LNF-89/057

G. Basini, M. Ricci, P. Spillantini, P. Piccozza

A COSMIC ANTIMATTER DETECTOR ON A POLARORBIT SATELLITE

Estratto da: Nuovo Cimento 103B, 635 (1989)

IL NUOVO CIMENTO VOL. 103 B, N. 6 Giugno 1989

A Cosmic Antimatter Detector on a Polar-Orbit Satellite.

G. BASINI and M. RICCI
Laboratori Nazionali INFN - Frascati (Roma)

P. SPILLANTINI
INFN - Sezione di Firenze

P. PICOZZA
Dipartimento di Fisica, II Università di Roma - Tor Vergata (Roma)

(ricevuto il 4 Aprile 1989)

Summary. — In order to get a high statistics in the collection of low-energy cosmic antiprotons and to maximize the probability to detect the hypothesized cosmic antialphas, the necessity of an experiment placed on a polar orbit is discussed in this paper. An apparatus able to detect $\bar{\alpha}$, $\bar{p}$ and e^+ with high accuracy in the range $(0.5 \div 5.0)$ GeV is also presented.

PACS 07.90 – Other topics in specialized instrumentation.
PACS 94.80 – Aerospace facilities and techniques; space research.

1. – Physical motivations for antimatter search.

1·1. *Antihelium and heavier antinuclei.* – One of the most fundamental questions of today's physics is whether a substantial quantity of antimatter of cosmological origin is present in the Universe (up to a matter-antimatter completely symmetric universe). The presence of antimatter has to be treated in a different way for antinuclei than for antiprotons and positrons, because antinuclei in cosmic rays can exist only under symmetric or very exotic hypotheses, while positrons antiprotons can be produced also via standard interactions between elementary particles. The particle-antiparticle symmetry observed in elementary-particle experiments, in addition to the conservation of baryon and lepton numbers, rises the question of why the Universe seems to be composed only of matter. The introduction of models of a matter-antimatter symmetric universe (in which the matter dominance would be only local) has been made in the past by several theorists (1-3) and more recently by Stecker and others (4-7); here we comment the consequence of these models: the existence of a detectable flux of antihelium nuclei (4). The first step in the search for cosmic antinuclei, if existent, is to look at antihelium (supposed to be dominant among antinuclei in cosmic rays like the helium among nuclei) because it has a real practical possibility to be detected to check the theories. In fact, assuming as a first approximation the ratios between antinuclei in cosmic rays equal to the ratios between nuclei, we remember that, increasing the atomic number, the proportions between cosmic nuclei are

$$\mathrm{H}:\mathrm{He}:[\mathrm{C}+\mathrm{N}+\mathrm{O}]:[9<Z<19]:[20<Z<30]:[30<Z]\sim$$
$$\sim 31\,000:5\,400:210:72:17:0.003\,.$$

Even if the statistics makes it very difficult to detect an antinucleus heavier than helium, its detection would be a very significant discovery because such a heavy antinucleus could neither have been synthesized in the big bang, nor produced in proton collisions with the interstellar gas. As Ahlen *et al.* affirm in ref. (8): «Even the harshest critics of baryon symmetric cosmologies concede that the *unambiguous* observation of just one heavy antinucleus would be compelling evidence for the existence of antistars in the Universe».

Despite the mentioned difficulties, the heavy-antinuclei search is so attractive that dedicated experiments have to be done, maybe looking at $\overline{\mathrm{Fe}}$ which seems to be the best candidate.

Let us now consider the antihelium, which is up to now the real chance to get an eventual proof of the existence of a large amount of primary antimatter in the Universe. With respect to heavier antinuclei, antihelium has the advantage of a much higher expected flux and the disadvantage to be not a complete proof of the existence of antistars but only a strong indication. In fact, antistars are, in principle, not necessary to explain antihelium as well as stars are not necessary to explain helium, which is estimated to be produced for 75% in the big-bang nucleosynthesis. But what is important is that $\overline{\mathrm{He}}$, like heavier nuclei, cannot be secondarily produced through elementary-particle interactions (the probability

---

(1) R. OMNES: *Phys. Rev. Lett.*, **23**, 38 (1969).
(2) F. HOYLE: *Nature*, **244**, 477 (1969).
(3) F. HOYLE and J. NARLIKAR: *Proc. R. Soc. London, Ser. A*, **290**, 143 (1966).
(4) R. W. BROWN and F. W. STECKER: *Phys. Rev. Lett.*, **43**, 315 (1979).
(5) G. SENJANOVIC and F. W. STECKER: *Phys. Lett. B*, **96**, 285 (1980).
(6) K. SATO: *Phys. Lett. B*, **99**, 66 (1981).
(7) F. W. STECKER: *Nucl. Phys. B*, **252**, 25 (1985).
(8) S. P. AHLEN, P. B. PRICE, M. H. SALOMON and G. TARLÈ: *Astrophys. J.*, **260**, 20 (1982).

that several antinucleons are created in the same element of phase space to produce an antinucleus has been estimated negligible by Hagedorn (9), being $\sim 10^{-55}$ for a $\overline{\text{Fe}}$ and $\sim 10^{-11}$ for an $\bar{\alpha}$) and thus the discovery of $\bar{\alpha}$'s would be the proof of the existence of primary antimatter in the Universe.

However, in a matter-antimatter symmetric universe, one should expect that the ratio $\bar{\alpha}/\bar{\text{p}}$ would be the same of the ratio α/p (10,11), which is experimentally not true and, equivalently, that the ratio $\bar{\alpha}/\alpha$ would be equal to the ratio $\bar{\text{p}}/\text{p}$, whereas it is lower (by now the best confidence limits are $\bar{\alpha}/\alpha < 1.0 \cdot 10^{-4}$ in the range $(4 \div 33)$ GeV/c (12) and $\bar{\alpha}/\alpha < 2.2 \cdot 10^{-5}$ in the range $(130 \div 370)$ MeV/nucl (13)).

Stecker, Protheroe and Kazanas (14) suggested that, if the most part of the cosmic rays comes from active galaxies, the photodisintegration of He antinuclei by low-energy γ-rays and spallation can reduce the $\bar{\alpha}$ flux compared with the $\bar{\text{p}}$ flux. The extragalactic component from normal galaxies is estimated to be $(I_{\text{ex}}/I_{\text{gal}})_{\text{NG}} = \xi_{\text{NG}} \sim (10^{-5} \div 10^{-4})$ while for active galaxies we have a higher value $\xi_{\text{AG}} \sim 10^{-3}$; then the active galaxies can really give the bulk of the extragalactic cosmic-ray flux.

Therefore, we expect that $\bar{\alpha}/\alpha \sim (1/2)\,\xi_{\text{NG}} \sim (5 \cdot 10^{-6}) \div (5 \cdot 10^{-5})$, values that are not reached in the present upper limits but, as we will discuss, can be reached with the future planned experiments.

1'2. *Antiprotons and positrons.* – Positrons and antiprotons can be produced through ordinary elementary-particle interactions (contrary to antialphas) and hence a detectable flux of such antiparticles, of secondary origin, is expected without any necessity of complex mechanisms. However, if the experimental results show a flux of positrons and antiprotons higher than expected via secondary production (which seems to be the case up to now), one must take into account also exotic mechanisms. Indeed, the e^+ and $\bar{\text{p}}$ measurements will not give un unambiguous conclusion as in the case of the discovery of the hypothesized antinuclei, but, being related to many different possible mechanisms (fig. 1 (15)), they are in principle able to verify several models ranging from

---

(9) R. Hagedorn: *Cargèse Lectures in Physics*, **6**, 643 (1973).

(10) G. Steigman: *Annu. Rev. Astron. Astrophys.*, **14**, 339 (1976).

(11) D. Eichler: *Nature*, **295**, 391 (1982).

(12) G. D. Badhwar, R. L. Golden, J. L. Lacy, J. E. Zipse, R. R. Daniel and S. A. Stephens: *Nature*, **274**, 137 (1978).

(13) A. Buffington, S. M. Shindler and C. R. Pennypacker: *Astrophys. J.*, **248**, 1179 (1981).

(14) F. W. Stecker, R. J. Protheroe and D. Kazanas: *Astron. Space Sci.*, **96**, 171 (1983).

(15) A. Buffington, S. M. Schindler and C. R. Pennypacker: *Astrophys. J.*, **248**, 1179 (1981); E. A. Bogolomov, G. Y. Vasilyev, S. Yu. Krut'kov, N. D. Lubyanaya, V. A. Romanov, S. V. Stepanov and M. S. Shulakova: *Proceedings of the XX*

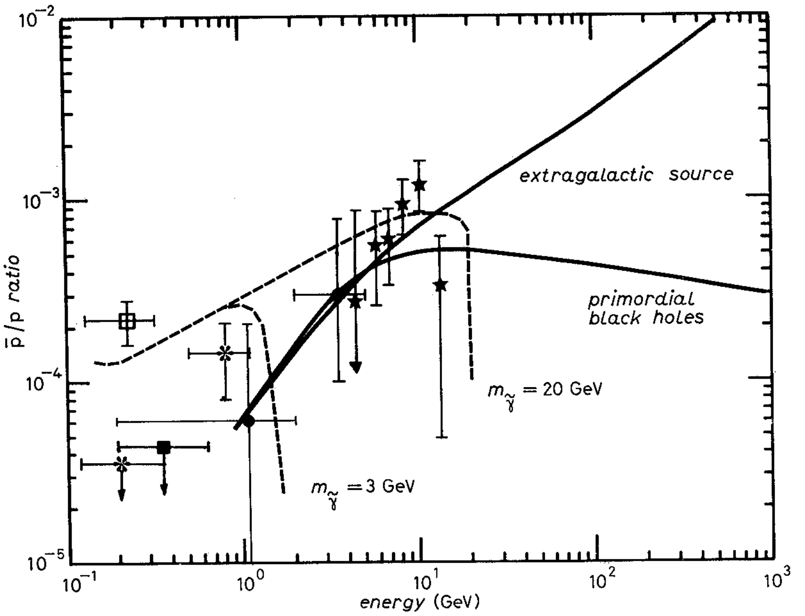

Fig. 1. – Different possible exotic mechanisms of production of cosmic antiprotons. The experimental points are referenced in (15). □ ref. (18), ● Bogolomov *et al.* (15), ★ Golden *et al.* (15), ■ Ahlen *et al.* (15), ∗ Golden *et al.*, 1988 (15).

elementary-particle physics (*e.g.* photino annihilation (16)) to cosmology (*e.g.* black-hole evaporation (17)) provided a sufficient statistics is attained.

2. – Motivations for a polar orbit.

In a paper of the «NASA Cosmic Rays program working group» published in December 1985 (18), among several ideas and experiments considered to be performed on the Space Station Freedom, a section is devoted to the experi-

---

International Cosmic Ray Conference OG, **6.1** (Moscow, 1987), p. 72; R. L. GOLDEN, B. G. MAUGER, S. NUNN and S. HORAN: *Astrophys. Lett.*, 24, 75 (1984); S. AHLEN, S. BARWICK, J. J. BEATTY, C. R. BOWER, G. GERBIER, R. M. HEINZ, D. LOWDER, S. MCKEE, S. MUFSON, J. A. MUSSER, P. B. PRICE, M. H. SALAMON, G. TARLÈ, A. TOMASCH and B. ZHOU: *Phys. Rev. Lett.*, **61**, 145 (1988). Other data have been presented by R. L. GOLDEN at the 6th Course of the International School of Cosmic Ray Astrophysics at Erice, Italy in April 1988 and are in course of publication.

(16) F. W. STECKER, S. RUDAZ and T. F. WALSH: *Phys. Rev. Lett.*, **35**, 1 (1985).

(17) S. HAWKING: *Mon. Not. R. Astron. Soc.*, **152**, 75 (1971).

(18) *The Particle Astrophysics Program for 1985-1995*, report of the NASA Cosmic Ray Program Working Group (December 1985).

ments which need a Polar Platform. As we will see, there are several scientific reasons to support the idea of such a facility, reasons that have been recognized even by the same group which strongly recommended the Space Station. In fact, in the range up to 4 GeV, the low inclination (28°) orbit of the Space Station makes it impossible to detect positrons and antiprotons because of the geomagnetic cut-off due to the terrestrial magnetic field; this limitation occurs of course also for antialphas and heavier antinuclei.

Now there are motivations to search for antimatter at low energy because of both physics and technology. The physical reasons are related to the $\overline{\mathrm{p}}$ production mechanism and to the $\overline{\mathrm{He}}$ abundancy. There should not be (unless energy degradation) secondary antiprotons produced by colliding protons below ~ 1.1 GeV/c due to kinematics, suggesting that low-energy $\overline{\mathrm{p}}$ would be produced through one or more exotic mechanisms raising the interest for their detection. For the hypothetic antialphas (that can be only primary) their rarity suggests to extend the research in the low-energy region under the assumption that the $\overline{\mathrm{He}}$ flux decreases increasing the energy.

The technological reasons are also very important being related to the necessity to detect an eventual $\overline{\mathrm{He}}$ with no ambiguity at all because of their rarity that makes it impossible to get a significant statistics. Now, low-energy antihelium is more easily detectable in comparison with a more energetic one because i) the annihilation event can be fully contained in a tracking calorimeter showing its clear signature (the typical «star») and ii) it is easier to make a significant comparison between the low momentum detected by a magnetic spectrometer and the high energy released in the calorimeter (because of the contribution of the annihilation). Therefore, the full containment (possible only at low energy) makes the experimenters sure of the signature even if very few $\overline{\mathrm{He}}$ are detected (remembering that the detection of even a single $\overline{\mathrm{He}}$ would be a major result for its cosmological implications). From these considerations it comes out that an apparatus able to cover a big energy range from 5 to 500 GeV using ASTROMAG-like detectors (¹⁹) (TRD $\mathrm{d}E/\mathrm{d}X$, magnetic field) for more energetic particles and a tracking silicon calorimeter for the less energetic ones, placed on a polar orbit so reducing the cut-off, would be an ideal tool for the systematic antimatter research.

Another possibility (depending on launcher disponibility) could be an apparatus placed in a very high orbit, outside the strong influence of the terrestrial magnetic field, getting even more advantages than a polar orbit in eliminating the geomagnetic cut-off.

Considering the U.S. strong engagement in the Space Station program, maybe a polar antimatter detector would be an excellent task for Europe (the

---

(¹⁹) *The Particle Astrophysics Magnet Facility*, Report of the ASTROMAG Definition Team, edited by J. F. ORMES, M. ISRAEL, M. WIEDENBECK and R. MEWALDT (May 1988).

European Space Agency and the National Space Agencies like the Italian ASI) getting the goal of using european launchers and satellites to achieve very significant results, possibly in close cooperation with American partners.

3. – Investigation approach.

To afford a systematic and sensible search for antimatter an experiment must

maximize the possible useful rate;

reach a powerful selectivity against background, possibly aiming to the maximum possible redundancy.

The maximization of the rate can be searched in three different directions:

a) Long exposure time. This is the obvious reason to have the apparatus in orbit around the Earth, either mounted on a supporting station, like ASTROMAG on Space Station Freedom, or as a free flier carrying the necessary supplies for a long run. A suitable «guaranteed running time» could be of the order of two years, with a hoped life of four or more years.

b) Big geometrical factor. Obviously, for a fixed configuration of the orbiting vehicle, the geometrical factor is linked to the total allowed weight and to the length of the exposure time, to which the weight of consumables is related. However, if we want the charge sign of the particle to be identified by curvature in a magnetic field, the geometrical factor is affected also by the dimensions of the region where the magnetic field is high enough to make the error due to multiple scattering ineffective, in practice where the magnetic path exceeds some kG m (fig. 2).

c) Low geomagnetic cut-off. The step dependence of the cosmic-ray flux from the energy/nucleon makes the total rate very sensible to the low-energy part of the spectrum, where the transparency of the Earth magnetic field to the charged particles (geomagnetic cut-off) plays a crucial role.

The difference in nuclei collection between an apparatus placed on the Space Station orbit (inclined of 28.5° with respect to the equator) or on a satellite in Polar Orbit (with an inclination close to 90°) is more than a factor 20 (fig. 3).
Assuming for the hypothesized antinuclei the same energy spectrum of the nuclei the use of the polar orbit appears mandatory for an experiment dedicated to their search. Another factor two could be gained running the experiment on a geostationary orbit, where the geomagnetic cut-off would be practically zero. However, the more strigent limitation in the total weight to be carried at so large distance from the earth could vanify this gain, so that the polar orbit is surely the first choice that is worthwhile being considered.

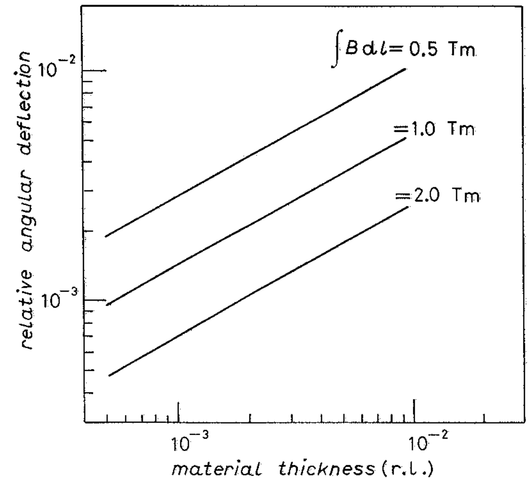

Fig. 2. – Relative angular deflection due to multiple scattering and magnetic bending as a function of $\int B\,dl$ and material thickness.

The experiment selectivity is essentially related to two main devices: a tracking system to give the charge sign, in the magnetic field, with a negligible error, and a calorimeter to give the energy released in the annihilation of the antinucleus. Other important parts could be an accurate t.o.f. system and an array of Cherenkov counters for the identification of the electrons and positrons, the Z determination and possibly a mass measurement enough accurate for the isotopic identification of the detected nucleus.

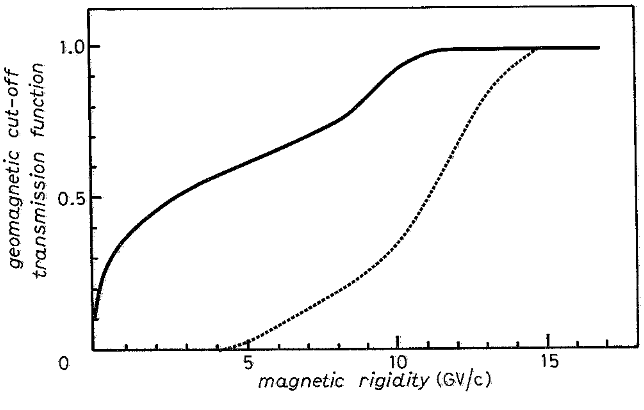

Fig. 3. – Difference in nuclei collection between space station and polar-orbit satellite. Solid curve: polar-orbiting platform (circular orbit, altitude 1482 km, inclination 98°, period 6934 s). Dashed curve: Space Station Freedom (circular orbit, altitude 555 km, inclination 28.5°, period 5745 s).

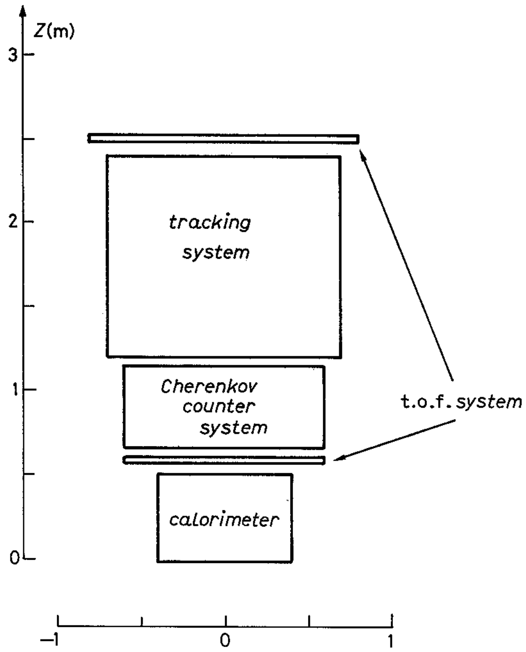

Fig. 4. – Scheme of the apparatus.

The scheme of an apparatus that matches the above criteria and does not exceed 3 tons of total weight is reported in fig. 4, where also an indication of the dimensions is given.

Before giving a brief description of the detectors we will remark that the real shape and dimensions will depend in an essential manner on the coil configuration adopted to produce the magnetic field. It must include at least two coils to produce a net zero dipole magnetic field to prevent the overall rotation of the experiment due to the interaction with the earth magnetic field. It was already pointed out (²⁰) that a toroidal configuration, possibly reduced to its minimum design of only two coils, makes the best use of the electrical current circulating in the coils. It is indeed this configuration to be considered in first approximation and special care should be put on the tracking device to be sufficiently well integrated in the coil design to avoid losses in the geometrical factor of the experiment (see in fig. 5*a*) the concept). The main parameters for the possible magnetic system are reported in table I.

Another possible configuration is similar to that used for the HEAO-type magnet (²¹) in which two separate coils are adjacent but with the current

---

(²⁰) M. A. GREEN, G. BASINI, M. RICCI, A. CODINO, P. SPILLANTINI and F. ROSATELLI: *IEEE Trans. Magn.*, 24, 1015 (1988).

(²¹) *Superconducting Magnetic Spectrometer Experiment for HEAO Mission B*, University of California, Space Science Laboratory Series 13, Issue 11, Berkeley, Cal. (December 18, 1970).

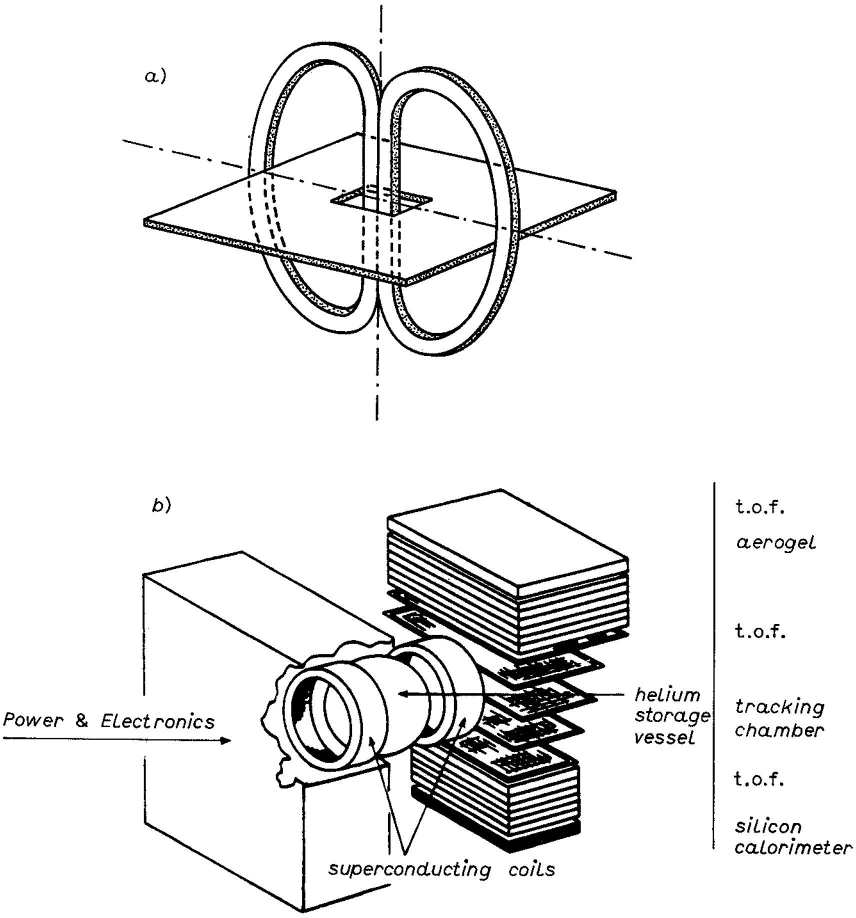

Fig. 5. – *a*) Pictorial view of a two-coil toroid, *b*) the HEAO-type configuration.

circulating in opposite senses (to have zero net dipole moment). This configuration is not the best for the acceptance but it has the advantage of being more compact to fit in a satellite. Another important advantage of this alternative

TABLE I. – *Toroid magnet parameters.*

number of coils	2
number of turns	2000
double-de dimensions	(1×1.8) m
coil width	50 mm
coil thickness	40 mm
active coil mass	75 kg
total cold mass of coil	150 kg
stored energy	1 MJ
current (A)	1000

configuration is that the coils are well separated from the detectors, thus avoiding to have material in the trajectory of the particles, as shown in fig. 5*b*).

The detector system, as previously said, is composed of four devices:

1) Tracking system. It must cover the whole region where the magnetic path exceeds 5 kG m. In this way the global deflection due to the field is one order of magnitude higher than the deflection due to the multiple scattering (on a 2% of radiation length total thickness of the tracking system). In any case the tracking system is required to have an accurate pattern recognition capability to avoid any possible error on sign assignement at level of one part in 10^7 or better. Also the precision on the sagitta measurement is mainly linked to the sign assignement. We will assume that the track position is measured at least 30 times in the detector with a precision of 100 μm in each point: this is more than enough for a wide superposition between the energy range covered by this experiment and the ASTROMAG experiment. A dE/dx measurement performed in all these 30 points will help in hunting for rare anomalies in the trajectory and in giving the right Z assignement to the particle.

2) Calorimeter. It is extremely important that the calorimeter should be «tracking». The visualization of the possible interaction of the particle inside the calorimeter makes a sort of redundancy that enters the pattern recognition in many ways, and constitutes an irreplaceable document of the attribution of the possible excess of energy released in the calorimeter to annihilation processes. A calorimeter of 2.0 interaction lengths is adequate to contain annihilation processes up to few GeV/nucleon. The absorber should be made of brass because it has an average Z high enough to absorb gammas near the interaction point allowing the charged products to give visible tracks and to be counted; moreover, the Z is not so high to make the total weight diverge for the required 2 interaction lengths. A sampling thickness of the detector of $(0.4 \div 0.5)$ radiation lengths is satisfactory for an enough detailed tracking and a good energy resolution (it must be noted that, given the low average energy of the interaction products—much less than 1 GeV in case of annihilation—the calorimeter behaves as a compensated calorimeter with a resolution for hadrons of the order of 30% at 1 GeV). At each sampling two projected images should be obtained with a resolution of few mm. The total number of channels necessary for such a tracking calorimeter will be about 20 000. To limit the total geometrical depth of the calorimeter the detector must be very thin, of the order of few mm: the most suitable choice is to make use of solid-state detectors, as already proposed for ASTROMAG (19).

3) Time of flight. On this part of the detector depend the definition of the geometrical acceptance of the experiment, the rejection of the albedo particles, the identification of electrons and positrons and a precise dE/dx measurement which, complemented with that performed in the tracking part, will allow the Z determination to better than 0.2 of unit charge up to iron at least. For these

tasks a scintillation counter system with a time resolution in the region of 200 ps is adequate. However, it will be very interesting to investigate the possibility of gaining one order of magnitude on this figure using small gap spark counters. To make them work at atmosferic pressure and without introducing material on particle trajectory requires a lot of R & D work that it is worthwhile being afforded because a good isotopic separation would be ensured for most of the collected nuclei with A as high as 70 (see fig. 3).

4) Cherenkov system. Even if not essential it will be very useful, not only in helping in electron and positron identification, but also in providing a good isotopic identification, complementary to that possibly supplied by the t.o.f.

TABLE II. – *General characteristics.*

geometrical factor		$0.2\,\text{m}^2\,\text{sr}$
power		0.8 kW
weight:	t.o.f.	0.2 t
	tracking	0.4 t
	calorimeter	1.2 t
	Cherenkov	0.3 t
	structure	0.5 t
	magnet	0.4 t
	L. He Supply	0.5 t
total		3.5 t

TABLE III.

a) Differential rates on $0.2\,\text{m}^2\,\text{sr}$.

protons	320/s
electrons	4/s
He	160/s
C	4/s
Fe	0.4/s

b) Yield in one year on $0.2\,\text{m}^2\,\text{sr}$.

protons	10^{10}
electrons	10^{8}
antiprotons	10^{6}
He	$5\cdot10^{9}$
C	10^{8}
Fe	10^{7}
Ne	$5\cdot10^{6}$
Ti	$5\cdot10^{5}$
Zn	10^{3}
$Z\geq90$	$\leq5\cdot10^{2}$

system. A system of three Aerogel counters with suitable choice of refraction indices will be a good solution, and its total thickness should be contained in not more than half meter.

The main parameters for the whole detector are reported in table II, while in table III the differential and integral rates attainable are reported.

● RIASSUNTO

In questo articolo si discute della necessità di un esperimento da porre su un'orbita polare allo scopo di rivelare con alta statistica antiprotoni cosmici di bassa energia e di rendere massima la probabilità di rivelare eventuali antialfa cosmici. Si presenta anche un apparato in grado di rivelare $\bar{\alpha}$, $\bar{p}$ ed e^+ con grande precisione nel range $(0.5 \div 5.0)$ GeV.

Резюме не получено.