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HIGH-ENERGY MUONS IN *PAMIR* EXPERIMENT

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Here we present an alternative explanation of the anomalies in hadron absorption in lead observed at an energy of about tens of TeV in deep lead X-ray emulsion chambers in the *Pamir* experiment [1, 2]. We check hypothesis proposed in [3] that high-energy muons with energy > 100 TeV are present in the atmosphere and can give the origin of additional cascades detected at large depth of lead.

Предлагается альтернативное объяснение аномалии в поглощении адронов с энергиями в десятки ТэВ в свинце, обнаруженной в эмульсионных свинцовых камерах эксперимента «Памир» [1, 2]. Проверяется гипотеза, предложенная в [3] и состоящая в том, что в атмосфере присутствуют высокоэнергичные мюоны с энергией более 100 ТэВ, которые и генерируют избыточные каскады, регистрируемые на больших глубинах свинца.

It is well known that the spectrum of atmospheric muons is very steep $I_\mu \sim E_\mu^\gamma$, $\gamma \sim -3.7$ (while $\gamma \sim -2.7$ for the primary proton spectrum) due to muon production through pion and kaon decays: with the rise of energy the meson decay length increases, and they begin to interact but not decay. So the intensity of high-energy muons is small. In principle, an additional component of muons with γ close to -2.7 can exist: prompt muons produced through charmed particles decays. Recently one more possible source of high-energy muons in the atmosphere was proposed [3]: «muons from the knee». This hypothesis can explain the sharp shape of the knee in primary cosmic-ray spectrum observed by means of extensive air showers (EAS). The knee means a very quick change of the slope from $\gamma = -2.7$ to $\gamma = -3.1$ at an energy of about 3 PeV. It was assumed [3] that a new process starts to work at this energy when part of the primary energy (missing energy $E_{\rm mis}$) is carried away by a component weakly absorbed in the atmosphere and not detected by EAS arrays. If the real CR spectrum is approximated as $E_{\rm real}^{-2.7}$ in full energy range, then the observed one should have a sharp knee at energy $E_{\rm knee}$ if $E_{\rm mis}$ satisfied the condition [3]:

$$E_{\rm mis} = E_{\rm real}(1 - (E_{\rm real}/E_{\rm knee})^{(\gamma 1-\gamma 2)/\gamma 2}); \quad E_{\rm obs} = E_{\rm real} - E_{\rm mis}, \qquad (1)$$

here $\gamma 1$ and $\gamma 2$ are the slopes of the spectrum measured before and after the knee; $E_{\rm real}$ is the real energy; $E_{\rm obs}$ is the energy measured by EAS arrays. It

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was proposed also that the part K_μ of missing energy is carried away by high-energy muons. The shape of the muon spectrum depends on K_μ as it can be seen from Fig. 1, where expected muon flux predicted by this model for different values of $K_\mu = 0.01, 0.05, 0.25$ is shown. One can see that there is a very flat part of the expected muon spectrum around the 100 TeV region due to a sharp start of the new process, much flatter than the spectrum of prompt muons. A goal of this paper is to understand whether this hypothetical muon component can reveal itself in deep lead chamber of *Pamir* experiment and explain the excess cascades detected at large depth of lead.

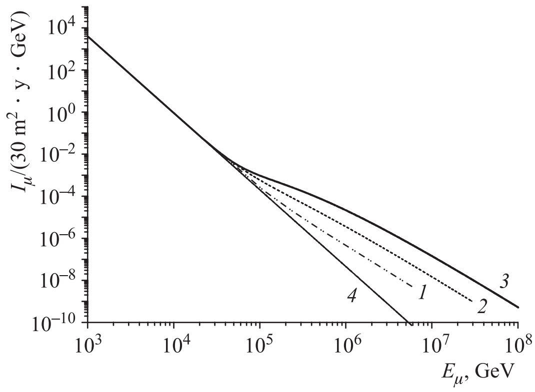

Fig. 1. Expected muon flux predicted by the model [3] for different values of part of missing energy carried away by muons $K_\mu = 0.01$ (*1*), 0.05 (*2*), 0.25 (*3*); $K_\mu = 0$ (*4*) means usual muons from pion and kaon decays

***Pamir* Experiment Data.** The *Pamir* experiment was aimed at the investigation of very high energy hadron–nuclei interactions initiated by cosmic ray particles. It was shown that the main characteristics of hadron-induced nuclear-electromagnetic cascades can be explained in the frame of the conventional concept of multiple production, but some anomalies in hadron attenuation behaviour in lead were not understood. The method of detection allows the registration of cascades produced by high-energy hadrons in successive interactions with lead nuclei if their energy E_γ^h exceeds the threshold of 6 TeV. The distribution of cascade origin points in the chambers characterized by an absorption length L is sensitive mostly to hadron cross sections and inelasticity coefficient. The summary area of exposed chambers of 1 m thick was 30.5 m^2. The measured value of L obtained in the interval 10–43 cm is $L = 212 \pm 19$ g/cm^2 that is a good fit to the results of calculations and other experiments. However, at depths $t > 43$ cm $L = 310 \pm 36$ g/cm^2 that is significantly higher. The excess of cascades with $E_\gamma^h > 6$ TeV at depth of lead > 43 cm is about 50 ± 15 cascades. This effect was explained earlier as a result of charmed particle production with abnormally large cross section [2]. It is obvious however that the electromagnetic cascades generated by muons in lead also can produce the excess cascades at large depth of lead since the distribution of muon-initiated cascade origin points is practically uniform. But the intensity of the cascades from usual muons is about 6–10 times smaller than the intensity of excess cascades and spectrum of usual muons exhibits $\gamma = -3.7$, while the observed spectrum $\gamma = -3.0$. Here we try to take into account the contribution of hypothetical «muons from the knee».

Simulation of Cascades from the Muons. At the first step we use the well-known program complex GEANT 3.21 to track high-energy muons through the X-ray emulsion chamber with muon bremsstrahlung and e^+e^--pair production cross sections changed to GEANT4 versions [4]. Bremsstrahlung photons and pairs give the rise to the electromagnetic cascades with energy $E_{\rm cas}$, detected by X-ray films. It was shown [4] that at $E_{\rm cas}/E_\mu > 0.1$ the bremsstrahlung process dominates, for $E_{\rm cas}/E_\mu < 0.1$ the probability of pair production exceeds bremsstrahlung by several orders of magnitude.

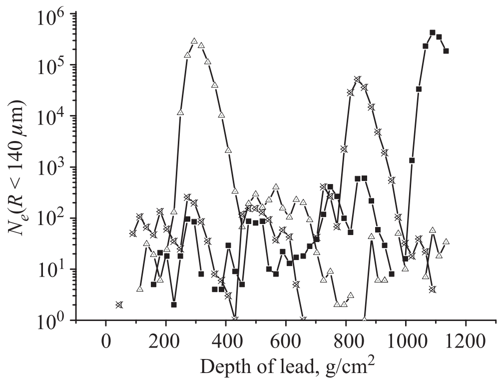

Fig. 2. Examples of three cascades initiated by 3 PeV muons in lead. Y axis presents a number of electrons inside the circle with radius $R = 140\ \mu$m

The examples of cascades initiated by very high-energy muons are presented in Fig. 2. They look like a «saw» with uniform distribution of small cascades along the chamber. Even for very high-energy muons (3000 TeV) these small cascades are usually under the threshold of detection. But sometimes the energy release is much higher than the average one, these cascades are above the threshold and they look like pure electromagnetic cascades. The most number of cascades from hadrons near the threshold energy also look like pure electromagnetic cascades [1].

Using the above-mentioned features we calculated the spectrum of cascades $I_{\rm cas}(E_{\rm cas})$ initiated in lead by muons with power-like spectra with different exponents: $\gamma = -3.7$ (usual muons), -2.7 (prompt muons) and for «muons from the knee» $\gamma \sim -1.7 - -2$. To characterize the transition from muon spectrum to the spectrum of cascades the value of efficiency was calculated: $\eta = I_{\rm cas}(E_{\rm cas})/I_\mu(E_\mu)$ at $E_\mu = E_{\rm cas}$ as it is usually done. This value depends on energy very weakly, but very strongly on the γ. We present η only at fixed energy 10 TeV for four values of γ in the table.

Efficiency of generation of muon cascades η at $E_\mu = E_{\text{cas}} = 10$ TeV per g/cm^2 for two main processes and total

Process $\mid -\gamma$	3.7	2.7	2.0	1.7
Brem. photons	$2.54 \cdot 10^{-06}$	$4.18 \cdot 10^{-06}$	$7.58 \cdot 10^{-06}$	$1.14 \cdot 10^{-05}$
e^+e^- pairs	$8.09 \cdot 10^{-08}$	$6.25 \cdot 10^{-07}$	$1.07 \cdot 10^{-05}$	$5.59 \cdot 10^{-05}$
Total	$2.62 \cdot 10^{-06}$	$4.80 \cdot 10^{-06}$	$1.83 \cdot 10^{-05}$	$6.73 \cdot 10^{-05}$

The value of η increases with modul of γ decrease. Besides, for very hard muon spectra the pair production process begins to dominate over the bremsstrahlung. Next important conclusion is that for the case when we have two component muon spectrum with different exponents $\gamma = -3.7$ («usual muons») and $\gamma = -1.7-2.0$ («muons from the knee») with the point of spectrum flattening about 100 TeV, the measured spectrum of cascades should have the point of flattening at energy much lower than 100 TeV, because the contribution of the hard muon component will be stressed due to larger value of η. But spectrum of muons from the knee deviates from the pure power-like form. So, we calculated the spectra of cascades for the muon spectra shown in Fig. 1, expected for three variants of ratio of missing energy carried by muons K_μ, and we present spectra in real muon energy and spectra of cascades in Fig. 3. The spectra of cascades are normalized by intensity to the muon spectrum at energy near 1 TeV. We show also LVD data [7], where the vertical muon spectrum at the sea level was reconstructed using the muon absorption curve in ground, and MSU experiment [5] where the muon spectrum was derived from the spectrum of cascades detected in

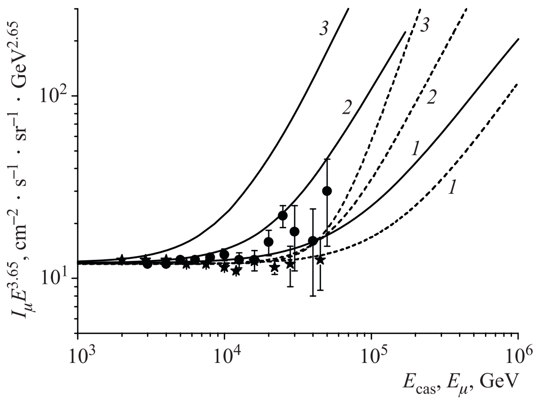

Fig. 3. Expected spectra of cascades (solid lines) and corresponding muon spectra (dashed lines) for three variants of ratio of missing energy carried by muons K_μ, together with experimental data obtained in MSU [5] (circles) by cascades and in LVD by absorption curve [7] (stars). *1* — $K_\mu = 0.1$; *2* — $K_\mu = 0.05$; *3* — $K_\mu = 0.25$

the lead emulsion chamber. Firstly, it is worth noting that there is a difference between the two experiments, and may be this difference itself points out the presence of high-energy muons in the atmosphere: it is clearly seen especially for the calclulated curves *3* ($K_\mu = 0.25$) that the region of flattening of cascade spectrum ($\sim 3{-}10$ TeV) is much lower than the region of flattening of muon spectrum ($\sim 20{-}70$ TeV). The spectrum of cascades is much more sensitive to the presence of high-energy muons. Unfortunately, we cannot compare directly the MSU data with calculated spectra of cascades, because MSU data were converted in [5] to muon energy. The indication that the difference between MSU and LVD data can be explained by the presence of high-energy muons requires additional study. Bearing in mind nontrivial shape of the muon spectrum it is necessary to take into account more accurately the procedure of transition to muon spectrum from cascades in MSU experiment and from absorption muon curve in LVD experiment. But one can see that hypothesis of A. A. Petrukhin [3] does not contradict LVD absorption curve data (in muon energy) and MSU experiment (in cascade energy), at least for $K_\mu < 0.05$. (The contribution of prompt muons from charmed particles as an explanation of the flattening of MSU spectra was considered in [6].)

Then the integral spectrum of additional cascades from muons was calculated in the angular interval $0-60°$, taking into account the intensity of primary protons and the exposure factor of X-ray chamber. We have obtained that about 50% of excess of cascades detected at large depth of lead can be explained by high-energy muons but only for the variant when muons responsible for the knee carry away not less than 0.25 of the primary energy.

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