A Cherenkov light detection experiment at Mount Chacaltaya to study nuclear composition of cosmic rays

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***Abstract*. Cosmic ray composition is very important to clarify the origin of cosmic rays. In particular, the composition in the energy region at and beyond the knee is of special interest, because it must be closely related to sites of cosmic ray productions and mechanisms of particle accelerations. In the BASJE (Bolivian Air Shower Joint Experiment) group, we constructed a new air shower array at Mount Chacaltaya (5,200m above the sea level) to observe cosmic rays with energies greater than 10^{15} eV. Moreover, we have designed Cherenkov light detectors operated together with the air shower array. It is known that the longitudinal development of a particle cascade in the atmosphere strongly depends on the type of the primary nucleus, and an air shower initiated by a heavier nucleus develop faster than that by a lighter primary. It has also been pointed out that the longitudinal development of an air shower can be measured by detecting Cherenkov light emitted from electrons in the shower. We carried out a Monte-Carlo studies of air showers and found that primary cosmic ray nuclei types can be distinguished by measuring lateral distributions and arrival timings (waveforms) of Cherenkov lights associated with air showers. In our experiment, we install ~ 18 Cherenkov light detectors in the air shower array and will carry out a hybrid experiment to observe air showers by determining directions and primary energies of cosmic rays from air shower array data, and identifying primary particle type from Cherenkov light detector data.**

***Keywords*: Cosmic rays, Knee region, Cherenkov lights**

I. Introduction

The *knee* region in the energy spectrum of primary cosmic rays at and above 10^{15} eV is the key to clarifying the source of cosmic rays. The nuclear composition of primary cosmic rays in this region is very important to resolve the cosmic ray origin, because it is strongly affected by the source abundance and acceleration mechanisms. It is predicted that if cosmic rays are confined in supernova remnants and accelerated at strong shocks through the Fermi process, cosmic rays are enriched by heavy nuclei (as irons) as the primary energies increase. On the other hand, it is believed that cosmic rays of more higher energies (say $\sim 10^{19}$) are extra-galactic origin, and they are dominated by lighter components because of spallation processes during the propagation in the inter-galactic space. This suggests that there could be a "transition" of cosmic rays of Galactic and extra-galactic origin at a certain energy region, and it is observed as a change of cosmic ray composition as a function of energies. It is challenging to find such transition.

In the BASJE (Bolivian Air Shower Joint Experiment) group, we have reported measurements of cosmic ray composition around the knee by using three independent observation techniques, those are measurements of arrival time distribution of Cherenkov light associated with air showers [1], lateral distribution of Cherenkov lights [2], and the longitudinal development curves obtained from equi-intensity cuts using shower size spectra for various arrival directions [3]. These results are in agreement and show that the mean (logarithmic) mass of primary cosmic rays increases as the energy increases around the knee region, and it is dominated by the heavy component as iron (Fig. 1). It is consistent with the predictions, the cosmic ray origins are supernova remnants of massive populations as Wolf-Rayet stars.

In order to study mass composition of cosmic rays of more higher energies, we have constructed a new air shower array at Mount Chacaltaya [4] with effective detection area $\sim$ 100 times larger than that of the array used in our previous composition studies [5]. Moreover now we plan to add detectors of another type, Cherenkov light detectors. It is known that the arrival time distribution of air Cherenkov light and their lateral distributions depend of the longitudinal development of air showers, therefore they can be used to recognize primary particle types [6], as carried out in our previous experiments [1] [2]. In our new experiment, we measure both the arrival time distribution of the Cherenkov light and their lateral distribution. The details of our detectors are described in the next section.

II. AIR SHOWER ARRAY

The Chacaltaya air shower array is comprised of 68 scintillation detectors installed in an area of $700\mathrm{m} \times 500\mathrm{m}$ with separations 75 m. The performance of the array is studied with Monte-Carlo shower simulations. The air shower generator employed here is based upon the code developed by Shirasaki and Kakimoto [7], in which the VENUS hadronic interaction model is used (the longitudinal development of air showers generated with this code is quite similar to those obtained using the CORSIKA-QGSJET code). The trigger criterion of the array is a coincidence of neighboring 4 detectors (“square” hit pattern) among the twelve detectors near the array center within a time window of $4\,\mu$s. The incident angles of the simulated showers are chosen uniformly up to the zenith angle of $45°$, and the core locations are also uniformly distributed within a circle of $200\mathrm{m}$ radius centered at the center of the triggering detectors. From the ratio of the triggered showers to the simulated showers for each triggering criterion, the aperture of the array is calculated as a function of the primary energy (Fig. 3). It can be seen that the detection efficiency is 100% for cosmic rays with energies above $10^{15.5}\,\mathrm{eV}$ within the circle. We calculate expected distribution of cosmic ray energies to be observed using the aperture of the array and an assumed cosmic ray energy spectrum [3]. For example, the number of events with energies greater than $10^{17}\,\mathrm{eV}$ to be observed in one-year exposure is estimated as ~ 100. We also evaluated the accuracies in determination of shower arrival directions and shower sizes by comparing the simulated showers with the reconstructed events. The angular resolution of the array is $\sim 0.8°$, and the error in the determination of logarithms of the shower sizes is ~ 0.1.

The construction of the detectors and the development of the DAQ system were completed in 2006, and we have started observation runs in Spring 2007. The expected trigger rate is about 2 Hz, and the real trigger rate is the same level in the observations.

III. CHERENKOV LIGHT DETECTORS

A. Components

Our Cherenkov light detector (CD) consists of two photomultiplier tubes and a digital oscilloscope to record data. We use HAMAMATSU R1250 (diameter of 5 inches) which has a good time response. The detectors are installed in the air shower array with separations of 50m and connected with the control room located at the center of the air shower array. The difference of this experiment and our previous experiments is that the air shower array is 10 times larger in size. Therefore it is difficult to use shower array triggers for CD triggers due to a limited data buffer size, or to send waveform signals using long coaxial cables without attenuation. These are resolved to employ a ”semi-self trigger” and a local data acquisition system (see the next section). All the components are contained in a box with a sliding cover (Fig. 4).

B. Data Acquisition

Each CD is triggered with a coincidence of the two tubes in the CD and signals of two shower particle counters nearest it. In order to measure and record signal waveforms in good accuracies, the signal is digitized in the CD and stored in a local data storage. The CDs are connected via ethernet, but the network traffic is small during observation, since the CDs and the control room communicate only at the start and the end of observation. The data acquisition is started by a command sent from the control room to all the CDs. During observation only monitor data as numbers of triggers are sent from each CD to the control room. After stopping data acquisition (at morning), the data stored in each CD are transfered to the central data storage via network. The data size is estimated as 2 GB in 6 hours observation for each CD. The correspondences between an air shower event and a Cherenkov light event is investigated *off-line* using time stamps.

A prototype CD has been developed including a phototube, a signal recorder, a triggering circuit, a micro-controller (MPU), and a computer (embedded Linux OS) (Fig. 5). We use an embedded Linux OS system with ethernet and USB interfaces. The trigger circuit has coincident signal inputs, three trigger outputs, and a CLEAR signal input. The trigger signals are for the computer, the recorder and GPS clock. The CLEAR signal is sent from the computer to the trigger circuit to permit and accept next trigger after storing a Cherenkov light signal. The MPU communicates with the computer via ethernet, and controls DACs to generate reference voltages to set trigger signal levels and high-voltage for the tube. The MPU is also used to control a motor to drive a detector box cover.

IV. SUMMARY

We have constructed a new air shower array at Mount Chacaltaya to study cosmic rays with energies at and above the knee region. We also plan to install detectors

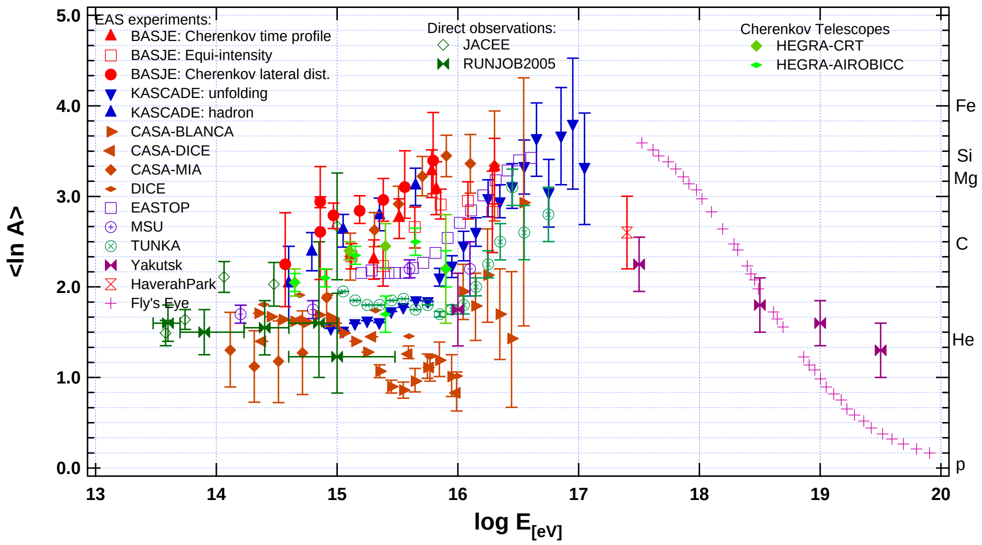

Fig. 1: Mean logarithmic mass of primary cosmic rays: The results of our previous experiments are showed by filled triangle (Cherenkov time profile), open square (equi-intensity cuts), and filled circle (Cherenkov lateral distribution).

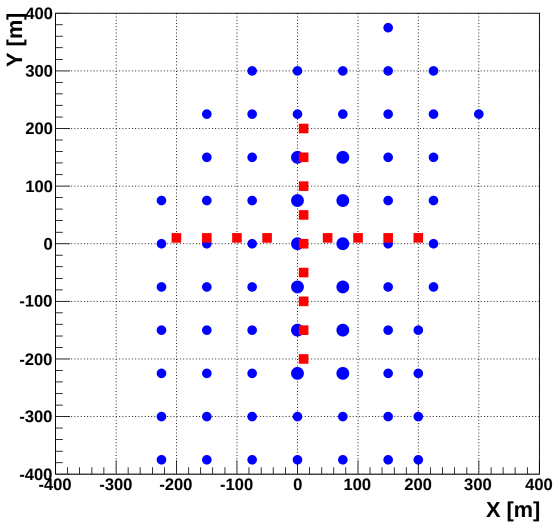

Fig. 2: Chacaltaya air shower array. The circles represent scintillation counters, and the squares are the positions of the Cherenkov light detectors.

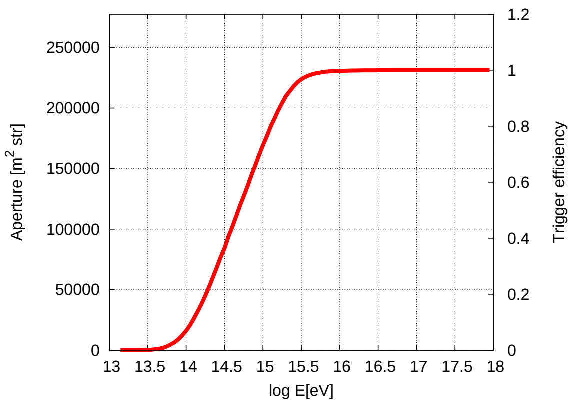

Fig. 3: Aperture of the air array

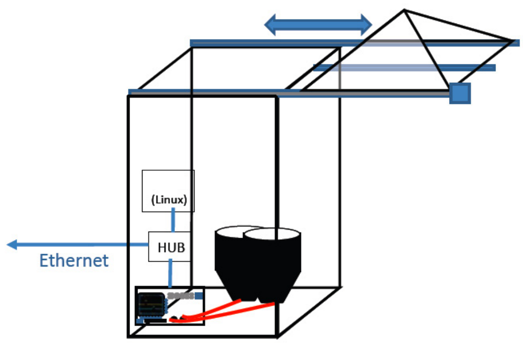

Fig. 4: Schematic view of the Cherenkov detector

of an another type, Cherenkov light detectors, using experiences in our previous experiments and revised designs. The detector has a stand-alone characteristics with a semi-self triggering and data storage system suitable for hybrid detection experiment with a large scale air shower array. A prototype detector has been developed and in test data acquisition. We plan to start observation in the next year.

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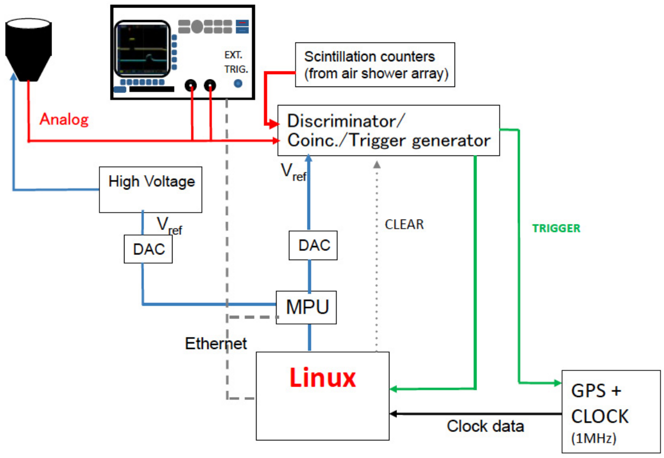

Fig. 5: Data acquisition system

REFERENCES

[1] Y. Shirasaki *et al. Chemical composition of primary cosmic rays with energies from* 10^{15} *to* $10^{16.5}$ *eV*, *Astropart. Phys.*, **15**, 357 (2001)

[2] H. Tokuno *et al. The cosmic ray primary composition at the knee region from lateral distributions of atmospheric Cherenkov photons in extensive air showers*, *Astropart. Phys.*, **29**, 453 (2008)

[3] S. Ogio *et al.* , *The energy spectrum and the chemical composition o f primary cosmic rays with energies from 1014 to 1016 eV*, *Astrophys. J.*, **612** 268 (2004)

[4] Y. Tsunesada *et al. Cosmic Ray Observation at Mount Chacaltaya for beyond the Knee Region*, *30th ICRC Proc.*, **HE1.2A**, 127 (2007)

[5] H. Yoshii *et al. Present experiment of BASJE group at Mt. Chacaltaya*, *Il Nuovo Cimento*, **24C**, 507 (2001)

[6] A.M. Hillas *The sensitivity of Cherenkov radiation pulses to the longitudinal development of cosmic-ray showers*, *J. Phys. G*, **8**, 1475 (1982)

[7] Y. Shirasaki and F. Kakimoto *et al. Monte Carlo simulation of air shower development for the study of cosmic ray composition*, *Astropart. Phys.*, **15**, 241 (2001)