Recent Results in Cosmic Ray Studies and Future Projects

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In the recent years, cosmic rays have been studied on Earth, with balloons and space experiments with good precision. I will review the results of selected experiments and give an outlook to upcoming experiments like BESS-Polar, Pamela and AMS-02, that will greatly enhance our knowledge of cosmic rays and improve actual results.

1 Introduction

Cosmic rays were discovered in 1912 by V.F. Hess in balloon flights. In the early days, cosmic rays meant a study of the basic properties of electricity and magnetism. Later, cosmic rays gave birth to particle physics through an extraordinary sequence of discoveries which ended only when large accelerators were built (see Tab. 1). Later still, it became astrophysics, studying the galactic sources of the lower energy cosmic rays, the magnetic fields in the heliosphere and the acceleration mechanisms in supernovae shock waves. Almost a century after its discovery, the study of cosmic rays still remains interesting and enters again the domain of particle physics including the recent discovery of neutrino oscillations by Superkamiokande [1].

Nowadays, there are basically two aspects in the study of cosmic rays: first, to understand and calibrate the composition and spectra of the cosmic rays, to have a better theory of its origin and acceleration as well as better simulation tools; second, to search for new physics with a very promising discovery potential: searches for nuclear antimatter or strange states of matter, indirect searches for dark matter using $\bar{\mathrm{p}}$, $\bar{\mathrm{D}}$, e^+ and γ rays and ultra heavy particle searches using cosmic rays with extreme energies.

Charged cosmic rays span at least 18 orders of magnitude in energy from solar wind particles of about $\mathcal{O}(10^2\,\mathrm{eV})$ to extremely energetic particles above $\mathcal{O}(10^{20}\,\mathrm{eV})$ and about 30 orders of magnitude in flux intensity (Fig. 1 left).

In this report I will concentrate on galactic cosmic rays with energies above $\mathcal{O}(1\,\mathrm{GeV})$. Most of the results have been presented by the individual experiments at the International Cosmic

Table 1: Early discoveries in elementary particle physics

Particle	Year	Discoverer (Nobel Prize)	Method
e^+	1897	J.J. Thomson (1906)	Discharges in gases
p	1919	E. Rutherford	Natural radioactivity
n	1932	J. Chadwick (1935)	Natural radioactivity
e^+	1933	C.D. Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	S. Neddermeyer	Cosmic Rays
$\pi^\pm$	1947	C.F. Powell (1950)	Cosmic Rays
$K^\pm$	1949	C.F. Powell (1950)	Cosmic Rays
π^0	1949	R. Bjorklund	Accelerator
K^0	1951	R. Armenteros	Cosmic Rays
Λ^0	1951	R. Armenteros	Cosmic Rays
Δ	1952	C.D. Anderson (1936)	Cosmic Rays
Θ^-	1952	R. Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	A. Bonetti	Cosmic Rays
p^-	1955	O. Chamberlain (1959)	Accelerators
		E. Segré (1959)	
anything else	>1955	various groups	Accelerators
ν oscillations	1998	SuperKamiokande	Cosmic Rays

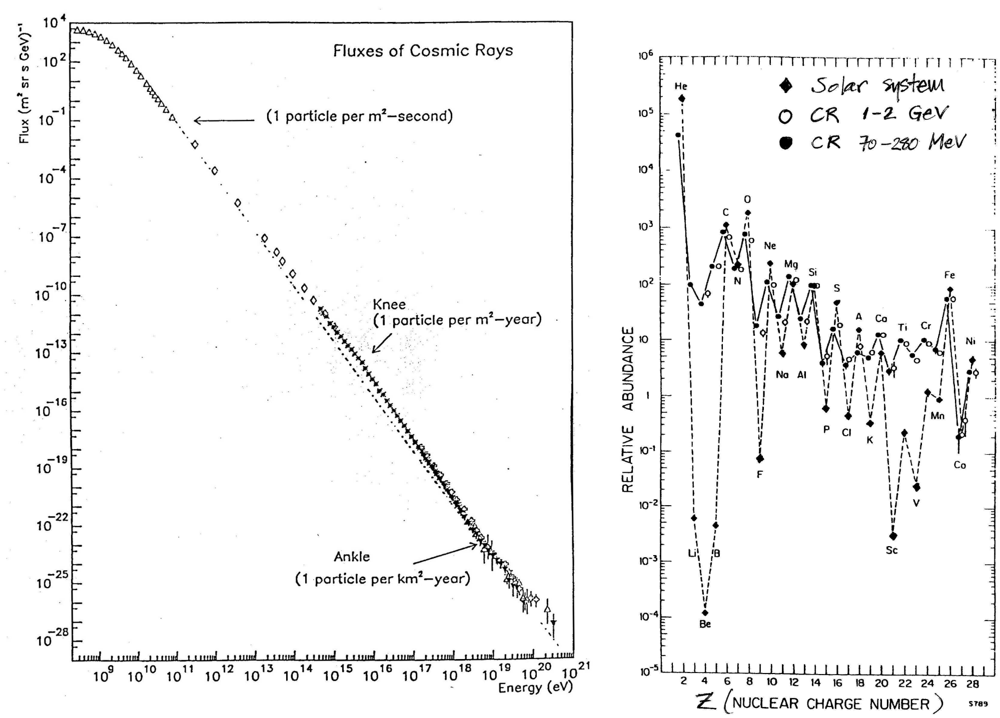

Figure 1: a) The cosmic rays energy spectrum, the low energy part below 10^8 eV is not shown. b) The cosmic rays elemental abundances from He to Ni compared to the solar system abundances, all relative to Silicon.

Ray Conference 2003 in Tsukuba, Japan [5]. After a brief overview of cosmic ray properties I will present results from ground based experiments, and move via balloon borne experiments to space borne experiments. I will finish with an outlook to upcoming balloon and space experiments.

2 Cosmic Rays Properties

Cosmic rays include all stable charged particles and nuclei with lifetimes of $\mathcal{O}(10^6\,\text{years})$ or longer. Apart from particles associated with solar flares, cosmic rays have their origin outside our solar system. The incoming particles are modulated by the solar wind which decelerates and partially excludes the lower energy galactic cosmic rays from the inner solar system. There is a significant anti-correlation between the solar activity and the intensity of cosmic rays with energies below a few GeV. In addition, low energy cosmic rays are affected by the geomagnetic field, which they must penetrate to reach the top of the atmosphere. Thus the intensity of any component of the cosmic rays below a few GeV depends both on the location and on time. Also, cosmic rays are affected by the galactic magnetic field ($5\,\mu$G) which confines and diffuses them and therefore have an isotropic distribution [2,3].

2.1 Cosmic Rays Energy

As mentioned before, the cosmic ray spectrum expands over many orders of magnitude in flux and energy. Figure 1 on the left shows the data above 1 GeV which is only weakly affected by solar activity. The spectrum can be well described by an inverse power law in energy with differential fluxes given by

$$\begin{aligned} \Phi &\propto E^{-2.7} && \text{up to the knee region at } 10^{15}\,\text{eV}, \\ \Phi &\propto E^{-3.0} && \text{from the knee to the ankle at } 10^{19}\,\text{eV}, \\ \Phi &\propto E^{-2.8} && \text{above the ankle, but here the spectral index in not precisely} \\ & && \text{known due to the lack of data at these high energies.} \end{aligned}$$

The change of slope at the knee is not understood [4]: It could be due to a change in either the acceleration or propagation mechanism, the elementary composition or interaction characteristics because of a new particle. A postulated composition change would increase the iron content. Recent experiments like RUNJOB and ATIC (see Table 2) have measured the composition of the cosmic rays up to iron in an energy domain approaching the knee (10^15 eV). No significant change in iron composition has been observed so far.

2.2 Cosmic Rays Composition

why 79 % and 70 % of the rest, why not 90 and 9??

About 89% of the primary nucleons are protons, about 10% are Helium nuclei and only about 1% is left for heavier elemenst . Still all elements from hydrogen up to uranium are present in the cosmic rays. The atoms reach the heliosphere fully ionized. Figure 1b compares the cosmic rays abundances of elements with the one found in the solar system. Both systems show the even/odd effect, with tighter bound even Z nuclei being more abundant.

The relative abundance of the cosmic rays is in general similar to the solar element distribution apart from two groups of elements Li, Be, B and Sc, Ti, V, Cr, Mn which are much more abundant in the cosmic radiation. These elements are not produced in the primordial nucleosynthesis (except ^{7}Li), nor made in stars. They are spallation products of the abundant nuclei of carbon and oxygen (Li, Be, B) and of iron (Sc, Ti, V, Cr, Mn) and are produced in the interstellar medium.

3 Recent Results from Cosmic Ray Experiments

3.1 Ground Based Experiments

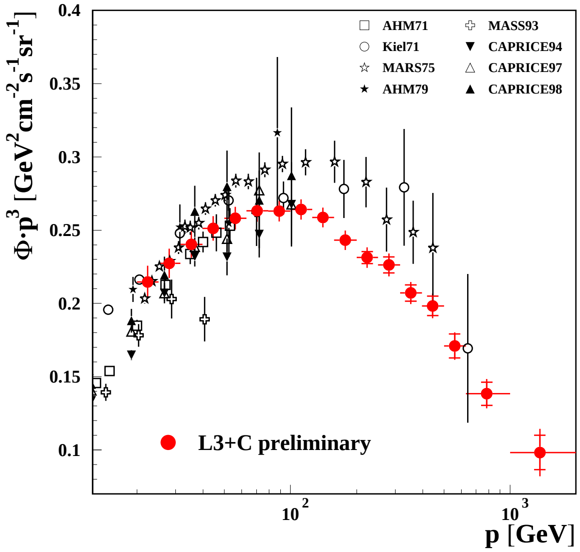

Figure 2: The L3+C vertical muon flux compared to previous results.

L3+C (+C for cosmics) is an excellent example for the synergy between pure particle physics experiments and cosmic ray studies. The existing LEP experiment L3 has been upgraded with scintillators on top of its magnets as well as air shower calorimeters on the roof of the experimental hall to measure cosmic rays in the last years of LEP operation. The physics goals are the study of the μ-momentum spectra and their charge ratio, as well as limits on primary antiprotons using the moon-shadow and primary cosmic ray composition. Because the cosmic rays were measured while the LEP-collider was still running, L3+C has extremely small and well controlled systematic errors, leading to the best measurement of the μ-spectrum worldwide (Figure 2).

The Auger collaboration aims for a full sky coverage with 7350 $\text{km}^2\cdot\text{sr}$ using two sites in the southern and northern hemisphere and is looking for cosmic rays at ultra high energies ($10^{19} - 10^{20}$ eV). The southern site in Mendoza (Argentina) will be fully equipped till end of 2005 with 24 fluorescence detectors (fly's-eye) and 1600 water cherenkovs. An engineering array has already seen first events above 10^{19} eV. The combination of fly-eyes and water cherenkovs aims to resolve discrepancies at ultra high energies from previous experiments (AGASA, Fly's-Eye Experiment) thus clarifying the question if there are events above the theoretical limit claimed by the GKZ-cutoff **REFERENCE??**.

3.2 Balloon Borne Experiments

Table 2 summarizes some of the balloon experiments with their main physics goals which have contributed to improve the knowledge of cosmic rays. It also shows recent highlights in ballooning, like the record long flight from TIGER (31.8 days, covering two complete round trips around the South Pole).

Some of the balloon experiments cover different physics topics in one mission (like BESS), while others try to measure specific quantities. ISOMAX e.g measures the ratio of ^{10}Be/^{9}Be. This ratio serves to study propagation mechanisms. Unfortunately, the ISOMAX results (Figure

Table 2: Summary of selected balloon experiments on charged cosmic rays.

Experiment	Magnet	Flight location	Flight duration	Physics aims	Energy [GeV/n]
HEAT	Supra	New Mexico Canada	22 hrs	e^-, e^+, $\bar{p}$	4-30
ISOMAX	Supra	Canada	13 hrs	$3 < Z < 8$	< 4
TIGER	no	Antarctica	31.8 days	$26 < Z < 40$	ultra high
ATIC	no	Antarctica	19.7 days	$1 < Z < 28$	20 - 10^5
RUNJOB	no	TransSiberia	6 days	$1 < Z < 28$	7 - 10^6
BESS	Supra	Canada	20 hrs	p, $\bar{p}$, He, $\overline{\mathrm{He}}$, $\bar{D}$	0.2 - 1.5
BESS-TeV	Supra	Canada	11.3 hrs	p, He	< 1000

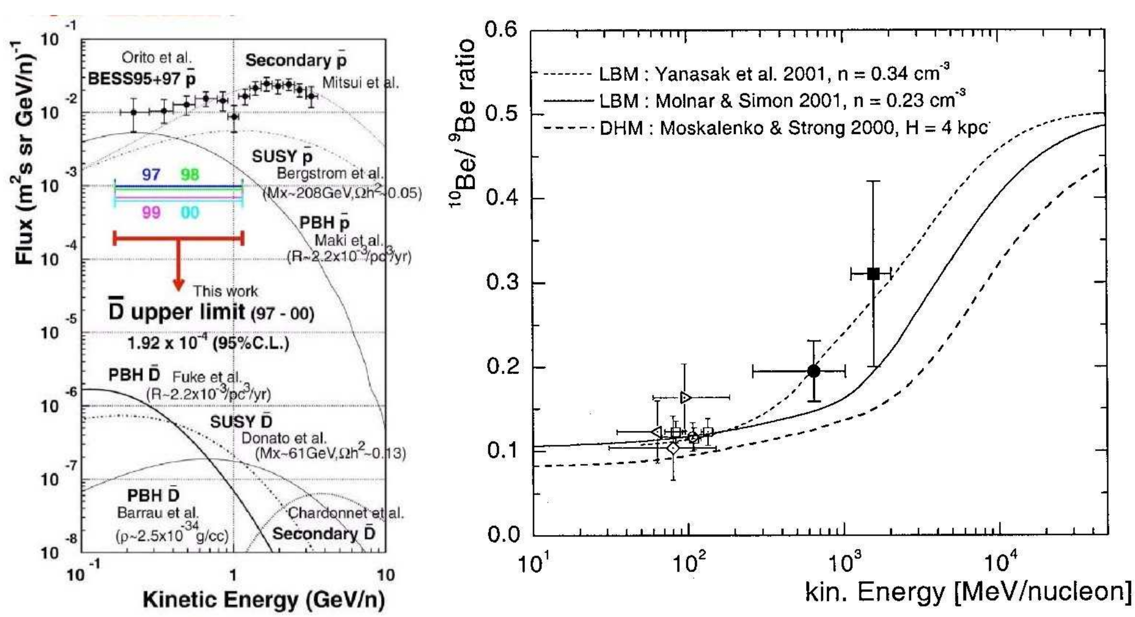

Figure 3: Left: BESS upper limit for $\bar{D}$ compared to other experiments. Right: ISOMAX (black dots) measurement of $^{10}Be/^{9}Be$ and model predictions.

3 right) are not significant enough to discriminate between different models. Future experiments (AMS-02 e.g.) will improve on this. BESS on the other hand shows that balloon experiments can be competitive, providing the world best limit on D̄ production (Figure 3 left).

3.3 Space Borne Experiments - AMS-01

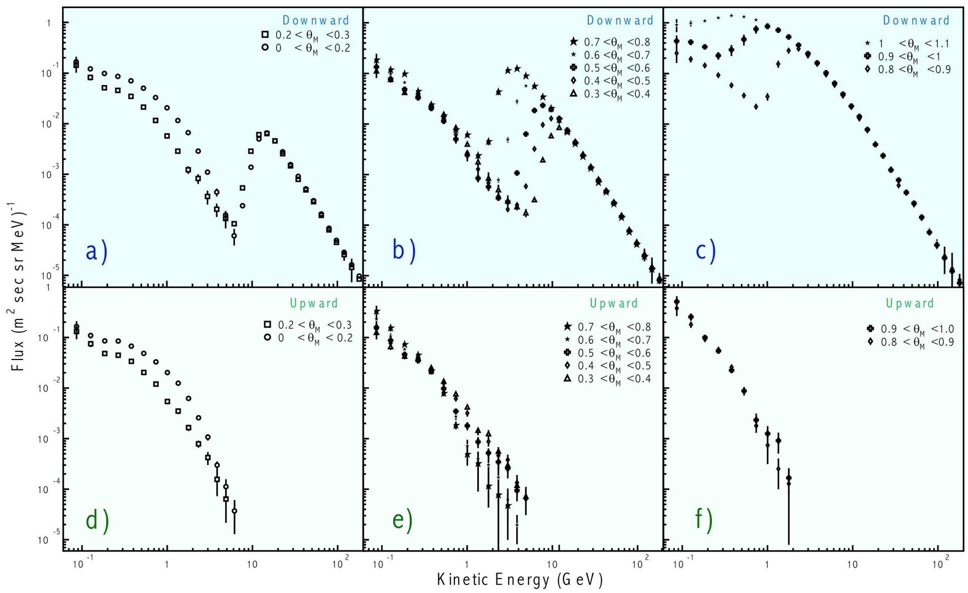

Figure 4: The proton spectrum measured by AMS-01. Geomagnetic latitudes are increasing from left to right. The lower part shows the contribution from upward protons (trapped in the geomagnetic field).

The AMS-01 pilot experiment flew on STS-91 in June 1998. The detector consists of a permanent magnet ($B = 0.14$ T), time-of-flight, a tracker with 2 m^2 of silicon-strips in 6 planes, cherenkov and anticoincidence counters. The primary physics goals are the measurement of $e^{\pm}$, p, p̄, He and $\overline{\mathrm{He}}$, their results can be found in [6]. The measured proton spectra is shown in Figure 4. It clearly shows the effect of the geomagnetic cutoff at different geomagnetic latitudes (latitudes increase from left to right). The lower part of the figure shows the upward proton spectrum, thus low energetic protons trapped in the geomagnetic field. AMS-01 was primarily a test bench for the upcoming AMS-02, but provided already very rich physics results, competitive with most actual experiments.

4 Future Experiments

During the upcoming 3 to 5 years, our knowledge of the flux and composition of the cosmic rays will be greatly improved thanks to two space borne experiments, PAMELA (Figure 5 left) on board of a Russian satellite and AMS-02 (Figure 5 right) on the International Space Station (ISS), both operating for at least three years in space. These two experiments will increase the statistical samples of charged cosmic rays by several orders of magnitude. In particular AMS-02 will be able to make measurements up to a few TV, a region unexplored so far und thus open for potential discoveries. AMS-02 will also allow high energy measurements of light isotopes ratios like D/p, ^{3}He/^{4}He and most important ^{10}Be/^{9}Be with unprecedented accuracy (see Figure 7). AMS-02 will be the only experiment able to measure simultaneously p̄, $e^{\pm}$ and D̄ but also high energy gamma rays. The PAMELA spectrometer despite its small acceptance will take data between AMS-01 and AMS-02 continuously monitoring the cosmic ray solar modulation.

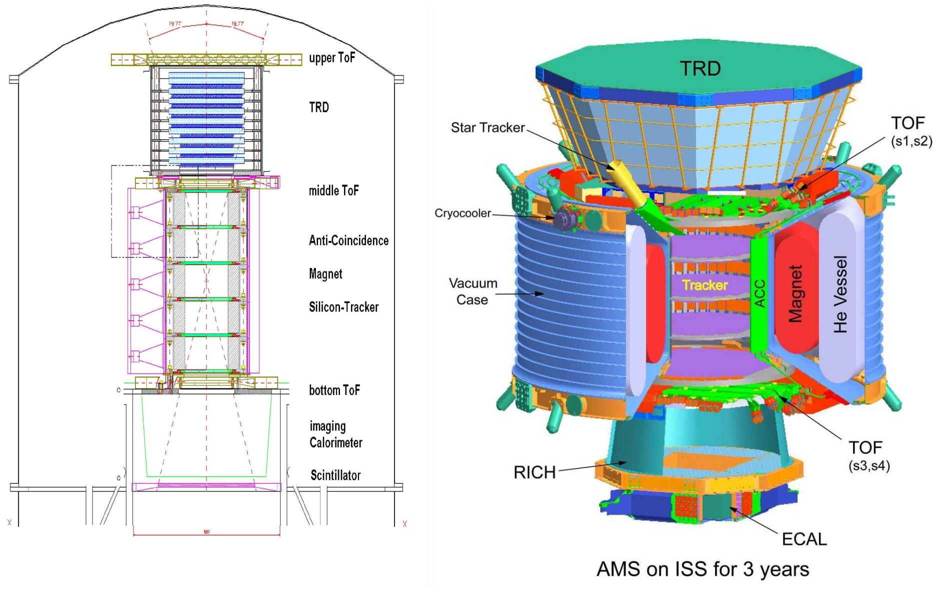

Figure 5: Left: PAMELA experiment apparatus. Right: The AMS-02 detector layout.

PAMELA also operates on a nearly polar orbit and can thus access lower energy cosmic rays than AMS-02, including p̄ down to 80 MeV and $e^{\pm}$ down to 50 MeV.

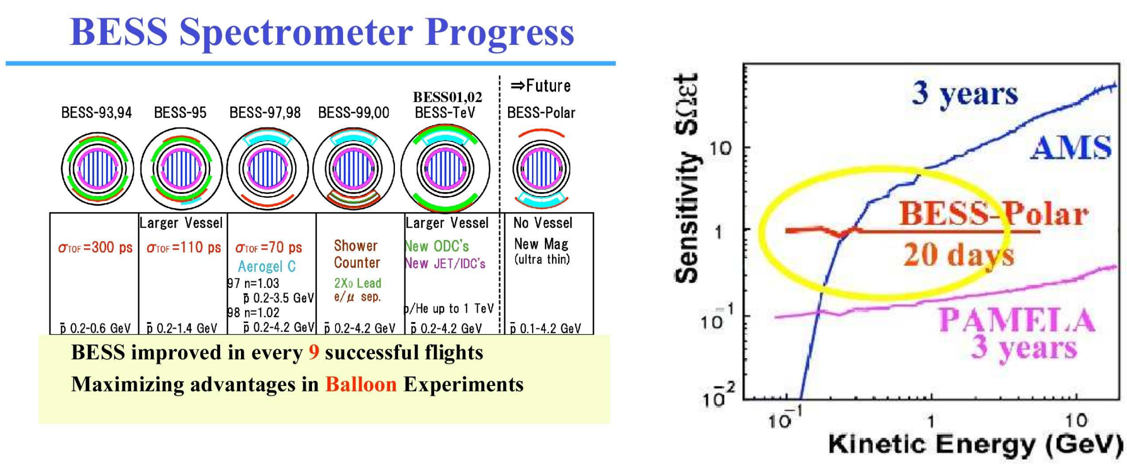

Figure 6: Left: BESS spectrometer progress. Right: Expected BESS-Polar sensitivity.

In addition, balloon experiments with single flights lasting almost one month could become competitive. The BESS-collaboration with its long experience of balloon flights will measure the low energy spectra down to 100 MeV for p̄, He, $\bar{\mathrm{D}}$/D, and $\overline{\mathrm{He}}$/He with its BESS-Polar payload in the Antarctica, as well as the high energy spectrum with new flights of BESS-TeV up to the TeV region for p and He. Figure 6 (left) shows the evolution of the BESS-spectrometer up to now. The highlight of the upcoming BESS-Polar is the new ultra-thin superconducting solenoid tested already at $B = 1.05$ T. Together with BESS's large acceptance (0.3 m^2·sr) and the foreseen flights during the solar minimun in 2004-2006, BESS-Polar is complementary to AMS-02 and PAMELA (Figure 6 right). A comparative chart of the upcoming experiments is shown in Table 3.

Table 3: Properties of the next generation spectrometer experiments and physics goals with expected sensitivities. MDR stands for maximum detectable rigidity.

Project	BESS-Polar	PAMELA	AMS-02
Acceptance ($m^2/cdot$sr	0.3	0.002	0.5
MDR (GV)	150	740	2500
Flight duration (days)	10+20	1000	1000
Flight Altitude (km)	36	690	350
Residual air (g/cm2)	5	-	-
Weight (tons)	1.5	0.38	7
Power consumption (W)	600	345	2000
Magnetic field (Tesla)	0.8-1	0.4	0.87
Flight latidude (deg.)	80	± 70	± 52
Energy region (GeV)	> 0.1	> 0.1	> 0.5
Flight vehicule	Balloon	Satellite	ISS
No. of exp. events for:			
protons (range in GeV/n)	$3 \cdot 10^9 (0.2 - 200)$	$3 \cdot 10^8 (0.08 - 700)$	$2 \cdot 10^{10} (0.5 - 2500)$
antiprotons	$3 \cdot 10^4 (0.2 - 4)$	$3 \cdot 10^4 (0.08 - 190)$	$3 \cdot 10^6 (0.08 - 700)$
e^-	-	$6 \cdot 10^6 (0.05 - 2000)$	$6 \cdot 10^8 (0.5 - 5000)$
e^+	-	$3 \cdot 10^5 (0.05 - 270)$	$3 \cdot 10^7 (1 - 400)$
$\overline{He}$/He	$3 \cdot 10^{-8}$	$7 \cdot 10^{-8}$	$1 \cdot 10^{-9}$
$\bar{D}$/D	10^{-5}	-	$3 \cdot 10^{-7}$

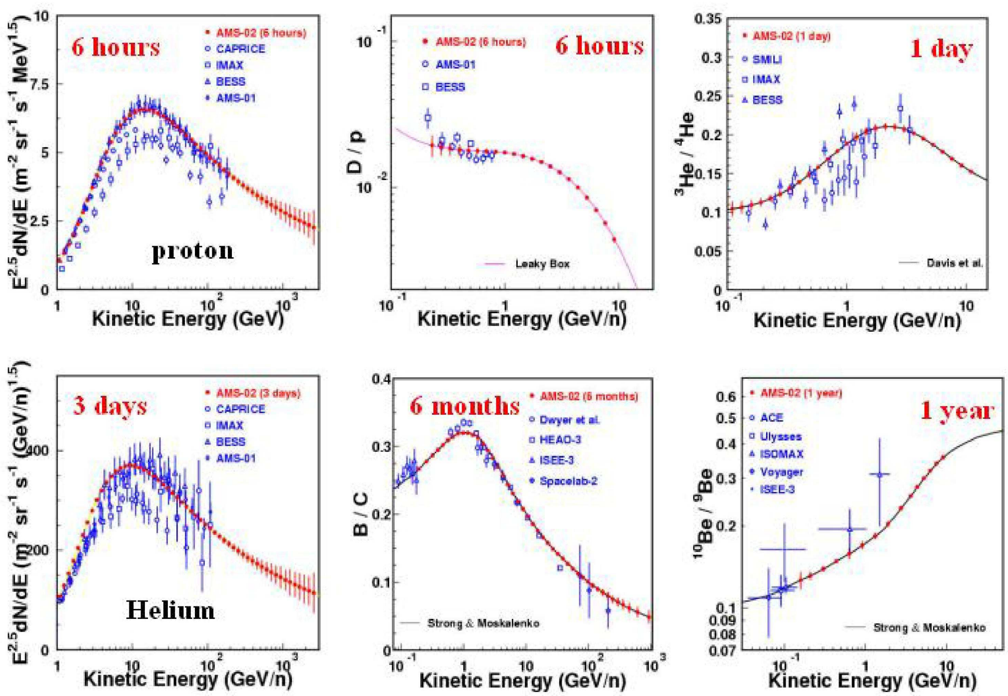

Figure 7: Expected accuracy of AMS-02 measurements for different cosmic ray isotopic components (Monte Carlo simulation).

5 Conclusions

Precise measurements of cosmic rays properties are available already now with the recent improvements in ballooning. Future experiments will further add to our knowledge of cosmic rays, either with huge air shower spectrometers on earth like AUGER, or with the upcoming space experiments like PAMELA and AMS-02 or further improved balloon missions like BESS-Polar.

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