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Direct detection of cosmic rays: through a new era of precision measurements of particle fluxes.

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Abstract

In the last years the direct measurement of cosmic rays received a push forward by the possibility of conducting experiments on board long duration balloon flights, satellites and on the International Space Station. The increase in the collected statistics and the technical improvements in the construction of the detectors permit the fluxes measurement to be performed at higher energies with a reduced discrepancy among different experiments respect to the past. However, high statistical precision is not always associated to the needed precision in the estimation of systematics; features in the particle spectra can be erroneously introduced or hidden. A review and a comparison of the latest experimental results on direct cosmic rays measurements will be presented with particular emphasis on their similarities and discrepancies.

Keywords: direct measurements, cosmic rays, systematic uncertainties

1. Cosmic rays direct detection

Cosmic rays were discovered about one century ago by Victor Hess. Hess was awarded with the Nobel prize in 1936 for his studies, but he was never able to actually perform a direct detection of the cosmic rays due to the technological limitations of balloon flights and of the detectors at his times. Indeed he was able to measure the amount of secondary produced radiation in the atmosphere, that is to study the development of cosmic ray showers generated by primary cosmic rays. It took several years to understand that the main component of cosmic rays is made of protons with a steeply falling flux as function of energy. The study of cosmic radiation and its interaction with the Earth atmosphere led to the discovery of new particles and set the basis for the experimental particle physics that is carried out today at accelerators.

The origin, acceleration and propagation mechanisms of charged particles traveling in the Space have been the main topics in the studies of cosmic radiation since its discovery. In the aim of solving these puzzling issues, in the 80s and 90s a massive campaign of experiments was carried out on stratospheric balloon flights and small satellites. With increasing knowledge on the cosmic rays, it began to be clear that it is very difficult to provide a satisfactory and self-consistent global model. Sources types, their chemical composition and their inner dynamics, acceleration processes, and propagation through the interstellar matter and in the heliosphere affect the shape and the composition of the fluxes measured at Earth.

The cosmic ray all-particle spectrum is shown in figure 1 [1]. Most experiments agree, at least qualitatively, that the spectrum consists of at least three regions. At the lowest energies, from tens of MeV to tens of GeV (below 10^{10} eV in figure), the particles coming from the interstellar space are deflected and influenced by the magnetic region generated by the Sun, the heliosphere. As a consequence, the observed spectrum is flattening. At higher energies, instead, the direct measurements of cosmic rays represent the interstellar flux and compo-

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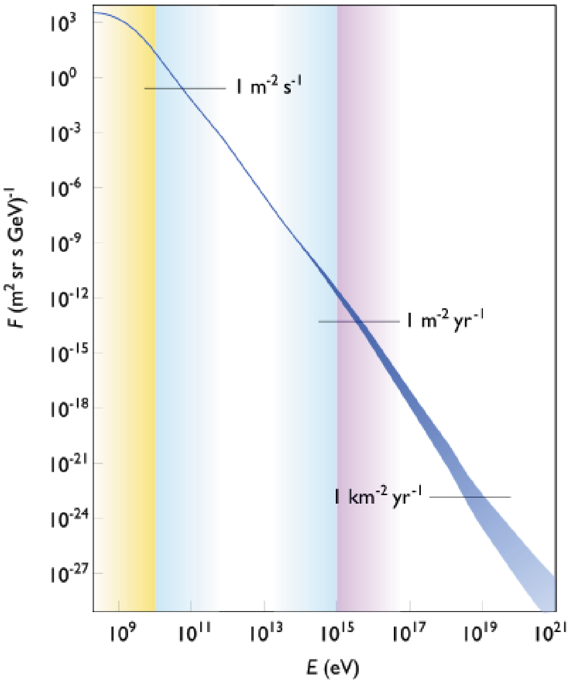

Figure 1: All-particle cosmic ray flux.

sition. For energies between tens of GeV and about 10^{15} eV, the spectrum can be fit with a power law with slope ~2.7. Due to such a steep spectrum, with current technology, a direct measurement is possible only up to about 10^{15} eV, the so-called "knee". Beyond the knee (10^{15} eV), the slope grows to ~3.1. Only indirect measurements are possible by exploiting the atmosphere as a large calorimeter and by making use of ground based detectors. At the highest energies particles have energies comparable to the Greisen-Zatsepin-Kuzmin limit (GZK cutoff), which occurs at about 5×10^{19} eV.

At the end of the 90s, experimental cosmic ray direct measurements were limited to few hundreds of GeV for protons and helium nuclei (major component of cosmic radiation) and to few tens of GeV for antiparticles. Due to the limited statistics and to quite large systematic uncertainties it was still not possible to answer to many fundamental questions concerning the cosmic rays. As a consequence, the experimental study of cosmic rays took three paths that are still effective. The first research line aims to push the direct measurements at the highest energies, possibly reaching the knee, in order to study sources and acceleration mechanisms. The second research line is dedicated to study the chemical composition of cosmic rays, measuring highly charged nuclei spectra, with the aim of understanding the source material, dust and gas, the nucleosynthesis and the propagation of cosmic rays in the interstellar medium. The third path, finally, is dedicated to the study of the rare antiparticle and anti-matter component, trying to search for signal of the elusive dark-matter, set anti-matter limits and understand the matter-antimatter asymmetry in the Universe.

Depending on the research line, different platforms and detection techniques have been adopted. In the following, I will describe the latest missions conducted on stratospheric balloons, satellites and on the International Space Station (ISS) while discussing the main physics results obtained in the recent years. I will categorize the results by type of particles and their role in the cosmic ray "standard model". With "standard model", figure 2, I refer to the idea that protons, helium nuclei, electrons and highly charged stable nuclei are accelerated as primary cosmic rays by supernoavae explosions. Deflected by the galactic magnetic field, these particles reach the solar system where they must enter the heliosphere and the Earth magnetic field (magnetosphere) to be detected by our detectors. During their travel, primary cosmic rays can interact with the interstellar matter gas and they can generate any kind of particle, secondary cosmic rays. In this model, fragile nuclei and antiparticles observed in the cosmic rays are only of secondary origin. Source distribution is supposed to be isotropic in space and time, and particles are assumed to gain energy via the second order Fermi particle acceleration process. The resulting fluxes in this model are smooth and steady.

2. Protons and helium nuclei spectra

Protons and helium nuclei are the most abundant cosmic ray component and hence, from the experimental point of view, the particle selection is significantly easier with respect to the one needed for studying the rare component.

Measurements of primary cosmic-ray proton and helium nuclei spectra have been performed over the years using different techniques: magnetic spectrometers and RICH detectors have been used for energies up to 1 TeV/n, while calorimetric measurements extended to higher energies. The majority of these results, especially concerning the high-energy ($\simeq$ 1 GeV) part of the spectra, were obtained by balloon-borne experiments. Recently, however, two space experiments presented their proton and helium nuclei results: PAMELA and AMS-02.

PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite-