ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-86/68

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Estratto da:
Nuovo Cimento 93A, 311 (1986)

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

IL NUOVO CIMENTO VOL. 93 A, N. 4 21 Giugno 1986

Search for Antimatter in Cosmic Radiation. A Matter-Antimatter Space Spectrometer.

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(ricevuto l'8 Luglio 1986)

Summary. — The open question of matter-antimatter symmetry can be investigated by measuring the antiproton flux in high atmosphere. In this paper a balloon-borne experiment using a superconducting magnet coupled to a tracking calorimeter is proposed to carry out such measurements at latitudes of low geomagnetic cut-off. An overwiev on further possible developments such as search for antinuclei to be performed with future planned facilities (NASA Space Station) is also presented.

PACS. 94.40. – Cosmic rays.

1. – Introduction.

Among the two kinds of elementary objects coming from the space, *i.e.* electromagnetic signals and particles, only for the first ones a systematic investigation (from millimetric waves to high-energy γ-rays) has been performed also outside the atmosphere. Indeed, because of the particle interactions with the atmosphere itself, several phenomena escape the possibility of being detected by Earth-based instruments and even the chance to find at least single evidence of primary antimatter in cosmic rays is ruled out.

Therefore, it would be very attractive to consider the possibility of designing and assembling space-based apparata devoted to the systematic research in the elementary-particle field. The difficulties in performing such a task have limited, up to now, the number of experiments that have attempted to open this new way of investigation, but the possibility, now achieved, of transferring technologies from high-energy physics makes it realistic to get an apparatus able to well-detect particles in the above-mentioned conditions.

In particular, an unambiguous identification of low-energy antiprotons is now available by matching calorimetry techniques with superconducting-magnet technologies. The feasibility of such an apparatus, for near and far future, is discussed in this paper in which the present experimental situation and some related theoretical interpretations are described as well.

2. – Physical motivations.

The symmetry between matter and antimatter is nearly exact in experimental elementary-particle physics. Only a small deviation in CP-violating decay of kaons is observed.

Hot big bang cosmology would lead to the conclusion that this symmetry should also be observed in the Universe unless the baryon-antibaryon symmetry is broken during the early evolution of the Universe (1).

Astronomical observations can establish the antibaryonic fraction to be $\sim 10^{-10}$ in the local group of Galaxies (a region of the Universe of dimensions ~ 1 Mpc), but are unable to give an answer to the large-scale baryon-antibaryon ratio.

Recent measurements (2-4) of antiprotons in cosmic rays have given an

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

(2) R. L. Golden, S. Horan and B. G. Mauger: *Phys. Rev. Lett.*, **43**, 1196 (1979).

(3) E. A. Bogolomov, N. D. Lubyanaya, V. A. Romanov, S. V. Stepanov and M. S. Shulakova: *Proceedings of the XVI International Cosmic Ray Conference*, Vol. **1** (Kyoto, 1979), p. 330.

indication that the ratio of antiprotons to protons would be much larger ($\sim 10^{-4}$) than the limit to antimatter fraction in the local group.

This first indication could support the idea that antiprotons in the cosmic rays might have an extragalactic origin. In this case the $\bar{p}/p$ ratio could indicate that antiprotons are radiated by antimatter galaxies and the Universe could be symmetric in matter-antimatter concentration.

In fact, starting from the inclusive antiproton production via proton-proton interaction

$$pp \to \bar{p} + \text{anything}$$

at laboratory energy threshold ~ 7 GeV for the incident proton, the differential antiproton spectrum (5) is given by

$$\text{(1)} \qquad \mathrm{d}N_{\bar{p}}/\mathrm{d}E \sim (2\langle y\rangle/m_p)\int_E^\infty (\mathrm{d}\sigma_{\bar{p}}/\mathrm{d}E)(E, E')(\mathrm{d}N_0/\mathrm{d}E')\,\mathrm{d}E' \, ,$$

where $\langle y\rangle$ is the mean path length of interstellar hydrogen traversed (in g/cm²), m_p is the proton mass (in grams), $(\mathrm{d}\sigma_{\bar{p}}/\mathrm{d}E)(E, E')$ is the cross-section (in cm²) for producing an antiproton of energy E in the collision of a proton of energy E' with an interstellar hydrogen nucleus and $\mathrm{d}N_0/\mathrm{d}E'$ is the differential primary proton flux.

Following GAISSER and MAURER (5), the determination of the $\bar{p}/p$ ratio can be obtained parametrizing from accelerator data (6) the $\bar{p}$ inclusive cross-section integrated over transverse momentum

$$\text{(2)} \qquad F(x, E_0) = \int E(\mathrm{d}\sigma_{\bar{p}}/\mathrm{d}^3p)\mathrm{d}p_\perp^2 \, ,$$

where E_0 is the incident-proton total laboratory energy and x is the Feynman variable ($x \equiv 2p_\parallel^{\text{c.m.}}/\sqrt{s}$). In this way, replacing $E/E' \to R$ from eq. (1), the $\bar{p}/p$ ratio is found to be

$$\text{(3)} \qquad \bar{p}/p \sim (2\langle y\rangle/m_p)\int_0^1 R^{\gamma-1}(\mathrm{d}\sigma_{\bar{p}}/\mathrm{d}E)(E, E/R)\,\mathrm{d}R \, ,$$

(4) A. BUFFINGTON, S. M. SCHINDLER and C. R. PENNYPACKER: *Astrophys. J.*, **248**, 1179 (1981).

(5) T. K. GAISSER and R. H. MAURER: *Phys. Rev. Lett.*, **30**, 1264 (1973).

(6) M. BANNER, J. L. HAMEL, J. P. PANSART, A. V. STIRLING, J. TEIGER, H. ZACCONE, J. ZSEMBERY, G. BASSOMPIERRE, M. CROISSIAUX, J. GRESSER, R. MORAND, M. RIEDINGER and M. SCHNEEGANS: *Phys. Lett. B*, **41**, 547 (1972); other data are referenced in (5).

where a power law primary spectrum ($\mathrm{d}N_0/\mathrm{d}E = kE^{-(\gamma+1)}$ with $\gamma \sim 1.6$) was assumed. Extrapolation to higher energies (beyond the ISR data) leads to the asymptotic value for the $\bar{\mathrm{p}}/\mathrm{p}$ ratio

$$\lim_{E\to\infty} \bar{\mathrm{p}}/\mathrm{p} \sim 4.6\cdot 10^{-4} \tag{4}$$

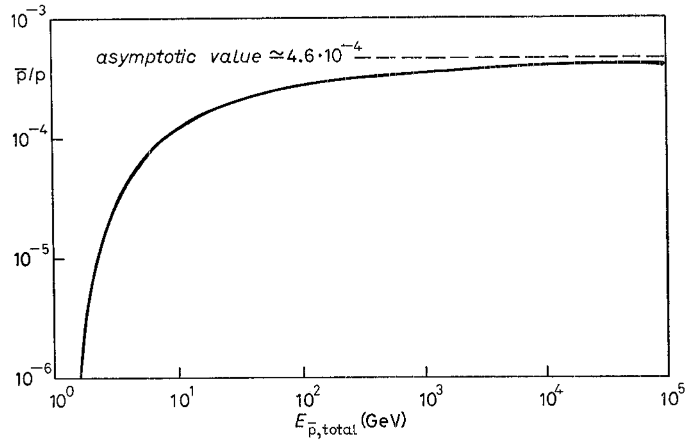

Fig. 1. – $\bar{\mathrm{p}}/\mathrm{p}$ *vs.* total antiproton energy (GeV).

showing an expectation of values rising from 10^{-6} to $\sim 5\cdot 10^{-5}$ in the range $(0.2 \div 5)$ GeV (fig. 1, taken from (5)), while present experimental evidence (4) claims for higher values.

By now, three experiments (2-4) have been performed to measure the $\bar{\mathrm{p}}$ flux, collecting a total number of some 40 antiprotons. The three experiments cover an energy range from 130 MeV to 10 GeV and the results agree in showing a flux larger than expected. In particular, the low-energy point (4), when appropriately corrected for solar-wind modulation, does not show any sign of kinematical decrease expected in secondary production, being, on the contrary, compatible with a constant $\bar{\mathrm{p}}/\mathrm{p}$ ratio $\sim 3\cdot 10^{-4}$ (fig. 2, taken from (7)).

Slight modifications of the standard scheme of cosmic-ray propagation fail to reproduce the observed flux, in particular at low energy. As a consequence, more radical alternatives have been proposed (8):

a) Neutron oscillations. If $\bar{\mathrm{n}}$-n oscillations are allowed, the subsequent $\bar{\mathrm{n}}$ decay into $\bar{\mathrm{p}}$ could in principle explain the observed flux (9). The ex-

(7) P. Kiraly, J. Szabelski, J. Wdowczyk and A. W. Wolfendale: *Nature (London)*, **293**, 120 (1981).

(8) For a review, see: P. Kiraly: in *Progress in Cosmology*, edited by A. W. Wolfendale (1982), p. 89.

(9) C. Sivaram and V. Krishan: *Nature (London)*, **299**, 427 (1982).

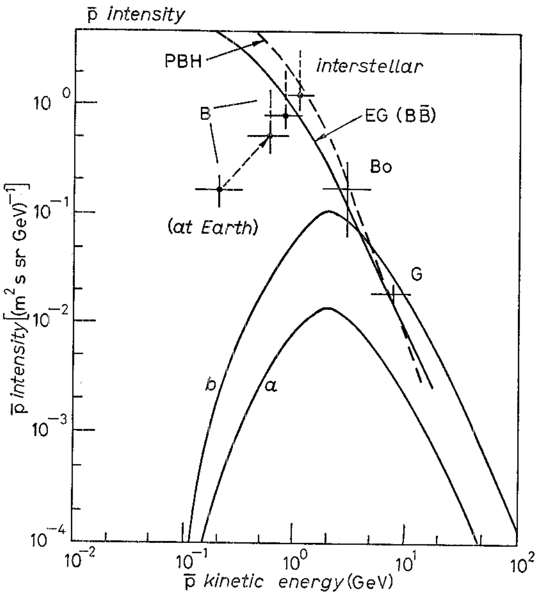

Fig. 2. – Secondary antiproton flux predictions. *a*) Leaky box model with $\lambda = 5\ \text{g cm}^{-2}$; *b*) closed Galaxy model. The displacement of the Buffington *et al.* (4) point (marked B) is to allow for solar modulation. The points correspond to mean adiabatic energy losses of 400, 600 and 900 MeV. The horizontal error bars represent the energy intervals from which $\sim 70\%$ of the measured flux at Earth is expected. The highest value (900 MeV) would be unreasonably high for protons or for primary antiprotons with a power law spectral shape, but is quite possible for the peaked spectra of secondary antiprotons. The dashed vertical bars represent plausible deviations from Liouville's theorem. Bo denotes Bogolomov *et al.* (3); G denotes Golden *et al.* (2); EG(B$\bar{\text{B}}$) denotes the prediction for extragalactic antiprotons generated in antigalaxies in a baryon-antibaryon symmetric universe normalized at 9 GeV. If there is a significant galactic wind, the $\bar{\text{p}}$ intensities will fall off with falling energy (<1 GeV). PBH denotes the prediction for the exploding primaeval black-hole model (quark version) normalized as above. The remarks about the influence of a galactic wind made in the last paragraph apply here too if, as is likely, many of the BHs are in the galactic halo.

perimental limit on the oscillations requires, however, some special circumstances.

b) Evaporation of primordial black holes (Hawking effect). This is a source of equal numbers of particles and antiparticles (7,10).

c) Relic massive photinos (11,12) with mass > 1 GeV could be a dominating component of dark matter in the halo of our Galaxy. Hence the $\bar{\text{p}}$ excess in cosmic rays could be a result of photino pair annihilation.

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(10) M. S. Turner: *Nature* (*London*), **297**, 379 (1982).
(11) J. Silk and M. Srednicki: *Phys. Rev. Lett.*, **53**, 624 (1984).
(12) F. Stecker, S. Rudaz and T. F. Walsh: *Phys. Rev. Lett.*, **55**, 2622 (1985).

3. – Experimental apparatus.

The cosmic antiproton differential flux from 130 to 320 MeV is expected to be $(1.7 \pm 0.5)\cdot 10^{-4}\,\text{m}^{-2}\,\text{sr}^{-1}\,(\text{MeV})^{-1}$ and the ratio to protons $(2.2 \pm 0.6)\cdot 10^{-4}$ (4). Hence the expected number of antiproton interactions that could be recorded in a space experiment with an acceptance of $1\ \text{m}^2\cdot\text{sr}$ over a range of $(100\div 500)$ MeV is of the order of 200 per hour, while the same experiment would be invested at the same time by $\sim 10^6$ protons in the same energy range.

In a simple calorimetric experiment in which the signature would be a total released energy of 2 GeV, a possible contamination could be originated by more energetic protons interacting in the calorimeter; thus a very rough estimate of the rate of such events could be

$$r = \eta \times \Phi(E > 2\ \text{GeV}) \times \pi A\ ,$$

where η is the probability of releasing more than 2 GeV in the calorimeter, Φ is the integral flux of protons and A is the calorimeter area. Assuming, conservatively, $\eta \approx 1/3$ and a spectral index for the cosmic-ray protons ≈ 2.7, we might expect that the number of proton interactions to be recorded would be of the order of 1000 per hour.

Therefore, we propose an experimental apparatus composed of a magnetic spectrometer equipped with track chambers and scintillation counters (as schematized in fig. 3) in order to measure the momentum and, respectively, to give the time of flight. Choosing a toroidal magnet lens the negative particles could be focused in a relatively small calorimeter area (*i.e.* less than $1\ \text{m}^2$), while the positive-charged particles would be deflected outside. The definition of the mass of the particle could be obtained measuring its time of flight, a procedure required also to avoid possible contaminations from albedo antiprotons and π^- produced by showering protons.

For a good containment of the annihilation event, the calorimeter should have high density and a ratio between radiation and interaction lengths $(\lambda_{\text{rad}}/\lambda_{\text{int}})$ as high as possible. This ratio is remarkably good for copper or brass $(\lambda_{\text{rad}}/\lambda_{\text{int}} \sim 0.1)$. Furthermore, tracking calorimeters (13) made of brass streamer tubes (14) make it possible to reach densities of $\sim 5\ \text{g/cm}^2$ with high

(13) G. Battistoni, U. Denni, E. Iarocci, G. Mazzenga, G. Nicoletti and L. Trasatti: *Nucl. Instrum. Methods*, **176**, 297 (1980).

(14) F. Celletti, A. Marchionni, P. Spillantini, Yu. Kamyshkov, V. Pojidaev, M. Cerrada, H. Zeidler, F. Ferroni, M. Steuer, K. Deiters, G. Gianolli, P. Lecomte, P. Le Coultre and H. Suter: *Nucl. Instrum. Methods Phys. Res.*, **225**, 493 (1984).

granularity ($\sim (5\times5\times5)\ \text{mm}^3$). Such a tracking calorimeter is a real improvement, in comparison with common total-absorption calorimeters, because its capability in reconstructing the vertex is strongly helpful in discriminating annihilation events from simple interactions. Some details of the calorimeter fitting our spectrometer are shown in fig. 4.

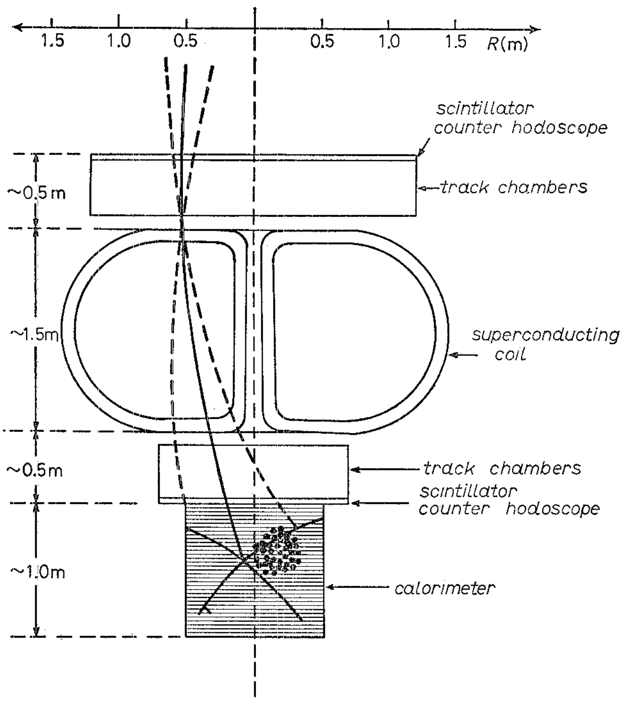

Fig. 3. – Schematic view of the spectrometer.

The toroidal lens does not require an extremely high magnetic field because of the low momentum of the incoming antiprotons.

In order to evaluate the acceptance of the spectrometer for different particles, a Monte Carlo simulation has been worked out.

The behaviour of the acceptances as a function of the magnetic field, as shown in fig. 5 ($|B|$ is the value of the magnetic field at 40 cm from the axis), indicates that already at 4 kG more than 5 % of the antiprotons crossing the first TOF counter (and only 1 % of the protons) can reach the calorimeter.

In such a field, a path of ~ 1.5 m gives an average error of 5 % on momentum determination due to the multiple scattering occurring in the interposed materials (*e.g.*, about 10 mm aluminium equivalent). This error must be combined with the measurement error which, assuming 10 mrad determination of the deflection angle, is of the order of 10 % p. The result is given by the

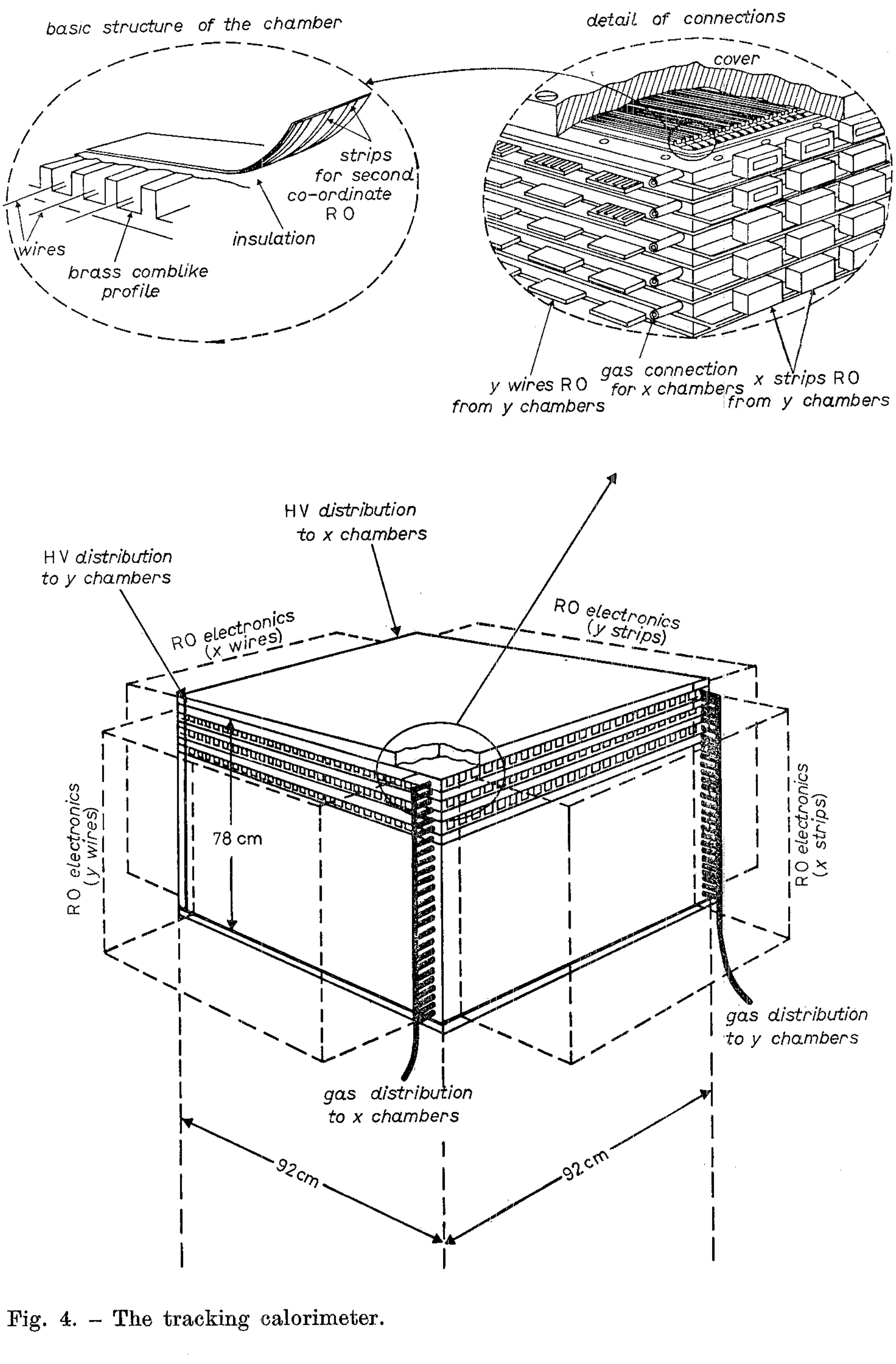

Fig. 4. – The tracking calorimeter.

formula

$$\Delta p/p = a + b\cdot p\,, \qquad p(\mathrm{GeV}/c),$$

where, in our case, $a = 0.05$ and $b = 0.1$.

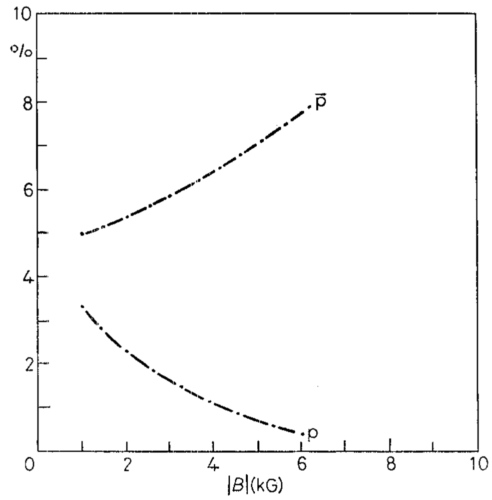

Fig. 5. – Percentage of particles (500 MeV/c) that reach the calorimeter for a magnetic field at 40 cm from the axis. The length of the magnetic field is 130 cm.

4. – Possible intermediate configuration.

There is in principle a possible intermediate step for this research which consists in using the proposed tracking calorimeter without the magnet but in connection with a box of scintillating counters placed all around in anticoincidence and a telescope, delimiting the acceptance, in coincidence.

In such a way, an accurate velocity determination of the incoming and outgoing particles coupled with the energy measurement and the vertex reconstruction ([15]) could be performed setting up an apparatus in due time as to profit of the minimum of solar activity in 1987.

In fact, a high solar activity is not a favourable working condition being responsible of the deceleration and deflection of charged particles: this solar-modulation effect is particularly relevant in the low-energy region—which is our case—as shown, for protons, in fig. 6 ([16]), so that the low-energy flux is drastically reduced and substantial correction of the data are required.

([15]) J. Lloyd-Evans, B. S. Acharya, V. K. Balasubrahmanyan, J. F. Ormes, R. E. Streitmatter and S. A. Stephens: *Proceedings of the XIX International Cosmic Ray Conference*, Vol. **3** (La Jolla, 1985), p. 254.

([16]) M. L. Goldstein, L. A. Fisk and R. Ramaty: *Phys. Rev. Lett.*, **25**, 832 (1970).

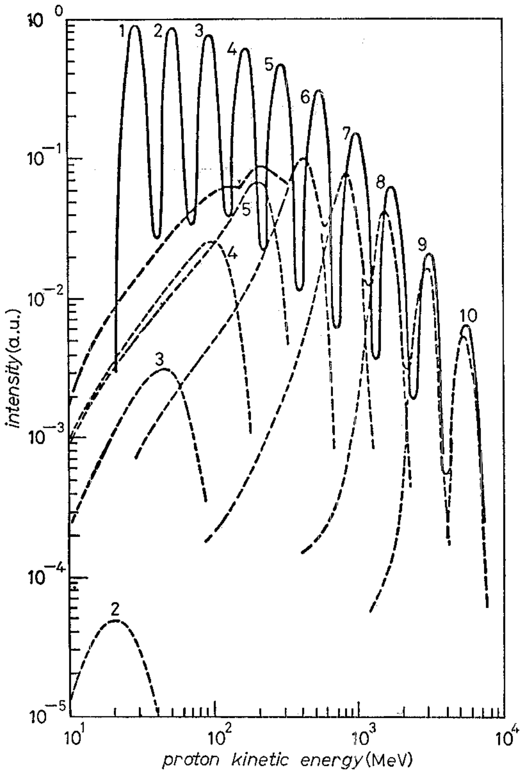

Fig. 6. – A series of essentially monoenergetic proton spectra in interstellar space (solid) and their resultant modulated spectra at 1 AU (dashed).

5. – In-flight configuration.

The experiment could be intended for the use on the pallet of the Spacelab to be run to collect data for a standard Shuttle space mission (7 days long), but at the moment is planned for a balloon launch (for which a comprehensive view of the apparatus is shown in fig. 7) at latitudes with low geomagnetic cut-off.

Therefore, a series of flights on a balloon could be considered as a preliminary significant phase of an experiment with the Shuttle, waiting for more attractive opportunities like the planned NASA Space Station (see sect. **6**).

The weight of the apparatus in its complete configuration, as sketched in fig. 7, will be about 2.0 tons, the calorimeter and the coil with its helium reservoir (see below) accounting for 600 kg and 300 kg, respectively.

For such a payload, possible lauching sites in the northern emisphere with logistic support for the campaign exist in the Andoya Range, Norway (geomagnetic latitude 67 degrees) and in the Esrange, Sweden (latitude 68

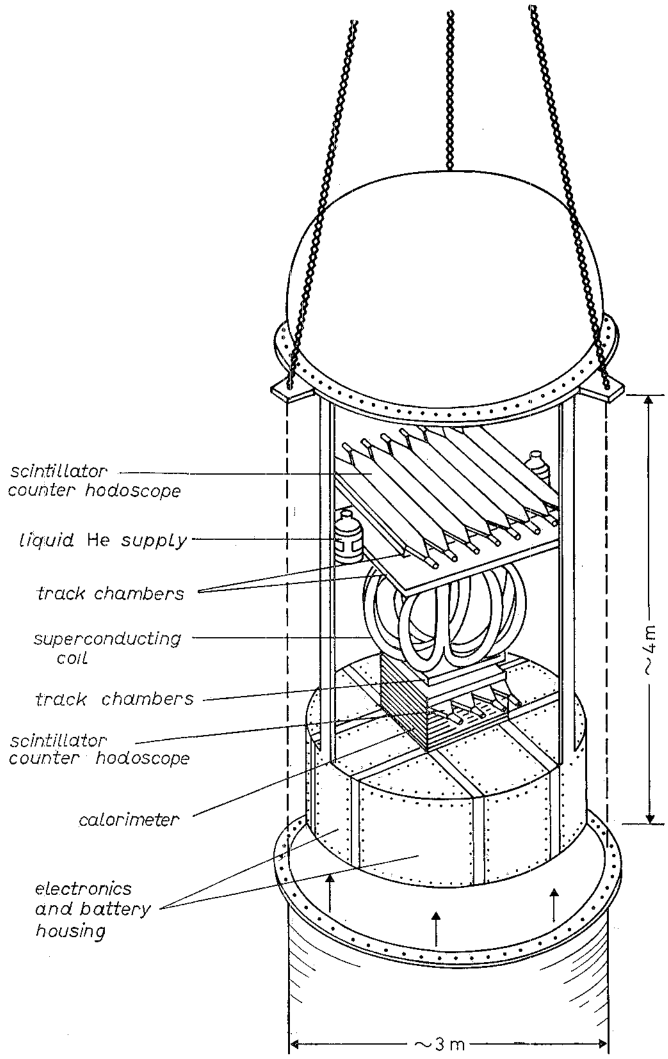

Fig. 7. – Comprehensive view of the apparatus for a balloon launch.

degrees) ([17]). Moreover, the CNES (Centre National d'Etudes Spatiales, France) could perform launching operations of balloons which could carry up to 3 tons (*i.e.* 1 Mm^3 balloons) even in not well-supported sites. Other opportunities, available in North America and related to some agreements with NASA, seem to be favourite at the present moment. A pictorial description of the launching technique as usually performed by NSBF, Palestine (Texas, USA), is shown in fig. 8.

([17]) ESA-SP-183 report.

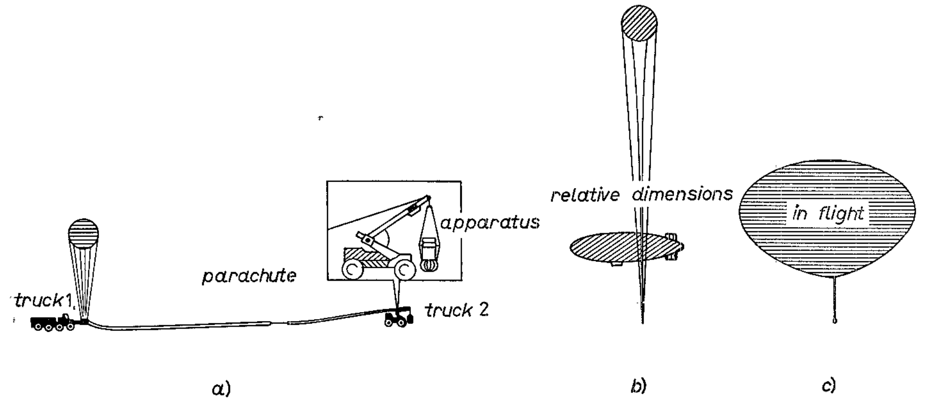

Fig. 8. – The launching technique. The balloon *a*) is initially connected to a truck which is in turn linked to a second truck carrying the apparatus. The launch is performed in two steps: first, when partially filled with helium, the balloon is slowly released; second, as the helium fill is completed, the apparatus is unhooked. Typical balloon dimensions *b*) are ~ 20 m maximum width at Earth, while in high atmosphere *c*) the diameter can reach ~ 150 m. At the end of the mission, the suspension cable of the apparatus is broken by a little remote control explosion and the apparatus itself is slowly parachuted and recovered.

Other constraints on the physical size of the experiment are to be investigated, both in the case of the Shuttle flight and of the balloon flight.

Power requirements are obviously more stringent in the case of the balloon flight, where power is to be supplied by batteries. A typical figure for organic high-efficiency batteries is 10 Ah at 1.5 V per element, with a weight of 80 g.

Thermal shielding of the apparatus is required with panels of polystirene foam. A totally passive thermal control is usually assured by the internal power dissipation of the electronics, if the external surface of the shielding is covered with white radiator foils, which limit the heat exchange with the Sun.

The superconducting magnetic lens is a passive device in which the magnetic field is stored and the energy for its maintenance is provided by the cryogenic fluid storage. Tentative preliminary evaluations indicate that a reserve of about 120 litres of liquid He ([18]) can assure the maintenance of the magnetic field for a 100 hour flight duration using a cryostat made of two concentric cylinders with interposed superinsulator in addition to a copper surface cooled by the evaporated helium. For safety of operation external dissipation of the current at the end of the flight must be provided.

A pressurized container made of thin aluminium (2 mm thick) could be

([18]) M. Spadoni (ENEA-Frascati, Italia): private communication.

used to contain the whole apparatus (rather than the tracking calorimeter only) following the technique already used by GOLDEN *et al.* [19] at the New Mexico University (USA). This approach seems to be the most attractive since the whole configuration can be assembled in such a way that the problem of thermal exchange can be tested on earth, the crossed matter not giving serious problems because of the small thickness of the aluminium surface.

6. – An overview on the future.

The planned ($\sim$ 1996) NASA Space Station will represent the future for this kind of physics [20] since it will be possible to assemble very large instruments in the space including apparata able to detect and identify cosmic rays up to 10^{16} eV. Among the proposed facilities to be installed on the Space Station the « Particle Astrophysics Magnet Facility » (PAMF or ASTROMAG), composed by a superconducting magnetic spectrometer, will make it possible measurements which are forbidden to the conventional balloons or satellites, namely:

1) Search for antinuclei. We stressed before the importance of matter-antimatter symmetry in cosmology and, if a precise measurement of antiproton flux is very interesting, the detection of primary antinuclei (probably only antihelium at the present level of theoretical knowledge) would set an extremely significant and unambiguous result for the comprehension of the Universe composition. Now, with this hypothesized spectrometer it should in principle be possible to detect even a very small flux of antinuclei because of its very high sensitivity (at the level of 10^{-8}). Since the extragalactic matter (where the cosmic rays come from) is considered at the level of 10^{-6}, even no evidence of antinuclei would lead to interesting cosmological consequences.

2) Measurement of the antiproton spectrum in the range $(4\div1000)$ GeV, which could lead to the comprehension of the phenomena that rule their production (*e.g.*, proton collisions with the interstellar matter or photino-antiphotino annihilation in the galactic halo).

3) Search for isotopic composition of cosmic rays and for electron and positron spectra. These kinds of research can provide indications of sites and mechanisms of particle acceleration.

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(19) R. L. GOLDEN, G. D. BADHWAR, J. L. LACY and J. E. ZIPSE: *Nucl. Instrum. Methods*, **148**, 179 (1978).

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

7. – Conclusions.

The described apparatus in a configuration not heavier than $(2 \div 2.5)$ tons, really complete and flexible enough for both planned employements (balloon and Shuttle) will be a very good tool to investigate the origin of cosmic-ray antimatter.

In our mind, the great variety of phenomena connected with the presence of antimatter in the Universe, the necessity, claimed by cosmologists, to have better statistics on $\bar{p}$ flux (and, thus, more refined equipments) in order to check the various cosmological models and, last but not least, the high technological interest in studying problems related to superconductivity and cryogenics under the conditions of this experiment, completely justify the opportunity in going on in this kind of physics.

Moreover, the results that will be obtained with such an experiment will contribute for a better degree of knowledge of the problem of antimatter research, helping to imagine and design suitable experiments for the ASTROMAG facility.

● RIASSUNTO

La questione ancora aperta della simmetria tra materia e antimateria può essere esplorata, misurando il flusso di antiprotoni in alta atmosfera. In questo lavoro si propone un esperimento trasportato su pallone che impiega un magnete superconduttore accoppiato ad un calorimetro tracciante atto ad eseguire tali misure a latitudini a basso taglio geomagnetico. Si presenta pure una panoramica su possibili ulteriori sviluppi come la ricerca di antinuclei da eseguire con le future facilities in progetto (Stazione Spaziale della NASA).

Резюме не получено.