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The antimatter component of cosmic rays and the PAMELA experiment

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ABSTRACT

In this lesson it will be adopted the following scheme:

- (a) - The antimatter component of cosmic rays:
  - (a.1) Predictions of the theories
  - (a.2) Status of the experimental observations
  - (a.3) Observation programs for the next future
- (b) - The PAMELA experiment

1 The antimatter component of cosmic rays.

1.1 Prediction of the theories.

I will begin my lesson following an historical approach.

The chronicle of the antimatter search can be summarized according the following table:

- 1928 prediction of antielectron (Dirac)
- 1932 discovery of positron in cosmic rays (Anderson)
- 1954 "antiproton induced" events in cosmic rays (Amaldi)
- 1955 antiproton manufactured in laboratory (Chamberlain et al.)
- 1965 antideuteron manufactured in laboratory (Massam et al.)
- 1960's Baryon Symmetric Cosmologies (Klein, Alfven,..)
- 1967 Sakharov's conditions (Sakharov)
- 1970's Baryon Symmetric Cosmologies (Stecker,...)
- 1970's gamma-ray "evidence"
- 1979 discovery of antiprotons in cosmic rays (Bogomolov et al., Golden et al.)
- 1996 antihydrogen manufactured in laboratory
- ???? ? antinuclei in cosmic rays? (??)

In the period between the 30's and the 60's the fundamental question that urged the cosmologists was:

how can the Universe contain equal amounts of 'particles' and 'antiparticles', as implied by the rigorous symmetry of the fundamental laws of the Nature?

The task was that of constructing mechanisms for separating particles and antiparticles on a cosmological scale. Many works were dedicated to this task, but it could not be solved at that time. The Big Bang models based on statistical fluctuations resulted in astronomical objects of very tiny mass, less than 10^{-30} of the mass of the Galaxy. Furthermore they could not avoid the so called 'annihilation catastrophe' at the very beginning of the history of the Universe, leading to an extremely low ratio of 10^{-18} between Baryons and Photons at the present time, to be compared to the observed 10^{-9}.

The CP violation observed in the weak interactions in 1964, allowed Sakharov to formulate the hypotheses for achieving a sufficient Baryon Asymmetry in the Early Universe:

- (1) Baryon decay allowed,
- (2) CP violation allowed,
- (3) a period out of equilibrium.

Of these assumption, the first one has not still been observed, the second one occurs in kaons decay, not with the required strength, and the third one is surely satisfied in the hot Big Bang models.

These three Sakharov's conditions are still the best that we have for conceiving the possibility of an "all matter" Universe. They offers a solution to the particles-antiparticles separation problem in a Baryon Symmetric Universe, according to the following scheme:

- (1) CP is spontaneously violated,
- (2) there can be domains with either all particles or all antiparticles,
- (3) and inflation can increase these domains to the astronomical scale.

The conclusion that we can formulate now from the history of the prediction of the theories is the following:

- The theory needed to support a Baryon Asymmetric Universe is far away from being complete.
- Our present understanding does not forbid a Baryon Symmetric Universe.

Concerning this last point it must be pointed out that the observation of an "all matter" Universe is a local phenomenon. It concerns only our supercluster of galaxies, a volume of 10^{-8} of the volume of the Universe, where the ratio antibaryon/baryon is observed to be less than 10^{-5} in the hypothesis of well-mixed baryon and antibaryon gas systems.

1.2 Status of the experimental observations.

In the lack of a guiding theory, we can only investigate by direct or indirect observation for understanding if Universe is or is not symmetric.

Indirect observations can be obtained by studying the spectrum of the gamma ray radiation arriving to us from the space. An abundant presence of antiprotons in the Universe should give a 'bump' in the gamma ray spectrum, due to the $\gamma's$ coming from the decay of the π^0's in the annihilation of the antiprotons with the interstellar and intergalactic matter. The absence of such a 'bump' allows putting limits on the fraction of existing antiprotons. These limits obviously depend from the volume of space considered around us. In the hypothesis that the gasses of protons and antiprotons are well mixed, the following figures are obtained:

- less than 10^{-15} in the particle clouds in the Galaxy;
- less than 10^{-10} in the halo of the Galaxy;
- less than 10^{-5} in our cluster of galaxies.

Until about 1995, it was claimed that the big bump observed in the high-energy diffuse cosmic X-ray background, in the energy region between 1 and 10 GeV, could be interpreted as a red-shifted signal of antiproton proton annihilation processes, with the $\gamma's$ of the π^0 decay arriving to us from cosmological distances, at red shifts of about 100. The existence of such bump was based on several balloon measurements conducted at the top of the atmosphere, very difficult and suffering of huge corrections and systematic uncertainty.

In 1995 the much more clean data of the COMPTEL experiment on board of the Compton Gamma Ray Observatory in Orbit around the Earth, made the bump disappear. With the bump disappeared also any possible indirect signal of a significant presence of antiparticles in the Universe. We can therefore only relay on direct observation of antiparticles reaching us from the space. These observations must necessarily be performed outside of the Earth atmosphere, by direct detection of the antiparticle component of cosmic rays on board of stratospheric balloons or of satellites.

This component consists of positrons, antiprotons and antinuclei.

• Positrons are not very useful for this kind of investigation. They suffer of the huge background coming from many astrophysical processes, and it is very difficult to pick up a significant contribution from extragalactic sources.
• Antiprotons are relatively abundant in cosmic rays, because they are produced as secondary in the interaction of protons with the interstellar matter. This is a background for the detection of possible extragalactic contributions. This background decreases at energies exceeding 10 GeV, and at much higher energies, around or more than 100 GeV, antiprotons could be an enough sensible probe of extragalactic contributions, either coming from 'dark matter' processes, or from the diffusion of antiprotons from 'all antiparticle' domains in the Universe. The 'dark matter' processes should show up as a 'bump' in the antiproton energy spectrum, while the antiproton diffusion from 'all antiparticle' domains should give a smooth rising of the antiproton/proton ratio with the energy.
• For what concerns the antinuclei, we have no idea of their abundance, neither of the possible background. If they diffuse from an 'all antiparticle' domain, we can guess that their chemical abundance could be similar to our 'all matter' domain. Therefore the antihelium nuclei should be much more abundant that the other ones, and are the first candidates we should look for. However there are two important difficulties that antinuclei should overcome to reach us:
◇ They cannot travel to us following a direct path. The intergalactic magnetic fields brakes their diffusion, and the probability of arriving is proportional to their energy. Therefore those antinuclei that should be much more abundant, with energies of one or a few GeV/nucleon, could have a low probability of arriving, while those that have higher energies and could arrive, could be much less abundant at the origin.
◇ The probability for an antinucleus to reach our position in the Galaxy could be also diminished by the difficulty it will find for winning the galactic wind flowing from the Galaxy. It is the analogous of the solar wind preventing the less energetic galactic cosmic rays to reach our position in the solar system. Unfortunately also the galactic wind contrasts the penetration of the potentially most abundant less energetic antinuclei.

At present all the direct measurements of the antiparticle component of cosmic rays were made by balloon borne experiments, and gave results for the positron and for the antiproton energy spectra up to about 50 GeV. The statistical and systematic errors of these measurements are somewhat large, up to about 30% for the highest points in energy. Inside these errors the fluxes of both these components can be justified by production of proton interactions on the interstellar matter (see the figures of the antiproton/proton and positron/(positron+electron) ratios in the *Balloon experiments* lesson). No antihelium nuclei have been detected, with a sensitivity down to 10^{-6} on the antihelium/helium ratio.

We can therefore conclude that at present, in the limits of the errors and of the explored energies, no experimental indications were obtained for the existence of significant quantities of cosmological antiparticles in the Universe.

1.3 Observation programs for the next future.

In order to obtain a more significant answer to the problem of the symmetry or of asymmetry of the Universe in its content of particles and antiparticles it is necessary to push the experimental investigation in the following directions:

- increase the statistics of the observation, either by long duration balloon borne experiments or by satellite borne experiments;
- the increase of the statistics will allow also to reach a higher energy in the study of the energy spectra;
- however this cannot be easily obtained by balloon borne experiments, because the secondary production on the residual air on top of the balloon prevents the possibility of exceeding 50 GeV without being flood by the background; therefore, for reaching higher energies it is mandatory to perform satellite borne experiments.

These directions are at the basis of the short coming experiments devoted to the study of the antiparticle components of cosmic rays:
• The BESS experiment will go on to increase the statistics in the measurement of the antiproton component at relatively low energies, from a few hundreds MeV up to a few GeV. At these energies the background due to the production of secondary antiprotons in the residual atmosphere is negligible. Therefore a significant increase of the statistics can be obtained by going from the present balloon borne experiment duration, of about 20 hours, to the long duration

balloon experiments in the Antarctic continent. The BESS program foresees to begin such experiments in 2003.

• The PAMELA experiment will be the first one that will study the antiparticle component in orbit around the Earth. It will be launched on board of a Russian satellite at the end of the year 2002, and will collect data for three years, allowing to measure the positron spectrum up to 270 GeV, and the antiproton spectrum up to 190 GeV. To the description of this experiment it will be devoted the last part of this lesson.

• A much larger acceptance experiment will follow up, the AMS-02 experiment on board of the International Space Station, starting in the year 2004 or 2005. Also if probably it will not allow extending very much the energy spectra for positrons and antiprotons, it will increase the sensitivity for hunting antinuclei down to about 10^{-10} in the antihelium/helium ratio. AMS-02 will be described in the lesson of Prof. Battiston.

2 The PAMELA experiment.

The PAMELA experiment is the most important activity of the international collaboration known by the name 'Wizard'. This collaboration was constituted 15 years ago for performing the WIZARD experiment at the cosmic ray facility ASTROMAG foreseen on board of the International Space Station FREEDOM. The ASTROMAG facility was based on the use of a powerful magnetic system based on superconducting coils. ASTROMAG was one of the two main programs foreseen in the general program for cosmic rays research recommended by the NASA Cosmic Ray Program Working Group established by NASA in 1984, following the recommendation made in 1982 by the National Academy of Sciences of USA. The other foreseen main program was an explorer sent in the interplanetary space for studying in detail the low energy portion of the galactic cosmic rays. This probe, known with the name ACE, is now working in space since a few years, sending the best low energy cosmic rays data until now collected. Instead the ASTROMAG facility could not be realized for the cancellation of the FREEDOM Space Station by the USA. For this facility were already selected three experiments, covering the most important open questions in the study of the galactic cosmic rays:

- The SCINATT experiment, proposed by a Japan-USA collaboration, dedicated to the study of the chemical composition of cosmic rays at energies up to 10^{16} per nucleus.
- The LISA experiment dedicated to the study of the chemical and isotopic composition of cosmic rays.
- The WIZARD experiment, based on an Italian-American collaboration, dedicated to the study of the antiparticle component in cosmic rays and to the search for antinuclei.

After the cancellation of the FREEDOM Space Station the WIZARD collaboration did not disbanded and decided to go on on the proposed researches by balloon borne and satellite borne experiments. The first balloon borne experiment was launched in 1989, afterwards the collaboration acquired an increasing experience, allowing to afford the much more complex PAMELA experiment (fig.1). The balloon experiments performed by the WIZARD collaboration are

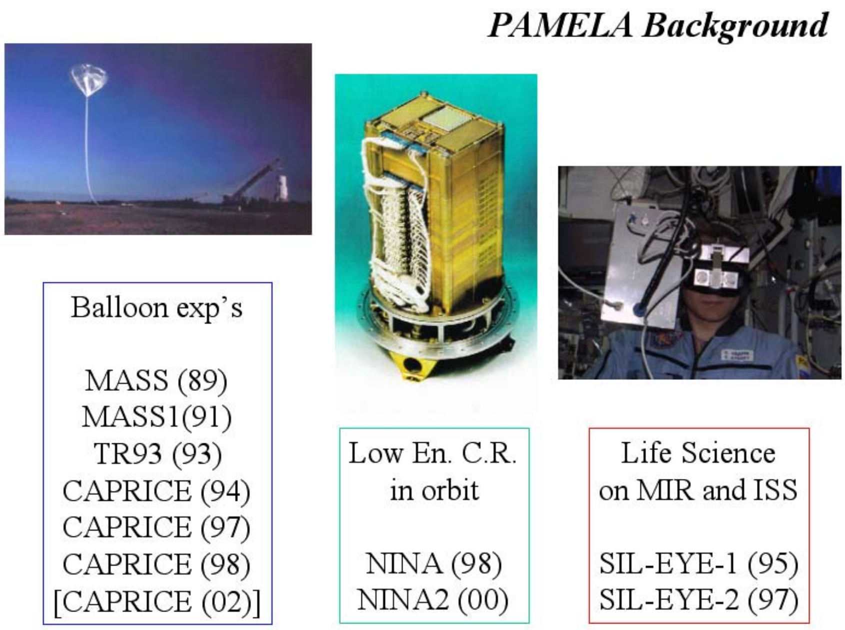

Figure 1: The Wizard background

shortly described in an other lesson of this course. The collaboration conducted also a number of experiments dedicated to the study of the low energy portion of the solar cosmic rays either on board of satellites (NINA and NINA2) or on the MIR Space Station (SIL-EYE-01 and SIL-EYE-02). These experiments are described in dedicated lesson of this course.

In the last part of this paragraph it will be described the PAMELA experiment. The main scientific objectives of PAMELA are:

- 1 - measurement of the energy spectrum of antiprotons up to 190 GeV and down to 80 MeV,
- 2 - measurement of the energy spectrum of positrons up to 270 GeV and down to 50 MeV,
- 3 - search for antinuclei with a sensitivity of 3×10^{-8} in the antihelium helium ratio,
- 4 - measurement of the energy spectrum of protons up to 700 GeV and down to 80 MeV,
- 5 - measurement of the energy spectrum of electrons up to 2 TeV and down to 50 MeV.

The PAMELA instrument will fly in a highly inclined (quasi polar) orbit, and will collect data during the period of transition of the solar activity from its maximum to its minimum, down to very low energies, overlapping with the energies studied with the NINA and NINA2 experiments. Therefore to the above main objectives of PAMELA the following by-product investigations can be added:

- 6 - modulation of galactic cosmic rays by the solar wind,
- 7 - study of the Solar Energetic Particle fluxes as a function of the time and of the energy,
- 8 - stationary and disturbed fluxes of particles in the magnetosphere.

The scheme of the PAMELA instrument is shown in fig.2, where also the main features of the detectors are reported. The instrument is constituted by a telescope of particle sensors, based on a magnetic spectrometer complemented by several detectors. The spectrometer is a system of five permanent magnets interleaving 6 plane of very sophisticated silicon sensors. Before the spectrometer the particle will encounter an extremely compact Transition Radiation

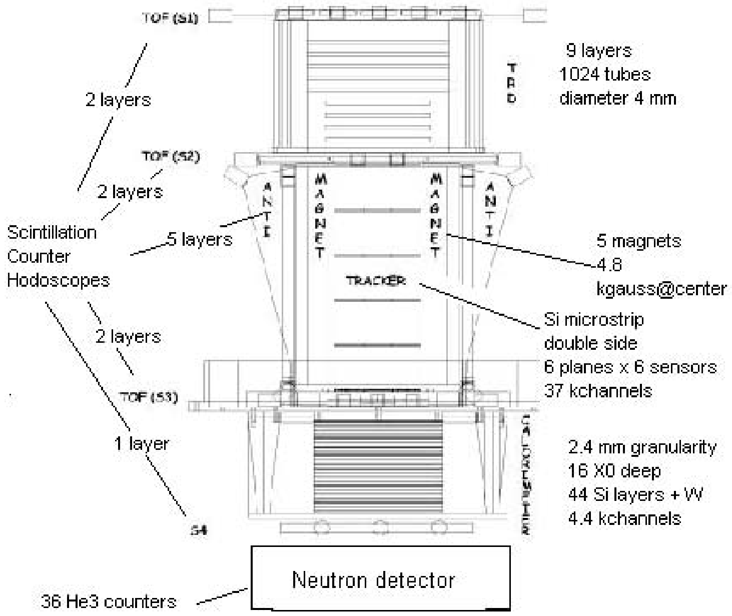

Figure 2: Scheme of the PAMELA instrument.

Detector (TRD) that will select the electromagnetic component of cosmic rays. After the spectrometer the particle will enter a very compact and deep imaging calorimeter, that will supply the detailed description of the interaction of the particle inside its volume, allowing to identify the nature of the particle. A set of scintillation counter hodoscopes (S1, S2 and S3) will supply the triggers, will measure the charge of the particle and its times of flight between the different hodoscopes. A penetration counter (S4) on the bottom of the imaging calorimeter will measure the flux of particles escaping from the calorimeter, and a neutron counter system (ND) will measure the number of neutrons escaping from the interactions in the calorimeter volume. Finally a system of several anticoincidence scintillation counters will protect the apparatus from external background. The total mass of the apparatus is 480 kg, its electric power consumption 345 W, its geometric factor $20.5 cm^2 sr$. The spectrometer has a Maximum Detectable Rigidity (MDR) exceeding 740 GV/c.

The PAMELA instrument will fly on board of the RESURS-DK1 Russian satellite in a highly inclined elliptic orbit (fig.3). Distinctive features of the

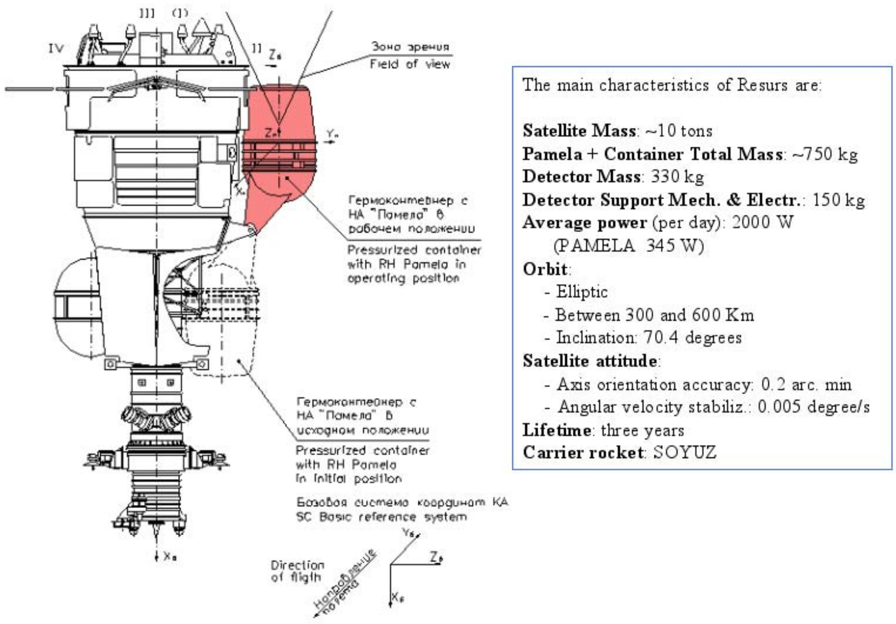

Figure 3: Scheme of the PAMELA instrument.

PAMELA instrument are the following:

• The wide energy range covered with the same instrument. This is obtained maximizing the MDR of the spectrometer (the position of the going through particle in each plane of the tracker is measured with a precision of $3 \mu m$) and minimizing the thickness of the triggering scintillation counters ($\leq 0.7 cm$).

• A robust separation between electromagnetic and hadronic particles, better than a part on 10^5 @ 90% efficiency. To obtain such separation the Imaging Calorimeter is 16 Xo deep, is highly granular and is complemented by the TRD,

the penetration counter S4 and the Neutron Detector.
• The Imaging Calorimeter can be calibrated in flight by selecting electrons in the TRD and measuring their momentum in the spectrometer.
• The multiple scattering in the magnetic spectrometer has been kept as low has possible (it contributes with less than 4% to the measurement error) by supporting the silicon sensors only at their edges, so that no other material than silicon is added on the particle path.
• The time of flight of the particle through the telescope is measured several times in order to improve its precision, but also for rejecting background.

Several prototypes of the various detectors have been constructed and tested on particle beams before affording the final construction. The performance of the final prototypes is:
♣ Magnetic spectrometer: the magnetic field supplied by the five magnets is 4.8 kgauss, uniform in all the magnetic volume of the spectrometer ($16 \times 14 \times 45 cm^3$). The tracker gives the position of the particle in each plane on the bending view with a standard error of $3\mu m$. [However, the above quoted value of 740 GV/c for the MDR assumes a field of 4.0 kgauss and a measurement precision of the position of $4\mu m$.]
♣ Imaging Calorimeter: the measured contamination of electrons on pions and of pion on electrons at 40 GeV/c is less than 10^{-4} at 90% efficiency for the selected particle. The energy resolution for the electrons is better than 5% up to 120 GeV.
♣ The TRD gives a separation of electrons from pions better than 10% at 90% efficiency from 2 up to 40 GeV/c.

With this performance the instrument assures that the objectives of the experiments can be reached for all the above quoted items. The expected measurement ranges for antiprotons and positrons are those reported in the fig. 14 of the lesson of A. Morselli, and the sensitivity in the antihelium to helium ratio is shown in figure 10 of the *Balloon experiments* lesson).

The final PAMELA instrument will be calibrated at CERN/SPS in summer of next year, and ready to be integrated on the RESURS-DK1 satellite in September 2002. The launch is scheduled for December 2002 from the Baikonur cosmodrome.