Multiple Interactions of Muons in Baksan Underground Scintillation Telescope

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***Abstract*—Analysis of experimental data on registration of high energy muons accumulated for a long period (1983-1993) of operation of Baksan Underground Scintillation Telescope (BUST) is presented. To increase the sensitivity to high energy particles, the method of multiple interactions is used. Phenomenological parameters and sensitivity of the method to the shape of muon energy spectrum are discussed. The experimental distributions are compared with results of calculations for a "usual" muon spectrum (using simulation of the response of the telescope for passage of muons by means of Monte-Carlo technique).**

1. Introduction

THE aim of this work is a search for very high energy muons ($E_\mu \geq 100$ TeV). Excess of VHE muons can be the evidence for new physics appearance at PeV energies (that correspond to TeV energies in the center-of-mass system) [1].

In the interval of hundreds TeV, it is impossible to use well-known methods of muon energy spectrum studies such as magnetic spectrometer (very small deviations of trajectory of particles in accessible magnetic field) and absorption curve (the fluxes of such muons and of neutrino-induced muons are comparable). Two other methods of muon energy evaluation are: ionization calorimeter and pair meter technique.

The paper concerned with the measurement of energy spectrum of muons by means of calorimetric method (measurements of big electromagnetic cascades with energy ~ E_μ) in BUST was published earlier [2]. In present work, in order to find VHE muons, the method of multiple interactions of muons based on the ideas of the pair-meter technique [3] (measurements of multiple cascades with energies << E_μ) is used. The rate of interactions of VHE muons in matter differs from that of muons with lower energies due to a fast increase of electron-positron pair production cross section with muon energy. Analyzing events with several muon interactions in the detector, it is possible to make some conclusions about the behavior of the muon spectrum at very high energies.

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2. Experiment

BUST [4] is located in an excavation under the Mt. Andyrchy at effective depth 850 hg/cm^2, that corresponds to threshold energy of detected muons 220 GeV. It is a four-flour building with 17×17×11 m^3 dimensions. 3150 scintillation detectors cover entirely all four horizontal planes (two of them are internal ones) and four vertical sides of the installation. Each of the detectors has dimensions 0.7×0.7×0.3 m^3 and consists of an aluminum tank filled with liquid scintillator viewed by a 15-cm diameter PMT (FEU-49). Most probable energy deposition in the detector at passage of a muon is 50 MeV (one relativistic particle). The anode output of PMT serves for trigger formation of various physical programs. Pulse channel with operating threshold of 12.5 MeV is connected to 12-th dynode of PMT and gives coordinate information of "yes-no" type. The signal from 5-th dynode of PMT is used to measure the energy deposition in the range from 0.5 to 600 GeV by means of logarithmic converter of pulse amplitude to the duration. Here we use only information from horizontal planes of the telescope. Upper scintillator plane consists of 576 (24×24) detectors, three lower planes contain 400 (20×20) counters each. The distance between neighboring planes in a vertical is 3.5 m. Total thickness of one layer (concrete and scintillator) is approximately 7.2 radiation length.

Preliminary selection of experimental data collected at BUST in 1983-1993 was carried out by means of physical master – energy deposition in at least one horizontal plane ≥ 2.5 GeV (counting rate – about 2000 events per day). Total "live" time of registration amounted to 2.46×10^8 second.

3. Simulation

Simulation of the response of the telescope for passage of single muons (Fig. 1) was performed by means of Monte-Carlo technique on the basis of Geant4 package [5] (version 9.1.p01). Before full-scale simulations were started, tests of electromagnetic muon interactions implemented in Geant4 have been performed in a wide range of energies and for different materials. It was found that theoretical dependences of the cross sections are well reproduced in the simulation.

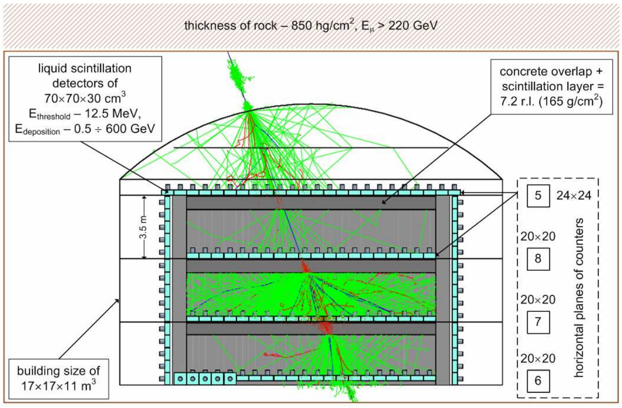

Fig. 1. Passage of high energy muon through the telescope. Interactions of muon in telescope layers and cascades of secondary particles are seen.

Total statistics of simulated events for muon energy ≥ 1 TeV exceeded the expected flux by 3 times, ≥ 10 TeV – by 15 times, ≥ 100 TeV – by 70 times. Note that the slope of integral muon spectrum γ was set equal to 2 (in order to increase the number of high energy particles), angular distribution of muons was taken isotropic. Passage of muons crossing all four horizontal planes of the telescope was simulated.

Data on energy depositions in scintillation counters, as well as information on the type, value and coordinates of the interactions with transferred energies more than 1 GeV for each event were saved for the further analysis.

To construct the distributions for different muon spectra, angular dependence, effective area of registration, statistics of events with different muon energies were taken into account with corresponding weights.

4. Method of Multiple Interactions

A. Phenomenological parameters of the events

The structure of BUST (4 horizontal planes) allows select events with two clearly separated muon interactions in the telescope (Fig. 2).

It was required that in a longitudinal profile of energy depositions (in horizontal planes) of the event there was a minimum in one of inner planes (E_{min}) and two maxima – atop and below it – were observed. Then, E1 is energy deposition in the largest maximum and E2 – in the lower ones, K2 =E2/E_{min}.

Parameters of E1, E2, K2, characterizing multiple interactions of high energy muons in the telescope, affect the selection of events in a following way:

1) shift in E2 is almost proportional to the shift in muons energy (from Fig. 3 it is seen that with the rise of E2 the most probable value of muon energy is also increasing);

2) increase of K2 allows to suppress nuclear cascades, which may imitate multiple muon interactions (the contribution of such false events is reduced from 14% at K2 ≥ 1 to 3% at K2 ≥ 10);

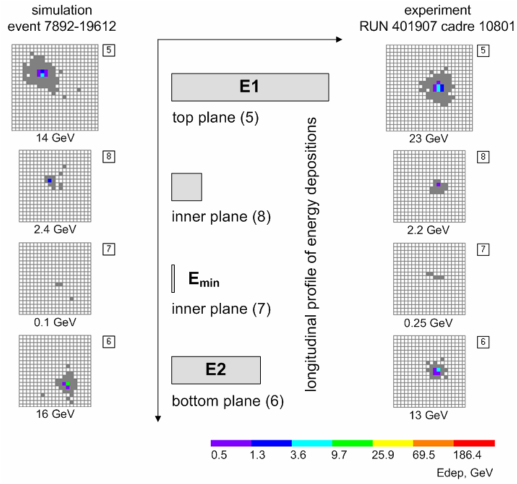

Fig. 2. Samples of events. Horizontal planes of BUST (top view) with hit detectors are shown.

3) introduction of selection threshold in E1 allows to reduce contribution of muons with energies of the order of TeV by about 10 times (at E1 ≥ 40 GeV), while considerable part of statistics (~ 1/3) for high energy particles (~ 100 TeV) is retained.

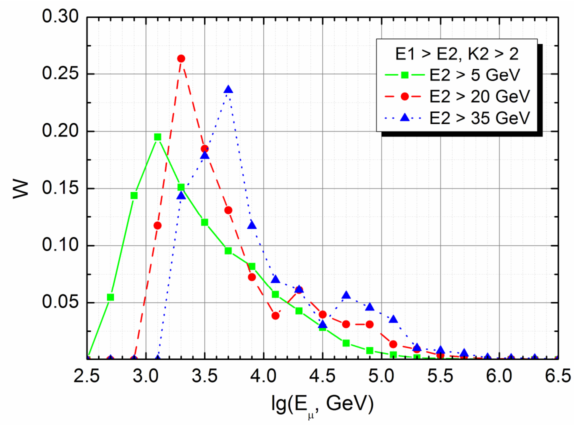

Fig. 3. Distributions of muon energies, giving contribution to the events with different parameters of E2 for a “usual” spectrum of muons.

As it follows from the theory of pair-meter technique, spectra of rank statistics of energies transferred in interactions (in this case – the second in value cascade) are approximately similar to the muon spectrum. Since the energy in the lower of two maxima E2 is determined mostly by the second in value cascade, it is reasonable to use event distributions in E2 for the analysis.

B. Sensitivity of the method

To check the sensitivity of the method of multiple interactions to the shape of energy spectrum of muons, integral distributions of simulated events in E2 for different muon spectra (Fig. 4) have been constructed.

In Fig. 5, the ratio of distributions in E2 for spectra with power index γ=2.5 and γ=2.7+“prompt” (i.e. taking into account production of muons through charmed-particle decays) to the distribution for a "usual" spectrum of muons (γ=2.7) are shown; conditions of event selection are E1 ≥ 20 GeV and K2 ≥ 2. As one can see from this figure, at large E2 (~ 100 GeV) the sensitivity of the method to the shape of muon spectrum substantially increases: a change of the slope of distributions appears, whereas in the range of low E2 they differ from each other practically only in absolute value.

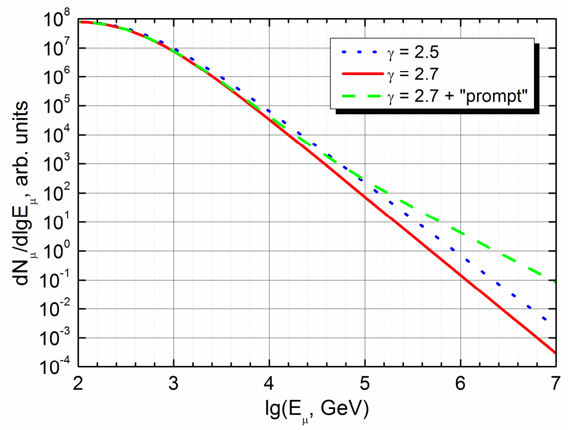

Fig. 4. Differential spectra of muons for different power indices.

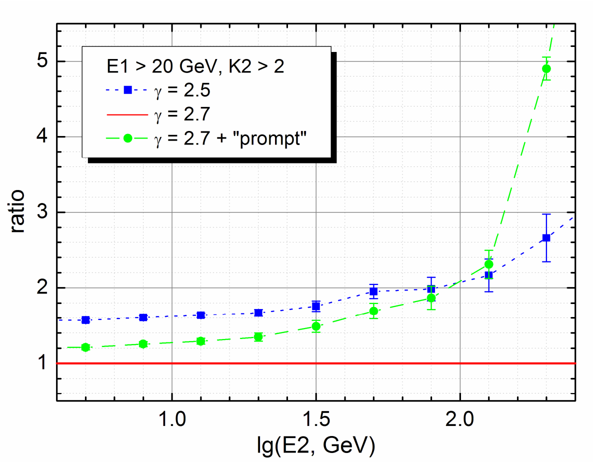

Fig. 5. Ratio of integral distributions of events, calculated for spectra of muons with power index γ = 2.5 and γ = 2.7 + "prompt" to distribution for a "usual" muon spectrum (γ = 2.7).

5. Comparison of experimental data with simulation

In case when muon group passes through the installation, processing of experimental events becomes complicated, since the energy deposition in the plane of the telescope consists of energy deposition of the cascade from muon in interest and energy depositions of cascades from other muons of the group. Therefore, first in each of the horizontal planes of the telescope compact "spots" of hit detectors are found (compact "spot" is an area in which hit detectors touch each other at least with corners). Energy deposition in the compact "spot" is calculated as a sum of energy depositions in constituent detectors. If spots on all four planes belong to the same trajectory of the muon, parameters of E1, E2, E_{min} are calculated. Then a recalculation from energy depositions in compact "spots" to energy depositions from cascades is carried out.

To ensure the identity of selection and the analysis of simulation and experimental events, the parameters E_{min}, E1, E2 for simulated data were calculated by energy depositions in horizontal planes of the telescope (as only single muons were simulated, the energy deposition in the plane corresponds to energy deposition from the cascade).

Calculations for a "usual" muon spectrum (from π-, K-decays in the atmosphere) with γ = 2.7 according to Gaisser and Stanev formula [6] on the basis of simulated events were performed, and normalization to the expected number of muons with energy above 1 TeV at the surface during the exposition was carried out taking into account the aperture of telescope.

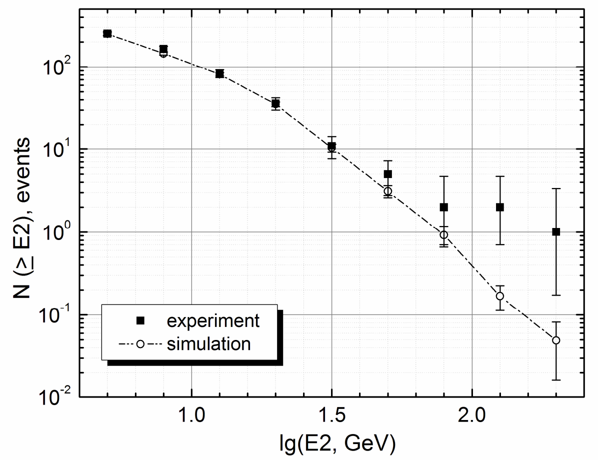

Fig. 6. Integral distributions of experimental and simulated events (for a "usual" muon spectrum) in energy deposition E2; selection parameters are E1 ≥ 20 GeV and K2 ≥ 2.

In Fig. 6, integral distributions of experimental and simulated events in E2 (energy deposition in lower maximum of longitudinal profile of energy depositions in horizontal planes of the telescope), selected with conditions E1 ≥ 20 GeV and K2 ≥ 2, are presented.

It is seen that within the statistical errors the experiment and calculations are in a good agreement, except for the "tails" of distributions, where the intensity observed in the experiment considerably exceeds the expectation (at a level of 1-2 events). As was shown above, the sensitivity of the method is increasing namely here. Estimated average and logarithmic average energies of muons, giving contribution to such events, are hundred TeV and several tens TeV, respectively (Table 1).

It is necessary to note that detection of very high energy muons is more probable in the case when EAS axis crosses the telescope. At energies of primary particles $E_0 \sim 10^{16}$ eV the muon density near the axis is high, and cascades from different muons will be overlapped, therefore their separation within this methodology is difficult.

TABLE I.
ESTIMATES OF MUON ENERGIES, GIVING CONTRIBUTION TO EVENTS WITH MULTIPLE INTERACTIONS IN BUST FOR DIFFERENT THRESHOLD VALUES OF PARAMETER E2 (UNDER SELECTION CONDITIONS $E1 \geq 20$ GEV, $K2 \geq 2$).

lg(E2, GeV)	average E_μ, TeV	logarithmic average E_μ, TeV
0.7	10.5	3.8
0.9	13.0	4.5
1.1	14.6	4.8
1.3	17.0	5.1
1.5	26.2	6.7
1.7	39.2	13.0
1.9	55.4	15.7
2.1	106.2	30.9
2.3	166.2	51.1

6. CONCLUSION

The presented analysis confirms that BUST, despite of a small thickness and low number of layers, in principle, can be used to search for very high energy muons by means of the method of multiple interactions. Some excess of the number of experimental events over the expected one from a "usual" muon spectrum, generated as a result of π-, K-decays in the atmosphere, is observed; estimated energies of such muons are ~ 100 TeV. It is necessary to note that very high energy muons flying near the axis of EAS initiated by primary particles with energies above the spectrum "knee" remained outside of the frame of the present consideration. Therefore a different approach to the analysis of such muons is required.

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