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A new measurement of the primary cosmic ray spectra

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Abstract. A new measurement of the primary cosmic ray spectra was performed during the balloon-borne CAPRICE experiment in 1998. This apparatus consists of a magnet spectrometer, with a superconducting magnet and a drift-chamber tracking device, a time of flight scintillator system, a silicon-tungsten imaging calorimeter and a gas ring imaging Cherenkov detector. This combination of state-of-the-art detectors provides excellent particle discrimination capabilities, such that detailed investigations of the antiproton, electron/positron, muon and primary components of cosmic rays have been performed. The analysis of the primary proton component is illustrated in this paper.

1 Introduction

Accurate measurements of the spectra of primary cosmic rays have deep astrophysical and cosmological implications, since they allow the mechanisms of galactic production and propagation of cosmic rays to be investigated.

Recently, the importance of the normalization of the primary cosmic-ray flux has been emphasized in connection to the atmospheric neutrino observations performed by underground experiments. A correct interpretation of these measurements depends on the accuracy of the predictions to which they are compared. The assumptions about the flux of cosmic rays which impinge on the Earth turn out to be among the main sources of inaccuracies in the simulation of atmospheric showers. More accurate measurements have been consequently advocated (e.g., Gaisser, 1998).

Measurements of primary particles have been performed using different techniques: magnet spectrometers have been used for energies up to 100–200 GeV/n, while calorimetric measurements can extend to higher energies. However, comparisons among such measurements show sometimes significant discrepancies.

From this experimental scenario, the need arises for measurements extended over a large energy range performed with a good control of the systematic uncertainties. In this paper we report a new measurement of the primary proton spectrum which satisfies both these requirements.

2 The CAPRICE98 experiment

The balloon-borne CAPRICE (Cosmic AntiParticle Ring Imaging Cherenkov Experiment) detector was flown from Ft. Sumner, New Mexico, USA on May 28-29, 1998 at a vertical rigidity cutoff of about 4.3 GV. The data analyzed for this work were collected at an average atmospheric depth of 5.5 g/cm^2, during an exposure time of almost 21 hours.

The experimental setup was a renewed configuration of the

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CAPRICE94 apparatus which was successfully used in a previous balloon experiment at low geomagnetic cutoff in 1994. The CAPRICE98 apparatus is shown in Figure 1: it consisted of a superconducting magnet spectrometer, a time-of-flight device, a gas ring imaging Cherenkov detector (RICH) and a silicon-tungsten imaging calorimeter.

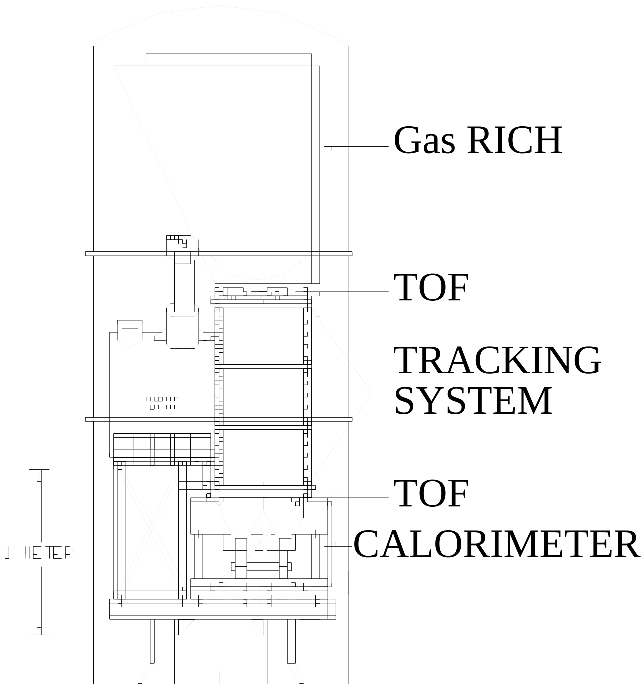

Fig. 1. The CAPRICE apparatus in the 1998 configuration (CAPRICE98).

The magnet spectrometer consisted of a single coil superconducting magnet, which had been used in all the previous flights operated by the WiZard Collaboration, and a tracking device consisting of three modules of drift chambers (Hof et al., 1994). This system performed 18 measurements along the direction of maximum bending and 12 measurements along the perpendicular view, with a resolution better than 100 μm. The total height of the spectrometer was about 110 cm. The magnet was operated at a current of 120 A, giving rise to a field of intensity 0.1–2 T in the region of the tracking device. The Maximum Detectable Rigidity (MDR) for this configuration of the spectrometer was estimated better than 300 GV for singly charged particles.

The time-of-flight (ToF) system consisted of two planes of plastic scintillator, located immediately above and below the tracking stack. Each plane was segmented into two paddles viewed at opposite ends by photomultipliers. The signals from each photomultiplier were independently digitized for time-of-flight measurements as well as for pulse height analyses. This system reached a time resolution of the order of 200 ps.

The RICH detector (Francke et al., 1999, Bergström et al., 2001) used a 1 m tall gas (C_4F_{10}, $\gamma_{th} \simeq 19$) radiator and a photosensitive multiwire proportional chamber mounted above it. The Cherenkov photons were reflected into the chamber by a segment of spherical mirror located at the bottom of the radiator. The chamber was filled with TMAE-saturated ethane gas. The signals were acquired by means of a pad readout implemented on one cathode plane.

The calorimeter (Bocciolini et al., 1996) consisted of 8 silicon planes interleaved with tungsten converters. Each plane was equipped with two sensitive layers segmented in strips along perpendicular directions. This design provided a high longitudinal and transversal granularity for shower imaging. The total depth of the calorimeter was 7 radiation lengths and 0.25 interaction lengths for protons.

The combined use of these sophisticated particle detectors made particle identification possible over large energy ranges. Elsewhere at this Conference are reported results from this experiment on antiprotons (Boezio et al., 2001), muons (Hansen et al., 2001) and on the deuterium abundance (Vannuccini et al., 2001). Results on electrons and positrons have been shown previously (Boezio et al., 1999).

More details on the instrumental setup and particle discrimination capabilities of this experiment can be found in Ambriola et al. (1999).

3 Data analysis

Protons can be reliably identified in the CAPRICE98 apparatus. Namely, the reconstruction of the track in the spectrometer allowed single clean events to be selected for which the deflection (hence, momentum) was reliably determined.

Because of the overabundance of protons among primary cosmic rays, the selection was optimized to have an efficiency as high as possible. The time-of-flight information was used in order to select downward moving particles. The pulse height information from the top scintillator was used to select singly charged particles. The RICH was used as a threshold device to select protons. At less than 18 GV protons are below the Cherenkov threshold and, hence, below this rigidity they were selected requiring that no signal due to Cherenkov light was present in the RICH.

In addition, the calorimeter information was also available. The calorimeter provided topological information used to select non-interacting particles or to discriminate between hadronic and electromagnetic showers. The energy measurements performed by the silicon strips of the calorimeter allowed also the charge of non-interacting particles to be measured. However, because of the low efficiency of this selection, the calorimeter was only used to select proton and helium samples for efficiency studies of the other detectors.

It should be also emphasized that, aside from the particle discrimination capabilities, the combination of detectors of the apparatus provided the redundant measurements needed for cross-checks of the in-flight detector performances, necessary for accurate efficiency determinations.

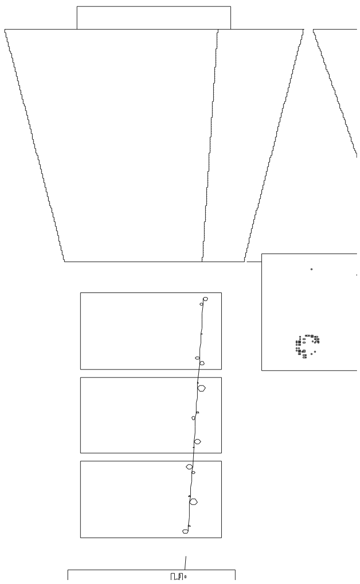

Fig. 2. Display of a 31.3 GV proton traversing the CAPRICE98 apparatus. The instrument is shown in the *x* and *y* view. From top to bottom the following are displayed: the RICH as seen from the side and from above, the tracking system and the imaging calorimeter. Note that the calorimeter is not in scale.

Fig. 2 shows a schematic view of a 31.3 GV proton in the CAPRICE98 apparatus. The figure shows two panels, corresponding respectively to the view along the direction of maximum bending (*x*, left) and to the view along a perpendicular axis (*y*, right) of the apparatus. The RICH detector is shown at the top. A rotated view of the signals in the pad plane of the multiwire proportional chamber is shown in the square frame in the centre of the figure. The ionization cluster of pads can be seen well separated from the Cherenkov ring typical of a $\beta \simeq 1$ particle. The three central boxes are the drift chambers of the tracking system. The box at the bottom shows the calorimeter information: the proton interacts in the calorimeter producing a hadronic shower. The line drawn through all detectors represents the fitted track of the particle.

The number of detected particles was corrected in order to compensate for the fraction of events lost due to interactions in the payload. Then, further corrections were made in order to propagate the flux values measured at the level of the detector back to the top of the atmosphere: we need in fact to subtract the events produced in interactions above the detector, to compensate for the fraction of events lost because of interactions and to account for the energy lost by ionization during propagation.

It is important to point out that the velocity measurement performed by the RICH detector permitted to analyze possible systematic uncertainties of the tracking system caused by, for example, an offset in the deflection measurements. This was done using both muons collected at the ground prior to the flight and protons at float. The variation of the Cherenkov angle, measured by the RICH, as a function of the deflection, measured by the tracking system, was studied both for μ^+ and μ^-. No difference was found in the behavior of μ^+ and μ^-, which could result from systematic uncertainties in the deflection measurement. It was then inferred that if an offset existed, at a 95% confidence level it could not be larger than 0.001 GV^{-1}, which is significantly smaller than the smallest value of deflection considered in this analysis, 0.003 GV^{-1}. A similar result was obtained with the proton data at float from which the spectrometer resolution function was also determined (Vannuccini et al., 2001).

4 Results

Our results on the energy spectrum of primary cosmic ray protons are shown in Fig. 3 together with results from other recent experiments. We note a nice agreement of these data with the measurements performed by our Collaboration in previous experiments (MASS91 and CAPRICE94 in the figure). There is also a satisfactory agreement between the CAPRICE98 results and the other experiments shown in Fig. 3. However, discrepancies may be noted in the comparison to the BESS and AMS data which are both higher than our results for energies larger than 10 GeV at a level which is barely consistent with the estimated uncertainties. This occurrence is intriguing, since the agreement between the CAPRICE98 and the BESS results, as well as between the CAPRICE94 and BESS results, seems to improve at lower energies.

In spite of these discrepancies, we may note that the level of agreement among the most recent measurements is within 10-20% , which constitutes a significant progress with respect to previous years. This occurrence is particularly important in consideration of the fact that the normalization of these recent measurements, including the CAPRICE98 results, is significantly lower than some of the older measurements (e.g., Webber et al., 1987, not shown in Fig. 3).

It should be noticed that neither the CAPRICE98 nor the CAPRICE94 results were deconvolved for the effect of the intrinsic spectrometer resolutions since the effect on the measured spectra is smaller than the statistical errors.

Assuming a power-law spectrum in kinetic energy for the CAPRICE98 fluxes, a spectral index of -2.766 ± 0.018 was found above 20 GeV.

5 Conclusions

We have shown primary proton results from the latest CAPRICE balloon-borne experiment, performed in 1998. The excellent performances of this detector allowed us to perform an accurate measurement of the spectrum extended over a

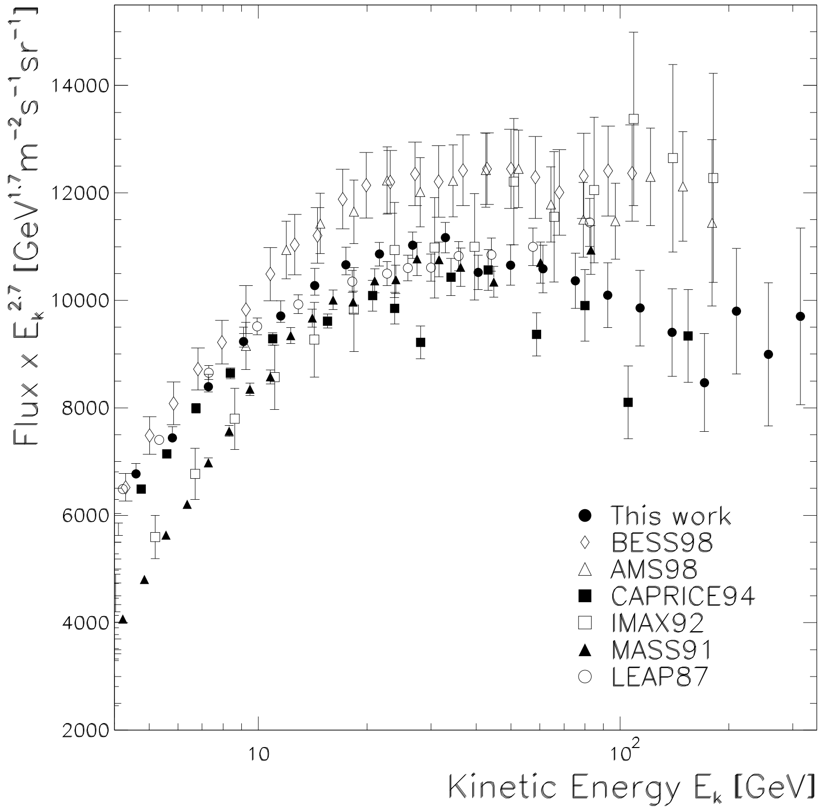

Fig. 3. The proton energy spectrum at the top of atmosphere detected by CAPRICE98. Results from other recent experiments are also shown (BESS98: Sanuki et al., 2000; AMS98: Alcaraz et al., 2000; CAPRICE94: Boezio et al., 1999b; IMAX92: Menn et al., 2000; MASS91: Bellotti et al., 1999; LEAP87: Seo et al., 1991).

large energy range. The results are in good agreement with other recent measurements.

The analysis of the helium nuclei is in progress and results will be presented at the Conference.

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