New Measurement of the Flux of Atmospheric Muons

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(Received 4 January 1999)

We report a new measurement of the momentum spectra of both positive and negative muons as a function of atmospheric depth in the momentum range 0.3–2 and 0.3–40 GeV/c, respectively. The measured flux values have been compared with the spectra obtained from simulations, which were carried out to interpret the atmospheric neutrino data. We find that our data disagree with the results from the simulations. The ratio of the flux of muons derived from simulations to that measured is at largest 1.8 and varies with atmospheric depth and muon momentum. [S0031-9007(99)09347-3]

PACS numbers: 96.40.Tv, 14.60.Pq, 14.60.Ef

Recently the Super-Kamiokande collaboration has reported evidence for neutrino oscillations from the study of atmospherically produced neutrinos in the 50 kt underground water detector [1]. The fully contained neutrino interactions in this experiment are in the energy range 0.1–10 GeV with most events having energies around 1 GeV. The reported value of the ratio $R = (\nu_\mu/\nu_e)_{\mathrm{data}}/(\nu_\mu/\nu_e)_{\mathrm{MC}}$ is 0.63 ± 0.05, in agreement with earlier results of less statistical significance [2]. This result indicates that either too few muon neutrino induced events or too many electron neutrino induced events were observed in this experiment.

Several calculations have been made of the flux and interaction rates of atmospherically produced neutrinos [3–5]. Recently Gaisser *et al.* [6] have compared different calculations and concluded that, although the neutrino fluxes may differ by as much as 30% between the different calculations, the ratio of the flux of muon neutrinos to that of electron neutrinos is consistent within 5%. The differences in the calculated flux values have been attributed to (i) the different parametrization of the particle production in strong interactions of the cosmic ray protons and helium nuclei with atmospheric nitrogen and oxygen nuclei; and (ii) the absolute energy spectra of primary cosmic ray proton and helium nuclei, which differed between experiments by as much as 40%. More recent measurements of the primary cosmic ray spectra are in agreement within ±10% on the proton and helium spectra between 10 and 50 GeV [7,8]. On the other hand, the available accelerator data on the production of pions in proton-nucleus and helium-nucleus collisions are unfortunately limited, and they do not cover relevant ranges of transverse momentum and Feynman variable x. Furthermore, Perkins [9] has pointed out that the Feynman x distribution of produced charged pions that is used in the simulations does not agree with the existing data for low values of x.

The Super-Kamiokande data have been compared with the calculation by Honda *et al.* [3]. For neutrino data below about 1.3 GeV, where the majority of the events are [1], the simulations give 15% less electron events and 36% more muon events than observed. A neutrino energy of 1 GeV on the average corresponds to a muon energy of about 3 GeV. It is essential at this stage to check the other predictions of the simulations by observations. A direct measurement of the flux of muons in the atmosphere, together with the simultaneous measurements of the primary proton and helium spectra [8,10], is a powerful method, which provides a direct test of these simulations. We report in this Letter a new measurement on the flux of atmospheric muons by the CAPRICE94 experiment. As a function of atmospheric height, we have measured the spectrum of positive muons in the range 0.3–2 GeV/c and of negative muons in the range

0.3–40 GeV/c, in analogy with what our collaboration has done in two previous experiments [10,11].

The measurements were made with the balloon borne WIZARD/CAPRICE94 magnetic spectrometer. The launch took place on 8 August 1994 at Lynn Lake, Canada (56.5° N, 101.0° W). During the 3 h ascent to the float altitude of 38 km, corresponding to 3.9 g/cm^2 residual atmosphere above the payload, the experiment was active and collected data on charged secondary cosmic rays. At float, data were collected over a period of 23 h. The instrument, which was housed inside a cylindrical aluminum pressure vessel, included [12] a ring imaging Cherenkov detector (RICH), a time-of-flight (TOF) scintillator system, a superconducting magnet spectrometer equipped with multiwire proportional chambers and drift chambers, and a silicon-tungsten imaging calorimeter. This instrument identified the nature of the particle, its charge, and rigidity. The unique feature of this instrument is the combination of a high efficiency charge one sensitive RICH detector (sodium fluoride radiator of refractive index 1.4), TOF detectors with scintillators, and a calorimeter with high electron identification capability. These independent detectors allow accurate determinations of detector efficiencies and rejection powers.

During the 3 h ascent, 0.68×10^6 particles were recorded, all moving downward in near vertical direction. The number of observed events is not large enough to allow a measurement of the angular distribution within the narrow zenith angle interval allowed to particles (9° typically, 20° at maximum). However, the muon spectra are expected to vary as $\cos(\theta)$, where θ is the zenith angle [13]. The effect is thus small. After applying the selection criteria, we obtained a sample of $1878\mu^+$ in the momentum range 0.3–2 GeV/c and $4627\mu^-$ in the range 0.3–40 GeV/c. From the 23 h float data, the corresponding number of events were 5.5×10^6 giving $2064\mu^+$ in the momentum range 0.15–2 GeV/c and $1601\mu^-$ in the range 0.15–20 GeV/c. In the case of float events, the selection criteria were the same for both μ^+ and μ^-, whereas, for the μ^- in the ascent data, less stringent criteria could be used because of the smaller background. The background conditions are very different for positive and negative muons, and they also vary with atmospheric depth. The major background for μ^+ is protons and at float the p/μ^+ ratio is about 1000 for rigidities above the geomagnetic cutoff of about 0.5 GV. A powerful proton rejection is therefore necessary. The proton flux decreases approximately exponentially in the atmosphere with a characteristic attenuation length of about 120 g/cm^2, while at the same time the muon flux increases. The muon flux reaches maximum at about 200 g/cm^2, where the p/μ^+ ratio is only about 4. Negative muons are easier to select since there is only a small background of electrons.

The selection of $\mu^\pm$ was done using the TOF system, the RICH, and the calorimeter. The combination of these detectors effectively rejected protons below 2 GeV/c and $e^\pm$. Details can be found in [14–17].

The possible admixture of pions in the muon samples was carefully studied [15,17]. From this we conclude that for float data the upper limit of the pion contamination in the total muon sample above 1 GeV/c is 10% and in the range 0.5–1.0 GeV/c this upper limit is 20%, equally for both signs. Because the p/μ ratio decreases fast with increasing atmospheric depth, the above upper limits decrease fast. The data have not been corrected for any pion contamination; rather the upper limit should be considered as a maximum systematic error on the flux.

The absolute particle fluxes were calculated from the number of observed muons taking into account the spectrometer geometrical factor and live time as well as selection efficiencies. Details can be found in [8,15,16]. The agreements found between our results and that from other experiments for several different particle spectra, e.g., protons, electrons, and ground muons, give us confidence in our procedures. Of particular relevance for the results presented here are the excellent agreement found for ground level spectra of both positive and negative muons with other experiments and also our simultaneous measurements of the incident proton and helium spectra [8,15].

The muon spectrum at float is shown in Figs. 1a and 1b. The apparent increase of the positive muon flux above 2 GeV/c is because the RICH rejection of protons becomes insufficient. We thus limit the positive muon data to below 2 GeV/c. Between 1.5 and 2 GeV/c

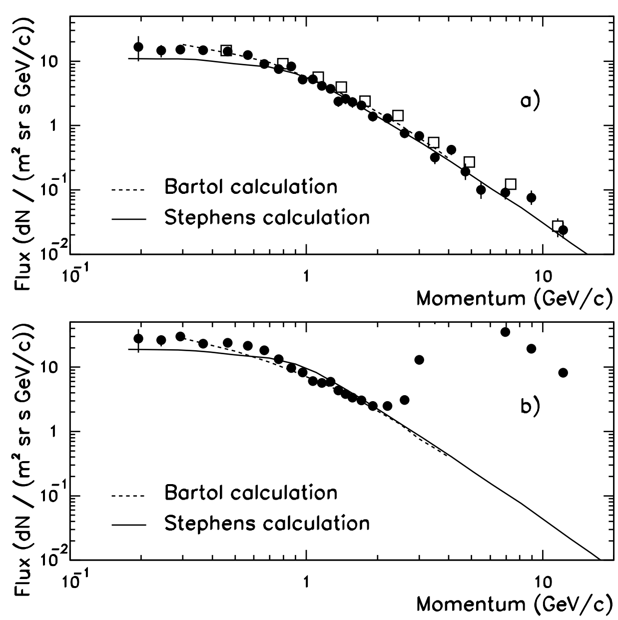

FIG. 1. The flux (full circles) at float (3.9 g/cm^2 residual atmosphere) as a function of momentum for (a) μ^- and (b) μ^+. The open squares show μ^- data from the MASS89 [18] experiment. The calculated values are from the Bartol group [4] and from Stephens [19].

a proton contamination (found to be less than 20%) was subtracted. For negative muons, our data are in good agreement with another measurement for low geomagnetic cutoff, i.e., MASS89 [18], taken at 5 g/cm^2 atmospheric depth. Above 1 GeV/c the spectrum is a power law in momentum with an index of -2.14 ± 0.04. Also shown in Fig. 1 are the simulations of the Bartol group, Barr *et al.* [4] (dashed curve). An earlier calculation by Stephens is also shown [19] (solid curve). The results of the Bartol group [4], using as input the proton and helium spectra from the LEAP experiment [7], agree well with the float data over the range 0.3–4 GeV/c. For positive muons the momentum range is limited and the agreement with Bartol calculation is off by about 35% between 0.4 and 0.8 GeV/c.

The μ^+/μ^- ratio at float as a function of momentum is shown in Fig. 2, along with results from the same calculations. The data are consistent with a constant value of 1.59 ± 0.06. Notice that the effect of a possible systematic error in the flux because of a pion contamination is small and is estimated to be ± 0.08. The simulation [4], carried out for the conditions of the CAPRICE94 experiment (solar modulation and geomagnetic cutoff of about 1 GV), give a value of the ratio averaging about 1.4, a disagreement in comparison with our data at a two standard deviation level. The muons at float are the results of the first hadronic interaction since the mean free path is about 90 g/cm^2. The discrepancy between simulations and experimental results therefore may point to an important problem with the assumptions underlying the simulations. It is interesting to note that the earlier calculation by Stephens [19] (solid curve) agrees better with the data.

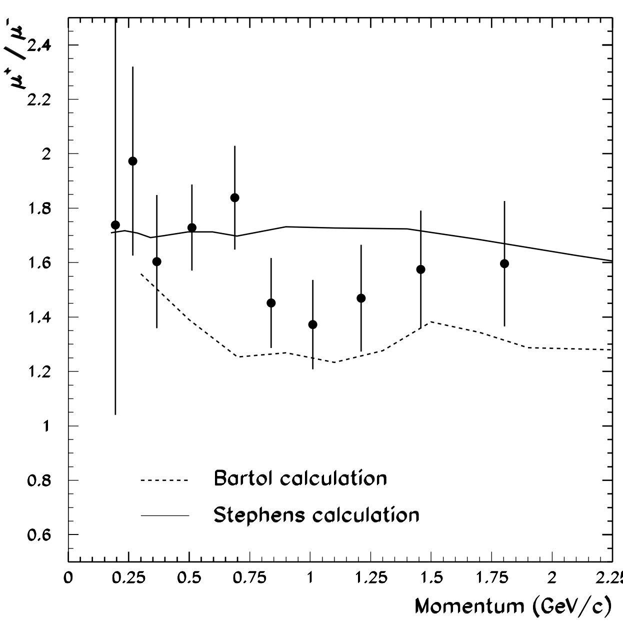

FIG. 2. The μ^+/μ^- ratio at float (3.9 g/cm^2 residual atmosphere) as a function of momentum. The calculated values are from the Bartol group [4] and from Stephens [19].

Figure 3 shows the atmospheric growth of muon flux for nine momentum bins for negative muons and six momentum bins for positive muons. The data are compared with the simulation results of the Bartol group which are shown by solid curves. Our data for negative muons agree inside the errors with the only other published data, i.e., MASS89 [11] and MASS91 [10]. The calculated growth curves from the Bartol simulations [4] show that the flux increases more rapidly with atmospheric depth than our data. The common feature between these calculations and the data is that, for each momentum bin, the atmospheric depth at which the flux attains its maximum appears to be in agreement with the calculation.

A detailed comparison between our data and the results from the Bartol simulation reveals the following picture. For momenta below and around 1 GeV/c, the ratio of the simulation results to the measured negative muon flux values increases with atmospheric depth from about 1.1 ± 0.1 at float altitude to 1.8 ± 0.1 at the maximum of the growth curve around 200 g/cm^2. The above errors are statistical and a systematic error of about 10% should be added [17]. We may point out that, on average, the neutrino takes about one-third to one-fourth of the muon momentum. Thus, the simulation overestimates the flux of 0.2–0.3 GeV muon neutrinos and probably also the flux of the electron neutrinos. However, the effect for neutrinos may be smaller than for muons because of bending of the muons in the earth's magnetic field [20]. The data for positive muons over a more

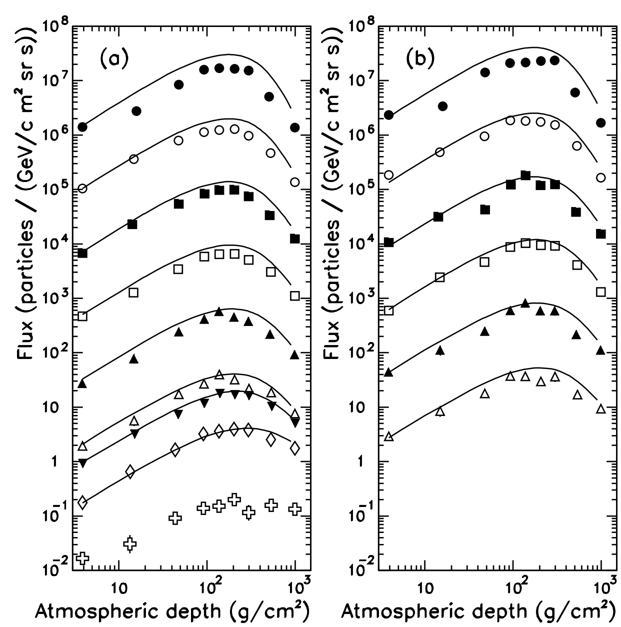

FIG. 3. Atmospheric growth curves for (a) μ^- and (b) μ^+. From top to bottom are the momentum ranges in GeV/c: 0.3–0.53 (scaled by 10^5), 0.53–0.75 (10^4), 0.75–0.97 (10^3), 0.97–1.23 (10^2), 1.23–1.55 (10), 1.55–2 (1), 2–3.2 (1), 3.2–8 (1), and 8–40 (1). The μ^+ results are shown up to 2 GeV/c. The solid lines are calculations by the Bartol group for the conditions of the CAPRICE94 flight [4].

limited momentum range show a similar behavior. As a final remark, we note that published results of the simulations are based on one dimensional propagation. Three dimensional calculations are in progress [20]. We would like to point out that recent results on the low energy sea level muons indicate possible geomagnetic effects [21]. The geomagnetic effects on zenith angle distributions of sub-GeV atmospheric neutrinos have also recently been studied by Lipari *et al.* [22].

In conclusion, we have presented new experimental data on atmospheric muons that show a slow growth of the flux with the atmospheric depth and a larger μ^+/μ^- ratio at float than the predictions of the simulations used to interpret the underground neutrino data. These new data are important constraints for refining the interaction models used in the simulation packages.

We wish to thank T. K. Gaisser and T. Stanev for useful discussions.

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