Estimation of Primary Cosmic Ray Energy Registered at the EAS Yakutsk Array

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Abstract

The energy for primary particles generating showers in the energy interval of $10^{17} - 10^{19}$ eV is estimated by using EAS Ĉerenkov light data at the Yakutsk array. For vertical showers the main relations between the energy and measured parameters $S300$ and $S600$ obtained by the calorimetric method are given. $S300$ and $S600$ depending on a zenith angle are studied. The change of these parameters in the wide region of atmospheric depth can be described as a sum of two exponents with strongly different attenuation lengths.

1. Introduction

The primary energy E_0 at the EAS arrays is estimated by a base parameter determined experimentally. Usually the relation between such a parameter and E_0 at the atmospheric depth X_0 corresponding vertical showers ($\vartheta = 0^o$) is found. To estimate E_0 in the events with $\vartheta \geq 0^o$, the found value of parameter is recalculated to the vertical level according to a zenith angular dependence. In the most experiments this relation is determined for the vertical showers by means of model calculations. At the EAS Yakutsk array three main components are measured: the charge particle flux, Ĉerenkov light and muon component. It allows to use the calorimetric method to estimate the energy and obtain experimental relations between the base parameters and primary energy [1].

2. Calorimetric Method

The relation between the measured parameters $S300$, $S600$ and primary particle energy for the showers, close to the vertical, was determined by the calorimetric method [1, 3]. The basis for this method is the experimental estimation of the energy, dissipated by a shower over the observation level, by using EAS Ĉerenkov light measurements. The showers with $\vartheta < 20^o$ are selected in the groups with different values of $S600$ ($S300$). The total energy E_0 in each group

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is determined as a sum of several components:

$$E_0 = E_i + E_{el} + E_\mu + E_{\mu i} + E_\nu + E_h, \tag{1}$$

where E_i is energy lost by a shower over the observation level, it is $\sim 70\%$ and estimated by measurements of total Ĉerenkov light flux; E_{el} is the energy conveyed below the array level, it is estimated by the attenuation of the number of charged particles through the atmosphere depth; $E_\mu + E_{\mu i}$ is the energy of the muon component, it is estimated by the total number of muons at the absorption level; $E_\nu + E_h$ is the energy of the neutrino and on nuclear reactions in the atmosphere, it is added on the basis of model calculation results ($< 5\%$).

If $S300$ and $S600$ will be recalculated to $X_0 = 1020$ g cm^{-2}, corresponding to $\vartheta = 0^o$, then we obtain:

$$E_0 = (6.5 \pm 1.6) \cdot 10^{16} \cdot S300(0^o)^{0.94 \pm 0.02} \text{ eV} \tag{2}$$

$$E_0 = (4.6 \pm 1.2) \cdot 10^{17} \cdot S600(0^o)^{0.98 \pm 0.03} \text{ eV} . \tag{3}$$

The main contribution to an error for the constant multiplier in (2) and (3) gives the uncertainty of the absolute calibration of the Ĉerenkov light detectors which is constant for all energies and cannot influence on the energy spectrum form.

3. Zenith-Angular Dependence of $S300$ and $S600$

To determine the primary energy for the individual shower on (2) and (3), the value of $S300$ or $S600$ for the zenith angle ϑ must be recalculated to $\vartheta = 0^o$ according to the corresponding attenuation length $\lambda 300$ for $S300$ and $\lambda 600$ for $S600$. To determine $\lambda 300$ and $\lambda 600$, the change of these parameters depending on ϑ at the fixed energy must be studied. For this purpose, besides of the equi-intensity method, at the Yakutsk array the experimental parameter $Q400$ (density of Ĉerenkov light flux at the 400 m distance from a shower core) is used. $Q400$ is a good equivalent of the primary energy which is practically independent of ϑ, if the absorption of light in the atmosphere is taken into account.

In Fig. 1 the open indices ($S1 - S7$) are the values of $S300$ at the different atmospheric depth X, corresponding to 7 different values of fixed intensities for the spectra in different angular intervals. Solid indices ($Q1 - Q6$) are $S300(X)$ for 6 energy intervals by using $Q400$. Experimental points for the two methods are consistent with each other quiet well.

The analysis of the dependence obtained for depths $X < 1500$g cm^{-2} of a form

$$S300(\vartheta) = S300(0^o) \cdot \exp\left((X_0 - X)/\lambda_{300}\right) \tag{4}$$

$$X_0 = 1020 \text{ g cm}^{-2}, X = X_0 / \cos\vartheta$$

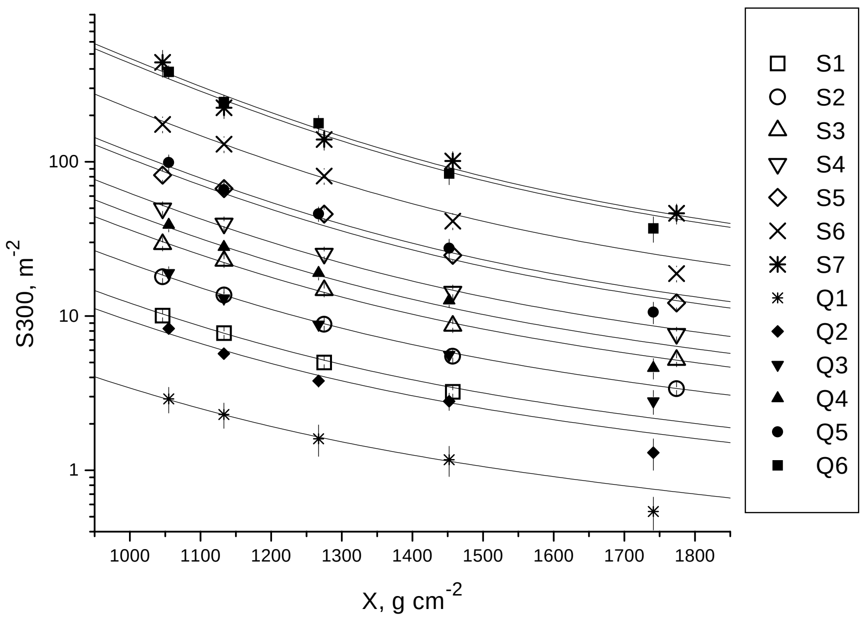

Fig. 1. $S300$ versus the atmospheric depth X for different energies. Open indices ($S1-S7$) are equi-intensity method data, solid indices ($Q1-Q6$) are data by $Q400$ method

shows that the change of $S300(\vartheta)$ for each group of energies is consistent with the constant $\lambda300$ within the experimental errors. If we use data of both methods then we obtain the following formula:

$$\lambda300 = (434 \pm 15) - (62 \pm 9) \times \lg\left(S300(0^o)\right). \quad (5)$$

Experimental data by $S300$ for great depths ($\vartheta > 45^o$) don't consistent with (4) and (5) that leads to the significant excess in estimation of the primary energy. Previously [2] we used a formula where $\lambda300$ depended on both E_0 and the depth. To take into account the analogous effect in the exponent index, at the AGASA array [4] the third degree polynomial by X is used. Such a description of the dependence is not visual to interpret physically the shower development. The parameter $S300$ reflects the behavior of a charged particle. Electrons and muons contribute to the scintillation detector response. The electron component damps in depth considerably more quickly than the muon component. Therefore we assume that the actual change of $S300$ ($S600$) depending on the atmospheric depth must be described as a sum of soft and hard components having the different attenuation lengths:

$$S(\vartheta) = S(0^o) \cdot (1-\beta) \cdot \exp\left((X_0 - X)/\lambda_E\right) + \beta \cdot \exp\left((X_0 - X)/\lambda_M\right), \quad (6)$$

where λ_E is the attenuation length for the soft component (electrons), λ_M is the same for the hard component (muons), β is a portion of the hard component in the total response of $S(0^o)$ at the depth of 1020 g cm^{-2}. As the number experimental points is small for each energy, in the fitting procedure we taken $\lambda_E = 200$ g cm^{-2}, $\lambda_M = 1000$ g cm^{-2} which were approximately consistent with the attenuation length for electrons and muons, respectively. Determining parameters $S300(0^o)$ and β_{300} and in (4) we use values X corresponding to $\vartheta < 45^o$.

The experimental dependence of parameter β_{300} on $S300(0^o)$ can be described by the formula:

$$\beta_{300} = (0.563 \pm 0.032) \cdot \ S300(0^o)^{-0.185 \pm 0.02}. \quad (7)$$

The solid lines in Fig. 1 are the change of $S300$ depending on the atmospheric depth by using (6) and (7). It is seen that the curves describe well experimental data for $\vartheta < 45^o$ and are consistent with the points for $X = 1750$ g cm^{-2} which did not take into account at the selection of parameters.

The analogous consideration by (6) and using the same λ_E and λ_M leads to the following formula for β_{600}:

$$\beta_{600} = (0.62 \pm 0.06) \cdot \ S600(0^o)^{-0.076 \pm 0.03}. \quad (8)$$

4. Conclusions

The dependence of $S300$ and $S600$ on the atmospheric depth in the form of (6) with two attenuation lengths and the decrease of a portion of the hard component with the increase of the energy according to (7) and (8) is consistent with experimental results quiet well for the two methods. Formulae (2), (6), (7) allow to estimate the primary energy for individual showers with $E_0 > 10^{17}$ eV by $S300$ or $S600$ for $\vartheta \leq 60^o$. The suggested parameters β_{300} and β_{600} characterize a contribution of muons and electrons associated with them to the total density of charged particles at the distances 300 and 600 m from a shower core at the atmospheric depth $X_0 = 1020$ g cm^{-2}.

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