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Problem of the knee and very high energy muons

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Abstract. A new approach to explanation of the knee of cosmic ray energy spectrum in the atmosphere is considered. The concept of missing energy, which can be taken away by muons and neutrinos, is introduced. It is shown that in this case a big excess of VHE muons and neutrinos must be produced. Existing VHE muon experimental data are analysed. Possible experiments on VHE muon investigations are discussed.

1 Introduction

For the first time, the knee as a change of the slope of EAS size spectrum was observed by Khristiansen and Kulikov (1958). And during forty years the question about its nature is discussed, since in principle there are two possibilities of the explanation of the knee of cosmic ray energy spectrum in the atmosphere: the change of primary energy spectrum slope (or/and composition) and the appearance of new physical processes in interactions at these energies. After similar changes of spectrum slopes in muon number and in EAS core energy had been observed, the knee was interpreted mainly as a change of primary cosmic ray energy spectrum and composition. Nevertheless, from time to time papers appear (see, e.g., Nikolsky, 1995 and 1999) in which the second point of view is supported and new processes and particles for explanation of various cosmic ray phenomena at energies higher than knee are proposed. However, these ideas are usually considered within the frame of traditional methods of EAS investigations.

In 1999, a new approach to the knee problem was proposed. The point is that PeV energy region in the laboratory frame, where the knee is observed, corresponds to TeV energy region in the centre-of-mass system, where the appearance of various kinds of new physics is expected (technicolor, megacolor, compositeness, quark-gluon plasma, and so on). If any new physical process begins to work in this energy interval, it can lead to a change of measured spectrum of EAS in the atmosphere and to generation of VHE muons and neutrinos (Petrukhin, 1999).

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2 Cosmic ray energy spectrum without the knee and muon energy spectrum

Results of cosmic ray energy spectrum measurements around the "knee" (based on EAS observations) may be described by a power function

$$N = N_0 \left(\frac{E_0}{E} \right)^{\gamma}, \tag{1}$$

and the change of the spectrum slope is given by the change of γ at energy $E_0 \sim 5{\times}10^3$ TeV. Below the "knee" $\gamma = \gamma_1 \sim 1.7$, above the "knee" $\gamma = \gamma_2 \sim 2.1$.

Let us suppose that above the "knee" the primary spectrum is not changed, but some heavy and short-lived particles are generated. These can be any heavy particles or states of matter which are predicted by various theoretical models, but cannot be produced at existing accelerators, since the position of the "knee" corresponds to the energy more than 3 TeV in center-of-mass system. If these heavy particles decay (directly or through intermediate particles) into leptons in final state – e, μ, τ, ν_e, ν_μ, ν_τ, the energy of ν_e, ν_μ, ν_τ and μ (!) will be missing energy for EAS arrays, since muon detectors can measure the number of muons, but not their energy.

From the comparison of two spectra (1) for γ_1 and γ_2 (see Fig. 1), the following formula for missing energy ΔE above the "knee" may be obtained:

$$\frac{\Delta E}{E_1} = 1 - \left(\frac{E_0}{E_1} \right)^{\Delta\gamma/\gamma_2}, \tag{2}$$

where $\Delta\gamma = \gamma_2 - \gamma_1$; E_1 is the energy of the primary particle .

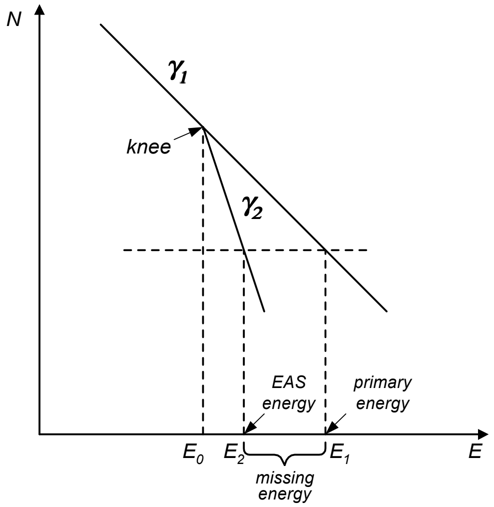

Fig. 1. Missing energy definition.

The calculations of missing energy give the following results (Table 1).

Table 1. Missing energy ΔE, PeV

E_1	E_1/E_0	ΔE
5	1	0
50	10	18
500	100	280

As one can see from the table, the value of missing energy is considerable. Among four leptons (ν_e, ν_μ, ν_τ, μ) only muon energy can be measured. For accurate calculations of muon energy spectrum some additional suppositions about new particle production mechanism, energy dependence of the cross section, etc., are required. But for evaluations of limiting cases of possible contribution of these muons in the total energy spectrum, the simple energy relations can be used. Maximum flux will correspond to the minimum number of produced particles, when each of four particles (3 neutrinos and 1 muon) takes away the energy ~ $\Delta E/4$ (Fig.2). Minimum flux will correspond to multiple production of muons, when the missing energy ΔE is shared between many particles. Total number of muons in the latter case will be limited by the mass of new particle (or new state of matter) and the process of their production. For example, if muons are produced through decays of $W(Z)$-bosons, the number of them cannot exceed ~ 10 particles at m_x ~ 1 TeV. In this case the average muon energy is ~ $\Delta E/40$, but many muons will be produced. It is necessary to underline that $W(Z)$-boson decay modes with the production of hadrons and electrons contribute to the usual EAS development. One can see from the figure that new source of cosmic ray muons begins to prevail over the known processes of their generation at energies $\gtrsim$ 100 TeV, i.e. in the region of very high energies.

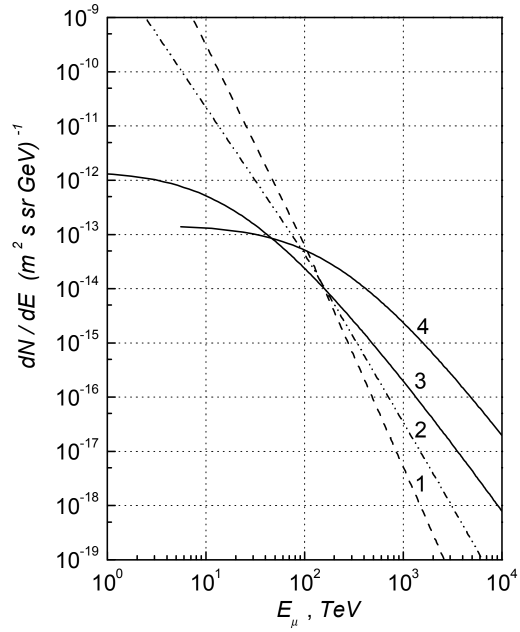

Fig. 2. Differential muon energy spectrum: 1 – muons from π- and K-decays; 2 – upper limit of prompt muons; 3, 4 – minimum and maximum contribution of new processes.

3 Discussion

The first and the most important question connected with this new approach is: How can one obtain the large cross-section (order of tens millibarns) of new heavy particle or state production, which is needed for the explanation of the change of EAS spectrum slope?

In a general case

$$\sigma \sim \alpha_x^2 \left(\lambda\!\!\!^{-} + R\right)^2 l\left(l+1\right). \qquad (3)$$

Therefore the solution of the problem is possible in the following ways:

- to introduce a new interaction at distances ~ 10^{-17} cm and correspondingly new coupling constant α_x;
- to postulate interaction of object with size R (fireball, quark-gluon plasma, …);
- to suppose interaction with very large orbital momenta l.

In any case, not small corrections to Standard Model, but the introduction of really new physics is required. Detailed analysis of possible theoretical models is not a purpose of this paper. But, for example, one can mention singlet quarks in famous 27-plet of E_6 group, which can generate mesons with necessary lifetime and lepton decay branching.

The second question is: Do we have any evidences for the existence of any excess of VHE muons? The answer is very simple: yes.

Apparently, the first observation of VHE muons was done by Japanese physicists (Matano et al., 1965), who found the air shower with energy about 300 TeV at zenith angle ~ 86°. This shower could be generated by muon only, but the probability of the production of such muon in π- and K-decays is very small. But if one takes into account new processes of muon generation, the probability to detect similar event becomes quite reasonable.

The marked excess of muon-induced cascade showers with energies $\gtrsim$ 10 TeV was observed by MSU group in X-ray emulsion chambers (Il'ina et al., 1995). Authors interpreted their results as an evidence for prompt muons (due to charmed particle decays), but with large value of $R_{\mu\pi} \sim 3\times10^{-3}$. Modern theoretical calculations give the value of $R_{\mu\pi}$ about 10^{-4} (Gelmini et al., 2000). At the same time, taking into account "new" muons in calculations of electromagnetic cascade shower spectrum due to muon bremsstrahlung, it is possible to easily explain the result of this experiment.

Some excess of muons with energies > 10 TeV seemingly was observed also in the underground experiment LVD in Gran Sasso (LVD Collaboration, 1997).

Very interesting event was observed in the NUSEX detector. Multiple interactions of high energy muons in the detector consisting of 130 planes of iron absorber with thickness 1 cm were analysed to evaluate the average muon energy at the depth about 5000 m w. e. (Castagnoli et al., 1997). In one of the events (Fig.3) muon permanently interacts in the target. As calculations show, the probability of the production of secondary cascade showers by muon increases with energy, reaching the value of ~ 0.9 at energy about 100 TeV, and muon begins to look as practically continuous luminous lace. Taking into account the relatively small area of the detector (about 12 m^2) and large depth of its location, the observation of such muon from conventional sources is improbable.

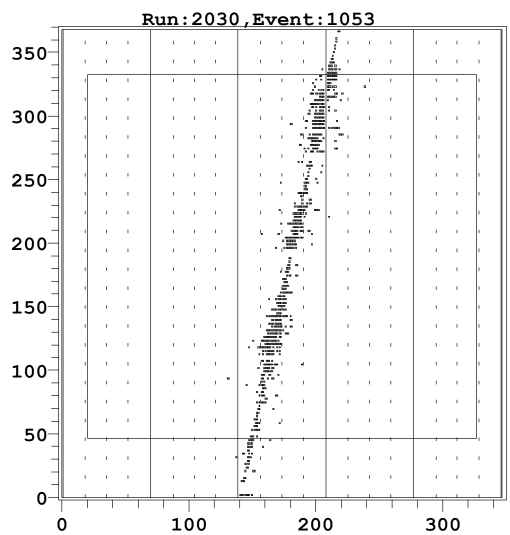

Fig. 3. VHE muon in the NUSEX detector.

Thus, the presented analysis shows that cosmic ray physics came very close to promising region of VHE muons. It is possible that VHE muons from new physical processes are detected in various experiments but the available data are insufficient to prove that.

4 Possible future experiments

Since the number of VHE muons is small, it is impossible to observe them by measuring the total number of muons in EAS on the Earth surface or in underground laboratories, and the direct measurements of their energies are required. At present, no detector exists for measurements of muon energies in hundred TeV region. Therefore let us consider the possibilities of some proposed experiments and detectors being constructed. The only known method of muon energy measurements in this interval is the pair meter technique (Kokoulin and Petrukhin, 1990). This method allows to evaluate muon energy from multiple production of electron-positron pairs in a thick layer of matter, has no limitation for measurable energy and will work very good at energies $\gtrsim$ 100 TeV. To reach 50% accuracy of individual muon energy measurements, the thickness about 500 radiation lengths is needed (8 m Fe, or 200 m water). To detect the expected flux of VHE muons, a sensitive area more than 500 m^2 is required.

Suitable parameters will have large scale neutrino detectors of the new generation: Baikal, AMANDA, ANTARES and MONOLITH. Unfortunately, in Baikal and AMANDA setups most of photomultipliers are directed downward, therefore modifications of these detectors are required. Much better the situation will be in ANTARES, where PMs are directed horizontally. In this case, equal conditions for up-going and down-going muons exist.

Very good possibilities for muon energy measurements in the interval around 10^2 TeV can be provided by the MONOLITH detector (MONOLITH Collaboration, 1999), which is a proposed massive (34 kt) magnetized tracking calorimeter at the Gran Sasso laboratory in Italy, optimized for the detection of atmospheric muon neutrinos. It will consist of 120 plates of iron (8 cm) interleaved with RPC, and will have area about 450 m^2. The main goal of this detector is to establish (or to reject) the neutrino oscillation hypothesis through an explicit observation of the full first oscillation swing. But on the other hand MONOLITH will be very good pair meter for muon energy measurements. In 3 years, the MONOLITH detector will register about 100 events with surface muon energies exceeding 100 TeV even for conventional muon production mechanisms.

From the point of view of the search of new physical processes in cosmic rays, the most direct experiment must include the simultaneous detection of EAS around the knee and correlated with them VHE muons. The absence of these muons at EAS energies below the knee and their appearance above the knee will be irrefutable proof of the inclusion of new physical processes.

Unfortunately, the appropriate experimental complex for the solution of this task (an EAS array and full scale pair meter) is absent. After EAS-TOP in Gran Sasso was dismantled (re-analysis of the old data can be performed only), there remained one complex in Baksan ("Andyrchi" with BUST) which has good EAS array, but not so thick muon detector. In this situation, to find some evidences for a new process influence, a detailed analysis of spatial and energy distributions of muons is needed.

There are two other detectors: BARS (Big liquid-ARgon Spectrometer) in Protvino (Kokoulin et al., 1999) and NEVOD-DECOR (Cherenkov water calorimeter with coordinate detector) in MEPhI (Petrukhin et al., 1999), which provide very good conditions for investigations of spatial and energy distributions of muons. But they need to be supplemented with EAS arrays.

5 Conclusion

Usually, the searches of new particles and states of matter are connected with the construction of new accelerators. In particular, the further advancement in multi-TeV energy region, where the appearance of various kinds of new physics is expected, usually is associated with the construction of LHC in CERN. But investigations of VHE muons may give a key to the search of new physical processes in cosmic rays. At present, there are experimental evidences that some excess of VHE muons exists. Taking into account that multi-TeV region, where new physics is expected, will be investigated at LHC not earlier than in 2006, a real and may be the last possibility appears in cosmic rays to make a serious contribution in the study of matter at distances about 10^{-17} cm. Even the negative result of the search of VHE muons will be very important, since the last possibility of the knee explanation due to new processes of interactions will be closed.

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References

Castagnoli, C., Castellina, A., Saavedra, O. et al., *Astroparticle Physics, 6*, 187, 1997.

Gelmini, G., Gondolo, P. and Varieschi, G., *Phys. Rev. D*, *61*, 036005, 2000.

Il'ina, N.P., Kalmykov, N.N., Rakobolskaya, I.V. et al., *Proc. 24th ICRC*, *Rome*, *1*, 524, 1995.

Khristiansen, G.B. and Kulikov, G.V., *Journ. Eksperim. Teor. Fiz. (in Russian)*, *35*, 635, 1958.

Kokoulin, R.P. and Petrukhin, A.A., *Sov. J. Part. Nucl.*, *21*, 332, 1990.

Kokoulin, R.P. et al., *Proc. 26th ICRC*, *Salt Lake City*, *2*, 24, 1999.

LVD Collaboration, *Proc. 25th ICRC*, *Durban*, *6*, 341, 1997.

Matano, T., Nagano, M., Shibata, S. et al.:, *Proc. Int. Conf. Cosmic Rays*, *London*, *2*, 1045, 1965.

MONOLITH Collaboration, *Progress Report*, *LNGS-LOI 20/99*, *CERN/SPSC 99-24*, *SPSC/M636*, 1999.

Nikolsky, S.I., *Nucl. Phys. B* (*Proc. Suppl.*), *39A*, 228, 1995.

Nikolsky, S.I., *Nucl. Phys. B* (*Proc. Suppl.*), *75A*, 217, 1999.

Petrukhin, A.A., *XIth Rencontres de Blois "Frontiers of Matter"*, *Blois*, *France*, 1999.

Petrukhin, A.A. et al., *Proc. 26th ICRC*, *Salt Lake City*, *2*, 460, 1999.