BALLOON MEASUREMENTS OF COSMIC RAY MUONS IN THE ATMOSPHERE

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for

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ABSTRACT

The atmospheric neutrino anomaly has long puzzled the cosmic ray community. Recently, evidence for neutrino oscillations has been claimed, based on the measurements performed by some underground neutrino detectors. The interpretation of the atmospheric neutrino observations depends on the normalization of the simulation codes which calculate the expected rates of particles produced in cosmic ray showers in the atmosphere. Muon measurements may provide a powerful means of cross-checking such calculations. Here we report on the current status of atmospheric muon measurements.

1. Introduction

Atmospheric neutrino observations have recently led to the claim that neutrinos oscillate[1)]. The latest observations by Super-Kamiokande[1)], Soudan-2[2)] and MACRO[3)] have come to set a complex scenario, which evoluted from the first reports of the so-called atmospheric neutrino anomaly several years ago. The anomaly consisted in the low ratio of ν_μ- to ν_e-induced events measured in several underground

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experiments with respect to the expectations[4,5,6,7,8].

Whether the anomaly was due to a deficit of ν_μ events or to an excess of ν_e, has been a puzzle for a long time, since the accuracy of the atmospheric neutrino calculations did not allow either of the two possibilities to be discarded. Recently, the situation has evolved to a much more definite picture. Firstly, the CHOOZ detector has reported negative results for $\nu_\mu \leftrightarrow \nu_e$ oscillations in a large region of oscillation parameters[9], thus excluding previously proposed interpretations of the atmospheric neutrino observations[10]. Secondly, the first results of Super-Kamiokande have been reported[1]. The characteristics of this detector and the large event statistics collected are such that accurate studies of the angular distributions as well as of the energy spectra of contained events can be performed. Thirdly, more evidence for neutrino oscillations has been provided by other underground detectors[2,3]. For instance, the long observed deficit of upward going events in MACRO has been recently interpreted as evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations[3] with oscillation parameters consistent with the current estimates by Super-Kamiokande[11].

The normalization of the atmospheric neutrino calculations is evidently crucial for these investigations, as discussed in the next section. Muon measurements can provide constraints to such calculations, which in turn may help in the interpretation of the atmospheric neutrino observations. In the following, we will try to illustrate the current status of atmospheric muon measurements, with special emphasis on the contribution provided by the WiZard Collaboration.

2. Atmospheric Neutrino Calculations

The expected rates of neutrino induced events in underground detectors may be calculated by convoluting the neutrino fluxes by the quasi-elastic cross-sections for charged lepton creation and then by folding in the efficiency for lepton detection[12]. Each of these terms may contribute to the total inaccuracy of the results. A detailed investigation has shown, however, that the approximations introduced in the parametrizations of the neutrino cross-sections can not be the only reason for the apparent neutrino anomaly[13]. On the other hand, beam tests at KEK have provided a direct confirmation of the estimated particle detection efficiencies with water Cherenkov detectors[14]. Also, proposed background sources for the neutrino observations have been investigated and finally excluded[15,16]. All of these negative results have increased the reliability of the atmospheric neutrino results. On the other hand, it turns out that most of the uncertainties in the neutrino rate expectations may be due to the inaccuracies of the neutrino flux calculations.

Several calculations have been performed of the atmospheric neutrino flux, many of which have undergone a long refining process. The Super-Kamiokande data[1] have been compared to the calculations by Honda *et al.*[17] which agree to the level of 10% with the Bartol results[18]. Lee and Koh[19] made an attempt to have a three-dimensional extension of the Bartol calculations. Bugaev and Naumov[20] have performed an independent calculation, which seems to have a lower normalization. All of these calculations have been modified in order to take into account the muon polarization. In addition, the Bartol group is now working on a three-dimensional model of their code[21]. Another group has recently proposed three-dimensional neutrino calculations based on an independent particle interaction generator[22].

A detailed comparison of most of these calculations has been performed[23] in order to find the main reasons of discrepancy and to estimate the global accuracy that can be achieved. The main indication of this study is that much of the differences among the different calculations may be ascribed to the different parametrizations of the interaction cross-sections of nucleons on atmospheric nuclei, especially in the phase space regions of the secondaries that are not constrained by the available accelerator data.

In addition, significant differences in the calculated neutrino fluxes may be due to the different assumptions about the primary cosmic ray flux. Former measurements of the primary cosmic ray spectra showed discrepancies which might get as large as 50%, in large energy ranges[24]. More recent measurements are in a closer agreement, even though discrepancies of the order of 10-20% at particle energies of 10–50 GeV/n can not be excluded[25]. In addition to these experimental inconsistencies, the primary cosmic ray flux at low energy is affected by the geomagnetic suppression and by the almost periodic modulation in the heliosphere. While significant progress has been accomplished in describing the geomagnetic cut-off[26], the intrinsic variability of the solar modulation may be harder to describe in a model. Because of these difficulties, it is a widespread opinion that neutrino flux calculations can not reach a level of accuracy significantly better than 20% [27].

Due to this occurence, the emphasis in the atmospheric neutrino investigations has focussed on the observations of those quantities for which the uncertainties linked to the absolute normalization of the fluxes almost cancel out. Among these are the ratio of neutrino fluxes $(\nu_\mu+\overline{\nu}_\mu)/(\nu_e+\overline{\nu}_e)$,[a] the zenith asymmetry of the events, which may allow the distortions due to neutrino oscillations as a consequence of the pathlength changes to be detected, the fraction of stopping muons out of the total of upward-going muons.

The normalization of the neutrino flux is currently treated as a free parameter, within the limits of accuracy discussed above, in the fitting procedures for the estimate of the neutrino oscillation parameters. The Super-Kamiokande results[1] seemed to suggest that the current estimates[17] of the neutrino flux may be underestimated by a factor of 15%. However, more recent results tend to prefer a slightly smaller normalization factor, while at the same time favoring a somewhat different region of allowed oscillation parameters[11]. Since much of these differences seem to be connected to

[a]Similar considerations hold for the ratio $(\nu_\mu+\frac{1}{3}\overline{\nu}_\mu)/(\nu_e+\frac{1}{3}\overline{\nu}_e)$, which is closer to what is measured in underground neutrino detectors.

the upgrades made to the simulation codes, this occurrence may be considered as a further indication that a better normalization accuracy of the neutrino fluxes is needed for a definitive interpretation of the atmospheric neutrino observations.

Muon measurements have been often advocated as a means of cross-checking the atmospheric simulation codes[28)]. This is due to the tight link between muons and neutrinos, which originate together in the decays of secondary mesons in the atmosphere. In fact, at energies such that the probability that muons decay in flight before reaching the ground can be neglected, the neutrino flux could be determined from measurements at the ground level of the muon flux and charge ratio, as already shown by Hayakawa[29)]. However, at low energy muon decays contribute significantly to the neutrino flux—in fact, most of the electron neutrinos originate in muon decays. It turns out, therefore, that high altitude muon measurements are needed for this purpose.

3. Muon Measurements in the Atmosphere – The Role of the WiZard Collaboration

While ground muon measurements have been performed extensively in the past[30)], up to a few years ago muon measurements in the atmosphere were only available in a short range of atmospheric depth. These experiments were mainly performed with airplane-borne detectors[31,32)] or at mountain sites[33,34,35,36,37)]. A list of these early measurements is shown in Table 1, where they are compared according to the measurement approach and to the ranges of energy and altitude investigated. Most of these results have been discussed by Allkofer[38)]. A thorough review of these early measurements is presented by Circella[39)].

A pioneering measurement of muons, performed with a balloon-borne magnet spectrometer in the stratosphere, was reported by Bogomolov[40)]. In fact, balloon-borne detectors are usually deployed for performing measurements at residual atmospheric depths as low as a few g/cm^2 (i.e., altitudes as high as 40 km). A balloon-borne detector can therefore explore a very large range of atmosphere during the ascent phase of the flight, and possibly during the descent as well.

A new era of muon measurements in the atmosphere started in 1993, when the WiZard Collaboration reported the first muon measurements performed continuously in the atmosphere from the ground level to the depth of 5 g/cm^2 [41)]. The WiZard Collaboration is involved in a wide program of antiparticle measurements in primary cosmic rays with balloon- and satellite-borne detectors. It has performed successful balloon flights with the detectors MASS (Matter Antimatter Spectrometer System, 1989 and 1991), TRAMP-Si (TS93, Transition RAdiation detector Measuring Positrons with a Silicon calorimeter, 1993) and CAPRICE (Cosmic AntiParticle Ring Imaging Cherenkov Experiment, 1994 and 1998). All of these detectors made use of

Table 1. Early muon measurements in the atmosphere. The symbol $\mu^{\pm}$ in the second column indicates that the measurements are given separately for the two charges or that enough indications are given to allow the two components to be separated. In the altitude column, the altitude or depth information originally reported is quoted: a range is shown, when appropriate.

Ref.	Particle	Technique	Momentum	Altitude
Conversi[31] (airplane)	$\mu^{\pm}$	counter telescope, Pb shield and graphite absorber	315–348 MeV/c	200–1030 g/cm^2
Baradzei *et al.*[32] (airplane)	μ^{-}	cloud chamber	0.3–6 GeV/c	9000 m
Blokh *et al.*[33] (mountain)	μ	counter telescope and Pb shield	$\geq$ 250 MeV/c	600–1000 g/cm^2
Kocharian *et al.*[34] (mountain)	$\mu^{\pm}$	magnet spectrometer and absorbers	0.4–100 GeV/c	3200 m
Vaisenberg[35] (mountain)	$\mu^{\pm}$	magnet spectrometer and Pb shield	0.22–1.2 GeV/c	3250 m
Allkofer *et al.*[36] (mountain)	$\mu^{\pm}$	magnet spectrometer	0.2–20 GeV/c	3200-5200 m
Quercia *et al.*[37] (mountain)	$\mu^{\pm}$	counter telescope and magnetic lens	$\geq$ 550 MeV/c	475–1030 g/cm^2
Bogomolov *et al.*[40] (balloon)	$\mu^{\pm}$	magnet spectrometer, Cherenkov and scint.	0.15–2.6 GeV/c	11 g/cm^2

the superconducting magnet spectrometer of the Robert Golden Particle Astrophysics Laboratory, New Mexico State University equipped with detectors for particle identification.

The first muon measurements reported were performed with the MASS apparatus[42], shown in Fig. 1, which consisted of the WiZard/NMSU magnet spectrometer, at that time equipped with a tracking device with 8 multiwire proportional chambers, a scintillator time of flight device, a streamer tube brass calorimeter and a threshold gas Cherenkov detector. The spectrometer had an MDR of the order of 120 GV, allowing the negative muon spectra to be investigated in the 0.3–40 GeV/c momentum range

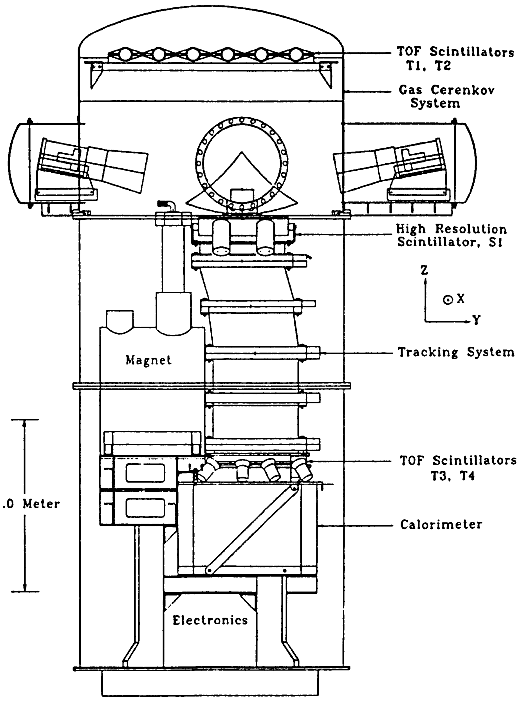

Figure 1: The MASS apparatus in the 1989 configuration.

Following this work, other groups have proposed similar analyses, as summarized in Table 2. However, for several years, the WiZard/NMSU spectrometer remained the only detector to have reported absolute measurements of the muon flux: the IMAX flux[51] was normalized to the ground measurements performed by MASS before its flight[43], while HEAT reported muon charge ratio results from two experiments[54,55] before estimating absolute fluxes[56].

As shown in Table 2, negative muon investigations have been performed in a wide momentum range, while positive muon measurements were usually limited to the sub-GeV/c momentum region, due to the high level of proton background. This situation is going to be improved significantly soon, thanks to the first results coming from the CAPRICE experiment performed last year[57,58]. We show in Fig. 2 the detector

Table 2. Recent balloon measurements of muons in the atmosphere. R_c in the last column shows the vertical rigidity cutoff for the experiments.

Experiment	Year	Results	Momentum Range	Altitude	R_c
MASS[47,48]	1989	μ^- spectra	0.3–40 GeV/c	5–910 g/cm^2	0.5 GV
MASS[49,50]	1991	μ^- spectra charge ratio	0.3–40 GeV/c 0.3–1.5 GeV/c	5–886 g/cm^2	4.5 GV
IMAX[51]	1992	charge ratio	0.42–0.47 GeV/c	5–960 g/cm^2	0.65 GV
CAPRICE[52,53]	1994	μ^- spectra charge ratio	0.3–40 GeV/c 0.3–2 GeV/c	3.9–940 g/cm^2	0.65 GV
HEAT[54]	1994	charge ratio	0.3–0.9 GeV/c	7–850 g/cm^2	4.5 GV
HEAT[55,56]	1995	μ^- spectra charge ratio	0.3–50 GeV/c 0.3–0.9 GeV/c	3–960 g/cm^2	0.65 GV
CAPRICE[57,58]	1998	charge ratio	0.3–1 and 2–20 GeV/c	5–886 g/cm^2	4.5 GV

configuration in that experiment[44], in order to illustrate the improvements that had been made to the original apparatus in almost ten years of balloon campaigns: the tracking system consisted of three sets of drift chambers located in the field of the superconducting WiZard/NMSU magnet. The MDR for such magnetic spectrometer was more than 300 GV. The spectrometer was located inside a scintillator time of flight device, with a time resolution of the order of 230 ps, while the particle identification was performed by means of a 7 radiation length silicon-tungsten imaging calorimeter[45] and a gas RICH detector[46]. Such combination of sophisticated particle detectors provided excellent particle discrimination capabilities, such as proton rejection up to about 20 GeV/c and pion-muon discrimination in the 2–6 GeV/c momentum interval.

4. Muon Measurements and the Atmospheric Neutrino Flux

Several authors have tried to compare calculated fluxes of muons to muon mea-

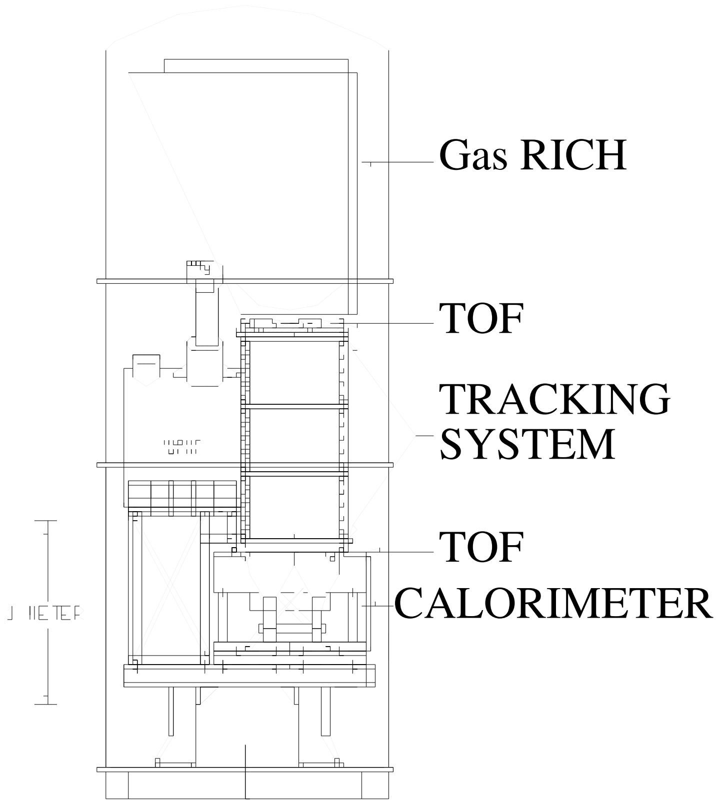

Figure 2: The CAPRICE apparatus in the 1998 configuration.

surements in the atmosphere, following the example of Bugaev and Naumov[59] who were the first to propose such a comparison with all the measurements available at the time.

The MASS results[47] are compared in Fig. 3 to the calculations by Honda *et al.*[17], who originally compared their results to the preliminary muon measurements from the experiment[41]. This figure may serve to illustrate some recurrent features of such comparisons, namely *i*) the overall agreement looks promising, even though *ii*) discrepancies may be noted, which typically are more evident at low energy and high depth in the atmosphere.

The same data were used in a comparison to the Bartol calculations in order to point out the dramatic effects which may result from different assumptions about the normalization of the primary cosmic ray flux[60]. Once the specific experimental conditions have been properly taken into account, the Bartol calculations appear to satisfactorily reproduce the MASS data[47,49] in the full range of atmospheric depth at muon momenta larger than 1 GeV/c [60]. However, depth-dependent discrepancies between the calculations and the measurements arise at lower momenta. How much of these inconsistencies can be removed by a three-dimensional extension of the calculation is still under investigation[21].

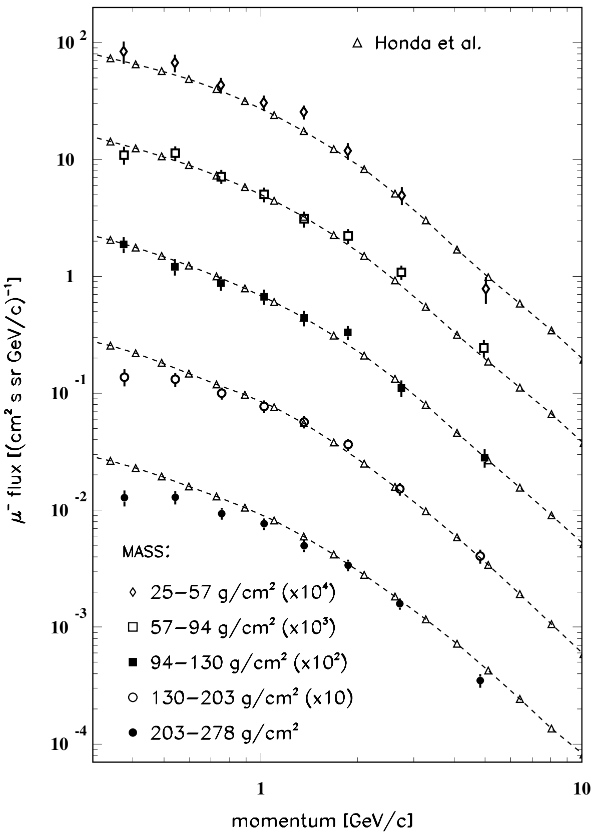

Figure 3: Negative muon spectra in different depth bins compared to calculations. The measurements are from the MASS experiment of 1989 [47]. The calculations are by Honda *et al.*[17]. Some of the curves have been scaled as indicated. The calculated results refer to the same depth bins as for the closest experimental points.

Further to this study, the WiZard Collaboration has proposed the approach of presenting simultaneous measurements of muons and primaries taken in the same experiment[49]. The purpose of this approach is twofold: *i*) the calculations of the expected fluxes of particles may be performed by assuming as primary input spectra those measured in the same experiment, thus taking into account the specific conditions of solar modulation and geomagnetic cutoff of the experiment; *ii*) possibile systematic inaccuracies that affect the two measurements to comparable extents may not affect the comparison to theory.

The CAPRICE[53] data compare to the calculations in a similar way as for the MASS data, but the discrepancies are more evident, as shown in Fig. 4. The HEAT group[56] has also reported larger discrepancies with respect to the Bartol calculations than in the MASS experiments. Also in these cases, the largest discrepancies are apparent at low muon energy. It is interesting to note that both these experiments took place near a minimum of solar activity, while the two previous MASS measurements had been performed during an intense maximum of solar activity. Therefore, this occurrence leads to the indication that part of the discrepancies between calculations and measurements might be ascribed to how the mechanisms of solar modulation are taken into account in the calculations.

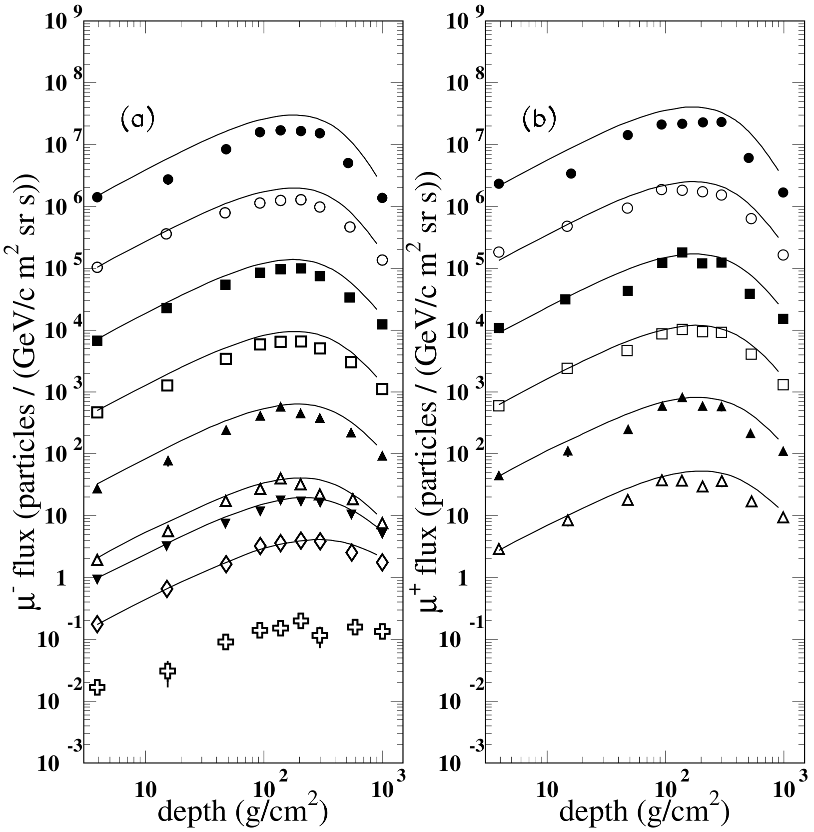

Figure 4: Flux growth curves with atmospheric depth for (a) negative and (b) positive muons in different momentum intervals, from top to bottom: 0.3–0.53 GeV/c (fluxes scaled by 10^5); 0.53–0.75 GeV/c (10^4); 0.75–0.97 GeV/c (10^3); 0.97–1.23 GeV/c (10^2); 1.23–1.55 GeV/c (10); 1.55–2 GeV/c; 2–3.2 GeV/c; 3.2–8 GeV/c; 8–40 GeV/c. Positive muon results are available in the 0.3–2 GeV/c momentum range. The measurements are from the CAPRICE experiment of 1994 [53]. The solid lines show the calculations by the Bartol group[61] for the experimental conditions of this flight.

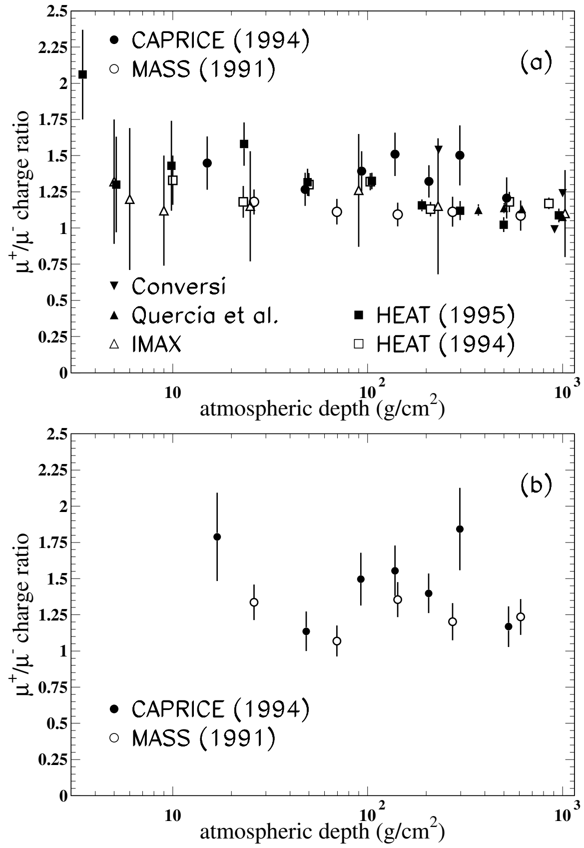

Figure 5: Measurements of the muon charge ratio in the atmosphere by the MASS 1991 [49] and CAPRICE 1994 [53] experiments: a) 0.3–0.9 GeV/c; b) 0.9–1.5 GeV/c. Results from other experiments are also shown: Conversi[31] (0.315–0.348 GeV/c), IMAX[51] (0.42–0.47 GeV/c), Quercia *et al.*[37] ($\geq$460 MeV), HEAT 1994 [55] and HEAT 1995 [56] (0.3–0.9 GeV/c).

If magnetic effects play a role in such discrepancies, then it is important to check the muon charge ratio. The muon charge ratio is, in fact, a very sensitive parameter to the geomagnetic cutoff conditions and, to a smaller extent, to the level of solar modulation. This is due to the fact that the nucleons bound in a helium nucleus have a different (namely, lower) kinetic energy per nucleon, at the same magnetic rigidity, than for a free proton. Depending on the different geomagnetic and solar modulation conditions, therefore, the role of the bound nucleons, which include neutrons as well as protons, will change with respect to the free protons. In addition, the East-West effect may play a major role. Positive muons come in fact predominantly from cosmic rays arriving from the East, while it is the opposite case for negative muons. This eventually leads to a depression of the muon charge ratio for low geomagnetic latitudes[62]. Finally, comparisons of the muon charge ratio may also be important because secondary particles propagating in the atmosphere also get bent by the geomagnetic field. Consequently, the path will increase with respect to a straight trajectory and the interaction and decay probabilities, as well as the fraction of energy lost by ionization, will increase for equal vertical distances covered. Since most of the current calculations are performed in a unidimensional approximation, this effect may be difficult to be taken into account.

The measurements currently available of the atmospheric muon charge ratio (Fig. 5) show differences which are presumably ascribable to the different experimental conditions. It is important, therefore, that these data be compared to calculated values in order to check that the solar modulation and the geomagnetic effect are correctly described in the simulation codes. Apparently, calculations for high geomagnetic cutoff agree better with the measurements[60] than for lower cutoffs[53].

Finally, we note that muon comparisons can provide effective constraints to neutrino calculations only for what concerns those factors which affect the muon and neutrino fluxes to similar extents. They can not, however, completely determine the neutrino fluxes. The energy distributions of the neutrinos from the muon decays, in fact, are affected by the muon polarization. In addition, the kaon role is different for muons than for neutrinos. It turns out, therefore, that an approach like that originally proposed by Olbert[63] and recently adopted by Perkins[64], namely to estimate the neutrino fluxes from a pion decaying spectrum adjusted to fit the muon measurements, can lead to accurate results only if such factors are taken into account by some means.

5. Conclusions

The use of balloon-borne detectors has made it possible to extend atmospheric muon investigations to a much larger range of atmospheric depth than in previous measurements performed at mountain sites or with airplane-borne detectors. Following the original approach of the WiZard collaboration[41], several sets of muon measurements in the atmosphere are now available for a cross-check of the neutrino calculation procedures. They cover the momentum range up to 40–50 GeV/c for negative muons. Positive muon observations have been recently extended up to 20 GeV/c [57,58].

The full implications of such comparisons of theory to measurements still need to be investigated, especially for what concerns the extent at which the neutrino fluxes mwy be affected. However, no calculation so far has been able to reproduce exactly the muon measurements. More detailed comparisons should take into account the primary cosmic ray spectrum appropriate to the specific experimental conditions of the muon measurements, i.e. as simultaneously detected by the same detector in the same experiment[49].

Finally, we point out that a dedicated balloon flight, as also proposed by the WiZard collaboration, would serve a threefold purpose: a much larger event sample would be collected than during the ascent of a flight, the depth dependence of the muon flux could be investigated more accurately, with no need of the complex procedures implemented so far[47,49], and more extensive checks of the detector performances could be performed.

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