered information in chambers above and below the magnet cross in the magnet.

Even if there are more than two trajectories satisfied above criteria at the same time, there are rejected in this analysis, because such an event cannot be reconstructed the trajectory and be determined the momentum. Figure 2-(b) shows the projection of X-Z plane and Y-Z plane of the telescope for a typical event we determined a muon momentum. We have determined each muon momentum for 344 single trajectory events.

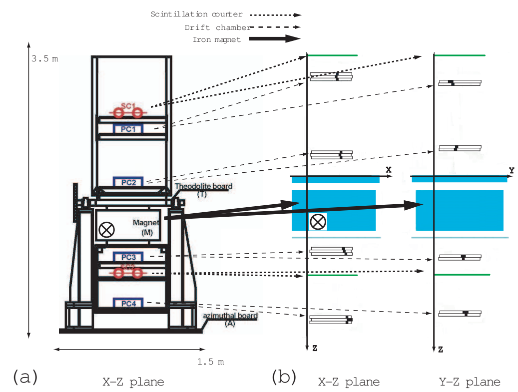

Figure 2: (a): The section of X-Z plane of the telescope. (b): Imaging of a typical event in the projection of X-Z and Y-Z plane of the telescope. Block points in drift chambers indicate registered events.

Simulation

For EAS simulation, AIRES [5] program is used with SIBYLL2.1 and the Hillas Splitting Algorithm. The dependence on the hadronic interaction model for the muon spectrum in EAS have been reported to be weak in reference [6].
Figure figure 3 shows the response function for the apparatuses and this distribution is calculated from

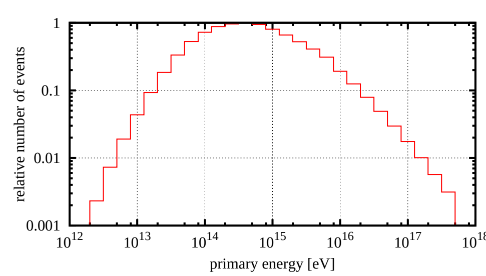

Figure 3: Relative primary energy distribution.

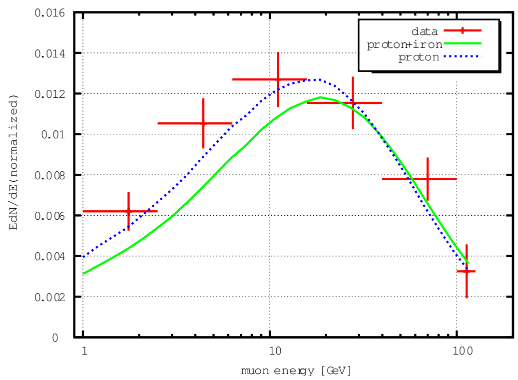

Figure 4: The comparison between the muon energy spectra obtained by the experiment and simulations. The cross marks indicate experimental result. (a): Solid line indicates simulation result (proton+iron) primary. (b): Dash line indicates simulation result (proton) primary.

the effective area for the apparatuses and the primary flux [7]. The energy of primary particles is sampled from figure 3 and FWHM is from about 50 TeV to 5 PeV. The sensitive area in which EAS particles can be detected, is about 1200 m^2 from core position.
The zenith angle of primaries is not necessary to be considered because the telescope narrows the acceptance and limits the zenith angle within about 10 degree. The proportion of the thinning energy to the primary energy is set on 10^{-5}. We assume two cases for the primary composition. One of the case is proton only and another case is the ratio of proton and iron is about 5:1 [8].

Results and conclusions

In figure 4, the cross marks show the experimental data and the error bar shows statistic error. Those distributions are normalized by area which is calculated by integrating each distribution.
For the experiment data, the mean and the median energy of spectrum lie on about 27GeV and 10 GeV, and its FWHM is 2 to 80 GeV. Figure 4-(a) shows the simulation results using proton and iron for primaries. In figure 4-(a), the mean and the median lie on about 38GeV and 10 GeV, and its FWHM is 2 to 78 GeV. Figure 4-(b) represents the simulation results using proton primary. In figure 4-(b), the mean and the median lie on about 38GeV and 10 GeV, and its FWHM is 2 to 68 GeV. For FWHM, (proton+iron) primary is better agreement with the experimental data than the proton primary. The muon energy spectrum below 20 GeV tends to be consistent with the case of the proton dominant composition. Above 20 GeV, the obtained spectrum indicates no significant difference between primary composition.

Acknowledgements

This work was partially supported by the Academic Frontier Project from Ministry of Education, Culture, Sports, Science and Technology in Japan.

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