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# A balloon-borne experiment to measure the fluxes of cosmic-ray muons in the atmosphere

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**Abstract.** The WiZard Collaboration is preparing a balloon-borne experiment to perform a detailed investigation of the muon fluxes in the atmosphere. This dedicated effort will take place in 2002. We illustrate here the detector configuration and our novel experimental approach, which will allow us to get significantly improved results with respect to existing measurements.

## 1 Introduction

The interest in atmospheric muon measurements has undergone a renaissance during the past decade. This renewed interest can be attributed to two factors: i) A number of large underground experiments have consistently reported neutrino fluxes that disagree with the predictions of theoretical models (Hirata et al., 1992; Becker-Szendy et al., 1992; Berger et al., 1989; Aglietta et al., 1989; Allison et al., 1997); ii) the disagreement has been interpreted as evidence for neutrino oscillation (Fukuda et al., 1998; Ambrosio et al., 1998; Allison et al., 1999). While awaiting for an independent confirmation from long-baseline experiments, it is prudent that we strive to fully understand the atmospheric neutrino scenario. In particular, the normalization of the atmospheric shower calculations has long been questioned: It is a widespread opinion that the accuracy of these simulations can hardly reach the level of 10-15%, due to the current uncertainties on the primary cosmic-ray flux and on the interaction cross-sections for meson production (e.g., Lipari, 2001).

An effective method of testing the neutrino production models is to study the atmospheric muons. Atmospherically produced muons are closely connected to the neutrinos since both are produced in the decay of pions and kaons with additional neutrinos being produced via muon decay. Any simulation of neutrino production also contains a prediction of the muon content, as well as other secondaries. The muon measurements are intriguing because they can be measured *in situ*, as a function of atmospheric depth, with a balloon-borne detector. Measurement of the flux of muons in the atmosphere provides therefore a powerful method to probe the limitations of atmospheric neutrino calculations.

The data collected during the short ascent phases of several cosmic-ray balloon flights are already being used to cross-check calculations, and significant discrepancies have been noted in several cases (Boezio et al., 1999; Coutu et al., 2000). As improvements to the production codes are made, it is essential that the quality of the muon measurements keeps pace.

It should be noted that ground measurements of muons, which can be more easily and extensively performed, are of limited usefulness for this purpose. Muons in fact lose energy while propagating in the atmosphere and they also may

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decay in flight. These occurrences have profound implications for these investigations. Measurements on the ground can only detect the fraction of particles that are formed very close to the ground or those that were created, with a larger energy, at higher altitude and survived to the ground. In fact, the large number of sub-GeV muons that are produced at high altitudes (about 15 km), together with neutrinos with similar energies, can not be detected at the ground. In addition, the contribution from muon decays to the neutrino flux can not be inferred from ground level measurements. Therefore muons have to be measured *in situ*.

The WiZard Collaboration is preparing a dedicated muon flight which will allow us to:

– measure the flux of both positive and negative muons over the momentum range from 0.3 GeV/$c$ to 30 GeV/$c$ (50 GeV/$c$ for $\mu^-$'s);

– significantly improve the statistics with respect to previous measurements;

– simultaneously measure the primary proton and helium spectra along with the muons. These spectra are important because they serve as *inputs* to the atmospheric production models.

## 2 Previous muon results - the WiZard Collaboration contribution

The WiZard Collaboration pioneered the use of balloon-borne instruments for the investigation of the cosmic-ray muon component over a large momentum interval and a broad range of atmospheric depths. The first measurement was performed with the Matter Antimatter Superconducting Spectrometer (MASS) instrument, which consisted of a superconducting magnet spectrometer, equipped with a tracking device with 8 multiwire proportional chambers, a scintillator time of flight device (ToF), a streamer tube brass imaging calorimeter and a threshold gas Cherenkov detector. Using this payload, the negative muon spectrum was measured between 0.3 and 40 GeV/$c$ over the depth range from 5 to 910 g/cm$^2$ (Bellotti et al., 1996; Codino et al., 1996; De Pascale et al., 1993).

A subsequent flight of this apparatus and the two CAPRICE (Cosmic AntiParticle Ring Imaging Cherenkov Experiment) experiments extended the investigation to positive muons over an increasing range of momentum (Bellotti et al., 1999; Boezio et al., 2000; Carlson et al., 1999; Circella et al., 1999; Kremer et al., 1999; Hansen et al., 2001). In particular, in the CAPRICE experiment of 1994 the simultaneous use of a 7 radiation length silicon-tungsten calorimeter (Bocciolini et al., 1996) and a solid radiator ring imaging Cherenkov detector (RICH) (Carlson et al., 1994) made it possible to identify positive muons up to 2 GeV/$c$, even at low geomagnetic cutoff and during a period of minimum solar modulation. The second CAPRICE experiment, in 1998, represented a further step forward in particle identification capabilities for balloon-borne detectors. This detector, which will be used in our dedicated muon experiment, is described in Section 4.

## 3 The new muon flight

As summarized in the previous section, in the past decade the WiZard Collaboration has played a leading role in developing and refining the experimental techniques to study atmospheric muons. The next generation of muon measurements should fulfil the following criteria:

– the fluxes of both $\mu^+$'s and $\mu^-$'s should be measured over a broad momentum range and at a large number of depths in the atmosphere;

– the *input* proton and helium spectra have also to be measured simultaneously with the same instrument;

– the $\pi$ contribution must be measured, if only over a restricted momentum range, so that the pion contamination correction can be accurately normalized;

– the exposure times must be improved in order to obtain the statistics needed to provide information on the angular distribution of muon events.

All of these criteria can be satisfied in our dedicated experiment, planned for 2002: The CAPRICE apparatus, described in the next section, has demonstrated in the 1998 flight to meet the required particle identification criteria; the exposure time for our planned flight profile will be approximately ten times larger than for previous measurements.

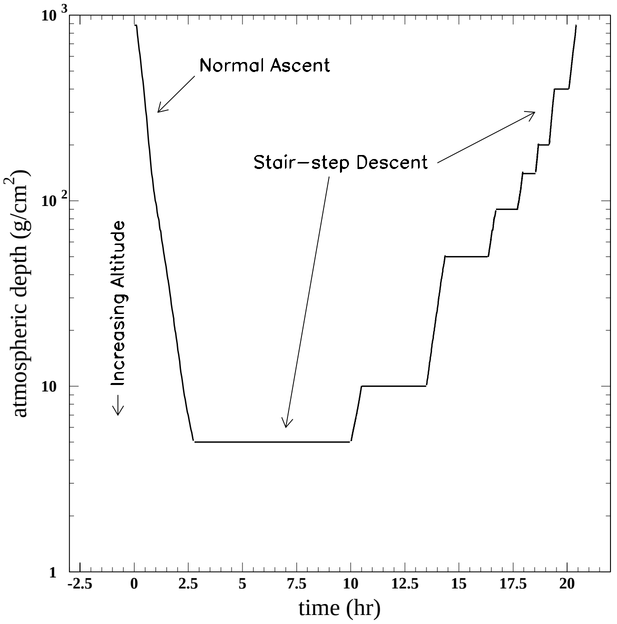

**Fig. 1.** Proposed flight profile for the muon experiment.

Figure 1 shows the proposed altitude profile for our flight. The first portion of the flight will be dedicated to measuring the flux of primary protons and helium nuclei at very low depth. Next, the payload will *stair-step* down, stopping at different atmospheric depths to sample the muon flux. We have selected a number of depth regions which are interesting to cross-check various factors relevant to the atmospheric shower simulations. Such an approach will overcome the main limitation of conventional balloon muon measurements, namely that the data taking is limited to the ascent phases of the experiments which typically last about 3 hours. In addition, we will also get rid of the problem of averaging the values of atmospheric depth of the measurements, since the data will be collected at approximately fixed altitudes. A total exposure time from 20 to 30 hours is expected.

## 4 The detector

The CAPRICE detector in the 1998 configuration will be used in this muon experiment. The apparatus is shown in Figure 2 and is briefly described in the following. Some more details can be found in Ambriola et al. (1999).

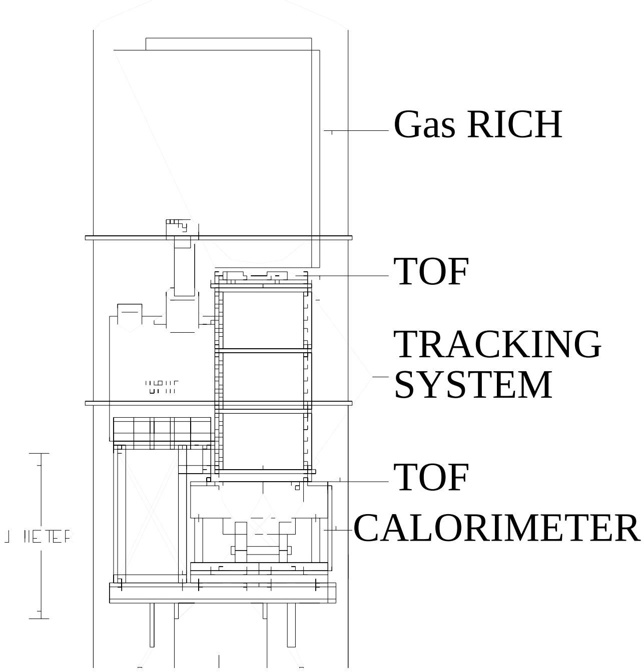

**Fig. 2.** The CAPRICE apparatus in the 1998 configuration (CAPRICE98). This detector will be used in our atmospheric muon experiment of 2002.

The detector includes a ToF system and an improved magnet spectrometer, consisting of the same superconducting magnet used in the previous WiZard flights and a drift-chamber tracking device, with a maximum detectable rigidity (MDR) of more than 300 GV. A gas RICH and a Si-W imaging calorimeter provide state-of-the-art particle identification capabilities. Of particular interest for the muon measurements is the ability of the RICH detector to identify muons (and reject protons) over a broad range of momentum (2–20 GeV/$c$). It should be pointed out that before the deployment of this detector, the measurements of $\mu^+$'s were limited to a narrow momentum band below 2 GeV/$c$.

Aside from the particle discrimination capabilities, this combination of detectors also provides the redundant measurements needed for cross-checks of the in-flight detector performances necessary for an accurate efficiency determination. Figures 3 and 4 show two plots that illustrate the particle discrimination capabilities of the CAPRICE98 instrument.

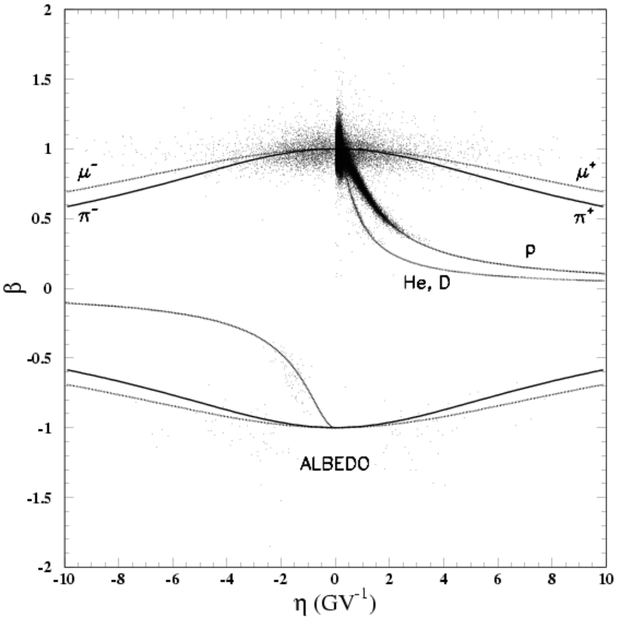

**Fig. 3.** Velocity ($\beta = v/c$) from the ToF measurement as a function of deflection $\eta$ for a sample of particles collected during the ascent of the 1998 flight. The code for the albedo components is as follows: solid line for pions, dash-dotted line for muons, dashed line for protons. The large 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 $39\,092$.

Muon results from the CAPRICE98 flight have been reported earlier (Carlson et al., 1999; Circella et al., 1999) and will be also discussed at this Conference (Hansen et al., 2001). The muon selection for these studies may be performed in the following manner: i) we select good tracks in the spectrometer that allow a reliable rigidity to be determined; ii) we remove albedo events with the ToF measurement; iii) we use the tracking information from the calorimeter to select events that produce clean, non-interacting tracks with deposited energy (dE/dx) consistent with a singly-charged minimum ionizing particle; iv) we use the scintillator (ToF) information to double check for charge-one particles. In addition, depending on the momentum range: v) in the momentum range 0.3-1 GeV/$c$, we can use the ToF information to identify muons (reject protons) and require that no Cherenkov light be present in the RICH (this condition removes the electron/positron residual contamination); vi) in the momentum range from 2 to 20 GeV/$c$ we require that

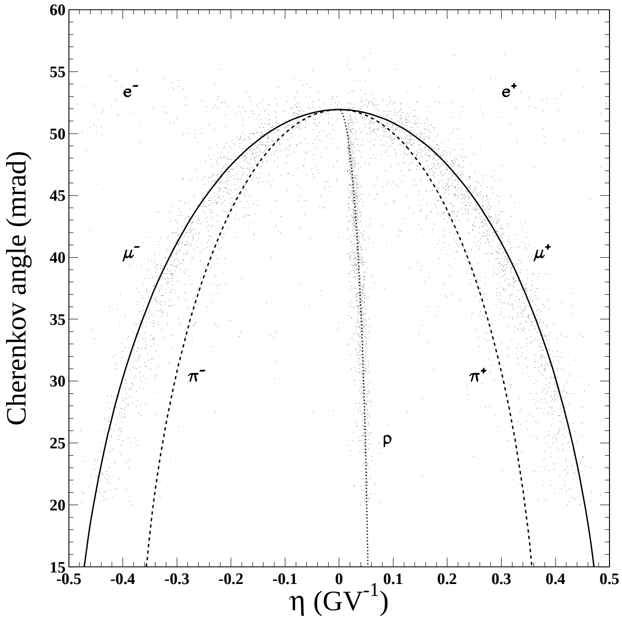

**Fig. 4.** Cherenkov angle in the RICH detector as a function of deflection $\eta$ for a sample of particles collected during the ascent of the 1998 flight. The number of events in this plot is $4\,335$.

the ring produced in the RICH detector be consistent with a muon having the momentum measured by the spectrometer. It should be emphasized that the resolution of the RICH detector is sufficient to identify pions in the momentum range from 2 to 6 GeV/$c$.

All of the detectors are ready and performed in an excellent way during the CAPRICE98 flight. Upgrades are currently being made to the readout system of the payload in order to reduce the readout time for the events. We estimate that the upgraded system will be capable of handling acquisition rates up to about 120 events per seconds, which will contribute to increase the overall statistics of the experiment.

## 5 Conclusion

We plan to fly our WiZard/CAPRICE detector in a balloon experiment dedicated to a measurement of the muon fluxes in the atmosphere in 2002. The detector setup will be an upgraded configuration of the detector which was flown succesfully in 1998. The flight profile will be optimized in order to collect as large a muon data sample as possible at specific altitudes in the atmosphere. Both the excellent performances of our apparatus and this new measurement approach will allow us to perform a muon investigation at a level of systematic uncertainty and statistial significance unprecedented for atmospheric muon measurements.

## References

Aglietta, M. et al., Europhys. Lett. B, 8, 611, 1989.
Allison, W. W. M. et al., Phys. Lett. B, 391, 491, 1997.
Allison, W. W. M. et al., Phys. Lett. B, 449, 137, 1999.
Ambriola, M. et al., Nucl. Phys. B (Proc. Suppl.), 78, 32, 1999.
Ambrosio, M. et al., Phys. Lett. B, 434, 451, 1998.
Becker-Szendy, R. et al., Phys. Rev. D, 46, 3720, 1992.
Berger, C. et al., Phys. Lett. B, 227, 489, 1989.
Bellotti, R. et al., Phys. Rev. D, 53, 35, 1996.
Bellotti, R. et al., Phys. Rev. D, 60, 052002, 1999.
Bocciolini, M. et al., Nucl. Instr. Meth. A, 370, 403, 1996; see also Ricci, M. et al., Proc. 26th ICRC, Salt Lake City 1999, OG 4.1.13, 5, 49.
Boezio, M. et al., Phys. Rev. Lett., 82, 4757, 1999.
Boezio, M. et al., Phys. Rev. D, 62, 032007, 2000.
Carlson, P. et al., Nucl. Instr. Meth. A, 349, 577, 1994.
Carlson, P. et al., Proc. 26th ICRC, Salt Lake City 1999, HE 3.2.05, 2, 84.
Circella, M. et al., Proc. 26th ICRC, Salt Lake City 1999, HE 3.2.02, 2, 72.
Codino, A. et al., J. Phys. G, 22, 145, 1996.
Coutu, S. et al., Phys. Rev. D, 62, 032001, 2000.
De Pascale, M. P. et al., J. Geophys. Res., 98, 3501, 1993.
Francke, T. et al., Nucl. Instr. Meth. A, 433, 87, 1999.
Fukuda, Y. et al., Phys. Rev. Lett., 81, 1562, 1998.
Hansen, P. et al., *A new measurement of the muon spectra in the atmosphere*, Proc. of this Conference.
Hirata. K. S. et al., Phys. Lett. B, 280, 146, 1992.
Kremer, J. et al., Phys. Rev. Lett., 83, 4241, 1999.
Lipari, P., Nucl. Phys. B (Proc. Suppl.), 91, 159, 2001.