Changes of interaction mechanisms in the knee region of the primary cosmic rays spectrum

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Abstract: A primary cosmic ray event in the stratosphere with energy above $10^{16}$ eV has been further analyzed. Central cascades with the highest energies of the event were emitted with a strong azimuth asymmetry. Probability of such asymmetry due to statistical fluctuations has been estimated to be about a few one-hundredths percent. A similar asymmetry has been observed by J.N. Capdevielle in a stratospheric event with energy above $10^{16}$ eV. To study of possible change of interaction mechanism, the direct generation of muon beams and other possibilities are proposed.

Keywords: spectrum knee, azimuth asymmetry

Integral energy spectrum of primary cosmic rays can be approximated within a wide range of 20 orders of energy magnitude as a linear function in a double logarithmic scale: $I(>E) \sim E^{\gamma}$ with a slope $\gamma \sim 1.7 \div 3.1$ [1, 2]. This line has a knee at energy $E \sim 10^{15} \div 10^{16}$ eV, where $\gamma$ changes by $\Delta \gamma \sim 0.4$ [1]. As cosmic rays at the knee region have an extreme low flux rate: $\sim$1 particle per m$^2$ per year, their energies use to be measured only in extensive air showers (EAS). If the spectrum knee is caused by changes in primary cosmic rays interactions within atmosphere at certain energy, that energy is not to be dependent on the altitudes of the EAS detector sites. In fact, such correlation has not been observed [3].

Stratospheric experiments have found so far 2 events [4, 5] of nuclear interactions of cosmic rays with energies $\sim 10^{16}$ eV. These events have a remarkable signature of secondary energy-predominant particles emitted asymmetrically in azimuth.

The Figure 1 [6] shows the layout of the stratospheric emulsion chamber of the Lebedev Physical Institute, which have been exposed at altitudes of 30 km on a balloon flight from the Kamchatka Peninsula to the Volga River. It shows also a sketch of the event also known as the Siberian event [5] or STRANA (an acronym for Stratospheric Event of N.A. Dobrotin). A primary cosmic particle with energy above $10^{16}$ eV interacts in the air (point A) producing a leading particle with energy $\sim 10^{15}$ eV, which in turn interacts inside the chamber (point C).

Figure 2 is an emulsion layer sample placed at the depth of 8 cascade units within the lead layers. It shows cascades of the central part of the shower. The particles are seen to be scattered asymmetrically in azimuth. The particle diagram is shown in Figure 3.

As another remarkable feature, the STRANA superfamily shows also an unusual electromagnetic cascade, which is clearly seen in the center of the event (Figure 2). This cascade develops to the maximum black density at the depths of $\sim$8 cascade lengths in the lead, while its energy measured being about 300 TeV. A single lepton at such energy would have a maximum in significantly lower layers. It suggests, therefore, that the central cascade might consist of many particles with sub threshold energies of $2 \div 3$ TeV per particle. Applying the uncertainty principle to the size of the central cascade, the size of inflation area turns out to be $\sim 10^{-12}$ cm.

The possibility of central cascade creation was analysed by standard nuclear interactions of high energetic atomic H. In Figure 4 one can see that the calculated lateral distributions are not described completely the experimentally measurement darkness D.
The central cascade in Figure 2 is seen against background of multiple black points. Those might be secondary particles from a similar cascade produced in the primary interaction point A (Figure 1), somewhere 100 m in the air above the chamber. These two co-axial cascades give a reliable experimental evidence for multiple lepton and gamma generation in nuclear interactions of cosmic rays with energies around $10^{15}$ eV. Energy transferred from the leading particle to such leptons, that is, to those inside the central cascade, is measured to be about 30%. Given this value to be roughly the same for nuclear interactions above $10^{15}$ eV, one can estimate the power index change $\Delta \gamma$ in the energy spectrum of the primary cosmic rays. Estimation for the STRANA event gives $\Delta \gamma \sim 0.4$, which is in a good agreement with [2].

The azimuth asymmetry in a scattering of secondary particles from cosmic ray interactions with energies $\sim 10^{16}$ eV was also observed in [5]. The event was detected by an emulsion chamber exposed in the stratosphere during Concorde aircraft-borne experiment. The distribution of the most energetic $\gamma$-quanta is shown in Figure 5.

Taking into account the increasing interest to the physics of nuclear interactions at energies above the spectrum knee, where gravitational effects could possibly manifest themselves, a project for a new stratospheric experiment is under discussion at the Lebedev Physical Institute. Balloon-borne experiments are probably the only ones that are able to carry a large-area emulsion chamber of $15 \div 20$ m$^2$ to the upper atmosphere layers.

Besides the event-by-event investigation of nuclear interaction at energies higher $10^{15}$ eV, it could be prospective to define the nature of central cascade leptons. For this purpose, the IceTop could be added by roentgen emulsion chamber of large area for search of direct muon beams.

Both the generation of unusual cascades like those mentioned above, with multiple leptons produced within a small inflation area, and the azimuth asymmetry of their secondary particles would have a beguiling explanation as a result of a missing Kaluza-Klein graviton in the warped extra dimensions model [8].

In conclusion, the authors wish to express their appreciation to the colleagues from the Skobeltsyn Institute of Nuclear Physics (Moscow State University) for hard work in providing additional measurements and data analysis of the STRANA event [6,7].

References