# 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.** The simultaneous observation of $\gamma$-families and accompanied air showers enables us to obtain the primary proton flux around the knee energy region where no direct measurements are available up to now. We operated a hybrid experiment which consists of emulsion chambers and the Tibet-II air-shower array (AS) at Yangbajing (4,300 m a.s.l., 606 g/cm$^2$) in 1996-1999. The total area of emulsion chamber (EC) and burst detector (BD) complex was 80 m$^2$ and they were set up near the center of the Tibet-II air-shower array. We already published the primary proton flux in the energy region ranging from $2 \times 10^{14}$eV to $10^{15}$eV using the BD and AS data. We used an artificial neural network to select the proton-induced events from the EC data set. The proton fluxes obtained from this experiment are presented in the knee energy region. Our result suggests that the primary becomes heavy dominant in the knee energy region.



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## 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 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 unresolved 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, although definite conclusion has not been established until now.

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 detection of $\gamma$-families by large-area emulsion chamber at high mountain altitude. From the simulation study, following advantages in doing such experiment are clarified. One is that the primary energy generating both of air showers and $\gamma$-families can be estimated with high accuracy due to small fluctuations in air shower size. Another is that air shower events accompanied by $\gamma$-families are strongly favored to the protons among primaries, 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 was carried out at Yangbajing (4300 m above sea level) in Tibet during the period from 1996 through 1999 (Amenomori et al. (2000)). The apparatus consists of the Tibet-II air-shower array and emulsion chambers (ECs) combined with burst detectors. The ECs were constructed near the center of the Tibet-II air-shower array. The total area of ECs was 80m$^2$, having a 50cm$\times$40cm area and 14 c.u. thickness (lead) in each unit, where X-ray films were inserted at 4, 6, 8, 10, 12 and 14 c.u. depths. The burst detectors with the same area were placed just below ECs. Each burst detector contains a plastic scintillator with the size of 160 cm $\times$ 50 cm $\times$ 2 cm, namely, 4 ECs were placed above one burst detector. X-ray fiducial marks were irradiated from the side of each EC units at several positions to guarantee the space reconstruction of the cascade showers. Thus, 400 blocks of ECs and 100 burst detectors in total were used in this experiment.

The detection of $\gamma$-families in ECs was made as in usual emulsion chamber experiment. The X-ray films in ECs were exchanged by new ones every year to suppress the background. The selection criteria of $\gamma$-family events is : E$_{\gamma th} \geq$ 4 TeV, N$_\gamma \geq 4$ and $\sum E_\gamma \geq$ 16 TeV, where E$_{\gamma th}$ is the minimum detection energy for cascade showers, N$_\gamma$ the number of constituent showers in a $\gamma$-family and $\sum E_\gamma$ the sum energy of showers in a $\gamma$-family. For each $\gamma$-family event detected in ECs, its accompanying air shower can be found using the burst and air shower data. Experimental periods are shown in Table 1.

| Year | Exposure time of EC (days) | Operation time of BD (days) |
|---|---|---|
| 1996.10-1997.7 | 286.26 | 250.60 |
| 1997.8-1998.8 | 366.27 | 340.20 |
| 1998.9-1999.8 | 351.01 | 328.20 |

Table 1. Experimental period

## 3 Simulation calculation

Since the derivation of the proton flux is essentially based on the generation efficiency of $\gamma$-families, an extensive simulation calculation is required. We used the Cosmos code with a 'Skeleton' method(Kasahara (2001)) to reduce the computing time, which allows us to simulate more than 4$\times$ 10$^8$ events among which only around 10$^4$ events are needed to have detailed information about $\gamma$-families and air shower sizes. A calculation was made using two different primary composition model, i.e, heavy dominant model (HD2) and proton dominant model (PD2) as shown in Table 2 and 3, respectively. We simulated the events under the following conditions : 1) minimum primary energy is 30 TeV ; 2) observation level is set at Yangbajing ( 606 g/cm$^2$) ; and 3) isotropic primary injection at the top of the atmosphere (maximum zenith angle 60 degrees).

The experimental conditions for detecting $\gamma$-families are adequately taken into account, for example, the overlapping of the neighboring cascade showers and contribution of hadron jets in the lead plates inside ECs are also simulated. Namely, showers with relative distance less than 100 $\mu$m are combined to one shower whose energy is the sum of both shower energies. Showers having their starting point less than 6 c.u. in the emulsion chamber are regarded as $\gamma$-rays.

Secondary particles in the air showers are traced down to 1 GeV and the Approximation B of a well known cascade theory is used to obtain air shower size ($N_e$).

| PD2 Model | Primary energy | | |
|---|---|---|---|
| | $10^{14}$eV | $10^{15}$eV | $10^{16}$eV |
| Proton | 39.9% | 38.1% | 37.5% |
| He | 20.4% | 19.4% | 19.1% |
| CNO | 15.2% | 16.1% | 16.5% |
| Heavy | 9.4% | 9.9% | 10.2% |
| Very Hv | 5.8% | 6.2% | 6.3% |
| Fe | 9.4% | 9.9% | 10.2% |

Table 2. PD2 Composition model

| HD2 Model | Primary energy | | |
|---|---|---|---|
| | $10^{14}$eV | $10^{15}$eV | $10^{16}$eV |
| Proton | 22.6% | 11.0% | 8.1% |
| He | 19.2% | 11.4% | 8.4% |
| CNO | 21.0% | 22.6% | 17.8% |
| Heavy | 9.0% | 9.4% | 8.1% |
| Very Hv | 5.6% | 6.2% | 5.8% |
| Fe | 22.2% | 39.1% | 51.7% |

Table 3. HD2 Composition model

A correlation between the air shower size accompanied by $\gamma$-family and the primary energy at Yangbajing altitude was examined by a Monte Carlo simulation(Saito et al. (1993)). The correlation between $E_0$ and $N_e$ becomes almost linear above $N_e \geq 10^5$.

| Sec($\theta$) | 1.0-1.1 | 1.1-1.2 | 1.2-1.3 | 1.3-1.4 | 1.4-1.5 |
|---|---|---|---|---|---|
| $\alpha$(PD2) | 2.20 | 2.26 | 2.55 | 2.78 | 3.50 |
| $\alpha$(HD2) | 2.19 | 2.28 | 2.56 | 2.76 | 3.42 |

Table 4. The list of conversion factor($\alpha$)

The conversion from the size $N_e$ to the primary energy $E_0$ can be expressed as $E_0 = \alpha \times N_e^{0.99}$ and the conversion factor $\alpha$ takes a value between 2.2 - 3.5 GeV/particle depending on the incident zenith angle. The value of $\alpha$ is listed in Table 4 as a function of zenith angle. The systematic error contained in this energy estimation is estimated to be about 18% at energies around $10^{16}$eV. This error mostly comes from the uncertainties of the primary-particle species.

## 4 Data analysis

### 4.1 Family analysis

The number of $\gamma$-families observed in 1996 exposure is 115. The $\sum E_\gamma$ spectrum of $\gamma$-family events is almost consistent with the previous observations at Mt.Fuji and Mt.Kanbala while there exists a little excess in $\sum E_\gamma < 100$ TeV region.

In the following analysis, we used only $\gamma$-families with its mean lateral spread larger than 2 mm. The present experiment was carried out inside the hut having the roof materials (very thin iron plates). According to a Monte Carlo simulation, cosmic rays (mostly protons) produce local jets in the roof material and then they are also observed as narrow $\gamma$-families in the emulsion chamber. Another is that we used only high sensitive X-ray films (Fuji 200X) while other mountain EC experiments used fine grain X-ray films (Fuji 100X) together with high sensitive films to measure each shower energy in the narrow $\gamma$-families with a better energy resolution. Thus, in this experiment there is a difficulty in estimating each shower energy in the narrow $\gamma$-families with the mean lateral spread $< r >< 2$ mm. Thus, we rejected those events with $< r >< 2$ mm from our analysis to avoid these problems introducing the appropriate correction factor instead, which was derived from the simulation. After this reduction, analyzed number of events is 90.

### 4.2 Data matching between $\gamma$-families and air showers

The matching of the data between $\gamma$-families found in the EC and AS events triggered by the burst detector are made as follows. Every $\gamma$-family should be found just at the position of the burst detector giving the maximum burst size among all hit BDs in a given AS event, which we call the top detector. Since ECs have no time information, we list every burst triggered AS events with informations of the top detector; the channel number, burst size, expected burst location which are derived from the photodiode signals attached at four corners of BDs, AS size and arrival direction of AS accompanied by its burst size greater than $10^5$. Matching candidate event was searched for every families from above mentioned table by finding AS event which gives minimum $\chi^2$. Definition of $\chi^2$ is

$$\chi^2 = (\Delta\theta/\sigma_\theta)^2 + (\Delta x/\sigma_x)^2 + (\Delta y/\sigma_y)^2.$$

where $\Delta\theta$ denotes opening angle between $\gamma$-family and AS, $\Delta x$ and $\Delta y$ the distance between energy weighted center of $\gamma$-family and burst location. $\sigma_\theta$ is estimated as 2.5 deg. $\sigma_x$ and $\sigma_y$ are known as 10 cm from a calibration experiment using 1 GeV electron beam and also with use of the Monte Carlo simulation taking into account of the experimental conditions. $\chi^2$ distributions for the top candidate which gives the minimum value among all listed events and the second candidate (which gives the second minimum value of $\chi^2$) are shown in Fig.1, where the top candidates distribution is in good agreement with $\chi^2$ distribution of the degree of freedom 3. $\chi^2$ test was applied to adopt the matching event with 10% rejection area ($\chi^2_{min} = 6.25$).

Above mentioned procedure was applied to 90 events and 54 candidates of matching events are found. The expected number of events is 56$\pm$ 8 taking into account of the alive rate of Tibet-II air-shower array during exposure period being 69.1% and $\chi^2$ test rejects 10% of events.

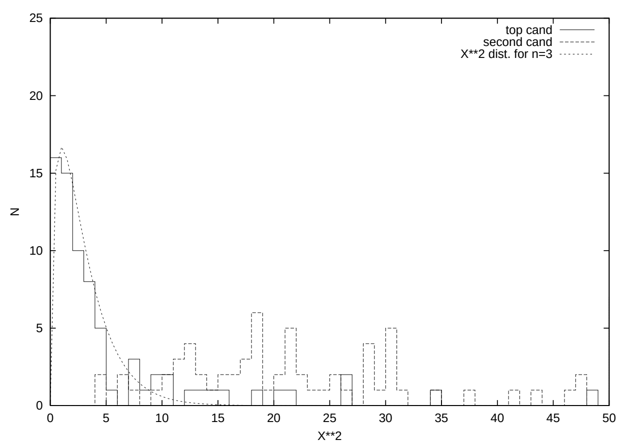


**Fig. 1.** $\chi^2$ distributions used for the data matching

## 5 Proton flux

We used a feed forward artificial neural network(ANN) to select the proton-induced events. Details of this method will be found elsewhere. The following 5 parameter are input to ANN (Jetnet 3.5 (Lonnblad (1993))) : 1) $\Sigma E_\gamma$ ; 2) $n_\gamma$ ; 3) the geometrical lateral spread of family $< r >$; 4) the lateral spread of each family energy $< Er >$ ; and 5) air shower size $N_e$. The ANN target value for protons was put to 0 and for other nuclei to 1. Then, characteristics of ANN output

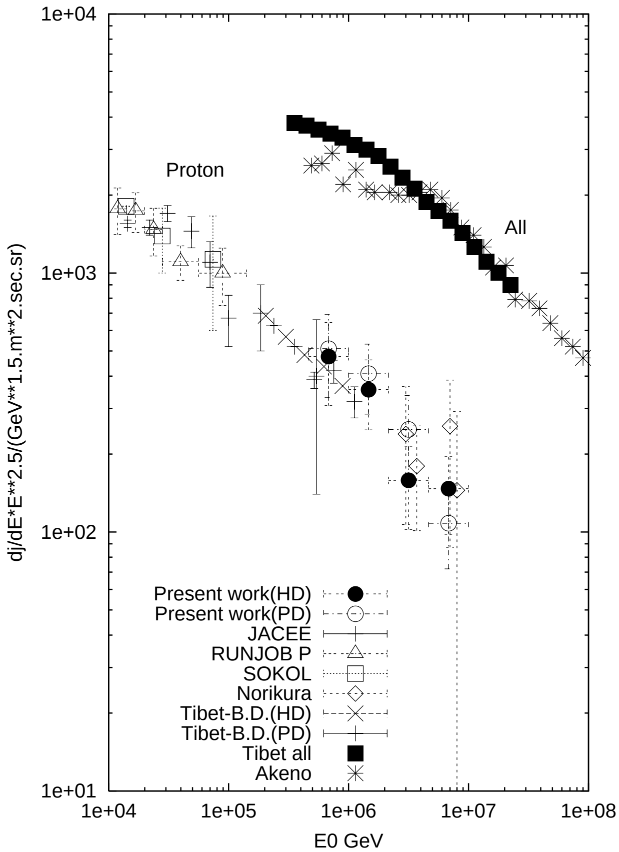


**Fig. 2.** Energy spectrum of protons in comparison with other experiments.

parameter distribution is examined and a critical value for selecting proton-like events is set as 0.3 within which 42% of the observed events are contained while the simulation shows 39.6% and 66.4% for the HD2 model and the PD2 model, respectively. The purity of protons in this region is 87% in both models. The energy spectrum of protons is shown in Fig.2 and compared with other experiments (Amenomori et al. 1996 ; Amenomori et al. 2000; Saito et al. 1993; Nagano et al. 1984; Asakimori et al. 1998; RUNJOB 2000 & Ivanenko et al. 1993). The results from two composition models in simulation agrees well within statistical error. It means the result is model independent.

## 6 Summary and discussion

The differential energy spectrum of primary protons from 600 TeV to 10000 TeV was derived using the data set obtained with the hybrid experiment of AS array and EC complex. ANN method was applied to derive the proton flux under assumptions of two typical chemical compositions. One is heavy dominant case and another is proton dominant case. Since the method to derive the proton flux used in present analysis rely on the generation efficiency of $\gamma$-families, the results should not depend on assumed chemical composition in the simulation. We confirmed that the present result does not depend upon the composition model in the energy range up to $10^{16}$eV.

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