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Positive charge excess of leptons at very high altitude

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Abstract. The positive charge excess of muons is simulated at different altitudes for the different balloon experiments such as CAPRICE, HEAT, MASS, IMAX . . . The enhancement of the positive charge observed near 3–5 g/cm^2 is compared to the simulations carried out with CORSIKA code. We have taken into account the isospin conservation and the charge exchange mechanisms while assuming a primary spectrum dominated by protons (for both quiet and active sun periods). The contamination of positive pions and protons is examinated. We have also used CORSIKA for simulation in the shuttle environment to point out some correlations with the important excess of positive electrons recorded by the AMS experiment near 400 km altitude.

1 Introduction

The study of atmospheric leptons provides a powerful tool to calibrate the calculations of the propagation of cosmic rays in the atmosphere. In particular, muon measurements can be used as a test to the calculations of neutrino fluxes which are crucial for the interpretation of neutrino-induced signals in underground experiments (neutrino atmospheric anomaly). As for electrons, the positron to electron ratio at high altitude is a very sensitive parameter for understanding the primary cosmic ray spectra and the behavior of atmospheric secondary particles in the upper layer of the atmosphere. This work presents some results from Monte Carlo simulations of the propagation of leptons in the atmosphere focusing in particular upon the muon and the electron charge ratios at very high altitude. We have used for this purpose the program CORSIKA (Heck *et al.* 1998) coupled with Gheisha code (Fesefeldt 1985) for the treatment of low energy hadronic interactions (below 80 GeV) and HDPM algorithm (Capdevielle 1989) for hadronic interactions at higher energies.

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2 Positive charge excess for atmospheric muons

The well-known positive charge ratio for the atmospheric muons reflects, on the one hand, the excess of π^+ over π^- in the forward fragmentation region of proton initiated interactions and, on the other hand, the predominance of protons over neutrons in the primary spectrum. At sea level, the measured value for the muon charge ratio above 1 GeV/c lies between 1.1 and 1.4 (Kremer *et al.* 1999). However, below 1 GeV/c, measuments indicate a systematic dependance on the location due to geomagnetic effect (Kremer *et al.* 1999).

Figure 1 shows the calculated muon charge ratio μ^+/μ^- as a function of the atmospheric depth for primary vertical protons of energies ranging from 4.5 GeV to 10^8 GeV, separately for three momentum bins. The lower limit of the primary energy range has been selected according to CAPRICE98 experiment (Circella *et al.* 1999) where measurements were performed at a vertical rigidity cutoff of about 4.5 GV. One million events have been simulted at each altitude. We have assumed a primary spectrum dominated by protons with a differential spectral index of 2.7. Furthermore, the isospin conservation and the charge exchange mechanisms have been taken into account. An excellent agreement is found with recent balloon-borne measurements in comparable momentum intervals: CAPRICE98 (Circella *et al.* 1999), CAPRICE94 (Boezio *et al.* 1999), MASS (Bellotti *et al.* 1999), IMAX (Krizmanic *et al.* 1995) and HEAT (Tarlé *et al.* 1995). We note a week dependance of the charge ratio on altitude: the μ^+/μ^- ratio slightly decreases with increasing atmospheric depth. Moreover, it increases with increasing momentum.

We have also calculated the muon charge ratio at a small atmospheric depth (4 g/cm^2) over a wide range of momentum. As shown on figure 2a, the μ^+/μ^- ratio for vertical protons of 2 GeV is rather high: it increases as much as the muon energy is closer to the primary proton energy (Capdevielle and Muraki 1999). This may explain the enhancement of the positive charge ratio for muons observed by CAPRICE94 experiment (Boezio *et al.* 1999) where the measurements were performed at a lower vertical cutoff (100 MeV) in compar-

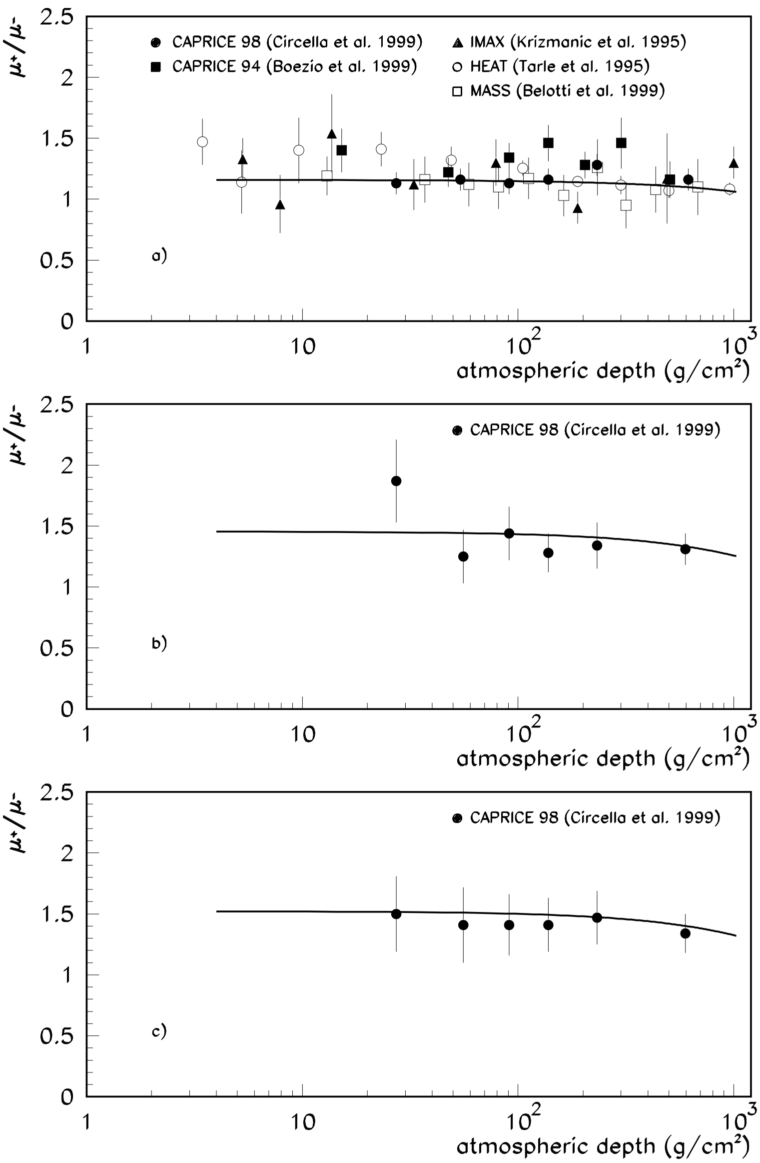

Fig. 1. Muon charge ratio versus atmospheric depth for three momentum intervals: a) 0.3–1 GeV/c; b) 2–4.5 GeV/c; c) 4.5–15GeV/c. The full line represents the Monte Carlo calculations.

ison to CAPRICE98 (Carlson *et al.* 1999) where the cutoff was equal to 4.5 GeV.

3 Positive charge excess for atmospheric electrons

One of the most striking results from the Alpha Magnetic Spectrometer (AMS) experiment is the observation at altitudes near 400 km of a second lepton spectrum characterized by a predominance of positrons over electrons, especially at the equator where a e^+/e^- ratio equal to 4 was recorded (Alcaraz *et al.* 2000). To understand the origin of this excess, we have calculated the electron charge ratio for vertical primary protons of different energies at an atmospheric depth of 4 g/cm^2 (Fig. 2b). As expected, the electron charge ratio at 2 GeV is rather high, just like the muon charge ratio at the same energy. At higher energies, we note a slight excess of positrons over electrons. This can readily be explained by the fact that atmospheric electrons and positrons at this altitude are mostly the end products of short-lived mesons (via the decay $\pi^\pm \to \mu^\pm \to e^\pm$) produced by the interactions of primary cosmic-ray particles in the overlying atmosphere. It is obvious that the high excess of positrons over electrons calculated at low energies is relevant to the situation observed by the AMS exoperiment (Alcaraz *et al.* 2000). Figure 2b shows another Monte Carlo calculation (Stephens 1981) carried out at the same altitude which gives a rather low value of the electron charge ratio.

We are performing more detailed calculations involving the differential primary energy spectrum and the particular

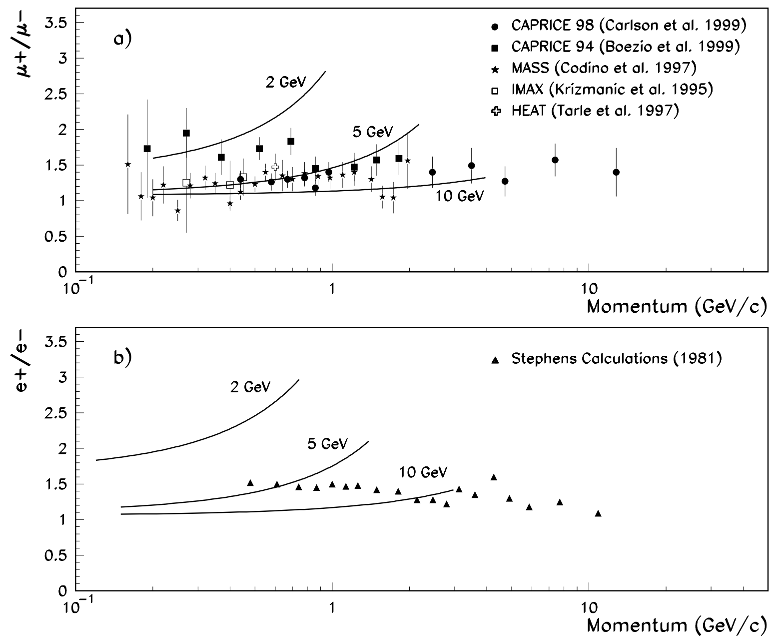

Fig. 2. Muon charge ratio (2a) and electron charge ratio (2b) versus momentum at an atmospheric depth of 4 g/cm^2.

contribution of the cascading in the high atmosphere (200 km below the shuttle, near the equatorial region). Both spectra (quiet and active Sun) will be considered though we expect in each case similar results in reason of the highest energy thresholds for protons near 0° latitude. The e^+/e^- ratio, according to figure 2b, is probably connected with three factors:

1. the largest number of colliding hadrons (p or π^+) is probably just above the energy threshold for pions and kaons production;

2. the shape of p and π cross-section near the energy for resonances production;

3. in all cases the neighbourhood of proton primary energy and energy of particles detected.

A complex mechanism has then chance to generate the positron excess; the direct sources are not primary genuine protons of 2 GeV which cannot reach directly the equator region with the magnetic rigidity required. They come from the cascading of primary protons above the threshold (15 GeV up to 100 GeV protons) interacting in the upper atmosphere (under 200 km altitude and 200 km below the shuttle) along a path crossing the atmosphere with a small column depth, with a favourable geometry for the secondaries leaving the atmosphere and ascending in the direction of the shuttle. At those low densities where decay processes are dominant, the cumulative excess after π^+/π^- excess in the hadronic component are combined with the excess of μ^+/μ^- to turn at large distance to the e^+ excess. As indicated in Capdevielle and Muraki (1999), a similar excess will occur in the neutrino/antineutrino abundances for experiments deep underground. We are now developing special simulations taking into account the geomagnetic effect with different incidences.

4 Conclusion

This work presents some results from Monte Carlo calculations of the muon and electron charge ratio as a function of the atmospheric depth or the momentum. It clearly shows that the enhancement of the muon charge ratio observed by some experiments at high altitude is due to geomagnetic effect. Moreover, these calculations indicate that the excess of positrons over electrons recorded by the AMS experiment is very likely correlated to the excess calculated for low energy protons at very high altitude.

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