00

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Perugia

INFN/AE-96/36

17 Ottobre 1996

B. Alpat:

**AMS (ALPHA MAGNETIC SPECTROMETER) EXPERIMENT FOR
ANTIMATTER, DARK MATTER SEARCH ON INTERNATIONAL
SPACE STATION ALPHA**

SCAN-9703078

CERN LIBRARIES, GENEVA

SW 9713

**AMS (ALPHA MAGNETIC SPECTROMETER) EXPERIMENT FOR ANTIMATTER,
DARK MATTER SEARCH ON INTERNATIONAL SPACE STATION ALPHA**

B. Alpat

INFN-Sezione di Perugia, Via A. Pascoli, I-06100 Perugia, Italy

1. INTRODUCTION

The existence (or absence) of antimatter is one of the greatest puzzles of modern cosmology and particle physics. The detection of antimatter of cosmological origin would be a discovery of fundamental importance for our understanding of the origin of the universe [1,2,3]. The standard Big Bang theory, which explains many features of the evolution of early universe, requires matter and antimatter to be equally abundant at very hot beginning [4,5]. At present, the evidence for the existence of antimatter is very limited. However, this information come mostly from balloon borne experiments [6,7,8,9,10] which are limited by the effects of residual atmosphere and statistics.

During the past 25 years, there have been two attempts to send a magnetic spectrometer in space. In 1970's a group led by Louis Alvarez from Berkeley developed a superconducting spectrometer to be flown on the second High Energy Astronomical Observatory (HEAO-B). But unfortunately the HEAO mission was redirected and the spectrometer and other programmed experiments were not flown. In 1989, another superconducting magnet spectrometer (Astromag [11]) was reviewed and approved for deployment on the Space Station Freedom. But at the end of 1990, because of the budget constraints, the construction of the Freedom Space Station was delayed and the attached payload program including the Astromag facility was postponed indefinitely.

Therefore, AMS [12] will be the first magnetic spectrometer in space. A new type of rare earth

permanent Nd-Fe-B magnet with resolving power of $BL^2=0.15 \text{ T}\cdot\text{m}^2$ and a precision spectrometer with geometrical factor of about $0.6 \text{ m}^2\cdot\text{sr}$ will give AMS the possibility to search for anti matter of cosmological origin with sensitivities of 4 to 5 orders of magnitude better than the current limits.

In addition to its primary objective of "anti matter hunting", the scientific goals of AMS will include dark matter searches, astrophysics studies such as relative abundances of elements and isotopes in cosmic rays and gamma ray astronomy.

A reduced configuration of the AMS experiment will have a ten days long precursor flight on shuttle STS-91 during May 1998. The aim of the shuttle flight is the study of albedo background at 300-500 km from earth as well as the verification of the detector performance under actual space conditions including ground control and data communication in flight. During the year 2001 the full AMS apparatus will be installed on the International Space Station Alpha (ISSA [13]) at 51° orbit where will be operational for three years.

In the following we discuss in some detail the AMS detector design, together with its scientific objectives and potentials.

2. THE AMS EXPERIMENTAL APPARATUS AND DESIGN PRINCIPLES

Fig.1 shows the general assembly of the AMS detector while its main parameters are listed in

Figure 1. AMS general assembly.

Table 1 (tracker spatial resolutions are given both for bending (1) and non bending (2) planes).

IMPORTANT PARAMETERS OF AMS	
Weight	3 tons
Power	1 kW
GF	$0.6 \text{ m}^2 \cdot \text{sr}$
BL^2	0.15 Tm^2
Field Strength	0.1 T
TK resolution (1)	$10 \mu\text{m}$
TK resolution (2)	$30 \mu\text{m}$
ToF resolution	100 ps

Table:1 The main parameters of AMS.

The AMS detector consists of the following components (see Fig. 2):

- A ring permanent magnet of 1.8 tons made out of 64 premagnetized highest grade rare earth Nd-Fe-B pieces ($B \times H > 50 \cdot 10^6 \text{ GOe}$). This magnet with good homogeneity, low fringe field and vanishing dipole moment will have a field of about 1 kG.

- Anticoincidence counters surrounding the inner wall of the magnet to reject background induced by the passage of charged particles through the magnet.
- A tracker consisting of six layers of high precision, very transparent ($7 \times 10^{-3} X_0/\text{layer}$) double sided silicon detectors. Four layers will be inserted into the magnet while the first and the last layers will be located at top and at bottom of the magnet in order to have the largest geometrical factor ($0.6 \text{ m}^2 \cdot \text{sr}$). Spatial resolutions of $10 \mu\text{m}$ and $30 \mu\text{m}$ in bending and non-bending planes, respectively, will give precise measurement of the rigidity (p/Z) up to a $MDR=500 \text{ GV}$. The particle trajectory will give the sign of the particle charge. Each layer will give a separate measurement of dE/dX , which combined with that of time of flight system, will contribute to determine with precision the absolute particle charge.
- Four layers of scintillators (S1 to S4) will

Figure 2. The sketch of AMS detector.

provide first level trigger, ToF measurements, particle direction (up/down separation) and dE/dX measurements up to $Z=26$.

- Aerogel Čerenkov counters (C1 and C2) to improve the albedo rejection and the determination of the particle mass by measuring its velocity (the momentum will be determined by the spectrometer).
- Transition radiation detectors (straw tubes filled with Xe/Co₂ and interleaved with polyethylene radiators) for second and third level triggers and for discrimination between protons, electrons and pions.

Figure 3. Momentum resolution of the AMS silicon tracker.

3. PERFORMANCE OF THE AMS DETECTOR

AMS aims to unambiguously detect single anti-nuclei (i.e. antihelium or anticarbon) over about 10^{10} background particles. An extensive Monte Carlo study has been performed using 10^{10} equivalent Carbon events to study sources of background mimicking antimatter candidates. Charge confusion is mostly originated by single (or double) nuclear scattering inside the tracker. Applying the following cuts one can reduce the large angle scattering without compromising the detection efficiency;

- The L1 and L2 are required to form a continuous curve (see Fig. 2),
- P1 determined from L1 and P2 from L2 are required to be equal.

The results have shown that for rigidities between 0.5 to 20 GV the acceptance is around 80% and the charge confusion probability is better than 10^{-10} . It is worth noting that, these results were achieved without using the charge determination and particle discrimination capabilities of Aerogel Čerenkov counters and TRD. As it is shown in Fig. 3, the transverse momentum

of particles can be measured up to a maximum detectable rigidity of 500 GV.

The momentum resolution is limited to $\approx 6\%$ due to multiple scattering.

Recent beam test results with ToF prototypes have shown 105 ps second time resolution can be achieved. More details about the tracker performance and AMS detector can be found in references [12,14,15].

4. PHYSICS OF AMS

4.1. Antimatter

The present state of the universe is characterized by four large-scale phenomena: the expansion of the universe (Hubble's law), the 2.76 K highly isotropic cosmic microwave background radiation, the ratio of 10^{-9} for the number of nucleons (baryons) per photon and the light element abundances. All these phenomena find explanation in the Big Bang theory which also predicts equally abundant matter and antimatter at the very hot beginning. In particular, there is a remarkable agreement between the light element observations and the theoretical predictions. But, at present, experimental results lead us to exclude the existence of significant amount of antimatter within about 10 Mpc from the earth.

The baryogenesis, which is the evolution of the a symmetric universe into an asymmetric one, requires baryon number and CP to be violated [16]. These violations are fundamental properties of elementary particles theories which also allow for the baryon number violation. CP non conservation has been observed in K and B systems but the amount of the measured non conservation is not enough to explain the observed baryon, antibaryon asymmetry. Since, experimental evidence for baryon number violation in accelerators or in proton decay experiments has not yet been provided, the observed lack of antimatter in our part of the universe is the strongest evidence for baryon number violation.

Theories predicting total absence of antimatter, such as Grand Unified Theories (GUT's [17,18]) or electroweak theories [19,20], can explain the absence of antimatter if there is a very strong breakdown of T symmetry. GUT's require

the existence of monopoles and massive neutrinos which both have not been observed yet. Electroweak theories require the mass of Higgs to be about 40 GeV while the present measurements gives $M_H > 60$ GeV. Theories predicting the existence of antimatter [21] postulate that the breakdown of the time-reversal symmetry in the early universe might have set different signs of CP in different regions of space. Since there are 10^8 clusters of galaxies and the observational constraints are limited to the scale of the clusters, the universe can be symmetric on a larger scale. Then, the observed matter-anti matter asymmetry would be a local phenomenon.

Since antiprotons and positrons are not direct indicators for the existence of primordial antimatter, the antimatter in AMS will be searched by measuring helium or heavier nuclei (CNO group). Particle rigidity and charge sign will be measured with the tracker, velocity with the ToF and absolute charge with the combined measurements of dE/dX in the tracker and ToF systems. After three years of data taking AMS will reach a sensitivity of antihelium/helium ratio of about 10^{-10} , 3-4 orders of magnitude better than the predictions based on matter-anti matter symmetric universe (see Fig. 4).

If no antinuclei is observed with AMS then the presence of anti matter up to the edge of the universe (≈ 1000 Mpc) could be excluded.

4.2. Dark Matter

Rotational velocities in spiral galaxies and dynamical effects in galactic clusters provide us convincing evidence that almost 90% of our universe is constituted by dark matter [22,23]. The "kind" of dark matter is strongly related to the large scale structure and galaxy formation in the early universe. There is a commonly used distinction between "hot" and "cold" dark matter. Hot dark matter consists of particles which are still relativistic when they separate (freeze out) from matter in an early phase of the universe. Hot relics such as light neutrinos have densities comparable to photons. On the other hand, cold dark matter is made out of heavy particles which are already nonrelativistic at freeze out. Cold relics candidates are axions, neutralinos, higgsinos or Weakly

Figure 4. Left: Sensitivity of AMS for antihelium search (95% C.L.). The curve is based on the predictions for matter-antimatter symmetric universe. Right: Sensitivity of AMS as compared with current limits (95% C.L.) for $Z > 2$ antinuclei.

Interacting Massive Particles (WIMP's).

In AMS, annihilation products of WIMP's, ($\bar{p}$, γ , e^+) or of neutralinos decay (γ) can directly be searched by high precision spectral measurement of high energy positrons, antiprotons and photons. AMS will measure the antiprotons with ToF which will reject the electron and pion background up to about 1.5 GeV while a threshold aerogel Čerenkov detector will extend the range to about 3 GeV/c. AMS will collect about 540 antiprotons during the Shuttle flight and $50 \cdot 10^5$ in 3 years on ISSA.

In Fig. 5 antiprotons data on Shuttle are indicated with black dots; neutralinos contribution to the spectrum (solid curves) for M_χ of 30 and 60 GeV are also shown.

AMS will measure the energy spectrum of cosmic ray positrons by ToF up to about 2 GeV/c. It will be extended up to over 100 GeV/c by multilayer TRD's.

In Fig. 6 the present positron/electron data are compared with the expected AMS result on ISSA ($10^8 e^+$ events, dotted line). The precise

Figure 5. $\bar{p}/p$ versus kinetic energy. The dots are 540 $\bar{p}$ events expected with AMS on Shuttle.

AMS PHYSICS POTENTIALS				
Physics	Particle	Rigidity Range (GV)	Detection Method	Expected Rate (3 yrs.) or Sensitivity
Antimatter	He, C	0.5 ÷ 20	A	1.1 10 ⁻⁹ (He/He) 1.3 10 ⁻⁸ ($\bar{C}$ /C)
Dark Matter	e ⁺	0.1 ÷ 100	B	1.5 10 ⁷
	$\bar{p}$	0.5 ÷ 3	C	5.10 ⁶
Astrophysics	γ	0.1 ÷ 300	D	$\sigma_{ang.}(E)=0.83 (E_\gamma/1 \text{ GeV})^{-0.907}$
	D/H	0.5 ÷ 4	A	1.1 10 ⁹ (D)
	³ He/ ⁴ He	1 ÷ 3	A	(4.10 ⁸ ³ He)/(4.10 ⁹ ⁴ He)
	¹⁰ Be/ ⁹ Be	1 ÷ 2	A+E	1.1 10 ⁶ (¹⁰ Be)
	B/C	1 ÷ 100	A	

- A = Rigidity (TK), Sign of Z (TK), v from (ToF), $|Z|$ by dE/dx (ToF,TK)
B = ToF up to 2 GV, TRD up to 100 GV
C = ToF up to 1.5 GV, Aerogel Čerenkov up to 3 GV
D = W converter, e[±] direction and energy by (TK)
E = Aerogel Čerenkov up to 2 GV

Figure 6. e^+/e^- as a function of kinetic energy. AMS expectations for ISSA (dotted line) is compared to present data. The numbers in parenthesis are events observed by that experiment.

measurement of positron spectrum over large energy ranges will also give valuable information on many galactic processes such as production and propagation of cosmic rays.

4.3. Astrophysics

AMS, because of its particle identification capabilities, will be able to perform important measurements in cosmic ray physics. Below we will summarize these measurements.

4.3.1. Isotopes

The study of relative abundances of elements and isotopes will yield to a better understanding of the origin, propagation and confinement time of the cosmic rays in our galaxy [24].

The observed relative abundances of elements in solar system and in cosmic rays are in good overall agreement. However, both solar system and cosmic ray abundances show the odd even effect with even Z nuclei being more abundant. This implies that most of the solar system elements and cosmic rays heavier than helium were synthesized in stars. The comparison of the measurements of rare isotopes ²H and ³He, which are dominant secondary products from the primary ⁴He interactions, to those of heavier secondaries will determine whether He and heavier nuclei cos-

Figure 7. Particle identification with ToF vs rigidity (upper) and helium mass separation vs rigidity (lower) measured by silicon tracker

mic rays have the same origin [25,26]. AMS will identify the deuterons up to about 4 GV and by collecting $6 \cdot 10^8$ events in 3 years, it will reduce the uncertainty on D/p by a factor 100. Furthermore, AMS will be able to separate ^3He from ^4He up to 5 GV improving the $^3\text{He}/^4\text{He}$ ratio by a factor of ≈ 200 .

Fig.7 shows the velocity versus rigidity of deuterium (upper) and helium (lower) as determined with AMS detectors.

Accurate determination of B/C ratio over wide energies will provide crucial information relative to the cosmic ray propagation in the galaxy [27]. In particular will help to determine the parameters of galactic wind which reduce the accessi-

Figure 8. Accuracy of the measurement of B/C ratio by AMS with one day of data. The ratios are computed assuming the halo thickness of 2 kpc and zero convection velocity.

bility of extragalactic cosmic rays to our galaxy. AMS in one they will have better statistics on B/C ratio than the present data up to rigidities of about 100 GV.

In Fig. 8 is shown the precision of the B/C measurement by AMS with one day of data.

The study of the radioactive isotope ^{10}Be to stable isotope ^9Be ratio will give the possibility to determine the mean interstellar matter traversed by cosmic rays hence the accurate determination of their galaxy confinement time [28]. At present there are 15 ^{10}Be events reported leading to an error on confinement time of 25 ± 10 Myr [29,30]. Aerogel Čerenkov detectors of AMS will perform accurate measurements up to rigidities about 2 GV by collecting 100's of ^{10}Be /day (see Fig.9).

4.3.2. Gamma Rays

Inserting a $0.3 X_0$, high Z (tungsten) converter plate between TRD's above S1-S2 counters (see Fig. 2) AMS becomes a γ -ray detector. The γ -ray energy and direction will be determined from the measurements of electrons momentum

Figure 9. Reconstructed mass of ${}^9\text{Be}$ and ${}^{10}\text{Be}$ with aerogel Čerenkov detector (for 3 years on ISSA).

and direction. AMS with its γ -ray detection capability will study the galactic (pulsars, γ -ray bursters) and extra galactic sources (Active Galactic Nuclei (AGN), Blazars) in a wide energy range (0.3–300 GeV). It will give valuable information on the determination of the isotropic γ -ray background. Further details are given in reference [31].

5. CONCLUSIONS

We have discussed the design goals and physics potentials of the AMS experiment on ISSA. The AMS will be the first magnetic spectrometer in space and will search for antinuclei with a sensitivity of better than 10^{-10} . The detection of antimatter by AMS would bring light on a number of issues that have profound implications for both cosmology and particle physics. After 3 years on ISSA, if no antimatter is detected AMS will exclude its presence to the edge of the universe.

In addition the particle detection capabilities of its detectors will give AMS the possibility to study other various "hot" topics such as dark

matter and relative abundances of elements and isotopes.

REFERENCES

1. G. Steigman, *Ann. Rev. Astron. Astrophys.* 14, 339(1976).
2. E.W. Kolb, M.S. Turner, *Ann. Rev. Nucl. Part. Sci.* 33, 645(1983).
3. A. De Rújula, *Antimatter in the universe?*, To be published on proc., TOLEDO-95.
4. P.J. Peebles, *Principles of Physical Cosmology*, Princeton University Press, Princeton, N.J. (1993).
5. P.D.B. Collins, A.D. Martin, E.J. Squires, *Particle Physics and Cosmology*, WILEY-Interscience, 1989.
6. P.V.R. Murthy and A.W. Wolfendale, *Gamma Ray Astronomy*, 2nd edition, Cambridge University Press (1993).
7. R.L. Golden, et al., *Phys. Rev. Lett.* 43, 1196(1979).
8. M.H. Salamon, et al., *Ap.J.* 349, 78(1990).
9. R.E. Streitmatter, et al., *Proc. 21st Inter. Cosmic Ray Conf.* 3, 277(1990).
10. C. Pfeifer, et al., LNF-96-010-P, Subm. to, *Astrophys. J.*
11. *Astromag Phase A Study Report*, NASA and Goddard Space Flight Center, December 1989.
12. *Alpha Magnet Spectrometer (AMS) for Extraterrestrial Study of anti matter, Matter and Missing Matter on The International Space Station Alpha*, AMS collaboration, Proposal, December 1994.
13. D. Blanchard, et al. (NASA Johnson Space Center Study Team and AMS Collaboration), *anti matter Spectrometer in Space-Study of Feasibility on International Space Station Alpha and Space Shuttle Flight: Final Report*, August 26, 1994.
14. M. Pauluzzi, *The Large Silicon Tracker for the AMS Experiment on the International Space Station Alpha (ISSA)*. To be published on *Nucl. Inst. and Meth.*
15. R. Battiston, *Nucl. Physics B(Proc. Suppl.)* 44 (1995) 274–281.
16. A.D. Sakharov, *JETP Lett.* 5, 24(1967).

17. S. Dimopoulos, L. Susskind, Phys. Rev.D18, 4500(1978).
18. V.A. Kuzmin, et al., Phys. Lett.76B, 436(1978).
19. A.G. Cohen et al., Ann. Rev. Nucl. Part. Phys. 43, 27(1993).
20. V.A. Kuzmin, et al., Phys. Lett.155B, 36(1985).
21. A.H. Guth, Phys. Rev. D23, 347(1981).
22. I. Novikov, Proc. Vulcano Workshop, S.I.F., V.47, 79(1994).
23. K. Pretzl, Proc. Vulcano Workshop, S.I.F., V.47, 89(1994).
24. P. Ferrando, Proc. 23rd Inter. Cosmic Ray Conf.3, 279(1993).
25. W.R. Webber, et al., Ap.J.380, 230(1991).
26. J.J. Beatty, et al., Ap.J.413, 268(1993).
27. W.R. Webber, et al., Ap.J.390, 96(1992).
28. A. Lukasiak, et al., Ap.J.423, 426(1994).
29. M.E. Wiedenbeck, D.R. Greiner, Ap.J.239, L139(1980).
30. J.A. Simpson, M. Garcia-Munoz, Space Sci. Rev.46, 205(1988).
31. E. Fiandrini, these proceedings.