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The WiZard Collaboration cosmic ray muon measurements in the atmosphere

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Balloon-borne experiments allow cosmic ray measurements to be performed over large ranges of atmospheric depths. The WiZard Collaboration is involved in a long-range investigation of the cosmic ray muon fluxes in the atmosphere. In this paper, we will discuss the relevance of such measurements to the atmospheric neutrino calculations and will review the results reported by the Collaboration, with particular emphasis on those coming from the latest flight CAPRICE98.

1. INTRODUCTION

A profound interest in muon measurements in the atmosphere has been renovated in the last decade, due to the increasing evidence of the atmospheric neutrino anomaly [1–5]. In the last few years, the atmospheric neutrino scenario has evolved dramatically, and the claim that neutrino oscillations are at work has been raised by several experiments [6–8]. Most of the evidence for such interpretation is based on the angular distribution and on the zenith asymmetry of the detected events which are not strongly model-dependent. However, the need for more accurate calculations of the atmospheric shower remains. In fact, the best-fit procedures for the estimation of the oscillation parameters require a knowledge of the absolute spectrum of neutrinos produced in the atmosphere.

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2. MUON MEASUREMENTS AND ATMOSPHERIC SHOWER CALCULATIONS

It is a widespread opinion that the accuracy of the atmospheric neutrino calculations is not better than 20% on the fluxes and 5% on the ratios of fluxes of neutrinos of different flavours [9]. These limits are based on the accuracy with which some of the input parameters for the calculations, such as the cross-sections for production of mesons in interactions of nucleons with atmospheric nuclei and the absolute spectrum of the primary cosmic ray nuclei, are known.

Muon measurements have been frequently advocated as a means of cross-checking such calculations. In fact, it is evident that the muon flux is very tightly linked to the neutrino flux, since the two particles arise from decays of mesons and muon decays also contribute to the neutrino flux. However, to what extent the muon flux normalization effectively constrains the neutrino flux estimates is still not accurately known, since several parameters (e.g., the k/π ratio or the polarization of the muons arising from 2-body meson decays) affect differently the two fluxes. As a consequence, a muon calibration of the atmospheric shower calculations is yet to come.

On the other hand, comparisons of calculations to the measurements have been frequently proposed in order to check for the overall agreement and discuss the apparent discrepancies [10,11] or to point out the effects due to different assumptions about the inputs to the calculations [12]. In all of these works, the energy and depth dependences of the discrepancies between measurements and calculations provide valuable clues in order to understand the discrepancies.

3. THE WIZARD COLLABORATION CONTRIBUTION

The WiZard Collaboration first exploited the approach of using ballon-borne detectors to investigate the cosmic ray muon component in a large energy interval and over a large range of depth in the atmosphere [13]. The WiZard Collaboration is involved in a wide ranging 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 the superconducting magnet spectrometer of the Robert Golden Particle Astrophysics Laboratory, New Mexico State University equipped with detectors for particle identification.

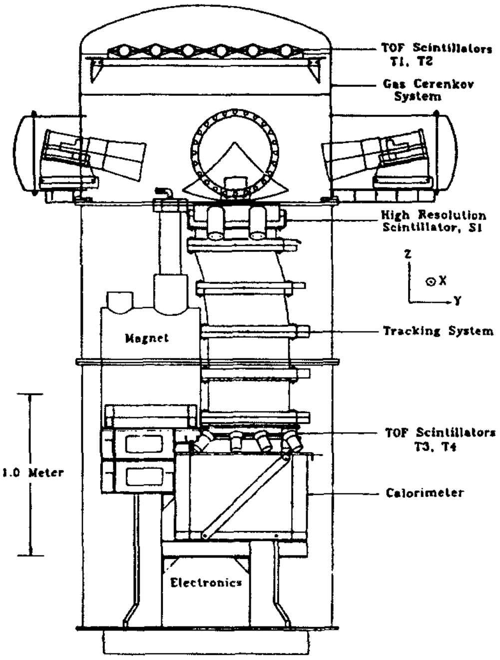

Figure 1. The MASS apparatus in the 1989 configuration.

The first muon measurements as a function of atmospheric depth were performed with the MASS apparatus, shown in Fig. 1 [14], which consisted of the WiZard/NMSU magnet spectrometer, equipped with a tracking device with 8 multiwire proportional chambers, a scintillator time

Table 1
Recent balloon measurements of muons in the atmosphere. The WiZard Collaboration experiments include the two MASS flights and the two CAPRICE flights.

Experiment	Year	Results	Momentum Range	Altitude
MASS [15,16]	1989	μ^- spectra	0.3–40 GeV/c	5–910 g/cm^2
MASS [17,18]	1991	μ^- spectra charge ratio	0.3–40 GeV/c 0.3–1.5 GeV/c	5–886 g/cm^2
IMAX [19]	1992	charge ratio	0.42–0.47 GeV/c	5–960 g/cm^2
CAPRICE [10,20]	1994	μ^- spectra charge ratio	0.3–40 GeV/c 0.3–2 GeV/c	3.9–940 g/cm^2
HEAT [21]	1994	charge ratio	0.3–0.9 GeV/c	7–850 g/cm^2
HEAT [22,23]	1995	μ^- spectra charge ratio	0.3–50 GeV/c 0.3–0.9 GeV/c	3–960 g/cm^2
CAPRICE [24,25]	1998	charge ratio	0.3–1 and 2–20 GeV/c	5–886 g/cm^2

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 [15,16].

The investigation was then extended to include positive muons and to explore different experimental conditions with the subsequent flights [17,18,10,20]. These studies were possible due to the continuous upgrading of the detectors of our balloon-borne instrument: the magnetic spectrometer configuration had been improved since the MASS experiment of 1991 by the addition of two sets of drift chambers, which led to an increase of the MDR of the instrument to more than 200 GV. In the CAPRICE experiment of 1994 the simultaneous use of a 7 radiation length silicon-tungsten calorimeter [26] and a solid radiator ring imaging Cherenkov detector [27] made it possible to identify positive muons up to 2 GeV/c, even at locations of low geomagnetic cutoff and during the period of minimum solar modulation [10].

A compilation of recent atmospheric muon results, which includes experiments performed by other groups, is shown in Table 1.

4. THE CAPRICE98 EXPERIMENT AND RESULTS

The CAPRICE98 experiment [28] was carried out from Ft. Sumner, NM on May 28, 1998. The vertical rigidity cutoff for this location is about 4.5 GV. The solar modulation conditions for that period were close to minimum activity. We have analyzed the data sample collected during the ascent of the flight in order to investigate the muon component from the ground level (about 886 g/cm^2) to about 5 g/cm^2 of residual atmosphere.

The CAPRICE98 apparatus, shown in Fig. 2, consisted of the WiZard/NMSU superconducting magnet spectrometer equipped with a drift-chamber tracking device, with an MDR larger than 300 GV, a time of flight (ToF) scintillator system with a time resolution of the order of 230 ps, a gas Ring Imaging Cherenkov (RICH) detector [29] and the silicon-tungsten calorimeter used in the previous CAPRICE experiment. This configuration of detectors ensured good particle discrimination capabilities along with the measurement redundancy needed for cross-checks of the detector performances and for efficiency estimates.

We show in Fig. 3 the particle discrimination which can be obtained from the ToF measurement at low energy: Albedo events can be easily rejected at any energy. In addition, positive muons can be discriminated from proton events up to about 1.5 GeV/c.

The selection of positive muons at higher energy can be achieved by means of the velocity measurement from the RICH detector, as illustrated in Fig. 4.

The combined use of the information collected from different detectors enabled us to select a good-quality sample of muon events. In this work, we present results from two momentum

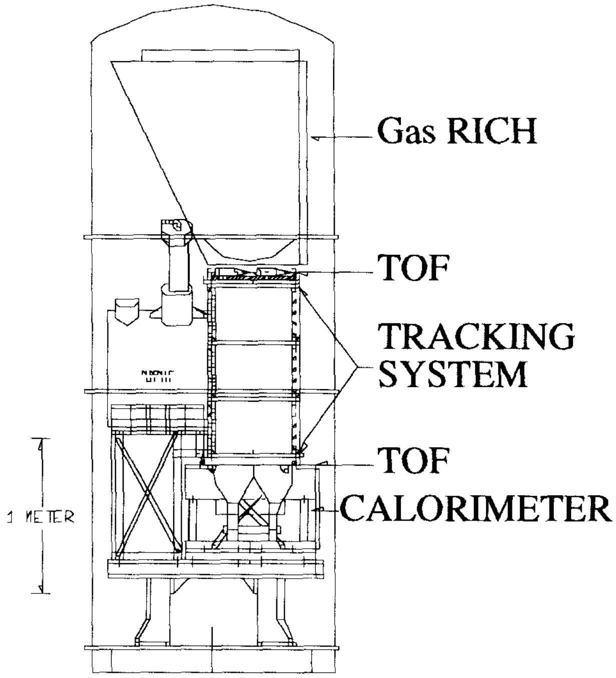

Figure 2. The CAPRICE apparatus in the 1998 configuration (CAPRICE98).

bins, 0.3–1 GeV/c and 2–15 GeV/c. The muon selection was performed as follows: i) we required a good-fit track to be reconstructed in the spectrometer. This allows the rigidity of the particle to be determined; ii) we removed the albedo events by means of the ToF measurement; iii) the calorimeter information was used to select clean tracks due to non interacting, singly charged particles; iv) the scintillator pulse height was checked to reject higher charge particles. In addition, depending on the momentum of the particles: v) we imposed a ToF selection (in order to reject protons) and required that the particles do not show a signal in the RICH detector (in order to remove any residual electron/positron contamination) in the 0.3–1 GeV/c momentum range; or vi) we required a Cherenkov ring in the RICH detector compatible with that expected for muons according to their momentum in the 2–15 GeV/c momentum range.

This redundant classification allows a good quality sample of muons to be selected. In fact, electrons and positrons are removed by the calorimeter selection with a rejection factor of the order of 10^{-4} at high energy and by the combination of the calorimeter and RICH selection at low energy. Protons are removed by means of the calorimeter and RICH selection at high energy and by the calorimeter and ToF selection at low energy. Pions, finally, can also be classified and removed by means of the RICH measurement in the 2–6 GeV/c momentum range.

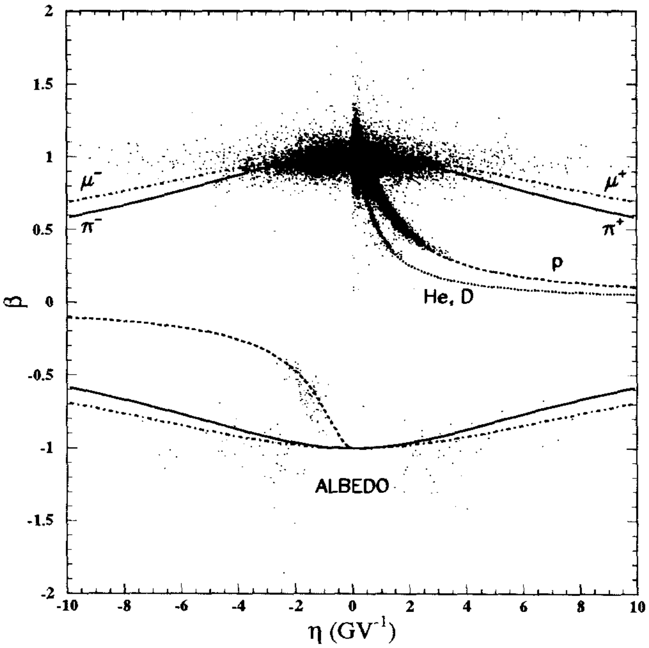

Figure 3. Velocity ($\beta = v/c$) from the ToF measurement as a function of deflection η for a sample of particles collected during the ascent of the flight. The code for the albedo components is as follows: solid line for pions, dash-dotted line for muons, dashed line for protons. The large number of particles at small deflection is due to the primary protons which can reach the detector above the geomagnetic cutoff. The number of events in this plot is 39 092.

We show in Fig. 5 the muon charge ratio measured in this work, along with the previous results available. No significant dependence on the atmospheric depth may be noticed in any of the three momentum intervals considered. We note a good agreement of the current results at low energy with other measurements performed at comparable values of geomagnetic cutoff [18,23], while experiments at higher latitudes have reported higher values of the charge ratio [10,22]. These data therefore seem to point out latitude dependent effects. The results in Fig. 5(b)-(c) represent the first measurement of the muon charge ratio at momenta larger than 2 GeV/*c* performed over a large depth range from 5 to 886 g/cm^2. The results in Fig. 5(c) agree well with our previous observations from the MASS experiment of 1991, also in the 5–15 GeV/*c* momentum range, which were limited to depths larger than 100 g/cm^2 [33].

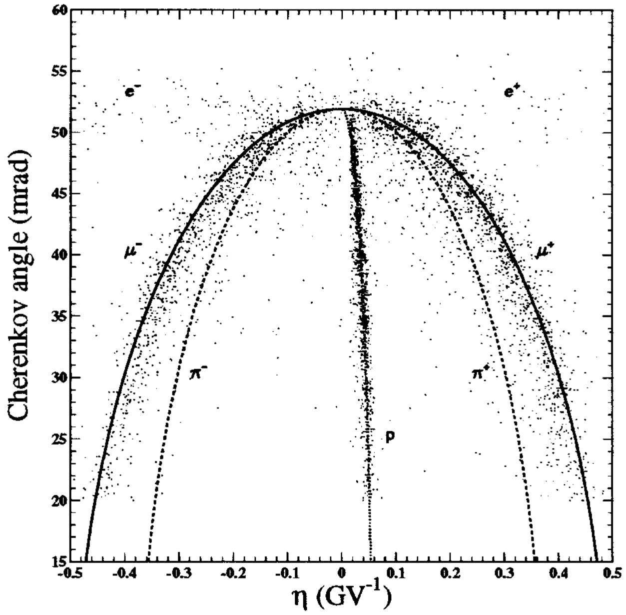

Figure 4. Cherenkov angle in the RICH detector as a function of deflection η for a sample of particles collected during the ascent of the flight. The number of events in this plot is 4 335.

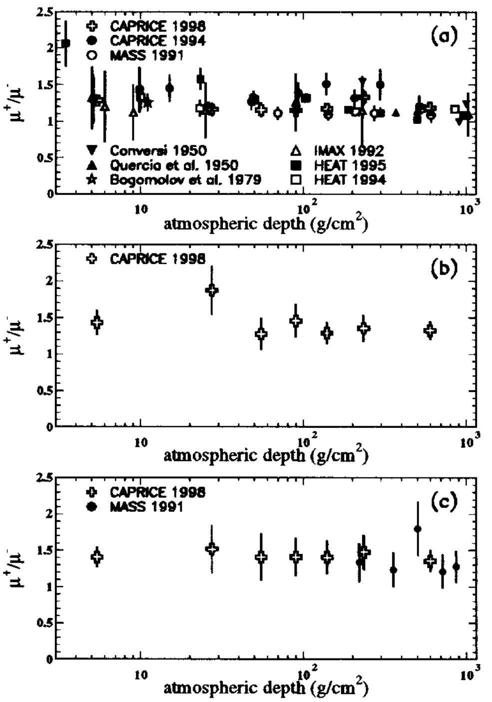

Figure 5. Muon charge ratio measured by CAPRICE98 in different energy intervals: (a) 0.3–1 GeV/*c*; (b) 2–4.5 GeV/*c*; (c) 4.5–15 GeV/*c*, along with results from previous experiments: CAPRICE 1994 [10] (0.3–1 GeV/*c*), MASS 1991 [17] (0.3–0.9 GeV/*c*), Conversi 1950 [30] (0.315–0.348 GeV/*c*), Quercia et al. 1950 [31] (≥460 MeV), Bogomolov et al. 1979 [32] (0.3–1.3 GeV/*c*), IMAX 1992 [19] (0.42–0.47 GeV/*c*), HEAT 1994 and 1995 [22,23] (0.3–0.9 GeV/*c*). The results from MASS 1991 in panel (c) are taken from [33] (5–15 GeV/*c*).

5. CONCLUSION

The WiZard Collaboration has reported results on the atmospheric muon flux from a series of four balloon experiments performed in different experimental conditions. In this paper, we have presented preliminary results on the muon charge ratio from our latest experiment, CAPRICE98, whose characteristics are such that they allow us to identify for the first time positive muons at momenta larger than 2 GeV/*c*, over the whole range of atmosphere down to very shallow atmospheric depths.

Muon measurements in the atmosphere can provide useful constraints to the atmospheric shower calculations. The low-energy charge ratio results from the most recent measurements seem to point out possible geomagnetic cutoff effects. The CAPRICE98 results on the positive muon spectra, extended to the largely unexplored energy range up to 15 GeV/c, are forthcoming.

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