A New Measurement of the Atmospheric Proton and Muon Fluxes

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Abstract

We report on a new measurement of the momentum spectra of protons as well as of positive and negative muons as a function of atmospheric depth in the momentum ranges 0.5-40, 0.3-2 and 0.3-40 GeV/c, respectively. The measurements were carried out by the CAPRICE94 experiment from Lynn Lake, Manitoba, Canada, 8-9 August 1994. The measured muon flux values have been compared with the spectra obtained from one dimensional simulations, which were carried out to interpret the atmospheric neutrino data. We find that our data of the absolute muon flux disagree with the results from these simulations. The ratio of the muon flux derived from simulations to that measured is at largest 1.8 and varies with atmospheric depth and muon momentum. Also the measured ratio of the flux of positive and negative muons at 3.9 g/cm^2 overburden differs significantly from the simulations. The atmospheric proton flux could be a valuable independent cross-check of the simulation results.

1 Introduction

The Super-Kamiokande collaboration has reported evidence for neutrino oscillations from comparison between measurements of atmospherically produced neutrinos in the 50 kt underground water detector (Fukuda et al. 1998) and simulations (Honda et al. 1990, 1995).

Several simulations have been made of the flux and interaction rates of atmospherically produced neutrinos (Honda et al. 1990, 1995, Barr et al. 1989, Gaisser et al. 1995, 1998). It is essential at this stage to check the predictions of the simulations by observations. A direct measurement of the flux of protons and secondary muons in the atmosphere, together with the simultaneous measurements of the primary proton and helium spectra (Boezio et al. 1999, Bellotti et al. 1999, Circella et al. 1999), is a powerful method, which provides a direct test of these simulations. We report on a new measurement on the flux of protons and muons in the atmosphere by the CAPRICE94 experiment (Boezio et al. 1999). As a function of atmospheric height, we have measured the spectrum of protons in the momentum range 0.5-40 GeV/c, of negative muons in the momentum range 0.3-40 GeV/c, and of positive muons in the range 0.3–2 GeV/c.

2 Particle Selection

The instrument consisted of a time-of-flight (ToF) system of scintillators, a superconducting magnet spectrometer including drift chambers and multiwire proportional chambers, a solid radiator ring imaging Cherenkov (RICH) detector and an imaging Si-W electromagnetic calorimeter (Barbiellini et al. 1996a).

The protons were selected using the ToF system alone, and a contamination of μ^+ was subtracted from the sample above 1.2 GeV/c. The contamination was estimated from the μ^- flux, which can be selected without any significant background, multiplied with the altitude dependent μ^+/μ^- ratio. This introduces a systematic uncertainty on the proton flux which is negligiable at high altitudes, but could be as high as 20% at 500 g/cm^2.

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 $e^\pm$.

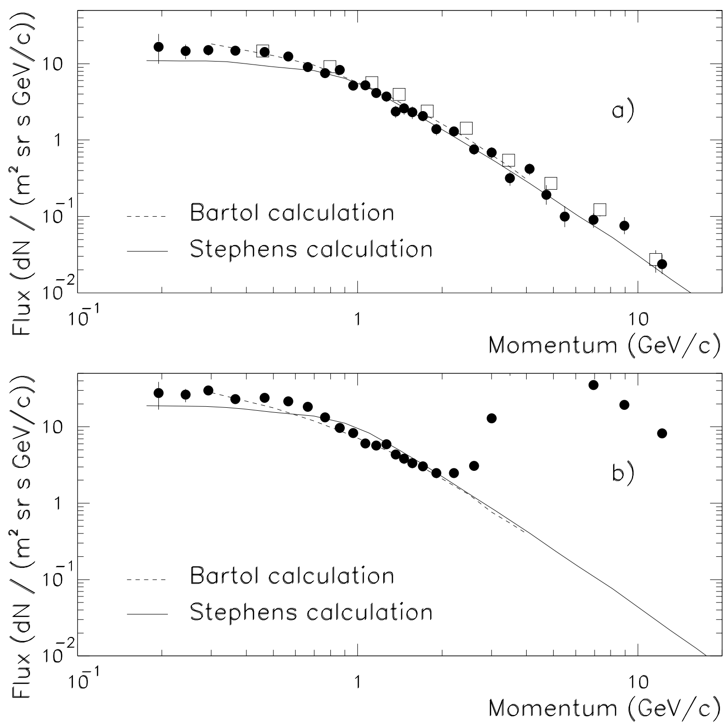

Figure 1: The flux (full circles) at float (3.9 g/cm^2 residual atmosphere) as a function of momentum for a) μ^-, b) μ^+. The open squares show μ^- data from the MASS89 (Brunetti et al. 1996) experiment. The calculated values are from the Bartol group (Gaisser et al. 1995) and from Stephens (1981).

The possible admixture of pions in the samples was carefully studied (Boezio 1998). From this we conclude that for float data the upper limit of the pion contamination in the total 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. Since the p/μ ratio decreases fast with increasing atmospheric depth the above upper limits also 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. The agreements found between our results and that from other experiments for several different particle spectra, e.g. protons, electrons, ground muons, give us confidence in our procedures (Boezio et al. 1999, Boezio 1998, Barbiellini et al. 1996b).

3 Results and Discussion

The muon spectra at float are shown in Fig. 1. 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 a proton contamination (found to be less than 20%) was subtracted. For negative muons, our data are in good agreement with another measurement at low geomagnetic cutoff, i.e. MASS89 (Brunetti et al. 1996), 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.* 1989) (dashed curve). An earlier calculation by Stephens (1981) is also shown (solid curve). The results of the Bartol group, using as input the proton and helium spectra from the LEAP experiment (Seo et al. 1991), 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 Bartol simulation, 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 (1981) (solid curve) agrees better with the data.

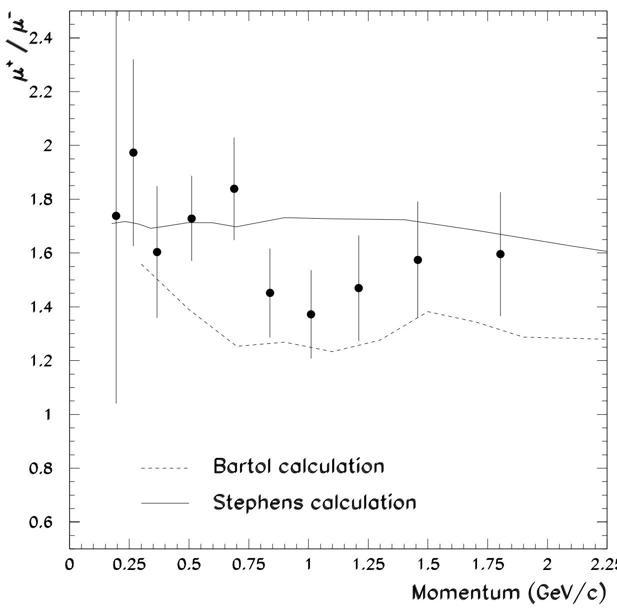

Figure 2: The μ^+/μ^- ratio at float (3.9 g/cm^2 residual atmosphere) as a function of momentum. The calculated values are from the Bartol group (Gaisser et al. 1995) and from Stephens (1981).

Fig. 3 shows the atmospheric growth of the proton and muon fluxes. The muon data are compared with the simulation results of the Bartol group which are shown by the solid curves. Our data for negative muons agree inside the errors with the only other published data, i.e. MASS89 (Bellotti et al. 1996) and MASS91 (Bellotti et al. 1999). The discrepancies between our data and calculated growth curves from the Bartol simulations become larger at increasing atmospheric depth. 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.

For momenta below and around 1 GeV/c the ratio of the Bartol 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. The data for positive muons over a more limited momentum range show a similar behaviour.

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. The proton flux dominate over the μ^+ flux down to atmospheric depths of about 500 g/cm^2 (5.5 km).

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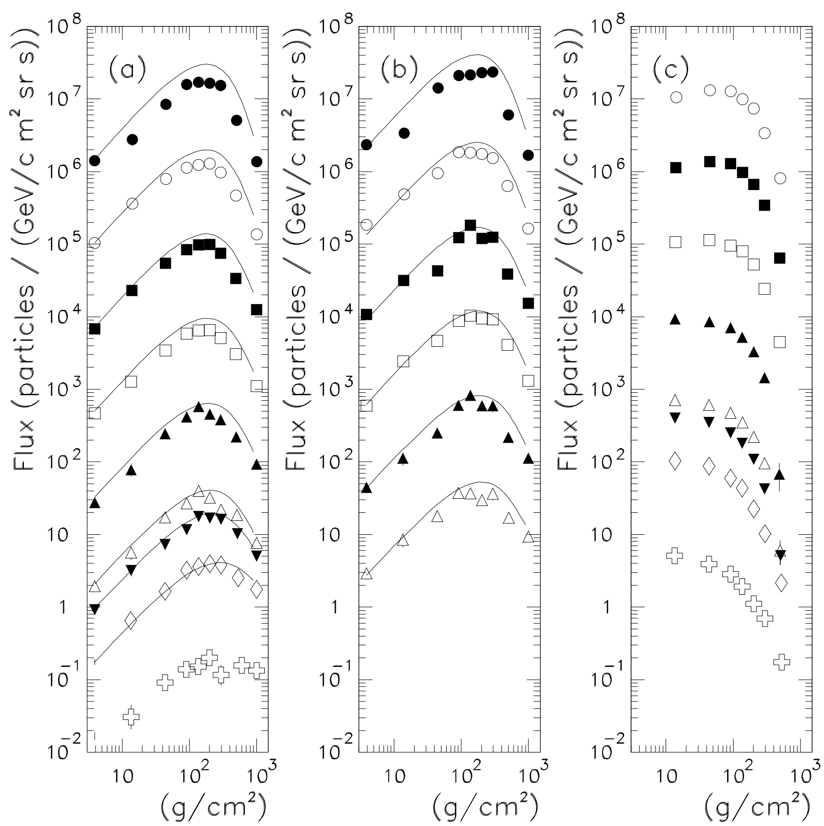

Figure 3: Atmospheric growth curves for a) μ^-, b) μ^+ and c) protons. From top to bottom are the momentum ranges for muons and protons in GeV/c: 0.3–0.53 (scaled by 10^5), 0.53–0.75 (10^4), 0.75–0.97 (10^3), 0.97–1.23 (10^2), 1.23–1.55 (10), 1.55–2 (1), 2–3.2 (1), 3.2–8 (1) and 8–40 (1). The μ^+ results are shown up to 2 GeV/c. The proton results are shown for momenta higher than 0.53 GeV/c. The solid lines are calculations by the Bartol group for the conditions of the CAPRICE94 flight (Gaisser et al. 1998).