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# Primary Proton Flux around the "Knee" Region Deduced from the Observation of Air Showers Accompanied by Gamma Families


**The Tibet AS$\gamma$ Collaboration**

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### Abstract

We started a hybrid experiment of emulsion chamber and the Tibet II array at Yangbajing (4,300 m above sea level) in 1996. The total area of emulsion chamber (EC) and burst detector complex is 80 m$^2$. This detector complex is placed near the center of the Tibet II array. Using the data obtained during the period from 1996 September through 1997 July, we detected 84 combined events of family and air shower. The rate of combination of family events and air showers is estimated to be 93 %. From this data, we obtained a preliminary result on the proton flux around the knee energy region.


## 1 Introduction :

The energy spectrum of primary cosmic rays has been observed over a wide energy range from $10^9$ eV to $10^{20}$ eV with various instruments on board satellites or balloons and also ground based air shower detectors. The observed spectrum shows a steepening of the slope between $10^{15}$ eV and $10^{16}$ eV which is called a " Knee" region. A great effort has been devoted to explain the reason why the spectrum changes at the knee region since this may be closely connected with the acceleration and propagation of high energy cosmic rays in our galaxy. It is well known that particle acceleration at supernova blast waves gives a very nice account of the origin of the bulk of the cosmic rays as well as of a power-law spectrum of particle energies. This is unlikely to be the whole story, however, and it is most unlikely that this process can account for ultra-high energy (UHE) cosmic rays, $> 10^{15}$ eV, for which the gyro-radii are of the same size as the supernova remnant itself. Probably another mechanism has to be sought for UHE cosmic rays.

The mass composition of cosmic rays beyond the knee region still remains unobserved and the subject of much debate, since direct measurements are almost inaccessible in this energy region due to their extremely low fluxes. The primary composition around the knee region has been extensively studied with air shower technique. The number of muons contained in the air showers has a sensitivity to the primary mass composition, but the problem of determining the composition of primary cosmic rays from such air shower measurements is obviously difficult because of the primaries are not observed directly and also the multiplicity observed involves a convolution of muon production with the energy spectrum as well as with the composition.

It is possible, however, to improve the sensitivity of an air shower array to the primary composition as well as to get some information about the primary energy of each event by measuring the air shower in coincidence with a large large-area emulsion chamber. One of the advantages in doing such experiment is that the primary energy generating both of air showers and families can be uniquely estimated by measuring air shower sizes as discussed elsewhere. Furthermore, air shower events accompanying families are very sensitive to the protons in the primary, so that we can get direct information about the protons around the knee region. Protons in the primary are the key component to understand the origin of the knee.

## 2 Experiment :

The experiment has been operating at Yangbajing (4300 m above sea level) in Tibet since 1996. The apparatus consists of the Tibet-II air shower array and emulsion chambers (ECs) combined with burst counters. The ECs are constructed near the center of the Tibet-II array. Also, a small air shower array is additionally set up to detect the events which may be recorded during the dead time of the Tibet-II array. The total area of ECs each unit having a 50cm×40cm area and 14 c.u. thickness (lead) is 80 $m^2$ and the burst counters with the same area are placed just below ECs. Each burst counter contains a plastic scintillator with the size of 160cm × 50cm × 2cm. Thus, 400 blocks of EC and 100 burst counters in total are used in this experiment. The photodiodes(PDs) are attached at four corners of each scintillator to read light signals generated by a large number of particles passing through the counter. These cascade particles (burst particles) are created in ECs by high energy gamma rays or hadrons in a family.

The ADC values from four PDs provide information about the total number of shower particles and its shower position detected by the burst counter. The response of burst counter was examined by using the electron beams from accelerator. The position of burst particles is estimated with an error of about 10 cm in each burst counter and the size range to be measured with burst counter is from about $10^3$ to $3 \times 10^6$ particles. This size region roughly corresponds to the detection of showers with energies from about 1 TeV to about 300 TeV.

Events are triggered at any two fold coincidence of signals from 4 PDs in the burst counters. When the burst counters trigger the event, its accompanying air shower is simultaneously recorded. Detection of gamma families in ECs is done as in usual emulsion chamber experiment. The X-ray films in ECs are exchanged with new ones every year to suppress the background. The selection criteria of family events is : $E_{th} \geq 4$ TeV, $N \geq 4$ and $\sum E \geq 20$ TeV, where $E_{th}$ is the minimum shower energy, N the number of constituent showers in a family and $\sum E$ the sum energy of showers in a family. For each family event detected in ECs, its accompanying air shower can be found using the burst and air shower data. Table 1 is the summary of the experiments done so far.

| No. | Year | Exposure time of EC (days) | Operation time of AS array (days) |
|---|---|---|---|
| 1 | 1996.10-1997.7 | 286.26 | 250.90 |
| 2 | 1997.8-1998.8 | 366.27 | 339.26 |
| 3 | 1998.9- | Running | Running |

Table 1. List of the experiments.

## 3 Results :

84 combined events of family and air shower, satisfying the criteria above, were observed from the experiment 1 (1996.10 - 1997.7). The rate of combination between family events and air showers is estimated to be 93 % in this experiment. 7 % loss can be attributed to the dead time of air shower array.

The $\sum E$ spectrum of the family events obtained with ECs is shown in Fig. 1 together with the Monte Carlo result (We used a COSMOS code by Kasahara). Our data seem to favor in the heavy dominant primary as those in the Fuji-Kanbala emulsion chamber experiments [4], while statistics of the present data is still not enough to reach a conclusion. When we compare the absolute flux with other experiments [4], the attenuation length of family events in the atmosphere is estimated to be $\sim$110 g/cm$^2$. We also examined the lateral spread of family events, and found that these are also consistent with those expected from the heavy enriched primary composition.

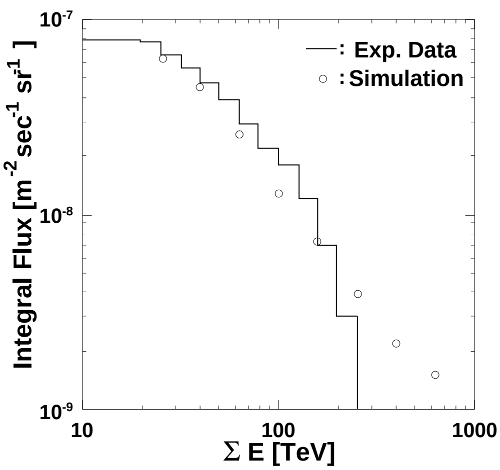


Fig.1 Integral energy-flow spectrum of gamma-ray family events. Simulation results of the heavy enriched primary model is presented to compare with experimental results.

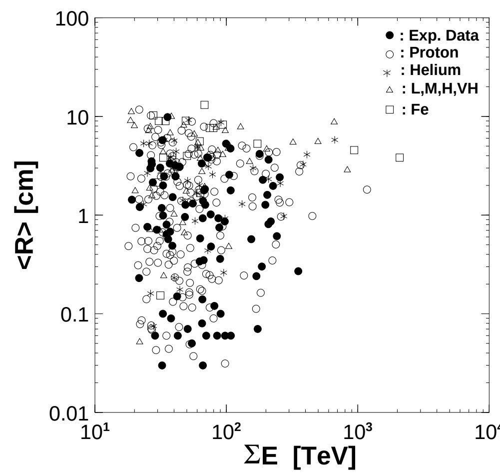


Fig.2 Scatter plots of the mean lateral spread of family event, $< R >$, and energy-flow, $\sum E$, for the events with $N_e \geq 2 \times 10^5$. Experimental results are compared with simulation results.

A correlation between the air shower size and the primary energy at Yangbajing altitude was examined by a Monte Carlo simulation. In this simulation the observation condition and detector response are adequately taken into account. A conversion factor from the size to the primary energy is estimated to be 2.4 GeV/particle, that is, $E_0 = 2.4(GeV) \times N_e$, where $N_e$ is the air shower size. The systematic error contained in this energy estimation is about 25 % at energies around $10^{15}$ eV. This value is mostly due to the uncertainties of primary composition and hadronic interactions.

Figure 2 shows a scatter diagram of the lateral spread of family event, $< R >$ and the energy flow, $\sum E$, where $< R >$ is the mean lateral spread of each family. It is seen that proton-induced events scatter very widely, while the mean spread is smaller than other nuclei. On the contrary, heavy particles such as iron nuclei give large spread and small fluctuation. The overall behavior of the observed events is almost consistent with the simulation as seen in this figure.

Shown in Fig. 3 are scatter plots of $\sum E/E_0$ and $< R >$ for the events with $\sum E \geq 80$ TeV and $E_0 \geq 2 \times 10^{15}$eV. It is well seen that the proton-induced events distribute around the upper left region while heavy-induced events tend to gather around the lower right region in this figure.

Based on the result shown in Fig.3, we selected the candidates for proton-induced event by imposing the conditions of $\sum E/E_0 \geq 0.032\times < R >^{1.5}$. 15 candidate events with $E_0 \geq 2 \times 10^{15}$ eV are found in the region above the dotted line shown in Fig.4. We also calculated the detection efficiency of such events by a Monte Carlo simulation.

Figure 4 is the preliminary result on the primary proton flux obtained from this experiment in comparison with other experiments. The integral flux values at $2 \times 10^{15}$ eV and $5 \times 10^{15}$ eV are estimated to be $(5.98 \pm 1.37) \times 10^{-8} m^{-2} sec^{-1} sr^{-1}$ and $(1.04 \pm 0.26) \times 10^{-8} m^{-2} sec^{-1} sr^{-1}$ respectively. By lowering the threshold energy of family events and increasing the statistics, our experiment can cover the energy range between $10^{15}$ and $10^{16}$ eV.

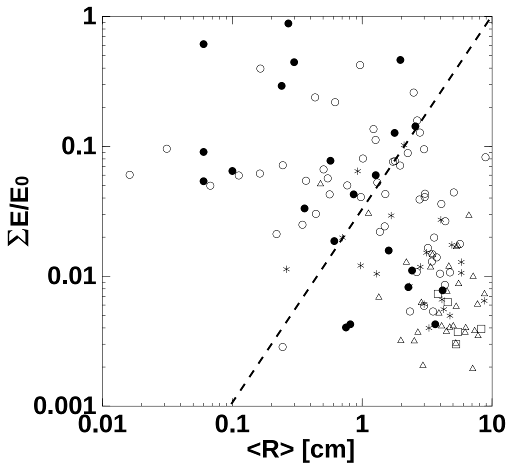


Fig.3 Scatter plots of $\sum E/E_0$ and $< R >$ for the events with $\sum E \geq 80$ TeV and $E_0 \geq 2 \times 10^{15}$ eV. Symbols are the same as those in Fig. 2.

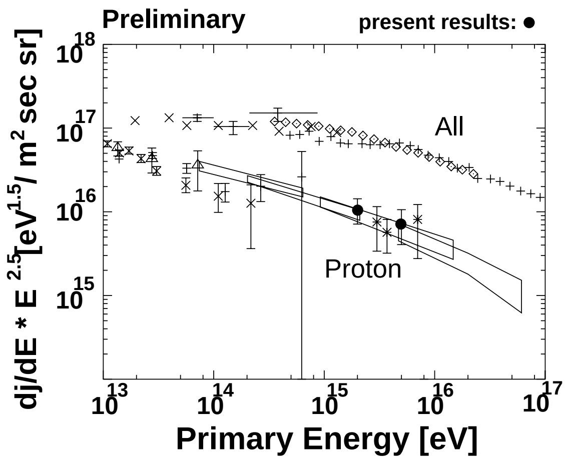


Fig.4 Energy spectra of primary cosmic rays. Present results are shown by closed circles. Asterisks and areas by solid lines are from Norikura [1] and Fuji-Kanbala [4] experiments, respectively. For other data, see Fig. 9 of Ref. 2.

## 4 Summary :

The experiment for simultaneous observation of family events and air shower showers has been successively continued at Yangbajing in Tibet since 1996 October. Using the data obtained during the period from 1996 through 1997, we observed 11 proton-induced events with the energy higher than $2 \times 10^{15}$ eV and estimated the absolute intensity of protons around the knee region. This experiment will finish this summer and the total exposure of emulsion chambers becomes about 240 m$^2$. The threshold energy of families can be lowered to about 10 TeV by careful scanning of X-ray films so that the proton flux will be obtained in the energy region from $5 \times 10^{14}$ eV to $10^{16}$ eV.

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