THE SEARCH FOR COSMIC ANTIMATTER

FEDERICO PALMONARI
INFN and University of Bologna, Italy

Dedicated to the memory of my invaluable wife Biancamaria

The apparent absence of primary antimatter in our Universe is not completely explained by the Big Bang cosmological model based on the standard theory of particles and fields. Space is left for global symmetry, for the existence of domains or local sources of antimatter. The status of its search and the discovery potential of the cosmic ray spectrometer AMS-02 are described.

1 Introduction

The question is an old one and can be introduced with the words of Dirac [1] in his Nobel lecture of December 12, 1933: “If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole Solar System), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods”.

The year before the first antiparticle, the positron, identical to the electron apart from the opposite charge, had been discovered in cosmic-ray interactions in a track chamber by Anderson. This was however not antimatter, as the symmetry of the nuclear force binding protons and neutrons in the atomic nucleus of ordinary matter had not yet been studied and proved. Only 32 years later, the first true piece of antimatter, an antideuterium nucleus could be observed [2] in high-energy interactions of protons produced in the laboratory.

Today, in the same laboratories physicists can build antiatoms, elements of antimatter with the same chemical properties of matter elements. Why in nature we do not find what can be easily reproduced in the laboratory?

Lot of progresses have been made since then both in astrophysics and in the theory of elementary forces between particles. A Standard Model of particles and fields has been established, based on experimental observation of particle interactions at very high energy. A standard Big Bang model for the birth and the evolution of the Universe has solid observational bases. However a clear reason why antistars and antigalaxies cannot exist has not yet been formulated.

Nowadays, 75 years later, we have to stay on a statetement by T. D. Lee, made on December 1995 in Bologna when concluding his lecture at the Accademia delle Scienze [3]: “Thus, the

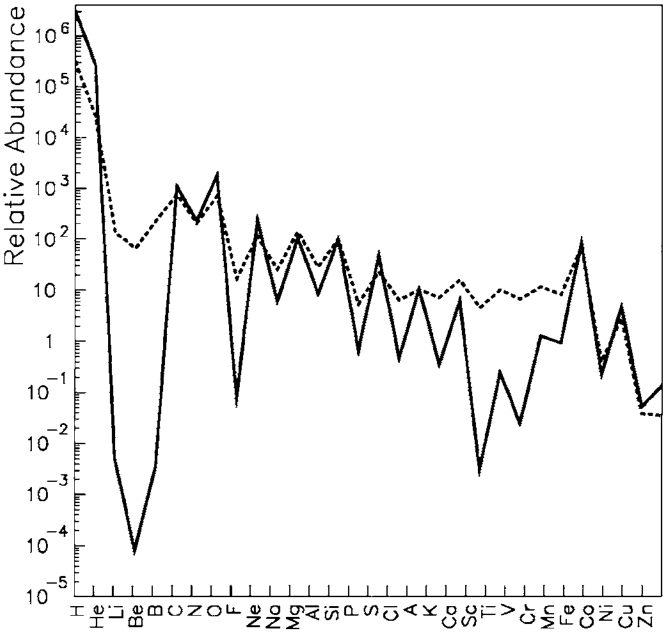


Fig. 1 The relative abundance of cosmic rays at the top of the atmosphere (dashed curve) compared with Solar System and local interstellar abundance (solid curve) all arbitrarily normalised to silicon (=100) [4].

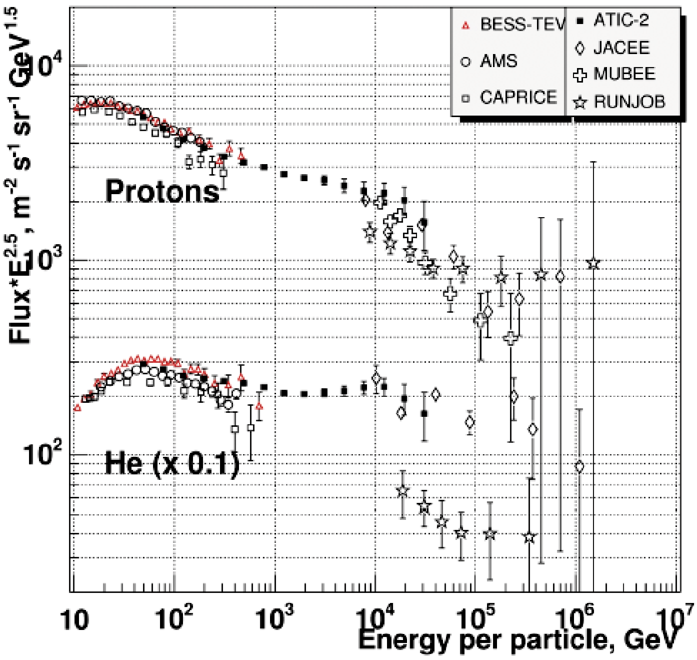


Fig. 2 H and He spectra at the top of the atmosphere compared to previous results [5].

CPT theorem rests on a foundation which has to be unsound, at least at the Planck length, and maybe at a much larger distance. The symmetry of matter and antimatter must rest on experimental evidence".

2 Experimental evidence

To study the presence of antimatter in the observable Universe, as stated by Dirac, we cannot use electromagnetic waves coming from hypothetical antistars, because matter and antimatter radiate in the same way. We must therefore rely on non-elecromagnetic signals coming on Earth from distant stars and galaxeis, *e.g.* cosmic rays and neutrinos. Neutrinos, although they could be a very efficient messenger, are too difficult to be detected. This review will be focused on cosmic rays, in particular on the nuclear component, in which eventually the products of nucleosyntesis of antimatter can be found.

Primary Cosmic Rays

Since the discovery of cosmic rays it was clear that the positive charge was prevailing on the negative charge. When the study of their flux could be extended above the atmosphere bringing charged-particle detectors with baloons flights, the direct detection of the cosmic rays coming from space showed that the so-called "primary" cosmic rays are mainly protons, about 20% He nuclei and a small 1% fraction are heavier nuclei.

Their detailed study permitted to observe the abundance of the nuclear species and to find a quite remarkable correspondence with the abundance of elements on our Solar System, fig.1.

This result was a convincing confirmation of the models describing the primordial nucleosyntesis of light nuclei, the formation of stars and the build-up of heavier elements in the gravitational collapses of supernovae. The baryonic matter components of cosmic rays are residuals of the same processes which have produced the Solar System and our planet Earth. In fig. 1 the relative abundances of elements in the Solar System (full line) and in primary cosmic rays (dashed line) are compared and the only relevant difference is due to the interactions of the primary elements on the interstellar medium which tend to produce less abundant nuclei like Li, Be and B.

The energy spectrum of primary cosmic rays has a typical power low behaviour, with an exponent of about 2.5, first explained by Fermi with his cosmic-particles acceleration model in the galactic magnetic field. Nowadays the particle acceleration associated with supernova remnant shocks appears to better explain how galactic cosmic rays achieve

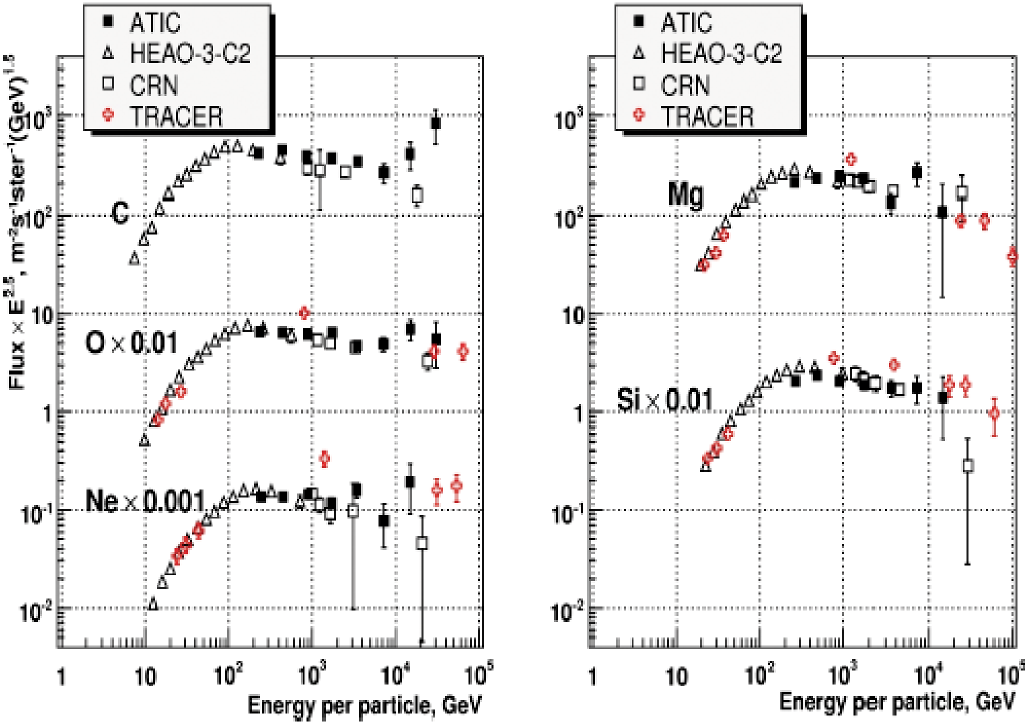


Fig. 3 Spectra of even abundant nuclei compared to the results of other experiments [5].

their high energies. Evidence that particles acceleration is taking place at supernova remnants is provided by electron synchrotron and gamma-ray emission measurements. Moreover, the supernova remnant shock acceleration mechanism is expected to have an upper energy limit imposed by the conditions in the expanding shell following the supernova explosion. Thus, one might well expect to find changes in the cosmic ray spectra of different elements as observations move to higher and higher energy.

Experimental data on primary cosmic-ray fluxes from the last 2007 Cosmic Rays Conference are reported below.

Flux data on nuclei

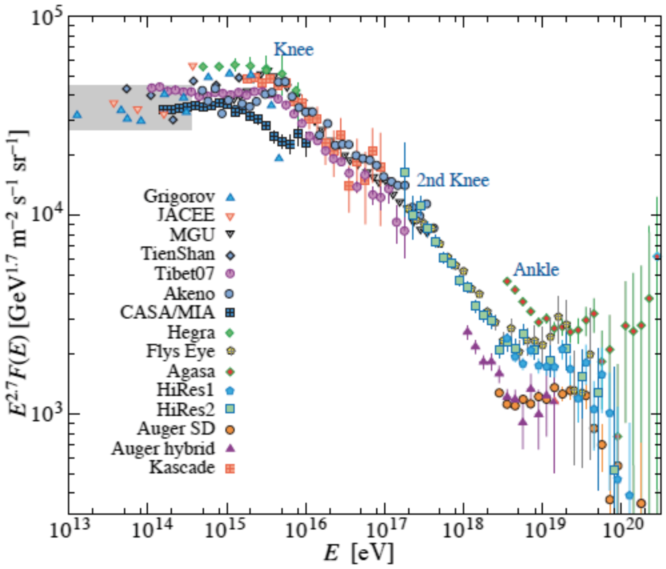
The most recent results on primary cosmic nuclei fluxes are by the ATIC Collaboration [5]. Figure 2 shows p and He spectra compared to previous work at lower energy and to emulsion chamber results at higher energy. Data are in good agreement with BESS and AMS results in the 100 GeV region and demonstrate spectra that flatten as energy increases. The He spectrum differs significantly from H, which is in basic agreement, at high energies, with previous emulsion chamber results. Since the H and He spectra are different, the H/He ratio is energy dependent. The ratio continues to decrease with energy, becoming unity above 10 TeV.

Results for C, O, Ne, Mg and Si compared to previous data are shown in fig. 3 above. The agreement is, in general, good in the region between ~0.2−20 TeV per particle confirming previous results. The one exception is carbon (not measured by TRACER) for which ATIC-2 shows a turn-up beyond 10 TeV, which was not seen by CRN. Heavy nuclei follow more closely the helium spectrum, and the agreement among the experiments measuring the abundant heavy nuclei is good.

Above 10 TeV, cosmic rays can only be studied with the tecnique of extensive air showers [6]. Figure. 4 shows the "all-particle" spectrum. The differential energy spectrum has been multiplied by $E^{2.7}$ in order to display its features that are otherwise difficult to discern. The steepening that occurs between 10^{15} and 10^{16} eV is known as the *knee* of the spectrum. The feature around 10^{19} eV is called the *ankle* of the spectrum.

Assuming that the cosmic-ray spectrum below 10^{18} eV has galactic origin, the knee could reflect the fact that most of the cosmic accelerators in the Galaxy have reached their maximum energy. Some types of expanding supernova remnants, for example, are estimated not to be able to accelerate protons above energies in the range of 10^{15} eV. Effects of propagation and confinement in the Galaxy also need to be considered.

Concerning the ankle, one possibility is that it is the result of a higher-energy population of particles overtaking a lower-energy population, for example, an extragalactic flux beginning to dominate over the galactic flux. Another possibility is that the dip structure in the region of the ankle is due to energy losses of extragalactic protons on the 2.7 K cosmic microwave radiation background. This dip structure has been cited as a robust signature of both the protonic and extragalactic nature of the highest-energy cosmic rays. If this interpretation is correct, then the end of the galactic cosmic-ray spectrum would be at an energy lower than 10^{18} eV, consistent with the maximum expected range of acceleration by supernova remnants. If the cosmic ray flux above the second knee is cosmological in origin, there should be a rapid steepening of the spectrum (called the GZK



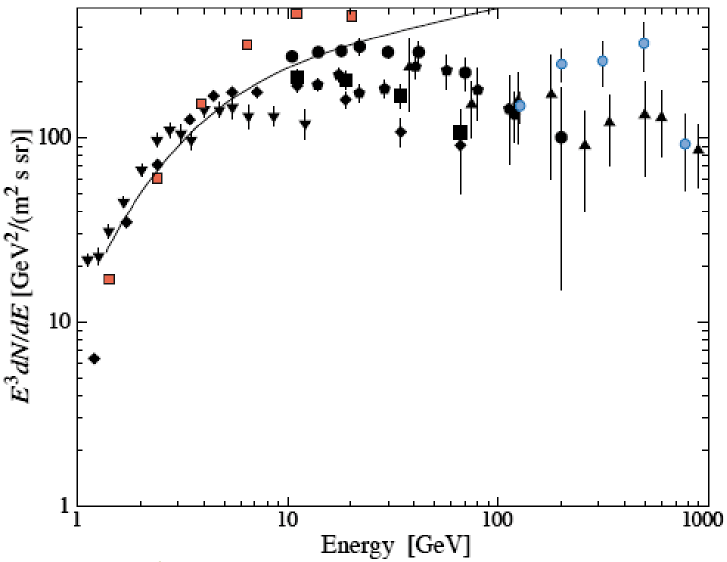


Fig. 4 The all-particle spectrum from air shower measurements. The shaded area shows the range of the direct cosmic-ray spectrum measurements [6].

Fig. 5 Differential spectrum of electrons plus positrons multiplied by E^3. The line shows the proton spectrum multiplied by 0.01 [6].

feature) around 5 × 10^{19} eV, resulting from the onset of inelastic interactions of ultrahigh-energy cosmic rays with the cosmic microwave background. Although experiments have detected events of energy above 10^{20} eV, the spectral shape above the ankle is still not well determined. The HiRes and Auger spectra show a significant steepening of the cosmic-ray spectrum above 3–5 × 10^{19} eV, which is consistent with the onset of inelastic interactions with astrophysical photon fields, mostly cosmic microwave background radiation. The continued power law type of flux beyond the GZK cutoff claimed by the AGASA experiment is not supported by the HiRes and Auger data.

In November 2007 the Auger Collaboration reported [7] a correlation of the arrival directions of the highest-energy cosmic rays with active galactic nuclei at a distance less than 75 Mpc. Twenty of the 27 events with energy above 6 × 10^{19} eV arrive at an angle less than 3.1° from the position of a nearby active galactic nucleus.

Electrons, positrons

The spectrum of electrons and positrons incident at the top of the atmosphere is steeper than the spectra of protons and nuclei, as shown in fig. 5. Positrons are believed to be mainly created in secondary-production processes resulting from the interaction of cosmic-ray nuclei with the interstellar gas. The positron fraction, $e^+ / (e^+ + e^-)$, can be used to investigate possible primary sources. If secondary production dominates, the positron fraction is expected to fall as a smooth function of increasing energy. The positron fraction decreases from 0.2 below 1 GeV to 0.1 around 2 GeV and to 0.05 at the highest energies for which it is measured (5–20 GeV). The last results are based on the very interesting data-set collected by the satellite cosmic-rays spectrometer PAMELA [8] between July 2006 and February 2008.

Figure 6 shows the positron fraction as function of energy on a set of 151672 electrons and 9430 positrons identified in the energy interval 1.5–100 GeV [9]. The experiment confirms with high statistical significance the growth of the positron flux above 10 GeV, and the source of this growth is to be understood.

Antiprotons

The discovery of the antiproton in 1955 [10] was the starting point in the serch for cosmic antimatter. Antiprotons can be produced from collisions of energetic cosmic-ray particles, primarily protons, with the constituents of the interstellar gas such as hydrogen and helium. Possible primary sources of galactic antiprotons include the annihilation of dark-matter particles and the evaporation of primordial black holes. The ratio of antiprotons

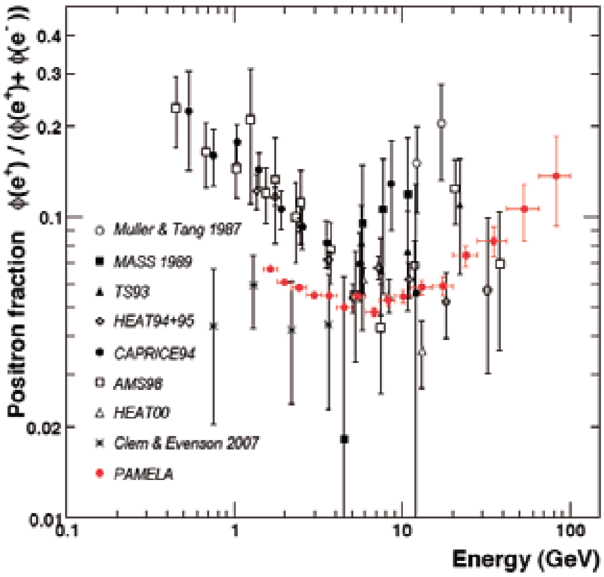


Fig. 6 The positron fraction measured by the PAMELA experiment compared with other recent experimental data. One-standard-deviation error bars are shown [8].

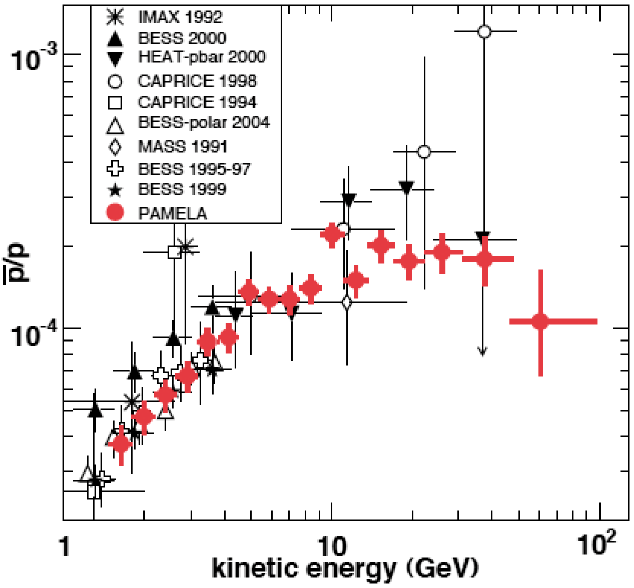


Fig. 7. The antiproton-to-proton flux ratio obtained by the PAMELA experiment compared with recent measurements [11].

to protons is 2×10^{-4} at around 10–20 GeV, and there is clear evidence for the kinematic suppression at lower energy that is the signature of secondary antiprotons. The last results come from the PAMELA satellite experiment [11], whose data on the antiproton flux are in excellent agreement with recent data from other experiments, as shown in fig. 7.

Antinuclei

There is at this time no evidence for a significant "primary" component in the sense we want to explore, namely the footprints of cosmic domains of antimatter formation. No antinucleus has ever been observed in the cosmic radiation, which most likely excludes the presence of large domains of antimatter in our region of the Universe. No antihelium or antideuteron, the most reliable signature of the existence of antistars have been found. As we will see in section 4, the best current measured upper limit on the ratio antihelium/helium is approximately 7×10^{-7}. The upper limit on the flux of antideuterons around 1 GeV/nucleon is approximately 2×10^{-4} m^2 s sr GeV/nucleon.

3 Symmetry of matter and antimatter

Symmetry in physics has always been a fundamental principle guiding the mathematical formulation of theories. The time *T* symmetry in relativistic mechanics, the charge symmetry *C* and the parity *P* in quantum electrodynamics, the *CPT* conservation theorem in field theories have been guiding lines in the developement of Quantum Electro Dynamics. The violation of those conserved quantum numbers, when experimentally discovered, was always going in parallel with the better understanding of new forces operating in Nature, like the weak forces between leptons and quarks. The same *CPT* conservation, as pointed out by T. D. Lee, is questionable at Planck lenghts.

Is there place for antimatter in a totally asymmetric Universe as ours seems to be?

When the first theories on baryogenesis have been put forward by Alhen and Gamow, the problem soon arose of the apparent absence of antimatter in the Universe. The necessary conditions for baryogenesis pointed out by Andrei Shakarov are [12] :

- Baryon number *B* non-conservation
- *C* and *CP* symmetry non-conservation
- Out-of-equilibrium conditions for *T*-symmetry–violating decays

These conditions were at that time (year 1947) in contradiction with the known facts. The first difficulties to be possibly removed have been those referring to *C* and *CP* which have been found non-conserved already at the relative low temperatures of weak interactions. On the other hand the stability of the proton is firmly established, the lower limit on its decay lifetime being many orders of magnitude bigger than the age of our Universe.

The developements in the study of elementary particles and their interactions, made possible by the accelerator machines at progressively higher energies have changed the cosmological-problem perspective. The nuclear-matter elementary constituents, protons and neutrons, have been found not to be really elementary, and nowadays the Standard Model of elementary particles and fields is a well-tested theory based on quarks and leptons.

In this new perspective the Big Bang scenario is changed a lot, because the primordial baryogenesis giving origin to stars and the following nucleosynthesis of heavier elements is a very late stage of a hot beginning. In the absence of experimental observations at temperatures corresponding to elementary-particles energies exceding 100 TeV, we can make only suggestions and put forward fascinating theories, based on the hypothesis that approaching the very hot beginnining all known forces get the same strength and merge, like electromagnetic and weak force do at the relative low energy of 100 GeV. In this framework the conserved quantum numbers and the asymmetries we observe must be the results of some spontaneous symmetry breaking of the primordial forces governing the very first start of our Universe.

It is difficult to think of being able in the future to reproduce in the laboratory with higher and higher energy accelerator machines the temperatures at the first stages after the Big Bang, and study the properties of unified forces. If this were possible, we could observe experimentally the origin of the apparently asymmetric Universe. In the well-established Standard Model there is still something missing. The mass of matter particles should be generated by an already undiscovered boson, the Higgs. Field theories try to depict plausible scenarios in which matter particles (spinors) and field particles (bosons) are on the same ground and trasform into each other. Theoretical efforts are underway in various directions: to build a unified theory of strong and electroweak forces, to bring the gravitational fundamental force in the realm of quantised field theories, to build a grand unification scenario of all four fundamental forces, to describe the very onset of space-time.

The astrophysics has enormously refined its observational data. As a result the actual picture of our Universe is possibly more misterious than 50 years ago. The necessity of introducing dark matter and dark energy on solid observational grounds is a challenge both to experiments and theory. Also to explain the very high uniformity of the primordial Universe around us, as shown by the cosmic-microwave-background data, is a difficult theoretical task.

A new theory, the so-called "inflationary universe", has been put forward, in which the time expansion was so rapid that the primordial thermodynamic equilibrium was possible before the subsequent non-equilibrium phase transitions.

The consequences of the "inflationary universe" are a matter of purely theoretical speculations and cannot at present exclude a Universe with antimatter.

On the one hand, they can explain why in our observable Universe there is no antimatter. The inflation is a natural scenario where a baryogenesis can take place: it allows the out-of-equilibrium condition requested by Sakarov and it can avoid the *a priori* hypothesis of initial symmetric conditions [13].

On the other hand, one can speculate of a globally symmetric universe being only locally asymmetric. In a totally symmetric universe, high-energy cosmic rays could escape from an antimatter domain and get to our Galaxy. However, on the basis of γ-rays observations it is inferred that our matter-dominated region has at least the size of a cluster of galaxies. In the matter-dominated universe there is also the possibility of small insertions of antimatter regions. Quantum fluctuations of a complex, baryonic charged scalar field caused by inflation can generate antimatter regions that can survive annihilation [14]. In this scenario there can exist antistar globular clusters in our galaxy.

In conclusion the T. D. Lee observation quoted in the introduction, is still valid, and the absence of antimatter should be verified experimentally. The expected signature of such scenarios is a flux of anti-He nuclei accessible to large-acceptance cosmic-rays spectrometers.

4 The search for antimatter with AMS-02

The observed antiparticles coming from space, positrons and antiprotons, are believed to be "secondaries" produced mainly by cosmic-rays interactions with the interstellar medium through inelastic collisions. Theoretical calculations based on the accepted models of cosmic-rays propagation in the Galaxy and known collision cross-sections, give the correct order of magnitude for the ratio of antiparticles to the corresponding particles, namely $O\,(10^{-3})$ for positrons, $O\,(10^{-4})$ for antiprotons, $O\,(10^{-8})$ for antideuterons (still not observed). The growing interest on those antiparticle spectra is due to the fact that any deviation in excess from the calculated spectra could reveal the presence of totally new interactions in space due to the unknown nature of the dark matter. Therefore positrons and antiprotons, although very interesting candidates for new physics, are not to be considered good signatures for antimatter.

The order of magnitude for the ratio of secondary production is $O\,(10^{-12})$ for antihelium. Given the high percentage

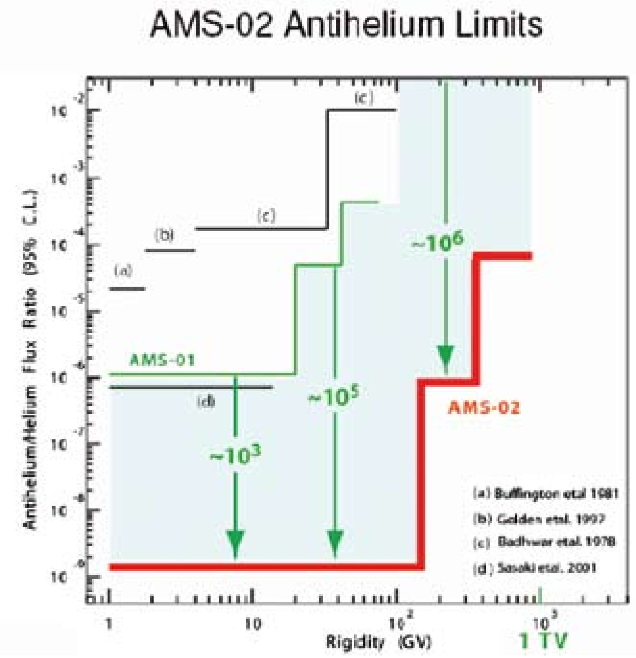


Fig. 8 Antihelium flux limits as function of rigidity of present (black lines) and future experiments for antimatter search in cosmic rays. AMS-01 present limit is in green, whereas the improvement factor in sensitivity of AMS-02 is marked by the thick red line.

of primary He in the cosmic matter and the very low probability for the production of antihelium secondaries via interactions in the Galaxy, the detection of even few clearly identified antihelium nuclei would be a very strong signature for antimatter. The same is true for light antinuclei like anticarbon, but their abundance is almost two orders of magnitude lower. Therefore all experiments measuring the flux of primary cosmic rays look for the antihelium signal to search for antimatter in terms of relative flux of antihelium over helium.

Figure 8 shows the presently established anti-He/He flux upper limits, as a function of particle rigidity. This upper limit was of the order of 10^{-4}. It has been lowered by two orders of magnitude (green line) by the first large-acceptance space spectrometer, AMS-01, in his 10 days flight on the Shuttle Discovery in June 1998 [15], and by the balloon polar flight experiment BESS in 2001 [16]. The thick red line marks the final sensitivity reacheable by the AMS-02 superconducting spectrometer experiment in three years of data-taking on the International Space Station.

The experiment is being assembled now at CERN and will go to the ISS in 2010. It will improve by almost three orders of magnitude the presently established upper limits extending the rigidity to the TV region and the sensitivity to regions of our Universe as distant as hundred Mparsec.

5 The experimental apparatus of the AMS space spectrometer

The AMS-02 apparatus is the final achievement of an international collaboration started in 1994 by S. C. C. Ting of MIT/CERN with the support of A. Zichichi. The collaboration includes 500 physicists of 60 research institutes in 16 countries [17]. (See fig. 9)

The participation of the Italian scientists, coordinated by R. Battiston, AMS deputy spokesperson, has been strongly supported by INFN and ASI [18]. The Italian contributions are very relevant, involving, in particular, the responsibility of the construction of the main particle identification subsystems: Time of Flight (INFN-Bologna [18 a]), Silicon Tracker (INFN-Perugia [18 b]), RICH detector (INFN-Bologna [18 c]) and Electromagnetic Calorimeter (INFN-Pisa [18 d]) and the gas monitoring electronics for the Transition Radiation Detector (INFN-Rome). The INFN-Milano group is responsible for the Italian segment of the ground data transfer system. The experimental program was approved and started in 1995. In less than two years the prototype version of AMS was ready to fly. After the success of the AMS-01 flight in 1998, the design of a superconducting magnet to replace the permanent one was started. AMS-02 was soon financed and started construction to be ready to fly in 2006 [19]. Although slowed down by the 2003 Shuttle flights stop, and by financial and technical issues which are unavoidable for such an ambitious astroparticle space spectrometer, AMS-02 will be ready to be delivered to NASA at the end of year 2009. AMS-02 is an improved version of the first AMS-01 space spectrometer, which was brought to space by the Shuttle Discovery mission STS-91 as a precursor test flight. AMS-01 took almost 90 hours of data at different flight attitudes, at Shuttle altitudes from 320 km to 390 km, at latitudes ±51.7° and all longitudes (South Atlantic Anomaly excluded). The AMS-01 spectrometer was a simplified version in which the magnetic field was given by a cylindrical dipole assembled with permanent magnetic bricks, but the essential elements

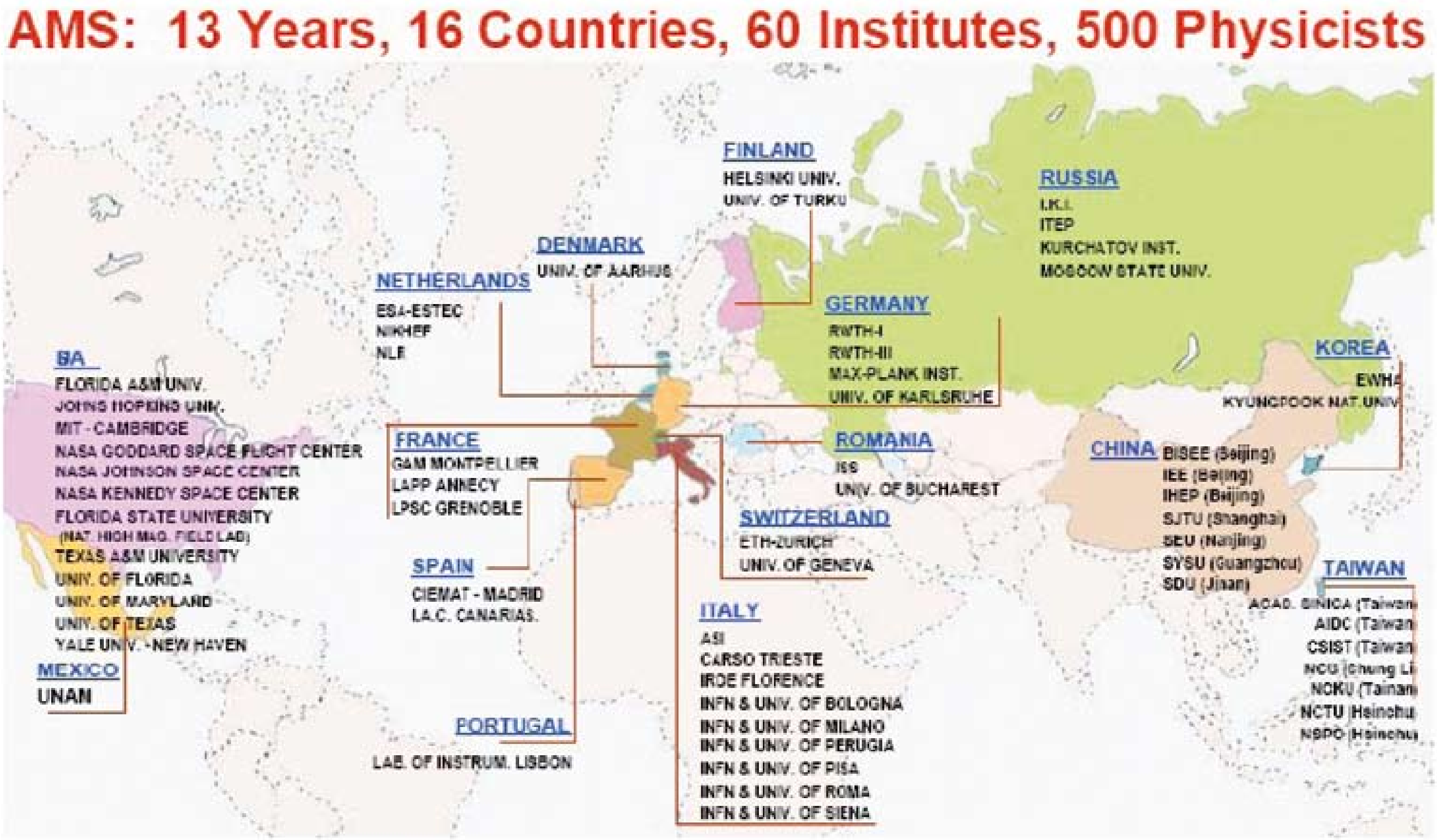


Fig.9 The geographical distribution of the scientific and technical Institutes participating to the International Collaboration AMS.

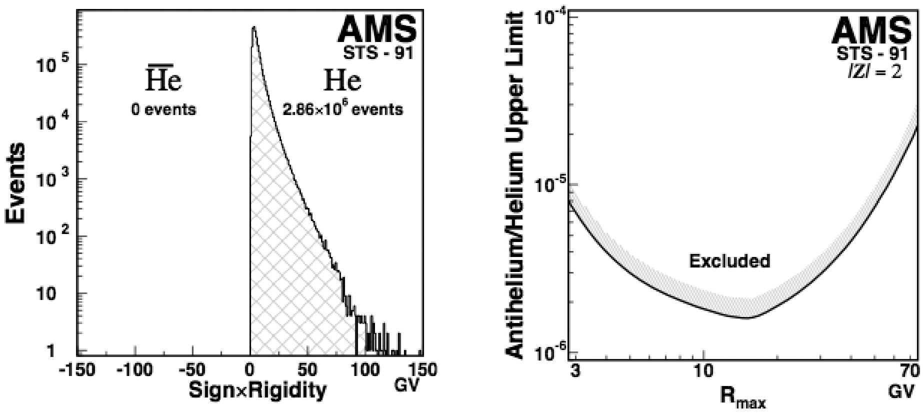


Fig. 10 Antimatter search results of the precursor test flight of the AMS-01 apparatus. Left: the rigidity spectrum of detected He, no anti-He detected. Right: the upper limit on the flux of anti-He as a function of the maximum value of measured rigidity (ref. [15]).

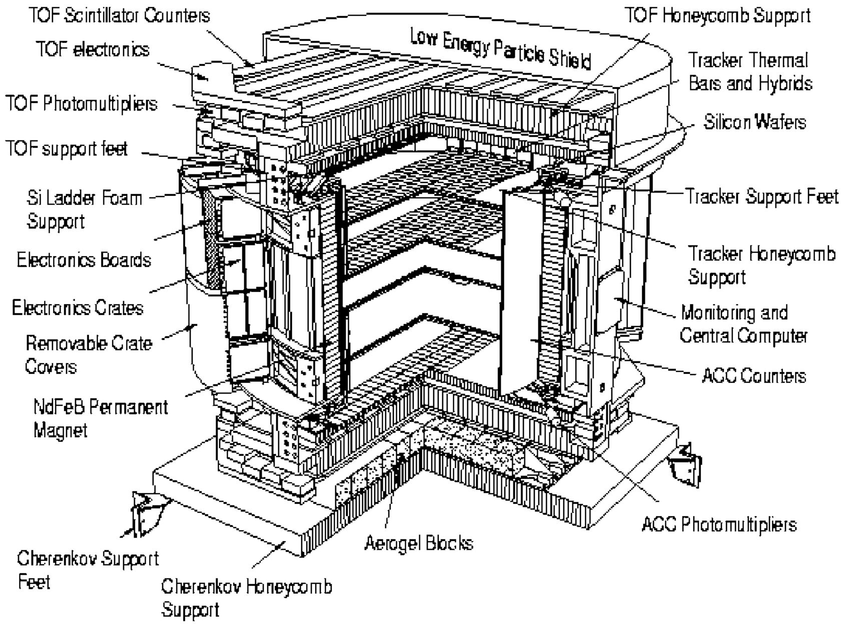


Fig. 11 The AMS-01 apparatus. The three particle detectors, silicon tracker, scintillation counters and threshold Čherenkov detector, are indicated.

Fig. 12 The AMS-02 apparatus and its particle detectors. With respect to AMS-01 one can appreciate the improved particle identification capability.

of the spectromenter, the silicon tracker measuring the tracks curvature and the scintillator telescope for trigger and time of flight, were essentially the same of the improved AMS-02, defining a large acceptance, 0.4 m^2 sr, for the cylindrical magnet, 110 cm in diameter and 80 cm high. In particular the technological challenge to be tested was the 6 m^2 of silicon microstrip planes, for the first time in a space experiment.

The detector was performing well in space and $\approx 10^8$ triggers were recorded on disk. Trigger rates were in the range 0.1–1 kHz with a corresponding data acquisition lifetime 90–40%. The mission was a success, and the published results, summarized in [20] refer to: i) study of the geomagnetic effects and first evidence of trapped cosmic rays under/over geomagnetic cutoff; ii) charged-cosmic-ray spectra of protons, deuterons, electrons, positrons , He and N nuclei; iii) upper limit on antihelium flux.

In fig. 10 the results of AMS-01 on antimatter search are shown [15]. The upper limit on the total number of observed antihelium nuclei with respect to detected He was 1.1×10^{-6}. The left figure shows the He spectrum, at right the flux limit as function of rigidity.

Figure 11 is a perspective view of AMS-01, with all parts visible, to be compared with AMS-02 as shown in fig. 12. Apart from the big magnet aperture and the time-of-flight scintillator trigger coverage which are the same, 0.4 m^2 sr, an essential characteristic of the spectrometer for the antimatter search, all parts of the detector have been inproved. The old silicon tracker structure supports two more planes in an optimised geometry, 8 in total. With its track resolution of 10 μm, it can measure rigidities in the TV range, thanks to a magnetic field 6 times stronger than in AMS-01. The superconducting magnet, with its 1200 l liquid-He tank ensuring an autonomy of three years in space with no human intervention, is in fact the major technological challenge of the improved apparatus.

Particle identification is enormously improved by the other detectors added, namely the upper transition radiation detector TRD, ensuring an electron/hadron separation better than a factor 10^2, the lower-ring imaging Čerenkov RICH giving a 0.1% resolution in the velocity for $Z > 1$ nuclei, and last but not least, the 3D sampling electromagnetic calorimeter ECAL, 16 radiation lengths thick, with 2% energy resolution for electrons and an electron/hadron rejection factor exceding 10^3.

The expected performances and the powerful particle identification capabilities of AMS-02 are best illustrated by table I, showing the numbers of identified cosmic rays in three years of data-taking on board of the International Space Station.

In fig. 13 AMS-02 is shown preassembled in the clean room especially built at CERN. As one can appreciate from the photo, it is a 4 m high, 7 tons weight payload, the first astroparticle detector of this size in space, which will be installed in the year 2010 on the International Space Station and will operate for at least three years, for an ambitious scientific research program.

6 Conclusion

The cosmological problem of the asymmetry of matter and antimatter in our Universe must be studied experimentally. The various theoretical frameworks, which try to describe the very first apparence 13.7 Gy ago, and the following evolution to the present time, of our Universe, cannot exclude the existence of extended domains of antimatter or even of local sources of antimatter cosmic rays. It is therefore still meaninful to search for them.

In few years from now the AMS-02 space spectrometer will give a significant experimental contribution to the problem. In any case, even if no antinucleus were to be found, this space experiment has a very interesting astrophysics program, going from the indirect search of dark matter with the high statistic of positrons and antiprotons, to the detailed study of the origin and propagation of cosmic rays with precise measurements on cosmic-ray nuclear species up to Z of 25 in the GeV-to-TeV energy range. Aside it has a gamma-ray directional detection capability up to 300 GeV energies. AMS-02 can have for astroparticle physics the same impact as the Hubble space telescope for astronomy. Cosmic rays are a natural beam of ultrahigh-energy particles, which have been in the past the place for exciting discoveries, permitting to observe events and interactions produced by the cosmic acceleretors, always many orders of magnitude more powerful than our laboratory machines.

Acknowledgements

Many thanks to L. Cifarelli who pressed me to write this contribution for the Italian Physical Society and to C. Vasini and A. Oleandri of SIF for their patience.

To S.Ting and R. Battiston, AMS spokepersons, my gratitude for their reading of the manuscript and useful suggestions. The paper has been written thanks to the support of the AMS group in Bologna, A. Basili, V. Bindi, F. Cindolo, G. Castellini, A. Contin, C. Guandalini, G. Laurenti, G. Levi, L. Quadrani, C. Sbarra and the technicians M. Lolli, and the retired F. Massera, G. Molinari and R. Pilastrini.

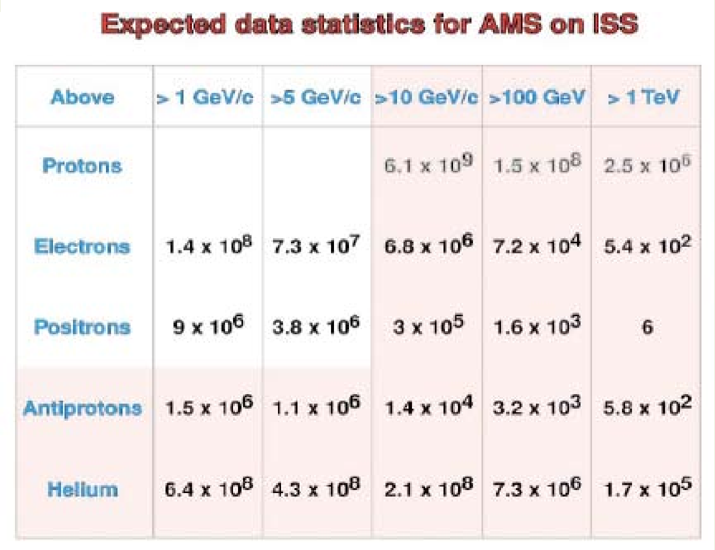
Special thanks to Alessandro, Veronica, Federico, Lucio and Cristina, who helped me in assembling and correcting the material for text and figures. Important contributions to the quoted AMS papers have been given by L. Baldini in AMS-01, D. Casadei, now at NYU USA, and F. Giovacchini now at CIEMAT, Spain.

For me this is a unique occasion to acknowledge all people who helped in pursuing, since 1995, the scientific program of AMS.

First A. Zichichi, who suggested me to take the responsability of this fascinating experiment.

Second the INFN directors P. Giusti, M. Basile and A. Zoccoli who supported the experiment, and the Physics Department directors A. Rossi and P. Capiluppi hosting our work.

Third T. Ferro, E. Amadei, the retired L. Battaglia and all the INFN administration personnel, A. Margotti, G. Pancaldi, S. Zagato, S. Zucchini, and all the mechanical workshop personnel, S. Finelli and the technical design workshop, I. D’Antone , F. Degli Esposti and the electronics workshop, R. Nania and the experiments support group, F. Brasolin, A. Paolucci and the computing support group, C. Spisni



Expected data statistics for AMS on ISS

Above	> 1 GeV/c	>5 GeV/c	>10 GeV/c	>100 GeV	> 1 TeV
Protons			6.1×10^9	1.5×10^8	2.5×10^5
Electrons	1.4×10^8	7.3×10^7	6.8×10^6	7.2×10^4	5.4×10^2
Positrons	9×10^6	3.8×10^6	3×10^5	1.6×10^3	6
Antiprotons	1.5×10^6	1.1×10^6	1.4×10^4	3.2×10^3	5.8×10^2
Helium	6.4×10^8	4.3×10^8	2.1×10^8	7.3×10^6	1.7×10^5

Tab. I Number of identified different (rows) cosmic-ray particles above a given energy threshold (columns) in three years of data-taking on board of the International Space Station.

for the logistic services of the Physics Department, and in Florence, the electronics technicians of Ifac-CNR, M. Tesi and L. Gabbanini now both retired.

Finally the students who spent with great enthusiasm their thesis study time in the AMS group, E. Prati, D. Alvisi, D. Minelli, K. Molino, E. Lanciotti, V. Vitale, L. Patuelli, A. Armaroli, M. Salvatore, R. Martelli, N. Carota, L. Amati, A. Oliva, L. Villa, D. Baldassarri, L. Brocco.

References

[1] Quoted from S. C. C. Ting, "*The discovery of nuclear antimatter and the origin of the AMS experiment*", in *Symposium in honour of Antonino Zichichi to celebrate the 30th anniversary of The Discovery of Nuclear Antimatter*, edited by L. Maiani and R. A. Ricci, *SIF Conf. Proc.*, vol. 53 (Editrice Compositori, Bologna) 1996, pp. 15-29.

[2] T. Massam, Th. Muller, B. Righini, M. Schneegans and A. Zichichi, "*Experimental observation of antideuteron production*", *Il Nuovo Cimento*, 39 (1965)10; D. E. Dorfan *et al.*, "*Observation of Antideuterons*", *Phys. Rev. Lett.*, 14 (1965) 1003.

[3] T. D. Lee, "*Are matter and antimatter symmetric*?", in [1], pp. 1-14.

[4] L. Bergstrom and A. Goobar, "*Cosmology and Particle Astrophysics*" (John Wiley & Sons)1999, p. 202.

[5] J. P. Wefel *et al.*, "*Revised Energy Spectra for Primary Elements (H – Si) above 50 GeV from the ATIC-2 Science Flight*", in *Proceedings of the 30th International Cosmic Ray Conference, Mexico City, Mexico, 2008*, vol. 2 (OG part 1), pp. 31–34.

[6] T. K. Gaisser and T. Stanev, "*Cosmic Rays*", in *Review of Particle Physics*, *Phys. Lett. B*, 667 (2008) 254.

[7] The Auger Collaboration, *Science*, 308 (2007) 938.

[8] P. Picozza *et al.*, "*PAMELA - A payload for antimatter matter exploration and light-nuclei astrophysics.*", *Astropart. Phys.*, 27 (2007) 296.

[9] O. Adriani *et al.*, "*Observation of an anomalous positron abundance in the cosmic radiation*", `arXiv:0810.4995v1 [astro-ph]` 28 Oct. 2008.

[10] O. Chamberlain *et al.*, *Phys. Rev.*, 100 (1955) 947.

[11] O. Adriani *et al.*, "*A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation*", `arXiv:0810.4994v1 [astro-ph]`, 28 Oct 2008.

[12] A. Sakharov, *JETP Lett. B,* 91 (1967) 24.

[13] L. F. Abbott *et al.*, *Phys. Lett.B*, 117 (1982).

[14] M. Y. Khlopov, S. G. Rubin and Al. S. Sakharov, `hep-ph/0210012`; M. Yu. Klophov *et al.*, *Phys. Rev D,* 62 (2000) 083505.

[15] M. Aguilar *et al.* (AMS-01 Collaboration), "*Search for Antihelium in Cosmic Rays*", *Phys. Lett. B*, 461 (1999) 387.

[16] M. Sasaki *et al.* (BESS Collaboration), "*Progress in search for antihelium with BESS.*", *Nucl. Phys. Proc. Suppl.*, 113 (2002) 202.

[17] `http://ams.cern.ch/AMS/ams_homepage.html`

[18] R. Battiston, F. Cervelli (Editors), *Proceedings of the 1st International Conference on Particle and Fundamental Physics in Space (Space Part 2002), La Biodola, Isola d'Elba, Italy, 14-19 May 2002, Nucl. Phys. Proc. Suppl.*, 113 (2002) pp. 125-201.
a) D. Casadei *et al*, "*The AMS-02 Time of Flight System*", ibid. pp.133-138;
b) W. J. Burger, "*The AMS Silicon Tracker*", ibid. pp.139-146;
c) J. Casaus, "The AMS RICH detector", ibid. pp.147-153;
d) F. Cadoux *et al.*, "The AMS-02 electromagnetic calorimeter", ibid. pp.159-165.

[19] R. Battiston, "Rapporteur talk on direct measurements and origin of cosmic rays" in "*Frontiers of cosmic ray science*", *28th International Cosmic Ray Conference (ICRC 2003), Tsukuba, Japan, 31 Jul-7 Aug 2003*; vol. 8 (*Tsukuba*) 2003, pp.229-249.

[20] M. Aguilar *et al.*, (AMS-01 Collaboration), "*The Alpha Magnetic Spectrometer (AMS) on the International Space Station, Part I, Results from the test flight on the Space Shuttle*", *Phys. Rep.*, 366/6 (2002) 331.

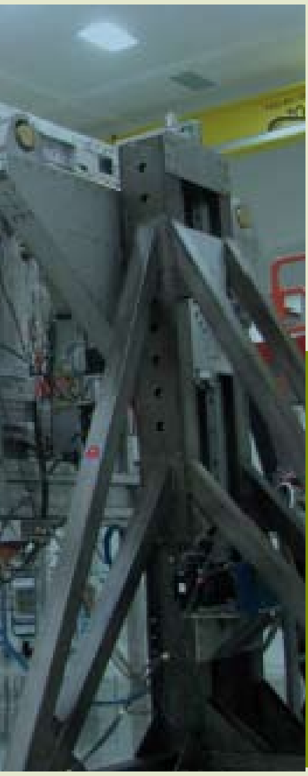


Fig. 13 The AMS-02 cosmic rays spectrometer as it appeared pre-assembled in a clean room at CERN in July 2008. The final assembly and testing will end in October 2009.

Federico Palmonari

Federico Palmonari is Senior Scientific Associate of INFN and contractor in the Science Faculty of Bologna University. Physics degree in Bologna (1963), research staff of INFN ('65-'80), CERN staff in Research Division ('73-'78), Professor of experimental physics at Perugia ('80-'82) and, since1982, in Bologna. His research started at CERN with the first measurement in gaseous H of the muon capture rate, then in Frascati with e+e- interactions at ADONE. Back to CERN he studied p-p interactions and heavy quarks at ISR. Visitor at DESY in the experiment ZEUS, since '95 has been responsible of the INFN-Bologna group in the Collaboration AMS.