Primary Cosmic Ray Mass Composition Studies and Muon Size Spectra of Extensive Air Showers

N.P. Il'ina,[1] N.N. Kalmykov,[2] G.V. Kulikov,[2] V.P. Sulakov,[2] and E.A.Vishnevskaya[2]

(1) Department of Physics, Moscow State University, Leninskie Gory 1, 119992, Moscow, Russia

(2) D.V.Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory 1, 119992, Moscow, Russia

Abstract

Results of the primary cosmic ray mass composition studies in the knee region are discussed using the experimental EAS data on size spectra of different EAS components. Special attention is payed to muon size spectra at different threshold energies and certain contradictions are pointed out. The analysis is performed in the framework of the quark-gluon string model (QGSJET) and an attempt is made to explain the existing data.

1. Introduction

Forty-five years ago it was found [7] that the extensive air shower (EAS) size spectrum changes its slope at primary energy about 3–5 PeV. But the nature of this phenomenon still remains a puzzle though the existence of the so-called knee in the cosmic ray energy spectrum seems to be widely accepted. As there are no direct measurements at the knee region it is not possible to put forward ultimate arguments connecting irregularities in size spectra to the cosmic ray energy spectrum only. It is a common knowledge that studies of the mass composition in the knee region are necessary to solve the knee puzzle. The natural choice is to employ the data on electron and muon components of EAS. First such experiments were carried out long ago (see review [6]) but at those times low statistics and absence of reliable hadronic interaction models prevented to get really interesting results: only pure protons or pure iron nuclei could be excluded. Gradually this situation improved and it became possible to give more detailed predictions. For example, the analysis of the MSU data [2] led to the conclusion that the primary mass composition becomes essentially heavier at energies above the knee. Extensive studies of the primary mass composition have been performed recently by the KASCADE collaboration [8, 9] and even energy spectra of four nucleus groups have been obtained. The mass composition derived from electron and muon size spectra measured by the KASCADE array agrees well with the MSU

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conclusions. But the general situation with the mass composition near the knee remains contradictory and even such a robust value as mean logarithmic mass of primaries differs from one experiment to another at super-high energies.

In this paper we dwell specially on the shape of the knee in experimental electron and muon spectra.

2. Knees in electron and muon size spectra

As it stands now electron size spectra obtained with different arrays display usually quite traditional knees and the difference $\Delta\varkappa_{\rm e}$ spectral indices after and before the knee is about 0.4–0.5 at sea level. For example, the KASCADE data [4] gave $\Delta\varkappa_{\rm e} = 0.45 \pm 0.02$ and this agrees with the MSU data [3] and with the majority of other data as well. But for muons the situation seems to be more complicated. The KASCADE array which operates with truncated muon number (integral over muon density from 40 to 200 m) gives almost no knee in the muon size spectrum ($\Delta\varkappa_\mu$ is about 0.1 [9], see Fig. 1) whereas other arrays produce approximately the same knee for muons as for electrons (or even greater). Partly, this could be due to the influence of muon thresholds; besides, the energy dependence of the truncated muon number differs slightly from the one of the total muon number. The KASCADE array measures muons with energies > 0.2–0.3 GeV and the exponent of the energy dependence α_μ is close to 1 (0.97 according to [5] and our estimations). At the same time $\alpha_\mu \sim 0.87$ for 10 GeV muons measured at the MSU array. So there is no much use to refer to the data obtained with high muon thresholds as, for example, if we adopt a homogenous mass composition we should unavoidably expect $\Delta\varkappa_\mu$ to be significantly less at $\alpha_\mu = 0.97$ than at $\alpha_\mu = 0.87$. But it may be instructive to compare the KASCADE results with the recent data of the EAS-TOP array [1] where size spectra of muons with energies > 1 GeV were investigated. In [1] the following values of ($\Delta\varkappa_\mu$ were reported: 0.40 ± 0.14 for $1.00 < \sec\theta < 1.05$ and 0.45 ± 0.14 for $1.10 < \sec\theta < 1.15$. The latter interval almost exactly corresponds to the KASCADE array depth for nearly vertical showers presented in Fig.1. The value α_μ for 1 GeV muons is about 0.93–0.94, i.e., rather close to the α_μ for the truncated muon number. Of course, a certain difference should exist between the KASCADE and EAS-TOP data but this difference is to be much less pronounced than in the case of high thresholds. Though the experimental errors are substantial one may conclude that the EAS-TOP data correspond to the traditional notions concerning the knee.

If fluctuations play no essential role then taking into account that $\alpha_\mu \simeq 1$ we should obtain for the truncated muon number spectrum approximately the same $\Delta\varkappa_\mu$ as $\Delta\gamma$ for the primary energy spectrum (about 0.3–0.4). Under the same conditions the spectral index of the truncated muon number spectrum before the knee must be about 2.80 if we adopt 2.75 as the specral index of the primary energy spectrum. But the experimental spectral index is greater by ap-

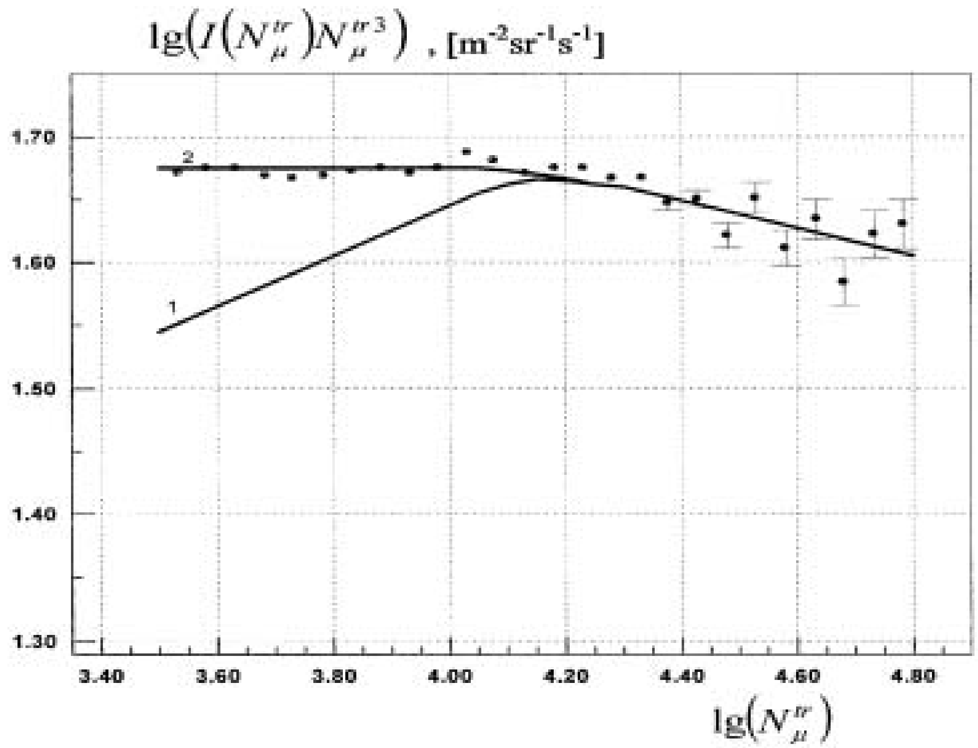

Fig. 1. Experimental truncated muon number for vertical showers obtained with the KASCADE array and results of calculations. Curve 1—the spectral index of the primary energy spectrum changes from 2.75 to 3.05; curve 2—the same spectral index but fluctuations of N_μ^{tr} increase as N_μ^{tr} decreases (see text).

proximately 0.2 and this throws doubt on the assumption that it is possible to neglect fluctuations. Instead another point arises—what fluctuations could produce necessary distortion of the experimental spectrum. Our estimations show (see Fig. 1) that the root mean-square deviation of $\ln(N_\mu)$ should increase from 0.30 to about 0.70 as the truncated muon number decreases from $1.26 \cdot 10^4$ (the knee point) to $3.2 \cdot 10^3$. This increase could hardly be due to the poissonian fluctuations because the number of muons registered by the KASCADE array remains sufficiently great (about 60) even at the lower limit. So some other reason must be responsible and the KASCADE group is in a better position to apprehend it.

3. Conclusion

It is possible to conclude that after a lond period of efforts contemporary EAS experimental arrays provide now a way of investigating the primary mass composition near the knee and estimating contributions of individual nuclear groups. This gives a clue to the knee origin. But at the same time there is still a number of serious problems. Certainly the main drawback of the deductions derived from EAS studies is the model dependence as one cannot guarantee the validity of models used outside the region where model parameters are established. Probably it is safe to assume that future LHC data will improve the reliability of model predictions.

It is of prime importance also to get around contradictory conclusions derived from experimental data obtained with different arrays.

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