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Pair meter technique measurements of horizontal muon energy spectrum

V. B. Anikeev[1], S. P. Denisov[1], G. Gennaro[2], S. N. Gurzhiev[1], T. M. Kirina[3], R. P. Kokoulin[3], V. M. Korablev[1], V. V. Lipaev[1], A. A. Petrukhin[3], A. M. Rybin[1], F. Sergiampietri[2], G. Spandre[2], and E. E. Yanson[3]

[1]Institute for High Energy Physics, 142284 Protvino, Russia
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, 56010 S.Piero a Grado (PI), Italy
[3]Moscow Engineering Physics Institute, 115409 Moscow, Russia

Abstract. Spectrometer BARS of the tagged neutrino facility of the Serpukhov accelerator (IHEP, Protvino) is used to measure the energy spectrum of cosmic ray muons at large zenith angles by means of the pair meter technique. The setup represents a fine-grained liquid-argon ionisation calorimeter with 3 m fiducial diameter and 18 m instrumented length, total target thickness being equal to 138 radiation lengths. Experimental data accumulated during 1996 - 1998 in a dedicated cosmic ray run (5480 hr net operation time, over 3 million reconstructed muon tracks) are analysed. Estimates of the muon spectrum parameters are obtained with various modifications of the pair meter technique. Comparison with the available magnetic spectrometer data is given.

1 Introduction

Pair meter technique is the method of muon spectrometry based on the energy dependence of the cross section of direct electron-positron pair production by muons. The idea of the method was suggested by Alekseev and Zatsepin (1960). In passing through a thick layer of matter, high energy muon produces secondary cascades, mainly due to electron pair production process. Measurements of the number and of energies of these cascades give the possibility to restore muon energy.

The theory of the technique was elaborated and necessary pre-requisites of its application were formulated by Kokoulin and Petrukhin (1988, 1990). In particular, it was shown that a big target thickness (hundreds of radiation lengths) and the sensitivity of the setup to low-energy muon interactions (with energy transfers of the order of 10^{-3} - 10^{-2} of muon energy) are required. The important advantage of the technique is the absence of the upper limitation on measurable muon energies: unlike in most of other methods of muon spectrometry, the relative measurement error in pair meter does not worsen with the increase of energy, which makes it attractive for applications in VHE muon and neutrino investigations.

In 1996, experiments with the big liquid-argon spectrometer BARS (IHEP) in cosmic ray flux were started (Belikov e.a., 1997a,b). The main purpose of these works was a detailed study of the pair meter technique and its application for horizontal cosmic ray muon energy spectrum measurements. Low-threshold calorimetry of the detector allows to identify muon-induced secondary cascades with energies as low as 0.2 - 0.3 GeV, whereas a large target thickness (138 rad. length) and a fine granularity of the setup give the possibility to observe up to 7 - 10 individual interactions of high-energy muon. Preliminary results (based on about 40 % of the available statistics) were presented at the last conference (Kokoulin e.a., 1999). In the present paper, the analysis of all data accumulated during about 1.5 year measurements is described. Estimates of the basic parameter of muon energy spectrum model (parent meson spectrum index) are derived and compared with magnetic spectrometer results. A new modification of energy estimation in the pair meter (based on the maximum likelihood technique) is considered.

2 Experimental data and simulation

Spectrometer BARS (Sergiampietri, 1993; Anikeev e.a., 1997) represents a liquid-argon ionisation calorimeter with a working mass about 200 t (70 % Ar + 30 % Al), 3 m diameter and 18 m length (2880 g/cm^2, or 138 rad. length). It contains 288 planes of ionisation chambers segmented into 48 cells across the setup. The inner triggering system of the spectrometer is formed by 24 scintillation planes with area 5.7 m^2 distributed along the calorimeter. Long-term exposition of the spectrometer in horizontal cosmic ray flux

Correspondence to: R.Kokoulin (kokoulin@nevod.mephi.ru)

Table 1. Estimates of pion integral spectrum slope.

Event sample			Mode of event grouping		
M_{min}	No. events	< lg E >	M	ε_4	$\{\varepsilon_\nu\}$
2	44199	2.25	1.621 ± 0.013	1.619 ± 0.013	1.624 ± 0.010
3	7510	2.62	1.643 ± 0.034	1.632 ± 0.033	1.689 ± 0.023
4	1432	2.94	1.794 ± 0.103	1.678 ± 0.082	1.708 ± 0.053

was conducted in the period since December 1996 to June 1998. As a trigger for the selection of near horizontal muons, triple coincidences of signals from three groups of scintillation planes: (2,3,4), (12,13,14), and (18,19,20) were used. During 5480 hr net operation time, over 3 million events with reconstructed muon tracks were recorded.

For the physical analysis, tracks crossing 3rd and 19th planes of scintillation counters have been selected. Such selection ensures muon detection efficiency not less than 97%. In addition, the length of the track within the inner volume of the calorimeter greater than 240 chamber planes (> 115 rad. length) is required; the number of events with these selection criteria amounts to 1.56 million. Cascades originated from individual interactions have been found on the basis of the analysis of the longitudinal profile of ionisation measured along the muon track. Thus, every muon event is described by a set of geometrical track parameters and a set of energies (and of locations) of reconstructed secondary cascades.

Simulation of the BARS response has been done for muons sampled in accordance with triggering system acceptance, taking into account angular and energy distribution of muons generated in π, K-decays (Volkova, 1969). As parameters of the trial muon spectrum, integral spectrum index γ = 1.7 of parent particles and K/π-ratio equal to 0.15 are used. For every muon, full Monte Carlo simulation has been performed on the basis of GEANT 3.21 package (with corrected description of direct electron pair production and photonuclear interaction of muons). Basic experimental distortions (such as electronics noise, digitisation threshold, etc.) are introduced into calculated energy depositions in calorimeter cells. After that, simulated events are treated by means of the same programs as real ones. Total MC statistics is about 7 times higher than in the experiment. To construct the expected distributions of event characteristics for muon energy spectrum different from the trial one, corresponding weights equal to the ratio of two spectra are attributed to every event.

3 Estimation of spectrum model parameters

Parameters of muon spectrum model (in particular, parent meson integral spectrum slope) are estimated on a statistical basis, by means of the comparison of the observed distributions of some or other event characteristics with the expectation. It is assumed that $\gamma_\pi = \gamma_K = \gamma$. Three different modifications of event grouping into statistically independent classes are used (Castagnoli e.a., 1997; Kokoulin e.a., 1999). In the first case, distribution of the events in the number of interactions M with energy transfers above a fixed threshold (ε_0 = 1 GeV) is analysed. In the second mode, events are classified according to the values of rank statistics of energies of cascades reconstructed in a given event. Rank statistics are defined by the condition $\varepsilon_{\nu+1} \le \varepsilon_\nu$, the forth rank statistics ε_4 being used in the present analysis. Finally, in the third case every event is characterised by a set of first five rank statistics, and the event distribution in 5-dimensional space of rank statistics vectors $\{\varepsilon_\nu\}$ is used for the evaluation of spectrum parameters.

Results of pion spectrum slope evaluation with these modes of event grouping are presented in Table 1. The lines in the table correspond to the treatment of samples of events with different minimal interaction multiplicities M_{min} (first column of the table), that determines different effective muon energies; estimated average logarithms of muon energy (GeV) are given in the third column. Errors quoted in the table are purely statistical. Estimates of γ obtained in different modifications of the technique are in a reasonable agreement with each other. At the same time, comparison of the statistical errors shows that the version based on multi-dimensional description of the events (rank statistics vectors) is the most sensitive to muon spectrum shape.

Estimates of the spectrum index obtained with the last mode of event grouping are shown in Fig.1 together with results derived from the data of magnetic spectrometers MUTRON (Matsuno e.a., 1984) and DEIS (Allkofer e.a., 1985). In all cases, the same spectrum model has been used (Volkova, 1969). In fitting tabulated data of spectrometers, points at momenta exceeding maximum detectable value (m.d.m.) are excluded. For magnetic spectrometers, the errors shown are statistical; for the BARS data, estimated systematic uncertainties are added (in squares) to statistical ones. Though a systematic difference (0.05 - 0.07) is seen between the estimates of γ obtained in the present experiment and in the fit of DEIS data, the agreement with MUTRON spectrum slope is much better. At least, in the latter case the difference is less than that between fits of the results of two magnetic spectrometers.

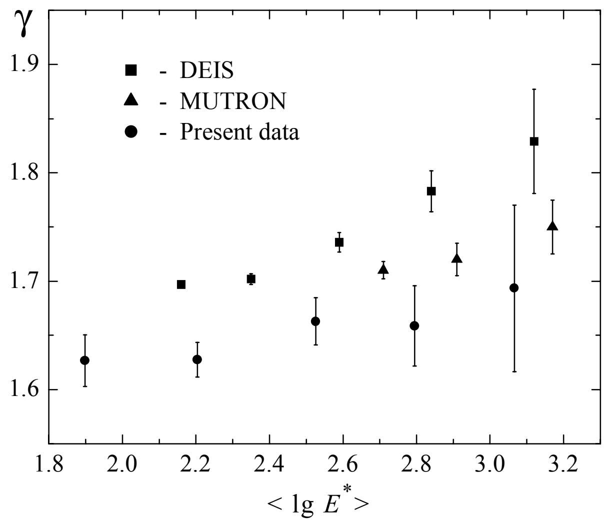

Fig. 1. Estimates of the integral spectrum index of parent particles in the upper atmosphere. Abscissa represents the log-average muon energy at production (GeV).

4 Likelihood estimation of muon energy

In the above analysis, spectrum model parameters have been derived only on statistical basis, and no attempt has been made to ascribe a certain muon energy to every event. Meanwhile, for various applications of the pair meter technique it is extremely desirable to obtain a single parameter, characterising the energy of individual muon, that would effectively take into account the information on all detected muon interactions. Such estimator may be constructed on the basis of the maximum likelihood method. For idealised pair meter model, represented by a layer of matter (with thickness X) capable to measure all transferred energies ε_j above a certain threshold ε_0, the logarithmic likelihood function (LLF) for muon energy may be written as (Kokoulin and Petrukhin, 1988):

$$L(E)=\sum \ln \sigma\left(E,\varepsilon_j\right)-X\sigma_{\text{int}}\left(E,\varepsilon_0\right). \quad (1)$$

Here $\sigma(E,\varepsilon)$ is the sum of differential interaction cross sections of muons for various processes, $\sigma_{\text{int}}(E,\varepsilon_0)$ is the integral cross section for interactions with $\varepsilon > \varepsilon_0$; summation goes over all interactions with energy transfers exceeding the threshold. The likelihood estimate of muon energy E_L maximises the LLF. By analogy with Eq.(1), we use for the real detector:

$$\tilde{L}(E)=\sum \ln \sigma\left(E,\varepsilon_j\right)-\tilde{X}\sigma_{\text{int}}\left(E,\varepsilon_0\right), \quad (2)$$

where

$$\tilde{X}=X-\kappa t_0\sum \ln\left(\varepsilon_j/\beta\right); \quad (3)$$

t_0 and β are radiation length and electron critical energy in the setup material. The last term in the latter equation is proportional to the sum of longitudinal sizes of the observed cascades and represents a phenomenological correction to the muon pass in the target, accounting for the loss of some low energy cascades because of the cascade superposition. The value of the correction coefficient κ = 1.5 has been chosen in such a way that the unbiased estimate of $\langle \lg E_L \rangle$ is reached in TeV range for simulated events. It should be noted however that the precise knowledge of κ, as well as the account for differences between true interaction energies and their calorimetric estimates, is not crucial so far as experimental and simulated events are treated by means of the same algorithms.

Estimates E_L have been obtained for all events, in which at least two reconstructed cascades with energies greater than 0.25 GeV have been found (about 306 thousand muons in the experiment). In Fig.2, the observed distribution of the energy estimates based on logarithmic likelihood function analysis is compared with the simulation results obtained for different values of γ. Calculation results are normalised to the total number of selected muon tracks (1.56 million). An overall agreement with the expectation and the sensitivity of the distribution to the spectrum slope are clearly seen.

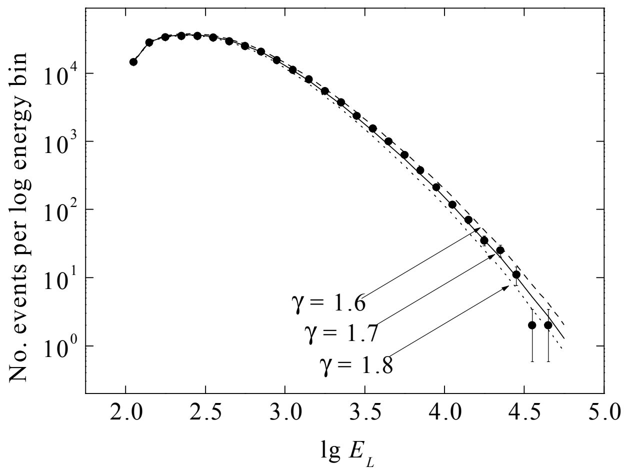

Fig. 2. Differential spectra of LLF-based muon energy estimates.

In conditions of measurements of a steep muon spectrum, the estimate E_L is biased in comparison with a true muon energy, the value of this bias in logarithmic scale is proportional to muon integral spectrum slope and squared relative measurement error (Kokoulin and Petrukhin, 1988). For conditions of the present experiment ($\gamma_\mu \sim 2.7$, $\delta_E \sim 0.9$ in TeV energy range), $\langle \lg(E_L/E) \rangle \sim 0.9$. In Fig.3, the ratio of observed and expected spectra of energy estimates is presented as a function of log-average energy of muons responsible for the events with given E_L. With an exception of the last point in the figure, which contains 5 events corresponding to log-average energies greater than 5 TeV, the reconstructed spectrum is in a good agreement with the expectation for γ= 1.7.

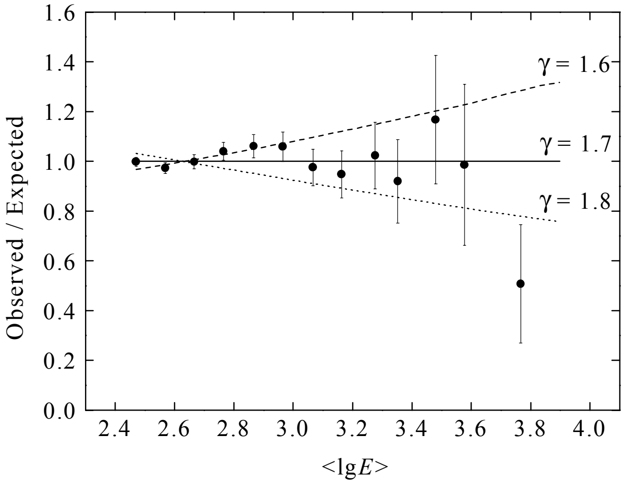

Fig. 3. Ratio of the observed and expected spectra of E_L as a function of log-average muon energy.

5 Conclusion

Pair meter technique has been implemented and applied for cosmic ray muon energy spectrum measurements at the big liquid-argon spectrometer BARS. Unique features of the detector and high statistics of events accumulated in the experiment have allowed to test and to compare various modifications of the technique of muon energy estimation in the pair meter. The agreement of the obtained results with the available magnetic spectrometer data in the overlapping energy range may be considered as a proof of the possibility of application of the technique for investigations of the characteristics of high-energy muon flux in cosmic rays with large-scale experimental arrangements of the new generation.

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