Nuclear Instruments and Methods in Physics Research A 662 (2012) S157–S163

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Direct cosmic-ray detection

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ARTICLE INFO

Available online 8 December 2010

*Keywords:*
Cosmic rays
Direct detection
Space- and balloon-borne experiments
Knee
Solar physics
Dark matter
Antimatter
Cosmic-ray propagation
Cosmic-ray sources and acceleration
Cosmic-ray spectra
Spectrometer
HEAO-3-C2
PAMELA
AMS
ATIC
TIGER
CREAM

ABSTRACT

One century after the discovery of cosmic rays, many questions remain open on their origin, nature, and transport. Experiments to detect them directly have constantly improved, and are today of highly diversified designs. Indeed, precise measurements of cosmic rays in an energy range from $\sim 10^4$ to $\sim 10^{15}$ eV allow one to study the mechanism of acceleration of primary cosmic rays up to very high energy, to characterise their possible sources, and to clarify their interactions with the interstellar medium. Such measurements of elemental cosmic-ray spectra require complementary and redundant charge- and energy-identification detectors, such as the balloon-borne Cosmic-Ray Energetics And Mass (CREAM) experiment, which measures cosmic rays from $10^{12}$ to $10^{15}$ eV for all elements up to and including iron. Here I present the current status of direct cosmic-ray measurements, with the focus on the latest CREAM results. Finally, I briefly discuss the cosmic-ray identification above the knee.



## 1. Introduction

After the discovery of cosmic rays, physicists quickly focused on their main features: the energy spectrum, composition and elemental abundances. The most remarkable feature is the energy spectrum. It is measured over 12 orders of magnitude up to energies of $10^{20}$ eV and can be described beyond several GeV/$n$ by a simple power law in energy $E$: $\mathrm{d}N/\mathrm{d}E \propto E^{-\gamma}$, where $\gamma$ is the spectral index. It also quickly revealed some discrepancies, such as the *knee*, which are still not understood. A key to understanding the knee is the measure of the cosmic-ray composition, which can provide information on sources and can also help in understanding propagation processes in the interstellar medium. It is possible to constrain the parameters of propagation models as well as the dark matter component of the Galaxy by different means based on precise measurement of elemental cosmic-ray fluxes. Such a measurement is the goal of several direct or indirect experiments.

Since the cosmic-ray flux decreases rapidly in energy, it gives rise to two types of measurements:

*Direct detection* of cosmic rays by space- and balloon-borne experiments in the energy range of $\sim 10^3$ to $\sim 10^{15}$ eV above Earth's atmosphere, in which the primary particles are mostly absorbed.

*Indirect detection* by ground-based experiments which measure air showers of secondary particles produced by the primary cosmic-ray particles interacting in Earth's atmosphere. This is relevant for energies above $10^{13}$ eV.

In this paper, I concentrate on direct detection of cosmic rays. I start with a short historical overview of the development of direct cosmic-ray detection in Section 2. I then present in Section 3 the main scientific challenges addressed by the space- and balloon-borne experiments described in Sections 5 and 6, respectively. These experiments are all based on the same principal measurement techniques, briefly described in Section 4, which allow precise energy and charge reconstruction. Finally, I conclude with some comments on the future of direct detection of cosmic rays.

## 2. A short historical overview

To check whether the source of the radiation ionising the atmosphere is actually located in the terrestrial crust, Hess began a series of balloon flights in 1911. He concluded in 1912 that "this ionisation might be attributed to the penetration of the Earth's atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity, which was still able to ionise the air at the Earth's surface noticeably" [1]. This was the beginning of the quest to higher altitudes and of direct cosmic-ray detection.

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doi:10.1016/j.nima.2010.11.133

The measurement of primary particles is possible at altitudes before they interact with Earth's atmosphere, i.e., in the stratosphere and above. The first successful stratospheric balloon flight was accomplished by the Swiss ballooning and cosmic-ray pioneers Auguste Piccard and Paul Kipfer, who reached an altitude of 15,785 m in 1931 [2]. During this flight, they were able to measure the air ionisation with the help of Geiger–Müller counters and extend and confirm Hess's and Kohlhörster's measurement of rising ionisation with altitude. With such stratospheric balloons available, it was then possible to start studying the primary component of cosmic radiation. In 1941, Schein et al. [3] were able to show that the hard component of cosmic rays are primarily protons. Seven years later, Freier et al. [4] measured cosmic rays at altitudes of 24–29 km, by visualising their tracks with photographic emulsions. They presented evidence for the existence of heavy nuclei in the primary cosmic rays with "atomic numbers ranging from that of helium to those of the region around molybdenum".

The launch of *Sputnik 1* in 1957 ushered in a new era of scientific development in many fields. It was supposed to also measure cosmic rays, but due to complications the detector flew as *Sputnik 3* in 1958, leaving the discovery of the Van Allen radiation belts to the American satellite *Explorer 1*. In 1971 the first space station, *Salyut 1*, was launched, enabling the installation of bigger and heavier scientific detectors than satellites were able to transport. The first magnetic spectrometer *MARIYA*, measuring the elemental composition of cosmic rays, was first installed on the *Salyut 7* later on the *Mir* space station, preparing the way for other stationary direct cosmic-ray detectors to come.

In the meantime, stratospheric balloon development has also progressed. Offering a cheaper and more flexible solution to space-based methods, experiments can fly in space-like conditions at altitudes of 40 km, where the atmosphere traversed by the particles is only 3–5 g/cm$^2$. The long duration balloon (LDB) programme[1] sponsored by NASA started in the 1980 s and successfully conducted the first circumpolar flight around the South Pole in 1990 and around the North Pole in 1997 [5]. These LDB flights can achieve a duration of up to 40 days, but this depends on gas losses due to the day-night cycle during which the balloon changes altitude. A super-pressure balloon (SPB)[2] is currently being developed by NASA, and was successfully tested for the first time in 2008.[3] Such a SPB keeps flight altitude even during the day–night cycle, and hence enables a flight duration of about 100 days.

## 3. Scientific challenges

Many questions raised soon after the discovery of cosmic-rays remain open on their origin, nature, and transport. Measuring the cosmic-ray spectra and abundances will not only help to answer these questions, but also to gather information on the composition and the structure of the Galaxy, as well as on the source distribution and the fundamental physical processes which govern its dynamics. In the following I give a short and non-exhaustive summary of the main scientific challenges addressed by cosmic-ray physics.

### 3.1. Solar physics

The solar wind and the rotation of the Sun create a spiral magnetic field, which acts as a diffusive shield over more than 100 AU. Indeed, low-energy ($<10^{10}$ eV) cosmic-ray particles are diffused and slowed within the heliosphere, a phenomena called *solar modulation*. The measurement of the low-energy cosmic-ray flux as a function of time will help us to understand propagation processes within the heliosphere. Additionally, the measurement of solar energetic particles, such as high-energy electrons, positrons, and protons, will allow us to study solar ejections and their composition. Finally, the measurement of the solar cosmic-ray spectra allows us to study acceleration mechanisms in the solar corona.

### 3.2. Cosmic-ray sources and acceleration

In contrast to neutrinos and $\gamma$-rays, which point directly back to their sources, charged cosmic rays are deflected by interstellar magnetic fields, so arrive isotropically at Earth. One possible way to identify the origin of Galactic cosmic rays is to study their composition. One of the biggest challenges in cosmic-ray physics is the explanation of the acceleration of cosmic rays in the sources and the interstellar medium. Indeed, these mechanisms should reproduce the observed power-law spectrum, accelerate particles up to energies of $10^{20}$ eV, and reproduce the observed cosmic-ray elemental abundances.

### 3.3. Cosmic-ray propagation

To answer the question of how cosmic rays propagate through interstellar matter, different types of nuclear ratios are studied. Stable secondary-to-primary ratios give information on how much matter primary particles encounter during their transport to the Solar system. Here primary cosmic rays designates particles originating in the source and secondaries are obtained by fragmentation of primaries while they travel through the Galaxy. Radioactive secondary-to-stable-secondary ratios allow one to determine the time spent by the cosmic rays in the Galaxy and hence infer the size of its diffusion halo.

### 3.4. Dark-matter indirect searches

The observation of an excess relative to the expected spectra of $\gamma$-rays, electrons, positrons, protons, antiprotons, and antideuterons can allow us to indirectly infer the presence of dark-matter through its annihilation.

### 3.5. Antimatter search

The Big Bang theory makes the prediction that matter and antimatter should be present in equal amounts in the Universe, but we have so far observed only baryonic matter. This imbalance of matter and antimatter, known as the baryon asymmetry, is still puzzling. The measurement of antihelium nuclei in the primary cosmic rays would prove the existence of primordial antimatter, anti nucleosynthesis and hence even very distant anti-Galaxies, from which the direct observed antinuclei have escaped.

## 4. Measurement techniques

In order to accomplish the challenging task of studying the large variety of scientific challenges described above, cosmic-ray detectors must be able to precisely reconstruct the particle properties. In this paragraph, I will shortly describe the most commonly used measurement techniques for a precise charge- and energy-reconstruction in direct cosmic-ray experiments. The combination of the following described techniques also allows us to infer other characteristics of the detected cosmic-ray particles, such as their

[1] http://sites.wff.nasa.gov/code820/index.html
[2] http://sites.wff.nasa.gov/code820/construction.html
[3] http://www.nasa.gov/topics/earth/features/superpressure_balloon.html