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Precise measurement of atmospheric gamma rays at high altitude

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Abstract. We have been observing the atmospheric gamma-ray spectrum from 30 GeV to 10 TeV for many years with the emulsion chamber at balloon altitude. Atmospheric gamma rays at high altitude of several g/cm^2 are almost produced by a single interaction of primary cosmic rays, and useful to interpret the various cosmic-ray phenomena inside the atmosphere. Especially, more conclusive understanding for the cosmic-ray transport inside the atmosphere is desirable to estimate the absolute flux of atmospheric neutrinos. This estimation is important for the detailed analysis of neutrino oscillation experiments particularly at high energy side. Since charged pions are produced almost two times of neutral pions, we estimate the muon flux at high altitude reliably from our observed gamma-ray spectrum without referring to the primary cosmic-ray flux or hadronic interaction models. We can also estimate the primary flux of cosmic rays, referring to an appropriate hadronic interaction model. Proton spectrum estimated by our observed gamma-ray spectrum covers the energy range from 400 GeV to 30 TeV filling a gap in the currently observed proton spectrum.

1 Introduction

Atmospheric gamma rays, muons and neutrinos are produced through the interaction of primary cosmic rays with the atmospheric nuclei and the decay in the following way.

$$\begin{aligned} p + N \quad &\rightarrow \quad \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ &\qquad\qquad \searrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu) \\ &\rightarrow \quad \pi^0 \rightarrow 2\gamma \end{aligned}$$

Atmospheric gamma rays are mainly the decay products of π^0. The number of charged pions produced are almost two times of π^0, if we ignore the minor contribution through the decay of η and K mesons. Hence we can estimate the production rate of charged pions reliably from atmospheric gamma-ray data. If necessary, we can correct for the minor contribution of η and K mesons. Since the muons are produced from the decay process of charged pions, we can directly estimate the muon flux without referring to the primary flux or hadronic interaction model. In the case of a single interaction of primary cosmic rays, we can also reliably estimate the primary proton flux, referring to an appropriate hadronic interaction model.

We have been observing the primary electrons at balloon altitude with the emulsion chambers 13 times from 1968 to 1998 and successfully obtained the electron spectrum in the energy region of 30 GeV to 3 TeV (Nishimura *et al.* (1980), Nishimura *et al.* (1998), Kobayashi *et al.* (1999)). Our emulsion chamber is only detector which have succeeded to observe electrons in TeV region. In the course of these electron observations, we have picked up simultaneously gamma-ray events to check a consistency of the observed data. BETS group have observed atmospheric gamma rays in the lower energy of a few GeV to several 10 GeV at mountain and various balloon altitudes deeper than our observations (Kasahara (2001b)).

When we observe atmospheric gamma rays at high altitude of several g/cm^2, the thickness of overlying atmosphere above the detector is less than 0.1 nuclear mean free path or 0.1 radiation lengths. The gamma rays are produced by almost a single interaction of primary cosmic rays of proton, helium and heavier nuclei.

In this paper, we present a precise measurement of atmospheric gamma rays from 30 GeV to 10 TeV at high altitude with emulsion chambers and estimate the muon and primary proton flux from the observed gamma-ray spectrum.

2 Detector

The emulsion chamber consists of nuclear emulsion plates and lead plates which are stacked alternately. In this detector, it is possible to measure the position of shower tracks in each emulsion plate with a precision better than 1 μm.

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Because of this high position resolution, we can inspect the shower starting points in detail and make clear identification of electrons, gamma rays, and other background events. The rejection power of electron to proton is found to be as large as 10^5 (Kobayashi *et al.* (1999)).

The energy is determined by measuring the transition curve of shower particles within a circle of 100 μm radius from shower axis. Hence, the number of the shower particles ceases faster than that of the total shower particles and the shower maximum appears at around 6 r.l. for 1 TeV electron. This means that we can observe higher energy electrons with thinner detector. The typical size and thickness of the detector are 40 cm $\times$ 50 cm and $\sim$9 r.l., respectively. Thus the emulsion chamber has a large effective area and wide field of view compared with other detectors. Because of the precise determination of the track location, we can estimate the geometrical factor ($S\Omega$) very accurately, which is difficult to be determined for some electronic detectors.

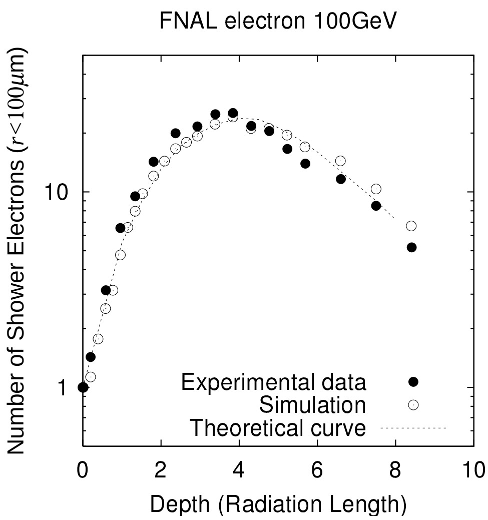

Fig. 1. Longitudinal development of the averaged number of shower electrons within a radius of 100 μm. Theoretical curve is taken from Nishimura *et al.* (1980).

The systematic errors of energy determination are serious to get accurate atmospheric gamma-ray spectrum. The energy was determined by comparing the number of shower tracks with the theoretical transition curves to fit the track lengths. The calibration of the energy determination was performed by using FNAL accelerator beams of 50, 100 and 300 GeV electrons (Nishimura *et al.* (1980)). However, as the chamber structure is slightly different at each flight, we calculated the shower development for each chamber using Monte Carlo simulation code called EPICS (Kasahara (2001a)). The EPICS code was confirmed by the chamber exposed to FNAL electron beams in which the shower of 100 GeV electrons were re-analyzed. The experimental data agree on the track length with the simulation with a precision of 5 %. Figure 1, 2 shows longitudinal development of the averaged number of shower electrons and energy distribution of the FNAL experimental data. The energy resolution is 12 % at 100 GeV, as shown in figure 2.

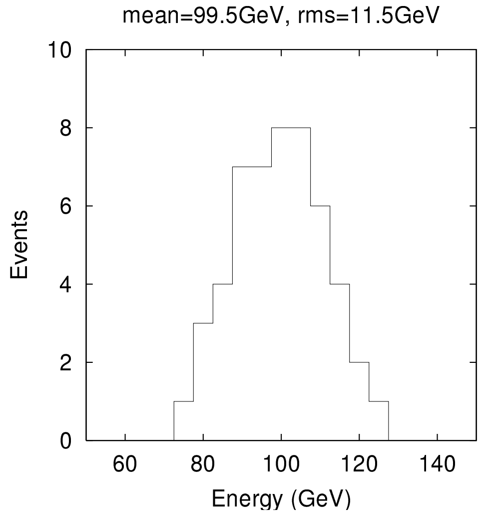

Fig. 2. Energy distribution of experimental data for FNAL 100 GeV electron.

3 Atmospheric Gamma-ray Observations

In our electron observations, gamma-ray events have been picked up in the course of data reduction to check a consistency of the observed electron data. The altitude of each flight ranges from 4.0 g/cm^2 to 9.4 g/cm^2 (6.4 g/cm^2 in average). Total effective exposure $S\Omega T$ is 6.45m^2$\cdot$day$\cdot$sr.

To obtain the atmospheric gamma-ray flux at 4 g/cm^2 from the observed data at each altitude, we took into account of the following factors.

- Gamma ray detection efficiency:
  We selected the gamma ray events which started showers with a depth of 3 r.l. The depth is corrected for the zenith angle of gamma rays. This detection efficiency is thus 90.2 %.

- Enhancement of flux due to energy resolution:
  The flux of gamma rays is enhanced in the case of the steep power law of the spectrum because of energy resolution of the detector. As the energy resolution $\Delta E/E$ of our detectors are $\sim$15 % in the energy region above 100 GeV, we estimate the enhancement factor of 1.01.

- Contribution from primary cosmic-ray electrons:
  We subtracted the gamma rays produced by brems-strahlung from primary cosmic-ray electrons and Galactic gamma rays. The contribution from primary cosmic-ray electrons is estimated to be less than 10 % at 100 GeV, and a few % at 1 TeV. Contribution of Galactic gamma rays is negligibly small and estimated to be less than 0.1 %.

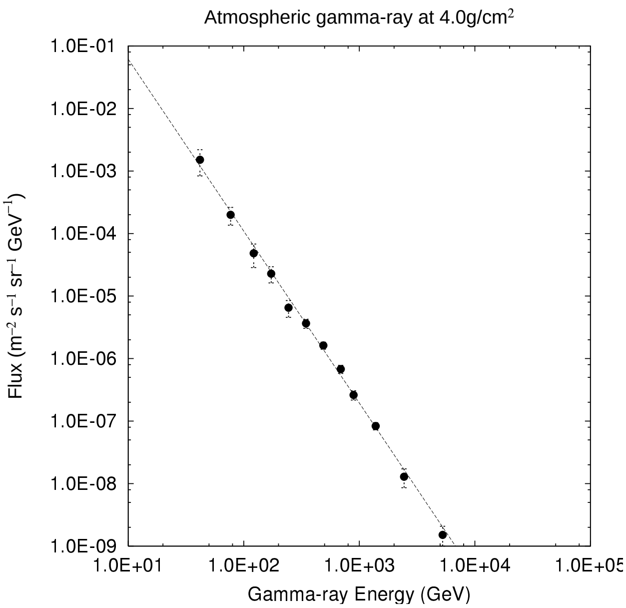

Fig. 3. Observed atmospheric gamma-ray spectrum normalized at an altitude of 4 g/cm^2. The broken line is the best fit spectrum of the data.

– Normalization to 4 g/cm^2:
  We corrected the observed flux at each altitude to the flux of gamma rays at 4 g/cm^2.

The number of observed gamma rays is 293 events in the energy region of 30 GeV$-$10 TeV. The observed spectrum of atmospheric gamma rays normalized at an altitude of 4 g/cm^2 is well represented by

$$dF/dE = (1.09 \pm 0.12) \times 10^{-4} (E/100\mathrm{GeV})^{-2.75\pm0.05}$$

$$(\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}),$$

which is shown in figure 3. It is to be noted that the spectral index of our gamma-ray flux is 2.75 ± 0.05. This value should be the same of the spectral index of primary cosmic rays at the corresponding energy, if the scaling law of hadronic interaction is held in this energy range.

4 Discussion

Estimations of the absolute flux of atmospheric neutrinos suffer from the primary cosmic-ray flux and hadronic interactions. Although the evidence of neutrino oscillation at low energy side by the Super-Kamiokande group is insensitive to absolute neutrino fluxes, the calculation of the fluxes with better accuracy is necessary for a precise determination of the oscillation parameters especially at higher energy side.

Most of atmospheric neutrinos are the decay products of pions and muons particularly at low energy side. Then the atmospheric muon spectrum at various altitude gives an important information to see the reliability of the calculations to estimate the neutrino flux Sanuki (2001) . However, the muon flux depends on the density of the atmosphere (i.e. detailed structure of atmosphere). This brings some complications and ambiguities of estimate of the muon flux.

On the other hand, the accurate measurement of the gamma-ray flux can be also used to reduce the uncertainty in the neutrino flux calculations, because of the relation of gamma ray and neutrino production in the atmosphere, as shown in section 1. It is to be noted that the flux of atmospheric gamma rays depends only on the atmospheric depth, which can be estimated less ambiguously than the muon flux.

Here we discuss the relation between our observed flux of atmospheric gamma rays and muon flux observed at similar altitude, and also make a prediction of primary proton spectrum above 100 GeV, filling the gap of the existing other data. The observation of the gamma rays have a merit to check the consistency with observed muon flux as well as to estimate precisely the primary cosmic-ray flux.

4.1 Relation of atmospheric gamma ray to muon flux at high altitude

Several observations of muon flux at high altitude have been performed by the magnetic spectrometers at balloon altitude of 4$-$6 g/cm^2. Since gamma rays are produced by π^0 and muons are produced by $\pi^{\pm}$, we can correlate with each flux as already mentioned. We transformed our gamma-ray spectrum to the flux of muons, and results are shown in figure 4, in which we made a brief correction due to η and K mesons. To compare the observed muon flux data, we take the spectrum of μ^+ and μ^- observed by BESS group (Sanuki (2001)) as a representative value, since the results by groups of BESS, MASS and CAPRICE are consistent with each other within statistical errors. It is to be noted that our estimated flux is total flux of $\mu^+$and μ^-. As shown in figure 4, the flux is on the extrapolation of each datum of BESS experiment and gives consistent values within statistical errors, although the energy region of our gamma rays is almost one order of magnitude higher than that of the direct observation of muons.

4.2 Primary proton flux estimated from the observed gamma rays

We estimated the primary proton flux from the observed gamma-ray spectrum by assuming an appropriate hadronic interaction model. As for an hadronic interaction model, we took Lund ver.7.02 which have been used in FRITIOF Monte Carlo code. Because of the scaling nature of the production cross-section, the flux of π^0 produced in each collision by protons of energy spectrum $J(E)dE$ with spectral index γ is represented by $\sigma_0 J(E)dE$. Here, we denotes $\sigma_0 = \int_0^1 \sigma(x)x^{\gamma-1}dx$ with $x = E_{\pi_0}/E_p$ and σ is the production spectrum of π_0. Using this relation, we can deconvolve gamma rays to proton flux. In the deconvolution, we include the effect of the contributions of primary He and heavier nuclei, and also include the minor contributions of gamma rays through η and K mesons. Our result is shown in figure 5 with the observed

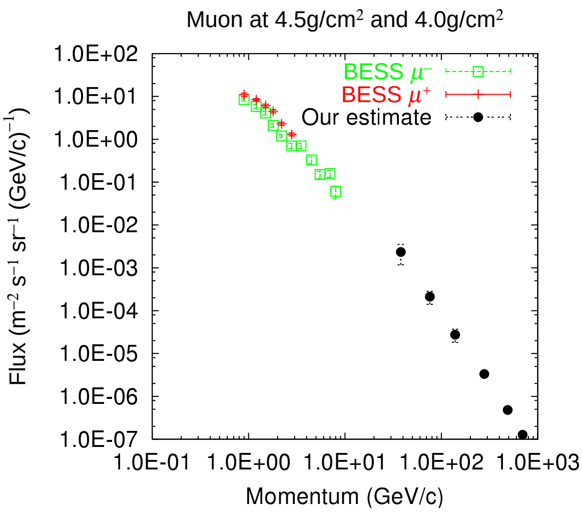

Fig. 4. Comparison of muon flux at 4.5 g/cm^2 observed by BESS and muon flux at 4.0 g/cm^2 estimated by our gamma-ray observation. In the BESS observation charged muons are measured individually, and in our estimation all charged muons are included together.

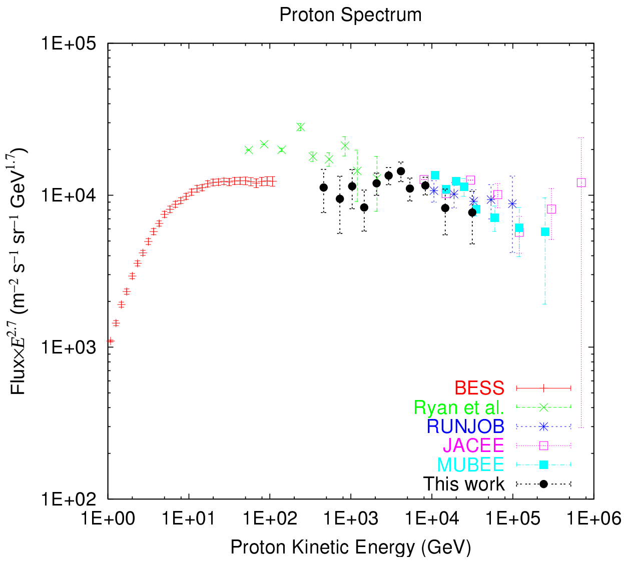

Fig. 5. Proton spectrum estimated by our gamma-ray observations with results of other observations.

data of other experiments (Sanuki *et al.* (2000)). Our estimated proton spectrum is slightly lower than the other previous data observed by calorimeter or emulsion experiments and well represented by

$$dJ(E)/dE = (5.4 \pm 1.1) \times 10^{-2} (E/100\mathrm{GeV})^{-2.75 \pm 0.05}$$

$$(\mathrm{m}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1} \cdot \mathrm{GeV}^{-1}).$$

As noted earlier, the spectral index of our estimated spectrum is 2.75 ± 0.05, which reflect the spectral index of protons by the scaling nature of cross-sections in this energy range. We can see that the absolute flux is almost consistent with the extension of the BESS spectrum with a spectral index of 2.75 ± 0.05, and gives the information in the energy range of a few 100 GeV to $\sim$30 TeV, filling the gap between BESS and the other data.

Chang *et al.* (2001) calculated atmospheric gamma-ray spectrum with different hadronic interaction models of DTUNIC, FLUKA and FRITIOF, assuming the primary proton spectrum of IMAX data. Since their calculated gamma-ray spectra are consistent with the different hadronic interaction models within several %, DTUNIC and FLUKA codes should also give the almost same result in our estimation.

As it is desirable to make a direct comparison with observed data in an overlapping energy region, we need to extent the atmospheric gamma-ray flux to lower energy side with more accurate statistics, and an effort along this line is now being expended.

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