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Direct observation of muon pair production by cosmic ray muons

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Abstract. Experimental data collected in a long-term exposition of the big liquid-argon spectrometer BARS in horizontal cosmic ray flux have been analysed to select the events corresponding to muon pair production by muons in the inner fiducial volume of the detector. The observed number of such events (7 among 1.9 million muons passing through the setup) is in agreement with recent theoretical calculations of the cross section but is about 7 times lower than the prediction obtained with the cross section formula widely used earlier for various estimations.

1 Introduction

The process of electromagnetic production of muon pairs by muons leads to formation of narrow muon bundles which are registered in cosmic ray and accelerator experiments. Though the cross section of the process is relatively small, it represents a serious source of the background in the search of new particles decaying into muons and of other new mechanisms of muon generation, in investigations of characteristics of multi-muon events in EAS, and in the studies of deep inelastic muon scattering.

Early works on calculation of the cross section of direct muon pair production by muons (Tannenbaum,1968; Kobrinsky and Tikhonin, 1972; Barger e.a., 1979; Akhundov e.a., 1980) were aimed at the analysis of accelerator experiments, and were performed only for specific initial muon energies, target nuclei, and fixed energy cuts for final state particles. By this reason, for interpretation of cosmic ray results, where the cross section in a wide range of particle energies is needed, an analytical formula for the cross section quoted by Bugaev e.a. (1970; hereafter BKR) was widely used. However, recent consideration (Kelner e.a., 1999; 2000) has shown that approximations used in the derivation of the BKR formula result in a serious overestimation of the cross section; a modified analytical expression (KKP) for the cross section differential in particle energies, taking into account the finite nuclear size and consistently including the effect of atomic screening, has been obtained.

Experimentally, the cross section of muon trident production was measured in 10.5 GeV muon beam on lead target, energy threshold of final particles being close to 1.5 GeV (Russel e.a., 1971; LeBritton e.a., 1981). Results of these experiments were in agreement with QED predictions. At higher muon energies, only the region of high transverse momenta has been explored in accelerator experiments, and trimuons of electromagnetic origin could not be distinguished from hadron decay background and particles produced in deep inelastic processes.

In cosmic rays, observation of muon pair production by muons was firstly reported by Morris and Stenerson (1968). The number of selected events resulted however in abnormally high (about two orders of magnitude larger than expected) estimate of the cross section. Results of this experiment were critisized by Barton and Rogers (1969) who obtained considerably smaller upper limit for the cross section of the process. Nevertheless, the work of Morris and Stenerson is still mentioned as a first experimental evidence for muon pairs produced by cosmic ray muons (e.g., Vissani, 2001).

In underground setups, the process of muon pair creation by muons leads to the formation of narrow trimuon and dimuon events. In MACRO experiment (LNGS), an excess of muon pairs at low separation distances in comparison with the expectation for usual EAS muons was found (Ambrosio e.a., 1999). Quantitative agreement of this excess with calculations based on BKR formula was interpreted as an evidence for the observation of muon trident production. However, later calculations utilising KKP expression for the cross section (Kelner e.a., 1999, 2000; Kudryavtsev e.a., 1999) showed that BKR formula leads to overestimation of the expected flux of di- and trimuon events by 3–5 times. Therefore, the question on the nature of the excessive flux of narrow pairs in MACRO is still open. Furthermore, formulae for the cross

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section of electromagnetic muon pair production by high-energy muons need a direct experimental verification.

In the present paper, muon tridents produced by horizontal cosmic ray muons in the big liquid-argon spectrometer BARS are analyzed. The first event of this kind was found already in a short two-week run of the spectrometer in cosmic ray muon flux (Belikov e.a., 1997). To the moment, processing of all data accumulated in a long-term cosmic ray exposition (about 1.5 year) has been completed. The observed number of trimuon events is compared with the expectation calculated on the basis of different cross section formulae.

2 Experimental data

BARS (Sergiampietri, 1993) is a large volume detector-target constructed for tagged neutrino experiments at the Institute for High Energy Physics (Protvino). The detector consists of two identical liquid-argon calorimeters. Each calorimeter tank is filled with 216 t of liquid argon, 154 t of those being contained within the fiducial volume. There are two types of detectors inside the cryostats: sections of ionisation chambers and scintillation planes.

Ionisaiton chambers are formed by alternating grounded and signal aluminium plates, the latter being segmented into 48 strips with 63 mm pitch. There are 12 such bi-gap structures along every section of chambers, or 288 bi-gaps in the whole cryostat. Signal strips in adjacent chambers are successively rotated by 120°, thus forming a system of three coordinates in the transverse cross-section of the setup. Signal-to-noise ratio for single muon detection in the calorimeter is about 4:1. The trigger system is built on the basis of 24 scintillator planes distributed along the calorimeter. Outer diameter of the ionisation chamber electrode system is about 3 m, and the total instrumented length of the detector is 18 m. The total target thickness along the setup axis is 2880 g/cm^2 (138 radiathion length, about 25 hadron interaction length). The average density of the material within the fiducial volume is 1.60 g/cm^3, and mass composition is given by (70.4 % argon + 27.4 % aluminium + 2.2 % PMMA) with average values Z/A = 0.461 and Z^2/A = 7.50.

Since 1996, one of the BARS calorimeters was used for investigations of horizontal cosmic ray muon flux. The main goal of this experiment was the measurement of muon energy spectrum by means of the pair meter technique. Some preliminary results on the subject were reported elsewhere (Kokoulin e.a., 1999). At the same time, due to large target thickness, low threshold, good tracking properties of the detector and high statistics of events, the accumulated material offers a good opportunity to study high energy muon interactions and to search for rare cosmic ray phenomena.

Data were taken in several dedicated cosmic ray runs between December 1996 and June 1998. Triple coincidences of signals from three groups of scintillation counter planes located in the beginning, in the middle, and near the end of the calorimeter were used for the selection of muons passing near horizontal direction. For events selected by trigger logic, amplitudes of signals in calorimeter cells (exceeding a certain threshold value, about 0.8 of probable single muon ionisation) were recorded. During total net operation time of 5480 hr, 3.07 million muons with tracks passing within the acceptance angle of the triggering system were detected. For the present analysis, 1.914 million tracks crossing the planes #3 and #19 (i.e., at least two planes in each trigger plane group) were kept. With such additional selection, triggering efficiency is better than 97 %; geometrical factor is about 0.22 m^2 sr, length of the tracks within the fiducial volume being greater than 1900 g/cm^2. Zenith angle interval corresponds to 75 – 90° with average value near 84°; estimated average muon energy is close to 70 GeV.

3 Selection of muon tridents

Events corresponding to muon pair creation by muons were selected on the basis of the analysis of longitudinal profile of ionisation yield along the reconstructed track. For every event, from 200 to 288 ionisation points measured in individual bi-gaps were available. Fiducial volume for possible interaction vertices was defined as follows: the interaction should occur not earlier than in 24th bi-gap after the track enters the inner calorimeter volume, in order to be sure that the single muon is observed before interaction; on the other hand, residual path of the particles after interaction should be not less than 90 bi-gaps (900 g/cm^2, about 8 hadron interaction length, over 40 r.l.). The latter condition determines the minimal energy of all muons in a final state as 1.5 GeV. The search of muon pairs was performed in two stages: fast program selection, and visual scanning of the images of remaining events.

The criterion for program selection was the following. The event was considered as muon pair candidate, if any track segment with a length of 90 consecutive planes of ionisation chambers was found, in any 70 planes of which the measured ionisation exceeded the threshold of 60 ADC counts (i.e., it was greater than about 1.7 single muon ionisation peak). In order to check the program selection efficiency, artificial trimuons were composed of longitudinal profiles of ionisation measured in real events. In the most unfavourable case of the vertex location near the end of the parent muon track (90 planes before the exit out of the calorimeter), the efficiency is close to 95 %; it rapidly improves for longer secondary tracks. With the above parameters, 4816 candidates were selected from the total 1.914 million muons.

The events selected by the program are mainly conditioned by "ordinary" interactions of muons: single high-energy electromagnetic cascade showers (~ 17 %); chains of several low-energy cascades originating from knock-on electrons and electron pair production by energetic muons (~ 69 %); nuclear showers produced as a result of photonuclear muon interaction (~ 14 %). These events, as a rule, are unambiguously separated from the cases of muon pair production at the stage of the visual

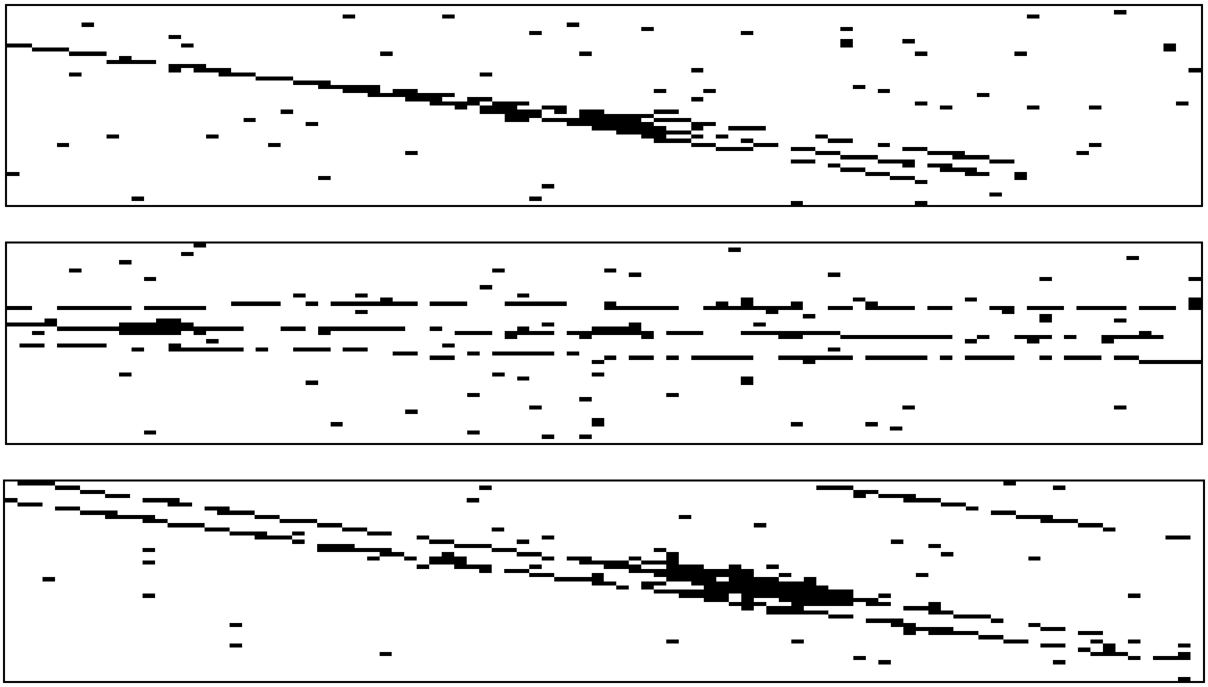

Fig. 1. Trimuon events detected in the BARS calorimeter. Top to bottom: muon pair creation by muon inside the fiducial volume; trimuon event formed in surrounding matter; high-energy muon bundle originated in the atmosphere.

scanning due to characteristic shape of electromagnetic cascades (with dips between them down to the single particle ionisation level), and a "friable" structure of nuclear showers, often being accompanied by short-range hadronic tracks with large fly-out angles.

All 4816 candidates were independently scanned by three experts. In all cases, the same 22 events containing three genetically related muon tracks were found. These events may be classified in the following groups:

(1) Seven events with muon interaction vertex inside the limited fiducial volume, single ionisation is observed before the interaction and triple one after it, ranges of all three particles after interaction being longer than 90 detector planes. In all cases, spatially separated particle tracks are clearly seen at least in one of detector views. It should be stressed however that the latter feature was not decisive for event selection, and primarily the criteria based on the measured ionisation were applied. These 7 events almost certainly represent the cases of direct muon pair production by muons.

(2) Two events with interaction vertex also contained inside the detector, but the length of one or both secondary tracks being shorter than the pre-defined threshold value. We did not include these events into final statistics since the selection efficiency for such events is uncertain.

(3) Twelve narrow muon bundles entering the setup, that may be interpreted as cases of muon pair production in the surrounding material (muon shield of the accelerator neutrino beam, steel of magnetic spectrometer toroids, building walls, etc.). These events are characterized with divergent tracks, typical track separation being less than 50 cm, the angles between tracks ranging from about 5 to 100 mrad. In these cases, interaction vertices are not observed, and various imitations are possible. Since estimation of detection probability and of selection efficiency for such events is rather uncertain, we did not use them in the quantitative analysis.

(4) Finally, one event represents a group of three muons produced in the atmosphere. Particle tracks are parallel within the measurement accuracy (better than 3 mrad). Zenith angle equals to 81°. It is interesting to note that all three particles are accompanied by several secondary electromagnetic cascades thus giving the evidence for high energies of muons (of the order of few TeV).

Examples of selected trimuon events of different groups are presented in Fig.1. For every event, one of three detector views is shown.

4 Comparison with expectation

Thus, the first group of selected events contains muon tridents with the vertex located inside the sensitive volume of the setup, reliably identified particles in the final state, and well defined energy threshold of secondary particles. Selection efficiency for such events is close to 1. The expected number of muon tridents may be easily evaluated as follows:

$$N_{\exp} = \int \sigma\left(E, E_{th}\right) R\left(E\right) dE, \qquad (1)$$

where $\sigma(E, E_{th})$ is the total cross section (in units cm^2/g) for the production of muon pair by muon with initial energy E in the target material, energies of all particles in a final state being greater than E_{th}; $R(E)dE$ is the total range (g/cm^2) of incident muons with energies between E and $(E+dE)$ within the fiducial volume. The latter function was computed taking into account all selection criteria and was normalised to the number of selected muon tracks. In calculations of $R(E)$, energy and angular distribution of muons produced in π, K-decays in the upper atmosphere with integral parent meson spectrum index $\gamma = 1.70$ and K/π-ratio equal to 0.15 (at production) was used.

The expected number of muon pair production events calculated with two different analytical expressions for the cross section of the process (BKR and KKP) is presented in the first two columns of Table 1. Variation of parent meson spectrum index by 0.10 changes the expectation by ± 10 %, whereas the change of K/π-ratio by 0.05 practically does not influence the calculation results. In principle, muon pair production events can be imitated by background processes, such as muon pair production by real photons in electromagnetic cascades, and punch-through hadrons or hadron decays in the showers originated from photonuclear muon interaction. However, the estimated number of such imitations (about 0.3 and less than 0.94 for these two sources of the background, respectively) is small. The observed number of the events (seven) is in good agreement with calculations based on KKP expression for the cross section. On the other hand, calculation results obtained with BKR cross section are in obvious contradiction with the experiment.

Table 1. Expected and observed number of trident events.

Calculated with cross section:		Observed
BKR	KKP	
48	8.9	7

As it was mentioned above, in conditions of the present experiment the average energy of incident muons is close to 70 GeV. Due to a fast increase of the cross section of the process near the threshold, the average energy of muons interacting with the production of muon pairs is considerably higher, and equals to about 270 GeV for E_{th} =1.5 GeV. At such energies, the cross section calculated with this energy cut amounts to about 70 % of the total cross section value (i.e., for threshold equal to muon mass).

5 Conclusion

The events corresponding to muon pair production by high-energy cosmic ray muons in the inner fiducial volume of the big liquid-argon spectrometer BARS have been selected. Big thickness of the target and large number of points of ionisation measurements along the track ensure high efficiency and good reliability of muon trident identification. These data provided the first experimental verification of the total cross section of the process in hundred GeV energy range. The observed number of muon tridents is in agreement with the expectation based on recent theoretical calculations of the cross section (Kelner e.a., 1999, 2000).

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