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What can we study through families and accompanied air showers ?

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At mountain altitudes, high energy γ-ray bundles (γ-rays in parallel one another and with the same direction to an air shower) can be observed in the central part of air showers. These γ-ray ($\geq 1\ TeV$) bundles and also associated air showers are observed simultaneously at Mt. Chacaltaya (5200 m) by our detectors. The γ-ray bundle in the air shower can give information on the primary composition and the characteristics of proton interaction. We report in this paper experimental results, simulations calculated for the present experiments, and also problems in simulations.

1. Introduction

We have been observing bundles of high energy γ-rays in the air shower cores by emulsion chambers in SYS air shower array at Mt. Chacaltaya (5200 m) in Bolivia in international collaboration of Japan and the Univeridad Mayor de San Andres in Bolivia. A unit of emulsion chamber is $50cm \times 50cm \times 15cm$ and consists of 15 layers of 1 cm Pb plates and two sheets of X ray films. Just below each unit, a scintillation particle number detector with the same area as the unit is set to get information to link air showers to γ-ray bundles.

We also have calculated formation of such γ-ray bundles and associated air showers by Monte Carlo simulation assuming phenomenological UA5 algorithm for the nuclear interactions in the atmosphere[1]. The simulation is found to give results which agree with those by other simulations used recently.

According to the present simulation, in the air shower size range $10^5 \sim 10^7$, primary protons produce γ-ray ($\geq 1\ TeV$) bundles, but primary irons can not. The present analyses depend on a limitation of γ-ray bundle formation for different kind of primary particles. Moreover, there are discrepancies between results by the experiment and by the simulation. We shall discuss such problems to be solved.

2. γ-ray bundle formation in air showers

In order to investigate the processes of γ bundle formation in air showers, we follow up all the particles which are produced from a primary proton in each simulated air shower event. Fig.1 shows an example of the event. The event has the primary energy of 2×10^{15} eV, air shower size 8.7×10^5, the total energy of γ bundle 64 TeV,

the number of γ-rays 33. The bundle of γ-rays is produced by a survival proton at 170 g/cm^2 from the top of the atmosphere.

According to the simulation, most of the primary proton energy is used for an air shower formation and γ bundle is produced with the rest of the energy by the following three processes.

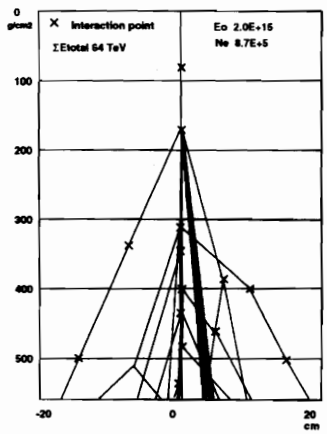

Figure 1. The example of simulated air shower event.

(a) When a high energy hadron in an air shower makes a nuclear interaction near the emulsion chamber, a γ-ray bundle is observed. However, in general, such hadrons have rather low energies, since the primary proton energy is divided into many secondary hadrons. We represent this process as "P−h".

(b) Though each produced particle has rather low energy compared with, for instance, the survival proton, the total sum of π^0 energies sometimes becomes quite high. When many π^0 are produced simultaneously in the first interaction of the air shower, a bundle of γ-rays, collimated in a narrow area even after long path, arrives at the emulsion chamber. This process is shown as "P".

(c) In the proton interaction, a survival proton is produced with energy about a half of the primary proton energy, on the average. Sometimes a survival proton has rather high energy even after several interactions in the atmosphere. Such a high energy survival proton can produce a γ-ray bundle near the emulsion chamber. This is shown as "P−P".

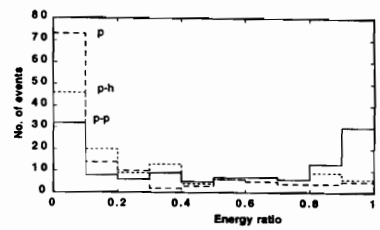

Figure 2. Number of events for each process and the energy ratio, calculated from simulation results.

In Fig.2, number of events for each process are shown against the energy ratio. From this figure, we can understand that γ-ray bundle with high energy are produced by the process "P−P" and the process "P" becomes dominant in lower energy region.

3. Experimental results and simulation

The number of γ-ray bundles in air shower size $\leq 10^7$ can give information on the primary chemical composition, since the γ-ray bundles are formed mainly by protons but not by heavy particles. In order to get a conclusion, we should compare experimental results with simulations.

(a) Efficiency to link a particular air shower to a γ-ray bundle

Since γ-ray bundles are measured by emulsion chambers without time resolution, it is not straightforward to link a γ-ray bundle to a particular air shower. However, as shown in Fig.3, the size spectrum of all the air showers coincide with one of air showers associated by γ-ray bundles in

the range of air showers $\geq 10^7$. This means that the efficiency to link both data is about 100%.

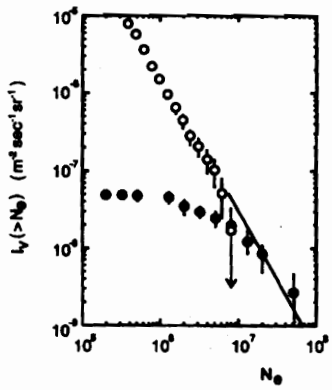

Figure 3. The integral size spectrum of all the air showers (open circles) and the air showers with γ-ray bundle (closed circles).

On the contrary, in the size range $\leq 10^7$, both size spectra do not coincide. This probably indicates that the efficiency of γ-ray bundle production are lower in such a low size range.

(b) Experimental results and the simulation

66 γ-ray bundles have been observed by a series of the exposure of 8 m^2 emulsion chamber. Each bundle has γ-rays above 5 and the total energy above 10 TeV. 11 γ-ray bundles have been linked to air showers with the size greater than 10^7 and 36 to air showers in size range $10^5 \sim 10^7$.

However, 19 events are not linked to any air shower. These unlinked γ-ray bundles are to be linked to the air showers with the size $\leq 10^7$, since the efficiency for air showers above 10^7 is about 100 %. Then, such 19 unlinked γ-ray bundles are added to number of event 36 in the range $10^5 \sim 10^7$. The final number of γ-ray bundles is 55 in the range $10^5 \sim 10^7$, and 11 in the range $\geq 10^7$.

This result is to be compared with simulations. Here, the results by the simulation are normalized to the observed number 11 for air showers with the size above 10^7. In these calculations, two kinds of primary chemical composition are used: the normal composition and the heavy dominant one. In the size range $\leq 10^7$, the number of events is 642 for the former and 332 for the latter by the simulation.

Since these calculated values are quite larger than experimental ones, we cannot conclude which chemical composition fits to the observation. Such differences may be due to differences of detection efficiencies and also a model of the γ-ray bundle formation. In this report we shall study on the second point.

4. Discrepancy between the experiment and the simulations

In the present experiments, the event number of γ-ray bundles by simulation is larger than experimental data. Similar discrepancy is already reported from large scale emulsion chamber experiments at mountain altitudes/citekawasumi96/citehonda96. That is, the integral energy spectrum of γ family is lower than calculated one in the range $10 \sim 10^3$ TeV. Here, the γ family is similar to the γ bundles except that the family is not accompanied by air shower information.

Moreover, similar situation is found in the following point, too. In the present experiment, we determine the average total energy of γ-ray bundles $\langle \sum E_\gamma \rangle_{exp}$ in some ranges of accompanied air shower size. Here, again the result by the simulation is larger than that by the experiment.

In order to solve these discrepancies, Fig.1 suggests that the inelasticity should be increased for γ-ray bundles with high energy region and the multiplicity should be increase for low energy bundles.

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Inelasticity Distribution of Hadron-Pb Collisions in 10^{14} eV (Revised)

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1. Experimental Procedure

1.1. Pamir Thick Lead Emulsion Chambers.

Emulsion chamber detects multiple particle productions, caused by cosmic-ray hadrons in the chamber, as showers which are initiated by γ-rays among the secondary particles. Hence the observed energy of the shower is a part of the hadron energy.[1]

Thick lead emulsion chambers, constructed at the Pamir Station (4,300 m, Tadjikistan)[1, 2], have distinguished quality of large thickness (60 cm Pb or 3.2 mean free path of inelastic collision of nucleon) and uniform structure (59 sensitive layers at every 1 cm Pb plate). The detection threshold energy of the chamber is *several* TeV.

The hadron, incident upon the chamber, makes a nuclear collision in the chamber. The surviving hadron and the produced hadrons undergo nuclear collisions again at various depths in the chamber, too. The process is repeated in the chamber until the hadrons, incident and produced, leave the chamber. Consequently a single high energy hadron, incident upon the chamber, produces in the chamber n showers ($n = 1, 2, \cdots$) which have appearance of aligning on the line *and* having the same direction. The event of $n \geq 2$ is called 'successive interactions', while the one of $n = 1$ is called 'single-shower'.

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1.2. z-distribution

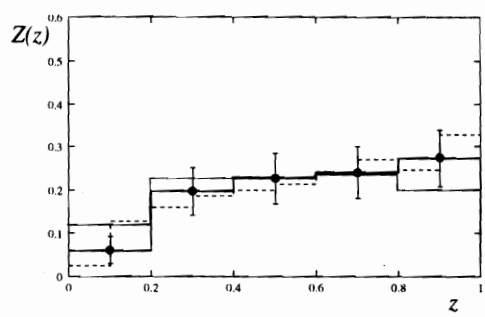

Figure 1. z-distributions of the experimental data (the bold solid line) and of the calculation (the thin solid line) where the *flat* distribution of the total inelasticity K is assumed. The dashed line is for the case when the best-fitting inelsticity distribution is assumed.

Let us denote the energy of the first, the second, $\cdots$, shower in the event by E_1, E_2, $\cdots$, and that of the incident hadron by E_0. The parameter z, defined as $z \equiv E_1/\sum E_i$, is a measure to estimate the inelasticity of the interaction of the first shower.

The distribution of z is shown in Fig. 1 from 66 events which have $\sum E_i > 30$ TeV with $E_{th} =$

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