ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2005. Т. 36. ВЫП. 5

УДК 537.591

THE ROLE OF VHE MUONS IN EXPLANATION OF UNUSUAL EVENTS OBSERVED IN COSMIC RAYS

A. G. Bogdanov, A. A. Petrukhin, A. V. Shalabaeva

Moscow Engineering Physics Institute (State University), Moscow

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2005. Т. 36. ВЫП. 5

УДК 537.591

THE ROLE OF VHE MUONS IN EXPLANATION OF UNUSUAL EVENTS OBSERVED IN COSMIC RAYS

A. G. Bogdanov, A. A. Petrukhin, A. V. Shalabaeva

Moscow Engineering Physics Institute (State University), Moscow

Unusual events observed in cosmic-ray experiments, which cannot be explained in frame of modern theories and models, are considered. The peculiarities of VHE ($\geqslant$ 100 TeV) muon interactions and their possible contribution to production of various unusual events in cosmic rays are analyzed. Some preliminary results obtained for explanation of unusual events detected in Tien-Shan calorimeter and in the Pamir experiment are discussed.

Рассматривается совокупность необычных событий, которые были зарегистрированы в экспериментах, проведенных в космических лучах. Анализируются особенности взаимодействия мюонов сверхвысоких энергий ($\geqslant$ 100 ТэВ) и их возможный вклад в образование необычных событий, наблюдаемых в космических лучах. Обсуждаются некоторые предварительные результаты, полученные для объяснения необычных событий, зарегистрированных в Тянь-Шаньском калориметре и в эксперименте «Памир».

INTRODUCTION

Cosmic-ray experiments have some peculiarities compared to accelerator ones. As a rule, the type of interacting particle, its energy, place of interaction and also the number and the type of accompanying particles are unknown. Therefore the attitude of considerable part of physicists to various unusual results and events which permanently are observed in cosmic-ray experiments is rather skeptical. And really, often unusual events observed in cosmic rays were connected with different technical or methodical reasons and were not confirmed in further experiments.

But during the last tens of years, a large set of really unusual events was observed in different experiments, and their reality is out of doubt. Since these unusual events were discussed widely elsewhere [1–3], we enumerate them only:

- Excess of high energy muons.
- Long-flying and penetrating components in hadron experiments.
- «Centauro» and «Anti-Centauro» type events with isotopic invariance violation.
- Alignment of near-placed cascade showers.

It is very important that practically all observed unusual events are connected with primary particle energies in PeV region. Though exact estimations of energy are impossible, but even uncertainty in 2–3 times does not change this conclusion. As is known, PeV energy region in laboratory system corresponds to TeV energy region in the centre-of-mass system, where appearance of new physics is expected according to many theoretical approaches and ideas. Therefore it is very probable that this expected new physics is being observed in cosmic rays for a long time. But numerous attempts to find a single approach to the explanation of all these unusual results and events were unsuccessful, and different hypotheses for different results were considered. Of course, a large abundance of ideas, models and approaches did not increase persuasiveness of new physics observations.

In this paper, the new approach to explanation of unusual results and events observed in cosmic rays from a single point of view is analyzed. As was noted in [4], in principle VHE muons can explain many unusual results due to specific interaction of muons at energies higher than 100 TeV. Previously the contribution of such muons to generation of unusual events was not considered since the flux of muons with energy more than 100 TeV is very small. But as it was shown recently [5], a considerable flux of VHE muons can appear at energies of the knee in cosmic-ray spectrum in the atmosphere if the appearance of the knee is connected with inclusion of some new physical processes (particles or states of matter). Of course we cannot claim the explanation of all unusual experimental results. Our task is to show how to do this in order that authors of different experiments could recalculate their results. One of such attempts was done at NANP-2003 and its results are published in this issue.

1. VHE MUONS

VHE muons in cosmic rays are muons with energies $\geqslant 100$ TeV. In favour of this definition the following arguments can be given.

This energy region is practically not investigated and the well-known methods of differential muon energy spectrum studies as magnetic spectrometers or transition radiation detectors cannot be used in view of very large uncertainties. The same situation occurs also with known methods of integral muon energy spectrum measurements. Absorption curve technique cannot be used since the flux of VHE muons is comparable with that of neutrino-induced muons deep underground. The ionization calorimeter technique cannot be used either since a probability for muon with energy ~ 100 TeV to interact with a large energy deposit in calorimeter is very small and does not exceed few per cent.

On the other hand, at about 100 TeV the character of interaction of muons is changed rather drastically. At these energies muons begin to interact practically permanently due to the process of electron–positron pair production. This circumstance is very important since the behavior of such muons will be similar to hadrons. But it is necessary to remark that a great difference exists between distributions of energy loss in two main processes of muon interactions: bremsstrahlung and electron–positron pair production (Fig. 1). The main characteristics of these two processes are given in Table 1.

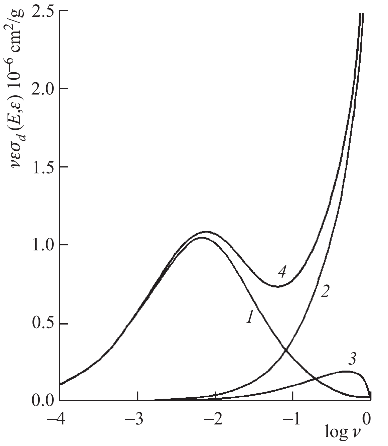


Fig. 1. Muon energy loss distribution for different processes [8]: *1* — pair production (e^+e^-); *2* — bremsstrahlung (γ); *3* — inelastic scattering (N); *4* — Σ. Here $\sigma_d(E,\varepsilon)$ is the cross section differential in the transferred energy ε, $\nu = \varepsilon/E$ is the relative energy loss

Table 1. **Basic characteristics of VHE muon interactions**

Process	Energy deposit ($\Delta E/E\mu$)	Probability of interaction
Bremsstrahlung and inelastic scattering	10^{-1}–1	10^{-3}–10^{-2}
Pair production	10^{-3}–10^{-2}	10^{-1}–1

Note that for bremsstrahlung (and inelastic scattering) the probability of interaction practically is independent of muon energy. For pair production, the probability of interaction increases with energy and for $E_\mu > 100$ TeV goes to ~ 1. These peculiarities lie in the background of two different methods of muon energy evaluation (Fig. 2): ionization calorimeter (integral muon energy spectrum measurements) and pair meter technique (individual muon energy estimation). Such behavior of muon interactions allows one to explain various unusual events observed in cosmic-ray experiments taking into account that in a real experiments any mixture of these two limiting cases can be detected.

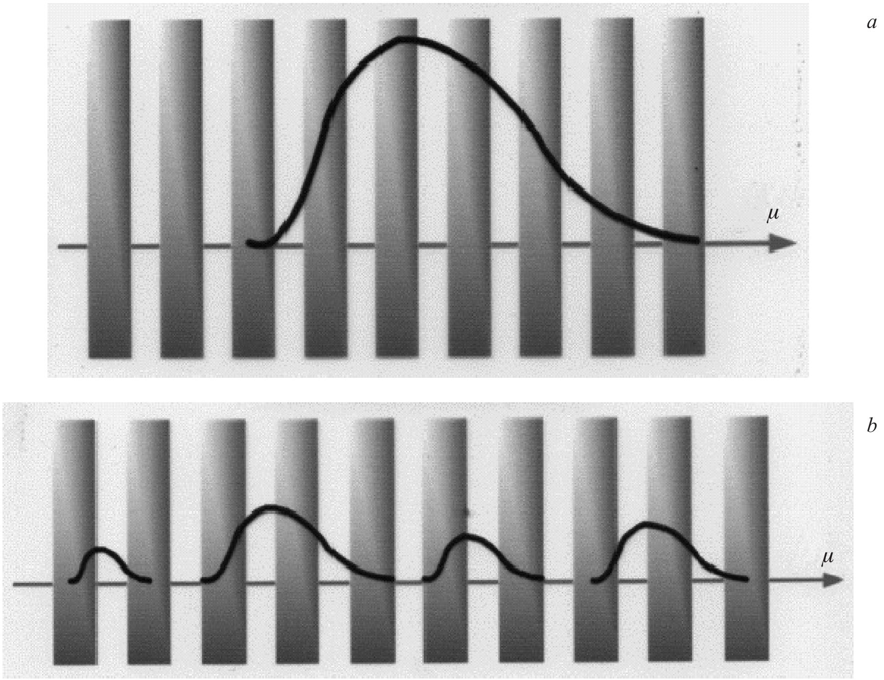


Fig. 2. Two methods of muon energy estimations: *a*) ionization calorimeter; *b*) pair meter technique

2. POSSIBLE EXPLANATION OF SOME UNUSUAL EVENTS

Of course, if to suppose that some excess of VHE muons exists, it will be very easy to explain the results of various experiments in which such excess of muons or cascade showers generated by muons was observed. Corresponding discussion was given in papers [4, 7]. The last evaluation of excess of VHE muons, which is required for explanation of the results of MSU X-ray emulsion chamber and LVD experiments, was done in paper published in this issue. Unfortunately, very poor statistics of experimental VHE-muon events do not allow one to make sufficiently strong conclusion about the flux of such muons.

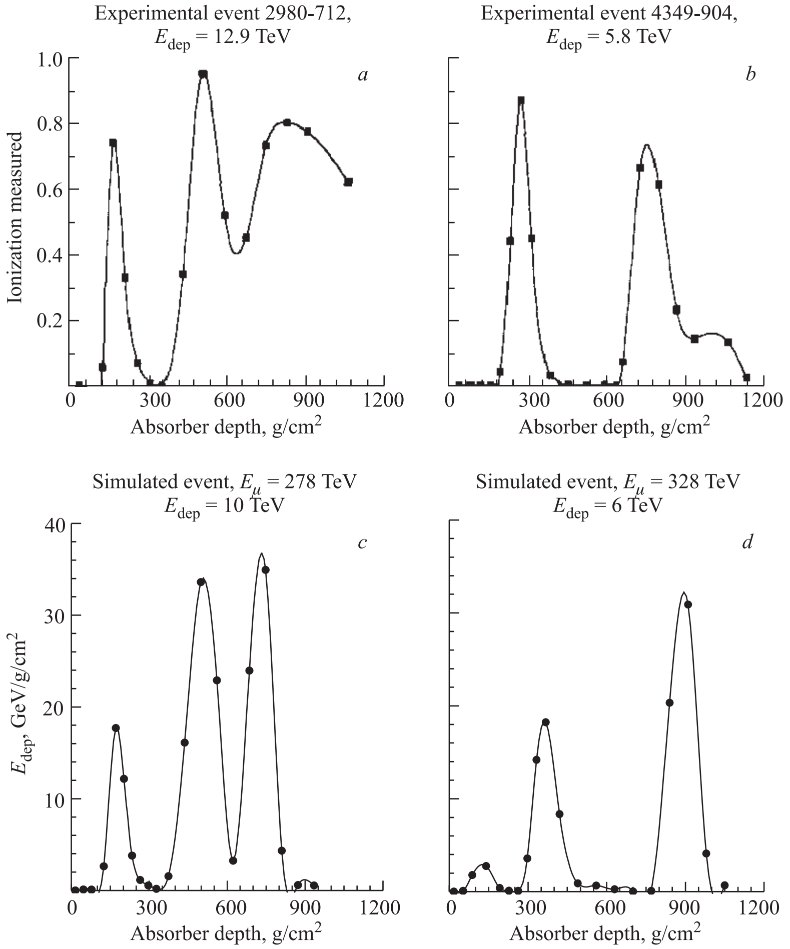
More interesting questions are connected with influence of VHE muons on the results of hadron experiments. On the whole, this influence can be described very simply. Let us consider very thick calorimeter with sufficiently large number of layers of detectors. If such calorimeter is placed at mountain altitudes, then the upper part of calorimeter will detect hadron component, and as a result the normal average cascade curve will be obtained. The probability of observing interactions of hadrons in the depth of calorimeter will be exponentially decreased. But at the same time muons will interact at any depth of calorimeter with practically equal probability. It is very difficult to separate these muon interactions in the upper part of calorimeter from hadron ones since the muon interaction cross section is much less than the hadron one. However at some depth the contributions of muons and hadrons to generation of cascade showers will equalize, and at larger depths contribution of muons will predominate. It is very important that the point of intersection of two contributions will depend on slopes of muon and hadron energy spectra. If the slope of muon energy spectrum is decreased (more hard spectrum), then cascade showers from muon interactions will begin to predominate at more shallow depths.

2.1. Tian-Shan Experiment. In the experiment with big ionization calorimeter two unusual results were obtained [3]. First, several so-called Anti-Centauro-type events, which consist of electromagnetic cascades only, were observed. Second, some elongation of average cascade with increasing of threshold energy from 4 to 12 TeV was found. For explanation of these results, VHE muons are very good candidates. To check this possibility, we made simulations of Tian-Shan calorimeter (15 layers with chambers, total thickness of lead absorber is 850 g/cm^2) by using GEANT4 (5.1p01 version). The response of the calorimeter was calculated for proton and muon energy spectra with differential slope indices $\gamma = 2.7$ and 3.7, correspondingly. To study the influence of VHE muons, additional flux of muons with energy more than 100 TeV was also used in simulations. For further analysis, the events with energy deposit ε_c in calorimeter more than 4 TeV were selected (this value corresponds to experimental threshold). The results are given in Table 2.

Table 2. **Results of Tian-Shan calorimeter simulations**

Particle	$E_{\rm th}$, TeV	Total number of particles	Number of cascades		
			$\varepsilon_c > 4$ TeV	$4 < \varepsilon_c < 5$ TeV	$\varepsilon_c > 12$ TeV
p	4	1529	868	285	122
μ	4	35105	83	33	4
μ	100	1500	165	39	55

One can see from Table 2 that probability of interaction for VHE muons is much higher than for muons with lower energies and draws near to that of protons. Especially drastically the energy dependence is changed compared to protons and lower energy muons (see two last columns). Among cascade showers generated by VHE muons, the samples which look as experimental Anti-Centauro-type events were found (Fig. 3). Therefore, the excess of cascades from VHE



Experimental event 2980-712, $E_{\text{dep}} = 12.9$ TeV

Experimental event 4349-904, $E_{\text{dep}} = 5.8$ TeV

Simulated event, $E_\mu = 278$ TeV $E_{\text{dep}} = 10$ TeV

Simulated event, $E_\mu = 328$ TeV $E_{\text{dep}} = 6$ TeV

Fig. 3. Anti-Centauro-type events: *a, b*) experimental; *c, d*) simulated from VHE muons

muons, in principle, can be the reason of elongation of average curve. For direct comparison of experimental data with the results of calculations more detailed simulations, taking into account a possibility of multiple VHE muon production, are required.

2.2. Pamir Experiment. Among unusual events in the experiment with total target thickness 60 cm of lead, several ($\sim$ 10) so-called penetrating cascades were observed [8]. Part of them can be explained as usual hadron cascades in which their beginning is flat because of the saturation of darkness. The increasing of this effect with the growth of energy gives a direct evidence in favor of this supposition (see Fig. 12 in [8]). But another part of penetrating cascades cannot be explained in frame of hadron interaction without some new ideas and approaches.

From this point of view, muons are good candidates for penetrating cascade production. To illustrate this possibility, simulations of response of X-ray emulsion chambers for VHE muons were performed by using GEANT4. Differential VHE muon energy spectrum with the slope index $\gamma = 2.7$ was taken. Calculations were done for two muon energy thresholds: 100 TeV and 1 PeV. Real parameters of X-ray emulsion chambers were taken into account. Each sensitive layer was separated into cells with area $S_{\text{cell}} = 50 \times 50\ \mu\text{m}$ in which the number of electrons N_{cell} with energy > 1 MeV was calculated. The darkness in the cell D_{cell} was calculated following the formula [9]

$$D_{\text{cell}} = D_0(1 - \exp(-\alpha\rho_e)),$$

where $D_0 = 4.0$, $\alpha = 3.25\ \mu\text{m}^2$, $\rho_e = N_{\text{cell}}/S_{\text{cell}}$. The total darkness in the slit with sizes $200 \times 200\ \mu\text{m}$ (usual sizes of photometric diagram) was calculated as

$$D_{\text{slit}} = \lg(S_{\text{slit}}/S_{\text{cell}}) - \lg \sum_i 10^{-D_{i_{\text{cell}}}}.$$

Total number of simulated events was 527 for $E_\mu > 100$ TeV and 71 for $E_\mu > 1$ PeV. The results of simulations are given in Fig. 4 and in Table 3. As one can see from Fig. 4, VHE muons can produce various events including penetrating cascades. The probability of generation of different events is given in Table 3. As in Tian-Shan calorimeter, probability of penetrating cascade production is rapidly increasing in the PeV interval of muon energy.

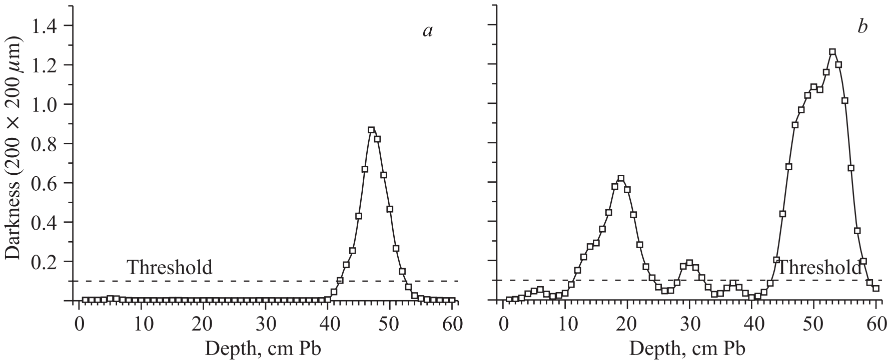


Fig. 4. Samples of simulated events generated by VHE muons in Pamir experiment: *a*) $E_\mu = 130$ TeV, $\theta = 23.9°$; *b*) $E_\mu = 2.9$ PeV, $\theta = 21.5°$

Table 3. **Probability of production of events with different number of layers with darkness exceeding the threshold**

Number of layers larger than	Probability for $D_{\mathrm{th}} = 0.1$, %	
	$E_\mu > 100$ TeV	$E_\mu > 1$ PeV
1	25	80
5	12	58
10	3.6	41
15	0.6	21
20	—	9.8
25	—	5.6

Of course, it is impossible today to give exhaustive explanation of all observed unusual events. For example, there is an idea to explain aligned events due to consecutive e^+e^- pairs produced by VHE muons over the detector. In this case some probability exists that two such pairs can give aligned event. But theoretical estimations show that angles between electron and positron are very small to generate two sufficiently separated cascades.

3. WHAT FLUX OF VHE MUONS WE NEED

For explanation of various unusual events different fluxes of VHE muons and their spectra will be required. The main uncertainty is connected with the number of unusual events, which can be explained in frame of normal hadron interactions taking into account possibly larger fluctuations than are usually assumed. But if to suppose that the knee appearance in the energy spectrum of cosmic rays in the atmosphere is connected with new physical processes, more strong limitations on possible flux of VHE muons will be applied. As was shown in [7], the missing energy which is required to change the slope of the measured energy spectrum can be carried away by four leptons only: three types of neutrinos and muons. Therefore total energy of VHE muons must be about 0.25 of full missing energy and can be shared between several muons.

Thus we can have two limits on VHE muon energy spectrum: the upper limit, which depends on correct knee position and differences between slopes of energy spectrum below and above the knee, and the lower one, which is determined by minimal flux of VHE muons required for explanation of different types of unusual events. These two limits can give possibility to evaluate some characteristics of new physical objects, which appear in the PeV energy region in cosmic rays (the TeV energy region in the centre-of-mass system).

CONCLUSION

The main purpose of our paper is not to explain unusual events observed in cosmic rays by means of introducing additional flux of VHE muons, but to demonstrate a possibility to do this. And detailed simulations of each experiment for various suppositions about VHE muon energy spectrum are required. In our opinion, such analysis could give an opportunity to find convincing evidences of new physics existence.

REFERENCES

1. *Slavatinsky S. A.* // Nucl. Phys. B (Proc. Suppl.). 2003. V. 122. P. 3.
2. *Tamada M.* // Ibid. P. 349.
3. *Yakovlev V. I.* // Ibid. P. 417.
4. *Petrukhin A. A.* // Ibid. P. 259.
5. *Petrukhin A. A.* // Proc. of the XI Rencontres de Blois «Frontiers of matter», Blois, France, 1999. Vietnam. 2001. P. 401.
6. *Kokoulin R. P., Petrukhin A. A.* // Nucl. Instr. Meth. A. 1988. V. 263. P. 468.
7. *Petrukhin A. A.* // Yad. Fiz. 2003. V. 66. P. 544.
8. *Arisava T. et al.* // Nucl. Phys. B. 1994. V. 424. P. 241.
9. *Tamada M., Kopenkin V. V.* // Nucl. Phys. B. 1997. V. 494. P. 3.