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Horizontal Cosmic Ray Muon Energy Spectrum Measurements by Means of the Pair Meter Technique

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Abstract

Big liquid-argon spectrometer BARS (3 m diameter, 18 m instrumented length, 200 ton target mass) operated as a pair meter is used for cosmic ray muon spectrum measurements. The fine structure of the detector ensures the reconstruction of small cascade showers generated by high energy muons via direct electron pair production process. Distributions of various characteristics of multiple interaction events are sensitive to muon spectrum shape, and allow to estimate the parameters of the spectrum model. Preliminary results of the analysis of the data obtained during 2140 hr operation time (685 thousand muons) are presented.

1 Introduction:

Muon energy spectrum carries information about primary cosmic ray spectrum and muon production mechanisms. Experimental data on muon spectrum in TeV energy range are not conclusive and often controversial. The reason is that the most of energy spectrum measurement techniques subject to serious experimental uncertainties and limitations at high muon energies.

Alekseev and Zatsepin (1960) suggested a new method of muon spectrometry based on the energy dependence of the cross section of direct electron pair production by muons. In passing through a thick layer of matter, high-energy muon produces secondary electromagnetic cascades, mainly due to electron pair production process. Measurements of the number and energies of these cascades allow to estimate muon energy. The theory of the method (which is now called the pair meter technique) was elaborated by Kokoulin and Petrukhin (1988, 1990). The most important advantage of the pair meter is that the measurement accuracy is not deteriorated with the increase of muon energy.

Application of the pair meter technique implies a big thickness of the detector ($\geq$ 100 rad. length), and sensitivity of the setup to low energy muon interactions (of the order of 10^{-3} of muon energy). Recently, experiments on muon spectrum measurements by means of the spectrometer BARS used as a pair meter were started in IHEP, Protvino (Belikov e.a., 1997), and long-term cosmic ray expositions have been conducted. The size and the structure of the detector are adequate to pair meter technique realisation. In the present paper, preliminary results of the analysis of the part of collected data (December 1996 - July 1997) are described.

2 Experimental:

Big liquid-argon spectrometer BARS (Sergiampietri, 1993) has 18 m instrumented length (138 r.l.) and 3 m diameter, and contains 288 layers of bi-gap ionization chambers (each segmented into 48 cells across the

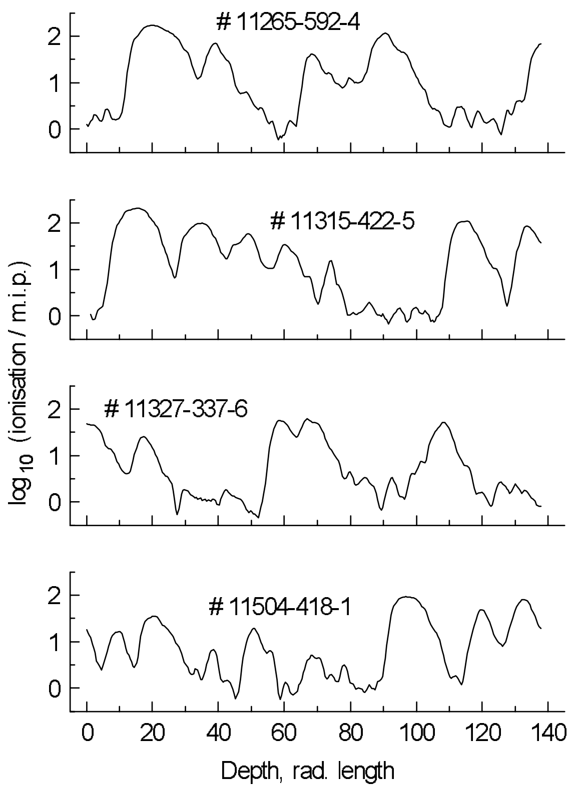

Figure 1: High energy muon events detected in BARS. Smoothed longitudinal profiles are given in units of minimum ionising particles (m.i.p.).

calorimeter), and 24 scintillation trigger planes with area 5.7 m^2. Typical signal-to-noise ratio for relativistic muon detection in ionization chamber cells is about 4.

For the selection of horizontal muons, 3-fold coincidences between three groups of scintillation planes - (2, 3, 4), (12, 13, 14), and (18, 19, 20) - were used. In all, about 1.2 million horizontal muons have been detected during 2140 hr net operation time. In the further physical analysis, muon tracks crossing 3rd and 19th trigger planes (about 685 thousand events) have been used. For such events, geometrical factor of the setup is about 0.22 m^2 sr, average trigger efficiency is close to 97%, and muon track length in the calorimeter fiducial volume exceeds 90 r.l.

Cascades from individual interactions of muons were found on the basis of the analysis of longitudinal profile of ionisation measured within ± 30 cm road along the muon track. Two cascades were considered separated when the minimum in a smoothed longitudinal profile between them was twice less than each of the corresponding maximums. Cascade energy was estimated as the area under the transition curve (minus average muon contribution within the cascade boundaries). Absolute energy calibration of the calorimeter is based on the position of single muon peak (probable ionisation). Examples of detected high-energy muons are given in Fig.1.

3 Simulation:

The detector response was calculated for a trial spectrum $N_0(E,\theta)$ of muons produced in π, K-decays in the atmosphere (Volkova, 1969). Power index of integral parent particle generation spectrum was taken as $\gamma_\pi = \gamma_K = \gamma = 1.70$; K/π - ratio is fixed at 0.15.

For muons sampled in accordance with the trial spectrum and trigger acceptance, BARS response is simulated on the basis of GEANT 3.21 (CERN, 1994). However, the treatment of electron pair production and photonuclear muon interaction (seriously distorted in the original version of GEANT) has been corrected. Another modification of the code included extension of muon energy range from 10 to 100 TeV. Basic experimental distortions (electronic noise, inter-channel cross-talk, detection threshold, electronics saturation at high signals) are introduced into calculated energy depositions in calorimeter cells, the parameters of these distortions being measured experimentally. After that, simulated events are processed with the same computer routines as real ones.

To construct expected distributions of event characteristics for some muon spectrum $N(E,\theta)$ different from the trial one, the weight equal to the ratio of the spectra is attributed to each of the events. In a similar way (by means of the weights) the corrections for muon absorption in surrounding material and trigger plane efficiencies have been introduced. Total Monte Carlo statistics used in the present analysis is about 2.8 times greater than experimental one.

4 Data reduction:

Distributions of various characteristics of multiple interaction muon events are sensitive to muon energy spectrum shape and allow to evaluate the spectrum parameters. Three different modifications of the pair meter technique (considered for idialised pair meter model by Kokoulin and Petrukhin, 1988 and applied recently by Castagnoli e.a., 1997) have been used in the present work.

In the first mode, distribution of the events in the number M of reconstructed cascades with energy transfers more than a fixed threshold ε_0 = 1 GeV is considered (Fig.2). The second version of data reduction is based on the use of rank statistics of cascade energies. In every event, these energies are arranged in a decreasing order: $\varepsilon_{\nu+1} \leq \varepsilon_\nu$; thus, ε_4 corresponds to the forth value of cascade shower energy (in those events where it is found). Cascade shower energy rank statistics with sufficiently high rank ($\nu \geq 3$ for BARS thickness) are nearly proportional to muon energies. For the events plotted in Fig.1, $\varepsilon_4 > 4$ GeV; comparison with MC simulation shows that this corresponds to log-average muon energies greater than 3 TeV. Experimental and calculated integral spectra of rank statistics of reconstructed cascade energies are presented in Fig.3. In this analysis, the spectrum of ε_4 (together with statistically independent numbers of events with $M < 4$) is used for evaluation of muon spectrum model parameter γ.

In both versions considered above, every event is described by a single parameter (number of interactions M or rank statistics value ε_4). In the most informative mode of the pair meter technique, all the energies transferred in individual interactions have to be taken into account. In the third mode of data reduction, we characterize the event by a set $\{\varepsilon_\nu\}$ of first five rank statistics, and analyse the event distribution in 5D-space of rank statistics vectors. In each of the dimensions, 7 energy bins have been selected, the boundaries corresponding 0.5, 1, 2, 4, 8, and 16 GeV. In all, taking into account the rank condition ($\varepsilon_\nu \geq \varepsilon_{\nu+1}$), 462 independent classes of the events have been formed.

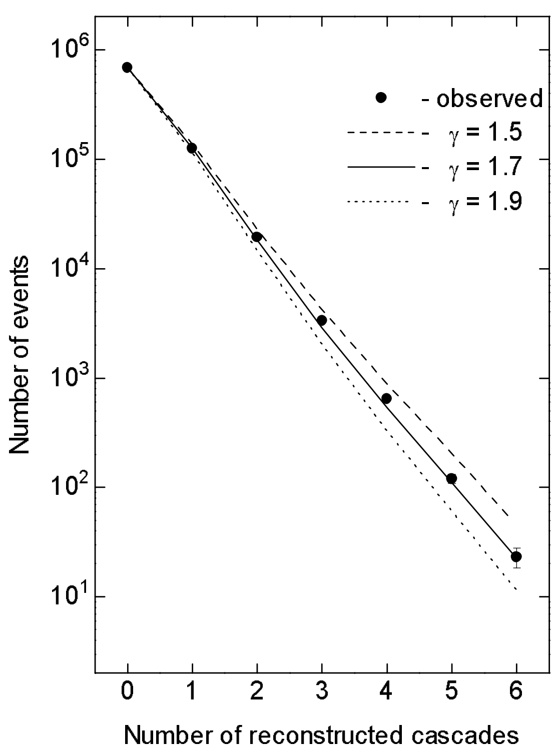

Figure 2: Integral distribution of the events in the number of reconstructed cascades with energies $\varepsilon > 1$ GeV. Curves: calculations for different γ.

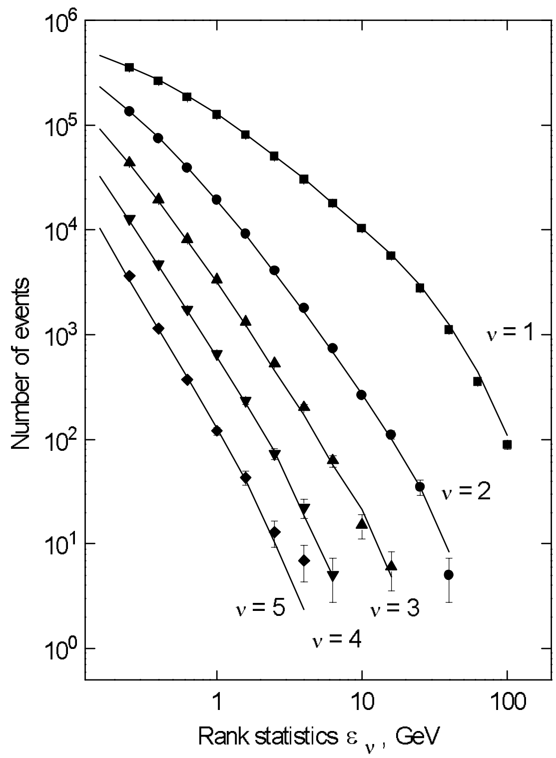

Figure 3: Integral spectra of cascade energy rank statistics. Curves: simulation results (γ = 1.65) normalised to the total number of muons.

5 Parent meson spectrum:

Results of the evaluation of integral parent meson (π, K) spectrum index γ for different methods of data reduction are presented in Table 1. Analysis of the events with a different minimal interaction multiplicity M_{min} allows to select data samples with different log-average muon energies (second column in Table) and thus to follow energy dependence of the spectrum slope. Errors quoted in the Table are purely statistical and are determined by experimental number of events. Systematic errors (related mainly with the uncertainties in muon absorption in the surrounding matter) prevail at low muon energies. Errors caused by a limited MC statistics amount to about 0.6 of experimental ones and should be added quadratically.

Table 1. *Experimental estimates of parent meson integral spectrum index.*

M_{min}	$\langle lg\ E,\ GeV \rangle$	No. events	Multiplicity	ε_4 spectrum	ε_v - vector
0	1.58	685411	1.674 ± .005	1.674 ± .005	1.678 ± .004
1	1.88	125405	1.598 ± .009	1.598 ± .009	1.600 ± .007
2	2.24	19362	1.606 ± .020	1.604 ± .020	1.608 ± .015
3	2.61	3338	1.662 ± .052	1.642 ± .052	1.666 ± .032
4	2.92	648	1.838 ± .130	1.721 ± .133	1.676 ± .071

Estimates obtained with three modes of data reduction agree well with each other. Comparison of the statistical errors given in the Table shows that the modification based on multi-parameter description of the events (ε_v vectors) is the most sensitive to muon energy spectrum shape and allows to appreciably decrease the uncertainty at high energies.

6 Conclusion:

Preliminary results of a first high-statistics application of the pair meter technique for cosmic ray muon spectrum measurements are presented. Comparison of experimental data with MC simulation confirms the adequacy of the description of the detector response. Distributions of various characteristics of multiple interaction events are sensitive to muon spectrum shape and allow to estimate spectrum model parameters. The further analysis of experimental data, increase of MC statistics and consideration of possible sources of systematic uncertainties are in progress. The use of all accumulated experimental material (more than 1 year exposition) will allow to obtain information on muon spectrum in TeV energy range by means of a new independent technique which is free of the distorting influence of upper limitations on measured muon energies.

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References

Alekseev, I.S., and Zatsepin, G.T., 1960, Proc. Intern. Conf. on Cosmic Rays, Moscow, 1, 324.
Belikov, S.V., Denisov, A.G., Denisov, S.P. et al., 1997, Proc. 25th ICRC, Durban, 6, 329.
Castagnoli, C., Castellina, A., Saavedra, O. et al., 1997, Astropart. Phys., 6, 187.
GEANT - Detector Description and Simulation Tool. CERN Program Library, W5013, Geneva, 1994.
Kokoulin, R.P., and Petrukhin, A.A., 1988, NIM, A263, 468.
Kokoulin, R.P., and Petrukhin, A.A., 1990, Sov. J. Part. Nucl., 21, 332.
Sergiampietri, F., 1993, Proc. 4th Intern. Conf. on Calorimetry in HEP, La Biodola, 357.
Volkova, L.V., 1969, Preprint FIAN SSSR No.72, Moscow.