The excess of muon-rich EAS cores detected in lead ionization calorimeter at Tien-Shan mountain station

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Abstract: We confirm the result, obtained earlier at Tien-Shan mountain station with the large 36 m² lead calorimeter, that in extensive air showers (EAS) with energies of few PeV the attenuation of core energy deposit in lead becomes slower than at lower energies and than it could be predicted by modern codes. To study the absorption of EAS hadrons and muons in a lead ionization calorimeter the EAS development in the atmosphere was simulated in the framework of the CORSIKA+QGSJET code whereupon the passage of hadrons and muons through the lead calorimeter has been modeled with using the FLUKA transport code. It is shown that this effect is connected with the appearance of the excess (8 ± 3%) of abnormal cores with a large ionization released in lower layers of the calorimeter and these EAS cores attenuate in a lead as high-energy muon groups. Neither the abundance of heavy nuclei in primary cosmic ray flux, nor the prompt muons originated in the atmosphere from charmed particles can help to explain this excess.

Introduction

A development of extensive air showers (EAS) originated by high-energy primary cosmic rays have been studied during half a century. However only a few EAS arrays included the deep hadronic detectors to study an absorption of EAS hadron component in the substance that is very sensitive to the composition of the core particles. The oldest array where the EAS hadron component was studied in detail with the big lead ionization calorimeter (BIC) is the EAS array of the Tien Shan mountain station sited at 3340 m a.s.l. Data obtained by this array continue to be unique due to a calorimeter’s large area (36 m²) and a large thickness (850 g·cm⁻²), that corresponds to five proton’s mean free paths.

One of the unexplained results obtained with BIC is the growth of the absorption length with rise of primary energy [5], that was explained by the charmed particle generation with large cross sections being much higher than it is predicted from the theory.

The main goal of this work is to analyse this effect from the other point of view and check the hypothesis that the change in the absorption length of EAS cores can be associated with the change in composition and spectra of EAS core particles, since the EAS-core absorption in lead depends on energy spectrum of EAS core hadrons very significantly [4].

Experimental data used for the analysis

The Tien-Shan big ionization calorimeter (BIC) of 36 m² cross-sectional area consists of lead layers interspersed by 5.5 × 11 × 300-cm³ copper-wall ionization chambers. The ionization chambers are filled with argon at a pressure of 5 atm. The active readout layers are alternated with the lead layers of thickness 2.5 or 5 cm. The overall thickness of the calorimeter is 850 g·cm⁻². The total number of the active layers was equal to 15 during the earlier exposure ("old BIC") and 17 during the later one ("new BIC"). For the analysis, we use published data [2] concerning average ionization curves (be-
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low the dependence of ionization on calorimeter’s depth is called the ionization curve). Besides we use the bank of individual cascades presented by V.I.Yakovlev.

Codes used for simulations

We used CORSIKA+QGSJET02 code to simulate EAS’s at the mountain level. To calculate the EAS core particles passage through the BIC, a new version of the FLUKA particle transport code [1] was used. This code was chosen because some low energy processes (neutron cascade, nuclear disintegrations and so on) playing important role in the formation of ionization in calorimeters are included very accurately.

Comparison of simulated and experimental average ionization curves

Average ionization experimental curves $I(H)$ for EAS cores sampled in different groups by the energy $E_h$ released inside the calorimeter were plotted [2]. In the every group an absorption length $\Lambda$ was measured in the interval $H = 340 - 850$ g/cm$^{-2}$ by fitting the experimental points by exponential function $I \sim \exp(-H/\Lambda)$. We apply the same procedure for experimental and simulated cascades.

In Figure 1 the measured values of $\Lambda$ are presented in dependence on effective primary energy $E_{0 \text{eff}} = \langle E_h \rangle / K_{ef}$ ($K_{ef} = 0.043$ see [3]) for two series of measurements: "new BIC" and "old BIC" in a comparison with the theoretical dependence, calculated for primary protons. The same values of $\Lambda$ were obtained for primary helium and carbon nuclei. One can see that the calculated absorption length very slowly increases with the growth of effective energy, while the experimental values of $\Lambda$ start to rise rapidly at primary energy near a few PeV.

Comparison of simulated and experimental individual ionization curves

Further we investigate the dependence of the absorption length in different groups of simulated EAS cores on the various characteristics of air showers. It was obtained that the value of absorption length depends negligibly on a cosine of a zenith angle, a sort of primary particle, a primary energy, a hadron energy of EAS, a model of interactions and so on. It was noted that calculated ionization curves are getting smooth with growth of core energy due to an obvious increase on the number of hadrons in the core. But many from high energy experimental ionization curves have very irregular shape in a contradiction with the expectation.

For the quantitative analysis of different types of ionization curves (IC) we introduced 4 parameters characterizing the shape of the every individual curve in a comparison with the pure exponential approximation in the interval $340 - 850$ g/cm$^{-2}$:

1) depth of the calorimeter where the maximal ionization was produced – $H_{\text{max}}$;
2) value of maximal ionization relatively to the exponential approximation – $Y_{\text{max}}$;
3) value of the ionization in the end 15th layer relatively to the exponential approximation – $Y_{\text{end}}$;
4) the value of the remaining ionization in the calorimeter – $\Delta I$.

Figure 1: Measured values of $\Lambda$ in dependence on effective primary energy for two series of measurements: "new BIC" (open squares), "old BIC" (big stars) in a comparison with the theoretical dependence, calculated for primary protons (full circles).
4) diversity of an ionization in different $N$ layers $(I_{exp})$ in relation to the exponential approximation $(I_{app})$: $\chi^2 = \left(\Sigma((I_{exp} - I_{app})/I_{app})^2/N\right)^{1/2}$.

The last parameter reflects the irregularity of ionization curves.

Further we consider these parameters of individual experimental curves in the energy interval $E_h = 80 - 400$ TeV and individual simulated ionization curves, selected with the same $E_h$, in the dependence on the value of $1/\Lambda$. All EAS cores with $1/\Lambda < 0$ can be considered as EAS cores with a slow absorption in lead.

In Figure 2 we present the scatter plots $\chi^2 - 1/\Lambda$, $H_{\text{max}} - 1/\Lambda$, $Y_{\text{end}} - 1/\Lambda$ for experimental and simulated events. All enumerated parameters for the value $1/\Lambda < 0$ are noticeably larger than those for the simulated cores. It means that the abnormal absorption is connected with the appearance of cores with the large ionization released at the large depth of the calorimeter. The similar plot: $\chi^2 - 1/\Lambda$, $H_{\text{max}} - 1/\Lambda$, $Y_{\text{end}} - 1/\Lambda$ calculated for lower energies $E_h = 5 - 10$ TeV reproduces well the experimental parameters. We checked the influence of additional fluctuations in measured value of ionization. Even if we introduce the additional non controlled fluctuations 30%, the excess could not be explained, because in this case we should observe the excess of small value of $H_{\text{max}}$ and $Y_{\text{end}}$ also.

The ionization curves of abnormal events look like ones produced by the group of high energy muons. To demonstrate this conclusion we present in Figure 3 only muon content of the simulated ionization curves. One can see that groups of muons in air showers explain very well the area of small value of $1/\Lambda$ and large value of $H_{\text{max}}$, $\chi^2$, $Y_{\text{end}}$.

Comparing the calculated and experimental data we have estimated that the excess of muon-like ionization curves is about $(8 \pm 3)\%$ at $E_h > 80$ TeV. We considered several possible explanations of the excess: nor the abundance of heavy nuclei in primary CR nor the 'prompt' muons originated in the atmosphere from the charmed particles. It requires for the explanation a new process, responsible for the appearance of excess of ionization at large depth of lead.

We do not touch the hypothesis of generation of charmed particles with large cross section in the
interaction of core particles with lead [5], but it can explain (in contradiction with muons) the irregular energy behavior of attenuation length found in the experiment (see figura 1).

**Conclusions**

It was shown that for the EAS with energy around a few PeV the absorption of energy in lead becomes slower than it is predicted by the modern codes. This effect could be connected with the appearance of the excess (about 8%±3%) of EAS cores with the ionization curves in lead which look like the ionization curves of high-energy muon groups.

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**References**