

Experimental research on antiprotons and light antinuclei in cosmic rays

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Abstract. This review summarizes recent experimental studies of antiparticles in cosmic rays, including antiprotons, antideuterons, and antihelium nuclei. The discussion is centered on results from both direct and indirect measurements of the galactic component, while a separate section addresses secondary antiparticles (albedo), among them particles trapped in the Earth's magnetic field and part of the radiation belts. To provide historical context, the review also outlines the earliest accelerator-based experiments in which light antinuclei were first detected, thereby establishing the fundamental possibility of their existence in nature. A detailed overview is given of balloon-borne, satellite, and ground-based missions dedicated to measurements of the antiproton energy spectrum across a wide interval—from several hundred MeV to several hundred GeV—with indirect estimates extending to energies above 1 TeV. Particular attention is devoted to recent progress in searches for heavier antinuclei, such as antideuterons and antihelium nuclei, which hold significant promise for studies of dark matter and the baryon asymmetry of the Universe. Finally, prospects for future experiments are considered in light of current observational constraints and technological challenges.

Keywords: antiprotons, antinuclei, sources of antinuclei, antiproton detection experiments, cosmic rays

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1. Introduction

In the late 19th and early 20th centuries, studies of gas ionization in sealed vessels led researchers to conclude that an unknown penetrating radiation existed. In 1900–1901, C.T.R. Wilson was the first to propose the hypothesis that this radiation was of extraterrestrial origin. This hypothesis was confirmed in 1909–1914, when V. Hess and W. Kolhörster, working independently in balloon-borne experiments, observed a systematic increase in ionization with increasing altitude. This effect indicated that the radiation arrives from space and is absorbed by the atmosphere [1]. The term ‘cosmic rays,’ which is now universally accepted, was introduced and popularized in the scientific community by R. Millikan in 1925 [2]. A few years later, D.V. Skobeltsyn made the first direct observation of cosmic particles by recording their tracks in a Wilson cloud chamber [3–6].

Today, cosmic rays (CRs) are most commonly defined as particles with energies above a few MeV that arrive from space at the boundary of the Earth's atmosphere [7–9]. They may be classified according to their origin: solar particles, accelerated as a result of active processes on the Sun; galactic particles, whose sources are supernovae or other astrophysical objects in the Galaxy; and extragalactic particles, produced or accelerated in the vicinity of extragalactic objects and arriving in the Galaxy from intergalactic space. Cosmic rays also include particles produced in the Earth's atmosphere by interactions of the aforementioned CR components.

During their propagation, cosmic particles change their energy and direction, decay if they are unstable, or take part in elastic and inelastic interactions with the interstellar or intergalactic medium, as well as with the background radiation in the Universe. These processes give rise to new

particles from the primary component, some of which can also reach near-Earth space and be detected there. Such particles are referred to as secondary cosmic rays. There is, however, an alternative division of the concepts of primary/secondary cosmic rays: according to it, all particles arriving at the upper boundary of the Earth's atmosphere are considered primary, regardless of their origin, whereas secondary particles are those produced through interactions of primary particles with the atmosphere.

Thus, information on the chemical composition and the energy spectrum of cosmic rays makes it possible both to study the properties of their sources and to determine the characteristics of the intergalactic and interstellar medium, of the heliosphere, and of the Earth's magnetosphere and atmosphere.

It is known today that the principal components of cosmic rays are protons (about 90% of the total flux) and helium nuclei (about 8%); heavier nuclei (carbon, oxygen, iron, etc.) and electrons are also present, amounting to about 1%. In addition to particles of matter, particles of antimatter are present in the CRs: positrons [10] and antiprotons [11, 12], and candidate events for antideuterium and antihelium nuclei have been reported [13]. According to the experimental data on cosmic ray fluxes, the fraction of antiprotons relative to protons is approximately 10^{-5} to 10^{-4} , depending on the energy range [14, 15], while the fraction of positrons is from 10^{-3} to 10^{-2} [16].

In the present review we discuss antiprotons, the experiments devoted to their search and observation, and also briefly touch upon the physical consequences of the results obtained.

Antiprotons were detected in cosmic rays in 1979, independently, by the research groups of V.A. Romanov [11] and R.L. Golden [12]. Subsequently, their results were confirmed and refined in other experiments, for example in the measurements of A. Buffington [17] and in the PBAR [18] and LEAP [19, 20] experiments, among many others. It is worth noting here that the earliest measurements of the antiproton flux were performed by A. Buffington [21]; today, however, those results are considered to be erroneous.

Already in the early works an excess of the antiproton-to-proton flux ratio over the values expected under the assumption of a purely secondary origin of antiprotons was recorded [22–30]. This could testify to the existence of additional sources of antiparticles, for which large antimatter structures in the Universe or various extragalactic objects were then considered [22, 31, 32]. By that time H. Alfvén had proposed a mechanism for the coexistence of antimatter and matter [33], so that the new experimental evidence generated serious interest in this subject within the scientific community.

Contemporary theoretical models describing the origin of antiprotons assume that their sources may be known astrophysical objects [34], the evaporation of primordial black holes [32, 35], or dark matter particles [22, 31, 36, 37].

The energy spectrum of antiprotons produced by the processes indicated undergoes changes as they propagate from the sources to the region of observation. The study of antiproton spectra in cosmic rays has attracted the interest of the scientific community ever since their discovery. The first experiments, carried out at the end of the 20th century, revealed an excess of the observed antiproton flux in the low-energy region as compared with the predictions of theoretical models based on the secondary production of particles in the interaction of CRs with the interstellar

medium [25–30]. This discrepancy stimulated an active study of alternative mechanisms of antiproton generation, including the hypothesis of the existence of primary sources of antiparticles. Even after the experimental data had come into agreement with the standard 'leaky-box' model [38], the search for alternative explanations continued. In particular, various scenarios of a primary origin of antiprotons were proposed [36, 39, 40–42], among which particular attention was paid to supersymmetric theories (SUSY) and to attempts to constrain their parameters by means of cosmic observations.

In addition, antiprotons of comparatively low energies (up to tens of GeV) are also of considerable interest. For example, their accurate and long-term measurement makes it possible to study the effect of solar modulation, i.e., the influence of the Sun and of solar activity on the fluxes of galactic particles in the heliosphere. One of the interesting features of solar modulation is its charge dependence, in which the variations of the particle fluxes are related to the sign of their charge and to the polarity of the solar magnetic field [43]. Measurements of antiproton fluxes have also yielded new information on the modulation hysteresis, on the dependence of the mean free path on the magnetic rigidity of the particles and on the phase of the solar cycle, and on other effects [44, 45].

Finally, in 2011 antiprotons were discovered in the composition of the Earth's albedo and among the particles trapped in the inner radiation belt [46]. For a long time they remained in the shadow of scientific research; and although it is well known that secondary particles and antiparticles are formed in near-Earth space in inelastic reactions of cosmic rays with the Earth's atmosphere, the main attention was devoted to the study of electrons and positrons. Nevertheless, theoretical work on the fluxes of secondary antiprotons was also carried out, and with its help it became possible to understand more deeply the mechanisms of albedo-particle generation, including direct production and production via CRAND/CRANbarD (Cosmic Ray Albedo Neutron/anti-Neutron Decay), as well as the conditions of capture and retention of charged particles in the Earth's magnetosphere [47–50].

Antinuclei with $A > 1$ in cosmic rays, such as antideuterons ($\bar{d}$) and antihelium nuclei (${}^3\bar{\text{He}}$, ${}^4\bar{\text{He}}$), may also be of secondary origin, but in that case their abundance in the CR composition will be low. An excess over the predicted fluxes of the secondary component of these antinuclei may be regarded as indirect evidence for the existence of exotic sources of these particles, for example in the form of hypothetical dark matter particles [51, 52]. Since the fluxes of primary cosmic rays fall rapidly with increasing energy, the fluxes of secondary antinuclei in the CRs are expected to be suppressed in the high-energy region; hence, as an indicator of dark matter particles, the search for antinuclei should be conducted at kinetic energies above 1 GeV/nucleon.

2. Discovery of antiprotons at particle accelerators and in cosmic rays

The relativistic theory proposed by P. Dirac unified the principles of the special theory of relativity and of quantum mechanics, which made it possible to predict the existence of antiparticles [53]. One of the key predictions of the Dirac equation was the existence of an intrinsic angular momentum of the electron (spin) and of a magnetic moment. The best-

known consequence, however, was the appearance of two solutions of the equation: one described the known electrons, whereas the second pointed to the possibility of the existence of particles with the mass of the electron but with a positive charge [54]. This prediction remained hypothetical until C. Anderson discovered the positron in 1932, thereby confirming the existence of antiparticles [10].

Dirac's theory showed that the mechanism he predicted holds not only for the electron but for all subatomic particles with spin $1/2$, known as fermions [54]. To test this hypothesis, a particle accelerator intended for the detection of the antiparticle of the proton—the antiproton—was built at Berkeley. Its detection became an important step in the development of elementary-particle physics and in the deepening of our understanding of a fundamental symmetry of nature [55].

2.1 Production of antiprotons at accelerator complexes

In 1954 E. Lawrence supervised the construction of a proton accelerator called the Bevatron at the Radiation Laboratory in Berkeley (California, USA), which made it possible to accelerate protons to an energy of 6.2 GeV, exceeding the threshold energy of 5.6 GeV for antiproton production. A year later, in November 1955, O. Chamberlain, E. Segrè and co-workers published a paper announcing the discovery of a new subatomic particle, identical in all respects to the proton except that its electric charge was negative rather than positive [55]. The detection of the antiproton at the accelerator provoked a wide public response, and a month before the scientific paper appeared *The New York Times* carried the news on its front page: “Found New Atom Particle; Termed a Negative Proton.” With the discovery of the antiproton, one more piece of evidence was obtained for the existence of a symmetry between matter and antimatter, to the search for which subsequent experiments were directed. E. Segrè and O. Chamberlain were awarded the Nobel Prize in Physics in 1959 “for their discovery of the antiproton.”

In the experiments of O. Chamberlain and E. Segrè, proton beams that had reached an energy of 6.2 GeV, sufficient to create a proton–antiproton pair in the reaction $p + p \rightarrow p + p + p + \bar{p}$, were made to collide with a copper target [55]. The identification method employed was based on determining the mass of the negatively charged particles produced in the copper target of the accelerator upon collision with the proton beam. To confirm that antiprotons are indeed produced in this reaction, the energy of the products formed as a result of annihilation was measured. For this purpose, a further Cherenkov counter was placed after the scintillation counter, which made it possible to record the velocity of the antiproton annihilation products. It was expected that in the annihilation of a nucleon and an antinucleon at rest an energy equal to twice the rest energy of the nucleon (about 1.9 GeV) would be released. Indeed, it was found that as antiprotons passed through the detecting system a signal was released in the Cherenkov counter whose amplitude exceeded 1 GeV.

The results were confirmed in an improved experiment of O. Chamberlain [56, 57], in which the annihilation of an antiproton with one of the protons of the emulsion chamber was recorded from the tracks in a stack of photographic emulsions (Fig. 1). A charged particle passing through a photographic emulsion ionizes the atoms of the medium along its trajectory, and after development this produces a visible track. As the particle slows down its ionizing power

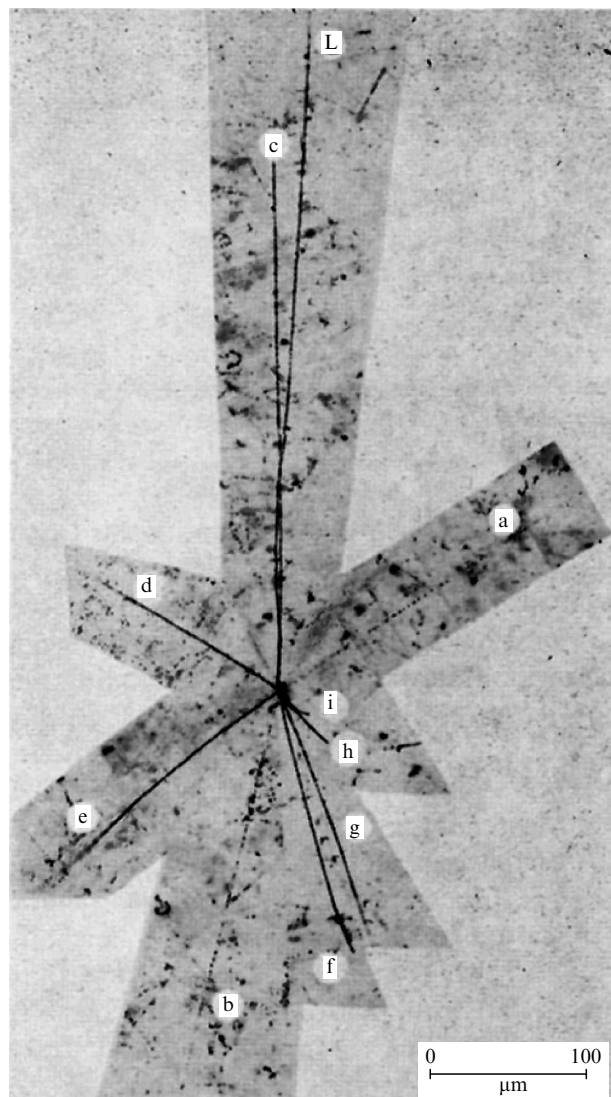


Figure 1. Reconstructed image of an antiproton annihilation (star). L is the antiproton track. Only the tracks b and c were reliably identified, as a pion and a proton respectively. The remaining tracks were identified with lower confidence and were assumed to be protons, while track a was assumed to be a pion [56].

increases, so that the segments of the track just before it stops appear denser and darker; this is used to identify the particle type. Antiproton annihilation is accompanied by the release of energy that is converted into the kinetic energy of secondary particles (pions, protons, etc.), which form a characteristic ‘star’ of numerous tracks emerging from a single interaction vertex. Comparison of the total energy of the secondary particles with the energy expected for antiproton annihilation on a nucleus makes it possible to assign the event reliably to antiproton annihilation.

The ionization produced by the antiproton and the magnitude of the angular scattering in the material of the emulsion were measured independently, which made it possible to determine the mass of the particle with high accuracy. The first method, based on the measurement of the ionization recorded from the grain density along the particle track in the emulsion, made it possible to estimate its velocity and energy. In addition, the range of the particle—the distance traversed before it came to a complete stop—was used, which allowed the mass to be refined. The

second method consisted in measuring the angular scattering of the particle on different segments of its track, which provided information on its momentum and hence on its mass. Additionally, in order to refine the mass, a method based on the measurement of the residual range and the magnetic rigidity was used, which made it possible to determine the momentum of the particle from its trajectory in a magnetic field and to compare it with the distance traversed in the emulsion material. As a result of applying these methods, the ratio of the antiproton mass to the proton mass was found to be 1.010 ± 0.034 . These experiments confirmed the existence of antiprotons in nature, opening the way to the active study of antimatter at accelerator complexes.

In 1956, less than a year after the detection of antiprotons, a group of researchers led by B. Cork, working at the Bevatron, successfully used antiprotons to produce antineutrons. Antineutrons appeared in the reaction of collisions of proton and antiproton beams: $\bar{p}p \rightarrow \bar{n}n$ [58]. Note that this reaction underlies the theories explaining the origin of antiprotons in near-Earth space (see Section 3.2 for details).

This discovery posed a new question to the scientific community: can antiprotons and antineutrons combine to form antinuclei? The answer to this question was obtained in 1965, when antideuterons — antimatter nuclei consisting of an antiproton and an antineutron — were recorded for the first time. This result was obtained simultaneously by two independent groups of researchers: one of them, led by A. Zichichi, used the proton synchrotron at CERN [59], while the other group, led by L. Lederman, carried out experiments at the AGS accelerator at Brookhaven National Laboratory [60].

The improvement of methods of antiproton generation made it possible to begin detailed studies of proton-antiproton collisions. In 1964 a project was proposed for the ISR (Intersecting Storage Rings) proton storage facility, built at CERN between 1966 and 1971. Initially it was designed for the study of elastic proton-proton interactions and for the production of new particles, but its construction made it possible to accumulate antiprotons in one of the two rings simultaneously with the accumulation of protons in the other [61]. A problem remained, however — the absence of an intense and monochromatic source of antiprotons — which was solved later by the development of electron [62] and stochastic [63] cooling methods.

The next important milestone in antiparticle research was reached at CERN in 1978, when in the course of the Initial Cooling Experiment (ICE) antiprotons produced by the collision of protons accelerated in the PS (Proton Synchrotron) with a tungsten target were held in a magnetic trap for 85 hours [64]. From that moment large-scale experiments with high-energy antiprotons began.

Thanks to the newly available possibilities of confinement, accumulation and acceleration of antiprotons, the principal tasks of the experiments of the 1980s became the search for the carrier particles of the weak interaction, now known as the $W^\pm$ - and Z^0 -bosons, discovered at the SPS accelerator in January and March 1983 [66, 67]. In 1980 the Antiproton Accumulator (AA) was built at CERN, in which high-energy antiprotons produced in the PS were held for injection into the larger Super Proton Synchrotron (SPS) [68–70]. The SPS thus became the first proton-antiproton collider ever built. The layout of the CERN accelerator-storage complex operating in the 1980s is shown in Fig. 2. As of

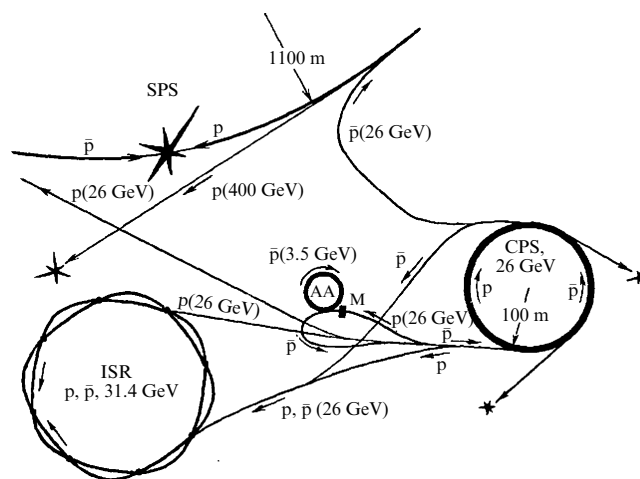


Figure 2. Layout of the CERN accelerator-storage complex as of the mid-1980s. CPS is the proton accelerator up to an energy of 28 GeV, the injector of protons and antiprotons into the ISR and the SPS; ISR is the storage ring for colliding proton-proton and proton-antiproton beams with energies of 31.4 GeV; SPS is the proton accelerator up to an energy of 570 GeV and the storage ring for colliding proton-antiproton beams with energies of 270 GeV [65].

1985 the center-of-mass energy of the colliding protons and antiprotons in the SPS reached 540 GeV, which at that time was a record value [65].

In 1982 LEAR (Low Energy Antiproton Ring) was built at CERN, which supplemented the CERN accelerator-storage complex and operated until 1996 [71]. Specifically for its creation, cooling methods were adapted in the Antiproton Accumulator (AA): the new and most efficient one proved to be electron cooling, which made it possible to reach energies of 2 MeV (momentum $61 \text{ MeV } c^{-1}$). In electron cooling, antiprotons transferred energy through collisions to a velocity-matched (co-moving) electron beam, so that the increase in the volume of their phase space was effectively transferred to the phase space of the electron beam. That beam, continuously replenished with cold electrons from its own source, carried away the kinetic energy of the antiprotons. Typical antiproton beam momenta achieved at LEAR were $106 \text{ MeV } c^{-1}$ (corresponding to an energy of 6 MeV). In addition to these deceleration capabilities, LEAR could also re-accelerate antiprotons with a momentum of $600 \text{ MeV } c^{-1}$ to $1.6 \text{ GeV } c^{-1}$, which made it possible to address various problems, including experiments on antihydrogen production [72, 73].

A team headed by W. Oelert in 1996 synthesized atoms of antihydrogen for the first time at the LEAR facility at CERN [74]. Nine of these atoms were produced as a result of collisions between antiprotons and xenon atoms, each of them existing for about 40 billionths of a second. This experiment was the first successful case of combining antimatter particles (antiprotons and positrons) into antihydrogen atoms, which represents a significant breakthrough in antimatter research [74]. This achievement opened up new possibilities for precise measurements of the properties of antihydrogen [72], including spectroscopic studies [75–78] and tests of fundamental symmetries such as CPT invariance [78–81]. CPT invariance, which assumes a symmetry between particles and antiparticles with respect to charge conjugation (C), spatial inversion (P) and time reversal (T), is a key element in understanding the nature of antimatter and its

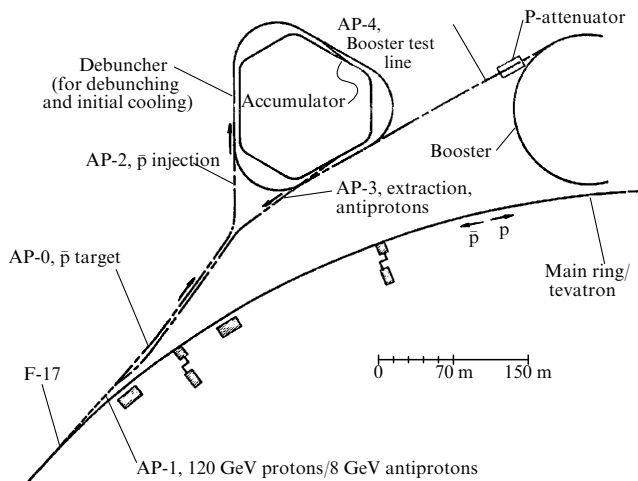


Figure 3. Layout of the Fermilab antiproton source [84].

differences from ordinary matter [82]. Testing this symmetry at the level of antihydrogen atoms makes it possible to probe the Standard Model of elementary-particle physics and to search for possible deviations that could point to new physics beyond it [78, 81].

Simultaneously with the experiments at CERN, the production of antiproton beams began in 1983 at the Fermi National Accelerator Laboratory (Fermilab) [83]. Antiparticles were synthesized in order to carry out experiments at the proton-antiproton collider called the Tevatron, which remained the most powerful particle accelerator in the world until 2009. The Tevatron was a ring accelerator with a circumference of 6.3 km, capable of accelerating protons and antiprotons to an energy of 980 GeV (900 GeV per beam). At the beginning of the collider's operation, the antiproton yield in the beam relative to the proton yield was about 10^{-7} . The main goal of the collider was the study of the fundamental properties of matter and antimatter, including the search for new particles and the verification of the predictions of the Standard Model.

The layout of the Fermilab antiproton source is shown in Fig. 3. To obtain an antiproton beam in the Fermilab experiment, high-energy protons from the Main Ring bombarded a fixed target. These antiprotons were then collected, cooled and accumulated in the antiproton accumulator before injection into the Tevatron.

One of the key achievements of Fermilab was the discovery of the top quark in 1995 at the proton-antiproton collider Tevatron [85, 86]. Antiprotons colliding with protons created the conditions for the production of top quarks, which decayed into W bosons and b quarks. The decay products were recorded by CDF (Collider Detector at Fermilab) [87] and DØ (DZero) [88], which made it possible to confirm the existence of the t quark experimentally for the first time. This discovery became an important step in elementary-particle physics and confirmed the Standard Model.

Besides the discovery of the top quark, experiments with antiprotons at Fermilab contributed to the study of CP violation and of the properties of W bosons. For example, the CDF collaboration carried out precision measurements of the asymmetry in B-meson decays, which made it possible to refine the parameters of CP violation and to test the predictions of the Standard Model [89].

Also at the Fermilab accelerator [90], in 1998, antihydrogen atoms were obtained by means of collisions of relativistic

antiprotons with a hydrogen target. This achievement opened up new possibilities for studying the properties of antimatter and for testing fundamental symmetries such as CPT invariance [78, 81].

At present the PUMA (antiProton Unstable Matter Annihilation) experiment is being conducted at CERN, aimed at investigating the surface properties of stable and rare (unstable) isotopes [91]. The study uses low-energy antiprotons (in the eV–keV range), since they possess a unique sensitivity to the distribution of neutrons and protons in the annihilation region, which may occur in the outer part of the nucleus—in the ‘tail’ of the distribution. In this region the density of nuclear matter is considerably reduced as compared with the central part; antiprotons are captured by the nucleus and annihilate with nucleons at a distance of about 2–2.5 fm from the surface [91]. Charged pions are formed as a result, and by measuring their characteristics one can determine the ratio of neutrons to protons in this region [72]. Moreover, antiprotons are particularly sensitive to exotic structures such as neutron halos [92, 93] and neutron skins [94, 95], which manifest themselves precisely in the tail of the nuclear density [96, 97]. This makes antiprotons a powerful tool for studying the properties of nuclear matter in low-density regions inaccessible to other methods.

In addition, experiments on the detailed study of the properties of antiatoms are being carried out. Antiprotonic atoms are formed as a result of the capture of low-energy antiprotons into an atomic state, in which the antiproton replaces an ejected electron [73]. The capture process is governed by the atomic and molecular properties of the target medium, but it has not yet been studied in detail. It is assumed that the antiproton is captured into a highly excited orbital with a large principal quantum number, ~ 100 for light atoms [72]. In the course of cascade transitions the antiproton descends to lower orbitals until it reaches the region where annihilation with nucleons occurs. The exact details of this process, including the radius of the initial capture orbit, require further experimental and theoretical study [98].

Another interesting direction is the test of the action of gravity on antimatter; for this purpose the ALPHA experiment [99, 100] uses the Antiproton Decelerator (AD) [101, 102] and ELENA [103] facilities at CERN. Thanks to the successes in producing antihydrogen atoms, ALPHA carried out the first precise measurements of the 1S–2S atomic transitions and of the hyperfine spectrum of antihydrogen [78]. On the basis of these achievements the ALPHA collaboration plans to extend its program by including a measurement of the gravitational acceleration of antimatter. The new ALPHA-g experiment [104], employing improved methods of trapping and of modelling antihydrogen orbits, aims to test the weak equivalence principle to an accuracy of 1% [100, 105]. Recent results of the ALPHA-g experiment demonstrate a gravitational attraction between antihydrogen atoms and the Earth [105].

Advances in the production, cooling and accumulation of antiproton beams, as well as the production of antimatter at CERN for high-precision measurements [74–76, 100, 106, 107], together with the latest developments of the PUMA collaboration [108] in antiproton transport, open up new possibilities for studying their influence on biological structures and for developing technologies aimed at using antiprotons in the fight against cancerous tumours [109–111].

Thus, studies of antiprotons at accelerator complexes, beginning with their discovery at the Bevatron, have led to

significant breakthroughs in elementary-particle physics. The improvement of methods of generation, cooling and accumulation of antiprotons has made it possible to carry out precision experiments, including the search for the top quark, the study of CP violation and the testing of CPT invariance. Contemporary projects such as PUMA and ALPHA-g are investigating exotic nuclear structures, the gravitational properties of antimatter and its possible application in medicine. These achievements have confirmed the principles of the Standard Model and opened new horizons for the search for physics beyond it.

2.2 Detection of antiprotons in cosmic rays

Assumptions about the existence of antiprotons in cosmic rays arose soon after the discovery of these antiparticles at the accelerator. Analysis of the east-west asymmetry of the CRs observed at low geomagnetic latitudes with instruments installed on the Aerobee sounding rocket [112] led M.I. Fradkin to the conclusion that the presence of negatively charged particles in the primary cosmic radiation could not be excluded (not less than 13% of all particles) [113]. The absence of electrons in such quantity, however, prompted him to estimate theoretically the fraction of $\bar{p}$ in cosmic rays, which according to his calculations amounted to 0.2%; this demonstrated the timeliness of setting up dedicated experiments to detect these antiparticles. Later calculations using the measured cross sections for antiproton production at energies accessible at accelerators showed that the expected fraction of $\bar{p}$ is about an order of magnitude smaller than this early estimate [114]. Over the following two decades many serious attempts were made to search for sources of antiparticles arriving in the cosmic radiation, using detectors with nuclear emulsions and magnetic spectrometers.

Although the first experiments on the detection of cosmic radiation with nuclear photoemulsions were carried out as early as the first half of the 1960s [115–117], systematic searches for antiparticles with their use began only at the end of the 1960s [118]. The technique for identifying low-energy antiprotons consisted in searching for events corresponding to their annihilation in the emulsion material [119].

In 1961 H. Aizu et al. carried out a balloon experiment [115] in which the maximum energy of the detected particles was limited by the thickness of the emulsion and did not exceed 0.5 GeV/nucleon. The thickness of the residual atmosphere through which the cosmic ray particles passed before reaching the stack of photographic emulsions was estimated at 7.6 g cm^{-2} . By studying the stopping points of singly charged nuclei in the emulsion and assuming that all the observed nuclei were of cosmic origin, they established an upper limit on the ratio of antiproton to proton fluxes of $\sim 3 \times 10^{-3}$.

In the 1960s N.L. Grigorov and colleagues carried out measurements of cosmic ray fluxes with detectors installed on artificial Earth satellites at an altitude of about 300 km [120, 121]. In the course of the analysis of the data obtained by exposing stacks of nuclear photoemulsions, it was established that the fraction of antinuclei with $Z > 2$ in the primary cosmic radiation does not exceed 0.1% [117].

Later, in 1968, Ivanova et al. [122] performed a detailed analysis of the cross sections for the interaction of antinuclei with photoemulsion nuclei. They also estimated the influence of the differences between the interaction cross sections of nuclei and antinuclei on the determination of the upper limit on the antinucleus content in cosmic rays. In their work, based on data from the experiment on the Kosmos-4 satellite,

an upper limit of $n_{\bar{A}} < 0.59\%$ was obtained for the multiply charged component of the primary cosmic rays with energies up to 1.4 GeV/nucleon. This result agrees with previously published data [115, 117] after allowance for corrections for the secondary origin of the particles and for the differences in the interaction cross sections [122].

In 1962 the group of M.V.K. Apparao carried out an experiment to search for antiproton annihilation in stacks of nuclear photoemulsion at a residual atmosphere of 4.2 g cm^{-2} [118]. After scanning the stacks of nuclear photoemulsions, interactions were selected in which at least one particle was produced with a track thickness corresponding to an energy deposit of not more than 2 mip (minimum-ionizing singly charged particles) [123]. This criterion guaranteed that a π meson characteristic of annihilation was produced in the interaction [124]. Then all tracks whose directions lie within a given solid angle had to be traced from the interaction vertex to the top of the emulsion stack. For such trajectories the direction of arrival is established by reconstructing the track from the traces caused by ionization losses. If one of the tracks corresponds to a particle that entered the photoemulsion stack from above, slowed down and annihilated, then its total energy can be measured. Next, the remaining tracks are identified and the energies of the corresponding particles are measured. The total energy of all particles is then compared with the energy of the particle that arrived from above. If the total energy released in the interaction significantly exceeds the kinetic energy associated with the incoming track, then the particle is identified as an antiproton.

In the experiment carried out by Apparao's group in 1967, a total of 5000 interactions were studied, and not a single event associated with antiproton annihilation was found. This made it possible to establish an upper limit on the ratio of antiproton to proton fluxes of 3×10^{-4} in the energy range from 50 to 150 MeV [118, 125].

Reference [126] presented a method, new for that time, of searching for antimatter in the primary cosmic rays using a combination of scintillation detectors and a gas Cherenkov counter. A high-altitude balloon experiment carried out in the equatorial zone (Kampala, 15° N) made it possible to establish an upper limit on the content of antinuclei with $Z \geq 6$ at the level $N_{\bar{A}}/N_A < 7.5\%$ (95% CL) for rigidities of 10–18 GV and energies of 5–9 GeV/nucleon. As shown in Fig. 4, this result extends the energy range of the previous measurements [117, 120, 122], performed in the region $< 1 \text{ GeV/nucleon}$. The authors emphasize that the increased particle energy raises the probability of their extragalactic origin, which makes the test of the symmetry of matter and antimatter in the Universe more relevant.

At the end of the 1970s antiprotons with energies of the order of several GeV were recorded in cosmic rays for the first time. In the USSR, experiments on the search for antiprotons in the CRs were conducted at the Leningrad Physico-Technical Institute (LPTI) under the leadership of V.A. Romanov in 1972, 1974 and 1977 [11]. The flights were performed at altitudes with a residual atmosphere of $\sim 10 \text{ g cm}^{-2}$ and a geomagnetic cut-off rigidity of $\sim 3.5 \text{ GV}$ [127].

The detector, whose layout is shown in Fig. 5, consisted of scintillation detectors (SD1–SD5) assembled into a telescope and a system of spark chambers (SC1–SC4) needed to reconstruct the trajectories of particles bent by the field of a permanent magnet (M). To eliminate the background (electrons and π mesons), a gas threshold Cherenkov detector (GCC) was used, while a directional solid-state

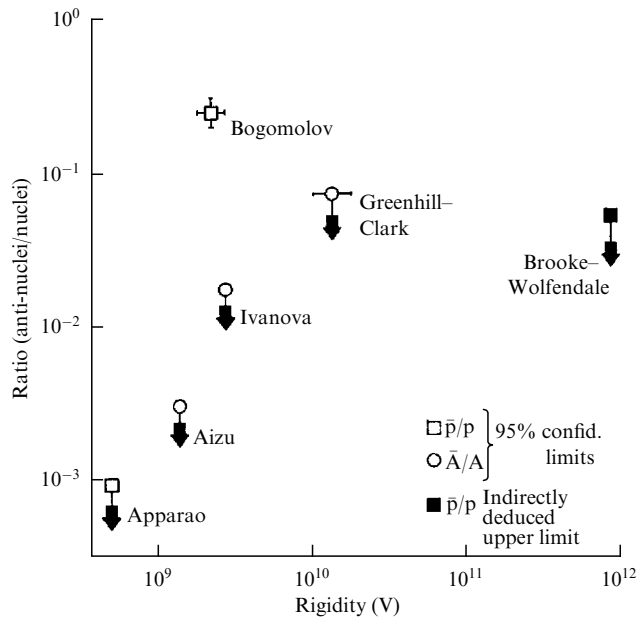


Figure 4. Upper limits on the fluxes of antiparticles in the primary cosmic radiation according to the data of experiments carried out from 1960 to 1970 [126].

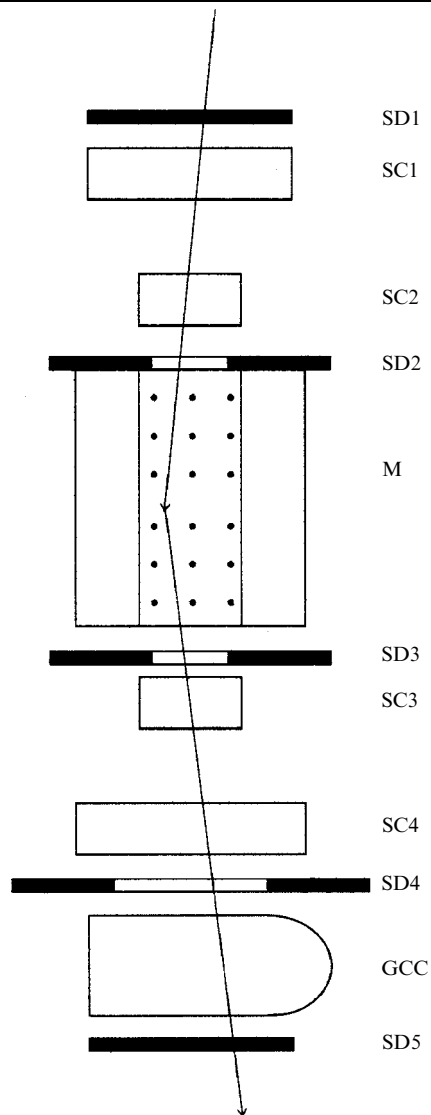


Figure 5. Layout of the balloon-borne magnetic spectrometer in the experiment of Romanov's group. SD1–SD5 are scintillation detectors, GCC is the gas Cherenkov counter, SC1–SC4 are spark chambers, M is the magnet [128].

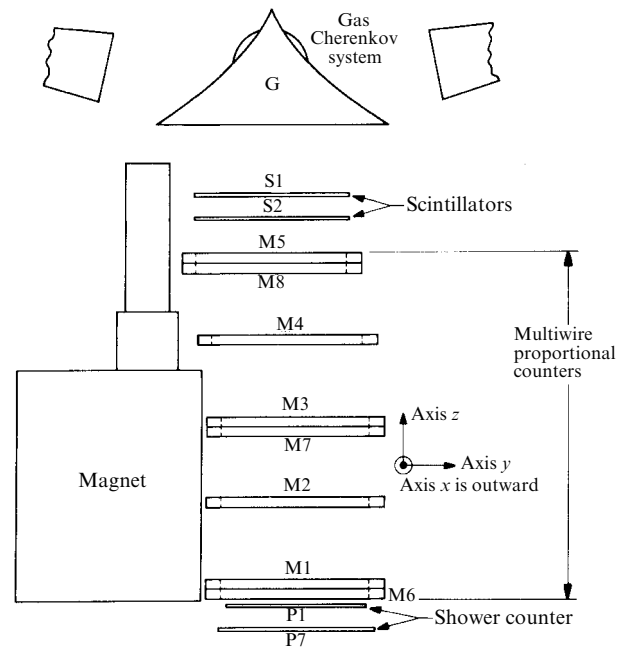


Figure 6. Layout of the superconducting magnetic spectrometer in Golden's experiment. Indicated are: G — Cherenkov detector, S1/S2 — scintillators, M1–M8 — proportional chambers, P1–P7 — scintillation counters of the calorimeter [132].

Cherenkov detector was used to suppress albedo particles. As a result of these experiments antiprotons were recorded for the first time, as reported at the 16th International Cosmic Ray Conference (ICRC) in Kyoto in 1979 [129]. The measured ratio of antiproton to proton fluxes in the energy range 2–5 GeV was $(6 \pm 4) \times 10^{-4}$.

In 1983–1985 the same group repeated the experiment for the low-energy antiproton flux. The measured ratio of antiproton to proton fluxes in the energy region 0.2–2 GeV was estimated at the level $0.6^{+1.4}_{-0.5} \times 10^{-4}$ [128, 130, 131].

In the same years successful experiments on the search for antiprotons were carried out under the leadership of R.L. Golden in the USA [12, 132]. The first flight in this series of balloon experiments took place in 1979 in Texas [12]. The measurements were performed under a mean residual atmosphere of 5.4 g cm^{-2} . The geomagnetic cut-off rigidity during the flight varied from 4.55 GV to 5.5 GV, and the data accumulation time was 7.89 hours. A magnetic spectrometer, whose layout is shown in Fig. 6, was used to detect antiprotons. The detector consisted of a gas Cherenkov detector (G), two scintillators (S1 and S2), eight multiwire proportional counters (M1–M8) and seven scintillators (P1–P7).

The total number of events identified as antiprotons was about 28, and the flux ratio $\bar{p}/p$ measured in this experiment in 1979 in the rigidity range from 5.6 to 12.5 GV was $(5.2 \pm 1.5) \times 10^{-4}$. A repeated analysis of the data in 1982, however, showed an increase of this ratio to $(6.8 \pm 1.7) \times 10^{-4}$, which is explained by a substantial revision of the estimate of the background events.

The main sources of background were antiprotons produced as a result of the interaction of cosmic ray protons with the Earth's atmosphere, the initial estimate [133] of which had been overstated by about a factor of three. According to subsequent calculations [134, 135], the contribution of atmospheric antiprotons decreased from 6.5 to 1.9 events. The contributions of other background compo-

nents were revised in a similar way. The background of antiprotons produced as a result of interactions with the detectors (secondary interactions), initially estimated at 3.4 events, turned out to be negligibly small thanks to strict selection criteria including requirements on the emission angle of the particles and on track consistency. The background from albedo antiprotons, which in the early estimate amounted to 2.5 events, was completely excluded. At the same time, the new analysis took into account the previously unconsidered effect of coherent nuclear scattering in the detector [17], contributing 2.0–3.0 events, which was confirmed by Monte Carlo simulation. The contribution from the decay of atmospheric mesons (5.0–7.7 events, predominantly π and K) and from the false identification of high-energy protons as antiprotons (0.2–1.2 events) remained practically unchanged. As a result, the total background decreased from 17.6 events in the initial estimate to 10.7 in the initial sample and 14.5 events for the extended energy range, which considerably increased the reliability of the measurement of the $\bar{p}/p$ ratio and explains its increased value in the final results.

In the 1980s the scientific group of A. Buffington in the USA was also engaged in the detection of antiprotons in the energy range 130–320 MeV [17]. The technique they used, however, differed from that of other experiments in that antiprotons were identified not by the curvature of the trajectory in a magnetic field, but by the characteristic topology of annihilation in the lead plates of a spark chamber [17]. The detector, whose layout is presented in Fig. 7, consisted of a system of scintillators (S1–S4), a plastic Cherenkov counter, and upper and lower spark chambers. The scintillation detectors (S1–S3) had an energy threshold making it possible to reject low-energy particles, while the detector S4 recorded the annihilation products that passed through all the lead plates of the spark chamber. The Cherenkov counter, operating in anticoincidence mode, was used to suppress the background from relativistic particles. The upper spark chamber was used to record the tracks of primary particles, while antiprotons were identified from the characteristics of their annihilation in the lower, lead, spark chamber. The main measurements were carried out during a balloon flight over Canada at an altitude of 28.5 km at a residual atmosphere of approximately 9 g cm^{-2} , which made it possible to ensure a low energy threshold for the detection of antiprotons and to minimize the atmospheric background. The measured antiproton-to-proton ratio was $(2.2 \pm 0.6) \times 10^{-4}$ [17].

Figure 8 presents the data obtained in 1984 by R.L. Golden in comparison with the results of the experiments of the group of V.A. Romanov (1979) and of A. Buffington (1981) [11, 17, 132]. For convenience, the results of these measurements are summarized in Table 1. Reference [132] presents a detailed analysis of the energy dependence of the $\bar{p}/p$ ratio in the range 4.4–13.4 GeV and shows that the observed ratio substantially (at the level $< 10^{-4}$) exceeds the predictions of the standard ‘leaky-box’ model for a traversed matter thickness of 7 g cm^{-2} .

Subsequent measurements performed at the LPTI [128, 130] made it possible to conclude that there exists a kinematic cut-off of the antiproton spectrum at energies below 1 GeV, characteristic of their secondary origin in cosmic rays. These results contradicted the early data of Buffington’s group, a contradiction that was subsequently confirmed in the more accurate balloon experiments PBAR [18] and LEAP [19, 20]. It is worth noting that the data of Golden et al. [132] and the

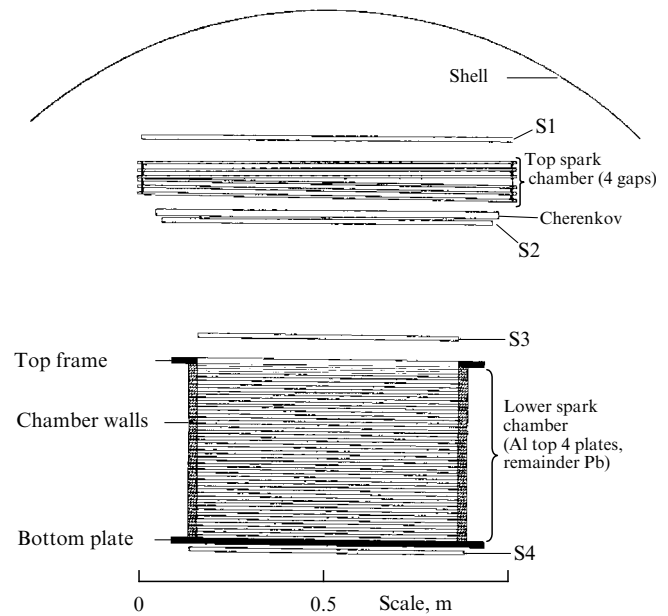


Figure 7. Layout of the detector used in Buffington’s experiment [17].

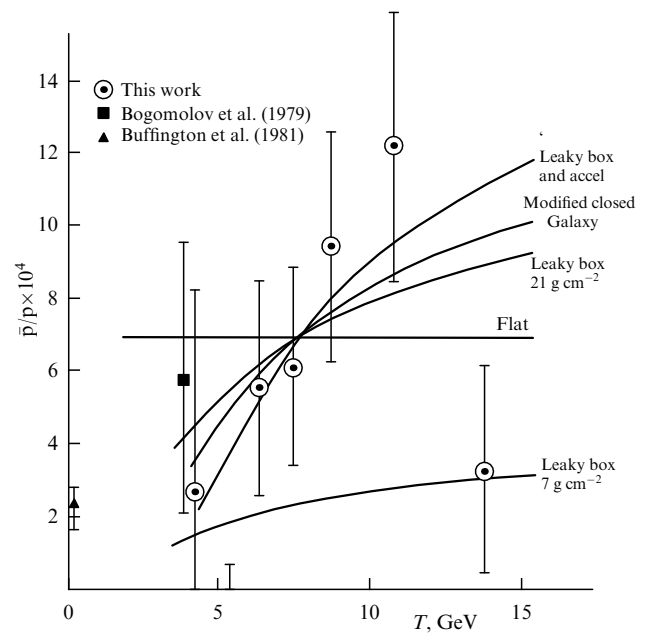


Figure 8. Antiproton-to-proton ratio measured by R.L. Golden in 1984 in comparison with the data of other experiments. The dashed curves show the predictions of various models [132].

Table 1. Comparison of measurements of the $\bar{p}/p$ ratio.

Measurement	Year	Energy range, GeV	Ratio $\bar{p}/p$
Bogomolov et al.	1979	2–5	$(6 \pm 4) \times 10^{-4}$
Golden et al.	1979	4.7–11.6	$(5.2 \pm 1.5) \times 10^{-4}$
Buffington et al.	1981	0.13–0.32	$(2.2 \pm 0.6) \times 10^{-4}$
Bogomolov et al.	1987	0.2–2	$(0.6^{+1.4}_{-0.5}) \times 10^{-4}$

LPTI results (Bogomolov et al. [128, 130]) are statistically compatible (within the errors) in the overlapping range 2–5 GeV and also complement each other in the non-overlapping energy ranges, which made it possible to explain the origin of cosmic antiprotons. Thus, Golden at intermediate energies (4–13 GeV) and Romanov’s group at low energies (0.2–2 GeV) jointly refuted Buffington’s results and sup-

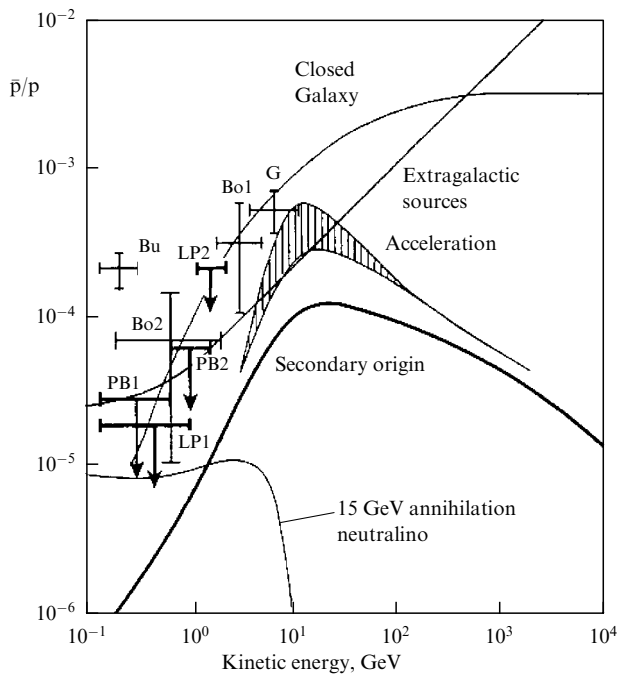


Figure 9. Upper limits on the ratio of antiproton and proton fluxes and comparison with theoretical models and other experiments [18–20]. The PBAR results are denoted PB1, PB2; the LEAP results are denoted LP1 and LP2.

ported the hypothesis of secondary generation with modifications of the propagation model (in particular, with the mean matter thickness increased to 21 g cm^{-2}).

The development of these studies stimulated interest not only in the problem of the baryon asymmetry of the Universe, but also in the fundamental mechanisms of cosmic ray generation, including a possible contribution from the annihilation of dark matter particles. Figure 9 shows a comparison of various theoretical predictions with the experimental data, including Golden's results. In particular, the 'leaky-box' model with an increased matter thickness ($\sim 21 \text{ g cm}^{-2}$) and the modified closed-Galaxy model [136] describe the observed excess of antiprotons better.

The experiments of Romanov, Golden and Buffington made it possible not only to detect antiprotons in cosmic rays reliably for the first time, but also to lay the foundation for sub-sequent high-precision measurements. These works played a key role in the development of modern ideas about the mechanisms of generation and propagation of cosmic rays in the Galaxy.

3. Observations of antiprotons with energies from tens of MeV to hundreds of GeV in cosmic rays

The PBAR magnetic spectrometer performed measurements over a wide energy range from 100 to 1580 MeV inclusive in Canada in 1987. The balloon flight was carried out at an altitude of 36 km over 10.5 hours, and the density of the residual atmosphere was 4.8 g cm^{-2} . From the data of the PBAR experiment, upper limits on the ratio of antiproton to proton fluxes were obtained in two energy ranges: from 100 to 640 MeV— 2.8×10^{-5} , and from 640 to 1580 MeV— 6.1×10^{-5} [18].

The LEAP (Low Energy AntiProton) experiment was aimed at studying the flux of cosmic antiprotons in the

Table 2. Upper limit for the $\bar{p}/p$ ratio.

Measurement	Energy range, GeV	Upper limit for $\bar{p}/p$
PBAR	0.10–0.64	2.8×10^{-5}
PBAR	0.64–1.58	6.1×10^{-5}
LEAP	0.60–1.20	2.3×10^{-4}

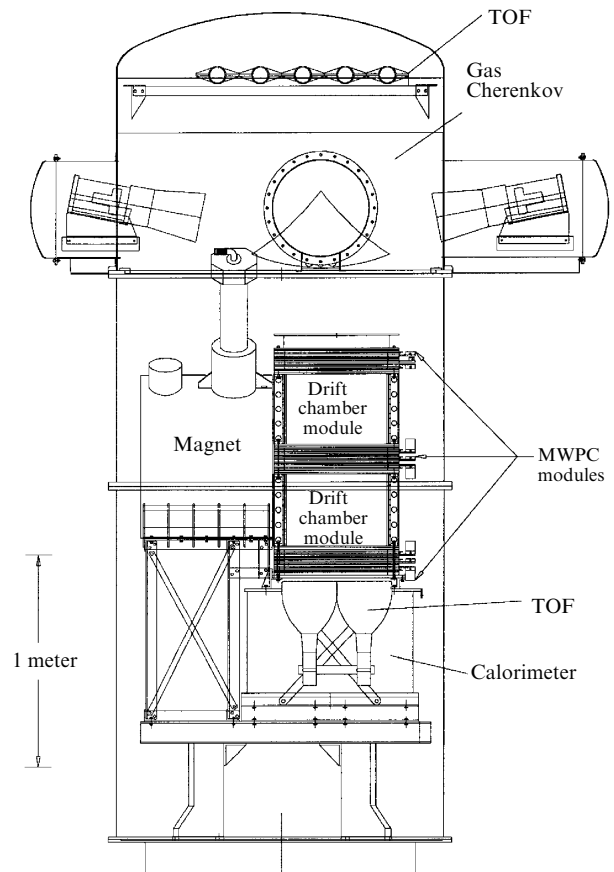


Figure 10. Layout of the MASS91 spectrometer [137, 138].

energy range 600–1200 MeV. The main detectors of LEAP were a magnetic spectrometer, a time-of-flight system and Cherenkov counters. From the data of the LEAP experiment an upper limit on the ratio of antiproton to proton fluxes of 2.3×10^{-4} was obtained [20].

The results of the PBAR and LEAP experiments are upper limits on the ratio of antiproton to proton fluxes, which are presented in Fig. 9 and summarized in Table 2. It was noted that the limit obtained is consistent with models of the secondary production of antiprotons (the 'leaky-box' model). At that time this was the most stringent upper limit on the $\bar{p}/p$ ratio.

Antiprotons were expected to be produced as secondary products of the interaction of primary cosmic-ray nuclei (mainly protons) with the interstellar medium. The first measurements of cosmic-ray antiprotons [17, 128, 132], however, showed higher fluxes than were predicted by the contemporary models of secondary production. In the high-energy region this feature of the antiproton flux behavior manifests itself more markedly, as will be shown below.

Several subsequent experiments were built on the basis of LEAP and consisted in the modernization of individual detector systems [137–140].

In 1991, on the basis of LEAP, the balloon experiment MASS91 (Fig. 10) was carried out, which included the

Table 3. Antiproton fluxes measured in the MASS91 experiment.

Energy range, GeV	Antiproton flux, $\times 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$
3.7–6.3	$8.2^{+10.3}_{-6.6}$
6.3–11.6	$4.2^{+4.2}_{-2.7}$
11.6–24.1	$2.1^{+1.7}_{-1.1}$

following detectors: a powerful magnetic spectrometer, a time-of-flight system, a Cherenkov counter and a three-dimensional calorimeter—all components working together for the accurate identification of antiprotons [137, 138].

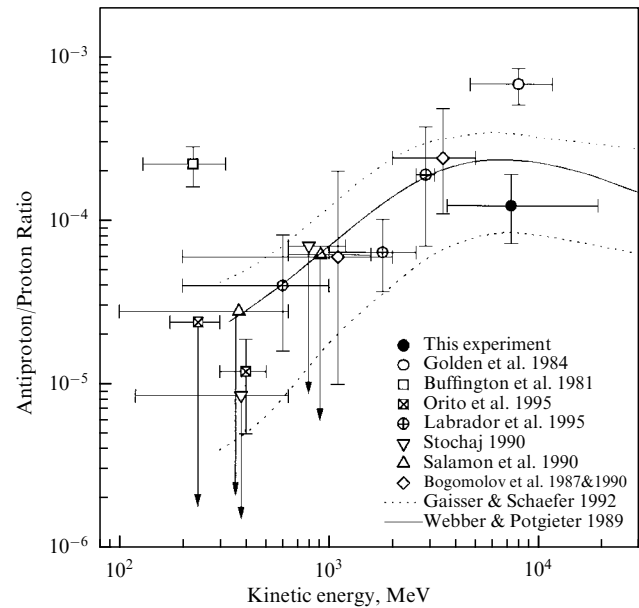
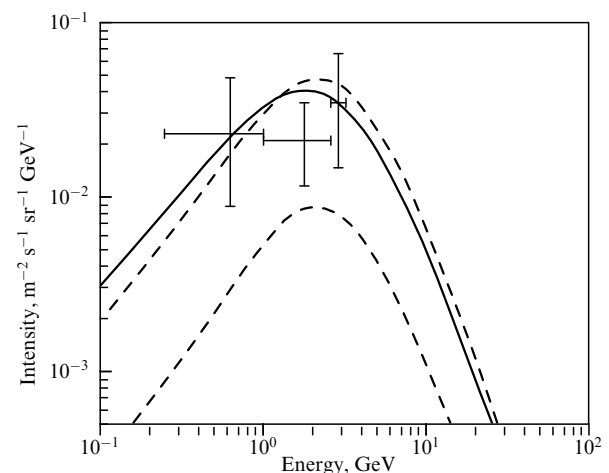
The magnetic spectrometer consisted of a superconducting magnet with a field strength of 2.2 T and a hybrid tracking system including two drift-chamber modules and eight planes of multiwire proportional chambers. The time-of-flight (ToF) system comprised two planes of plastic scintillators forming the data-acquisition trigger upon coincidence of the signals. These signals made it possible to measure the direction and velocity of the particle and to analyze the pulse amplitude in order to estimate the ionization losses. The time-of-flight system had a time resolution of 370 ps, which made it possible to separate albedo particles reliably. A Cherenkov detector installed beneath the upper ToF plane separated light particles (muons, electrons, positrons) from the heavier protons and antiprotons. A position-sensitive calorimeter was located beneath the lower scintillator and consisted of 40 layers of brass streamer tubes (7.33 radiation lengths). The tubes in alternating layers were arranged perpendicular to one another in order to obtain a three-dimensional image of the particle passing through the calorimeter. In this way the separation of electromagnetic and hadronic showers was ensured. The combination of the signals from the calorimeter and the Cherenkov detector helped to separate antiprotons from background electrons.

In the MASS91 experiment [137], in the energy range 3.7–19 GeV, 11 antiprotons and 69311 protons were recorded, corresponding to a ratio $\bar{p}/p = 1.24^{+0.08}_{-0.51} \times 10^{-4}$. In a later analysis of the MASS91 data [138] over the extended range 3.7–24.1 GeV, 15 antiprotons were found and their fluxes were measured; these are presented in Table 3.

The results of the MASS91 experiments [137, 138] confirm that the observed antiproton flux corresponds to their secondary origin as a result of the interaction of cosmic rays with the interstellar medium. This is consistent with the calculations of Gaisser and Schaefer (1992) [141] and of Webber and Potgieter (1989) [142], based on the standard propagation model ('leaky box') (Fig. 11).

The results of a similar balloon experiment, IMAX, were presented in 1996 for the energy range 0.25–3.2 GeV [139]. Measurements of the magnetic rigidity, of the ionization energy losses in the detectors and of the velocity were used to identify particles by charge and mass. According to the results obtained, the antiproton flux is consistent with the secondary nature of antiprotons and does not require exotic sources (Fig. 12).

During the minimum of solar activity (August 1994) the balloon experiment CAPRICE was carried out to measure the flux of cosmic antiprotons in the energy range from 0.62 to 3.19 GeV [140]. The flight was performed at an altitude of approximately 37 km, where the influence of the atmosphere is minimal. The apparatus consisted of a ring-imaging Cherenkov detector (RICH), a time-of-flight system (ToF), a magnetic spectrometer with drift and multiwire chambers, and a silicon-tungsten electromagnetic calorimeter. For the

**Figure 11.** Antiproton-to-proton ratio measured in the MASS91 experiment [137], in comparison with other experimental data and with the calculations of Gaisser and Schaefer (1992) (dashed lines) [141] and of Webber and Potgieter (1989) (solid line) [142].**Figure 12.** Antiproton flux measured by IMAX, together with the interstellar antiproton spectrum of Webber and Potgieter (solid curve) [142] and the spectrum limits of Gaisser and Schaefer (dashed curves) [141].

first time in the practice of balloon experiments on the study of cosmic rays, a combination of a ring-imaging Cherenkov detector and a calorimeter was applied, which made it possible to increase the efficiency of antiproton identification against the background of light negative particles—electrons, muons and pions.

The measurements established that the ratio of antiproton to proton fluxes increases in the range of kinetic energies from 0.6 to 3.2 GeV. This confirms the hypothesis of the secondary origin of antiprotons—their generation occurs as a result of the interactions of primary cosmic particles with the interstellar medium. The combined spectrum constructed from the results of various measurements [132, 137, 139], however, admits the possibility of a more rapid growth of the $\bar{p}/p$ ratio with energy than is predicted by the classical models of secondary origin [141] (Fig. 13).

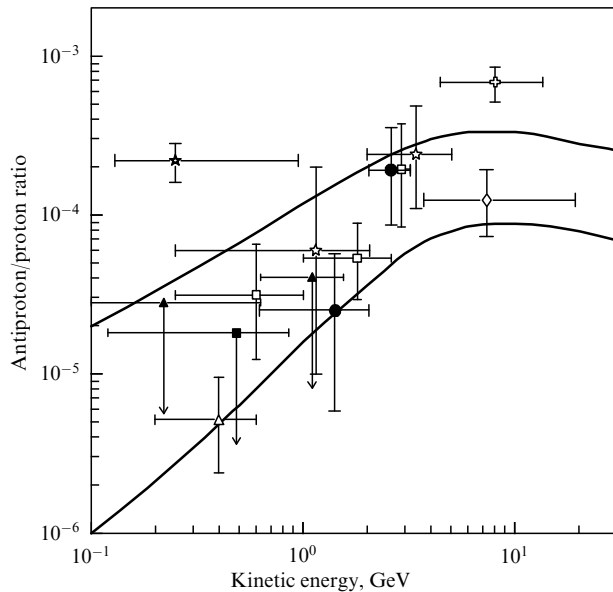


Figure 13. Spectrum of the $\bar{p}/p$ ratio in the upper layers of the atmosphere according to balloon experiments: open crosses — results of Golden et al. [132]; filled stars — measurements of A. Buffington [17]; open stars — measurements of Romanov's group [130, 131]; open squares — data of the IMAX experiment [139]; open triangles — data of the BESS experiment [29]; filled circles — CAPRICE [140]; solid lines — maximum and minimum of the $\bar{p}/p$ ratio calculated by Gaisser and Schaefer [141].

The CAPRICE experiment was continued as CAPRICE-98 [143], which extended the antiproton measurements to higher energies and showed that the $\bar{p}/p$ ratio grows insignificantly in the range up to ~ 50 GeV, but without a significant deviation from the model of secondary origin at the current statistics. This growth left open the possibility of a small contribution from primary sources; the data obtained, however, can also be described without such a contribution. In parallel, in the same years (mid- to late 1990s), the balloon experiment HEAT-bar [144] recorded for the first time an anomalous excess of positrons — a point substantially exceeding the prediction of secondary origin. This was perceived as a possible signal of exotic processes, since positrons and antiprotons can potentially be formed as a result of dark matter annihilation. The results of the CAPRICE-98 and HEAT-bar experiments generated increased interest in this hypothesis. Although this feature was subsequently not confirmed in the antiproton flux, interest in antiprotons did not wane, which promoted the development of new experiments (such as BESS, AMS and PAMELA), which are described below in Section 3.1.

In parallel with the experimental achievements, in 1998 the work of M. Simon et al. [145] was published, presenting improved theoretical calculations of the flux of secondary antiprotons in the interstellar medium. They were based on the standard ‘leaky-box’ model of cosmic ray propagation, but with a number of important improvements:

- new proton and helium spectra measured by the IMAX instrument were used [139, 146];
- the Monte Carlo model DTUNUC was applied to simulate nuclear interactions [147];
- the energy changes of antiprotons during their propagation were taken into account: non-annihilating interactions and elastic scattering [145].

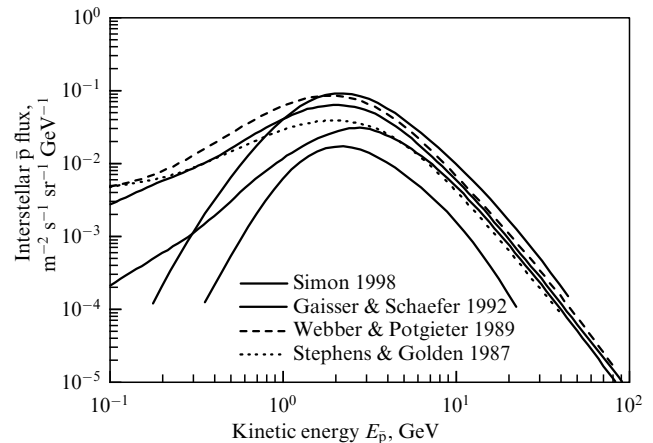


Figure 14. Comparison of the $\bar{p}$ spectrum obtained from the calculations of M. Simon et al. [145] with earlier theoretical results [123, 141, 142].

Figure 14 shows a comparison of the antiproton spectrum calculated in Ref. [145] with previous theoretical models [123, 141, 142]. The band bounded by the two solid lines reflects the range of uncertainty associated with the differences between models of cosmic ray propagation in the Galaxy. These models describe the mean amount of matter traversed by the particles before they leave the region where their interactions with the interstellar gas are possible. The greater this distance, the greater the probability that a primary cosmic proton will produce a secondary antiproton. The upper boundary of the region corresponds to calculations that take into account two key processes changing the energy of antiprotons during their propagation: elastic scattering and non-annihilating collisions with nuclei of the interstellar medium. In these interactions the antiproton is preserved, but its energy changes — mainly it decreases, which is particularly significant at low energies. Allowance for these processes leads to an increase of the antiproton flux at low energies. The lower boundary corresponds to a model in which such processes are ignored and the flux is formed only by the primary interactions of protons without subsequent reprocessing of the spectrum. Comparison with the theoretical models constructed earlier by Gaisser and Schaefer (1992) [141], Webber and Potgieter (1989) [142], and Stephens and Golden (1987) [123] shows that Simon's calculations (1998) [145] give less overestimated flux values at low energies; at energies above 1 GeV, however, the predictions of the new and old models converge, confirming the robustness of the theoretical approach in this region.

Figure 15 presents a comparison of the theoretical antiproton-to-proton ratio, obtained at the top of the atmosphere after allowance for solar modulation, with the experimental data available at the time of publication of Ref. [145]. The calculated ranges cover the key sources of uncertainty: variations in the parameters of particle propagation in the Galaxy, differences in the nuclear cross sections for antiproton production, and the influence of solar activity. The solid lines display the combined range of these uncertainties.

The dashed curves illustrate the sensitivity of the $\bar{p}/p$ ratio to a change of the level of solar modulation: the upper line corresponds to high values of the modulation potential ($\phi = 1000$ MV), the lower one to minimum conditions ($\phi = 500$ MV). It can be seen that the experimental points obtained in the CAPRICE [140], BESS [29], IMAX [139] and other experiments generally fall within the calculated range,

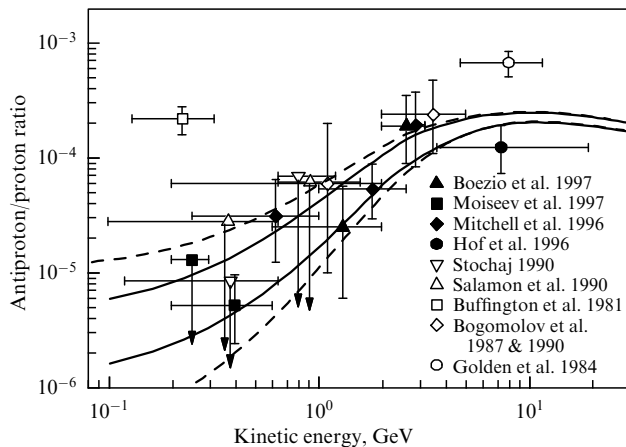


Figure 15. Comparison of the theoretical calculation of the $\bar{p}/p$ ratio [145] with the experimental data available at that time (CAPRICE [140], BESS [29], IMAX [139] and other experiments [17, 131, 132, 137, 158]). The region bounded by the two solid lines covers all the principal uncertainties considered in that work and was obtained for a solar modulation parameter $\phi = 750$ MV. The upper and lower dashed lines illustrate the sensitivity of this ratio to a change of the modulation parameter: at $\phi = 500$ MV the whole region shifts down to the lower dashed line, and at $\phi = 1000$ MV — up to the upper dashed line.

especially when the appropriate value of ϕ for each observation period is taken into account.

Thus, at the time of publication of Ref. [145] there was no need to invoke non-standard physical sources (for example, the annihilation of dark matter particles) to explain the observed antiproton flux. Nevertheless, the need to improve the accuracy and to extend the energy range of future measurements is emphasized, especially in the range above 10 GeV, where the differences between the models become more pronounced.

In the next section we consider the modern and prospective experiments designed to measure antiprotons in the composition of the galactic component of the cosmic rays and of the Earth's albedo.

3.1 Antiprotons in galactic cosmic rays

Most modern experiments on the search for antiprotons use multicomponent detector systems, which as a rule include a

superconducting magnetic spectrometer for determining the sign of the charge and the magnetic rigidity of the particle.

3.1.1 BESS. The first precision measurements of antiproton spectra were performed in the series of BESS (Balloon-borne Experiment with a Superconducting Solenoid) experiments. The BESS program [29, 149–153] was carried out with the aim of studying the origin and propagation of galactic and atmospheric cosmic rays. Within this program, 11 high-altitude balloon flights were performed between 1993 and 2008. Nine of them were carried out at northern latitudes over Canada (BESS 93–2002, BESS–TeV), and two others over Antarctica (BESS–Polar and BESS–Polar II). In each flight the detector configuration was modified and improved, which made it possible to increase the statistics of recorded antiprotons and to extend the energy range.

The BESS instrument is a magnetic spectrometer with a large geometric factor, employing a thin superconducting solenoidal magnet [154] and a tracking system with a high-resolution drift chamber [151]. The spectrometer is equipped with a time-of-flight (ToF) system and a Cherenkov counter based on silica gel and aerogel (ACC).

In the BESS configurations up to 2004 all the detectors and the magnet are located in a cylindrical shell under a pressure of 1 atmosphere, as shown in Fig. 16. The horizontal configuration allows the spectrometer to be compact and to have a wide aperture with a geometric factor of $0.3 \text{ m}^2 \text{ sr}$.

On entering the instrument, a particle passes through a constant field of 1 T created by a thin superconducting solenoid [154, 155]. The trajectory of the particle is recorded by the JET drift chamber, providing a spatial resolution of $200 \text{ }\mu\text{m}$ in the bending plane, and also by additional inner (IDC) and outer (ODC) drift chambers with a similar resolution in the bending plane and a resolution improved to $350 \text{ }\mu\text{m}$ along the longitudinal z axis. These chambers are used for the preliminary reconstruction of tracks. The maximum detectable rigidity (MDR) up to the year 2000 was 200 GV.

The first results of the BESS experiment, conducted in 1993, were published in 1995 [28]. The paper reported the detection of four antiprotons in the energy range from 300 to 500 MeV, which were for the first time identified by means of momentum and velocity measurements, allowing the particle masses to be determined unambiguously. In the lower energy range from 175

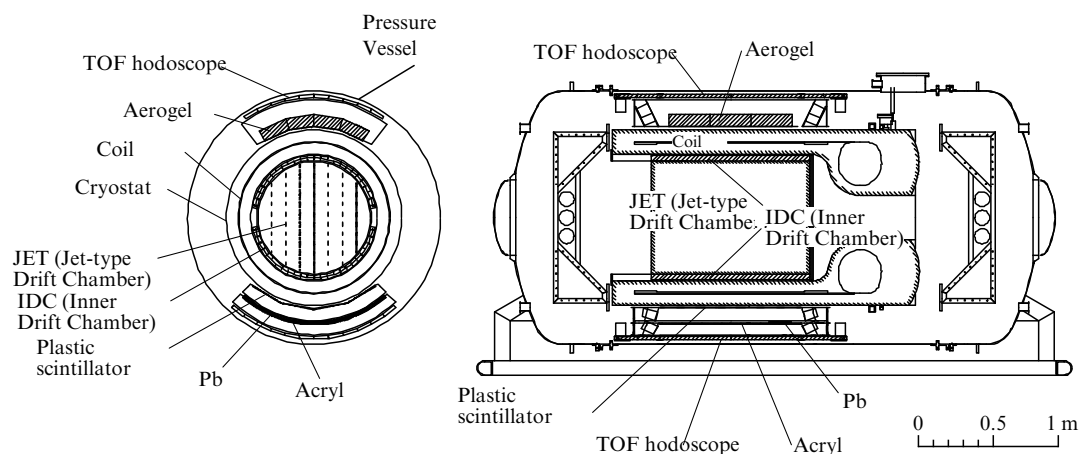


Figure 16. Cross-sectional layout of BESS: JET drift chamber, time-of-flight system (ToF), aerogel Cherenkov counter (ACC), inner drift chamber (IDC), outer drift chamber (ODC) [151].

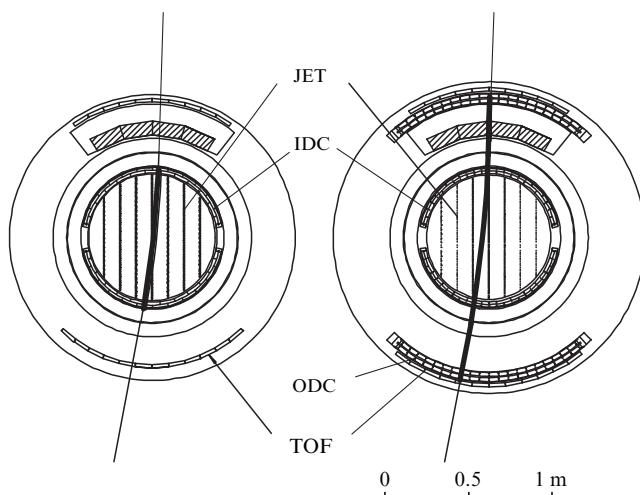


Figure 17. Layout of the BESS-TeV experiment in comparison with BESS-98 [156].

to 300 MeV no antiprotons were observed, but an upper limit on the ratio of antiproton to proton fluxes was obtained, equal to 2.9×10^{-5} , while for the full energy range this limit was $8.9_{-4.7}^{+7.9} \times 10^{-6}$. Later, in 1997, 7 antiprotons were recorded, and from this statistics the antiproton flux was reconstructed, amounting to $6.4_{-3.5}^{+5.5} \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$, as well as the antiproton-to-proton ratio in the energy range from 200 to 600 MeV: $5.2_{-2.8}^{+4.4} \times 10^{-6}$ [29].

In order to describe the whole of the BESS series of experiments, mention must also be made of BESS-TeV, which was an improved version of the BESS spectrometer implemented in 2002–2003. The aim of the upgrade was to extend the range of measurable rigidities and to increase the resolution of the tracking system for precision measurements of the spectra of protons, helium nuclei and atmospheric muons up to hundreds of GeV and above. One of the main purposes of BESS-TeV (Fig. 17) was the measurement of primary cosmic ray fluxes in the high-energy region up to 1 TeV [152]. To this end the JET drift chamber and the inner drift chambers (IDC) were improved, which increased the number of track points and improved the spatial resolution. In addition, new outer drift chambers (ODC) were installed, doubling the length of the measured track and providing higher accuracy in rigidity. As a result the maximum detectable rigidity rose to 1.4 TV [156], which made it possible for the first time to obtain accurate data on the spectra of protons (1–540 GeV), helium nuclei (1–250 GeV/nucleon) and atmospheric muons (0.6–400 GeV c^{-1}).

Although antiprotons in the TeV range were not measured in this experiment, BESS-TeV is of particular significance for the present review, since it was precisely this instrument that extended the energy range of the BESS experiments and initiated the antihelium search program [157] (see Section 5 for details).

The most advanced detector in the BESS program was the BESS-Polar instrument [151, 158–160], developed specifically for long-duration flights over Antarctica under conditions of minimal geomagnetic cut-off in order to measure the spectra of low-energy particles and antiparticles of the galactic cosmic rays. The main goal of the BESS-Polar project was to clarify the possible presence of an excess of low-energy antiprotons indicated by the data of the BESS 95+97 experiment [149], as well as to perform precision measurements of their energy spectrum in order to test models of the secondary origin of antiprotons. Additional tasks were the search for primary antiprotons from exotic sources, such as the evaporation of primordial black holes or dark matter annihilation, and the establishment of new limits on the antihelium content in cosmic rays (see Section 5 for details).

The relative arrangement of the detector systems of the spectrometer is presented in Fig. 18.

A uniform field of 0.8 T is created in a thin superconducting solenoid, whose design is described in Refs [162, 163], inside which a drift chamber with tracking detectors is located. The trajectory of the particles is reconstructed from 52 points with a resolution of the order of 140 μm in the bending plane, which made it possible to measure the magnetic rigidity with a resolution of 0.4% for 1 GV protons; the maximum detectable rigidity was 240 GV [164]. The geometric factor reached 0.3 $\text{m}^2 \text{ sr}$, which, combined with the long data-acquisition time, provided record statistics.

The upgrades, the energy range and the number of recorded antiprotons in chronological sequence were presented at the European Cosmic Ray Symposium in 2010 and are shown in Fig. 19.

The BESS-Polar program comprised two Antarctic flights, BESS-Polar I and BESS-Polar II. The BESS-Polar I flight (2004) lasted 8.5 days and recorded 900 million events, including ~ 1500 antiprotons in the energy range from 0.1 to 4.2 GeV [158]. Later the BESS-Polar II experiment was carried out, whose flight took place from December 2007 to January 2008, collecting data over a record 24.5 days and recording 4.7 billion events, of which ~ 8000 were antiprotons [164, 165]. Thanks to the low geomagnetic cut-off near the South Pole, BESS-Polar was able to perform statistically well-supported measurements of the low-energy antiproton flux. The flight trajectories and the geomagnetic cut-off rigidities are presented in Fig. 20.

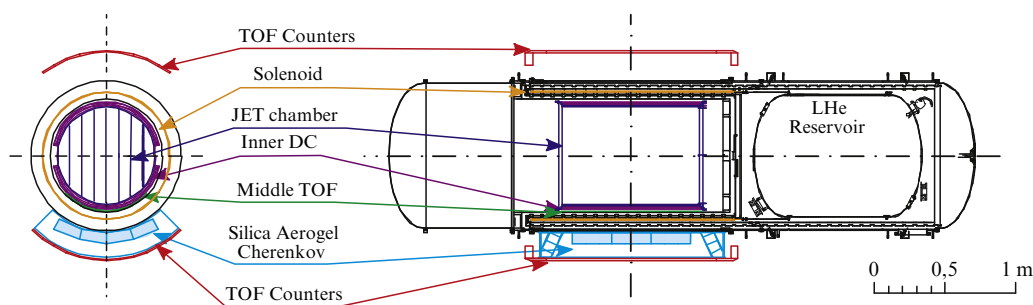


Figure 18. Cross-sectional layout of the BESS-Polar spectrometer [161].

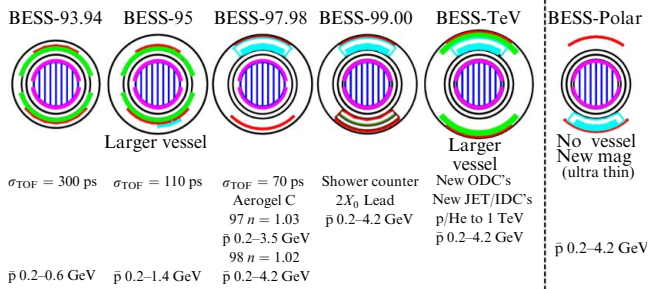


Figure 19. History of the BESS experiments, including BESS-Polar [165].

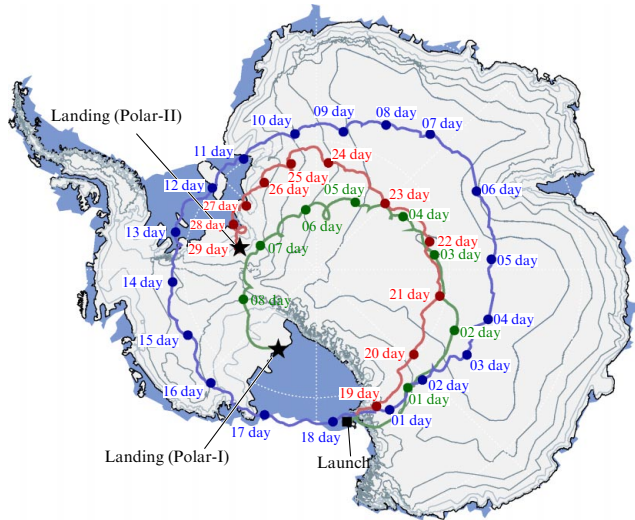


Figure 20. Flight trajectories over Antarctica of BESS-Polar I in 2004 (green) and BESS-Polar II in 2007–2008 (first pass—blue, second—red) [165].

Figure 21 shows the antiproton spectrum measured in the BESS-Polar II experiment [164] in comparison with the previous BESS 95 + 97 experiments [149], the satellite experiments PAMELA [166] and AMS-02 [15], and with theoretical calculations for the period of solar activity minimum. The BESS-Polar II antiproton flux agrees well with the PAMELA result. The difference in fluxes between BESS-Polar II and AMS-02 could arise from measurements in different phases of the solar cycle [160].

It is important to note that the BESS-Polar II flight [165] was carried out practically at the minimum of solar activity (Fig. 22), when the conditions are most favorable for detecting low-energy particles of the primary cosmic radiation, in particular antiprotons, since the influence of solar activity is minimal. Moreover, the BESS experiments have created the possibility of studying the effect of solar modulation as a whole, since their measurements cover practically a full cycle of solar activity (see Fig. 22). Solar modulation is caused by the interaction of cosmic rays with the magnetic field of the Sun, carried into interplanetary space by the solar wind. The polarity of the solar magnetic field, which changes roughly every 11 years, is of substantial importance here, and it is precisely this that makes it possible, on the basis of measurements of the ratio of antiproton and proton fluxes, to study the dependence of solar modulation on the sign of the charge [150, 167].

In the BESS experiments conducted in 1999 and 2000, during the maximum of solar activity and the reversal of the polarity of the solar magnetic field, a charge dependence of

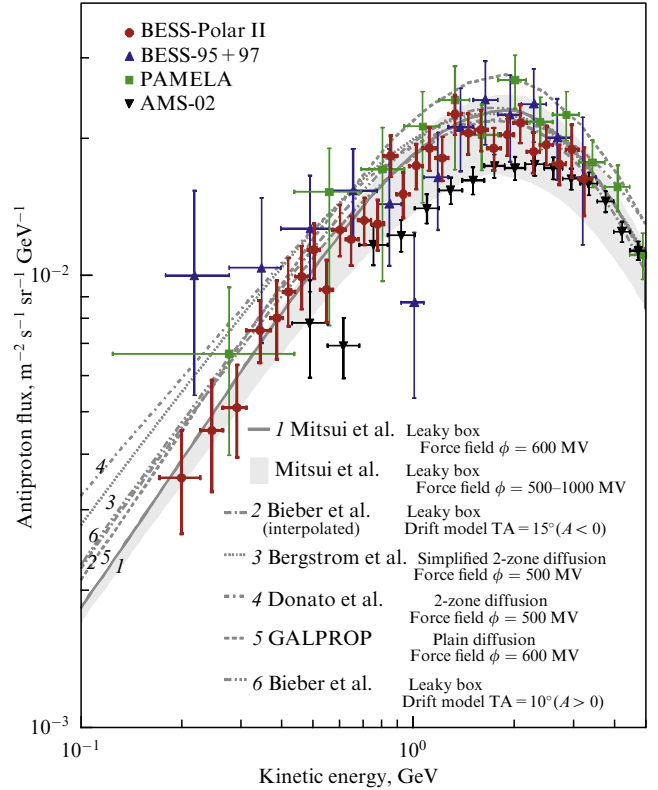


Figure 21. Antiproton flux in the composition of the galactic cosmic rays measured in the BESS-Polar II, BESS 95 + 97, PAMELA and AMS-02 experiments [160].

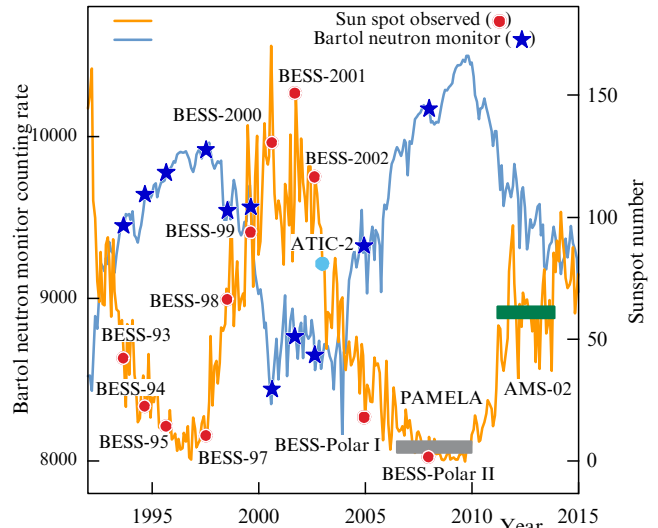


Figure 22. Solar activity during the BESS experiments. Red circles denote the BESS and BESS-Polar flights corresponding to particular years. Blue asterisks are the neutron-flux measurements obtained from the Bartol Neutron Monitor [160].

the modulation was discovered [150]. The ratio of antiproton to proton fluxes was measured in 1999 (before the field reversal) and in 2000 (after it) in the energy range from 0.18 to 4.2 GeV. The measurements showed that this ratio remained stable before the reversal, but after the change of polarity (2000) a sharp increase of the ratio of antiproton to proton fluxes was observed, which is consistent with the drift model [167], in which antiprotons and protons move along different paths in the heliospheric magnetic field [150].

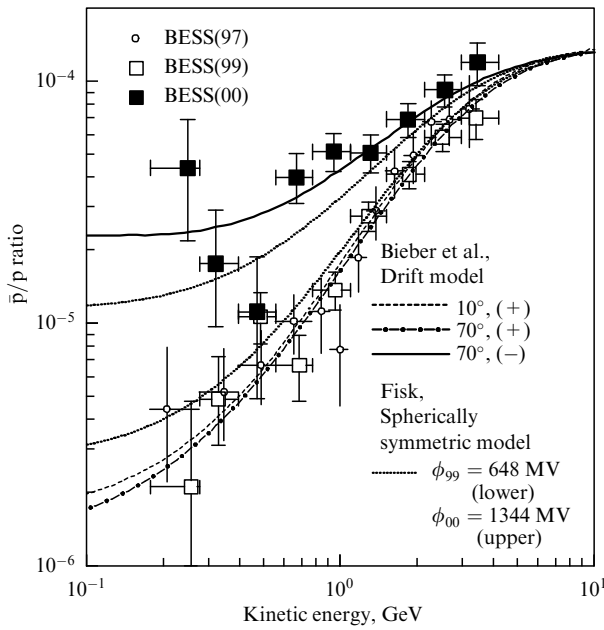


Figure 23. Ratio of antiproton and proton fluxes in the GCRs measured by the BESS spectrometer in 1997, 1999 and 2000 [150], in comparison with theoretical models [167, 169].

Figure 23 presents the measured values of the $\bar{p}/p$ flux ratio and the theoretical predictions. The spherically symmetric model [168] explains the increase of the antiproton-to-proton ratio near the maximum of solar activity mainly through a decrease of the proton flux, whereas the drift model [167] predicts a much more pronounced increase of this ratio, caused precisely by the dependence on the sign of the charge. As can be seen from the BESS data shown in Fig. 23, the observed values of the ratio of antiproton and proton fluxes $\bar{p}/p$ agree far better with the drift model.

The BESS-Polar I (2004) and BESS-Polar II (2007–2008) experiments [165] were carried out near the minimum of solar activity and the beginning of a new positive cycle (see Fig. 22). In particular, in BESS-Polar I the comparison of the proton and antiproton fluxes recorded within one and the same flight made it possible to exclude variations associated with external conditions and to interpret the data obtained reliably [162, 170].

Figure 24 presents the measurements of the $\bar{p}/p$ flux ratio performed in BESS [171] and BESS-Polar I [170], as well as the calculations from the drift model for various values of the tilt angle of the heliospheric current sheet [30, 167].

Of particular significance are the data obtained during the transition period of the polarity reversal (1999–2000) and during the solar minimum (2007–2008), when the influence of modulation on antiprotons becomes minimal. The results of these observations confirm the presence of a charge asymmetry and agree well with drift models, in particular with the model proposed by Bieber et al. [167], as well as with the calculations for a tilted current sheet with the parameter α [30]. This agreement is critically important for the correct reconstruction of the interstellar antiproton spectrum and, consequently, for the identification of possible primary sources of antimatter, such as evaporating primordial black holes or dark matter annihilation.

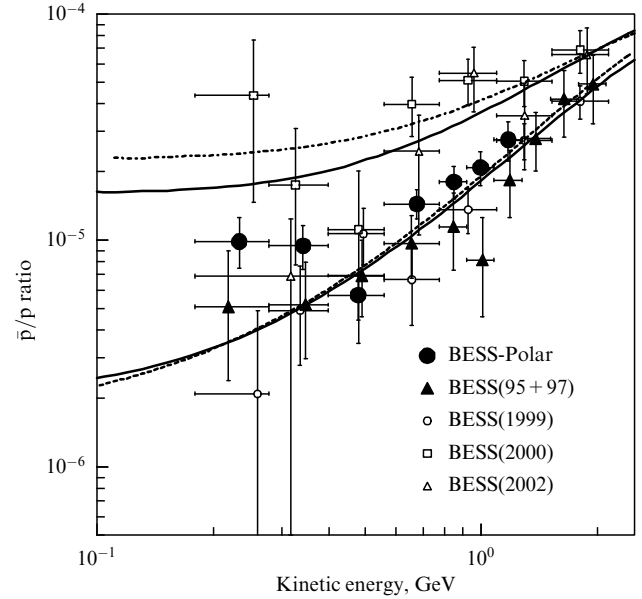


Figure 24. Ratio of antiproton and proton fluxes ($\bar{p}/p$) measured by the BESS (1995 and 1997) and BESS-Polar I (2004) experiments [170], in comparison with drift-model calculations for various tilt angles of the heliospheric current sheet. The curves from top to bottom at 0.7 GeV correspond to: $A < 0$ and 65° (dash-dotted), $A < 0$ and 25° (solid), $A > 0$ and 65° (dashed), $A > 0$ and 15° (solid). The calculations were performed according to the model of Moskalenko et al. [30].

3.1.2 HEAT-pbar. The balloon experiment HEAT-pbar [172] was conducted in 2000 and provided one of the first accurate measurements of the antiproton flux in the energy range from 4 to 50 GeV. The detector consisted of a superconducting magnet with a drift-tube hodoscope at its center, combined with a set of multiwire proportional chambers above and below the hodoscope (Fig. 25). Two layers of scintillators, one at the very top and the other at the very bottom of the instrument, provided the time-of-flight measurement and, together with the scintillator located directly above the hodoscope, formed the event trigger.

During the flight, which took place at an altitude where the residual atmosphere amounted to 7.2 g cm^{-2} , 71 antiprotons were recorded, which made it possible to determine reliably the ratio of antiproton and proton fluxes ($\bar{p}/p$). The experiment showed that $\bar{p}/p$ does not increase with energy and remains at a level corresponding to models of the secondary origin of antiprotons [30, 145, 172]. In the last energy bins the observed values of the ratio turned out to be smaller than those measured in the CAPRICE experiment [143], removing the need to invoke the mechanisms of primary origin discussed earlier.

Figure 26 presents the experimental results of the measurements of the ratio of antiproton and proton fluxes in cosmic rays. The plot includes the results of the HEAT-pbar [172], BESS [149], CAPRICE [143], MASS91 [137] and IMAX [139] experiments, as well as theoretical predictions for different scenarios of the origin of antiprotons.

Despite the fact that the results of balloon experiments remain contradictory (see Fig. 26) and do not allow an unambiguous conclusion about the nature of the origin of cosmic antiprotons, in some of them evidence has been found for a possible contribution of additional, non-secondary, sources of antiparticles [143]. Nevertheless, the short duration of balloon experiments and the presence of the residual atmosphere did not permit observations to be advanced in

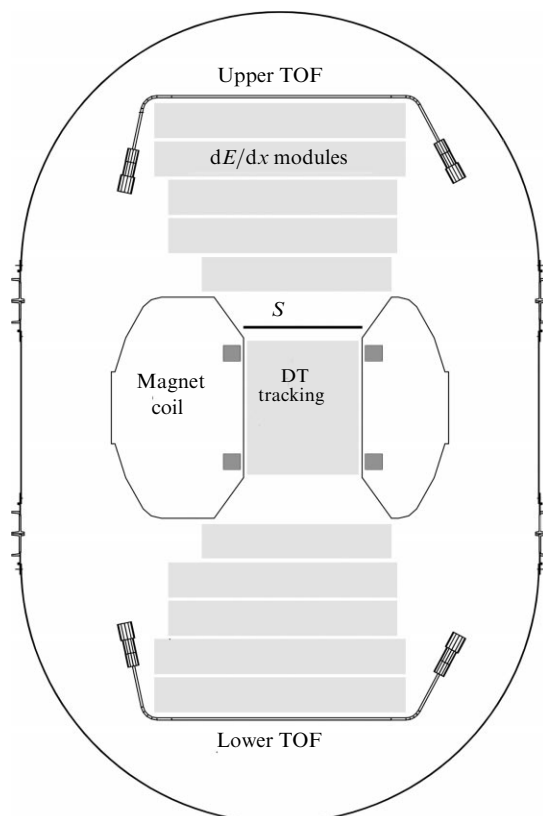


Figure 25. Layout of the HEAT-pbar magnetic spectrometer [172].

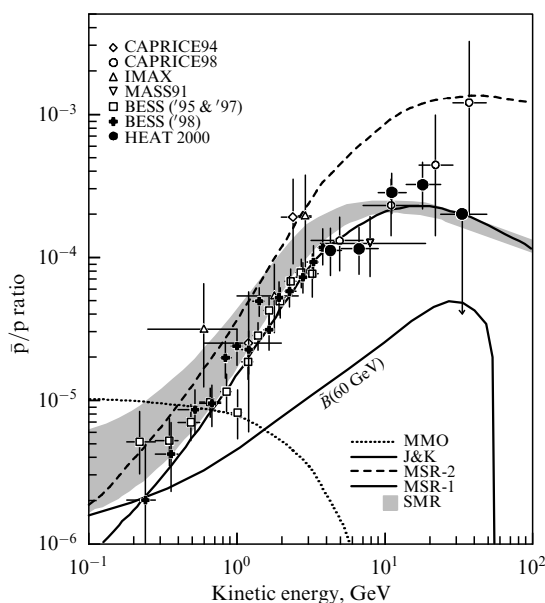


Figure 26. Ratio of antiproton and proton fluxes measured in the HEAT-pbar experiment, in comparison with the results of other experiments and with models of primary and secondary production [172].

energy beyond ~ 50 GeV. Taken together, these factors hamper the reconstruction of the energy spectrum, especially at high energies, and hence the testing of theoretical models of the origin of antiprotons.

3.1.3. AMS-01. The next stage in the study of cosmic antiparticles was the development of orbital missions, such as AMS and PAMELA, equipped with high-precision

measuring apparatus and placed in near-Earth orbit. Direct measurements in space provide a number of key advantages over balloon experiments: a significantly greater exposure and duration of observations (in the PAMELA and AMS-02 experiments), the absence of a residual atmosphere above the detector, which eliminates the background of secondary atmospheric particles, and the possibility of detecting particles over a wider energy range—up to hundreds of GeV. This opened up the possibility of testing models of the origin of antiparticles and of imposing constraints on the scenarios of their origin.

The AMS (Alpha Magnetic Spectrometer) experiment was aimed at investigating antiparticles in cosmic rays and was carried out in June 1998 on the STS-91 flight [173]. The schematic representation of the scientific apparatus in the bending projection (Fig. 27) shows the magnet, the tracking system (tracker), the time-of-flight counters, the Cherenkov detector and the anticoincidence detector.

The geometric factor of the spectrometer is $0.3 \text{ m}^2 \text{ sr}$. The trajectory of a charged particle passing through the magnetic field created by a permanent magnet of strength 0.14 T was recorded by the tracker, consisting of 6 planes of double-sided silicon microstrip detectors. From the curvature of the trajectory the magnetic rigidity of the particle and the sign of its charge were determined. The resolution of the time-of-flight system was 115–125 ps, depending on the length of the particular counter. The velocity measurements were performed independently by the time-of-flight system based on scintillation detectors and by the Cherenkov detector. The scintillation counters of the anticoincidence detector cover the inner surface of the magnet and serve to suppress background events.

As a result of the analysis performed, 186 ± 28 antiprotons were recorded in the AMS-01 experiment [173]. From these data, allowing for the geometric factor, the detection efficiency, the observation time and the spectrum reconstruction procedure (unfolding), the flux of primary antiprotons was obtained as a function of kinetic energy. Figure 28 presents a comparison of this flux with the data of the BESS 95 + 97 experiment [149].

The AMS-01 [173] and BESS spectra agree within the errors in the energy range from 0.5 to 2 GeV. Since both of these experiments were conducted under conditions of solar minimum, this minimizes the influence of solar modulation and makes it possible to compare the data directly. AMS-01 confirmed that at the minimum of solar activity (1995–1998) the shape and magnitude of the antiproton spectrum near 2 GeV remain practically unchanged, which corresponds to the predictions of models of solar modulation, for example the models of Fisk and of Simon with the parameter $\phi = 500 \text{ MV}$ [145, 169].

In the antiproton spectrum obtained in AMS-01 no excess at low energies is observed, which imposes constraints on the contribution of primary sources, such as dark matter annihilation or the evaporation of primordial black holes [40, 174], and points to their secondary origin. Thus, the results of AMS-01 strengthened confidence in the models of secondary origin and of solar modulation, and served as a basis for the subsequent precision measurements in the PAMELA and AMS-02 experiments.

3.1.4 PAMELA. In 2006 the satellite experiment PAMELA [14, 166, 175] began operation, intended for the study of the fluxes of charged particles in the cosmic radiation, with

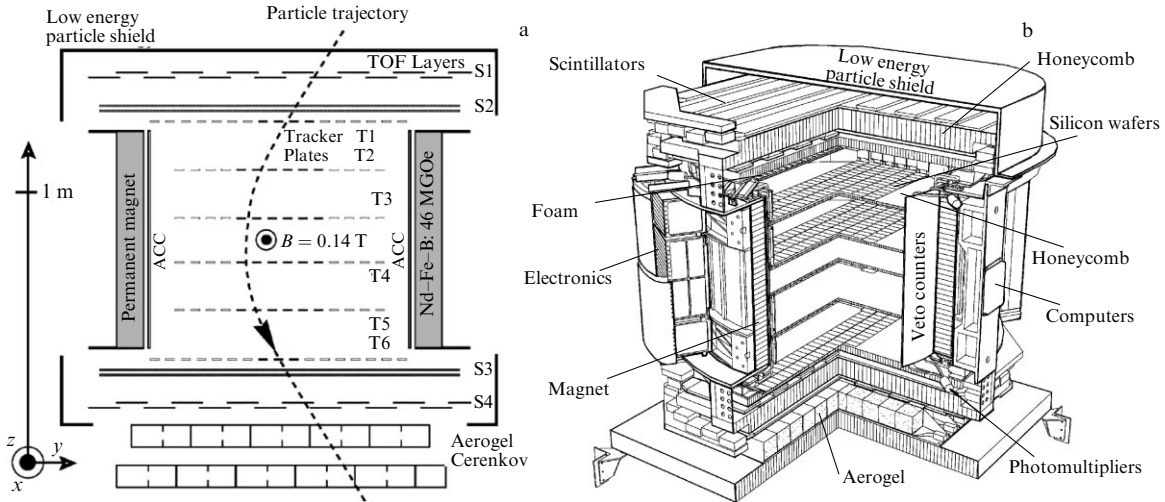


Figure 27. Schematic representation of the AMS-01 spectrometer on STS-91. (a) Permanent magnet, planes T1–T6 of the silicon microstrip tracker, time-of-flight counters S1–S4 (ToF), Cherenkov counter, anticoincidence counter (ACC) and low-energy particle shield (LEPS). (b) Isometric view of the AMS-01 detector. Some structural elements are shown, such as the honeycomb and foam, as well as the arrangement of the electronics boxes [173].

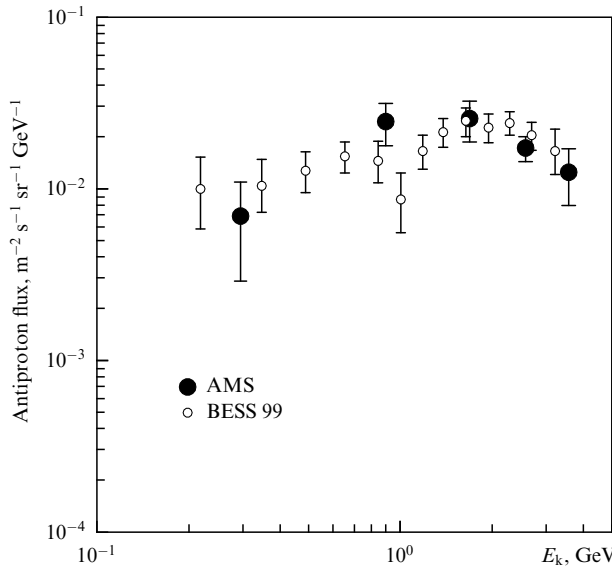


Figure 28. Antiproton flux according to AMS data in comparison with the BESS 99 measurements [173].

particular attention paid to the measurement of antiparticle fluxes. Among its main tasks were precision measurements of the energy spectra of antiprotons and positrons in the energy range from hundreds of MeV to hundreds of GeV in the primary cosmic radiation, as well as the search for antinuclei.

The PAMELA spectrometer includes a complex of detectors serving to identify the particle type and to measure the magnitude and sign of the charge, the rigidity, the velocity, the mass and the energy of the particles [176]. The scientific apparatus comprises: a magnetic spectrometer including a permanent magnet and a tracker; a position-sensitive electromagnetic calorimeter; a system of scintillation time-of-flight counters; a system of scintillation anticoincidence counters; a lower scintillation shower detector; and a neutron detector (Fig. 29).

The magnetic spectrometer contains a permanent magnet creating a field strength of 0.43 T, inside which a silicon tracking system with a geometric factor of $21.5 \text{ cm}^2 \text{ sr}$ and a maximum detectable rigidity of up to 1 TV is placed [176, 177].

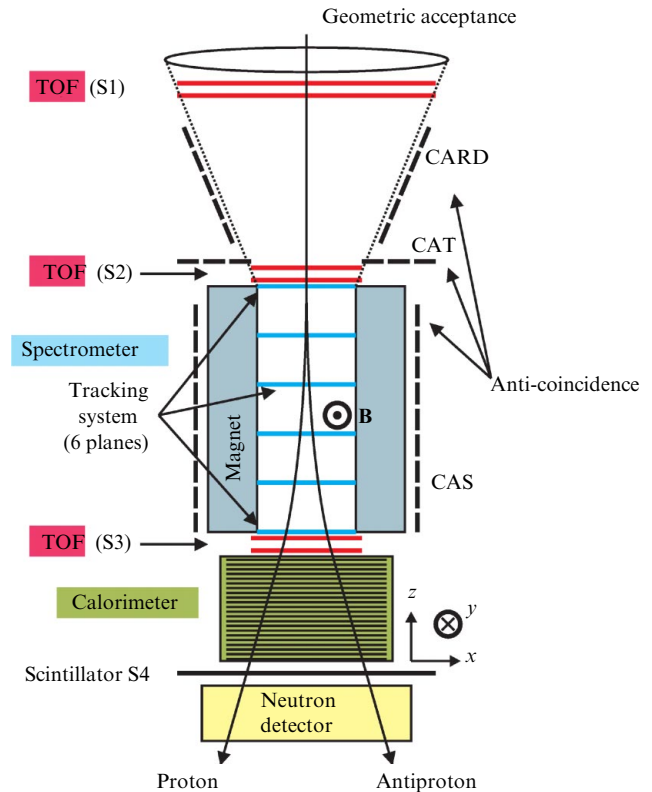


Figure 29. Schematic representation of the PAMELA spectrometer: time-of-flight system (ToF); anticoincidence system (CARD, CAT, CAS); position-sensitive tracking system (tracker); permanent magnet; position-sensitive calorimeter; scintillation shower detector (S4); neutron detector [176].

Planes of scintillators of the time-of-flight (ToF) system are installed above and below the magnet, providing the primary experimental trigger. The time resolution of the time-of-flight system makes it possible to identify albedo particles and also to perform proton/antiproton–electron/positron separation for particles with momenta below $1.5 \text{ GeV } c^{-1}$. The electromagnetic calorimeter, located beneath the magnet, measures the energies of incident electrons and makes it possible to perform a topological selection between electromagnetic and hadronic

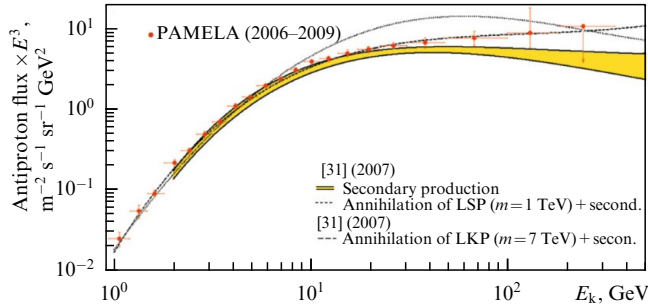


Figure 30. The yellow band shows the uncertainty in the flux of secondary antiprotons for various models of diffusion in the interstellar medium. The dotted and dashed lines correspond to signals caused by the annihilation of hypothetical dark matter particles in various models [176].

showers (or non-interacting particles). The scintillation system beneath the calorimeter is used to identify high-energy electrons and is supplemented by a neutron detector. The spectrometer is surrounded by a plastic scintillation shield of the anticoincidence system in order to exclude from the analysis events outside the aperture of the instrument.

Before the launch of PAMELA, more or less reliable results on antiproton fluxes had been obtained only in the range up to about ten GeV. At higher energies they were either absent (above 40 GeV) or had errors that did not allow a choice to be made in favour of one of the theoretical models. Figure 30 presents the antiproton spectrum multiplied by E^3 for the visual enhancement of deviations, in comparison with the predictions of secondary origin (yellow region) and with theoretical calculations of the fluxes from dark matter particle annihilation: SUSY (~ 1 TeV) (dotted line) and Kaluza–Klein (~ 7 TeV) (dashed line) [178].

The PAMELA experiment showed that, beginning at energies of ~ 20 – 30 GeV, the antiproton fluxes lie at the upper boundary of, or above, the models of their secondary origin. This does not exclude a contribution from primary sources — for example, from the annihilation of dark matter particles, especially in the presence of flux-enhancement mechanisms [179]. A similar excess was previously observed in the positron spectrum [180], which was likewise interpreted as a possible signal from dark matter particles and reinforced the arguments in its favour as a potential source.

Figure 31 shows the ratio of antiproton and proton fluxes as a function of kinetic energy obtained in the PAMELA experiment in comparison with the results of previous experiments [17, 61, 128, 130, 140, 143, 149, 150, 158, 172, 181]. A comparison is made of the PAMELA data with theoretical calculations in the model of secondary origin of antiprotons in the Galaxy and of plain diffusion in the interstellar medium [182] (solid line) and with the predicted uncertainty of the calculated flux of secondary antiprotons associated with their production and diffusion in the Galaxy in Ref. [37] (dashed lines).

In the PAMELA experiment the spectrum of galactic antiprotons was measured for the first time with high accuracy over a wide energy range up to 350 GeV. Its results confirmed the dominance of the secondary origin of antiprotons over a wide energy region, but did not exclude a possible contribution of dark matter at high energies. These data became the basis for the subsequent precision studies of antiparticles in the AMS-02 [15] and DAMPE [183] experiments.

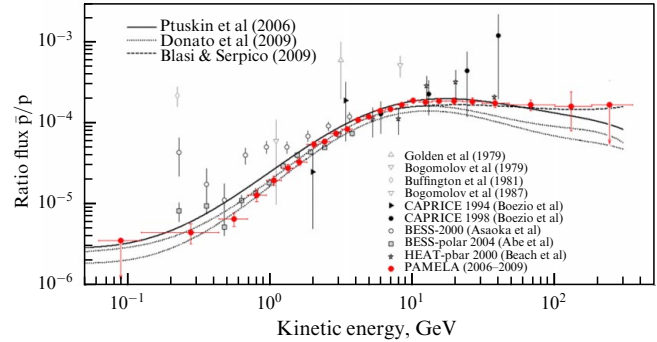


Figure 31. Ratio of antiproton and proton fluxes in the primary cosmic rays according to the data of the PAMELA spectrometer and of other experiments [176].

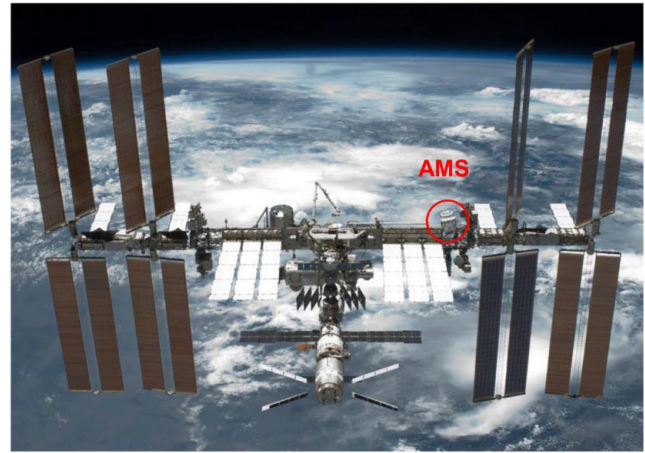


Figure 32. The AMS-02 spectrometer on board the ISS [184].

3.1.5 AMS-02. The next significant step in the study of antiparticle fluxes was the AMS-02 experiment. The scientific apparatus of the AMS-02 experiment is an improved version of its predecessor and is a precision magnetic spectrometer, which was launched into space on 16 May 2011 aboard the shuttle Endeavour (STS-134) and three days later installed on board the International Space Station (Fig. 32) [184]. Owing to such a setting of the experiment, it becomes possible to repair and upgrade the instrument, which contributes to its long-term operation.

The main goals of the AMS-02 experiment are precision measurements of cosmic ray fluxes, including antiparticles, the search for antinuclei with $A > 1$, and the detection of possible signals of the annihilation or decay of dark matter particles.

The layout of the AMS-02 detector, with an indication of the main elements and their functions, is presented in Fig. 33 [184]. The spectrometer makes it possible to identify particles and nuclei by their charge, energy and momentum, or magnetic rigidity, which are measured independently by the tracking system in the magnetic field (Tracker), the time-of-flight system (ToF), the ring-imaging Cherenkov detector (RICH) and the electromagnetic calorimeter (ECAL). The counters of the anticoincidence system (ACC), located in the bore of the magnet, are used to reject particles entering AMS outside the aperture (from the side) [184].

According to the AMS-02 data published in 2016 [15], 3.49×10^5 antiprotons and 2.42×10^9 protons were recorded. According to the 2025 publication, the statistics increased to

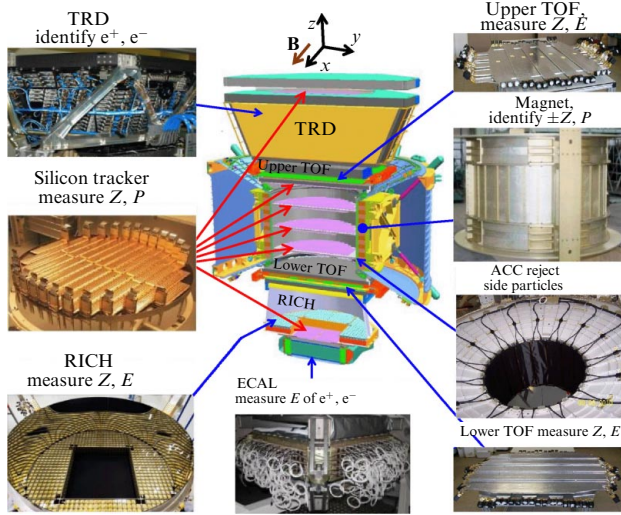


Figure 33. Layout of the AMS-02 detector [184].

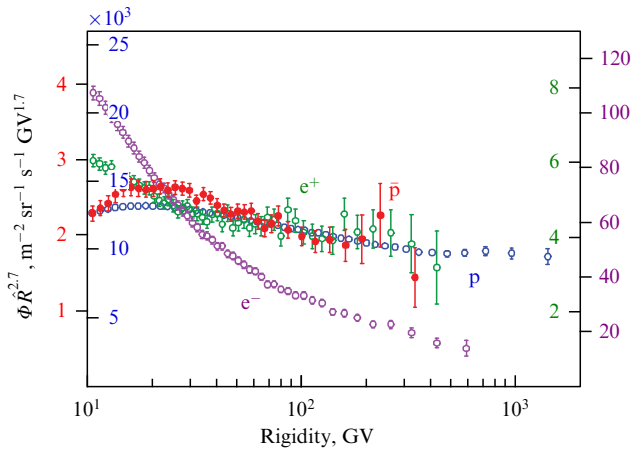


Figure 34. Antiproton flux (red, left axis) compared with the proton flux (blue, left axis), the electron flux (violet, right axis) and the positron flux (green, right axis) [15].

1.1×10^6 antiprotons in the rigidity range from 1.00 to 41.9 GV [45], which became possible thanks to the detection of more than 2×10^{11} cosmic events. These data cover almost a full 11-year cycle of solar activity, including the reversal of the Sun's magnetic field and the beginning of a new cycle.

In addition, according to the results published in 2021, 5.6×10^5 antiproton events were recorded in the AMS-02 experiment. This made it possible to obtain the antiproton spectrum and the antiproton-to-proton ratio over the extended rigidity range from 1 to 525 GV [184]. The data obtained agree with the results published in 2016 [15], but differ by their higher statistics and accuracy, which made it possible to improve substantially the detail of the spectrum and to analyze the influence of solar modulation.

Figure 35 shows the fraction of antiprotons in cosmic rays with energies up to 500 GeV according to the data of the PAMELA and AMS-02 experiments in comparison with theoretical predictions.

The ratio of the antiproton flux to the total flux of protons and antiprotons published in the AMS-02 experiment confirms the published results of the PAMELA experiment; at the same time the statistics have been significantly increased and the energy range extended [14, 166, 175].

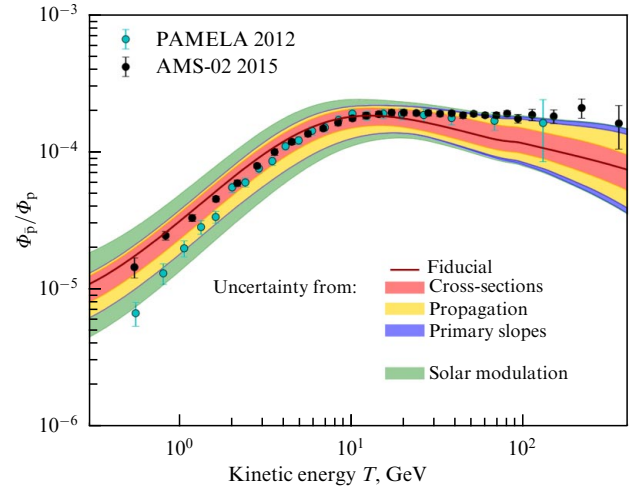


Figure 35. Ratio of antiproton and proton fluxes in the cosmic radiation according to the data of PAMELA [176] and AMS-02 [24].

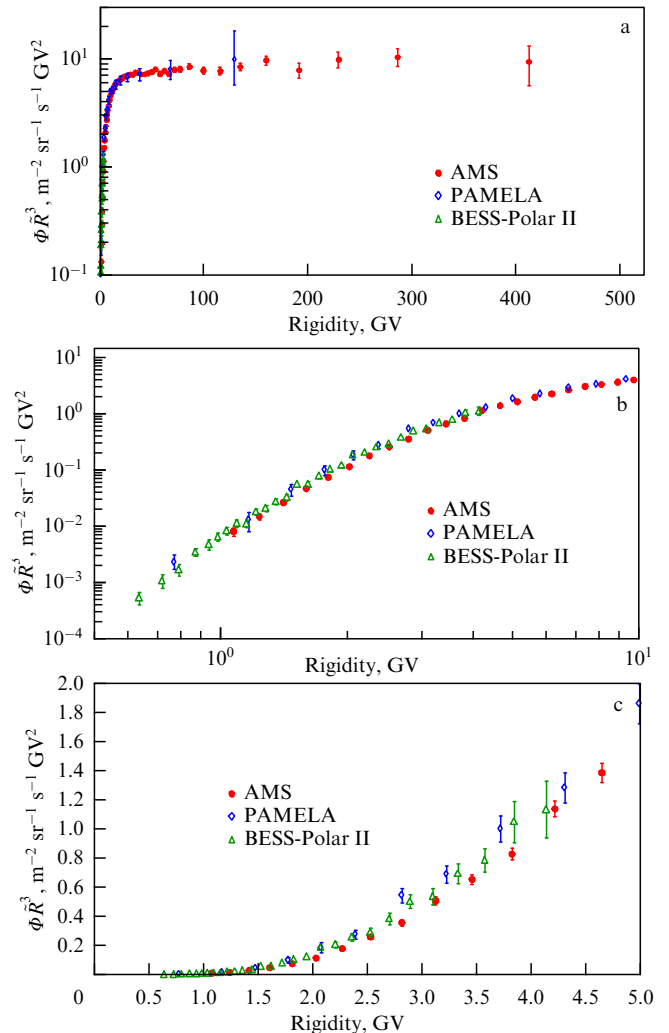


Figure 36. Spectrum of antiprotons in the cosmic radiation according to the data of AMS-02 [184], PAMELA [176] and BESS-Polar II [160].

Figures 36 and 37 present the spectra and the ratio of antiproton and proton fluxes obtained by AMS-02 in comparison with the results of the PAMELA and BESS-Polar II experiments [184].

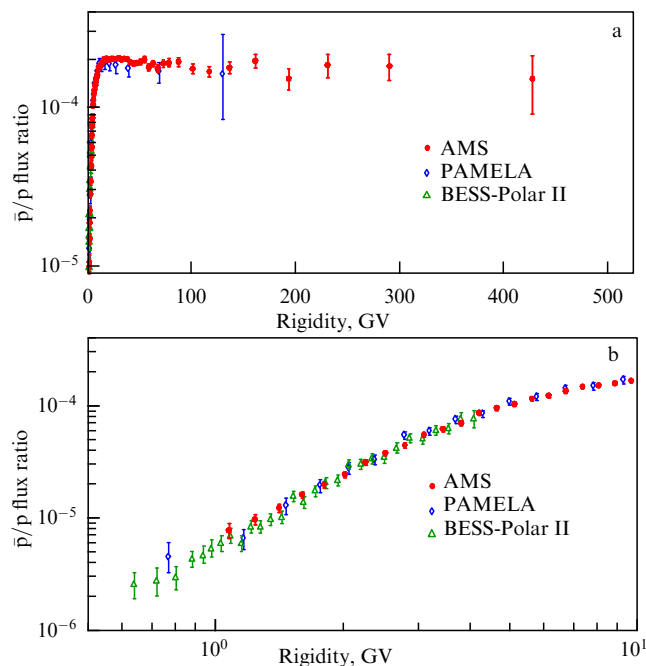


Figure 37. Latest results of AMS-02, BESS-Polar II [160] and PAMELA [176]: (a) ratio of antiproton and proton fluxes; (b) antiproton-to-proton ratio in the low-rigidity region (< 10 GV) [184].

The analysis showed that the shape of the antiproton/proton ratio does not exhibit the expected decrease at high rigidities, which would be characteristic of a purely secondary origin of antiprotons. This observation gave rise to theoretical debate concerning a possible contribution of primary sources, such as dark matter annihilation. After the publication of the AMS-02 antiproton spectrum, a series of theoretical works was proposed explaining the observed features by invoking both standard and new astrophysical scenarios [22–24, 185–198]. These works present various models of cosmic ray propagation and scenarios of dark matter annihilation, giving qualitatively different predictions for the shape and magnitude of the antiproton spectrum in the high-energy region.

Figure 37b presents a fragment of the spectrum in the low-rigidity region (< 10 GV), where the influence of solar modulation is most substantial. The modulation is caused by the interaction of charged particles with the solar wind and with the Sun's magnetic field, which leads to a change of the shape of the spectrum, especially at the minimum of the solar activity cycle.

Of particular interest is the analysis of the behavior of the ratio of antiproton and proton fluxes in the high-energy region. The AMS-02 experimental data [45] presented in Fig. 38 show the absence of the expected sharp fall of this ratio at energies above 10 GV, which contradicts the predictions of the standard models of the secondary origin of antiprotons [30, 199]. This effect is especially noticeable in comparison with the PAMELA and BESS-Polar II data in Fig. 36, where the theoretical curves for purely secondary antiprotons predict a more rapid decrease of the antiproton-to-proton ratio with increasing energy than is shown in Fig. 35.

The antiproton flux exhibits a substantially smaller amplitude of temporal variations as compared with other elementary particles, which points to the important role of the spectral shape in solar modulation [45]. As a result of the analysis of more than a million events in the rigidity range

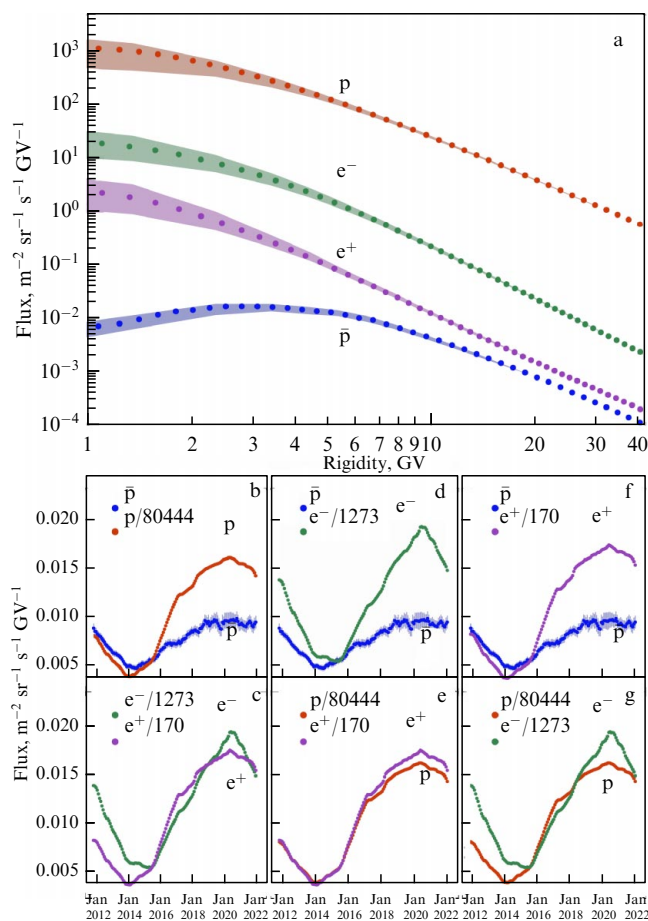


Figure 38. (a) The antiproton flux (blue) is shown together with the fluxes of protons (red), electrons (green) and positrons (violet). All fluxes are reduced to a common relative scale for a clear comparison of the modulation amplitudes. (b, c) Comparison of the fluxes of particles with opposite charge but the same mass; (d, e) comparison of particles with the same charge but different mass; (f, g) illustration of the differences in modulation between antiparticles and particles [45].

from 1 to 41.9 GV, it was established that the behavior of the antiproton flux ($\bar{p}$) differs substantially from the fluxes of other elementary particles: protons (p), electrons (e^-) and positrons (e^+). The amplitude of the temporal modulation of the antiproton flux is significantly smaller than that of protons, electrons and positrons. At the same time, a pronounced hysteresis effect is observed between the antiproton and proton fluxes, whereas a linear correlation is established between p and e^- . This emphasizes the importance of the sign of the charge in the processes of solar modulation.

In addition, by means of a model-independent analysis, a universal relation was revealed between the shape of the rigidity spectrum and the amplitude of the temporal variations of the fluxes. This relation holds equally for both positively and negatively charged particles. It was established that particles with a steeper spectrum exhibit a smaller modulation amplitude, other conditions being equal [45].

The results obtained provide unique information on the influence of mass, charge and spectral shape on the processes of transport of charged particles in the heliosphere. They also serve as an important basis for interpreting the origin of cosmic antiprotons and for refining models of cosmic radiation.

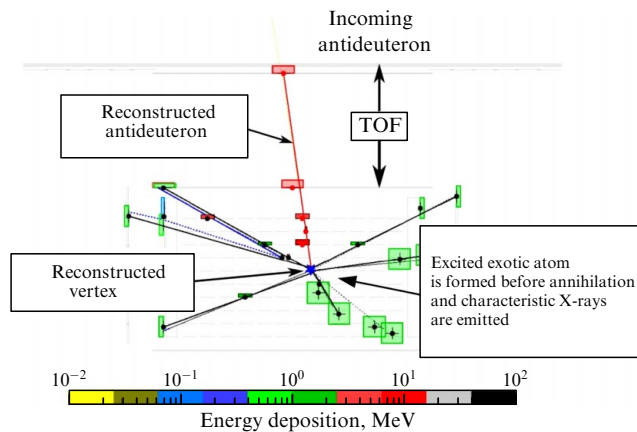


Figure 39. Scheme of the detection of antinuclei in the GAPS instrument, illustrated for $\bar{d}$: the $\bar{d}$ annihilates with the formation of an exotic atom, which leads to a final state with several pions [201].

3.1.6 GAPS. At present active preparations are under way for the launch of the balloon experiment GAPS (General AntiParticle Spectrometer), whose aim is the search for antiprotons, antideuterons and antihelium isotopes in the composition of cosmic rays with energies below 0.25 GeV/nucleon. The detector uses a unique method of detecting antinuclei: after being slowed down to a velocity $\beta \approx 0.2\text{--}0.5$ in a silicon target, the antinucleon is captured by a nucleus and forms an exotic atom in a highly excited state. There follows a successive emission of Auger electrons and of characteristic X-ray radiation, whose spectrum depends on the type of captured particle. The process terminates in the annihilation of the antinucleus, as a result of which several pions and protons are recorded in the detector. The identification of the signal is based on the joint analysis of the time of flight (ToF), the X-ray spectrum and the trajectories of the annihilation products, which provides the instrument with the ability to distinguish reliably the rare events associated with the detection of antinuclei and to suppress the background [200]. The detection principle is illustrated in Fig. 39.

The scientific goals of the experiment include the precision measurement of the spectrum of low-energy antiprotons in the range from 0.07 to 0.21 GeV, the search for antideuterons with a sensitivity exceeding the current constraints by 1–2 orders of magnitude, and the possible detection of antihelium-3, which would constitute a direct indication of non-standard mechanisms of the formation of cosmic ray antinuclei, including dark matter annihilation [201–203].

As of 2025 the GAPS instrument has undergone full integration and ground calibration at the McMurdo Antarctic balloon facility. Compliance with all the key technical parameters was confirmed: stable operation of the cooling system, an energy resolution of the X-ray channels of the order of 4 keV, and a high efficiency of the ToF trigger. The first launch attempt on 1 January 2025 was interrupted, however, because of damage to the payload and unfavorable weather conditions. Repeated launches in early January also proved impossible because of strong winds, and the campaign was officially postponed to the 2025–2026 season [203, 204]. If the launch is successful, GAPS will provide unprecedented event statistics and will open a new window for the detection of antimatter and of potential dark matter signals.

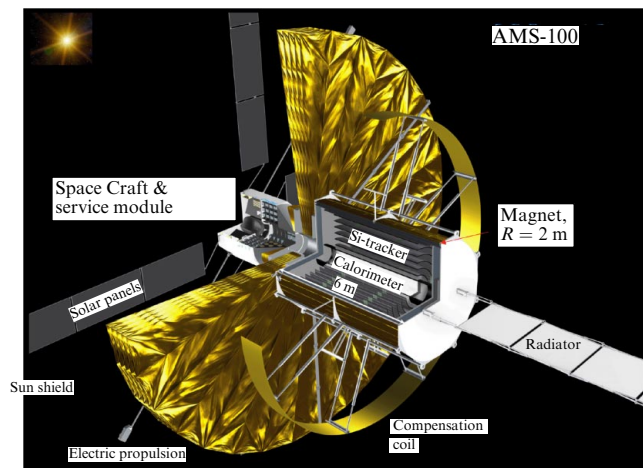


Figure 40. Conceptual layout of the AMS-100 spectrometer [205].

3.1.7 AMS-100. AMS-100 is an international project for the creation of a magnetic spectrometer intended for the measurement of cosmic ray nuclei and antinuclei, which is planned to be placed at the Lagrange point L2 of the Sun–Earth system. The main task of the instrument is the direct measurement of the spectra of charged particles and photons in previously unattainable energy ranges — up to 10^{16} eV for nuclei and up to 10 TeV for electrons and positrons [205]. Particular attention will be paid to the search for antiparticles with mass number $A > 1$, such as antihelium and antideuterons, the detection of which could serve as a unique indicator of the annihilation or decay of dark matter.

The AMS-100 spectrometer includes several detector systems (Fig. 40) placed inside a thin-walled superconducting solenoid. The magnet system based on REBCO tapes (high-temperature superconductors) creates a uniform magnetic field of strength 1 T, providing the deflection of charged particles, which makes it possible to determine their momentum and the sign of their charge. Inside the solenoid a silicon tracker is placed with a spatial resolution down to 5 μm and a maximum detectable rigidity of up to 100 TV, which will allow particle trajectories to be reconstructed with high accuracy. It is followed by a calorimeter based on LYSO crystals with a depth of 70 radiation lengths (or 4 nuclear interaction lengths), making it possible to measure the energy deposit of charged and neutral particles. The outer layers of the detector include scintillating-fibre (SciFi) trackers and a time-of-flight (ToF) system with a planned resolution of 15–20 ps, which is particularly important for distinguishing isotopes of particles and antiparticles [206].

Figure 41 presents the expected measurements of the proton energy spectrum that AMS-100 will be able to perform with high statistical accuracy. A comparison with the results of previous missions — AMS-02 [207], PAMELA [208], BESS-Polar [161], ATIC-2 [209], CALET [210], CREAM [211] — shows that AMS-100 will make it possible to extend the measurements to energies above 10^{15} eV, i.e., beyond the knee in the cosmic ray spectrum [205]. The dashed curve on the plot corresponds to a model spectrum with several smoothed breaks, illustrating the potential of the spectrometer for revealing complex structures caused by the transition from galactic to extragalactic sources or by features of the propagation of particles in the interstellar medium.

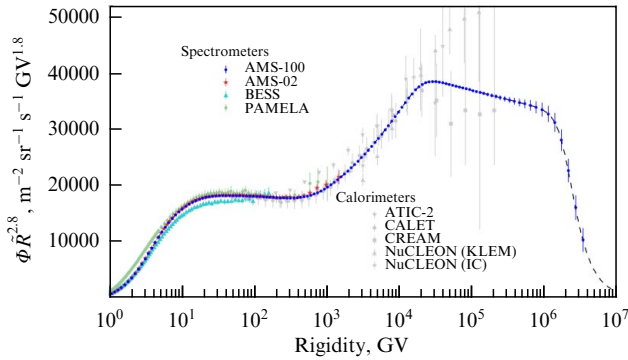


Figure 41. Energy spectrum of cosmic ray protons. Blue points — expected AMS-100 data [206]; red stars — AMS-02 [207]; green triangles — BESS-Polar [161]; green diamonds — PAMELA [208]; grey triangles — ATIC-2 [209]; grey points — CALET [210]; grey squares — CREAM [211].

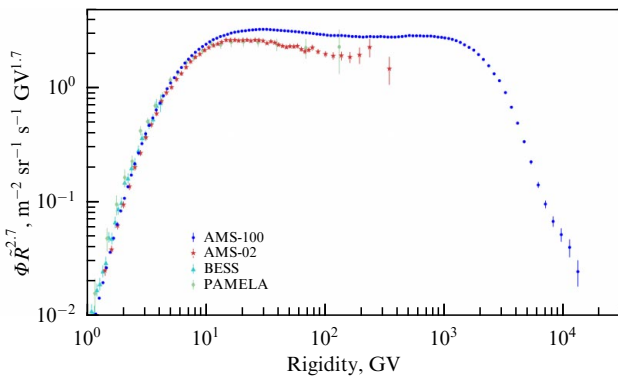


Figure 42. Energy spectrum of cosmic ray antiprotons. Blue points — expected AMS-100 data [206]; red stars — AMS-02 [15]; green triangles — BESS-Polar [164]; green diamonds — PAMELA [176].

A comparison was also made of the simulated antiproton energy spectrum with the data of the BESS-Polar, PAMELA and AMS-02 experiments (Fig. 42). The blue points show the expected data from AMS-100, calculated on the basis of the theoretical model [193] of the antiproton flux (up to 10 TeV) with only the statistical uncertainties indicated. Comparison of the prediction of this model with the AMS-100 simulation data will make it possible either to confirm it or to reveal the contribution of exotic processes (for example, of dark matter) to the formation of the antiproton spectrum [212].

This project is intended to become the successor of AMS-02 and to increase the statistics of recorded particles by a factor of 1000, thanks to a geometric factor of $100 \text{ m}^2 \text{ sr}$. The AMS-100 spectrometer is planned to be launched in 2039. The planned operating lifetime is at least 10 years.

The realization of the AMS-100 project will be an important step in the development of observational astrophysics and cosmic ray physics. Its scientific potential embraces a wide range of problems—from the refinement of existing models to the possible discovery of new physical phenomena. The unique technical parameters of the instrument will make it possible to count on qualitatively new results, capable of substantially influencing our understanding of the structure of the Universe.

3.2 Antiprotons in Earth's albedo

There are several processes that are considered as a source of antiprotons in near-Earth space [49, 213]. Antiprotons can be formed in the interaction of cosmic rays with the residual

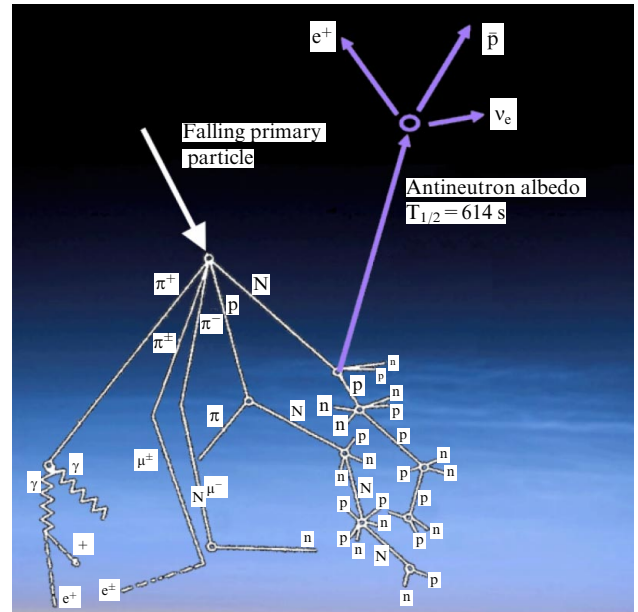


Figure 43. Illustration of the CRANbarD mechanism.

upper layers of the Earth's atmosphere, for example in the following reaction: $p + p \rightarrow p + p + p + \bar{p}$ (direct production of antiprotons). Antiprotons formed in this way can be trapped by the Earth's magnetic field, especially if they arise in zones with a suitable geomagnetic configuration. This leads to the accumulation of antiprotons in the inner magnetosphere of the Earth, where an antiproton belt is formed—an analogue of the Van Allen radiation belts, but consisting predominantly of antiprotons.

The fluxes of antiprotons formed as a result of direct production are one to two orders of magnitude greater than the antiproton flux in the composition of the GCRs. The maximum of the flux of antiprotons produced by this source falls in the region of near-Earth space with McIlwain coordinate [214] L from 1.20 to 1.25, while the pitch-angle distribution of the flux has a maximum at an equatorial pitch angle of 90° [213] (the L shell is a quantity measured in Earth radii and equal to the distance from the center of the Earth to the point of intersection of a magnetic field line with the plane of the geomagnetic equator).

Another source of antiprotons is the decay of albedo antineutrons. For albedo and trapped antiprotons this mechanism, which has been named CRANbarD (Fig. 43), is the most significant. Antineutrons are formed in the reaction $p + p \rightarrow p + p + n + \bar{n}$, which proceeds in the Earth's atmosphere. The magnetic field has no influence on the propagation of antineutrons, and this allows them to penetrate into forbidden zones, where they decay in the reaction $\bar{n} \rightarrow \bar{p} + e^- + \bar{\nu}_e$.

The flux of antiprotons formed by the CRANbarD mechanism is thousands of times greater and is located at larger L shells as compared with the direct source of antiproton production ($L \approx 1.4\text{--}1.5$) [215]. Thus, the mechanisms of generation and retention of secondary antiparticles in the near-Earth environment are closely connected with the features of the Earth's magnetosphere.

3.2.1 PAMELA. The orbit of the Resurs-DK1 satellite (inclination 70° and altitude 350–610 km), on which the spectrometer was located, allowed the PAMELA instrument to perform very detailed measurements of the cosmic

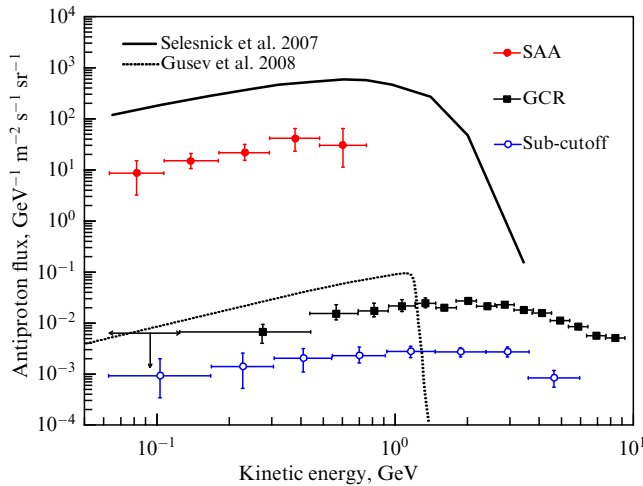


Figure 44. Antiproton spectrum measured in the PAMELA experiment (2006–2009) in the region of the South Atlantic (Brazilian) Anomaly (SAA, red points). For comparison, the antiproton spectrum in the atmosphere outside the SAA region (albedo, blue points) and the GCR antiproton spectrum (black points) are shown [46].

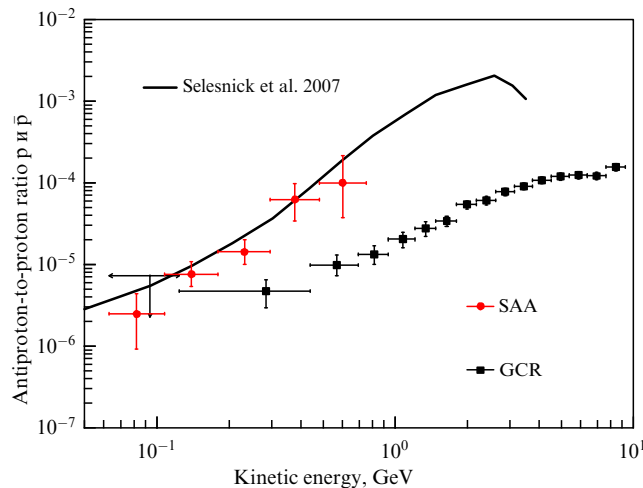


Figure 45. Ratio of trapped antiprotons and protons measured in the PAMELA experiment (2006–2009) in the SAA region (red points) [46] and its theoretical prediction [49] (black line). For comparison, data on the ratio of GCR antiprotons and protons are shown [166].

radiation in various regions of the Earth's magnetosphere, including the region of the South Atlantic (Brazilian) Anomaly (SAA), providing information on the nature and energy spectra of particles and antiparticles over a wide energy range.

In 2011, from the results of the measurements in the PAMELA experiment, antiprotons of secondary origin in near-Earth space were detected for the first time; the energy spectrum of the albedo and trapped components was measured in the kinetic-energy range from 80 to 750 MeV (Fig. 44), and the ratio of the fluxes of trapped antiprotons and protons was obtained (Fig. 45) [46].

The data of the PAMELA spectrometer show that the measured flux of antiprotons trapped in the SAA exceeds the flux of antiprotons recorded outside the radiation belts (albedo) and the flux of galactic cosmic ray antiprotons at the minimum of solar cycle 23/24 (negative polarity A^-) by four and three orders of magnitude, respectively.

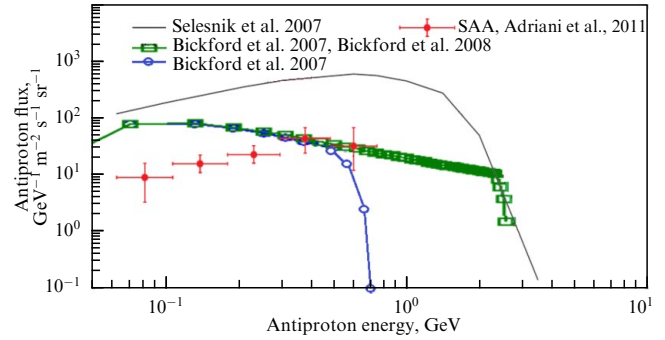


Figure 46. Comparison of the results of the calculations [49, 216, 217] with the data of the PAMELA experiment [46].

A comparison was made of the antiproton flux obtained in the PAMELA experiment with various theoretical models [49, 216, 217] (Fig. 46) [215]. These models rely on two different mechanisms: the direct production of antiprotons in the Earth's atmosphere ($p + p \rightarrow p + p + p + \bar{p}$) and the decay of antineutrons formed in the reactions ($p + p \rightarrow p + p + n + \bar{n}$), known as the CRANbarD mechanism.

According to the simulation results, the CRANbarD mechanism explains the significantly higher antiproton fluxes observed by PAMELA, especially in the region of shells $L \approx 1.4-1.5$, whereas the contribution from direct production is confined to lower L shells ($L \approx 1.2-1.25$) and to smaller fluxes. The best agreement between the calculations and the experiment is achieved in the energy region around 1 GeV, where both the absolute values of the flux and the shape of the spectrum coincide. For other parts of the spectrum, however, discrepancies remain, which may be due to differences in the treatment of the pitch-angle distribution of the antiprotons or of the localization of the sources over the L shells.

Despite the fact that the theoretically predicted spectrum of trapped antiprotons does not coincide in all details with the observed spectra, their coincidence at an energy of 1 GeV is noted.

3.2.2 AFIS. Within the framework of the Antiproton Flux in Space (AFIS) mission [218], the development of a small detector began in 2012, intended for the measurement of the flux of low-energy antiprotons trapped in the Earth's inner radiation belt. The measurements are based on Bragg spectroscopy in the volume of an active target consisting of scintillating fibres, with an analysis of the 'star' topology formed upon antiproton annihilation in the stopping region. The detector was to be implemented in the CubeSat form factor, and because of its small dimensions the instrument should, according to calculations, be sensitive to antiparticle energies from 25 to 100 MeV, which would make it possible to extend the energy range of the measurements of the PAMELA instruments into the low-energy part of the spectrum (Fig. 47).

Calibration at an accelerator and a test flight of a prototype on a high-altitude balloon took place by 2014, and the launch of the instrument into space was planned for 2018; after 2015, however, no new information on the AFIS mission has appeared.

Further study of the energy and spatial distributions of antiprotons, as well as of the temporal dynamics of their flux, is of key importance for refining the models of generation of secondary cosmic rays and for understanding the mechanisms

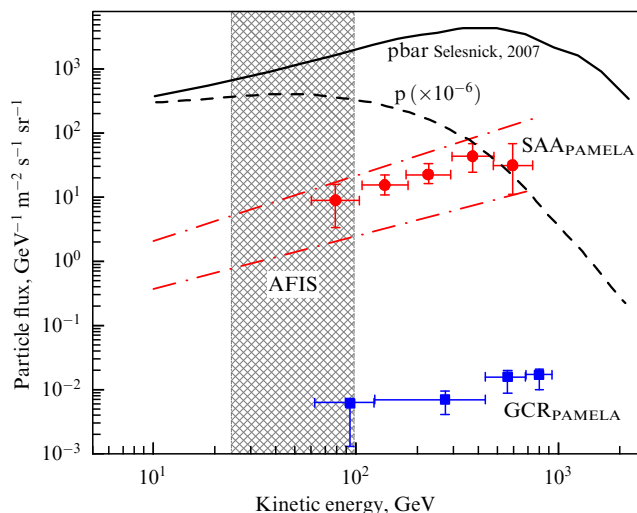


Figure 47. Fluxes of trapped antiprotons in the SAA region (red points) measured by the PAMELA spectrometer [46], and the theoretical predictions of Ref. [49] (black line). The expected measurement region of AFIS is shown in grey [218]. Blue points (for comparison) are the fluxes of galactic antiprotons obtained in the PAMELA experiment [46].

of their trapping in the Earth's magnetosphere. Measurement of the flux of low-energy (in the range from 25 to 100 MeV) trapped antiprotons will make it possible to test the reliability of the existing theoretical predictions [48, 50, 219], which diverge from the results of the PAMELA experiment by more than two orders of magnitude in this energy region [218].

4. Search for antiprotons with energies above 1 TeV

Direct observation of antiprotons with energies of the order of a TeV and above in balloon and satellite experiments is hampered by their low abundance in cosmic rays. To accumulate a minimum statistics, either an order-of-magnitude larger geometric factor of the instrument or a longer exposure time is required. For this reason an alternative, indirect method of observing antiprotons in experiments detecting extensive air showers (EAS) is considered in the literature, employing the shadows of the Moon and of the Sun.

By the shadows of the Moon and of the Sun one means the decrease in the number of detected high-energy cosmic ray particles from the directions corresponding to the positions of these celestial bodies, owing to their absorption. The existence of this effect was first suggested by G.W. Clark in 1957 [220], who noted the possibility of using the shadows to study the magnetic fields of the Moon and of the Sun.

For a long time direct observations did not lead to the detection of the Moon and Sun shadows, because of the smallness of the effect and the insufficient characteristics of the measuring installations. A deficit in the particle flux observed from a definite direction was first reliably recorded in 1990 [221] in the Cygnus experiment at Los Alamos. The angular resolution of the measuring installation was approximately 0.7°, whereas the angular sizes of the Moon and of the Sun in the sky are on average 0.52°. After the accumulation of a large event statistics, the statistical significance of the decrease of the cosmic ray flux amounted to 4.9σ. Figure 48 shows the angular density $dN/d\Omega$ of events as a function of the angular distance from the Moon or the Sun.

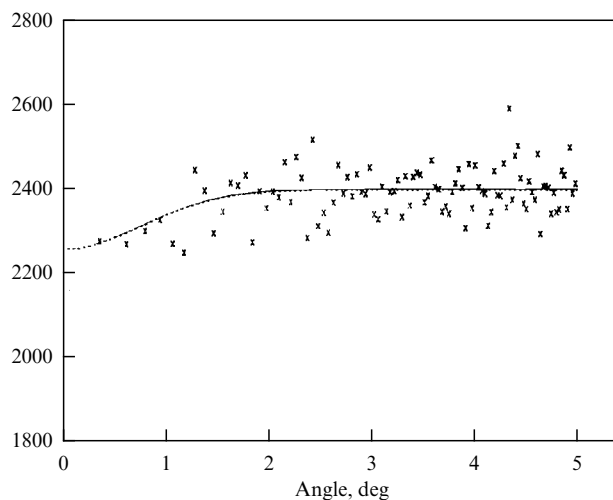


Figure 48. Angular density of events as a function of the angular displacement from the center of the Moon or of the Sun. The solid curve corresponds to the density predicted for a Gaussian angular resolution with a standard deviation of 0.75° [221].

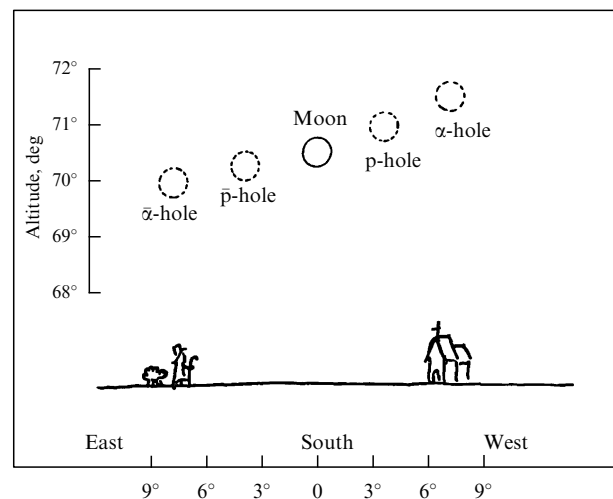


Figure 49. Scheme of how the Moon shadow in cosmic rays with an energy of 1 TeV will look [222].

The measured deficit is consistent with that expected under the assumption that the angular resolution is described by a Gaussian model. The levelling-off at around 1° corresponds to an angular resolution of 0.75°.

Direct observation of the Moon shadow made it possible to take the next step — the study of the charged component of the cosmic rays at high energies. The idea consists in using the Moon and the Sun as collimators. The cosmic ray flux passing through them is partially absorbed, while the remaining particles subsequently enter the Earth's magnetic field, as a result of which positively and negatively charged particles are, to a first approximation, deflected in opposite directions. Then, on observing the region of the sky in which a particle deficit is expected, one will see not a single spherical image corresponding to the obstructing body, but several images that are separated or partially overlap (Fig. 49).

In 1990 a group of researchers performed model estimates of the magnitude of the Moon shadows in the fluxes of various particles and of the degree of their overlap [222]. The calculation was carried out for cosmic rays with energies of 1–10 TeV; the Earth's magnetic field was taken to be dipolar, with a calculated error for such an approximation of

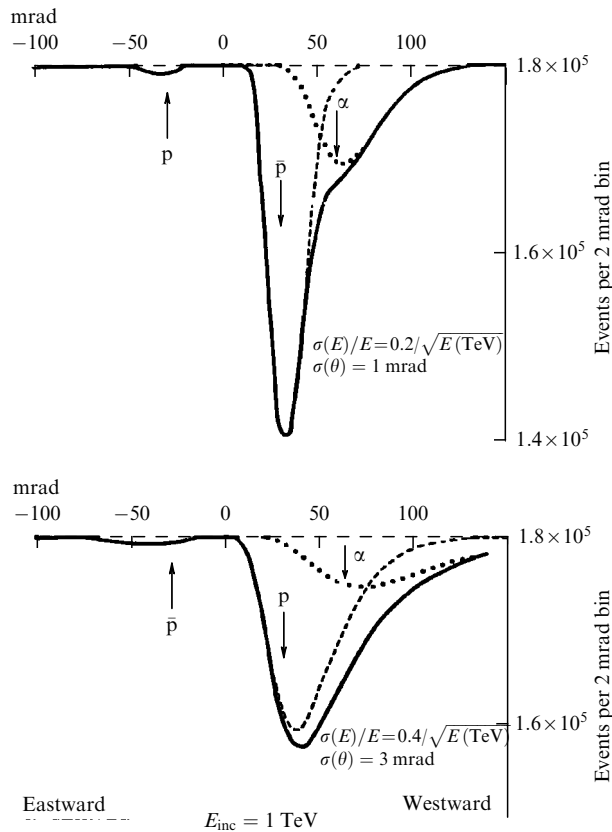


Figure 50. Simulation of the Moon shadow in the fluxes of antiprotons, protons and helium nuclei with energies of 1 TeV for two values of the angular resolution of the measuring installation, for observations over one year near the equator [222].

not more than 10%. It was noted that the non-dipolar configuration of the Earth's field at distances greater than 5 Earth radii, as well as the galactic and lunar magnetic fields, can be neglected because of their small magnitude. Long-term (several per cent per century) and short-term ($\sim 3\%$ over several hours) fluctuations of the geomagnetic field were also not taken into account, since they are not noticeable in long-term cosmic ray measurements extending over several months.

The results of the calculations are presented in Fig. 50 for antiprotons, helium nuclei and protons with energies of 1 TeV. The percentage content of the particles in the cosmic ray flux was taken to be 1%, 25% and 50%, respectively.

It can be seen from the plot that the expected signal from antiprotons has a much smaller amplitude, but is located at a noticeable distance from the signals of the two other particles. The signals from positively charged particles overlap at realistic resolution. Such behavior leads to the fact that, on the one hand, with large accumulated statistics the possibility arises of observing the shadow created by antiprotons, but, on the other hand, their percentage content relative to protons becomes impossible to estimate because of the merging of the latter with helium.

4.1 Tibet-AS γ

The Tibet-AS γ experiment was one of the first to demonstrate clearly the displacement of the lunar and solar shadows relative to their true positions in the sky [223]. The installation began systematic observations in the early 1990s within the framework of a program of searching for point gamma-ray

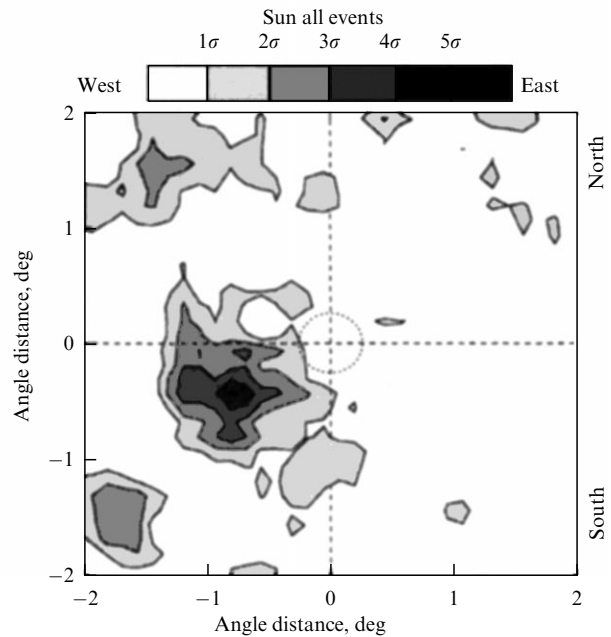


Figure 51. Arrival directions of events in a $4^\circ \times 4^\circ$ region around the Sun (circle with dashed line) [223].

sources and studying cosmic rays with energies from several TeV to PeV. The ground-based complex of 45 scintillation detectors was deployed on a regular grid with a spacing of 15 m and provided an angular resolution better than 1° for events with energies of about 10 TeV, which made it possible to observe the shadows of the Moon and of the Sun in this range.

In the 1993 publication the position of the Sun was calculated relative to the Earth with allowance for the perturbations of the orbit by other planets and by the Moon, and the coordinates of the Moon—with allowance for parallax. The errors of the calculations are substantially smaller than the visible diameter of the disc and the angular resolution of the installation. The observed deviation of the solar shadow (Fig. 51) is interpreted as the result of the combined action of the magnetic fields of the Sun, of the interplanetary medium and of the Earth. In the dipole approximation of the solar field (with an induction of 1 G at the poles), the estimate of the displacement for protons with an energy of 10 TeV gives a value of about 0.3° . The deflection in the geomagnetic field is estimated at 0.18° . The contribution of the interplanetary magnetic field is complicated and depends on its current configuration and on the solar activity.

A similar analysis was performed for the Moon. Figure 52 presents the map of the event density and the deficit profiles in a band of width 1° along right ascension (east–west) and declination (south–north) as functions of the angular distance from the center of the lunar disc. In both cases a small displacement of the shadow relative to the center is noticeable. Since the profile of the lunar shadow in the south–north direction is practically unaffected by geomagnetic deflection, the position of the maximum deficit along this axis can be used to estimate the systematic error: its magnitude amounts to about 0.1° . In the east–west direction the lunar shadow is broadened and systematically displaced towards the west by an angle of about 0.14° , which is on the whole comparable with the magnitude of the systematic error. An estimate of the percentage content of antiprotons in cosmic rays was not given in that paper.

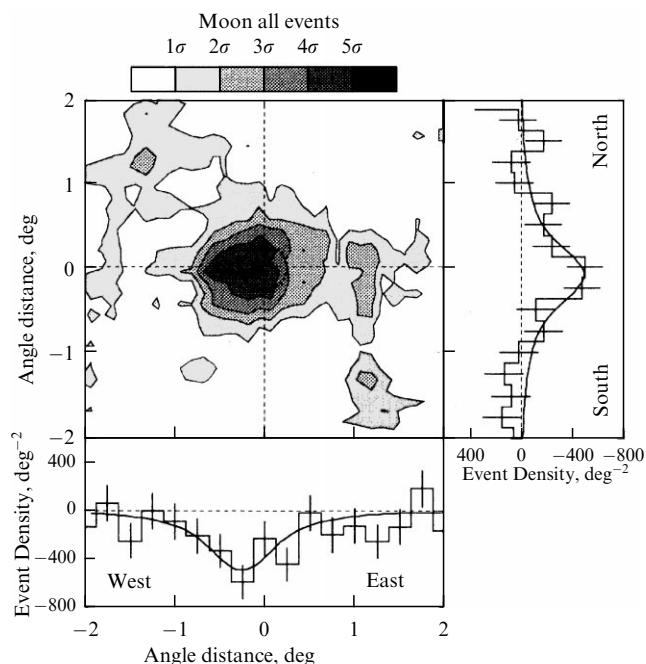


Figure 52. Arrival directions of events in a $4^\circ \times 4^\circ$ region around the Moon. On the outer side of the map are shown the profiles of the deficit of the event density as a function of the angular distance from the center of the Moon, in a band of width 1° along right ascension (west–east) and declination (south–north). The solid curves show the event-density distributions expected for an angular resolution of the installation of 0.87° [223].

4.2 CASA

In the CASA experiment in 1994 the shadows of the Moon and of the Sun were observed in cosmic rays with energies above 100 TeV [224]. The ground-based CASA installation consisted of 1089 scintillation detectors placed in a square grid with a spacing of 15 m over a total area of 0.23 km^2 . Each detector consisted of four separate scintillation counters. At that time it was the largest EAS detection complex in its class of installations (with a comparable density of detector placement), which provided a good angular resolution and a large event statistics.

Over approximately one year of data taking, about 4.7×10^6 events were recorded from directions in the vicinity of the visible positions of the Moon and of the Sun (about 3.7% of the events were excluded during processing). For each body the cosmic ray deficit relative to the mean value of the background for the given regions was estimated. Although the Sun and the Moon have the same angular size in the sky, the shadows they produce differ. Figure 53 shows contour maps of the shower density for the Moon (a) and the Sun (b) in the ecliptic coordinate system. They were constructed by subtracting from the measured mean background values the histogram of events arriving from the directions of the corresponding celestial bodies. The contours are drawn every $-30 \text{ events/grad}^2$, beginning at $-60 \text{ events/grad}^2$.

The shadowing effect for the Sun is somewhat less pronounced than for the Moon. The lunar shadow is symmetric and centered on the position of the Moon, whereas the solar shadow is irregular. The authors of that work note that the probable reason for this is the rigidity-dependent bending of the trajectories of cosmic rays by the solar magnetic field, which leads to an additional deflection of the particles and a blurring of the boundaries of the shadow.

4.3 MACRO

An important step in understanding the influence of geomagnetic conditions on the shape and position of the Moon shadow in cosmic rays was the study in the MACRO experiment [225]. The investigations were conducted using an underground installation by detecting the muon component of the cosmic rays over the period from 1989 to 2000. The considerable interval of time between the beginning of the observations and the publication is due to the need to create an installation with improved energy and angular resolution, as well as to accumulate sufficient statistics for the analysis.

A feature of the analysis is the study of the influence of the time of day on the observed Moon shadow. The event selection was divided into daytime and night-time periods, as a result of which the maps presented in Fig. 54 were constructed. It is clearly visible in them that the geomagnetic field exerts a greater influence during the daytime, significantly distorting the shape of the shadow. At night the shape of the shadow is closest to ideal symmetry; a displacement of the center of the shadow, however, is present both in the daytime and in the night-time data.

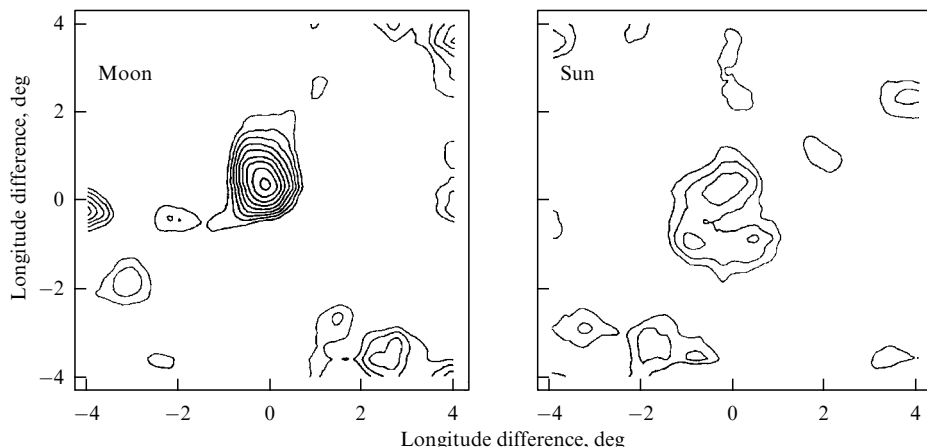


Figure 53. Contour distribution of the cosmic ray deficit from the Moon (left) and the Sun (right). The abscissa is the difference of ecliptic latitudes in degrees between the shower axis and the position of the object; the ordinate is the difference of longitudes in degrees between the shower axis and the position of the object [224].

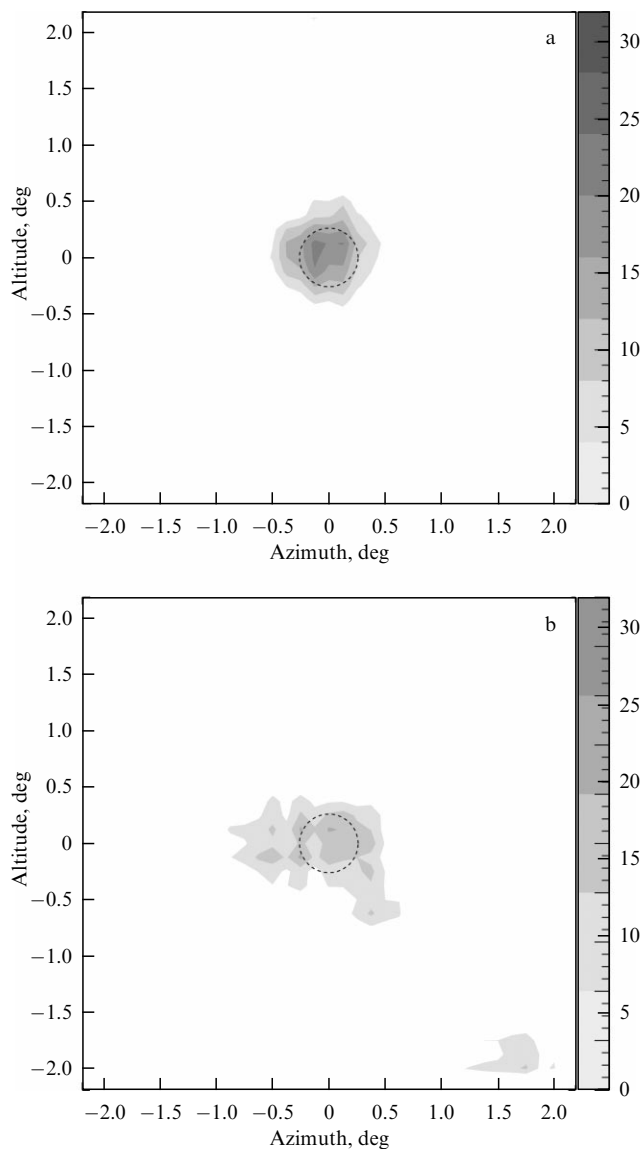


Figure 54. Two-dimensional distribution of χ^2 in cells of equal solid angle. (a) For night-time measurements, (b) for daytime measurements. The dashed line indicates the visible image of the Moon with a radius of the order of 0.26° . The values of χ^2 are presented on the scale at the right [225].

The analysis took into account the fact that during the observation period a full cycle of solar activity had elapsed — from maximum to minimum and back. At the same time, 62% of the events were recorded at a time close to the minimum of solar activity, when the neutral current sheet was close to the plane of the ecliptic. The displacement of the center of the lunar shadow made it possible to establish an upper limit on the antiproton-to-proton ratio $\bar{p}/p$, which amounted to about 0.51 at a significance level of 68% or 0.62 at a significance level of 90% for energies of about 20 TeV.

4.4 L3 + C

A more stringent estimate of the antiproton-to-proton ratio in cosmic rays was obtained in 2005 with the L3 + C muon spectrometer of the L3 detector installed at the CERN Large Electron–Positron collider [226]. A total of 6.7×10^5 events of muons from EAS arriving from directions within 5.0° around the Moon, where the lunar shadow effect in cosmic rays was observed, were analyzed.

The study was performed using two samples: a ‘high-energy’ (HE) sample with muon energies $E_\mu > 100$ GeV and a ‘low-energy’ (LE) sample with $65 \text{ GeV} < E_\mu < 100 \text{ GeV}$. To construct the image of the lunar shadow, a coordinate system was used in which the largest deficit in the cosmic ray flux is concentrated along one of the axes, θ_H . The resulting images of the shadows for both energy samples are presented in Fig. 55.

In the case of the LE sample the shape of the shadow is more elongated and its position is displaced further. The position and shape of the Moon-related deficit of events depend mainly on the deflection of the primary particle with which each muon of the sample is associated by the Earth’s magnetic field, and on the effective angular resolution of the installation. Under the assumption of the presence of a second shadow caused by the presence of antiprotons in cosmic rays, an upper limit on the flux ratio $\bar{p}/p$ was established, equal to 0.11 at a confidence level of 90% for primary particle energies of about 1 TeV.

4.5 Tibet-III

In 2007 the Tibet-ASy collaboration published the results of observations of the Moon shadow in the cosmic ray flux at the Tibet-III installation [227]. It is the result of the improvement and expansion of the original Tibet-I installation to Tibet-II in 1995 and 1996 by increasing the number of counters, and of the subsequent upgrade to Tibet-III in the autumn of 1999. As a result, the ground-based complex comprised 533 scintillation detectors located over an area of $\sim 22050 \text{ m}^2$ with a spacing of 7.5 m. Such a dense configuration made it possible to achieve an exceptional angular resolution — better than 0.9° at energies $\sim 3 \text{ TeV}$ — which is critically important for the problems of gamma astronomy and for the study of subtle effects such as the shadows of the Moon and of the Sun.

The main scientific tasks of Tibet-III were the measurement of the energy spectrum of all cosmic ray particles and the search for features in the region of the ‘knee’ of the spectrum, the study of the large-scale anisotropy of the cosmic ray flux, the search for and observation of discrete gamma-radiation sources in the TeV range, and also the use of the Moon-shadow method to search for rare cosmic ray components such as antiprotons. The Moon-shadow method, actively used by the collaboration, served two purposes: the independent calibration of the angular resolution and of the operating efficiency of the whole installation, and the search for physical effects associated with the deflection of charged particles in the Earth’s magnetic field. The high angular resolution of Tibet-III made it especially sensitive to small displacements of the shadow caused by this deflection.

In the course of the analysis of the data obtained over 1041 days of data taking in the period from 1999 to 2004, 1.5×10^{10} events with energies above $\sim 3 \text{ TeV}$ were selected. Figure 56 shows the measured lunar shadow in the form of a map of the statistical significance of the deficit of the event density.

In the central region of the map the significance level of the event deficit reaches $\sim 40\sigma$. The center of the shadow is displaced by 0.23° to the west of the visible center of the Moon, which is consistent with the expected deflection of protons in the geomagnetic field. At the same time, no signs were found of an additional shadow to the east of the Moon, which would indicate the presence of antiprotons. On the basis of these data an upper limit on the ratio of antiproton and proton fluxes $\bar{p}/p$ was established, equal to 0.07 at a confidence probability of 90% for energies of several TeV.

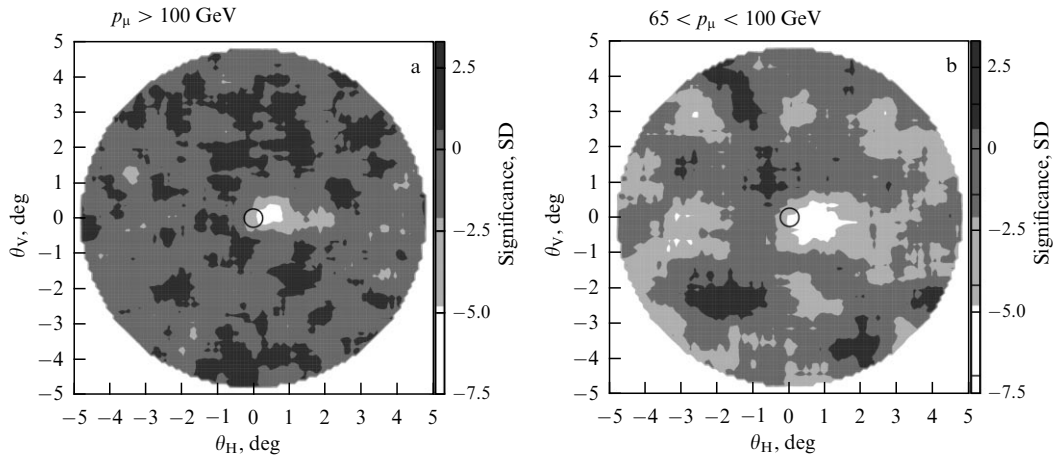


Figure 55. Images of the lunar shadow in the high-energy sample (a) and in the low-energy sample (b). The circle marks the true position of the Moon. The vertical grey scale shows the significance in units of standard deviation; negative values correspond to a deficit of events [226].

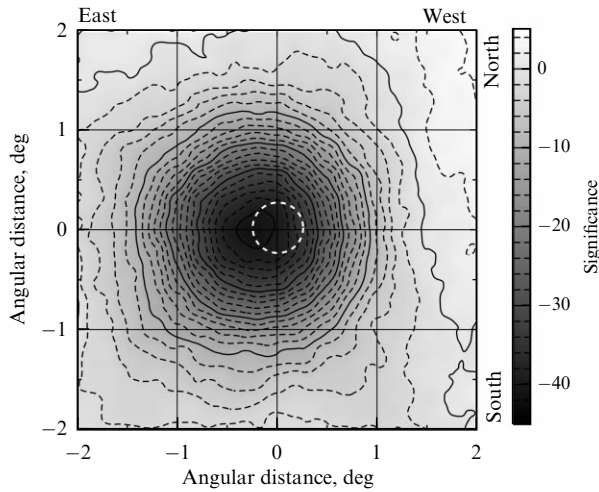


Figure 56. Map of the statistical significance of the deficit of the event density observed at the Tibet-III installation. The origin of coordinates indicates the center of the lunar disc; the boundaries of the disc are marked by a white dashed circle. The scale at the right shows the significance level of the deficit of the event density in units of standard deviation [227].

4.6 ARGO-YBJ

The next step in the study of antiprotons at energies of the order of a TeV was made in the ARGO-YBJ experiment. In a 2012 publication the collaboration presented the results of the measurement of the lunar shadow and the estimate of the $\bar{p}/p$ flux ratio made on the basis of these measurements [228].

The ARGO-YBJ installation (Fig. 57) consists of resistive plate chambers arranged in the form of a central array of area $74 \times 78 \text{ m}^2$ 130 clusters, surrounded by a ring of 23 clusters, which extends the total area of the installation to $\sim 100 \times 110 \text{ m}^2$. The dense arrangement of the detectors provides an angular resolution better than 5° for EAS initiated by particles with energies above 5 TeV.

For the observation of the lunar shadow, events accumulated over the period from July 2006 to November 2009 were selected, initiated by protons with a median energy of $\approx 750 \text{ GeV}$ arriving from a sky region of size $10^\circ \times 10^\circ$ at the center of which the Moon was located. Figure 58 shows the resulting map of the statistical significance of the event deficit.

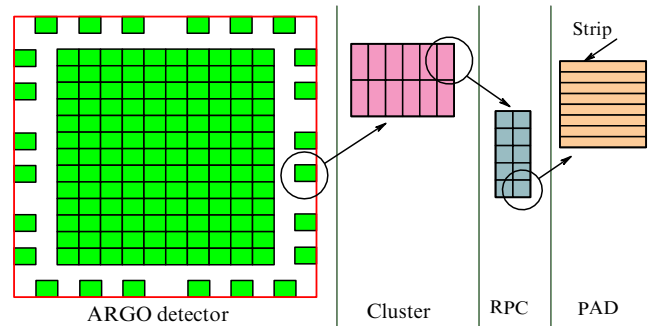


Figure 57. Layout of the ARGO-YBJ installation: a central array of 130 clusters and a surrounding ring of 23 clusters.

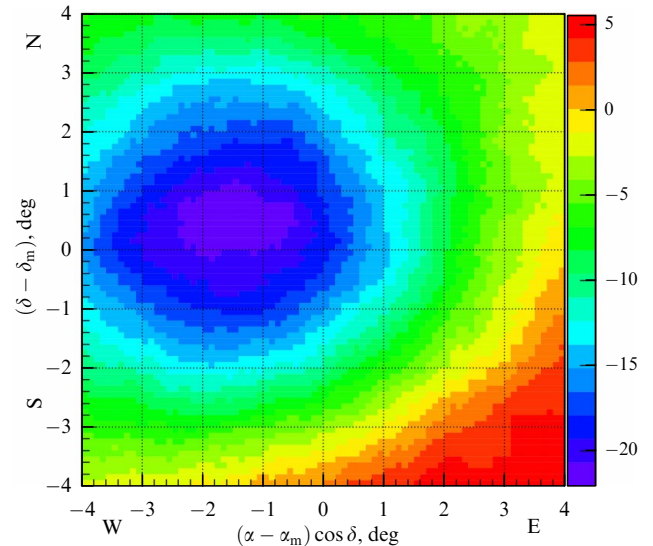


Figure 58. Map of the statistical significance of the event deficit according to the ARGO-YBJ data. The axes show right ascension (α) and declination (δ), reckoned from the position of the Moon (α_m, δ_m). The colour shows the statistical significance in units of standard deviation [228].

The center of the observed shadow is, as expected, displaced relative to the lunar disc, with its main part located on both sides of it, overlapping the deficit zone expected for antiprotons. After the calculations, no high-energy antiprotons were found in the cosmic rays, and an upper limit on the

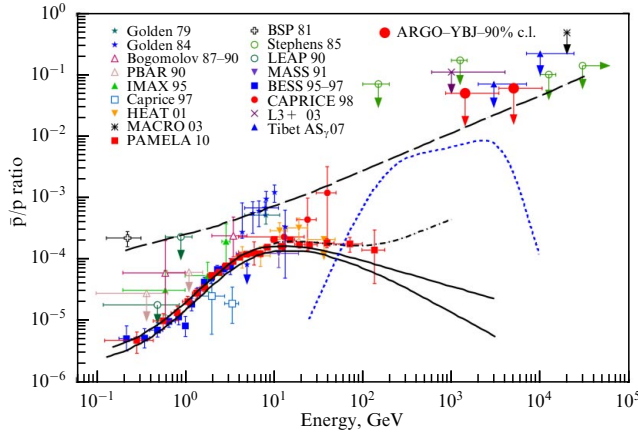


Figure 59. Ratio of the antiproton flux to the proton flux obtained in the ARGO-YBJ experiment, in comparison with other available measurements and with theoretical models [228].

ratio of their flux to the proton flux was established, equal to 0.05 at a median energy of 1.4 TeV and 0.06 at an energy of 5 TeV, at a significance level of 90%. Figure 59 presents a comparison of the results of the ARGO-YBJ experiment on the calculation of the $\bar{p}/p$ ratio with other ground-based and orbital observations. Besides the experimental results, this figure also presents theoretical calculations of the secondary production of antiprotons during CR propagation in the Galaxy (solid lines), a model of extragalactic production of primary antiprotons (dashed line), a model of the annihilation of heavy dark matter particles with the production of antiprotons (blue dashed line), and a model of antiproton production in old supernova remnants and acceleration at CR sources (dash-dotted line).

4.7 HAWC

The most stringent constraints on the antiproton content in cosmic rays available to date were published in 2018 by the HAWC collaboration from the results of measurements at the observatory of the same name [229]. The observatory consists of 300 water Cherenkov detectors located over an area of 22000 m².

The work used data accumulated between November 2014 and August 2017. The map of the region of the sky under consideration, in which the Moon shadow was expected, was constructed under the assumption of an isotropic cosmic ray background and of a shadow in the form of a deficit of their flux. The expected angular deflection $\delta\omega$ was estimated by the formula

$$\delta\omega \simeq 1.6^\circ Z \left(\frac{E}{1 \text{ TeV}} \right)^{-1} \quad (1)$$

for particles with charge Z and energy E .

The shadow in the proton flux was described by a two-dimensional Gaussian distribution, whose parameters characterize its amplitude, displacement, stretching and the blurring of its boundaries. It was assumed that the shadow in the antiproton flux is identical to the shadow in the proton flux, but is located symmetrically with respect to the center of the lunar disc and has a smaller amplitude. Figure 60 shows the map of the cosmic ray flux deficit together with the result of a fit by the sum of two Gaussian distributions.

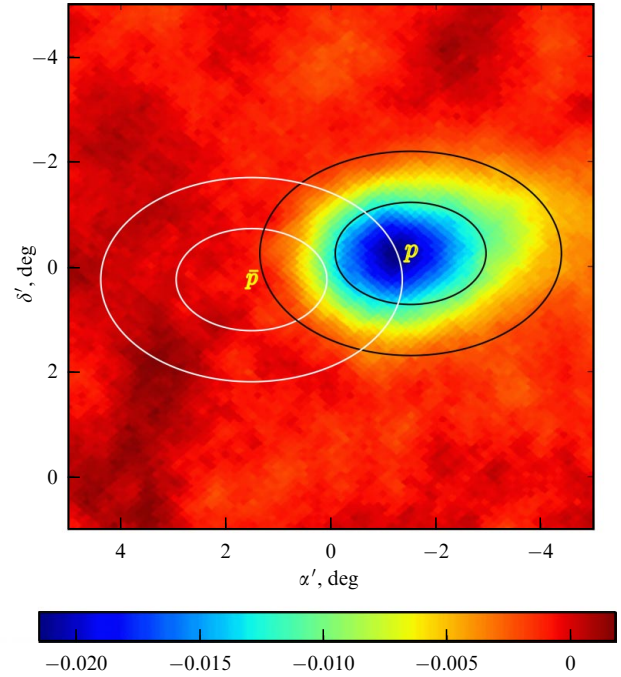


Figure 60. Moon shadow in the flux of protons with an energy of 1.6 TeV. The black ellipses show the 1σ and 2σ levels of the Gaussian distribution used to describe the shape of the shadow. The white ellipse indicates the assumed location of the antiproton shadow [229].

Applying this technique to all energy bins in the range 1–10 TeV, the authors obtained upper limits on the $\bar{p}/p$ flux ratio, shown in Fig. 61. It is worth noting that the upper limits presented correspond to a significance level of 95%, whereas in the earlier works the quoted limits are given for a significance level of 90%.

4.8 Other experiments

The Moon shadow has been observed in a number of other experiments, but a search for cosmic ray antiprotons was not carried out in them. As a rule, the detection of the lunar shadow was used to calibrate the measuring installation and to determine its angular resolution at various energies.

Thus, in the Soudan 2 experiment, whose goal was the observation of proton decay, the lunar shadow made it possible to estimate the angular resolution of the iron calorimeter that recorded the muon flux in the Soudan mine at a depth of 2090 m water equivalent [230]. In 2004 a similar experiment, MINOS, began, aimed at studying neutrino oscillations. The experiment used two iron calorimeters, one of which was located in the same mine. In a 2011 publication the collaboration reported the observation of the shadows of the Moon and of the Sun, which made it possible to measure the pointing accuracy for astrophysical objects [231].

In 1997 data taking began in the Italian experiment CLUE. The measuring installation was an array of optical telescopes optimized for detecting the UV component of the Cherenkov radiation from EAS using photodetectors with a low sensitivity to visible light. The tasks of the experiment included testing the viability of such a measurement technique and the direct observation of the Moon shadow. In a 2001 paper the collaboration published preliminary results of the observation of the lunar shadow [232].

The lunar shadow was observed in the IceCube experiment at the final stage of the construction of the observatory,

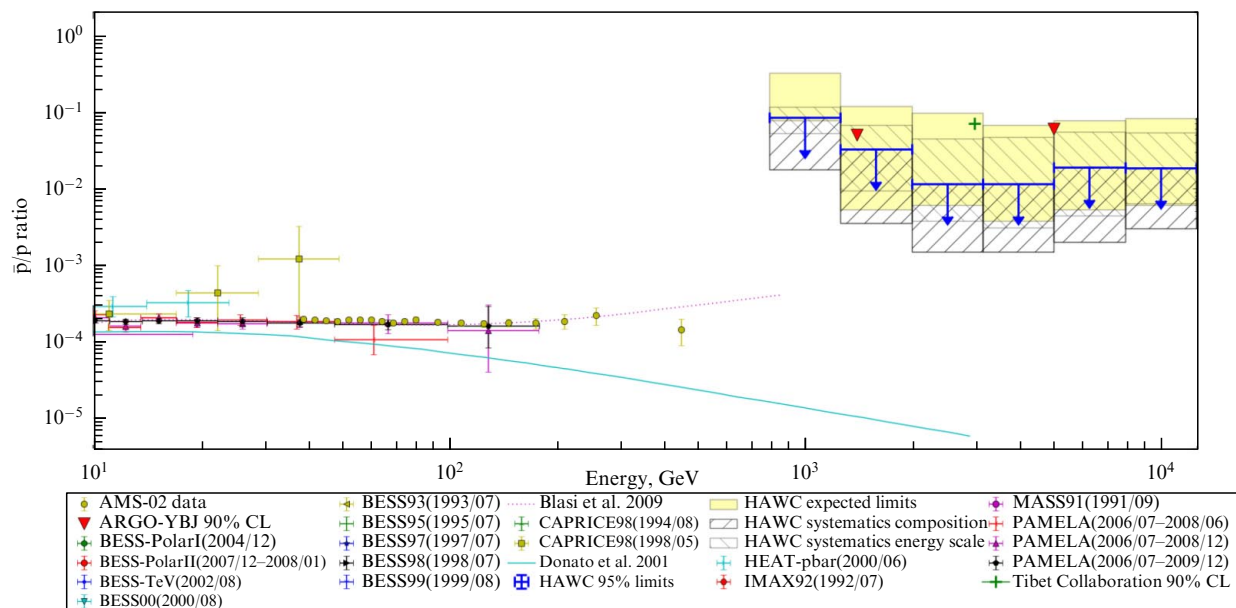


Figure 61. Ratio of the antiproton flux to the proton flux obtained in the HAWC experiment, together with earlier measurements. The yellow and hatched bands show the sensitivity of HAWC and the systematic uncertainty, respectively. The solid line shows the expected dependence of the $\bar{p}/p$ ratio on energy under the assumption of a secondary origin of antiprotons. The dashed line corresponds to the primary production of antiprotons in supernovae [229].

in measurements accumulated over the period from April 2008 to May 2010 [233]. The observatory consists of optical modules located on vertical ‘strings’ in the form of a three-dimensional array under the ice at depths of 1450–2450 m, intended for detecting Cherenkov radiation from muons. The main goal of the experiment is the detection of high-energy astrophysical neutrinos arriving from the northern half of the celestial sphere; the capabilities of the observatory, however, also include the observation of cosmic rays in the energy range from several TeV to PeV. The lunar shadow was used for an independent verification of the correctness of the simulation of the installation and of the event reconstruction technique.

The deep-water neutrino telescope ANTARES complemented the IceCube installation, providing observations of high-energy neutrinos from the southern hemisphere. Its design and principle of operation broadly repeat those of the IceCube installation, which also means the possibility of observing muons from EAS initiated by cosmic rays. In 2018 the ANTARES collaboration published the results of observations of the lunar shadow in the cosmic ray flux from observations over the period 2007 to 2016 [234].

Finally, the Moon shadow in cosmic rays has been observed at modern ground-based gamma-ray observatories and used for calibrating the installation and determining the angular resolution. In 2015 the VERITAS collaboration reported the results of such observations [235], and in 2021 and 2023 the LHAASO collaboration did so [236–239].

5. Antinuclei with $A > 1$

Antihelium-3 was first detected in 1970 at the IHEP accelerator [240, 241], and antihelium-4 was obtained in 2011 at the Brookhaven accelerator [242]. This made it possible to prove that antinuclei with $A > 1$ are also capable of being formed as a result of inelastic collisions of matter particles, like positrons and antiprotons.

Today it is beyond doubt that the detection of antinuclei in cosmic rays constitutes one of the most important problems connected with astrophysics and cosmology. These antiparticles can be generated in classical processes only with an extremely small probability, as a result of which their fluxes due to a secondary origin must be orders of magnitude smaller than the fluxes of the antiparticles already detected today [17, 38, 243]. Thus, according to the calculations [52, 244–248], the fluxes of secondary antihelium-3 and antihelium-4 should prove to be several orders of magnitude below the sensitivity of the largest precision instrument now in existence — AMS-02. The detection of antinuclei above the calculated values corresponding to secondary production would mean the presence of additional sources of them [244, 249, 250]. In such cases the processes most often considered are those connected with the properties of hypothetical dark matter particles [251, 252] or with black holes [253]. The comparatively low energies of the particles formed can be noticeably increased, for example, by second-order Fermi acceleration by magnetohydrodynamic waves in the interstellar medium [251, 254].

Nevertheless, in many cases it proves very difficult to reconcile the measurement results discussed below with theoretical calculations, since a simultaneous explanation of the fluxes of various components of the cosmic rays is required. In connection with this, other hypotheses are frequently encountered, resorting to various realizations of the evolution of matter in the early Universe, which can lead to inhomogeneities in the generation of an excess of matter or antimatter on different scales; this, in turn, may result in the formation at the present epoch of small antimatter domains representing individual antistars or their clusters. In this connection such results are also of fundamental importance for cosmology, providing new information for the study of the structure and evolution of the Universe [255–260].

The initial attempts to detect antinuclei and to estimate their fluxes were undertaken as early as 1975, when the first

constraints on the flux of antihelium nuclei were obtained in experiments using balloon-borne spectrometers [261]. These experiments, despite their technical limitations, became an important step in the search for antimatter in space, laying the foundations for subsequent studies.

5.1 Antihelium

The first measurements in which a constraint on the flux of antihelium nuclei was obtained were carried out in 1975 using spectrometers with superconducting magnets installed on high-altitude balloons [261].

Significant progress was achieved only two decades later with the beginning of the flights of the BESS spectrometer [151, 262, 263]. Over the first seven flights (1993–2000), 6.6×10^6 helium nuclei were recorded in the rigidity range 1–14 GV, and not a single antihelium candidate was found. The upper limit obtained on the ratio of antihelium and helium fluxes was 6.8×10^{-7} at a confidence level of 95%, under the assumption that antihelium and helium have the same spectrum [264].

Later, in the BESS-Polar I experiment, 8.1×10^6 helium nuclei were recorded in the rigidity range from 1 to 20 GV, but again not a single candidate for antihelium nuclei was found in this event sample. The upper limit obtained on the ratio of the fluxes of antihelium and helium nuclei was 4.4×10^{-7} , and from the analysis of the combined data of the BESS experiments up to and including BESS-Polar I an upper limit of 2.7×10^{-7} was established in the rigidity range from 1 to 14 GV [157, 165]. The number of recorded helium nuclei in the same rigidity range was increased to 4×10^7 in the improved BESS-Polar II experiment, but this did not make it possible to detect a single candidate event for antihelium [164]. As in the previous calculations of the BESS experiment, an analysis was carried out of the data recorded in all flights, including both BESS-Polar flights, as a result of which the most stringent limit of 6.9×10^{-8} (at a confidence level of 95%) was obtained under the assumption that antihelium and helium nuclei have the same spectrum [160, 165]. The limit on the ratio of the fluxes $\bar{\text{He}}/\text{He}$ obtained under the assumption that the spectra of helium and antihelium nuclei may differ was 1.0×10^{-7} in the same rigidity range at the same confidence level [160, 265]. Figure 62 shows the limits on the ratio of antihelium and helium fluxes in cosmic rays that were current at the time of publication of the BESS-Polar II data [160].

Thus, the BESS-Polar experiments made it possible to tighten substantially the upper limit on the ratio of antihelium and helium fluxes: by more than two orders of magnitude as compared with the first BESS result [262, 263] and by more than three orders of magnitude as compared with the early measurements [17, 266, 267]. The logical continuation of these studies became the space experiments PAMELA and AMS-02, conducted beyond the stratosphere and free from the background associated with particle production in the residual atmosphere.

After the analysis of the data of the PAMELA experiment collected over the period from June 2006 to December 2009, in the rigidity interval from 0.6 GV to 600 GV, about 6×10^6 events with charge $|Z| = 2$ were selected; all of them had a track curvature corresponding to events with positive rigidity. No events with charge $|Z| = -2$, which could be interpreted as antihelium nuclei, were found. On the basis of these data an upper limit on the ratio of the fluxes of the nuclei $\bar{\text{He}}/\text{He}$ was computed, equal to 4.7×10^{-7} at 95% confidence probability

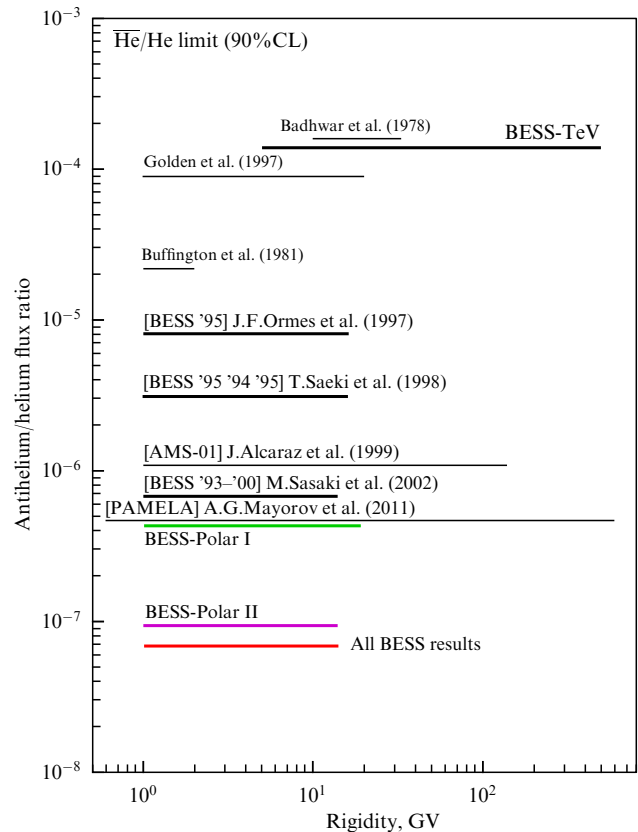


Figure 62. Upper limit on the ratio of antihelium and helium fluxes according to the data of the BESS series of experiments, calculated under the assumption of an identical shape of their energy spectra, in comparison with the results of earlier experiments [17, 266–270]. The limit in the absence of this assumption is about 25% higher [265].

under the assumption of an identical shape of the helium and antihelium spectra [269]. At rigidities above 14 GV this limit is the lowest among all the experiments carried out up to that time (see Fig. 62).

The search for antihelium is one of the priority directions of the work of the AMS-02 magnetic spectrometer; from the results of its first five years of operation (2011–2016) several events with charge $Z = -2$ were singled out, whose reconstructed masses correspond to ${}^3\bar{\text{He}}$ nuclei. The rate of detection of such events was of the order of one candidate per year; for the final confirmation of their nature, however, a suppression of the background, which consists of ${}^3\text{He}$ nuclei, at the level of 10^{-9} is required [271]. In 2016, at a conference devoted to a review of the results of the AMS-02 experiment, about ten events were shown having charges and masses corresponding to antihelium nuclei [13]. In subsequent reports, presented in 2018 at the conference “AMS Days at La Palma,” the continuation of the analysis and the selection of candidates for the antihelium nuclei ${}^3\bar{\text{He}}$ and ${}^4\bar{\text{He}}$ were reported. At a recent CERN seminar (Detector Seminar, 9 May 2025) it was noted in the presentation of Corrado Gargiulo [272] that AMS-02 has by now recorded more than 2.4×10^{11} events, which has extended the possibilities for singling out antiparticles. In particular, ten candidate antihelium events were again reported, eight of which are ${}^3\bar{\text{He}}$ and two are ${}^4\bar{\text{He}}$. Despite the considerable interest, there are as yet no refereed publications with the final statistics for both isotopes; work on the analysis of the AMS-02 data is continuing [272–274].

Even a single reliable antihelium-3 event would be a serious challenge to the standard models of secondary origin, since the fluxes expected from this source lie 1–2 orders of magnitude below the sensitivity of AMS-02 [184]. Contemporary theoretical models show that the inclusion in dark matter annihilation scenarios of channels involving heavy baryons (for example, $\bar{\Lambda}_b$) is capable of substantially increasing the probability of the binding of antinucleons into antihelium while preserving agreement with the antiproton constraints [243, 252]. An alternative to the dark matter scenarios are hypotheses about the existence of long-lived regions of antimatter in the Galaxy—so-called anticlouds or antistars. Recent reviews note that such objects can produce heavy antinuclei upon interaction with interstellar matter, increasing the expected flux of the antihelium-3 and antihelium-4 isotopes by an order of magnitude or more [257]. At the same time, long-lived antidomain structures must possess an extremely low rate of mixing with ordinary matter in order to avoid the stringent constraints from cosmic gamma radiation and from the microwave background radiation. A confirmed detection of even a single antihelium-4 nucleus would be especially difficult to explain within the framework of most existing models and would require an appeal to exotic sources or to new channels of formation of heavy antimatter [243, 248, 275].

5.2 Antideuterons

The search for antideuterons in cosmic rays constitutes one of the most promising problems, since their expected fluxes under standard astrophysical mechanisms of secondary origin are extremely small [51, 276]. This makes antideuterons a particularly sensitive probe for the search for non-standard sources—first and foremost the annihilation or decay of dark matter particles, and also processes connected with primordial black holes.

The first searches for antideuterons in the BESS experiments were carried out from the combined data obtained as a result of four high-altitude balloon flights from 1997 to 2000; not a single candidate, however, was recorded [170, 277]. Nevertheless, an upper limit at a confidence level of 95% was established for the differential flux of cosmic ray antideuterons in the energy range 0.17–1.15 GeV/nucleon at the top of the atmosphere, equal to $1.9 \times 10^{-4} \text{ (m}^2 \text{ sr GeV/nucleon)}^{-1}$.

Analysis of the BESS-Polar II data obtained in 2007–2008 under conditions of solar-activity minimum made it possible to improve this constraint substantially. As a result of processing 4.7×10^9 cosmic ray events, no $\bar{d}$ candidate was found, and a new upper limit on the $\bar{d}$ flux was established, amounting to $6.7 \times 10^{-5} \text{ (m}^2 \text{ sr GeV/nucleon)}^{-1}$ at a confidence probability of 95% in the energy range from 0.163 to 1.100 GeV/nucleon [278]. This limit is presented in Fig. 63 in comparison with the possible antideuteron fluxes at solar minimum obtained from theoretical calculations [279–281].

The modern BESS-Polar II result exceeds the BESS97 limit by more than a factor of 14 and for the first time attains a sensitivity sufficient to constrain a number of contemporary theoretical models. In particular, the predicted $\bar{d}$ fluxes from dark matter annihilation in the $b\bar{b}$ channel with a mass of ~ 70 GeV, from the decay of a gravitino with a mass of ~ 50 GeV, and from the evaporation of primordial black holes with a local density in the vicinity of the Solar System of $10^{-32} \text{ g cm}^{-3}$, prove to be comparable with, or are partially excluded by, the BESS-Polar II results [51, 279–281]. An important circumstance is that the astrophysical background of secondary antideuterons formed in the interactions of

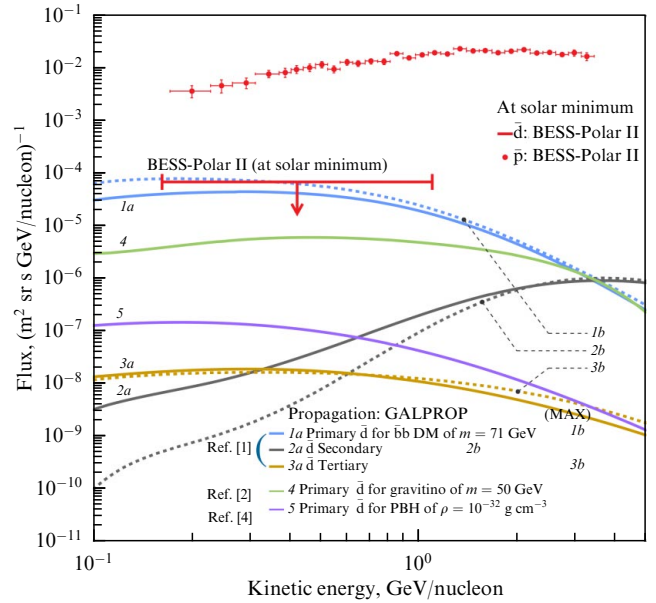


Figure 63. Upper limit on the antideuteron flux according to the BESS-Polar II data at the minimum of solar activity in 2007–2008; the red points show, for comparison, the antiproton flux for the same period of time. The solid curves (1a, 2a, 3a) and dashed curves (1b, 2b, 3b), calculated with different sets of propagation parameters, are shown for primary $\bar{d}$ produced as a result of the annihilation of DM particles into a $b\bar{b}$ pair, and for the secondary and tertiary contributions, respectively. The solid curves (4, 5), calculated with a single set of propagation parameters, are presented for theoretically possible sources of primary $\bar{d}$, such as the gravitino [279] and PBH [281].

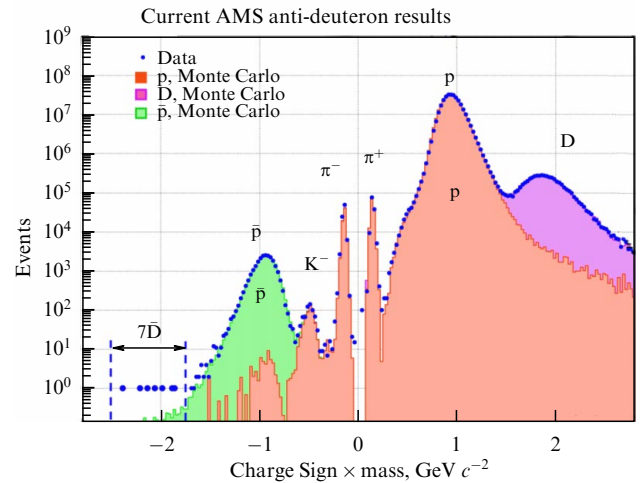


Figure 64. Candidate antideuteron events presented by the AMS-02 collaboration in June 2023 at a seminar at CERN [284].

cosmic rays with interstellar gas is, at low energies (< 1 GeV/nucleon), several orders of magnitude below the possible signal from non-standard sources [282]. This makes further searches for $\bar{d}$ especially promising.

In 2016, at a conference devoted to a review of the AMS-02 results, the preliminary selection of several antideuteron candidates was reported; up to now, however, these data remain without peer-reviewed publications [13]. Further discussion of the prospects for observing antideuterons and of their possible sources took place at the conference “2nd Cosmic-ray Antideuteron Workshop” at UCLA [283]. Later these candidate events were presented by the AMS-02 collaboration at a seminar at CERN in June 2023 [284].

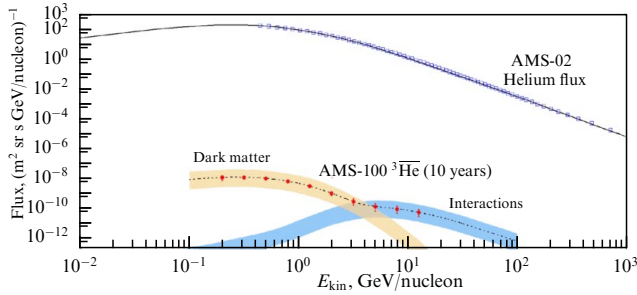


Figure 65. Prediction of the flux of antihelium-3 nuclei according to the AMS-100 data. For comparison, the helium flux according to the AMS-02 data is presented [285].

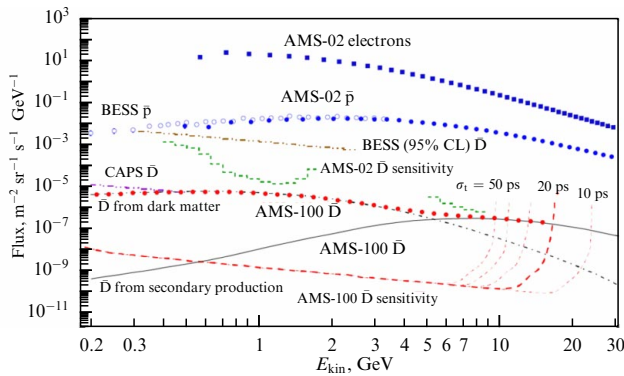


Figure 66. Comparison of the sensitivity of modern (AMS-02 and BESS) and planned (AMS-100 and GAPS) detectors to antiparticles with $Z = -1$ [285].

5.3 Future experiments

The AMS-02 experiment will be developed further in the new-generation spectrometer AMS-100 (see Section 3.1.7), whose priority task will be the detection of heavy antinuclei with $A > 1$. According to the calculations presented in Ref. [205], AMS-100 will be capable of detecting of the order of 1000 antideuteron events over ten years (Fig. 66).

Moreover, if one extrapolates the rate of detection of antihelium events by the AMS-02 experiment and takes into account the geometric factor of AMS-100, this gives a counting rate of the order of 1000 antihelium-nucleus events per year, which will make it possible to perform an accurate measurement of the shape of the spectrum of antihelium nuclei [205]. Thus, the resolution of AMS-100 will be sufficiently high to distinguish between the sources of antihelium nuclei (Fig. 65).

Particular hopes for increasing the sensitivity to antideuterons are placed on the GAPS experiment (Fig. 66), whose first launch in the form of a stratospheric flight (GAPS balloon) is expected in the coming years, while a satellite version (GAPS SAT) is being considered as a long-term prospect [282, 286].

The GAPS technique is based on the detection of cascades of X-ray and gamma radiation upon the formation of exotic antimatter atoms in a gaseous target. Such a technique is especially effective for low-energy antideuteron, where the background processes are minimal. According to the calculations, it is precisely antideuteron that are considered a reliable signal from dark-matter particles, since their secondary astrophysical background is extremely small [282].

The detector of the GAPS SAT experiment now under development may potentially be sensitive to WIMP [286]

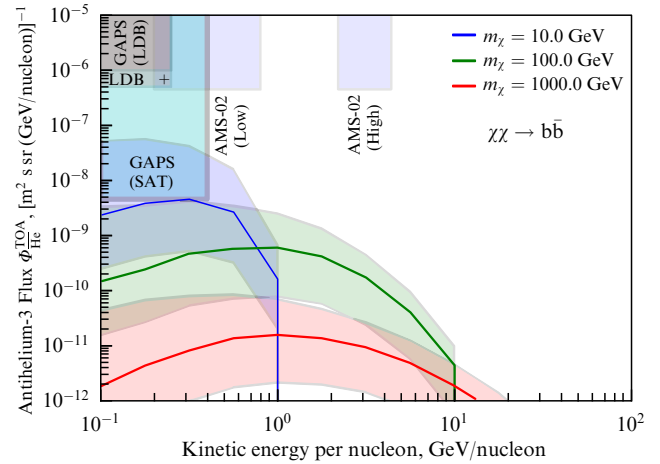


Figure 67. Flux of antihelium-3 arriving at the top of the atmosphere for different scenarios of dark matter annihilation [52].

annihilating into W^+W^- and $b\bar{b}$ [52]. Figure 67 shows the flux of antihelium-3 arriving at the top of the atmosphere for different scenarios of dark matter annihilation (W^+W^- and $b\bar{b}$) at various masses of the dark matter particles. The plots show that under optimistic scenarios the GAPS SAT experiment may record signals from the annihilation of dark matter particles if its mass is not greater than 10 GeV; higher masses, however, rapidly become inaccessible to observation, especially in the case of W^+W^- .

There are also more exotic ways of detecting cosmic ray antinuclei. Thus, in Ref. [222], discussed above, it was suggested that antiparticles with $A > 1$ might be observed by means of the Moon-shadow method. It was suggested that the shadow from antihelium could be observed farther out than the antiproton shadow, with possible overlap. No exact calculations, however, such as those for antiprotons, were given. At present there are no papers that apply this method to observational data. Only in a 2007 paper was it mentioned that in observations of the Moon shadow there is no evidence for the presence of negatively charged particles such as $\bar{p}$, $\bar{d}$, $\dots$, $\bar{Fe}$, $\dots$, if any exist. Thus, until the method is refined for the search for antiprotons, it is not possible to apply it to the search for other antiparticles.

6. Conclusion

The detection and observation of antiparticles, in particular of antiprotons, is a promising direction for studying the structure of the Universe on all scales: from the theory of the interaction of particles of different energies and the propagation of charged particles in the surrounding medium to the investigation of the structure of the Universe (baryon asymmetry), the existence of alternative sources of antiparticles, and the study of dark matter. The observed excess of antiparticle fluxes may be connected with unaccounted-for sources of antiparticles: astrophysical sources, the decay and/or annihilation of exotic particles beyond the Standard Model, or an incorrect assumption on our part about the composition of the interstellar medium and the differences in the interaction cross sections.

Thus, this review of the studies carried out on antiprotons and heavier antinuclei in cosmic rays demonstrates the important role that these particles play in the investigation of the fundamental processes of the Universe. Antiprotons,

along with other antimatter particles (positrons and antinuclei), represent unique particles that make it possible to investigate the mechanisms of generation and propagation of cosmic rays in the Galaxy. Understanding their origin and characteristics makes it possible to study not only the processes occurring in astrophysical sources such as supernovae and their remnants, but also phenomena of a more exotic nature, including the annihilation of dark matter particles and the evaporation of primordial black holes.

The prospects for research on heavy antinuclei, such as antihelium, also remain open. The detection of such particles, even in single events, could change our conception of the origin of antimatter and point to the existence of regions of antimatter or of cosmological processes differing from those of the standard model.

Accurate measurements of the antiproton spectrum over a wide energy range make it possible to constrain the parameters of dark matter models and provide valuable information about the processes of interaction of cosmic particles with interstellar matter. Despite the successes of recent years, open questions remain that require further experiments, especially in the high-energy region and in studies of heavier antinuclei such as antihelium. This creates the preconditions for new missions and for the development of more sensitive detectors.

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