Observation of Ground Level Muons at Two Geomagnetic Locations

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Abstract

Two extensive measurements of ground level muons were performed with the NMSU-WIZARD/CAPRICE magnet spectrometer at Lynn Lake, Manitoba, Canada and Fort Sumner, New Mexico, USA, in July 1994 and spring 1997, respectively. The spectrometer was equipped with a superconducting magnet, a time-of-flight system, an electromagnetic calorimeter and a Ring Imaging Cherenkov (RICH) detector. Two different versions of the RICH were used: one with a solid NaF radiator in 1994 and one with a gaseous C_4F_{10} radiator in 1997.

Both the muon spectrum and the μ^+ to μ^- ratio are presented in the momentum range from 200 MeV/c to 120 GeV/c for the two different geomagnetic locations. The spectra are compared with previous experimental results. The data show latitude dependent geomagnetic effects.

1 Introduction

Precise measurements of the muon energy spectrum and charge ratio at sea level over a wide energy range provide information on the propagation of cosmic rays in the atmosphere. Together with data on the primary cosmic rays, muon measurements can be used as a test of calculations of atmospheric cascades and neutrino fluxes (e.g. see Honda et al. 1995, Gaisser & Stanev 1995) which are used to interpret the recent results on neutrino oscillation from the Super-Kamiokande experiment (Fukuda et al. 1998). Furthermore, measurements of muons at low energies (below a few GeV) taken at different geomagnetic locations are useful to study the effect of Earth's magnetic field on the propagation of the secondary component in the atmosphere (Stephens 1979).

In the past the muon spectrum has been extensively measured, mainly by solid iron magnet spectrometers in which multiple scattering plays an important role in the momentum resolution particularly at low energies. Only two measurements have been performed using low mass superconducting magnet spectrometers (Stephens & Golden, 1987, De Pascale et al. 1993). In this paper we report on the muon momentum spectrum and charge ratio from 200 MeV/c to 120 GeV/c measured with the NMSU-WIZARD/CAPRICE magnet spectrometer at two different geomagnetic locations: Lynn Lake, Manitoba, Canada (56.5° N, 101° W), 360 m above sea level, 0.5 GV nominal vertical geomagnetic cutoff and Fort Sumner, New Mexico, USA (34.° N, 104° W), 1270 m above sea level, 4.2 GV nominal vertical geomagnetic cutoff (Shea & Smart 1983).

2 Detector Systems

The NMSU-WiZard/CAPRICE spectrometer was designed as a balloon-borne apparatus for cosmic ray studies. From top to bottom the instrument included a Ring Imaging Cherenkov (RICH) detector, a time-of-flight (ToF) system, a superconducting magnet spectrometer with a tracking system and a 7 radiation lengths silicon-tungsten imaging calorimeter. The instruments used in Lynn Lake and Fort Sumner differed in the tracking system and in the radiator material for the RICH. The instrument operated in Lynn Lake during July 1994 (see Boezio et al. 1999), hereafter called CAPRICE94, used a stack of multiwire proportional chambers (MWPC), two drift chambers and a RICH with a solid NaF radiator of threshold Lorentz factor of 1.5. The maximum detectable rigidity (MDR) was 175 GV. During the spring 1997 campaign in Fort Sumner, with the apparatus hereafter called CAPRICE97, the MWPCs were replaced by an additional drift chamber providing an MDR of 330 GV and the RICH used a C_4F_{10} gaseous radiator (Bergström et al. 1999) with a threshold Lorentz factor of 20.

3 Data Analysis

About 440000 and 1200000 events were recorded in Lynn Lake and Fort Sumner, respectively. The precise measurement of the particle trajectory in the tracking system combined with the excellent performance of the other detectors made it possible to identify muons with very small background of other particles in the energy range 0.2-120 GeV/c. At ground, muons are the main component of the cosmic radiation. However, electrons and positrons are a considerable fraction of the muon component at low energies while the protons amount to a few percent of the muons up to at least 10 GV (De Pascale et al. 1995). Because of the different RICH thresholds, two different muon selections were used to analyse the CAPRICE94 and CAPRICE97 data.

In both experiments, charge one particles moving downward in near vertical direction were selected using the time-of-flight and tracking information. In 1994, muons were above RICH threshold in the whole energy range of interest and they could be separated from electrons up to about 400 MV and from protons up to 5 GV, above which the Cherenkov angle of protons and muons overlapped (Boezio et al. 1999).

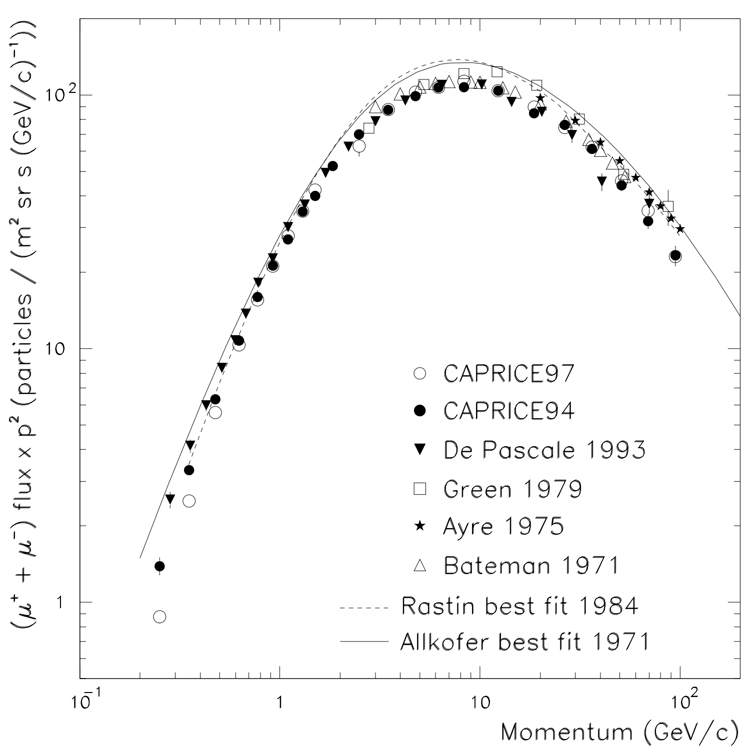

Figure 1: The $(\mu^+ + \mu^-)$ spectrum at sea level as a function of momentum measured by CAPRICE94 and CAPRICE97 (this work) and other experiments. The lines refer to best fits of experimental data not shown here. The fluxes are multiplied by p^2, where p is the momentum in GeV/c.

Hence, in CAPRICE94 the RICH muon selection was used from 0.2 to 5 GV. Electrons were removed by means of the calorimeter information. Above 300 MV muons could be selected with an efficiency close to 100% and with a negligible electron contamination (Boezio 1998). Above 3 GV $e^{\pm}$ amount to less than 0.1% of the muon component (De Pascale et al. 1995, Boezio 1998) and, consequently, the calorimeter muon selection was not used above this rigidity. However, the calorimeter was used to estimate the surviving proton contamination above 3 GV. This contamination was calculated rescaling the number of interacting particles in the calorimeter with factors obtained from data at float (CAPRICE94 flew on the 8th of August 1994). Protons were selected if they had a hadronic interaction in the calorimeter and the efficiency of this selection was estimated using a sample of charge one particles at float which can be assumed to be composed only of protons. Then, the resulting number of protons was subtracted from the positive muon sample. The proton to muon fraction decreases fast with momentum (e.g. see De Pascale et al. 1995) and the proton background becomes negligible above 20 GV.

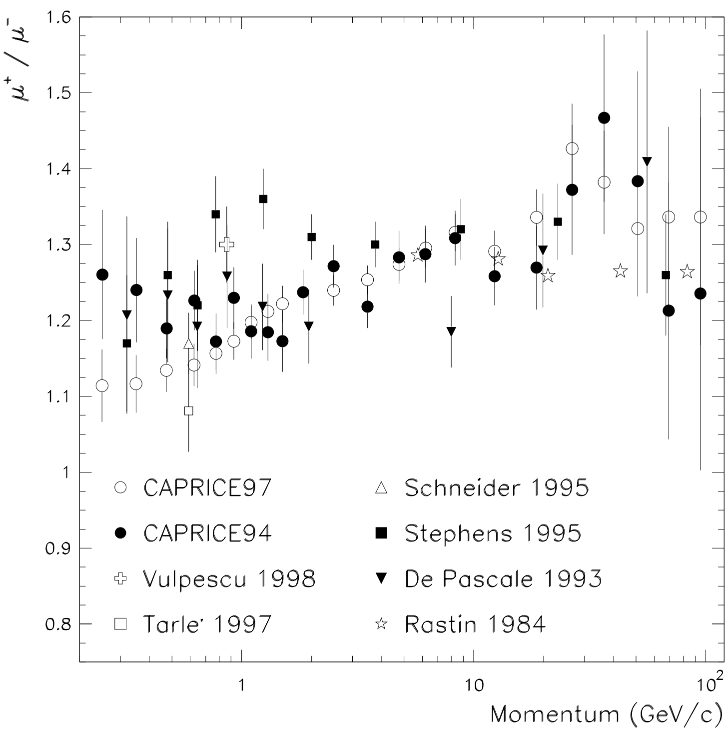

Figure 2: The muon charge ratio as a function of momentum measured at the ground by CAPRICE94 and CAPRICE97 (this work) together with other recent measurements (see Vulpescu et al., 1998, and references within).

In 1997, the low refractive index of the C_4F_{10} radiator permitted to extend the rigidity range of the RICH muon selection. Muons started to produce Cherenkov photons in the C_4F_{10} gas at 2 GV and protons at 18 GV while electrons were above threshold in the whole rigidity range of interest. Hence, muons were selected requiring Cherenkov light above 2.1 GV and no light below. In this way $e^{\pm}$ were rejected up to about 2 GV and protons up to about 20 GV. As noted above, above these rigidities the $e^{\pm}$ and proton backgrounds were negligible. Furthermore, the proton component was studied up to 20 GV and a proton to muon ratio compatible with CAPRICE94 and De Pascale et al. (1995) results was found. Below 2 GV, the RICH was not able to distinguish protons from muons since both were below threshold, hence the time-of-flight information was used. The time-of-flight system had a resolution of about 230 ps which, with a particle trajectory of about 1.2 m, gave a good rejection of protons against muons for momenta less than about 1.6 GV. Between 1.6 and 2.1 GV muons could not be separated from protons and no results are presented in this rigidity interval. Because of the good $e^{\pm}$ rejection of the RICH selection in the low energy range, the calorimeter is not used to select muons in the CAPRICE97 analysis.

4 Results

Figure 1 shows the muon spectrum $(\mu^+ + \mu^-)$ fluxes multiplied by p^2, where p is the momentum in GeV/c) resulting from our measurements (•:CAPRICE94 and ◦: CAPRICE97) extrapolated to the sea level together with other measurements and the best fits of experimental data. The extrapolation is performed scaling the fluxes with an exponential attenuation where the attenuation length is derived from the CAPRICE94 ascent muon data (Boezio 1998, Francke et al. 1999). The CAPRICE94 measurements were taken at an atmospheric depth of 1000 g/cm^2 and CAPRICE97 data at 886 g/cm^2, both depths derived from on site pressure measurements. This procedure may contribute to the uncertainty of the flux normalization at the level of at least 1%. An excellent agreement is found between the propagated CAPRICE94 and CAPRICE97 muon spectra above 1 GeV/c, the results differ by less than 3%, which is well inside the errors. An excellent agreement is also found with the muon data obtained by the MASS89 experiment (De Pascale et al. 1993) which used the same superconducting magnet but different detectors. The differences with the older measurements, mainly obtained using solid iron magnetic spectrometer, are up to 20% larger (e.g. Allkofer et al. 1971). Some data differ also in shape (Green et al. 1979, Rastin 1984) with our measurements.

Below 1 GeV/c the CAPRICE97 muon fluxes are lower than the CAPRICE94 results which could indicate a geomagnetic effect. This effect can be seen also in the muon charge ratio which can be compared without the uncertainty of the atmospheric extrapolation of the spectra. Figure 2 shows the charge ratio as a function of momentum obtained with CAPRICE94 (•) and CAPRICE97 (○) together with other recent experimental data (see Vulpescu et al. 1998 and references within). An excellent agreement is found between all the measurements above 1 GeV/c. Below this momentum the CAPRICE97 charge ratio decreases approaching 1.1 at 0.2 GeV/c, while the CAPRICE94 ratio remains constant at about 1.2. This indicates a latitude dependent geomagnetic effect, which suppresses comparatively more the μ^+ in respect of the μ^-. The relevance of geomagnetic effects to the neutrino calculations has been investigated by Lipari, Stanev & Gaisser (1998).

5 Conclusion

We have presented two new measurements of the ground muon spectra and charge ratio over three decades in momentum taken at two different geomagnetic locations. Above 1 GeV/c the two measured spectra agree with each other (at the level of about 3%) much better than previous sea level muon measurements. The measurements have been extended to low momenta where indication of geomagnetic effects both in the spectra and charge ratio are found.

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