An Upper Limit of Muon Flux of Energies above 100 TeV Determined from Horizontal Air Showers Observed at Akeno

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Abstract Determination of muon energy spectrum above 100 TeV by observing the extensive air showers from the horizontal direction(HAS) has been continued at Akeno for four years. No definite muon originated shower of sizes above 10^5 and zenith angles above 60^o has been observed. The upper limit of HAS intensity is $5x10^{-12}$ m^{-2} s^{-1} sr^{-1} (90% confidence level) above 10^5. The value indicates that the upper limit of muon flux above 100 TeV is about $1.3x10^{-8}$ m^{-2} s^{-1} sr^{-1} and is in agreement with that expected from the primary spectrum with a "knee", assuming scaling in the fragmentation region and 40% protons in the primary beam. The critical energy at which muon flux from prompt processes(decay of charmed particle) take over that from the conventional process is higher than 100 TeV at horizontal direction.

1. Introduction

The determination of the muon spectrum above 50 TeV is interesting in relation to the proton spectrum in the primary beam and the production cross-section of prompt muons through leptonic decay of charmed mesons($D,\bar{D}$) or charmed baryon(Λ_c^+) in hadronic interaction. Predictions of the prompt muon spectrum are made by various authors[(1)-(4)]. An estimated crossover energy where the prompt muon flux take over the ordinary muon flux is different from authors, ranging from 75 to 1000 TeV at horizontal direction[(5)] and hence some models may be discriminated with the present experiment.

The extensive air showers(EAS) observed at large zenith angle are most probably initiated by bremsstrahlung gamma-ray of high energy muons produced at the early stage of the shower development and are called HAS. This experiment was stimulated by the observation of muon poor showers at around 55^o - 60^o[(6)] as a supporting evidence of the flattening of muon spectrum by Mikamo et al[(7)]. By adding the timing channels and the track detectors of muons, the discrimination of HAS from EAS is much improved in this experiment.

2. Experiment

At Akeno air shower array, 153 unshielded scintillation detectors of 1 m^2 (6 of them 2 m^2) and 9 shielded detectors of 25 m^2(muon stations) are distributed over an area of almost 1 km^2[(8)]. At the center two towers of 10m height are built and the two detectors are arranged in order not to trigger the vertical small showers. Around the tower, 25 detectors of 1/4 m^2 area and 29 of 1 m^2 are arranged for the size and age determination of small HAS. Out of all scintillation detectors, 86 are accommodated with timing circuits. 28 channels are in the central part and their timing resolution is 2.5 nsec each. Others are detectors of 120m spacing with 10 nsec resolution[(9)]. At two of nine muon stations, two more layers of 50 proportional counters each are arranged 25 cm apart from the adjacent layers. Projected muon tracks obtained at two stations, in which proportional counters are arranged orthogonally to each other, are available to determine the zenith angle of muons.

The size and the arrival direction of the showers are determined by the least square fitting. For shower of size 10^5, the error in zenith angle determination is 3^o at the zenith angle of 60^o and 5^o at 75^o for small shower trigger. For large shower trigger that is about 8^o above 10^6 at 60^o. The zenith angles are also determined by measuring the muon tracks with three layer proportional counters. In case that the latter methods can be applied, zenith angle is determined within 3^o above 60^o. The error in size determination is less than 50% even for the flat shower of small size at 60^o.

Observation time is 1.07×10^8 sec. The effective collection area is size and age dependent and is evaluated by the Monte Carlo simulation.

3 Results

In fig. 1 are plotted N_e versus N_μ relation for showers of zenith angles larger than 60^o, which are selected by both timing and muon tracks. In case of muon poor showers, the arrival direction of some showers can not be determined by the muon tracks due to the lack of muons in three layer proportional counters. In such cases, the density map was used to check the arrival direction by comparing with that of artificial showers simulated with the determined electron size, core position and the arrival direction. The average N_e vs N_μ relations for showers of sec θ ranges 1.0 - 1.1 is drawn by a solid line for reference. The broken lines are upper and lower bounds of N_e vs N_μ relation for showers above 60^o estimated from the data distribution and the triggering inefficiency. There are many showers of relatively low muon contents for showers of small size. These are mainly due to the underestimation of muon size, since the number of detectors of zero muons increases for small showers.

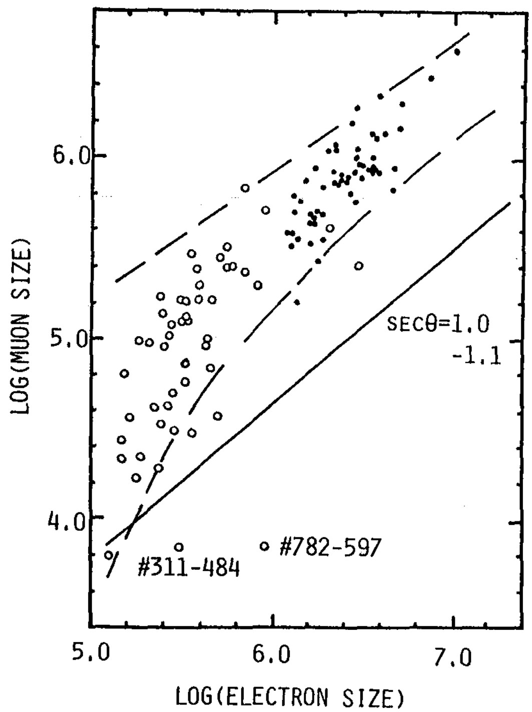

Fig. 1 Muon size vs. electron size for showers of zenith angles above 60^0. Two events with event numbers are candidates of HAS.

There are two showers whose muon contents are about 1/10 th of lower bound of N_e vs N_μ relations. In table 1 are listed the properties of two candidates at zenith angles above 60^o. These events are similar to the expected ones from HAS. However, there is no such candidate above 70^o against more candidates below 60^o. That is, the flux of this kind of

Table 1. Properties of two HAS candidates

Event No.	θ_{FT}	φ_{FT}	θ_μ	N_e	Age	N_μ	$(\frac{\rho_\mu}{\rho_e})$ at 32m
#311-484	68^o	163^o	$64^o \pm 3$	3.1×10^5	1.0	6.2×10^3	0.010 ± 0.008
#782-597	64^o	296^o	$63^o \pm 3$	9.6×10^5	0.65	7.5×10^3	0.004 ± 0.005

shower decreases with zenith angle and hence the zenith angle distribution is different from the expected one from conventional or prompt muons. Therefore, we can not conclude that these are showers initiated by high energy muons.

Assuming 1 event in each $\Delta \log N_e$ bin, the upper bound of the size spectrum of muon induced showers is evaluated. Since we have no definite HAS, the absolute value at 10^5 is determined by taking 2.3 events(C.L. 90%) above 10^5 after integrating $J(N_e)A(N_e)t\Omega dN_e$, where $A(N_e)$ is the size dependent effective area, and t and Ω are observed time and solid angle. The solid line with hatch in fig.2 shows the upper bound thus determined. The upper limit above 10^5 is 5×10^{-12} m^{-2} s^{-1} sr^{-1}.

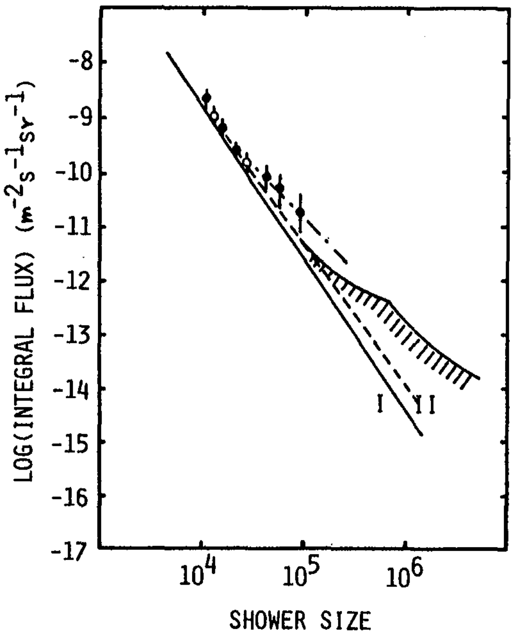

Fig. 2 Upper bound of HAS spectrum is shown by hatched area. Open circles are by Bohm and Nagano(10) and closed one by Mikamo et al(7). The expected HAS spectrum for two kinds of muon energy spctrum I and II are also shown.

4. Discussions

Though two events remained as candidates of muon induced showers among more than 500,000 triggered showers, they are not likely to be the showers initiated by muons from their zenith angle distributions. In fig.2, the previous results(7)(10) are also plotted. The flattening of muon spectrum is not observed in this experiment. If their spectrum extends further to our size region, we should observe HAS above 70^o more than 5 events during the observation time. The reason of the discrepancy of both experiments is not clear. The calculation of the effective area for each experiment was done by the same procedure. The acceptance times observation time for 10^5 of the present experiment is about three times larger than that of Mikamo et al(7).

The expected HAS spectrum from muon spectrum is evaluated and compared with the present upper limit of HAS spectrum. The muon spectra at 75^o are calculated by Mitsui(11) with two kinds of nucleon spectrum. The spectrum I is extrapolation of proton spectrum measured by Ryan et al(12) plus nucleon spectrum from other nucleus with the same proportion of each component at 1 TeV. The spectrum II is assumed one that the composition does not change, but the total energy spectrum with knee is taken into account. The results are shown in fig. 3, where the flux is multiplied by E^2. The broken line is that from the spectrum II and solid one from I. In the same figure prompt muon spectra calculated by various authors; EGS model 1, 2, 3(2), C(3) and IKK model 1, 2(4) are also drawn.

The expected size spectra at 75^o is derived by the Monte Carlo simulation by considering the bremsstrahlung process. The expected size spectra from I and II are drawn in fig.2 by a solid and a broken line, respectively. The upper bound at 10^5 is in agreement with the expected one from the primary spectrum with a "knee" and the so called "normal composition(40% protons)".

The present upper bound of HAS spectrum converted to muon energy spectrum is shown by shaded region in fig.3. The fluxes denoted by EGS model 1 and IKK model 2 are higher than our upper bound and hence may be

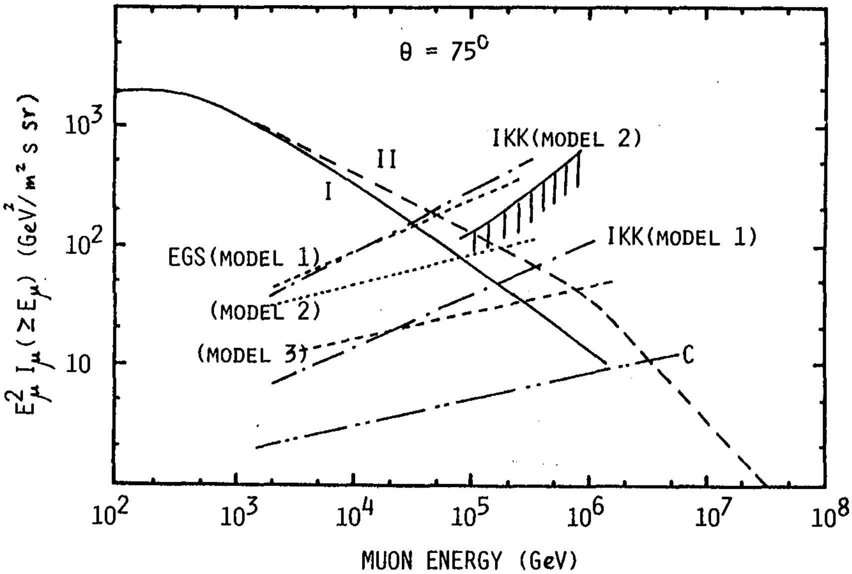

Fig. 3 Hatched region shows the upper bound of muon spectra estimated from the present upper bound of HAS spectrum. The muon energy spectra at $\theta=75^0$ calculated by Mitsui(11) with two different primary nucleon spectra I and II. The muon spectra from the prompt processes estimated by various authors are also shown.(2)(3)(4)

ruled out. The difference between models are mainly due to the differences of production cross-section of charmed particle and the fraction of energy delivered to charmed particle to incident energy. In case of EGS model 1, σ_{charm} (mb) = 0.36 ln(s/80 GeV^2). In model 2, this cross-section becomes constant(0.7mb) above s=4400 GeV^2. In two models denoted by IKK the diffractive production of D, $\bar{D}$ and Λ_c^+ are taken into account, whose contribution is about 40 times larger than their previous result with non-diffractive process[1]. This large difference is mainly due to the large transfer of energy to charmed particles in the diffractive process.

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