The Alpha Magnetic Spectrometer (AMS): search for antimatter and dark matter on the International Space Station

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The Alpha Magnetic Spectrometer (AMS) is a state of the art detector for the extraterrestrial study of antimatter, matter and missing matter. After a precursor flight on STS91 in may 1998, AMS will be installed on the International Space Station where it will operate for three years. In this paper the AMS experiment is described and its physics potential reviewed.

1. Introduction

The disappearance of cosmological antimatter and the pervasive presence of dark matter are two of the greatest puzzles in the current understanding of the universe.

The Big Bang model assumes that, at its very beginning, half of the universe was made out of antimatter. The validity of this model is based on three key experimental observations: the recession of galaxies (Hubble expansion), the highly isotropic cosmic microwave background and the relative abundances of light isotopes. However, a fourth basic observation, the presence of cosmological antimatter somewhere in the universe, is missing. Indeed measurements of the intensity of gamma ray flux in the MeV region exclude the presence of a significant amount of antimatter up to the scale of the local supercluster of galaxies (tens of Megaparsecs). It follows that, either antimatter has been destroyed immediately after the Big Bang by some unknown mechanism, or matter and antimatter were separated (by some other unknown mechanism) into different region of space, at scales larger than superclusters. All efforts to reconcile the the absence of antimatter with cosmological models that do not require new physics failed (see [1–3], for a review of these theories).

We are then currently unable to explain the fate of half of the baryonic matter present at the beginning of our universe.

Rotational velocities in spiral galaxies and dynamical effects in galactic clusters provide us convincing evidence that, either Newton laws break down at scales of galaxies or, more likely, most (up to 99%) of our universe consists of non-luminous (dark) matter. There are several dark matter candidates. They are commonly classified as "hot" and "cold" dark matter, depending on their relativistic properties at the time of decoupling from normal matter in the early universe. As an example, light neutrinos are obvious candidates for "hot" dark matter while Weakly Interacting Massive Particles (WIMP's) are often considered as "cold" dark matter candidates.

Figure 1. AMS on STS 91 (Discovery)

In either cases we are currently unable to explain the origin of most of the mass of our uni-
verse.

To address these two fundamental questions in astroparticle physics a state of the art detector, the Alpha Magnetic Spectrometer (AMS) has been recently approved by NASA to operate on the International Space Station Alpha (ISSA).

AMS is manifested for a precursor flight with STS91, (Discovery, may 1998, Figure 1), and for a three year long exposure on the International Space Station (ISS) (Figure 2), after its installation during Utilization Flight n.4 (Discovery, January 2002). AMS has been proposed and is being built by an international collaboration involving China, Finland, France, Germany, Italy, Romania, Russia, Switzerland, Taiwan and US.
2. Particle physics and antimatter

Particles and antiparticles are connected through three discrete space-time symmetries which are the foundations of relativistic field theory: charge conjugation (C), parity (P) and time reversal (T). We know today that each of these symmetries can be independently violated. Invariance of fundamental interactions under the three combined transformations is, however, always maintained (CPT theorem). The best tests of the CPT theorem are indeed based on the comparison of lifetimes and masses of particle and antiparticles, since the a CPT transformation links a particle to its antiparticle. An asymmetry between matter and antimatter in our universe would then be strictly related to a violation of these discrete symmetries. In 1967, Sakharov noted that baryogenesis, which describes the evolution from a symmetric universe to an asymmetric one, requires four ingredients, three of which, baryon number violation, C and CP violations are fundamental properties of elementary particles. Neither particle acceleration experiments nor proton decay experiments have yet provided evidence for baryon number violation. However, since there is a long range force associated with baryonic charge, there is no compelling reason for baryon number to be conserved. Nevertheless, until particle physics experimental data provides confirmation of these ideas, the observed lack of antimatter in our part of universe will be the strongest evidence for baryon number violation.

CP violation has been observed directly in three decays of the $K_L$ meson and nowhere else in particle physics experiments:

$$K_L \to \pi^+\pi^-, \quad K_L \to \pi^0\pi^0, \quad K_L \to \pi l\nu$$  \(1\)

($l$ is either an electron or muon). The absence of antimatter in our part of the universe (and perhaps in the entire universe), combined with Sakharov conditions, provides the only other evidence for CP violation.

Since CP violation as the origin of baryogenesis occurs at energy scales much greater and at much greater level than in the in the kaon system, the study of baryon asymmetry in the universe provides crucial informations in attempts to probe beyond the Standard Model of particle physics. Cosmological models that predict baryon symmetry on the scale of the observable universe may involve different sorts of CP violating mechanisms than those models which exclude antimatter altogether. Then, the determination by AMS of whether the universe does or does not contain domains of antimatter beyond our local supercluster of galaxies is of great importance to understand the fundamental laws of particle physics.

A comment about the study of CP violation on the B-meson system. The B-factories currently being developed to study CP violation in the B-meson system may provide information pertaining to baryon asymmetry. However current understanding suggest that CP violation in the B-system is most likely unrelated to the CP violation necessary to produce cosmological baryon asymmetry. In particular, just as CP violation, present in the kaon system from a phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, is too small to produce the observed cosmic asymmetry, similar conclusions are likely to hold for the B-system. However it is possible that CP violation beyond the phase of the CKM matrix...
is operative in the B-system, and B-factories are likely to reveal whether or not this is the case. However, new sources of CP violation which have been suggested for the origin of the baryon asymmetry do not typically lead to significant new CP violation in the B-system. AMS will then bring informations on the origin of CP violation which are complementary to those obtained at the accelerators (Figure 3).

Figure 5. Progress on permanent magnets

3. AMS experiment design principles

Search of antimatter requires the capability to identify with the highest degree of confidence, the type of particle traversing the experiment together with the absolute value and the sign of its electric charge. This can be achieved through repeated measurements of the particle momentum (Spectrometer), velocity (Time of Flight, Cerenkov detectors) and energy deposition (Ionization detectors).

The experiment configuration for the precurson flight is shown in Figure 4. It consist of a large acceptance magnetic spectrometer (about $0.6 \, m^2 \, sr$) made of a new type permanent Nd-Fe-B magnet (1), surrounding a six layer high precision silicon tracker (2) and sandwiched between four planes of the Time of Flight scintillator system (ToF) (3). A scintillator anticounter system (4), located on the magnet inner wall and a solid state Cherenkov (8) detector, complete the experiment.

The magnet is based on recent advancements in permanent magnetic material and technology (Figure 5) which make it possible to use very high grade Nd-Fe-B to construct a permanent magnet with $BL^2 = 0.15 \, Tm^2$ weighting $\leq 2 \, tons$. A charged particle traversing the spectrometer will trigger the experiment through the ToF system. The ToF will measure the particle velocity with a resolution of $\sim 100 \, ps$ over a distance of $\sim 1.4 \, m$ (Figure 6).

The momentum resolution of the Silicon Spec-
The physics objectives of AMS are:

- search for Antimatter (\(^{\bar{He}}\) and \(^{\bar{C}}\)) in space with a sensitivity of \(10^4\) to \(10^5\) better than current limits.

The breakdown of the Time-Reversal symmetry in the early universe might have set different sign for the production of matter and antimatter in different regions of space. Since there are \(O(10^8)\) super clusters of galaxies and the observational constraints are limited to the scale of the local supercluster, the universe can be symmetric on a larger scale. The observed matter-antimatter asymmetry would then be a local phenomenon.

Table 1
AMS silicon tracker parameters

| Parameter                               | Value       |
|-----------------------------------------|-------------|
| Number of planes                        | 6           |
| Accuracy (bending plane)                | 10 \(\mu\)m|
| Accuracy (non bending plane)            | 30 \(\mu\)m|
| Number of channels                      | 172000      |
| Power consumption                       | 400 W       |
| Weight                                  | 130 kg      |
| Silicon Area (double sided)            | 6 \(m^2\)   |

4. AMS physics potential

These measurements will allow direct searches for the various annihilation and decay products of WIMP’s in the galactic halo:

\(\bar{\chi} + \chi \to \bar{p} + X, e^+ + X, 2\gamma\) (2)

\(\chi, \bar{\chi} \to \gamma\nu\) (3)

Figure 9 shows the simulation of the 100 hour measurement of the \(\bar{p}\) flux on the precursor flight compared to a compilation of existing \(\bar{p}\) data together with a prediction of the effects of an heavy neutralino \([11]\).

Similarly Figure 10 shows the simulation of three years of AMS \(e^+\) data compared to the existing measurements. The accuracy of the AMS...
Figure 8. Sensitivity of AMS (3 years on ISSA) in a search for (a) $\bar{\text{He}}$; (b) $Z > 2$ antinuclei (95\% C.L.). $\bar{\text{He}}$ sensitivity is compared to a prediction assuming a matter-antimatter symmetric universe at the level of super-cluster of galaxies.

- astrophysical studies by high statistics precision measurements of $D$, $^3\text{He}$, $B$, $C$, $^9\text{Be}$, and $^9\text{Be}$ spectra.

Precision measurement of isotopes and elemental abundances in Cosmic Rays (CR) give very important information about CR origin, their galactic confinement time and their propagation inside and between galaxies. This is deeply related to the search for antimatter, since antimatter particles, to be detected, should escape a region of the universe dominated by antimatter, propagate through the intergalactic void separating superclusters and enter our galaxy. As an example AMS will measure in three months $5 \times 10^7$ deuterium events reducing the current uncertainty on $D/p$ by a factor of 100. Similarly, AMS will be able to separate $^3\text{He}$ from $^4\text{He}$ up to 5 $\text{GV}$ of rigidity, thus collecting in three years $4 \times 10^8$ $^3\text{He}$ and $4 \times 10^9$ $^4\text{He}$, reducing the existing uncertainties by a factor 200. The ratio $B/C$, which constrains the parameters regulating the outflowing galactic wind, can be measured by AMS better than the current data within one day and up to 100 $\text{GV}$ of rigidity. On the other side, the ratio $B/C$ determines the CR confinement time; at present, a dozen of $^9\text{Be}$ events have been detected during more than fourteen years of observations and the CR galactic confinement time is currently known within a large uncertainty ($\sim 40\%$). With AMS it will be possible to detect tens of $^9\text{Be}$/day in the 1 $\text{GV}$ range, thus dramatically reducing the error on CR confinement time.

In addition, the capability of AMS of detecting high energy $\gamma$ rays would make it possible to per-
Table 2
Physics capabilities of AMS after three years on ISSA

| Elements          | Yield/sensitivity | Range (GV) | Physics         |
|-------------------|-------------------|------------|-----------------|
| $e^+$             | $10^8$            | $0.1 - 100$| Dark Matter     |
| $\bar{p}$         | 500000            | $0.5 - 100$| SUSY            |
| $\gamma$          | $0.1 - 300$       |            | R-parity        |
| $\bar{He}/He$     | $10^9$            | $0.5 - 20$ | Antimatter      |
| $\bar{C}/C$       | $10^9$            | $0.5 - 20$ | CP vs GUT, EW   |
| $D, H_2$          | $10^9$            | $1.0 - 3.0$| Astrophysics    |
| $^3He/^4He$       | $10^9$            | $1.0 - 3.0$| CR propagation  |
| $^{10}Be/^{9}Be$  | 2%                | $1.0 - 3.0$| CR confinement  |

Figure 9. Simulated 100 hour shuttle flight $\bar{p}$ measurement by AMS, compared with a compilation of existing $\bar{p}$ data

Figure 10. Simulated 3 years AMS $e^+$ measurement compared with a compilation of existing $e^+$ data

form very important observations in gamma ray astrophysics after the turn off of the EGRET experiment (within one or two years). Simulations suggest indeed that the performances of AMS in monitoring the $\gamma$-sky in the multi GeV range are comparable to these of EGRET (however AMS on the Space Station will not be able to point to targets of opportunity) [16,17]. A comparison between the two experiments is shown in Table 3.

Before the advent of new generation gamma ray space facilities like GLAST [18], AMS will then be the only space born experiment to continue the EGRET mission at the beginning of the next century, covering the interesting region $E_\gamma = 30 - 300 GeV$. These data will extend our knowledge in key areas of $\gamma$ astrophysics like: Active Galactic Nuclei (AGN), blazars, $\gamma$-bursters. They will also allow a measurement of the ex-
| Parameter                             | EGRET                          | AMS               |
|--------------------------------------|--------------------------------|-------------------|
| Peak effective area (cm²sr)          | 1500                           | 900               |
| Angular resolution (68%)             | $1.7^{0}(\frac{E_\gamma}{1\,GeV})^{-0.534}$ | $1.27^{0}(\frac{E_\gamma}{1\,GeV})^{-0.874}$ |
| Mean opening angle                   | $\sim 25^0$                    | $\sim 30^0$       |
| Total viewing time                   | $\sim 2.5\,yr$                 | $\sim 3\,yr$     |
| Source flux sensitivity (>1GeV)      | $\sim 10^{-8}\,cm^{-2}s^{-1}$  | $\sim 10^{-8}\,cm^{-2}s^{-1}$ |
| Detector energy range (GeV)          | 0.02 to 20                      | 0.3 to 200        |

tragalactic $\gamma$ background and of the interaction of high energy $\gamma$ rays with the black-body microwave background.

The physics capabilities of AMS after three years of exposure on the ISSA are summarized in Table 2.

5. Conclusion

During the past forty years, there have been many fundamental discoveries in astrophysics measuring UV, X-ray and $\gamma$-ray photons. There has never been a sensitive magnetic spectrometer in space, due to the extreme difficulty and very high cost of putting a superconducting magnet in orbit. AMS will be the first large acceptance magnetic detector in space. It will allow measurements of the flux of all kind of cosmic rays with an accuracy orders of magnitude better than before. The large improvement in sensitivity given by this new instrument, will allow us to enter into a totally new domain to explore the unknown.

REFERENCES

1. Steigmann, G.: 1976, Ann. Rev. Astron. Astroph., 14 p. 339.
2. Kolb, E.W., Turner, M.S.: 1983, Ann. Rev. Nucl. Part. Sci. 33 p. 645.
3. Peebles, P.J.E.:1993, Principles of Physical Cosmology, Princeton University Press, Princeton N.J.
4. Ellis, J. et al.: 1988, Phys. Lett. B214, p. 403.
5. Turner, M.S., Wilzek, F.: 1990, Phys. Rev. D42, p. 1001.
6. S.P. Ahlen et al.: 1994, N.I.M. A350 351.
7. Sakharov, A.D.: 1967, JETP Lett 5, p. 24.
8. Palmonari, F.: 1996, private communication.
9. Battiston, R.: 1995, Nucl. Instr. and Meth. (Proc. Suppl.) B44, p. 274.
10. Ahlen, S. et al.: 1982 ,Ap. J. 260, p. 20.
11. Jungman, G., Kamionkowski, M.: 1994, P.R. D49, p. 2316.
12. Diehl, E.: 1995, P.R. D52, p. 4223.
13. Bergstrom, L.: 1989, P.L. B225, p. 372.
14. Berezinsky, V., Masiero, A., Valle, J.W.F. : 1991, P.L. B266, p. 382.
15. Stecker, F.W.: 2nd Int. Symp. on ”Sources and Detection of Dark. Matter in the Universe”, S. Monica, CA, February 1996, Nucl.Phys. B. Proc. Suppl. 51B, 299.
16. Fiandrini, E.: Proc. 6th Topical Seminar on ”Experimental Apparatus for Particle Physics and Astrophysics”, San Miniato al Todesco, Italy, 20-24 May 1996, Nucl.Phys. B. Proc. Suppl. in press.
17. Battiston, R., Salamon, M., Fiandrini, E., to be published.
18. E.D. Bloom, these Proceedings.