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# Testing the low energy hadronic models used in AIRES with CAPRICE98 results.

P. HANSEN[1], S. J. SCIUTTO[2], P. CARLSON[3], M. BOEZIO[4] AND E. MOCCHIUTTI[4]
[1]*Departamento de Física de Párticulas & IGFAE, Universidade de Santiago de Compostela, Campus Sur, 15782 Santiago de Compostela, Spain.*
[2] *Departamento de Física and IFLP (CONICET), Universidad Nacional de La Plata C. C. 67 - 1900 La Plata, Argentina.*
[3]*Royal Institute of Technology (KTH), AlbaNova University Center, S-10681 Stockholm, Sweden.*
[4] *Sezione INFN di Trieste, 34127 Trieste, Italy.*
*hansen@fpmacth1.usc.es*

**Abstract:** Air shower simulation programs are used to reconstruct the energy in the UHECR surface detectors. This reconstruction is based on the lateral distribution function obtained in the experiment. It is also known that this function at core distance greater than 1 km strongly depends on the low energy hadronic models used in the simulation. There are discrepancies in the particle production due to the different models that are used. This discrepancy is not only at high ($> 100GeV$) but also at low energy. Almost all collider experiments show difficulties in the measurement of the diffractive cross section since they do not register particles emitted into the forward direction. A new version of the air shower simulation programs AIRES, with an improved treatment of the diffractive cross section in the low energy hadronic model was developed. To cross-check this model, we compare the results of the balloon born experiment CAPRICE98, on atmospheric fluxes of particles with this new version of AIRES.

## Introduction

Comparing measurements of fluxes of particles at different altitudes with simulated data is a powerful tool to cross-check the results from the simulation programs that are used in UHECR surface detectors. Measured particle densities as function of distance from the shower axis is used to estimate the shower energy. This distance depend on the separation of the detectors that are located at a distances greater than 1km. The observed particle density is fitted and the lateral distribution function (LDF) is obtained. From this function the signal at 1000 m S(1000) (in the case of AUGER [1] ) or 600 m S(600) (in the case of AGASA [2] ) is obtained. This signal at a certain zenith angle is then correlated with the energy using Air Showers Simulation programs. In the case of hybrid detectors, this correlation is carried out using the energy obtained from the fluorescence detectors. Actually there is a disagreement between the results from these two techniques. So it is of extreme importance to obtain separate results to determine the accuracy of this measurement. To hold on the value of S(1000) or S(600) we need to look at the LDF at large distance. It is also known that the particles at core distance greater than 1 km, strongly depend on the low energy hadronic models, used in the simulation. Actually there are discrepancies in the particle production due to the different models that are used [3]. This discrepancy is not only at high but also at low energy. Most all collider experiments show difficulties in the measurement of the diffractive cross section since they do not register particles emitted into the forward direction. So in this work we will use the results from the balloon born experiment CAPRICE98 [4] to cross- check the low energy hadronic model.

### The CAPRICE98 experiment

The CAPRICE98 spectrometer [4] was flown by balloon from Ft. Summer, New Mexico, USA on May 28-29, 1998 at a vertical rigidity cut-off of about 4.3 GV. The experimental setup was a renewed configuration of CAPRICE94 [5] apparatus which was successfully used in a previous balloon experiment at low geomagnetic cuf-off in 1994. The CAPRICE98 apparatus consist of a superconduction magnet spectrometer, a time-of-flight device, a gas ring imaging Cherenkov detector (RICH) and a silicon-tungsten imaging calorimeter. More details on the intrumet can be found in [4]. The CAPRICE98 spectrometer accepts particles arriving with an inclination with respect to the vertical axis of less than 20 degree. This characteristic was taken into account when performing a simulation in order to reproduce correctly the experimental results. It is also important to point out that the axis of the spectrometer remained vertical during the flight. The results obtained by this experiment, that we will used in our calculation are:

- The primary flux of proton and helium at the top of the atmosphere. (this is used in the simulation as an input).
- Proton, helium nuclei and muon fluxes at different altitude in the atmosphere.
- Proton and muons fluxes at ground altitude (885 g/cm$^2$). (these two last items will be compared with the simulation)

To improve our results we also used ground level flux measured by the CPARICE97 [6] experiment. This baboon launched on 24 May 1997 but the flight had to be terminated after four hours due to pressure problems. All instruments survived the descent and landing, and a re-flight was done in 1998 (CAPRICE98). For this reason we only have available data at ground for CAPRICE97.

## The AIRES simulator

The AIRES program [7] is a Monte Carlo simulator where the majority of the processes that may undergo the shower particles are taken into account. In this work we compared the results from two versions of AIRES code, namely, A1: AIRES 2-8-4a as distributed publically; and A2: the same AIRES version, but including an experimental low energy hadronic model. In these two versions the high energy collisions are processed invoking the external package SIBYLL. We recall that in the range of primary energies that is relevant for this work, the influence of the high energy hadronic model is minimal.

## Simulating the flux

The main input for the simulation is the absolute flux of cosmic rays at the top of the atmosphere. In the calculation was included the fluxes of the following 11 cosmic nuclei: H (proton and deuterium), He (He$^3$ and He$^4$), C, N O, Ne, Mg, Si and Fe. The most important contribution to the total absolute flux at the top of the atmosphere comes from hydrogen and helium nuclei with only small contribution from other nuclei. It is also important to mention that photons and electrons do not contribute significantly to the flux of muons and therefore have not been included in the input. Hydrogen and helium fluxes obtained by the CAPRICE98 experiment has been used, thus ensuring that the bulk of the input flux is affected by the same systematic errors as all the secondary particles, since they are measured with the same apparatus. For more details about the input used in the simulation and the procedure to calculate the flux see [8]. In [9] it was studied how the uncertainties in the primary spectrum influence the development of the atmospheric muon. We do not pretend to discuss this subject in this work and we leave it for future studies. It is also important to stress that the effect of the geomagnetic field (GF) inside the atmosphere is taken into account in AIRES. The GF calculations are controlled from the input instruction by specifying the date and the geographic coordinates of a site. For this it is used the IGRF model. It is assumed that the shower develops within a constant and homogeneous local magnetic field that is evaluated for the location of the detector before starting the simulations. To estimate the cutoff we used the caprice experimental geomagnetic transmission function. This was obtained by comparing the shape of the spectra of alpha particles measured by the balloon borne experiment CAPRICE94 with the shape of CAPRICE98. These two balloon experiments flew in different locations: the first in Lynn Lake, Manitoba, Canada, where the geomagnetic cutoff (0.58 GV) is below the pion production threshold for proton, and the other is in Ft. Summer New Mexico (USA) where the vertical cutoff is 4.3 GV. This transmission function is only a function of rigidity. In [9] it was also calculated a theoretical geomagnetic transmission function and a good agreement between their results were find. When comparing with CAPRICE98 measurement only particles reaching the observing level with an inclination of less than $20^0$ have been considered (CAPRICE accept particles with an inclination less than $20^0$). The selected secondary particles are binned according to their momenta, using the momentum intervals of the experimental data. The procedure to evaluate the fluxes is repeated at each observing altitudes that are considered, using at each altitude an independent set of simulated showers.

## Results

The comparisons performed for this work include simulations of the fluxes of secondary particles for the following altitudes: 885 g/cm$^2$, 104 g/cm$^2$ 77 g/cm$^2$ and 5.5 g/cm$^2$ for proton and muons. For helium nuclei, simulated data is required for altitudes of 5.5 g/cm$^2$, 48.4 g/cm$^2$ and 111 g/cm$^2$. These fluxes are simulated with the two versions of AIRES, A1 and A2 already mentioned in section 1.2.

In order to illustrate that the simulation of fluxes of particles originated by cosmic rays is a powerful tool to check the low energy hadronic models, we will focus in this section on the highest altitudes where the first secondary particles created after interaction of the cosmic particles with the atmospheric nuclei begin to contribute significantly to the total flux. A complete study at all altitudes is beyond the scope of this work and will be published elsewhere [10].

In figure 1 the measured and simulated proton flux are plotted versus the proton momentum. The line histograms correspond to AIRES simulations, while the dots represent the experimental data. The dashed (solid) histogram correspond to code A1 (A2). The data correspond to an altitude of 5.5 g/cm$^2$ which is relatively close to the top of the atmosphere. The singular characteristics of this flux can be understood considering that the total flux is made of two main contributions, namely, (i) Cosmic protons (primaries) that have not interacted with the atmosphere yet. These particles account for the large momentum part of the curve, extending down to approximately 5 GeV/$c$. (ii) Secondary protons, generated within the atmosphere after nuclear collisions of primary particles (proton or nuclei). Such particles account for the low momentum part of the plots presented at figure 1.

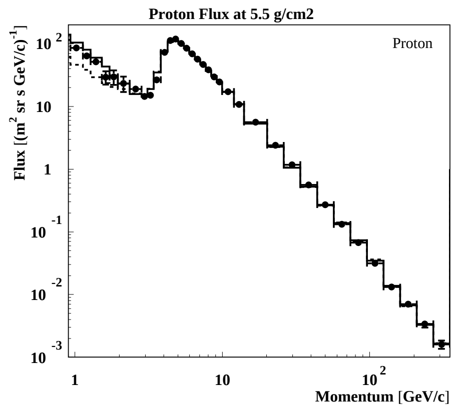


Figure 1: Absolute proton flux versus momentun, at an altitude of 5.5 g/cm$^2$. The solid circles correspond to CAPRICE98 data, while the histograms represent AIRES simulations using the A1 (dashed line) and A2 (solid line) codes.

In the large momentum part of the curves we can see that both the simulated and experimental data are virtually coincident. This is an indication of proper normalization of the fluxes and also that the low energy nuclear cross sections used in the simulations are appropiate for those energies:[1] substantially mistaken cross sections would necessarily give as output distorted fluxes, presenting, for example, a shifted position of the maximum located about 5 GeV/$c$.

On the other hand, the small momentum part of the curves can give us important information on how the secondary particles are generated in the simulations. In this case we detect a noticeable sensitivity to changes in the low energy hadronic model (compare the curves corresponding to codes A1 and A2).

As long as altitude over sea level diminishes, the fraction of secondary protons progresively domi-

1. In AIRES, the low energy nuclear cross sections are obtained from parameterization of experimental collider data.

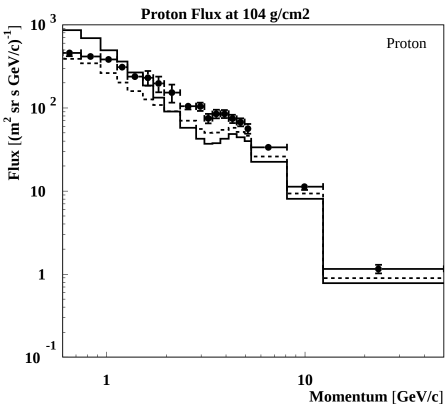


Figure 2: Same as figure 1 but for an altitude of 104 g/cm$^2$.

nates the measured proton flux. This can clearly be seen in figure 2 where the experimental and simulated proton fluxes at an altitude of 104 g/cm$^2$ have been plotted as functions of proton momentum.

In this case the secondary protons contribute to the flux at all the measured energies, and the remaining primaries add a small increment that extends from around 4 GeV/$c$ on. The primary contribution is responsible for the minute peak registered at 5 GeV/$c$.

In general, the simulated fluxes are slightly smaller than the experimental ones at this altitude (104 g/cm$^2$). Variations in the low energy hadronic model significantly alters both the total flux of protons as well as their energy distribution.

From these examples we can conclude that the measurements of the proton and helium fluxes at different altitudes in the atmosphere provide an important way of checking the low energy model used in air shower simulations which is complementary to the usual contrast with collider data since the flux measurement allow to directly check the impact of model characteristics on air shower observables. These checks will also produce tuned parameter sets of the hadronic models to be used in production air shower simulations.

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