CHANGE OF PRIMARY COSMIC RADIATION NUCLEAR COMPOSITION IN THE ENERGY RANGE $10^{15} - 10^{17}$ eV

T.T. Barnaveli∗(1), T.T. Barnaveli (jr) (1), A.P. Chubenko (2), N.A. Eristavi (1), I.V. Khaldeeva (1), N.M. Nesterova (2) and Yu.G. Verbetsky (1)

(1) Tbilisi Institute of Physics, Georgian Acad.Sci., Tamarashvili 6, Tbilisi 380077, Georgia
(2) Lebedev Physical Institute, Russian Acad.Sci., Leninsky prosp.53,Moscow 101000, Russia

Abstract

The dependence $E_h(N_e)$ of Extensive Air Shower (EAS) hadronic component energy flux on the number $N_e$ of particles in EAS is investigated in the primary energy range of the order of $10^{15} - 10^{17}$ eV. The work was aimed at checking the existence of irregularities of $E_h(N_e)/N_e$ behavior at these energies in several independent experiments. The investigation is carried out using large statistical material obtained at different configurations of experimental apparatus and under different triggering conditions.

The existence of irregularities of $E_h(N_e)/N_e$ behavior in the region $N_e > 2 \times 10^6$ is confirmed. These irregularities have the character of sharp deeps and are located near the same values of $N_e$ regardless of the experimental material and selection conditions used. So, at recent stage of research the existence of these irregularities of $E_h(N_e)/N_e$ behavior in the range of $N_e > 2 \times 10^6$ may be regarded as reliably established. This fact supports our earlier conclusion on the existence of primary cosmic radiation (PCR) nuclei spectra cutoff effect in the primary energy region $10^{15} - 10^{17}$ eV.

1 Introduction

In [1] - [5] we quoted some results which enable to suppose the existence of the PCR nuclei spectra cutoff in the energy range $10^{15} - 10^{17}$ eV. In [4] the analysis was based on the investigation of high energy muon groups in EAS.

The sharp decrease of the energy and intensity of high energy muon groups

∗e-mail: mantex@caucasus.net, barnaveli@hotmail.com
in EAS of primary energy higher than $2 \times 10^{16}$ was discovered. In [2, 3] and [4] the fluxes of the EAS hadronic component energy $E_h$ were analyzed. The essential irregularities of the type of strict deeps in hadronic component energy fluxes were discovered in the region of EAS particle numbers $N_e > 2 \times 10^6$, corresponding to the primary energies $E_0 > 5 \times 10^{15}$ eV.

Analysis of this phenomenon leads to the conclusion of the existence of PCR nuclei spectra cutoff in the primary energy region $10^{15} - 10^{17}$ eV [1] - [4]. In [1] and [3] the interpretation of this phenomenon was given - it can be explained by the destruction of PCR nuclei on some monochromatic background of interstellar medium, consisting of the light particles of mass < 30 eV.

The aim of this work is to carry out the investigation of EAS hadronic component energy flux using the additional statistical material, obtained at different configurations of the experimental apparatus and at different triggering and selection conditions. Thereby the aim was to compare the results of independent experiments.

Usage of essentially improved algorithms of data handling and increased capacity of computers made it possible to establish the EAS parameters with sufficiently high accuracy and to set much more rigid conditions at selecting the events in each separate case. This in turn enabled us to extract efficiently the peculiarities in $E_h(N_e)$ behavior and increase the accuracy of their localization along the $N_e$ axis. The above mentioned earlier results and conclusions were confirmed with high reliability.

2 Installation and experimental material

The archive material obtained by means of the hadron calorimeter of Tian Shan high mountain installation was used for the analysis. The Tian Shan EAS complex installation is located at the height of 3335 m above sea level. The detailed description of the installation can be found in [6]. The data bank was created in 1980 and its description is provided in [7]. The information concerning the EAS parameters was obtained by means of the part of the installation consisting of a central "carpet" of scintillators (64 x 0.25 m$^2$), of 8 groups of scintillators with a total area of 22 m$^2$, situated symmetrically at the distances of 15 and 20 m from the center of installation and of a group of scintillators with a total area of 10 m$^2$ at the distance of 73 m from the center of installation. The accuracy of the EAS coordinate estimation rises with the increase of EAS age parameter and of $N_e$. At $N_e = 10^5$ the error is approximately 0.6 - 0.7 m [8]. Taking into account that in our consideration the most important region of $N_e$ is higher than $4 \times 10^5$, the corresponding error will not exceed the above mentioned value. The energy flux of EAS hadronic component was measured by means of a multilayer ionization calorimeter with the area of each layer 36 m$^2$. At different stages of the experiment the calorimeter contained from 16 to 19 layers of ionization chambers with the total number of chambers from 768 to 912 correspondingly. Between the layers of chambers lead filters of the total thickness 1050 g/cm$^2$ were situated.

As is well known the data obtained with the ionization calorimeter at the energies under consideration do not allow for distinguishing the separate hadrons, especially in the central parts of EAS. One can judge about the number of particles and about their individual energies only approximately, by indirect
methods. Therefore we analyze immediately the energy fluxes of hadrons inside the fixed circle of a fixed radius around the center of EAS as a function of the particle number \( N_e \) in EAS or of the primary energy \( E_0 \).

The importance of the precise measurement of the distance from the hadron energy registration point to the EAS axis is obvious. Consequently the analysis was focused on the investigation of the energy flux through each separate chamber of the calorimeter in each event. For each single chamber the distance from its geometrical center to the shower axis was measured taking into account the axis inclination angle. The whole interval of investigated distances was divided into sections of the \( R \) cm length. \( R = 20 \) cm when working inside the 14 m diapason of core distances (the basic working diapason) and \( R = 1 \) m when working inside the 70 m diapason. In each separate event the contribution of energy flux through each chamber to the energy flux for each section of distances was taken into account. The measured part of the EAS spectrum was also divided into small intervals with respect to the \( N_e \) (providing the optimal statistics for each of the intervals). For each interval of \( N_e \) the mean value (over all events of this interval) of the energy flux density at the given distance from the EAS axis was derived. The result was multiplied by the area of \( R \) cm width ring of the mean radius equal to given distance. After this procedure it becomes possible to estimate the flux of hadron energy for each interval of \( N_e \) within the desired intervals of core distances.

The whole experimental material was processed in the computing centers of the Institute of Physics of the Georgian Academy of Sciences, of the Ministry of Communications of Georgia and in the computer firm Mantex Ltd. (Tbilisi).

As compared with [2, 5] the body of processed statistical material was increased essentially and further improvement of algorithms and data handling methods was carried out. As well as increased precision this gave us the possibility to widen the diapason of \( N_e \) under investigation.

The data of the different runs of experiment were analyzed. These runs differed by configuration of calorimeter (number of layers and presence or absence of target), by triggering conditions and by criteria of preliminary selection of events. As it was said above, at different runs of the experiment calorimeter contained from 16 to 19 layers of ionization chambers. Above the calorimeter was placed or was absent the carbon target which was 800 g/cm\(^2\) thick. The triggering conditions also might differ in different runs. In accordance with this the whole analyzed material may be naturally divided in parts, in frames of which the configuration of the calorimeter, triggering criteria and selection conditions remained stable. The triggering conditions and conditions of event registration are described in detail in [7].

The events registered at different configurations of installation and at different triggering conditions were selected according to the following conditions:

a) One part of the used archive bank contains the events which were subjected to preliminary selection at time of the creation of the bank. The requirements of selection were: the density of electrons at the distance 73 m from the center of installation greater then 0.45 particles/m\(^2\); X, Y coordinates of EAS axis intersection with the plane of the central scintillator carpet less then 7.0 m; EAS age parameter 0.4 < s < 1.6; total number of particles in EAS \( N_e > 1.3 \times 10^5 \). By reprocessing of these data under the new conditions a part of the calculated parameters shifted in one or another direction, often by a rather large factor.
b) Another part of the bank is constituted of events which were not subjected to the preliminary selection procedure. According to the conditions of recent processing of the data the selected events would satisfy the following requirements: at least one particle must be registered in each group of scintillators at distances 15, 20 and 73 m and in the central carpet; X,Y coordinates of EAS axis intersection with the plane of the central scintillator carpet less then 100 m; age parameter $0.3 < s < 1.9$. Namely under these conditions were reprocessed the events of "a)" above as well. Criterion "b)" is much more liberal then criterion "a)" however the data handling process itself is carried out with the maximum accuracy achievable to-day.

At the final stage of analysis an additional restrictions were put on the diapason of distances, on age parameter $s$ and on the precision and reliability of fitting of all basic parameters in each separate event.

In such a way the analysis was carried out using the criteria "a)" and "b)" for the 16-layer calorimeter without target and using criterion "b)" for the 19-layer calorimeter with the target and without it. Moreover, the statistically greater material, obtained by means of the 16-layer calorimeter without the target, was divided into two parts of almost equal bodies with different diapasons of registration zenith angles of 0 - 20 and 20 - 30 degrees. The aim was the same - to check the presence and localization of peculiarities of $E_h(N_e)/N_e$ behavior at different zenith angles of event registration.

200 000 events were selected out of the whole body of bank - 350 000 events, according the above quoted criteria. In the final results 51 000 events contributed due to screening by the conditions of the diapason of distances, of age parameter and of EAS parameters fitting the accuracy requirement needed.

3 Experimental results and discussion

The specific energies $E_h(N_e)/N_e$ of EAS hadronic component for the above quoted configurations of installation and selection conditions are given in Fig.1:

- curve 1 - 16 layer calorimeter, without target. The material not subjected to preliminary selection was handled according to criterion "b)" 37000 events in total. The diapason of registration zenith angles 0 -30 degrees.
- curve 2 - 16 layer calorimeter, without target. The material subjected to preliminary selection, was then handled according criterium "b)" 8 000 events in total. The diapason of registration zenith angles 0 - 30 degrees.
- curve 3 - 19 layer calorimeter, with target. The material subjected to preliminary selection, was handled according to criterion "b)" 6 000 events in total. The diapason of registration zenith angles 0 - 30 degrees.
- curves 4 and 5 - the material constituting the curve 1 is divided in two parts according to the diapason of registration zenith angles - 0 - 20 degrees (19 000 events) and 20 - 30 degrees (18 000 events) correspondingly.

The lower borders by $N_e$ are determined by the material available to-day and by triggering conditions (curves 1, 4 and 5) or by conditions of preliminary selection (curves 2 and 3). The upper borders are determined by statistical restrictions due to high steepness of EAS spectrum $I(N_e)$. The error bars allow for statistical errors. The errors of $N_e$ determination are of the order of 10 %. The difference of mean slopes of the curves to the left from the values $N_e < 10^6$ is easy to explain by the difference in triggering conditions $E_h(N_e)/N_e$ and of
The specific energies $E_h(N_e)/N_e$ of EAS hadronic component for the different configurations of apparatus and selection conditions. Details are given in the text. The left vertical scale (arbitrary units) is given for curve 1. The other curves are slightly shifted up or down to separate them from one another and to clarify the picture. The corresponding parts of vertical scales are shown at the right edge of the figure.

In the region of $N_e > 5 \times 10^5$ the deeps on dependence $E_h(N_e)/N_e$ are observed. Most clearly these irregularities are revealed in the region $N_e > 2 \times 10^6$, where the identical localization of these phenomena on all shown curves may be easily traced. The indicated deeps in $E_h(N_e)/N_e$ dependence are located in the regions of the same values of $N_e$, regardless of experimental material used and of triggering and selection conditions (curves 1, 2 and 3). Moreover, the localization of these deeps does not depend on the zenith angle of event registration (curves 4 and 5).

In the region of relatively low values of $N_e$, namely at $5 \times 10^5 < N_e < 2 \times 10^6$ the mutually equivalent irregularities may be seen as well. Here however the further increase of accuracy and of statistics is required. In the region $N_e < 5 \times 10^5$ at this stage of investigation the $E_h(N_e)/N_e$ dependence behavior reveals as completely smooth.

Actually here we are dealing with the results, obtained in several independent experiments. So at the given stage of data processing one can regard the existence of irregularities on $E_h(N_e)/N_e$ dependence as reliably established one.

Apparently the nice possible explanation for the creation of such behavior of EAS hadronic component flux can be given if one supposes the existence of PCR nuclei spectra cutoff in the primary energy region $> 10^{16}$ eV. The destruction of PCR nuclei is caused by their interactions with some light particle (component of nonbaryonic dark matter?) forming the monochromatic low temperature background in the interstellar space \[1,3\].

According to this picture the cutoffs of PCR nuclei spectra have a threshold character and depend on the primary energy of the nucleus and on the energetic
threshold of its destruction. For the heavy nuclei of Fe group this phenomenon takes place at \( N_e \)s higher then \( 1.5 \times 10^7 \), which correspond to primary energies of the order of \( 2.6 \times 10^{16} \) eV. The deeps at the \( N_e \) values higher than \( 2 \times 10^6 \) and \( 6 \times 10^6 \) are reflecting the destruction of He group and of middle group nuclei. At the energies higher then \( 5 \times 10^{16} \), at which the nuclei of Pb group are destructed (the last deep on the curve 1), the protons are dominating in the composition of PCR, may be with exception of small part of survived nuclei and of the most heavy nuclei like Uranium. The latter are destructed at the energies of the order of \( 10^{17} \) eV.

4 The mechanism of the irregularities formation

The essence of the deep formation mechanism on \( E_h(N_e)/N_e \) dependence is as follows. At a fixed value \( E_0 \) of primary particle energy the number \( N_e \) of particles in EAS fluctuates within a rather wide range with the certain mean value \( N_e' \) , and vice versa, the certain value of \( N_e \) can be registered in EAS initiated by the primary particle of the energy wedged within a rather wide interval of primary energies with the certain mean value \( E' \). There is some balance of contributions in showers of the given \( N_e \) from primary particles of different energies, depending on the slope of their spectrum.

Let the spectrum of the given certain component of PCR have the form \( I(E) = K^{-r} \). Now let the spectrum of a given component of PCR be cut off above some fixed value of primary energy \( E^* \) (cutoff energy), i.e. at primary energies higher then \( E^* \) the flux of this component of PCR sharply decreases (the value of coefficient \( K \) falls sharply). It is clear that the spectrum of the corresponding EAS will not be cut off above the value \( N_e' \) since the showers of the sizes \( N_e > N_e' \) will still be registered due to fluctuations of \( N_e \) in the showers of total energy \( E_0 < E^* \). The showers initiated by the primary particles (of the PCR component under consideration) of the energy \( E_0 > E^* \) will be present in extent of the new value of coefficient \( K' \). It is established that \( E_h \) rises in average with the rise of \( E_0 \) (and thus with the rise of \( N_e \)). Besides, at the fixed energy \( E_0 \) the anticorrelation of \( E_h \) and \( N_e \) fits naturally with the account of the approximate conservation of the sum of \( e^- \) and \( h^- \)-component energies. It follows here from, that in the case of spectrum cutoff the flux of hadron energy in EAS of \( N_e > N_e^* \) will decrease in average as compared with the case of the absence of cutoff, since the EAS for such \( N_e \)-s now will be generated by the primary particles of the energies \( E_0 < E^* \). The balance of contributions in showers of some given \( N_e \) generated by primary particles of different energies will be violated. The width of the interval in which this effect does occur will be of the order of width of the fluctuations of \( N_e \). At higher \( N_e \)-s exceeding the frames of this interval, all manifestations of the flux of this component will decrease sharply. However above the indicated interval the balance of contributions restores again and the mean energy of hadrons in EAS reaches its previous level. In the case of complete cutoff of the spectrum EAS from this component will vanish completely. For the mixed composition of PCR the spectra of different components will be cut off at different \( E^* \)-s and one has to expect deeps on the \( E_h(N_e)/N_e \) plot near the corresponding values of \( N_e \)-s. The widths of these deeps are determined by the ranges of \( N_e \).
fluctuations.

This mechanism of $E_h(N_e)/N_e$ dependence formation is analyzed in detail in [3], where the principles and results of the calculation of its expected features are given. It is to be noticed however, that the level of data processing and analysis in [3] was lower then reached to day, so the numerical values of model parameters and the localization of the signals along the $N_e$ axis differ remarkably from the present results. New parameters, corresponding to recent level of data handling are in preparation and will be published soon.

ACKNOWLEDGMENTS

The authors express their deep gratitude to O.V.Kancheli for numerous fruitful discussions and advise. The authors are sincerely grateful to Yu.D.Kotov for discussion, V.P.Pavluchenko and V.I.Iakovlev for useful discussions concerning the data bank and installation, N.R Tkeshelashvili, D.R .Tomadze and A.G.Mulkidjanian - the members of the staff of the Ministry of communications of Georgia - for their assistance in primary treating of the data array, J.M.Henderson - for interest to this investigation and his assistance in preparation of this paper.

This investigation is in part supported by a grant from the Georgian Academy of Sciences and by the firm Mantex ltd. (Tbilisi).

References

[1] T.T.Barnaveli, I.V.Khaldeeva, Z.T.Shergelashvili and N.A.Eristavi, Phys. Lett., B 346 (1995) 178.
[2] T.T.Barnaveli, T.T.Barnaveli(jr), A.P.Chubenko, N.A.Eristavi, I.V.Khaldeeva, N.M.Nesterova and Yu.G.Verbetsky, Phys. Lett., B 369 (1996) 372.
[3] T.T.Barnaveli, T.T.Barnaveli(jr), N.A.Eristavi, I.V.Khaldeeva, and Yu.G.Verbetsky, Phys. Lett., B 384 (1996) 307.
[4] T.T.Barnaveli, T.T.Barnaveli(jr), N.A.Eristavi, I.V.Khaldeeva and Yu.G.Verbetsky, in Very high Energy Phenomena in the Universe. Rencontres de Moriond, (1997) 419.
[5] T.T.Barnaveli, T.T.Barnaveli(jr), A.P.Chubenko, N.A.Eristavi, I.V.Khaldeeva, N.M.Nesterova and Yu.G.Verbetsky, Izvestia RAN., ser. phys. (2001) v.65, N11, 1631.
[6] T.P.Amineva, V.S.Aseikin, Iu.N.Vavilov et al. Trudi FIAN v.46 (1970) 157.
[7] N.M.Nikolskaia and E.I.Tukish, Preprint FIAN 91 (1980)
[8] V.S.Aseikin, N.G.Vildanov, A.G.Dubovoi et al. Preprint FIAN 215 (1982).