ASTROPARTICLE PHYSICS WITH AMS-02: THE QUEST OF ANTIMATTER

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*Abstract.*The Alpha Magnetic Spectrometer, to be placed on the International Space Station, will provide data on cosmic radiations in a large range of energy from 0.5 GeV to 3 TeV. Its main physics goals in the astrophysical domain are the anti-matter and the dark matter searches. The potential discovery of primordial antimatter by AMS-02 is presented. The observation of antinuclei or even of high energy antiprotons can be a signal to the existence of antistars in our universe. The anti-He^3 and anti-He^4 signals can probe the universe up to a redshift of about 1000. Possible investigated scenarios of baryogenesis are briefly discussed. Antiparticles, like positrons and antideuterons, as well as low energy antiprotons, can also reveal some exotic physics like dark matter.

1 The AMS experiment

The Alpha Magnetic Spectrometer (AMS) [1] in its prototype version (AMS-01) was flown for ten days on board the space shuttle Discovery (1998) . It performed environmental and background studies and fulfilled the constraints imposed by space. A limit on antimatter/matter in our universe was established, for the energy spanned by the detector [1]:

$$\frac{\overline{He}}{He} < 1.1 \times 10^{-6} \quad @\ 99\ \%\ C.L. \tag{1}$$

The knowledge obtained with the precursor AMS-01 was used to redesign and improve the detector for the Space Station and for a longer mission. The International Space Station (ISS), at about 400 km of altitude, has good geomagnetic and galactic coverage. The main orbit characteristics are:

- sixteen revolutions/day
- 51.7° of inclination (degrees parallel to latitude)
- 5° precession/day

Table 1 compares the typical resolutions and maximum fluxes of the spectrometers AMS-01 and AMS-02.

The new AMS-02 detector improves largely the analyzing power and momentum resolution thanks to, respectively, the use of a superconducting magnet and the improved tracker performance: 8 layers of double sided silicon tracker with an accuracy of $\sim 10\mu m$ in the bending plane and $\sim 30\mu m$ in the non bending

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Value	**AMS-01**	**AMS-02**
MDR	150 GV	$1 \div 2$ TV
Statistics	2.86×10^6	10^9
$E_{Max}(e^-)$	~ 30 GeV	1.4 TeV
$E_{Max}(e^+)$	~ 3 GeV	350 GeV
$E_{Max}(\bar{p})$	~ 3 GeV	450 GeV
BL^2	~ 0.15 Tm^2	~ 0.9 Tm^2
Acceptance	0.15 m^2sr	~ 0.45 m^2sr
$\frac{\Delta p}{p}(1GeV)$	$\sim 10\%$	$1 \div 2\%$

Table 1: Comparison of the overall statistics, Maximum Detectable Rigidity (MDR), analizing power (BL^2) , acceptance and momentum resolution (at 1 GeV) and maximum energy for different kind of particles, obtained with AMS-01 and expected for the next AMS-02 mission.

plane [2]. The basic idea in constructing AMS-02 detector has been: low matter traversed by the cosmic rays and many repeated measurements of particle velocity, momentum and charge (necessary redundancy to operate in space for at least three years). All the AMS-02 subdetectors [3] are designed to collect a huge statistics of all type of cosmic rays from 1 GeV/n to 1 TeV/n.

The subdetectors are, from top to bottom shown in figure 1:

- TRD: 20 layers for electrons/hadrons (e/h) separation ($1.5 \div 300$ GeV)
- TOF: 4 planes of counters for trigger, time, velocity and charge |Q| measurement ($\frac{\Delta\beta}{\beta} \sim 3 \div 4\%$)
- TRACKER: 8 layers of double sided Silicon sensors for momentum and charge $\pm$ Q measurement ($\frac{\Delta p}{p} \sim 2\%$ at 1GeV).
- VETO: counters sorrounding the magnet
- RICH: ring imaging cerenkov with pixellized PMTs, for β ($\frac{\Delta\beta}{\beta} \sim 0.1\%$) and |Q| measurements.
- ECAL: brick of lead and plastic fibers (15 X_0) read in 3-D by PMTs, for e/h separation (1.5 GeV $\div$ 1 TeV) with an energy resolution < 3 % for E>10 GeV

The spectrometer is designed in such a way to have a proton rigidity resolution of 20% at 0.5 TV and a Helium resolution of 20% at 1 TV, as you can see in figure 2. The RICH can allow good isotope separation, in fact: $\frac{\Delta m}{m} = \frac{\Delta p}{p} \oplus \gamma^2 \frac{\Delta\beta}{\beta}$ with p measured by the tracker. Clearly the error on the velocity is the dominant term as the momentum increases. For the Cerenkov angle, measured by the RICH, the relation is: $\frac{\Delta\beta}{\beta} = tan\theta_c \Delta\theta_c$ and the uncertainty on β scales as $1/\sqrt{N}$, where N is the number of detected photons.

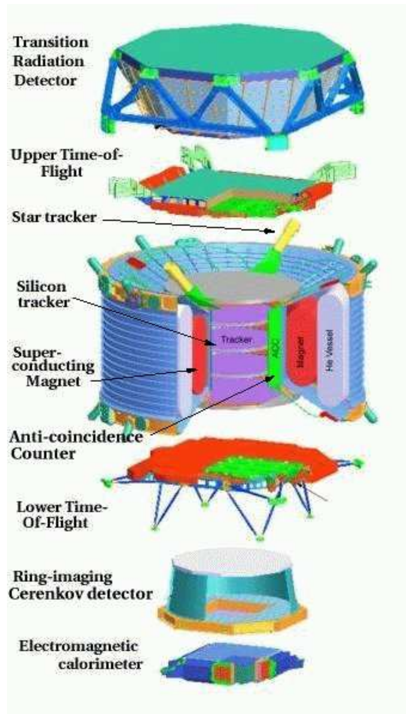

Figure 1: Exploded view of the AMS-02 sub-detectors.

2 Antimatter in our universe

The Physical laws are symmetric between baryons and anti-baryons at microscopic level. The physical universe, as we know, seems to be asymmetric because we have seen so far only matter.

The light elements (from proton up to ^7Li) are synthesised via nuclear reactions in the first $10^2 - 10^4$ second from the Big Bang (BB). In the standard theory of BB, the primordial abundances of light elements depend only on one free parameter: the nucleon energy density or, equivalentely, the ratio of the number of baryons (minus antibaryons) to photons: $\eta = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$. This number is important because it remained constant in most of the evolution of the universe. By comparing the primordial abundances predicted by the BB with those inferred from observations, η can be constrained: $\eta \sim 10^{-10}$. Although the matter-antimatter asymmetry appears to be large today ($n_B \sim n_b \gg n_{\bar{b}}$) the fact that η is small implies that at very early times the asymmetry was small ($n_B \ll n_b \approx n_{\bar{b}} \approx n_\gamma$) [4].

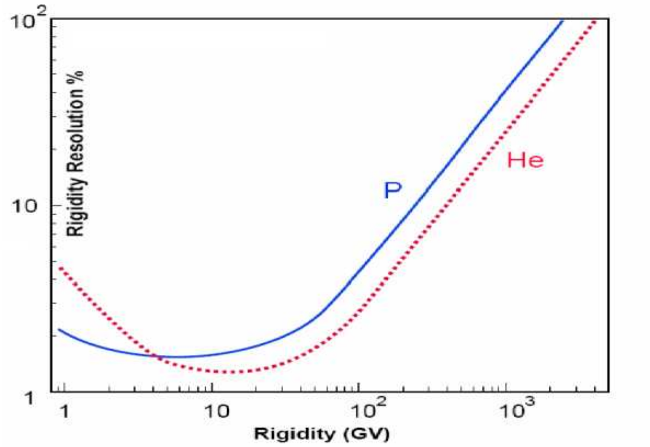

Figure 2: Simulated rigidity resolution of p and He [1].

The question that rises is: how an asymmetric universe can evolve (Baryogenesis), totally or even only locally, from a primordial Big Bang and with symmetric physical laws? Andrei Shakarov put the necessary conditions for baryogenesis [5]:

- Baryon number non conservation
- C and CP non conservation
- Out of thermal equilibrium decay

The inflation is a natural scenario where a baryogenesis can take place: it allows the out of equilibrium condition and can avoid the a-priori hypothesis of initial symmetric condition [6]. In a totally symmetric universe, antimatter nuclei could escape from their antimatter region and reach our galaxy, but, from γ rays observations, as γs would arise from domain borders annihilation, our matter dominated region is of the size of, at least, the cluster of galaxies ($\sim 100Mpc$). Nevertheless, it is worth while investigating since there could be also place for antistars in a matter dominated universe, as described in the following. In our universe there is the possibility of small insertions of antimatter regions [7]. In an inhomogeneus baryogenesis scenario, in fact, well above the electroweak energies, the quantum fluctuations of a complex, baryonic charged scalar field caused by inflation can generate antimatter regions that can survive annihilation. As a consequence, antistar global clusters can exist in our galaxy and the expected signature is a flux of $^3\overline{He}$ and $^4\overline{He}$ accessible by AMS-02, but not by AMS-01 [8].

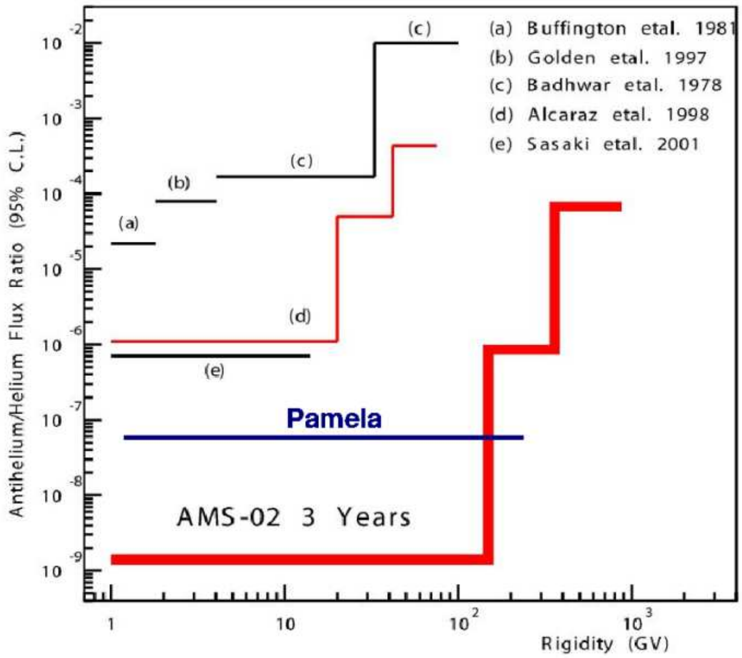

Figure 3: Present experimental limits for the antihelium/helium ratio and the sensitivities foreseen for the Pamela and AMS-02 experiments.

3 Antimatter and exotic physics search with AMS-02

Antinuclei can be found in cosmic rays with a spectrometer on top of the atmosphere (balloons) or on satellites (Pamela, AMS-02). In figure 3 are shown the limits reached so far for the ratio $\overline{He}/He$.

AMS-02 will have the possibility to detect an antinucleus or, at least, to lower the limit on antimatter/matter by a factor of 10^3. The detection of antimatter from an antimatter domain can also be done observing the high energy antideuterons or antiprotons ($E \geq 100GeV$), as described in 3.1 and 3.3.

Antiparticles can be produced by cosmic rays interactions with the interstellar medium (ISM) through inelastic collisions ("spallation" processes). Such secondaries fluxes are of the order: $\overline{He}$ O(10^{-12}), $\overline{D}$ O(10^{-8}), $\overline{p}$ O(10^{-4}), e^+ O(10^{-3}). Exotic sources of antimatter or dark matter annihilation, can produce additional fluxes of particles, as for instance the neutralino annihilation $\chi\chi \rightarrow WW \rightarrow \bar{p}, \bar{D}, e^+, ..$ leading to an excess of events, and idirect search in several channels can be made [9] [10].

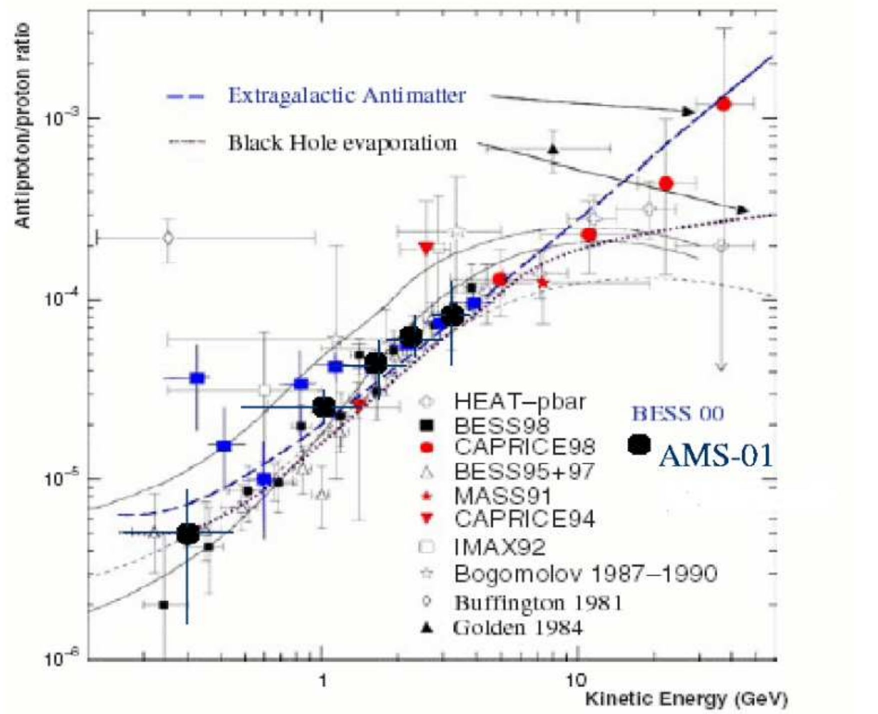

Figure 4: Collected data on $\frac{\overline{p}}{p}$ and various model superimposed [12] as discussed in 3.1. As you can notice, more data above $\sim 100GeV$ would discriminate between the various hypothesis.

3.1 antiprotons

Measurements of the ratio of secondary to primary nuclei suggest that the probability of a CR to escape from the galaxy (mean lifetime) falls with energy as $\sim E^{-\delta}$ with $\delta \sim 0.7$. Then the expected ratio $\frac{\bar{p}}{p}$, in the hypothesis of the existence of an anti-galaxy, should increase with the energy as $\sim E^{\delta}$, due to the fact that $\bar{p}$ would be mainly extragalactic while p mainly galactic (in the hypothesis of the same acceleration mechanism both in galaxy than in the anti-galaxy) [11]. In figure 4 you can see the most recent data on the ratio $\overline{p}/p$ and superimposed is the dashed line from an antigalaxy, that could be from an anti-super cluster of galaxies and also from an antistars global cluster in our own galaxy (as in 2). Superimposed on figure 4 are also other models: pure secondary production with and without solar modulation [12] and more exotic black hole evaporation model: from primordial black holes

$\overline{D}$ and $\overline{n}$, as also other particles, can evaporate through Hawking radiation [13]. The antiprotons are particularly sensitive to the physics details of cosmic ray propagation (controlled by B/C ratio), particularly at low momentum, so detailed measurements of their spectrum can discriminate between the various models of CRs propagation [9].

3.2 positrons

The ratio $\frac{e^+}{e^+ + e^-}$ can reveal neutralino annihilation, provided there is a sort of enhancement of the signal that could arise if we live in a clumpy halo. The HEAT collaboration found a possible excess of the ratio, around 10 GeV [14]. A "boost factor"can be estimated comparing the data with various Minimal Supersymmetric Standard Models and how fluxes are modified consequently. AMS-01 collected data up to ~ 3 GeV and measured such a ratio [1]. AMS-02 can measure up to 350 GeV a statistics of $\approx 10^6$ positrons. Due to the large p background ($p/e^+ \sim 10^3$), a strong proton rejection factor is needed (ECAL + TRD together rejection: $R \geq 10^6$).

3.3 antideuterons

Antideuterons are still to be observed in cosmic rays; the current limit on antideuterons has been given by BESS collaboration [15]. The secondary production of $\overline{D}$ has a probability of $\sim 10^{-8}$ and the reaction: $p + \overline{p} \rightarrow \overline{D} + X$ has a proton threshold momentum of 17 GeV giving antideuterons above ~ 2 GeV. As a consequence, an observation of antideuteron is more likely to be of "primary" origin, especially in the low energy region (~ 0.1 GeV) where secondary production is suppressed. The exotic component of $\overline{D}$ could come either from an antimatter domain or from neutralino annihilation in our galaxy halo [16]. The flux of $\overline{D}$ is O($\sim 10^{-4}$) the flux of $\overline{p}$, thus, for AMS-01, which observed $\sim 100\overline{p}$ the antideuteron was not observable. Small statistics $\bar{D}$ could be detected by AMS-02.

4 Conclusion

The AMS-02 detector on the International Space Station will measure cosmic ray fluxes with high precision for more than three years. The collected data on antinuclei or on high energy antiprotons will help to discover antimatter regions, both extragalactic and galactic as a relic from the inflationary period. AMS-02 will have also the sensitivity to detect the products of dark matter annihilation in our galaxy by analysing e^+, $\bar{D}$ and $\bar{p}$ data in a large energy range.

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