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MATTER AND ANTIMATTER IN THE SAME UNIVERSE?

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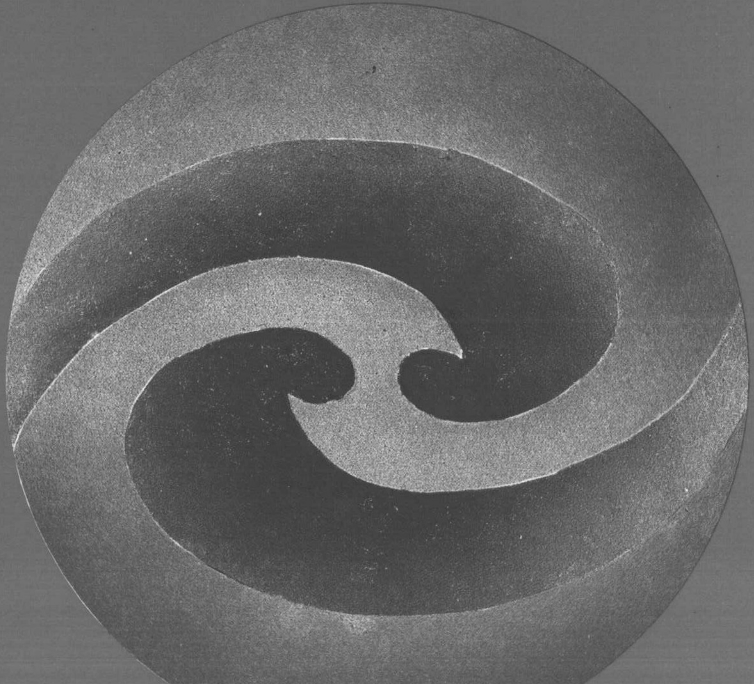

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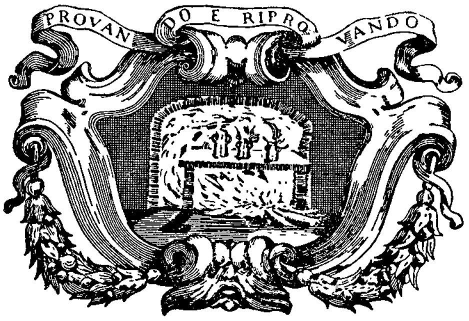

RIVISTA DEL NUOVO CIMENTO VOL. 12, N. 4 1989

Matter and Antimatter in the Same Universe?

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(ricevuto il 2 Dicembre 1988)

Introduction.

The question if the universe is made only of ordinary matter or also (via antibaryon synthesis) of antimatter is one of those able in principle to change our conception of the world and this is the deep reason of the great number of efforts made in the last decades in both experiments and theory.

(*) Also C.N.R. fellowship.

In this paper we try to summarize the situation of such efforts to put in evidence, as far as we can, what has been done and what has to be done.

The Dirac theory, and the successive generalizations, states that not only antiparticles exist, but also that they are created following the same rules of particles. This led to a new principle of symmetry in physics between matter and antimatter. In principle, to any reaction involving particles there corresponds a reaction related to the respective antiparticles governed by the same rules. After the discovery of the antiparticles (in 1932 Anderson for the first positron; in 1955 Chamberlain, Segré, Wiegand, Ypsilantis for the first antiproton; in 1965 Zichichi *et al.* for the first bound state, the antideuteron) and the confirmation of their symmetric production with particles, logically a question came out: why should the universe be made only of matter? In fact, if the matter-antimatter symmetry were perfect, there should be in principle antigalaxies. But now, if we accept, following experimental suggestions, that there was an instant of creation, why did not matter and antimatter annihilate immediately after the Big Bang?

In trying to answer these and other questions, we will not take into account hypotheses which result in strong conflict with theories well confirmed up to now (*e.g.*, hypothetic repulsive antigravity which contradicts the basis of general relativity), or pictures like the Stationary Universe which seems not able to take into account some experimental observations (like the red-shift, the 2.7 K background radiation and the quasar distribution peak at $(7 \div 9)$ billion light-y). We will thus proceed in the framework of the Big Bang theory and general relativity, but, of course, if one of these generally accepted concepts were even partially disproved, the considerations of this paper should be radically changed. Finally, we want just to remind that what we call universe is all that we can reach with our observations.

In sect. 2 we present the standard cosmology and the alternative conceptions; in sect. 3 the experimental situation and the theoretical attempts to fit the data are discussed; sect. 4 deals with the models of cosmic antiparticles production and, finally, in sect. 5 some significant future experiments concerning the antimatter problem are presented.

2. – From the Big Bang to a symmetric or asymmetric universe.

Here we will begin with a brief description of the standard model to define in which context the asymmetric and symmetric hypotheses arise.

2˙1. *The standard cosmology.* – The cosmological model that, up to now, better describes the evolution of the universe is the Big Bang model which postulates an evolutionary expanding universe from an initial singularity. Later we will mention other cosmological models, but there are three main phenomenological reasons that support the Big Bang theory. The first one, and the most evident, is the Hubble expansion: all distant galactic clusters and quasars seem to be receding from us and from each other at velocities proportional to the distances according to the law $V = H_0 r$, where H_0 is the Hubble constant which has the value

$$H_0 = 100\, h_0\, \mathrm{km\, s^{-1}\, Mpc^{-1}} \tag{1}$$

and the experimental observations [1] suggest that

$$0.4 \leq h_0 \leq 1.0 \tag{2}$$

(the subscript «0» indicates present-day value). The second one is the observation of the 2.7 K microwave background radiation that can be interpreted as a relic of the radiation dominance age: the third reason is the observation that the present distribution of galactic clusters seems to be essentially homogeneous and isotropic when viewed on a sufficiently large scale; this last argument implies that the expansion is adiabatic and the particular metric which describes this behaviour is that of Friedmann, Robertson and Walker [2]:

$$\mathrm{d}s^2 = \mathrm{d}t^2 - R^2(t)\left[\frac{\mathrm{d}r^2}{1 - Kr^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\, \mathrm{d}\phi^2)\right], \tag{3}$$

where $K = +1$, -1 or 0 for a closed, open or flat universe, respectively (fig. 1*a*)).

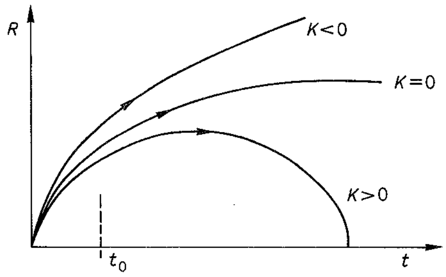

Fig. 1*a*. – Scale factor R as a function of epoch for the three Friedmann models. The present epoch is indicated schematically by t_0.

The physical meaning of K is more evident if one considers that K is related (see eq. (4)) to the energy density ρ and hence to the ratio $\Omega = (\rho/\rho_c)$ (where ρ_c is the «critical density» $\rho_c = (3H^2/8\pi G)$ depending on the velocity of expansion of the universe). According to Ω, the universe is permanently expanding ($\Omega < 1$), permanently expanding but with a decreasing expansion rate ($\Omega = 1$) or

Type of universe	Ratio of energy density to critical density (Ω)	Spatial geometry	Volume	Temporal evolution
closed	>1	positive curvature (spherical)	finite	expands and recollapses
open	<1	negative curvature (hyperbolic)	infinite	expands forever
flat	1	zero curvature (Euclidean)	infinite	expands forever, but expansion rate approaches zero

Fig. 1*b*. – See Guth *et al.* (1984). Three types of universe, classified as closed, open and flat, can arise from the standard Big-Bang model. The distinction between the different geometries depends on the quantity designated Ω, the ratio of the energy density of the universe to some critical density, whose value depends in turn on the rate of expansion of the universe. The value of Ω today is known to lie between 0.1 and 2 which implies that its value a second after the Big-Bang was equal to 1 to within one part in 10^{15}. The failure of the standard Big-Bang model to explain why Ω began so close to 1 is called the flatness problem.

collapsing after the end of the expansion ($\Omega > 1$) (fig. 1*b*)). Experimentally, the best evaluation of Ω ranges in the interval $0.1 \div 2.0$.

The evolution scale factor $R(t)$, which takes into account the expansion of the relative distance of cosmic objects (*), is governed by the field equation due to Einstein, that, in the case of a homogeneous and isotropic universe, becomes

$$\left(\frac{\dot{R}}{R}\right)^2 = H^2 = (8/3)\,\pi G \rho - \frac{K}{R^2}. \tag{4}$$

To determine the evolution of the universe, the above equation must be completed by thermodynamics using the equation of state for matter wich describes the density of the energy ρ, the entropy s and the number of particles n as a function of the temperature T:

$$\rho = \frac{\pi^2}{30} N(T)\, T^4, \tag{5}$$

$$s = \frac{2\pi^2}{45} N(T)\, T^3, \tag{6}$$

$$n = \frac{\zeta(3)}{\pi^2} N'(T)\, T^3, \tag{7}$$

(*) The function $R(t)$ has the dimension of a velocity, is a function of the cosmic time t and depends on the adopted cosmological model.

where $\zeta(3)=1.202\ldots$ is the Riemann zeta-function and $N(T)$ and $N'(T)$ take into account the effective number of boson and fermion degrees of freedom

$$N(T)=N_b+(7/8)N_f\,,\qquad N'(T)=N_b+(3/4)N_f\,. \tag{8}$$

Also the field equation can be expressed in terms of the temperature (only using the fact that $(d/dt)(R^3T^3)=0$, to obtain

$$\left(\frac{\dot{T}}{T}\right)^2+\varepsilon(T)\,T^2=\frac{4\pi^3}{45}GN(T)\,T^4 \tag{9}$$

with

$$\varepsilon(T)=\frac{K}{R^2T^2}=K\left(\frac{2\pi^2N(T)}{45S}\right)^{2/3}, \tag{10}$$

where S is the entropy

$$S=R^3s=\frac{2\pi^2}{45}N(T)\,T^3R^3\,. \tag{11}$$

If we consider the first instants of the universe, the term K/R^2 of eq. (4) is negligible and the field equation becomes

$$\left(\frac{\dot{T}}{T}\right)^2=\frac{4\pi^3}{45}GN(T)\,T^4\,. \tag{12}$$

If T is not near any mass threshold, $N(T)$ is constant in T and then we can easily integrate the above equation obtaining the known time-temperature relation

$$T^2=\frac{M_P}{2\gamma t} \tag{13}$$

with $\gamma=\sqrt{(4/45)\pi^3N(T)}$ and with $G=1/M_P^2$, where M_P is the Plank mass ($M_P\simeq 10^{19}$ GeV).

The description of the universe according to eq. (13) is well understood from the time at 10^{-2} s up to now ($\simeq 10^{17}$ s later) and the strength of the Big Bang model lies in the prediction of the relative abundances of light elements. Here we briefly remind how. From eq. (13) we can see that at $t=10^{-2}$ s we have $T\simeq 10$ MeV and a density

$$\rho=\text{const}\cdot N(T)\cdot T^4=10^9\ \text{g/cm}^3\,.$$

At this temperature we have thermic equilibrium between e^+e^- and γ and, due to the high density, also neutrinos, *i.e.*

$$e^+e^- \leftrightarrow \nu\bar{\nu}$$

and also protons and neutrons through the weak reactions

$$p + \bar{\nu} \leftrightarrow n + e^+ , \qquad n + \nu \leftrightarrow p + e^- .$$

The neutrinos contribute to the energy density with a factor $(7/8)3 \cdot \rho_\gamma$.

At $t = 100$ s, $T = 10^9$ K $= 0.1$ MeV, the neutrinos are decoupled and then the proton and neutron distribution obeys the Boltzmann statistics:

$$\frac{n_n}{n_p} = \exp\left[\frac{-\Delta M}{KT}\right] \simeq 0.13$$

(where $\Delta M = m_p - m_n \sim 1$ MeV).

Then we begin to have the interactions (*)

$$p + n \rightarrow d + \gamma , \qquad d + d \rightarrow {}^4He + \gamma .$$

The present abundance of ^{4}He depends in a critical way on the time elapsed from the decoupling of protons, neutrons and neutrinos to the beginning of the deuterium fusion process (due to the 15-minutes lifetime of the neutrons).

As we can see from eq. (13), through eq. (8), time depends on the number of neutrinos species, and, from the observed ^{4}He abundance, we can also put a constraint on the allowed number of neutrinos. Very exact calculations [3, 4] can be carried out not only for the ^{4}He but also for all the other light elements like H, D, ^{3}He, and Li (fig. 2) and the constraints on the neutrino's number are very strong: there cannot be more than four «light» neutrino species [4].

Only in Ellis *et al.* [5] it was suggested that astrophysical data (especially ^{3}He + D) may allow a number of neutrinos up to 5 or even 6.

By now, the best experimental limit from particle physics comes from the UA1 and UA2 data gathered at the CERN $p\bar{p}$ collider [6] and suggests that $3 < N_\nu < 4$ at 90% c.l.

The nuclei greater than ^{4}He are not stable at the temperature involved. After this initial period we have no dramatic changes for 10^5 y (period of «radiation dominance») until the atoms can be formed.

2·2. *The very early universe.* – What we have just described is the well-known part of the Big Bang standard model, but at earlier times ($t < 10^{-2}$ s) the

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(*) The chain reactions are more complex but the important point is that the formation of ^{4}He can occur only at this temperature even if the ^{4}He is stable at higher temperatures.

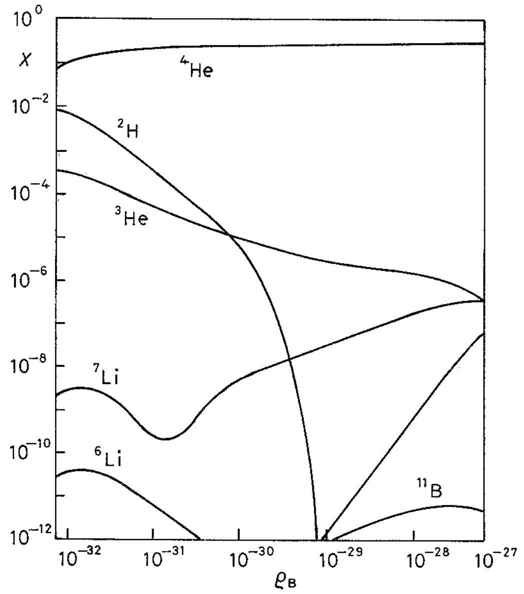

Fig. 2. – Predictions of the primordial abundances of d, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{11}B for different baryon densities ρ_B.

question is much more complex. Following the classical equation of general relativity (eq. (2)) it is not difficult to see that the existence of an initial singularity is unavoidable unless drastic things happen, like, for example, a hypothetic repulsive gravity [7, 8] above some critical temperature T_c. Indeed, if the standard Big Bang theory is successful in explaining the observable universe evolution, it is unsatisfactory in two respects: because it requires initial conditions arbitrarily fixed and because it is uneffective to explain the very early universe.

Forgetting about alternative options which exceed the limits of this paper (*e.g.*, the UMF, universe magnetic field [9]), we need now to introduce the new concept of the inflationary universe (which, up to now, seems the most promising) and proceed in the framework of GUTs (grand unified theories) the most generally accepted approach today.

The fundamental idea of the GUT, concerning the unification of forces through symmetries spontaneously breaking, shows itself very powerful in describing the different steps of the Big Bang evolution (fig. 3), but the introduction of GUTs in standard Big Bang is not sufficient for a convincing description of the early cosmic evolution because of the following three problems.

i) The horizon problem. Regions which at the beginning were disconnected because far from each other more than their «horizon distance» (*ct*) should not be homogeneous today, as they appear according to the 2.7 K radiation.

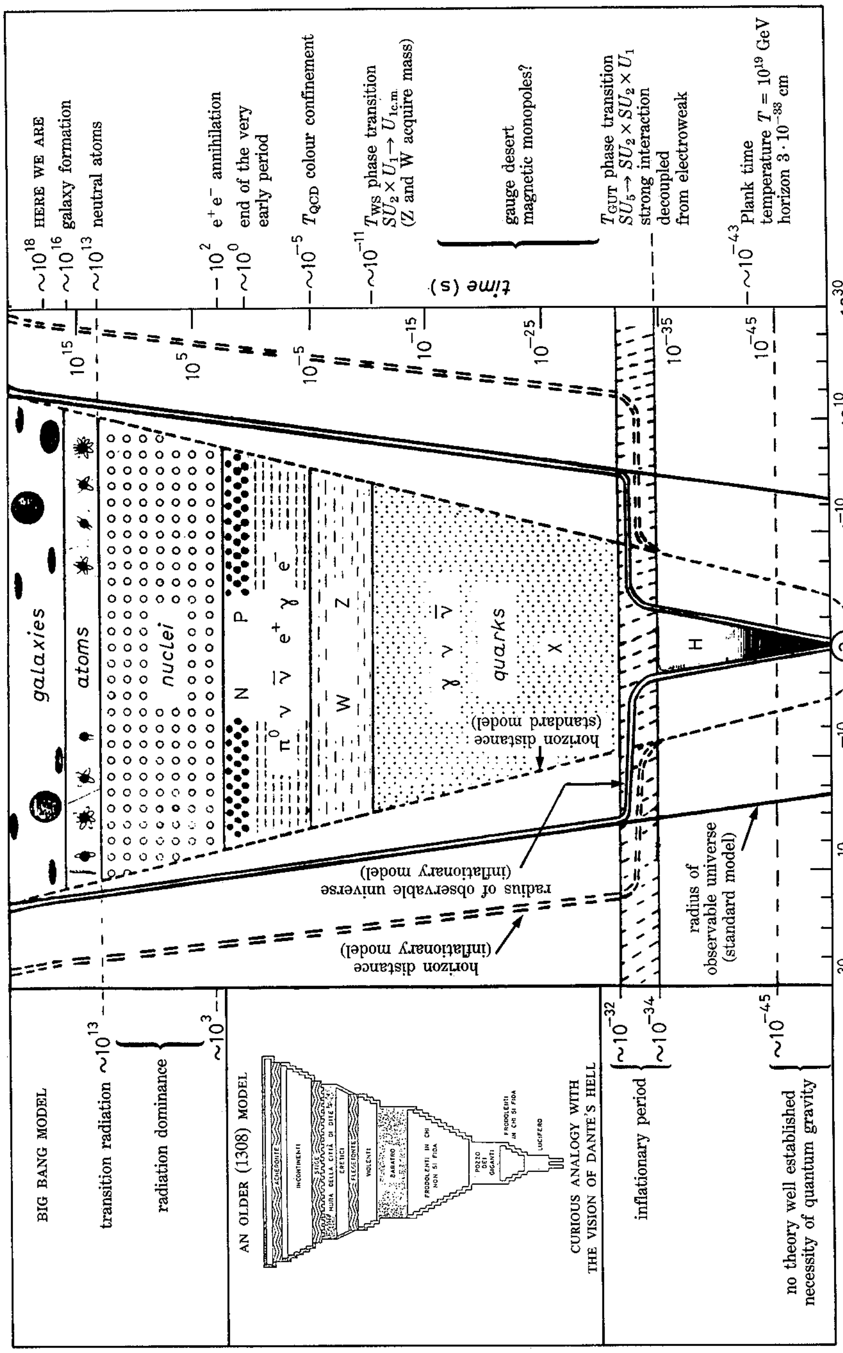

Fig. 3. – The Big Bang model. A pictorial view of the evolution of the universe.

ii) The space flatness problem. Experimentally, the ratio Ω = (energy density/critical density) seems close to 1—flat Euclidean space—which is in no way deducible from the theory, unless arbitrarily introduced at the beginning.

iii) The magnetic-monopole problem. The theory leads to the presence of a great number of pointlike and surfacelike imperfections—massive (10^{16} proton masses) magnetic monopoles and Bloch's domains—which, if existent in such amount, should reduce by a factor of $\sim 10^{12}$ the life of the observable universe, thus destroying the whole Big Bang picture.

The inflationary big bang model [10] plays a fundamental role in giving an explanation of such problems and in reducing the number of arbitrary constraints as initial postulates; this model is equivalent to the standard one (keeping its successful predictions) after the very early period, but it dramatically differs before $\sim 10^{-30}$ s postulating a phase transition in which a huge superexpansion (up to 10^{50} times in a period of 10^{-32} s) takes place.

Without going into a quantitative description, for which we recall ref. [10, 11], in the inflationary model the initial symmetry breaking, generated by the acquisition of a nonnull value of one of the postulated GUTs Higgs fields (*) (occurring at a temperature $T \leqslant 10^{27}$ K for thermodynamical convenience), produces two extremely important effects:

i) the observable universe would be the evolution, through the inflationary expansion, of a «bubble» that, by means of a quantum fluctuation, would have traversed the energetic barrier between the «false vacuum» region of the symmetric era to the real vacuum region of the broken symmetry era and this would occur with a mechanism of slow transition (**) [15] allowing the expansion;

ii) there should be more than one bubble.

There are still several problems in the inflationary model related to the exact definition of the energy density function (Coleman-Weinberg) describing the Higgs fields in order to obtain a proper phase transition; moreover, it is probably in the framework of a new class of superunification theories including the quantum gravity instead of GUTs, that the evolution of the universe (at least at $T > 10^{19}$ GeV) could be better explained. There is a lot of theoretical work that is going on using new approaches or taking again into account older points of view adapted to the present problems, namely multidimensional spaces, superstrings and several other ideas and techniques. We will not go deeply in this direction, we want just to remember few concepts.

(*) The Higgs field was first introduced by Higgs [12, 13] to explain the general mechanism of symmetry breaking; in the case of GUTs, specific Higgs fields can account for the spontaneous symmetry breaking in the very early universe.

(**) Up to now, the energy density potential which better describes this slow transition mechanism is the Coleman-Weinberg potential [14].

One question that requires to be settled at such very early times is the number of space-time dimensions. Modern unified theories like those which start from Kaluza-Klein approach [16] and superstrings [17] need more than four dimensions. The most favourable superstring number is $D = 10$ and now many people are discussing if it is possible that we live in a (four-dimensional Friedman universe) ⊗ (a constant internal space); this internal space is retired into itself in so small distances that we cannot see it (at the energy that we can reach today [18]).

As we have seen, the inflationary Big Bang model was born to overcome the inconsistency of the standard model but it brings unexpected big consequences:

i) The mechanism of formation and growth of bubbles is extremely intriguing because it is a sort of attempt to describe a materialization of virtual energy at a large scale. Let us refer the Guth's and Steinhardt's statement [19]: «Recently there has been some serious speculation that the actual creation of the universe is describable by physical laws». And, again: «it is then tempting to go one step further and speculate that the entire universe evolved from literally nothing».

ii) The formation of several different domains (bubbles), each one with its own evolution, leads to the real possibility that our observable universe is *only one* among several universes and maybe that our Big Bang (in the standard evolution after 10^{-30} s) is only one among several other Big Bangs.

In this section we have tried to summarize briefly a picture of the present development of the cosmology to give the reader a scenario in which to insert the antimatter problem, not because the inflationary model is so well established to already change in a predictable way the expectation for antimatter search, but only to stress the fact that the presence of antimatter is a complex argument also because it is based on a not well-established system.

Let us end this section recalling that we refer to the original article of Guth [10] the explanation of the problems of the standard theory known as the horizon, flatness and monopole problems. Here we emphasize only the fact that to solve all these problems we need a phase transition at $T \sim 10^{15}$ GeV associated with the breakdown of some symmetries, such as the breakdown of a chiral symmetry in the quark-hadron phase transition, or the breakdown of a possible grand unified symmetry.

As for the $SU(2) \otimes U(1)$ breakdown [20] one can have a metastable state with an energy density greater than today; it is as if on the right-hand of eq. (4) we have a constant term (that acts as a cosmological constant) that becomes quickly more important than the other terms. We have then

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8}{3}\pi G\rho_0 \tag{14}$$

that gives an exponential expansion

$$R = \exp\left[\left(\frac{8}{3}\pi G\rho_0\right)^{1/2} t\right] = \exp[\chi t] . \tag{15}$$

When the exponential expansion of the universe takes place, the density of all the particles which were present in the universe before inflation rapidly drops to zero. Matter is then introduced into the universe after inflation when the energy stored is released.

Thus, an important prediction of inflation is that all the quantities, conserved in the present universe, should vanish (this is certainly true for the electric charge of the universe) and, if the present baryon density of the universe is not zero, then the baryon number is not a conserved quantity and the violation must occur after inflation.

2'3. *The origin of the baryon-antibaryon asymmetric hypothesis.* – We know that the grand unified theories (GUTs) predict the existence of a X-boson which carries the forces between quarks. If at the end of inflation the universe was hot enough to produce X-particles, then, when it cooled, the X and $\overline{\mathrm{X}}$ would have been able to decay into pairs of quarks (q) or a quark (q) plus a lepton (ℓ). X-bosons induce lepton-quark transitions $\mathrm{qq} \to \mathrm{X} \to \overline{\mathrm{q}}\ell$ and, with a mass $M_\mathrm{X} \sim \sim 10^{15}\,\mathrm{GeV}$, they can mediate reactions like the proton decay (*e.g.*, $\mathrm{p} \to \mathrm{e}^+\pi^0$) with a proton lifetime of the order of $\tau_\mathrm{p} \geq 10^{30}$ y. Let us suppose that we have two dominant modes of decay:

$$\mathrm{X} \to \mathrm{q} + \mathrm{q} \quad \text{or} \quad \mathrm{X} \to \overline{\mathrm{q}} + \ell, \qquad \overline{\mathrm{X}} \to \overline{\mathrm{q}} + \overline{\mathrm{q}} \quad \text{or} \quad \overline{\mathrm{X}} \to \mathrm{q} + \overline{\ell} .$$

Defining r as the fraction of decays in $\mathrm{q} + \mathrm{q}$, and thus $(1 - r)$ as the fraction of decays in $\overline{\mathrm{q}} + \ell$, in the presence of C and CP violation we have $r \neq \overline{r}$; hence we can end up with an excess of quarks over antiquarks. Another necessary condition is to be not in thermodynamical equilibrium to avoid that the inverse reactions like $\mathrm{qq} \to \mathrm{X}$ or $\overline{\mathrm{q}}\ell \to \mathrm{X}$ have the same rate. Both these conditions can be realized in the Big Bang theory justifying the hypothesis of a baryon-antibaryon asymmetric universe. The annihilation of the q and $\overline{\mathrm{q}}$ leads to the production of radiation. The slight excess of remaining q and ℓ provides the matter of which the present universe is made. In this scheme the number of baryons and photons is

$$n_\mathrm{B} \propto n_\mathrm{q} - n_{\overline{\mathrm{q}}} , \qquad n_\gamma \propto n_\mathrm{q} + n_{\overline{\mathrm{q}}} .$$

Experimentally, the baryon-to-photon ratio is quoted as

$$\frac{n_\mathrm{B}}{n_\gamma} = 10^{-9\pm 1} , \tag{16}$$

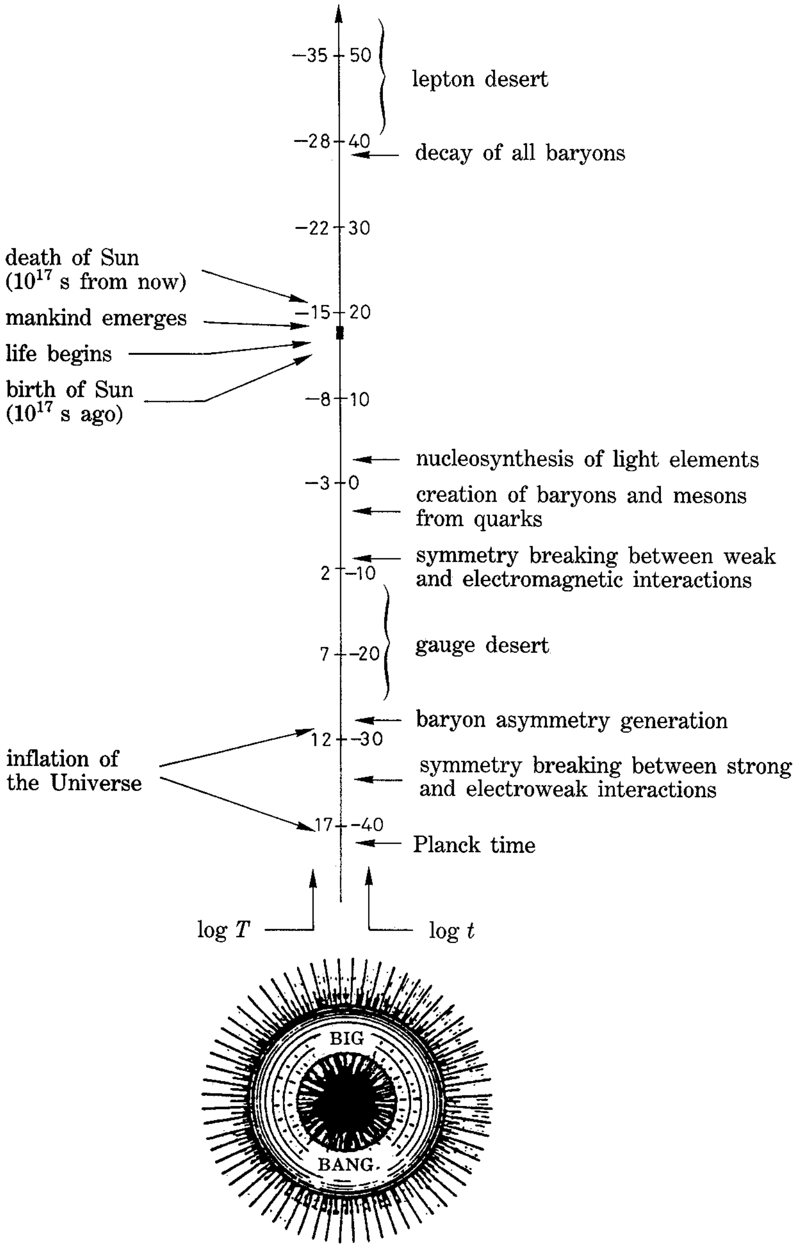

Fig. 4A. – The evolution of the universe.

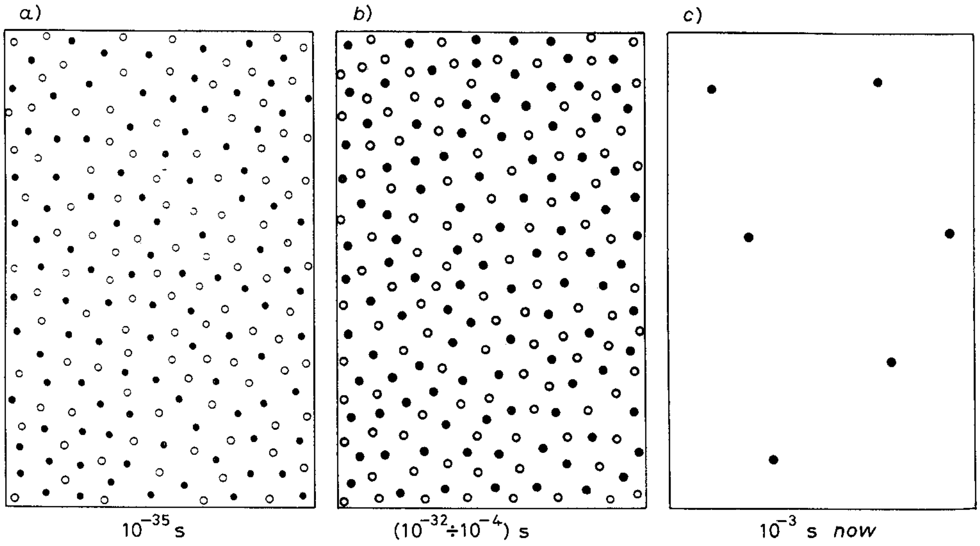

Fig. 4*B*. – (Taken from ref. [23].) Evolution of cosmic asymmetry between matter and antimatter is diagrammed in accordance with the predictions of the theories that unify the strong and the weak interactions. Panel *a*) symbolizes the universe 10^{-35} s after the Big Bang. The panel shows equal quantities of X particles (*black dots*) and their antiparticles, $\overline{\mathrm{X}}$'s (*open circles*). In the newborn universe such particles were copiously produced by ultrahigh-energy collisions. Panel *b*) shows the universe from 10^{-34} s through 10^{-4} s. The X's and $\overline{\mathrm{X}}$'s have decayed in ways that do not always conserve baryon number and *CP* symmetry. The result is a slight imbalance favoring protons (*black dots*) over antiprotons (*open circles*). The panel shows six more protons than antiprotons; actually the imbalance was much smaller, namely one part in a billion. Although the proton is less massive than the X by a factor of 10^{15}, the proton is shown as being larger because, according to quantum mechanics, mass is inversely proportional to uncertainity in position. Panel *c*) shows the universe from 10^{-4} s through the present. Each encounter of a proton and an antiproton has caused the annihilation of both particles and only the excess protons survive. They contribute to the apparent preponderance of matter over antimatter observed in the universe today.

where the large uncertainity is due to the well-known dark-matter problem [21]. This baryon-to-photon ratio can be explaned with a mass of the X, $m_{\mathrm{X}} = 10^{14}$ GeV [22]. In fig. 4 (fig. 4*B*) is taken from [23]) we have summarized the most important steps of the evolution of the universe as described before.

The matter-antimatter asymmetry of the universe, however, is fairly well established only in our galaxy and probably in our cluster of galaxies, because of the observed level of γ-rays background (see subsect. 1'5) which is incompatible with the large-scale annihilation, while experimental evidences are inexistent for a larger region.

Given the fact that there are $\sim 10^8$ clusters of galaxies in our visible universe, the baryon-antibaryon symmetry can be perfectly existent at the galaxy cluster level (*i.e.* cluster of galaxies made of matter and, well separated, cluster of antigalaxies made of antimatter).

So, the question if matter and antimatter play or not the same role in building galaxies remains open.

2·4. *The symmetric hypothesis.* – The above theory is the most general accepted theory for the universe evolution and we have seen that it is based on the CP violation in GUTs.

We must not forget, however, that the only proof of the validity of GUTs (besides our need of unification) is the tendency of the coupling constant to reach an equal value, and that we have no proof at all of the existence of CP violation in GUTs.

Therefore we can now consider what happens if after inflation we do not have CP violation. We will see in another section that the objection that we live in a universe made of matter is not necessarily a good one because observational limits do not deny that antimatter can exist in the universe if it is well separated from matter (at least at the level of galaxies).

What we need in this case is a mechanism for the separation of matter and antimatter during the expansion. In fact the baryon and the antibaryon are in thermal equilibrium due to the annihilation and pair creation processes. If there were not any separation, their number would decrease with temperature according to

$$n_{\mathcal{N}} = n_{\bar{\mathcal{N}}} \propto (MT)^{3/2} \exp\left[-\frac{M}{T}\right]. \tag{17}$$

The $\mathcal{N}$ and $\overline{\mathcal{N}}$ in the standard model were out of equilibrium only at $t \sim 10^{-3}$ s, $T \sim 20$ MeV and at this time the concentration of $\mathcal{N}$ and $\overline{\mathcal{N}}$ drastically fell down to

$$n_{\mathcal{N}} \sim n_{\bar{\mathcal{N}}} \sim (10^{-17} \div 10^{-18})\, n_{\gamma} \tag{18}$$

and this is in disagreement at least of ten order of magnitudes with the observed ratio (16).

A mechanism to avoid this discrepancy was proposed by Omnes [24]. He supposed that the separation of matter and antimatter takes place during the hadronic era (1 GeV $> T >$ 350 MeV, $10^{-6} < t < 10^{-5}$ s. A hypothesis on how this separation could take place is based on these assumptions:

1) strong attractive interaction between nucleons and antinucleons so that they can form bound states;

2) no distinction is made between a particle and a bound state.

Let us suppose for simplicity that the potential well of the nucleon-antinucleon bound state is a square of depth $V_0 > kT$ and range R. If a nucleon approaches an antinucleon by less than R, they form a mesonic bound state but the total number of mesons in equilibrium at temperature T is statistically determined. Thus, when all possible bound states are saturated, a net repulsion between nucleon and antinucleon takes place. This is called statistical repulsion and tends to separate matter and antimatter into domains. After the separation a new period begins, called annihilation period ($25\,\text{keV} < KT < 350\,\text{MeV}$) that starts with the growth in size of the domains; this is mainly due to the minimization of free energy which depends on their surface/volume ratio.

During this growth the baryonic density decreases and matter and antimatter start to recombine and annihilate producing pions, leptons and photons. At the end of the annihilation period the panorama of the universe is: domains of matter and antimatter, reduced in size and hadronic density, in a sea of lighter-mass and higher-momentum particles. At this stage, the pressure on the surfaces of the domains exerted by the ligthest particles gives rise to a coalescence phenomenon. This period is called coalescence period ($1/3\,\text{eV} < kT < 25\,\text{keV}$). After a successive recombination a structure made of galaxies of matter and antimatter is produced.

The Omnes theory is quite interesting but has several problems.

1) There are no experimental evidences that the hot plasma of baryons and antibaryons behaves like in Omnes theory.

2) According to Steigman [25], probably there are difficulties to explain the ^{4}He abundance.

The theory has changed many times during the years [26, 27] but none of the versions is fully satisfactory.

Other symmetric theories, the steady-state model [28, 29] and the Alfvén-Klein model [30] have also problems, and the attempt of introducing matter-antimatter separation as an initial condition of the Big Bang [31] is not very successful.

However, more recently Brown and Stecker [32] have proposed a quite plausible model in the framework of the Big Bang and GUTs.

As we have seen, for the generation of asymmetry in the early universe, we need the combination of three conditions, namely baryon number violation, thermal disequilibrium and CP violation. The expansion of the universe itself fulfills the thermal-disequilibrium condition, the GUT provides the baryon number violation, but nothing can be said on what kind of CP violation one should expect.

Brown and Stecker considered the hypothesis of a soft CP violation coming from spontaneous symmetry breaking (such a mechanism has been already proposed to explain the smallness of the CP violation implied by the small electric-dipole moment of the neutron [33]) with a scalar field that takes complex vacuum expectation values during the cooling of the universe (see fig. 5).

The idea was later improved [34-36] and the interesting thing is that, when

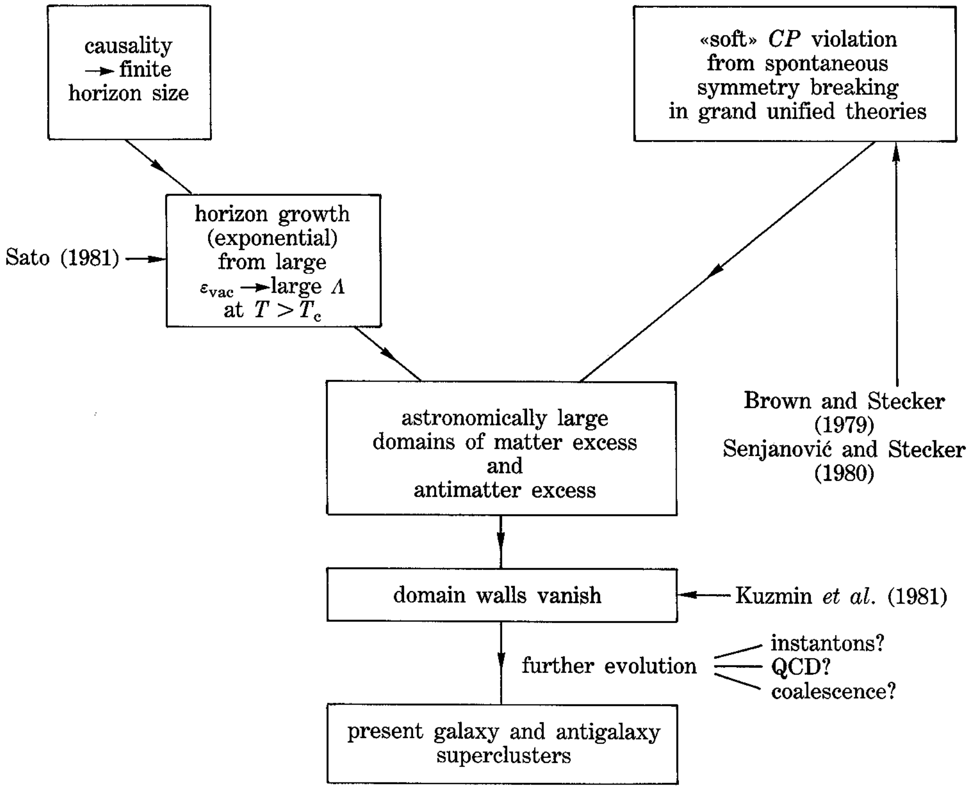
simplest baryon symmetric big-bang scenario

Fig. 5. – Simplest baryon symmetric Big-Bang scenario.

symmetry breaking occurs, say at time t_u, the *CP* violation can have a random different sign in a causally disconnected region (a region separated by a distance greater than ct_u).

If the model is right, the problem is very similar to the monopole one [37]. The monopole arises as a topological defect when causally disconnected regions with different oriented Higgs fields come in contact. The inflation mechanism was proposed also to reduce the too large number of monopoles created in $\sim 10^{83}$ regions. Up to now, it is a matter of discussion how many GUT monopoles can remain after inflation, because this depends on the shape of the Higgs potential. At present it ranges from only one (this is not a good number for the experiments that are searching for monopoles!) to the maximum allowed to give all the dark matter of the universe.

In the same way we do not know the number of the different disconnected *CP* regions that can remain after inflation but, if they are more than one, for statistical reasons they should be matter and antimatter regions.

It has to be noticed that in this way the Omnes problem of the separation in the plasma of matter and antimatter is overcome, because separate regions can rise in a very natural way.

2'5. *Observational limits on the presence of antimatter in the Universe.* – Now we take under consideration the experimental situation, first looking at the limit on the separation between matter and antimatter.

This limit can be calculated in the framework of γ-ray astronomy as it is clear that, if matter and antimatter are in contact, they annihilate producing γ-rays.

There is a lot of physical processes in cosmic space that can produce a γ-ray: photoproduction from binary stars, from active galaxy nuclei and from interactions of cosmic protons and nuclei with the interstellar medium. They can be produced also from Compton scattering of photons, bremsstrahlung of electrons, syncrothron radiation near neutron stars etc. But, being γ-rays also produced in annihilation, this puts in any case an upper limit on the possible amount of annihilating antimatter.

The number N of γ's is proportional to the density f of antimatter involved in the annihilation, to the density ρ of matter and to the annihilation rate $\langle \sigma_{\text{ann}} v \rangle$ according to the relation

$$N = f\rho^2 \langle \sigma_{\text{ann}} v \rangle \, .$$

The annihilation rate is known from experiments, ρ can be estimated from astronomical observations and we know N, so that we can put limits on f, that means two correlated limits on the total amount of antimatter and on the separation of matter and antimatter.

For example, if different galaxies inside a cluster are formed by matter and antimatter, f would be $\leqslant 10^{-5}$ because, if greater, it would be a discrete observable γ-rays source, so we can conclude that, if antimatter exists, it is separated from matter at least at the level of cluster of galaxies.

However, Stecker [38, 39] noticed that if we take into account the red-shift of the produced photons, the Compton scattering and pair production, the subsequent γ-ray spectrum can fit the γ-ray experimental data satisfactorily and can also explain the flattening of the spectrum at ~ 1 MeV, not easily explained in other ways. This attempt to make the presence of antigalaxies in the same cluster of galaxies compatible is based on a free parameter which is the time during which the annihilation occurs. So Stecker succeeds in maintaining the question open but not in giving the final answer.

To see how Stecker proceeds, one must solve the associated transport equation:

$$\begin{aligned}(19)\qquad & \frac{\partial I}{\partial t} + \frac{\partial}{\partial E}[-EH(z)\,I(E,z)] = \\ & \qquad = Q(E,z) - K_{\text{AB}}(E,z) + \int_E^{\varepsilon(E)} \mathrm{d}E'\,K_{\text{SC}}(E,z)\,I(E,E')\,\mathrm{d}E' \, ,\end{aligned}$$

where

$$I(E,z) \equiv (1+z)^{-3} I(E,z)\,, \qquad Q(E,z) \equiv (1+z)^{-3} Q(E,z)$$

and

$$\frac{\partial}{\partial t} = -\,(1+z)\,H(z)\,\frac{\partial I}{\partial z}\,, \qquad H(z) = H_0(1+z)(1+\Omega z)^{1/2}\,.$$

The second term in the equation expresses the energy loss from the red-shift effect. The third term is the γ-ray source term from $\mathrm{p\bar{p}}$ annihilation primarily into π^0's. The absorption term (K_{AB}) comes from pion production and Compton interactions with electrons at high z and the scattering integral puts back Compton scattered γ-rays at lower energies $E < E'$.

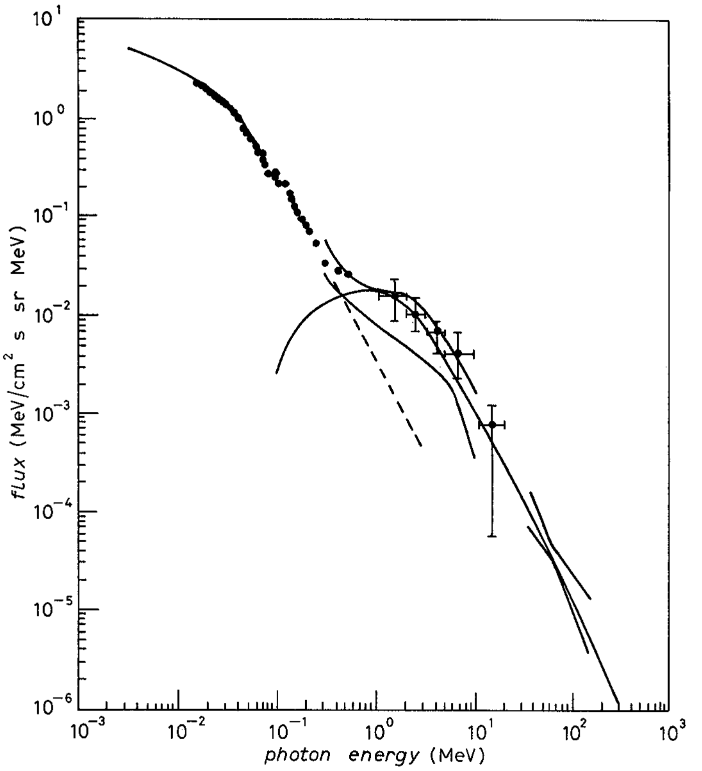

Fig. 6. – High-energy diffuse cosmic background. —— calculated annihilation flux, - - - extrapolated X-ray flux.

The result is shown in fig. 6. As we said, the model fits the experimental data in a satisfactory way. The dotted line is the extrapolated X-ray flux.

3. – Antimatter in the Universe.

3·1. *Cosmic antimatter: antihelium and heavier antinuclei.* – We have seen that the problem of whether a substantial quantity of antimatter of cosmological origin is present in the Universe (up to a matter-antimatter completely symmetric universe) is one of the most fundamental of today's physics. The antimatter presence 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 and antiprotons can be produced also via standard interactions between elementary particles. As we showed, the particle-antiparticle symmetry observed in elementary-particle experiments, in addition to the conservation of baryon and lepton numbers, suggests the question of why the universe seems to be composed only of matter. The presentation of models of a matter-antimatter symmetric universe (in which the matter dominance would be only local) having been made in the previous section, here we comment the consequence of these models: the existence of a detectable flux of antihelium nuclei [40]. In speculating about antinuclei, if existent, we have to speak mainly about antihelium because, at this stage of research, the antihelium (supposed to be dominant among antinuclei in cosmic rays like helium among nuclei) 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 have to recall that, increasing the atomic number, the proportions of cosmic nuclei are

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

Even if the statistics makes it very difficult to detect an antinucleus heavier than helium, its detection would be a fundamental discovery because such a heavy antinucleus could not have been synthesized in the Big Bang, nor produced in proton collisions with the interstellar gas. As Ahlen *et al.* affirm in ref. [41]: «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 in future dedicated experiments have to be done, maybe looking at $\overline{\text{Fe}}$ which seems to be the favourite candidate [41].

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.

In comparison with heavier antinuclei, antihelium detection 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 not in principle necessary to explain antihelium in the same way 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 that several antinucleons are created in the same element of the phase space to produce an antinucleus has been extimated negligible by Hagedorn [42], being $\sim 10^{-55}$ for an $\overline{\mathrm{Fe}}$ 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.

At this point there is a problem. In a matter-antimatter symmetric universe, one should expect that the ratio $\bar{\alpha}/\bar{p}$ would be the same of the ratio α/p [43, 44], which is experimentally not true and, equivalently, that the ratio $\bar{\alpha}/\alpha$ would be equal to the ratio $\bar{p}/p$, whereas the $\bar{\alpha}/\alpha$ is lower than $\bar{p}/p$ (by now the best confidence limits are $\bar{\alpha}/\alpha < 1.0 \cdot 10^{-4}$ in the range $(4 \div 33)$ GeV/c [45] and $\bar{\alpha}/\alpha < 2.2 \cdot 10^{-5}$ in the range $(130 \div 370)$ MeV/nucl [46]).

Stecker, Protheroe and Kazanas [47] solved this problem suggesting that, if the most part of the cosmic rays comes from active (*) galaxies, the photo-disintegration of He antinuclei by low-energy γ-rays and spallation, can reduce the $\bar{\alpha}$ flux compared with the $\bar{\mathrm{p}}$ flux. The extragalactic component from normal galaxies is estimated to be $(I_{\mathrm{ex}}/I_{\mathrm{gal}})_{\mathrm{NG}} = \xi_{\mathrm{NG}} \sim (10^{-5} \div 10^{-4})$ while for active galaxies we have a higher value $\xi_{\mathrm{AG}} \sim 10^{-3}$; then, the active galaxies can really give the bulk of the extra galactic cosmic-ray flux.

Just to have the order of magnitude of the effect, we can take a spallation cross-section for He of ~ 100 mb [48] and the spallation time at radius r given by

$$T_{\mathrm{spall}} \simeq \frac{6 \cdot 10^{44}}{L_{\mathrm{tot}}} \left(\frac{M}{M_{\odot}}\right) \left(\frac{r}{r_{\mathrm{S}}}\right)^{1/2} \mathrm{s}, \tag{21}$$

where $M/M_{\odot}$ is the black-hole mass in term of solar mass, r_{S} is the Schwarzchild radius (**) and L_{tot} is the total luminosity in erg s^{-1}.

Typical values are $L_{\mathrm{tot}} \sim (10^{44} \div 10^{46})\,\mathrm{erg\,s^{-1}}$, $M \sim (10^{8} \div 10^{10}) M_{\odot}$ and $(r/r_{\mathrm{S}}) \sim \sim (10 \div 10^{3})$, with which we obtain $T_{\mathrm{spall}} \sim (2 \cdot 10^{-1} \div 6 \cdot 10^{4})$ y. Since in our galaxy the cosmic rays are trapped for about 10^{7} y before escaping and in galaxies greater than ours this value would be even greater, it is very easy that almost all the $\bar{\alpha}$ would be destroyed before leaving the active antigalaxies.

The photo-disintegration time scale of nonrelativistic nuclei at a distance r from an active galaxy depends on the photon density in the γ-ray region and thus

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(*) We remember that an active galaxy is a galaxy with a very active nucleus, probably due to some efficient mechanism of production of energy.

(**) r_{S} is the radius of the surface that delimits the black hole as it comes out from general relativity: $r_{\mathrm{S}} \simeq 2GM/c^2 \simeq 3 \cdot 10^5 (M/M_{\odot})$ cm.

it depends on the γ-ray luminosity through the equation

$$T_{\text{photon}} \sim \frac{2.3\,\pi r^2 \varepsilon_0^2}{L(\varepsilon_0)\,\Sigma_{\text{d}}}, \tag{22}$$

where $L(\varepsilon)$ is the luminosity at energy ε (in MeV s^{-1} decade^{-1}), ε_0 is the peak energy of the dipole resonance (~ 30 MeV for He) and Σ_{d} is the energy integrated dipole resonance cross-section, ~ 60 MeV mb for He [49].

For example, for the quasar 3*C* 273 (*), $L \sim 2 \cdot 10^{46}$ erg s^{-1} decade^{-1} and the source radius is probably in the range 10^{15} to 10^{18} cm. This results in a photodisintegration time in the range $(3 \cdot 10^2 \div 3 \cdot 10^8)$ y. This process can thus be important for the disintegration of He but its efficiency depends on the photon density.

Therefore we expect that $\bar{\alpha}/\alpha \simeq (1/2)\,\xi_{\text{NG}} \simeq (5 \cdot 10^{-6}) \div (5 \cdot 10^{-5})$, values that are not reached in the present upper limits but, as we will discuss in subsect. 4˙3, can be reached with the future planned experiments, so that we will be able to check if the extragalactic hypothesis is a good one.

3˙2. *Cosmic-ray antimatter: antiprotons and positrons.* – Positrons and antiprotons share the property (which is statistically forbidden for antinuclei) of being produced through ordinary elementary-particle interaction and hence a detectable flux of such antiparticles, of secondary origin, is expected without any necessity of complex mechanisms. The problem raises when the experimental results show a flux of positrons and antiprotons higher than expected (which seems to be the case up to now) leading to take into account also exotic mechanisms. In some sense, the e^+ and $\bar{\text{p}}$ measurements will not give an unambiguous conclusion as for the discovery of the hypothesized antinuclei, but, being related to many different possible mechanisms, they are in principle able to verify several models ranging from elementary-particle physics (*e.g.*, photino annihilation) to cosmology (*e.g.*, black-hole evaporation), provided a sufficient statistics is attained. A more complete exposition will be presented in the following section dedicated to discuss in detail the different mechanisms and models; here we present a general view and a comparison with the existing experimental data.

The positrons (like the electrons) are a unique probe of the acceleration mechanisms, of the sources, of the distribution of acceleration sites and of the interactions in interstellar space, because of their low rest mass and because (contrarily to nucleons which, at high energies, suffer attenuations due to collisions with gas) they interact with the fields of the nuclei by bremsstrahlung, with photons by inverse Compton scattering and with magnetic fields through

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(*) The code 3*C* indicates the 3rd Catalogue of Radiosources of the Radioastronomical Observatory of Cambridge, England.

synchrotron radiation. An electron excess over positrons in the experimental data (fig. 7) in the region up to 20 GeV, in which electrons and positrons are both measured, shows that, beyond the production from the decay of pions and kaons (common to both e^+ and e^-, a large fraction of electrons has to be considered as coming from primary sources in our galaxy.

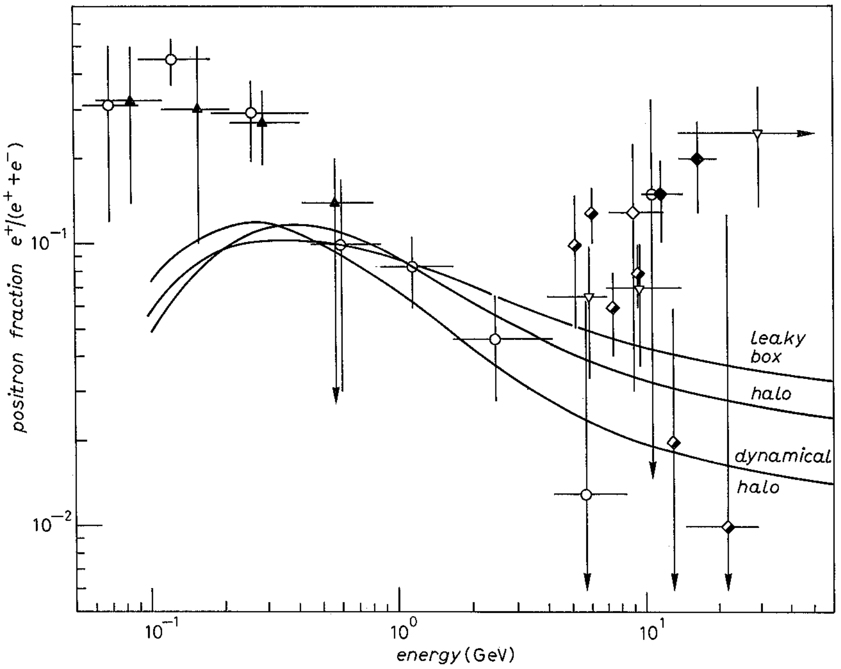

Fig. 7. – Measurements of the positron–to–total-electron ratio compared with the predictions of three cosmic-ray propagation models.

The problem of these sources, together with the acceleration mechanisms, still open, will probably find a solution with higher statistics collected in a larger energy range. Moreover, the positron measurement, by comparison with electrons or with the abundances of light nuclei (^{2}H, ^{3}He, Li, Be), will provide much information and can also give an estimation of the galactic magnetic field and of the containment time; however it is not effective for giving information on the possible extragalactic agglomeration of antimatter. In fact, owing to the radiative losses, high-energy positrons cannot propagate through large distances losing their energy in ($10^4 \div 10^5$) years and travelling less than hundred parsecs; thus if they are observed near the Earth they can only originate in a region dominated by matter.

3˙3. *Models and experimental situation.* – For antiprotons the situation is rather complicated because $\bar{p}$ can be produced through secondary processes

$\mathrm{p}+\mathrm{p}\rightarrow\mathrm{p}+\mathrm{p}+\mathrm{p}+\bar{\mathrm{p}}+$ *anything*, applied to the standard scheme of cosmic-ray propagation models which compute the expected $\bar{\mathrm{p}}$ flux starting from the proton flux, the antiproton production cross-section and the quantity of traversed matter.

As we will show in subsect. 4·1 the $\bar{p}/p$ ratio has the asymptotic value of $\lim \bar{p}/p \sim 4.6\cdot 10^{-4}$ for $E\rightarrow\infty$ with an expectation of values raising from 10^{-6} to 10^{-5} in the range $(0.2\div 5.0)$ GeV. This is inconsistent with the experimental data (with the exception of the few very recent ones [50, 51]) discussed below, showing the necessity of different models.

Due to the higher complexity of the antiproton problem in comparison with antinuclei and positrons, we will here present first the experimental situation, and then the attempts to fit the data leaving the detailed description of the models in sect. 4.

Table I shows the experimental situation with all the data collected up to

TABLE I. – *The present experimental situation on antimatter with balloon-borne observations.*

Rigidity (GV/c)	$\bar{\mathcal{N}}/\mathcal{N}$	Reference	Technique
Antiproton			
0.5 to 1	$(2.2\pm 0.6)\cdot 10^{-4}$	Buffington *et al.* (1981)	Annihilation Topology—Counter
<0.6	$<9\cdot 10^{-4}$	Apparao (1967)	Annihilation—Emulsion
<1.3	$<3\cdot 10^{-3}$	Aizu *et al.* (1961)	Annihilation—Emulsion
$3\div 6$	$<1\cdot 10^{-2}$	Bogomolov *et al.* (1971)	Permanent Magnet
5.6 to 12.5	$(5.2\pm 1.5)\cdot 10^{-4}$	Golden *et al.* (1979, 1984)	Superconducting Magnet
>16	<0.13	Durgaprasad and Kunte (1971)	Geomagnetic—Counters
<1	$<3.5\cdot 10^{-5}$	Golden *et al.* (1987)	Superconducting Magnet
<1	$<4.6\cdot 10^{-5}$	S. Ahlen *et al.* (1987)	Annihilation Topology—Magnet
Antihelium			
0.25 to 0.5	$<2.2\cdot 10^{-5}$	Buffington *et al.* (1981)	Annihilation Topology—Counter
$1\div 10$	$<1\cdot 10^{-3}$	Evenson (1972)	Permanent Magnet—Spark Chamber
$10\div 25$	$<8\cdot 10^{-3}$	Evenson (1972)	Permanent Magnet—Spark Chamber
$4\div 33$	$<5\cdot 10^{-4}$	Smoot, Buffington and Orth (1975)	Superconducting Magnets
$33\div 100$	$<2\cdot 10^{-2}$	Smoot, Buffington and Orth (1975)	Superconducting Magnets
<2.7	$<7\cdot 10^{-3}$	Aizu *et al.* (1961)	Annihilation Emulsion
<100	$<7\cdot 10^{-3}$	Damle *et al.* (1973)	Permanent Magnet—Emulsion

now by balloon-borne experiments of several different groups. Not all the data are compatible, as there are contradictions between some of them (*e.g.*, between Buffington [46] and Ahlen [50]), but is clear that with only 51 $\bar{p}$ collected summing all the experiment, it is difficult to discriminate between these results. This difficulty comes out because of the poor statistics and because no apparatus was significantly better than the others, as they were according to the case, without magnetic signature or without tracking calorimeter, or with a small acceptance.

There are also more experimental limits that come from indirect methods, *i.e.* the measurement of the ratio of pions to protons [52, 53] or the charge ratios of muons μ^+/μ^- [54] at mountain altitude and at sea level.

It has to be noticed that secondary production of $\bar{p}$ in the atmosphere makes this analysis very uncertain, as it dominates over the primary $\bar{p}$ and also the μ^+/μ^- ratio depends mainly on the correct propagation of muons in the atmosphere. But, in any case, we give these results because until now they are the only measurements at energies > 10 GeV. The results are given in table II and are shown in fig. 8 together with the experimental points from balloon flights.

TABLE II. – *Experimental limits on the $\bar{p}/p$ ratio obtained through indirect methods.*

Energy (GeV)	$(\bar{p}/p)\cdot 10^4$	Reference
$>10^3$	<500	Brooke and Wolfendale (1984)
>16	<820	Durgaprasad and Kunte (1971)
$100\div 200$	<700	Stephens (1985)
$(10^3\div 1.5\cdot 10^3)$	<1700	Stephens (1985)
$(10^4\div 1.5\cdot 10^4)$	<1000	Stephens (1985)
$>3\cdot 10^4$	<1400	Stephens (1985)

The upper limits shown here are with 67% confidence level.

In the future, new experiments will greatly help to get a more established scenario, but already now we can try to interpret the existent data.

The different models introduced to explain $\bar{p}$ production are presented with more details in the following section; here (in fig. 9) we present only how the models fit the data.

The fits correspond to the various models trying to explain the discrepancy from the standard leaky-box model (curve labelled 7 g/cm^2). The models differ in the amount of the trasversed matter by cosmic-ray protons, but are all based only on secondary production.

The curve labelled «21 g/cm^2» arbitrarily scales the proton path length by a factor of 3, in order to match the antiproton experimental values. Another proposed possibility is the so-called «closed (or lossless) galaxy model», in which

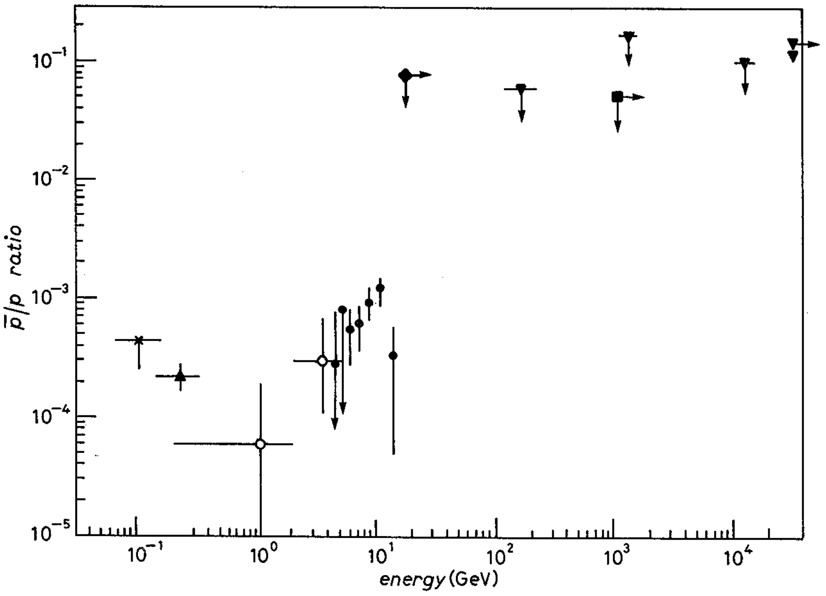

Fig. 8. – The ratio $\bar{p}/p$ as a function of kinetic energy. × Apparao *et al.* (1985), ▲ Buffington *et al.* (1981), ○ Bogomolov *et al.* (1987), ● Golden *et al.* (1984), ◆ Durgaprasad and Kunte (1971), ▼ Stephens (1985), ■ Brooke and Wolfendale (1964).

there are two cosmic-ray components, one of which is «old» and has traversed a great amount of matter.

Finally a model proposes that a portion of cosmic rays originates in sources surrounded by a thick shell of about 50 g/cm^2 of matter, *e.g.*, supernovae explosion in dense clouds.

The calculated slope of the antiproton spectrum from such models depends on the detailed assumptions of the chosen model itself. For example, the slope is predicted to be proportional to $E^{-2.7}$ if antiprotons are further accelerated after production at the source (collisional injection in fig. 9). All these models try to explain the high-energy data, but they are ineffective at low energy, because, unless there are mechanisms that significantly decelerate particles after their production, antiproton spectra resulting from high-energy interactions would be expected to exhibit a «kinematic cut-off» below ~ 1 GeV.

Despite the attempts, the proposed changements of the standard model of secondary production, do not seem to fit the existing data, showing that simple modifications of those models are unable to explain the observed points.

New and more exotic solutions have been investigated, among which neutron oscillation (n-$\bar{n}$ oscillation, if existent, could in principle explain the $\bar{p}$ excess because of the subsequent $\bar{n}$ decay into $\bar{p}$; we will examine this in subsect. 4·4), evaporation of primordial black holes (subsect. 4·5), photino pair annihilation (subsect. 4·6) and the generation of extragalactic antiprotons in antigalaxies in a baryon-antibaryon symmetric universe (subsect. 4·3).

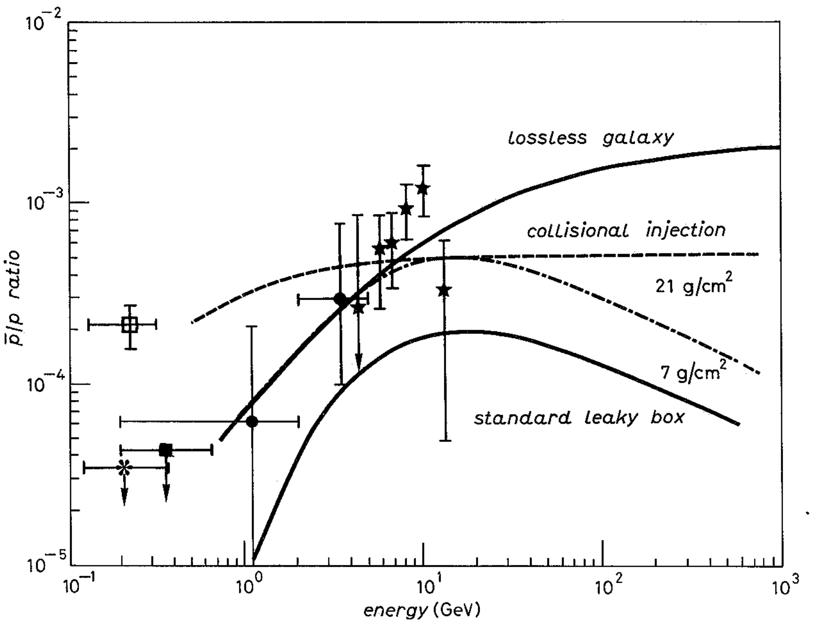

Fig. 9. – The experimental points are shown compared with the different models for the $\bar{p}/p$ ratio: cosmic-ray models cover the hypotheses of «lossless galaxy», production in the early dense phase of a Supernova explosion (collisional injection curve) and the standard leaky-box model with a traversed material density of 7 g/cm^2 and 21 g/cm^2. □ Buffington *et al.* (1981), ● Bogolomov *et al.* (1987), ★ Golden *et al.* (1984), ■ Ahlen *et al.* (1988), * Golden *et al.* (1987).

It is very important to get the highest possible statistics on antiproton research, because of the interest of the exotic mechanism suggested (fig. 10, 11). In fact, looking at the pictures, the contradictory experimental results can lead to completely different conclusions.

The Buffington point, for instance, is completely consistent with a photino annihilation, in contraddiction with the new limits of Golden and Ahlen, which are compatible with the existence of extragalactic antimatter sources or with primordial black-hole evaporation (Hawking effect). A very interesting hypothesis comes from the supersymmetric theories, which try to explain the very early universe and to unify the four foundamental forces of the nature.

The photino, the supersymmetric partner of the photon, has been proposed as a candidate for the dark matter in the universe and the observed flux of cosmic-ray antiprotons may result from the annihilation of photinos and antiphotinos.

As mentioned above (see fig. 11), photino annihilation results in antiproton spectra that cut-off at an energy corresponding to the photino mass; it is interesting to notice that the existing data are consistent with a photino mass of 15 GeV or greater.

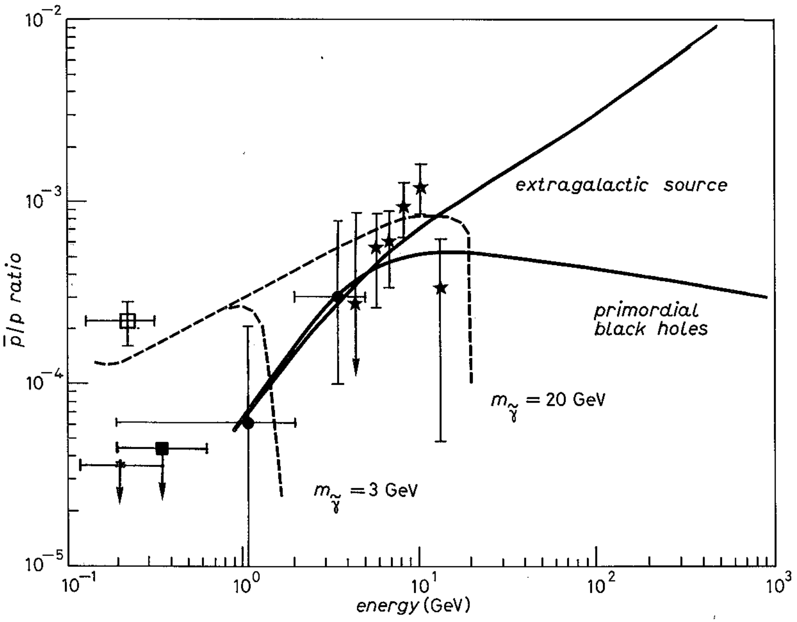

Fig. 10. – Same experimental points as in fig. 9 compared with more exotic models of production of antiprotons. Symbols are the same as fig. 9.

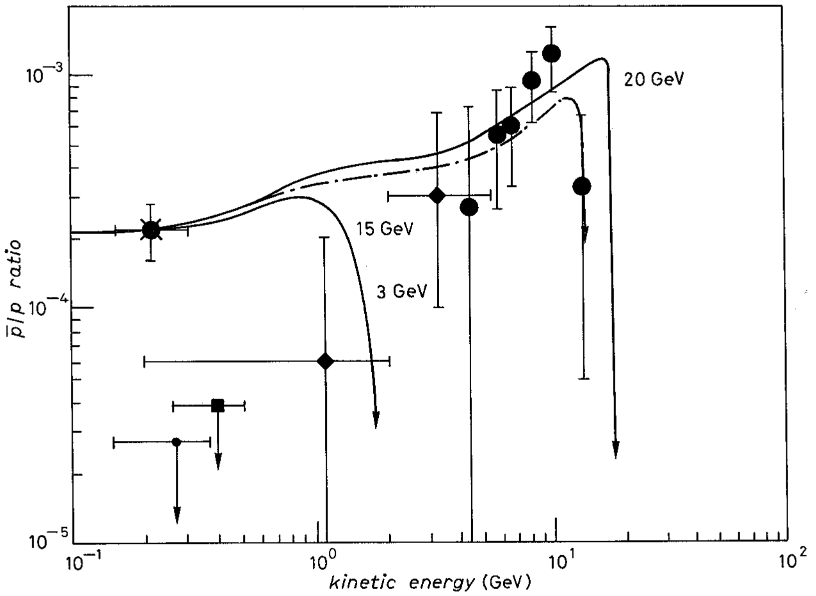

Fig. 11. – Calculated $\bar{p}/p$ ratios resulting from photino annihilation in the galactic halo compared with the available cosmic-ray measurements. Fits are shown for assumed photino masses of 3, 15 and 20 GeV. * Buffington *et al.* (1981), ◆ Bogolomov *et al.* (1987), ● Golden *et al.* (1984), ■ Ahlen *et al.* (1988), ● Golden *et al.* (1988).

If more precise measurements showed a sharp cut-off in the antiproton spectrum, this would be an indication for the existence of photinos or other Majorana fermions in the Galaxy. Gamma-ray lines may also be a signature of these particles.

4. – Antimatter in cosmic rays: the mechanisms.

In this section we present with some more details the models already used in the previous section trying to fit the experimental data. We will start with the standard calculation for the $\bar{p}$ secondary production and the ordinary models for the propagation in the interstellar space, then we will present more exotic hypothesized sources of antimatter.

4·1. *Secondary production of antiprotons.* – Many of the attempts to explain the detected excess of antiprotons in cosmic rays have pointed the attention to the secondary processes of production which are strictly related to the various proposed models of propagation and interaction of the cosmic rays in the interstellar gas; these theoretical models, together with the data on production cross-sections in p-p interactions coming from accelerator experiments, allow the evaluation of the energy spectrum of protons in cosmic rays and, consequently, of the $\bar{p}/p$ ratio which can be compared with the present experimental values. The first reliable calculation of the $\bar{p}/p$ ratio was made by Gaisser and Maurer [55] starting from the inclusive antiproton production via proton-proton interaction $\mathrm{p}+\mathrm{p}\rightarrow\mathrm{p}+\mathrm{p}+\mathrm{p}+\bar{\mathrm{p}}+\textit{anything}$ at laboratory energy threshold $\sim 7\,\mathrm{GeV}$ for the incident proton. The differential antiproton spectrum was then written as

$$\mathrm{d}N_{\bar{\mathrm{p}}}/\mathrm{d}E\sim(2\langle y\rangle/m_{\mathrm{p}})\int_E^\infty(\mathrm{d}\sigma_{\bar{\mathrm{p}}}/\mathrm{d}E)(E,E')(\mathrm{d}N_0/\mathrm{d}E')\,\mathrm{d}E'\,,\tag{23}$$

where $\langle y\rangle$ is the mean path length of interstellar hydrogen traversed (g/cm^2), m_{p} is the proton mass (in g), $(\mathrm{d}\sigma_{\bar{\mathrm{p}}}/\mathrm{d}E)(E,E')$ is the $\bar{\mathrm{p}}$ production cross-section (in cm^2) for producing an antiproton of energy E in the collision of a proton of energy E' with an interstellar hydrogen nucleus and, finally, $\mathrm{d}N_0/\mathrm{d}E'$ is the differential primary proton flux. Then, parametrizing from accelerator data the $\bar{\mathrm{p}}$ inclusive cross-section integrated over transverse momentum, one can write

$$F(x,E_0)=\int E(\mathrm{d}\sigma_{\bar{\mathrm{p}}}/\mathrm{d}^3p)\,\mathrm{d}p_\perp^2\,,\tag{24}$$

where E_0 is the incident proton total laboratory energy and x is the Feynman variable ($x\equiv 2p_\parallel^{\mathrm{c.m.}}/\sqrt{s}$). Finally, replacing E/E' with R in eq. (23), the $\bar{p}/p$ ratio can be evaluated as

$$\bar{p}/p \sim (2\langle y\rangle/m_p)\int_0^1 R^{\gamma-1}E(\mathrm{d}\sigma_{\bar{p}}/\mathrm{d}E)(E,E/R)\,\mathrm{d}R\,, \tag{25}$$

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 CERN-ISR data) leads to the asymptotic value for the $\bar{p}/p$ ratio

$$\lim_{E\to\infty}\bar{p}/p \sim 4.6\cdot10^{-4} \tag{26}$$

from which an expectation of values raising from 10^{-6} to $\sim 5\cdot10^{-5}$ in the range $(0.2\div5)$ GeV is expected (fig. 12).

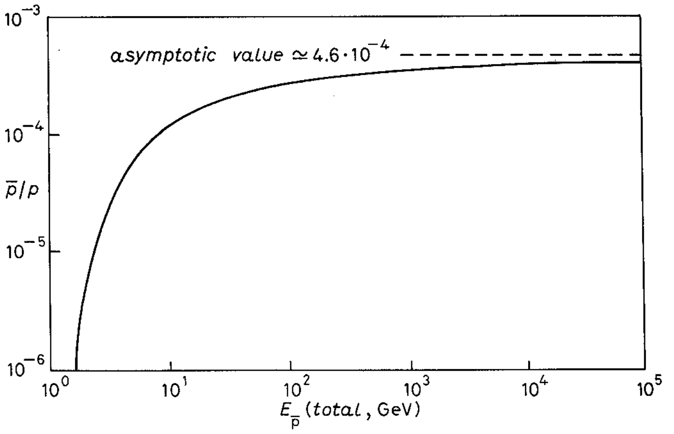

Fig. 12. – $\bar{p}/p$ *vs.* total antiproton energy (GeV) as a result of the calculations of Gaisser and Maurer.

The calculation of Gaisser and Maurer is based on the standard leaky-box model (SLBM) of cosmic-ray propagation with a mean escape length of 5 g cm^{-2} (and an interstellar medium composed entirely of hydrogen). The SLBM is the simplest way of representing how cosmic rays propagate in the Galaxy; in this model it is assumed that there is essentially equilibrium inside the Galaxy between the particles and their secondaries, both having a small but finite probability of escaping into extragalactic space after many collisions with the boundary of the Galaxy itself. If particles are subjected only to ionization losses and are not affected by other energy losses (or gains) during their interstellar travel, and if the gas density is assumed to be uniform all over the volume of cosmic-ray confinement, the only free parameter is the mean escape length λ_e, which may depend on energy or rigidity and velocity. However, the SLBM has shown not to be completely satisfactory, being not able to explain the experimental observation that the abundance ratio of secondary nuclei (*e.g.*, nuclei produced by the disintegration of heavier nuclei) to primary nuclei decreases with increasing energy, suggesting that high-energy cosmic rays traverse less amount of matter. In order to explain the variation of this ratio with energy and to understand the experimental data on $\bar{p}$, other models of propagation have been suggested: the modified leaky box model, the nested leaky box model, the closed galaxy model and the modified closed galaxy model.

In the modified leaky box model (MLBM), it is assumed that the confinement of cosmic rays in the Galaxy is energy dependent [56]; this means that, in the calculation of the equilibrium spectrum, the term relating to the loss of particles due to the leakage from the confinement volume must be corrected with an energy-dependent matter traversal parameter of the type

$$\lambda_e = \begin{cases} 22R^{-0.6} & \text{g cm}^{-2} \text{ of hydrogen for } R \geq 5.5\,\text{GV/c}, \\ 7.91 & \text{g cm}^{-2} \text{ of hydrogen for } R < 5.5\,\text{GV/c}, \end{cases}$$

where R is the rigidity. The spectrum of $\bar{p}$ calculated with this model, compared to the SBLM (and to the nested leaky-box model discussed below) and to the experimental data, is shown in fig. 13. It is evident from this figure that the

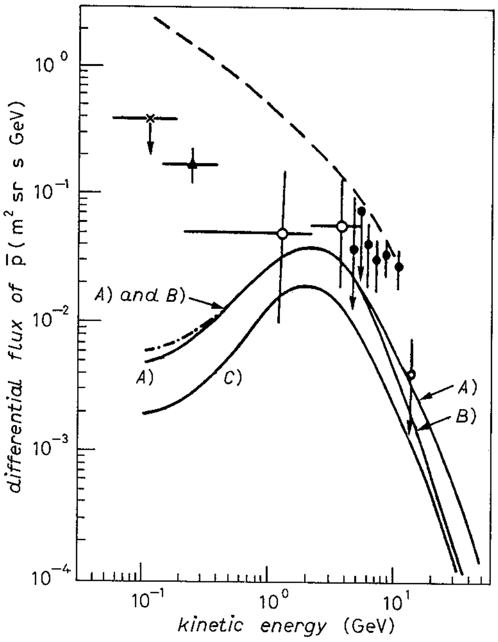

Fig. 13. – Differential spectra of $\bar{p}$ shown for different models of cosmic-ray propagation. Curve *A*) SLBM; curve *B*) MLBM, curve *C*) NLBM. Dashed curve is the demodulated spectrum of $\bar{p}$.

MLBM differs from the SBLM only at high energies, as only in this region the confinement becomes effective; moreover, the experimental points are much higher than those expected from this model; successive modifications of MLBM have been proposed in the attempt to better fit the data.

The nested leaky-box model (NLBM) puts the energy dependence of the matter traversal not in the galactic volume (as in the MLBM) but in the source region [57], assuming also that the subsequent transport in the interstellar medium and leakage from the Galaxy are energy-independent. Stephens and Golden [58] have assumed, applying this model to the production of $\bar{p}$, that the energy dependence in the source region behaves in the same way as the energy dependence in the galactic volume for the MLBM which depends on the parameter λ_e; assuming also a fixed confinement time inside the source for low-energy particles (and thus a velocity-dependent traversed matter) and propagating the $\bar{p}$ spectrum in the Galaxy using energy-independent confinement, the $\bar{p}$ spectrum can be calculated and the result is shown in fig. 13 (curve *C*)). Once again it is evident that the experimental data are not well fitted by this model, the discrepancy being even worse than the previous models; however, as we will see later, this model has not been completely ruled out, having been reproposed in combination with the closed Galaxy model.

In the first version [59] of the closed Galaxy model (CGM), cosmic rays are completely confined in the Galaxy until they are destroyed by interaction or by continuous energy loss processes. Later modifications, in order to explain the

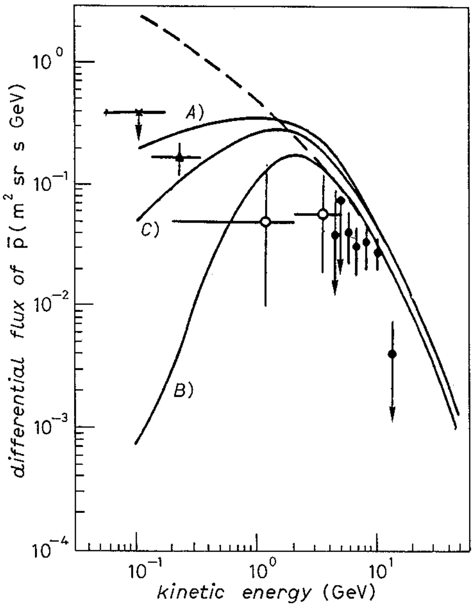

Fig. 14. – Same as fig. 13 in which predicted spectra of $\bar{p}$ based on CGM are shown. *A*) present calculation, *B*) Stephens (1981), *C*) Tan and Ng (1983).

observed energy dependence of the ratio of secondary-to-primary nuclei in cosmic rays [60], allowed the first calculation of the $\bar{p}/p$ ratio with this model [61] showing a value 10 times higher than that calculated with the SLBM. Other calculations of the $\bar{p}$ spectrum in the CGM have been perfomed [62, 63] and the results are shown in fig. 14 where it appears clear that at relativistic energies the CGM predicts values which are about a factor of 2 higher than the experimental points. Protheroe [64] made a calculation of the flux of secondary $\bar{p}$ using the version of the CGM proposed by Peters and Westergaard [60].

In this model, the sources of cosmic rays are located in the spiral arms of the Galaxy (called region «*S*»); the cosmic rays can leak out into an outer containment volume (called region «*H*»), but remain totally confined in the galactic halo without any possibility of escaping. Therefore, cosmic rays are formed by a «young» component contained in the region *S*, and an «old» component contained in the region *H*. The ratio of young-to-old component is proportional to $x_{\text{at}}/(K-1)\,x_{\text{s}}$, where x_{at} and x_{s} (expressed in g cm^{-2}) are, respectively, the attenuation mean free path and the escape mean free path for protons in spiral arms and *K* is the ratio of the total mass of interstellar gas in the Galaxy to that in the region *S*. The $\bar{p}/p$ ratio, calculated for $K = 50$, as a function of the energy and compared to the experimental points, is plotted in fig. 15 (curve *B*)), where the standard leaky box model (curve *A*)) is also shown.

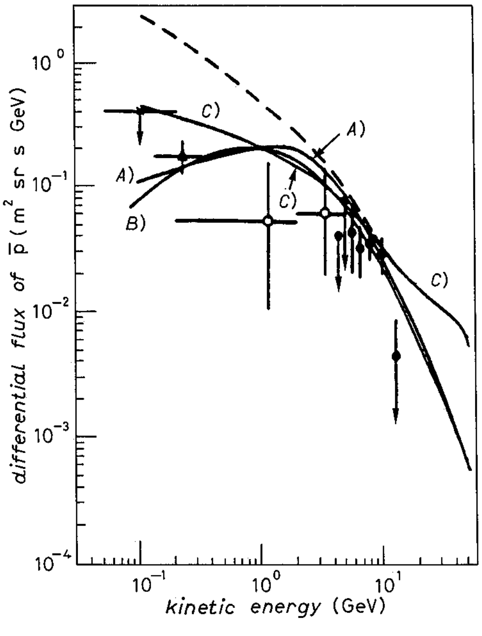

Fig. 15. – *A*) MCGM, *B*) Tan and Ng (1983), *C*) Dogiel *et al.* (1986). Same as fig. 13 showing the prediction of $\bar{p}$ spectrum from MCGM (curve *A*)), from nonuniform disk model (curve *B*)) and from acceleration in dense clouds (curve *C*)).

The last propagation model that we present, the modified closed Galaxy model (MCGM), is due to Stephens [65] and can be considered as a «half way» between the closed Galaxy model and the nested leaky-box model. In the MCGM, 50% of the observed cosmic-rays are of recent ($\sim 10^7$ y) origin and are propagated as in the NBLM; the other 50% remains totally confined. The $\bar{\text{p}}$ spectrum calculated with this model is shown in fig. 16. It is worth mentioning that this model can also explain the observations on e^+ and can estimate the abundance of deuterium at relativistic energies.

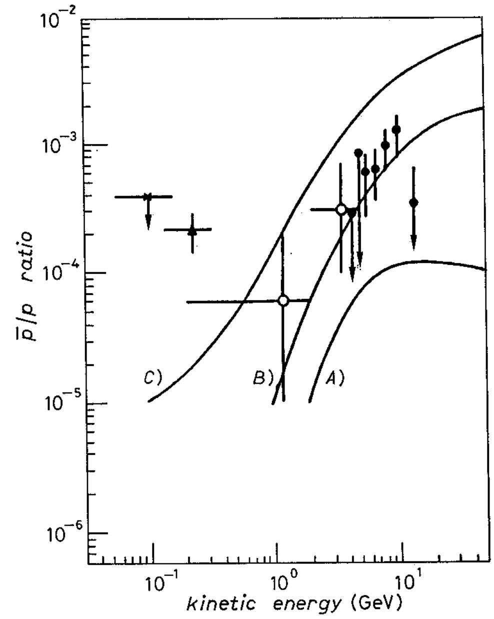

Fig. 16. – The ratio of $\bar{p}/p$ is plotted as a function of energy. Curves *A*) and *B*) are the calculated ratios based, respectively, on SLBM and MCGM with $K = 50$. Curve *C*) is expected from thick sources for $30\,\text{g}\,\text{cm}^{-2}$ of matter traversal (see ref. [68]).

As we have seen, all the models of production and propagation of cosmic rays so far presented allow the calculation of the $\bar{\text{p}}$ spectrum; on the other hand, the interpretation of the experimental data, with which the theoretical models have to be compared, must keep in consideration the effects of solar modulation; it is well known, in fact that the hydrodinamic outflow of ionized gas from the Sun results in a changement of the cosmic-ray intensity in the inner solar system during the years of solar activity; this phenomenon is particularly relevant in the low-energy region as shown, for protons, in fig. 17, so that the low-energy flux is drastically reduced and substantial corrections of the data are required.

4'2. *Antiprotons from thick sources.* – We have seen in the previous section that, in order to explain the energy dependence of the ratio of secondary-to-

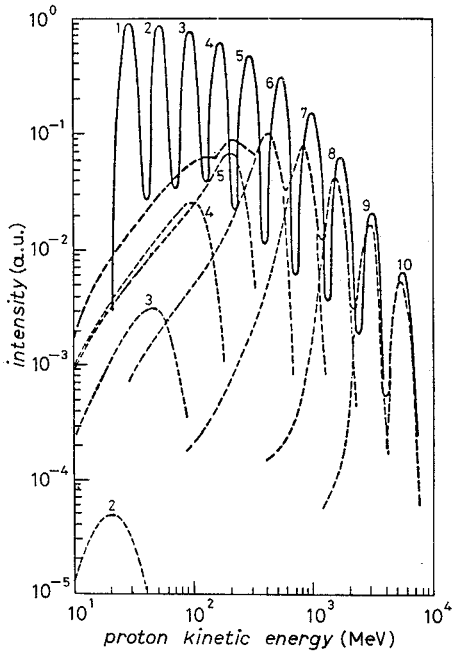

Fig. 17. – A series of essentially monoenergetic proton spectra in interstellar space (solid curve) and their resultant modulated spectra at 1 a.u. (dashed curve).

primary nuclei, a rigidity dependent parameter λ_e has to be introduced; however, this correction is not yet sufficient to completely account also for the observed $\overline{p}$ overabundance. But, as we know that the mean pathlength for nuclear inelastic collision at higher energies is $\lambda_p = 50\,g/cm^2$ for protons and only $\lambda_i = 35A^{-0.7}\,g/cm^2$ for nuclei with atomic mass A, we may assume that a certain part of cosmic-ray sources is composed of «thick sources», from which cosmic rays can escape traversing a very large amount of matter ($\sim (20 \div 30)\,g\,cm^{-2}$). Then it is possible to increase the ratio $\overline{p}/p$ altering only a little the secondary-to-primary ratio of heavier elements.

This model was first proposed by Cowsik and Gaisser [66], when the second *COS-B* catalog of high-energy gamma-ray sources was available, and the existence of ~ 25 gamma-ray sources with spectral index $\sim (1.5 \div 2.5)$ was established.

The authors supposed that, to generate such a spectrum, a cosmic-ray beam produced at the source must traverse about $50\,g/cm^2$ of material near the source, and they concluded that this can increase by a factor of three the $\overline{p}/p$ ratio derived from the SLBM.

Possible thick sources can be binary systems (see fig. 18), in which a neutron star acts like a proton accelerator and the companion star like the target, or supernovae explosions in dense clouds.

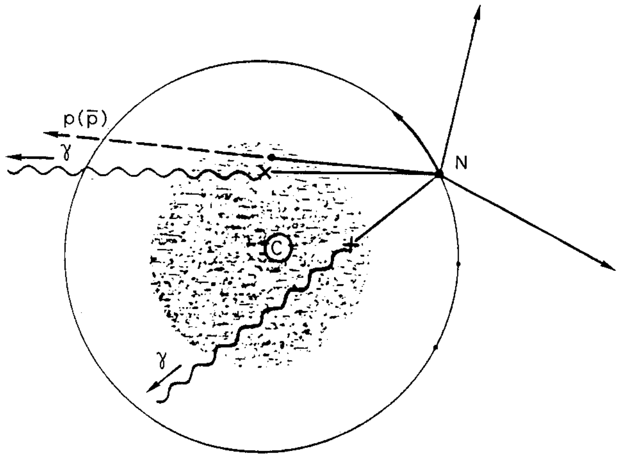

Fig. 18. – A pictorial view of a binary system formed by a neutron star (N) orbiting around its companion (C).

Also Cesarsky and Montemerle [67] reached the conclusion that the $\bar{p}$ flux could be understood if 40% of supernovae explode in dense clouds. Cesarsky and Lagage [68] re-examined the problem in 1985 and showed that with a «grammage» (matter traversed) $X \sim 30\ \mathrm{g/cm^2}$ they can fit the experimental point above 10 GeV; with this grammage, it is enough that the fraction of cosmic rays coming from thick sources be ~ 25% of the total cosmic rays, but for the 100 MeV point of Buffington a higher X ($X \geq 100\ \mathrm{g/cm^2}$) is necessary; thus they cannot account for all the experimental points at the same time (see fig. 19). Therefore,

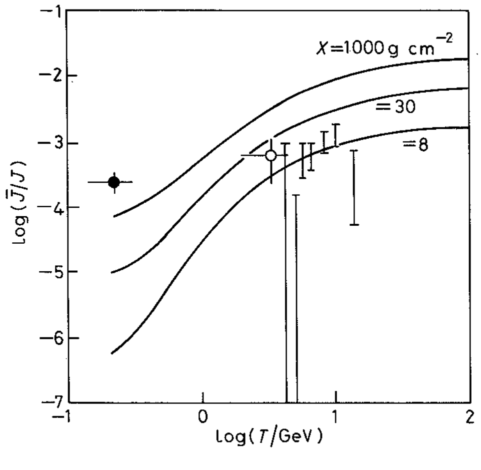

Fig. 19. – $\bar{p}/p$ flux leaving thick sources with grammages 8, 30 and 100 g cm^{-2}, compared with observations at different energies. The proton momentum spectrum is proportional to $p^{-2.1}$.

either the Buffington point is too high, or *ad hoc* hypotheses to better fit the data are required.

4'3. *The extragalactic antimatter model.* – The first extragalactic model, proposed by Stecker, Protheroe and Kazanas [69], shows that the experimental data are well fitted if a primary extragalactic component having $\bar{p}/p \simeq$ $\simeq (3.2 \pm 7) \cdot 10^{-4}$ (independent of energy), is added to the secondary contribution of the leaky-box model. The constant ratio is derived from the fact that the authors supposed for the extragalactic flux roughly the same shape as the galactic proton spectrum. Only at low energy (< 1 GeV) the ratio is a little lower due to the effects of $\bar{\text{p}}$ annihilation and solar modulation.

It has to be noticed that, probably (see subsect. 3'1) [70, 71], the extragalactic contribution of normal galaxies to the cosmic-ray flux is $\sim (10^{-5} \div 10^{-4})$ of the total and for active galaxies $\sim 10^{-3}$. If half of the extragalactic flux comes from antigalaxies, we obtain roughly the value taken for a good fit of the data.

In 1985, Stecker and Wolfendale [72] noticed that an extragalactic spectrum would be steeper than the galactic one for two reasons:

a) the ratio of secondary-to-primary nuclei in the cosmic radiation falls with the energy as $E^{-\delta}$, due to the trapping of the magnetic field (with the most probable value for $\delta \simeq 0.7$);

b) as recent studies on the sources of cosmic rays and the shock acceleration models show, the spectral index at the sources would be close to ~ 2.

So, since the proton spectrum falls as $E^{-2.7}$, from these considerations a rise as $E^{+0.7}$ of the $\bar{p}/p$ ratio is expected. In fig. 20 the curves for two values of δ, $\delta = 0.7$ and $\delta = 0.6$ are plotted; at high energy (> 1 TeV) it is quite interesting to notice that the values become comparable to the upper limits set by the pion-to-proton ratio and by the μ^+/μ^- ratio as well. Until now, these metods are too much indirect and Monte Carlo dependent to give a decisive contribution to the question.

In a previous work, Stecker and Wolfendale [73] first noticed another interesting thing, namely that, if we extrapolate both the flux of the galactic and extragalactic component (one with the spectral index $\gamma = 2.75$ and the other with $\gamma = 2$), at an energy of $\sim 10^5$ GeV the extragalactic component becomes comparable with the galactic one and then it becomes dominant (see fig. 21); the result is a flattening in the total spectrum at these energies, like the one that is claimed by some experimental measurements [74].

Finally, as we said in subsect. 3'1, the fact that the ratio $\bar{\alpha}/\alpha$ is smaller than the ratio $\bar{p}/p$, is not a problem for the extragalactic model if, as it seems, the bulk of the extragalactic cosmic-ray flux comes from active galaxies.

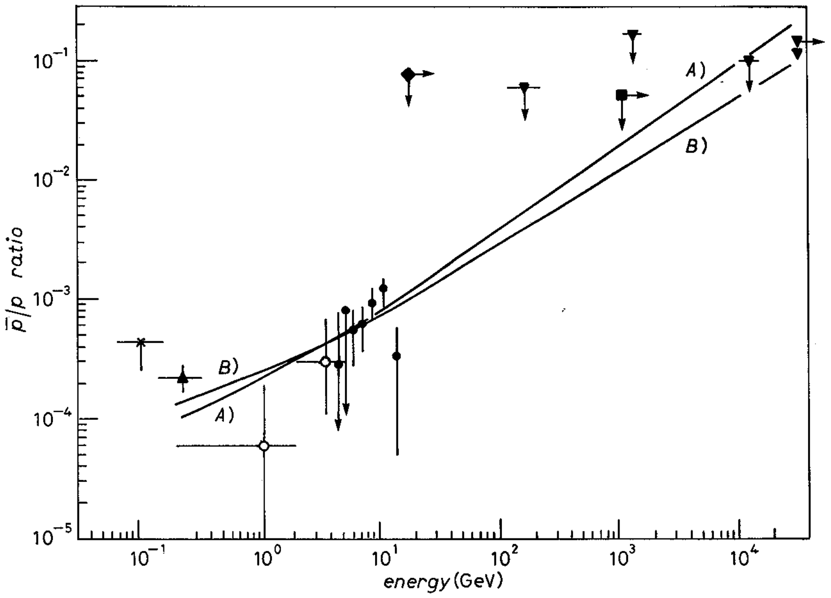

Fig. 20. – Calculated $\bar{p}/p$ ratio plotted as a function of energy according to the extragalactic models. Curves A) and B) correspond to different rigidity-dependent confinement in the galaxy, $\delta = 0.7$ (A)) and $\delta = 0.6$ (B)), respectively.

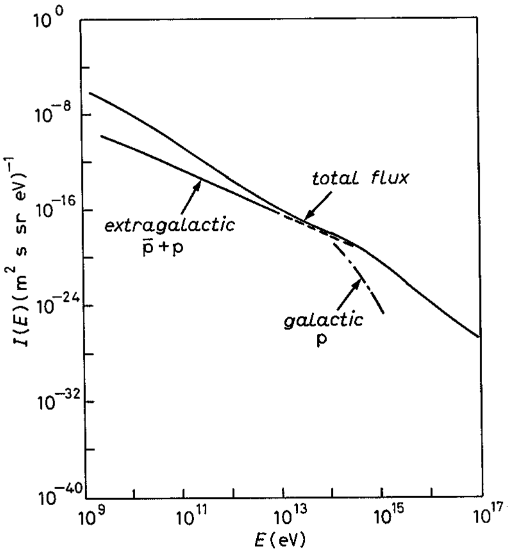

Fig. 21. – The effect of extragalactic primary protons and antiprotons on the total cosmic-ray spectrum. It can be seen that this model may account for the supposed flattening in the observed cosmic-ray spectrum near 10^{14} eV. $I(E)$ is the particle intensity in the units shown.

4˙4. *The neutron oscillation hypothesis.* – Another mechanism of production of antiprotons was proposed by Sivaran and Krishan in 1982 [75]. They noticed that many of the proposed models need some kind of deceleration of the antiprotons to reach the sub-GeV energies, whereas this is not needed if the neutron oscillation phenomenon exists. This was proposed as a consequence of Grand Unification Theories [76], and until now there are no significant experimental results due to the difficulty of such kind of experiments.

The neutron oscillation can play a role in the production of antiprotons whenever large fluxes of neutrons are involved as, for instance, in a supernova explosion, where about 10^{57} neutrons are released and the ratio neutron to proton can reach values between 2 and 8 [77]. Sawada *et al.* [78] suggested the possibility that neutrons transform in antineutrons in interstellar space because of oscillations and then decay in antiprotons.

For the parameter of the $n\bar{n}$ oscillation one can use only a theoretical estimation that predicts a characteristic time between 10^5 and 10^7 s with an associated transition energy $\Delta\rho$ of about 10^{-20} eV; then the $\bar{n}$ decays in an antiproton through β decay.

In the presence of a magnetic field there is a splitting of the neutron energy level $\Delta E = g\mu B$, where g is the anomalous gyromagnetic ratio, $\mu = e\hbar/2m_n c$ and B is the intensity of the magnetic field.

The transition rate is

$$\frac{\bar{n}}{n} = \frac{1}{2}\left[\frac{\Delta\rho}{\Delta E}\right]^2 . \tag{27}$$

The problem is the magnetic field B. If the value of 10^{-7} Gauss for the interstellar field is used, with $\mathrm{D}\rho \simeq \hbar/\tau \simeq 10^{-32}$ erg, $\mathrm{D}E = 9 \cdot 10^{-24} B$, we have $\bar{n}/n \simeq 10^{-4}$ and with $n/p \sim 10$, we have $\bar{p}/p \sim 10^{-3}$. Assuming 10^{57} n for every supernova explosion, this means 10^{54} antiprotons for each supernova, while for $\bar{p}/p$ of 10^{-4} also in the low-energy region, one needs $\sim 10^{55}$ antiprotons. Therefore, in this case a tenth of supernova explosions can fully account for the antiproton flux. If B is 10^{-6} Gauss, then $\bar{p}/n$ would be 10^{-6} and this requires more than 1000 supernova explosions; thus, with an explosion rate of one explosion in 10 years, we need $\sim 10^5$ y to reach the same number of antiprotons, and we think that in this case more studies about the propagation of antiprotons would be necessary.

4˙5. *Antiprotons from black holes.* – In 1974, Hawking [79] suggested a model which, taking into account the quantum-gravitational effects in the evaluation of the black holes (BHs), postulated that BHs emit radiation-losing mass. This effect can be considered negligible but with the significant exception of the last 0.1 s (in which a BH could radiate as much as 10^{30} ergs) in a finite life of a BH of 10^{71} $(M_{\odot}/M)^{-3}$ s. Due to the fact that the lifetime of a BH as massive as the Sun is longer than the calculated Universe age, one should see no effect of the final explosion, but in a previous work [80] Hawking suggested that small BHs (the so-called mini black holes, MBHs, with an order of magnitude smaller than the Sun) would have been created by fluctuations in the early Universe; these MBHs can explode somewhere in the Universe (up to now, any mini primaeval BH of mass smaller than 10^{15} g would have evaporated and exploded). Without any further detail on BH theory, which exceeds the limits of this paper, what is interesting to see is that several authors [81-83] hypothesized that, during the explosive phase, BHs composed of pointlike particles such as gluons and quarks can be a source of antiprotons. The spectrum of the emitted $\bar{\mathrm{p}}$ was evaluated by Kiraly *et al.* [72] by making use of the estimated fraction of energy going into different particles and of the emission rate as a function of MBHs mass; the calculated spectral shape is of the type

$$J_{\bar{\mathrm{p}}}(E_{\mathrm{K}}) = A(E_{\mathrm{K}} + E_0)^{-3.0}\,\bar{\mathrm{p}}\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1},$$

where A is a constant and $E_0 = 1$ GeV (see fig. 22). The rate of the BH explosion would be, according to the upper limit fixed by radio burst, of $2 \cdot 10^{-9}/(\mathrm{pc}^3\,\mathrm{y})$ [84],

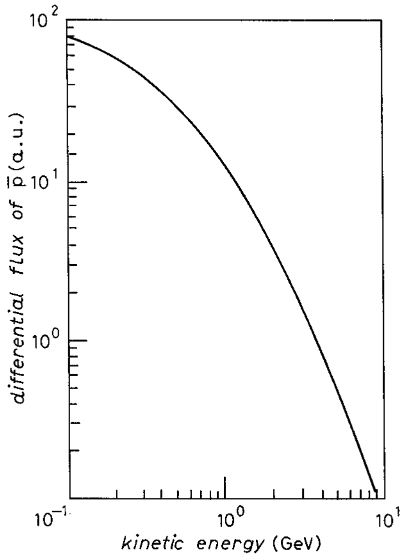

Fig. 22. – Differential antiproton flux *vs.* kinetic energy in the model of production from mini black holes.

too low to account for the observed $\bar{\mathrm{p}}$ flux, because, in order to do that, it must be at least 10^{-3} per $(\mathrm{pc}^3\,\mathrm{y})$. But, if instead of the radio burst we compare the BH explosion rate with another upper limit set by the Čerenkov atmospheric technique, the observed p̄ flux[85] seems compatible. Another process, involving BHs, is based on a model proposed by Penrose[86]. In this process, the energy is extracted from rotating BHs by the disintegration of the particles entering the ergosphere and Stephens[87] showed the possibility of the creation of $\mathcal{N}$-$\bar{\mathcal{N}}$ pairs in the strong gravitational field of the BH. Then the particle which escapes will bring an extra energy subtracted from the BH rotation energy.

4·6. *Photino's annihilation for antiproton production.* – The attempt of unification made through supersymmetric theories implies the existence of supersymmetric fermions with zero baryon and lepton numbers[88], fermions decaying in the lightest supersymmetric particles: photinos or gluinos.

The photino ($\tilde{\gamma}$) would be the supersymmetric partner of the photon and this

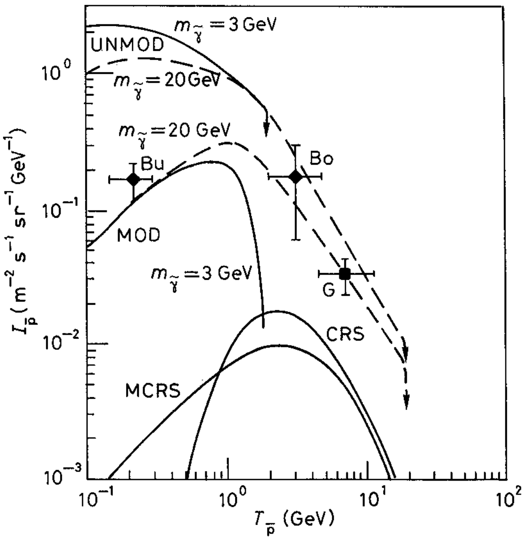

Fig. 23. – Unmodulated and modulated spectra for 3 and 20 GeV mass photino annihilation, compared to the data and to cosmic-ray secondary production (CRS) and modulated cosmic-ray secondary production (MCRS).

stable particle (spin 1/2), produced in the Big Bang, should be able to account for the dark matter in the Universe; in this picture, the Universe would be a photino-dominated Universe and the problem of p̄ overabundance would be resolved because of the annihilation of photinos and antiphotinos producing g, e^+ and p̄. Several theories[89, 90] have made a calculation of the antiproton's energy spectrum. In 1985, Stecker, Rudaz and Walsh[90] showed that, for photino masses above 10 GeV, the expression for the antiproton flux becomes

$$I_{\bar{\mathrm{p}}} = 4.6 \left(\frac{15\,\mathrm{GeV}}{m_{\tilde{\gamma}}}\right)^3 \left(\frac{30\,\mathrm{GeV}}{m_{\mathrm{sp}}}\right)^4 \beta_{\bar{\mathrm{p}}} \cdot \left[\exp\left[\frac{-11 E_{\bar{\mathrm{p}}}}{m_{\tilde{\gamma}}}\right] + 0.003 \exp\left[\frac{-2E_{\bar{\mathrm{p}}}}{m_{\tilde{\gamma}}}\right]\right] \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1},$$

where $\beta_{\bar{\mathrm{p}}}$ is the velocity of $\bar{\mathrm{p}}$, $m_{\tilde{\gamma}}$ and m_{sp} are the masses of $\tilde{\gamma}$ and of the supersymmetric fermions which decay to $\tilde{\gamma}$, respectively. From this equation, the calculated spectra, modulated for solar wind, for two different masses of the photino ($m_{\tilde{\gamma}} = 3\,\mathrm{GeV}$, $m_{\tilde{\gamma}} = 20\,\mathrm{GeV}$) are given in fig. 23. This figure shows the contribution that the $\tilde{\gamma}\bar{\tilde{\gamma}}$ annihilation can in principle give to the $\bar{\mathrm{p}}$ production in the attempt to explain the antiproton overabundance. In a recent (1988) paper, Rudaz and Stecker [91] revisited the problem of dark-matter annihilation for both antiprotons and positrons (and gamma-rays). The results are shown in fig. 24, 25. The calculations, made before the new experimental results of Ahlen *et al.* [50] and of Golden *et al.* [51] (see subsect. 3˙3) had been published, are consistent (for $\bar{\mathrm{p}}$) with data for a $m_{\tilde{\gamma}} = 15\,\mathrm{GeV}$, but inconsistent with the upper

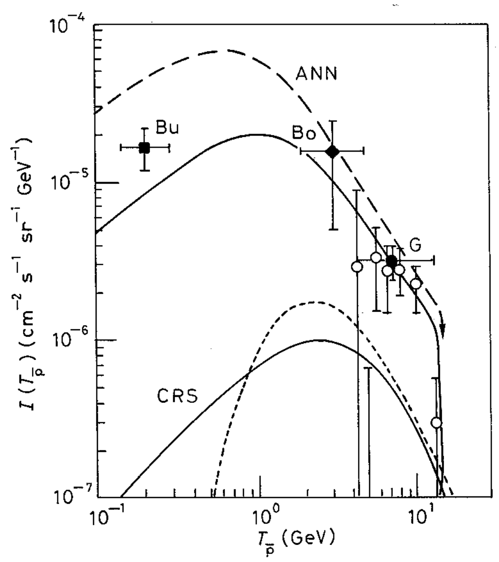

Fig. 24. – Interstellar (extra-solar system) cosmic-ray antiproton flux from $M = 15$ GeV dark-matter fermion annihilation (*dashed line*) and that spectrum modulated by the solar wind (*solid line*) compared with the observed fluxes measured by Buffington *et al.* (1981) (Bu point), Bogolomov *et al.* (1987) (Bo points) and Golden *et al.* (1984) (G points). Lower curves, marked CRS, show the predicted flux of antiprotons as cosmic-ray secondaries produced by cosmic-ray collisions in interstellar space.

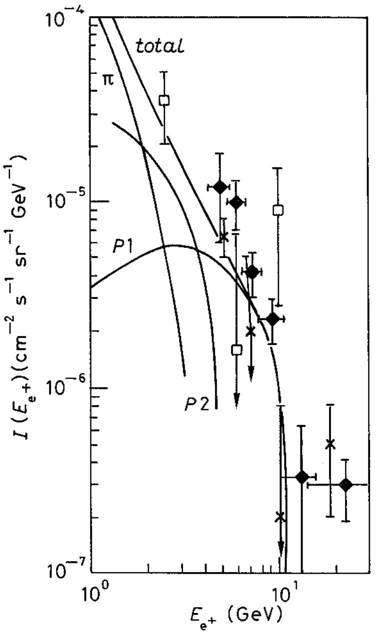

Fig. 25. – Cosmic-ray positron spectra from prompt first-generation ($P1$), prompt second generation ($P2$) and pion decay positrons (π) produced following galactic annihilations of 15 GeV fermions. Flux is shown for the value $k = 1.45$ chosen to fit the antiproton data. Total spectrum and flux are also shown along with the data. Open squares are from Faneslow *et al.* (1969), crosses are from Buffington *et al.* (1975) and filled diamonds are from Golden *et al.* (1986).

limits of the new experiments. In the absence of a much better statistics, the question if photino annihilation is or not a model really able to explain the $\bar{\mathrm{p}}$ spectrum, remains open as well as the reverse problem if $\bar{\mathrm{p}}$ and e^+ spectra are or not an indirect proof of $\tilde{\gamma}$ existence.

5. – The future of the antimatter search.

In this section we present some selected experiments and projects (without search of completeness) which can give a clear idea on what at present is going on in the field of antimatter researches. In some of these experiments the authors of this paper are directly involved. We choose to present an experiment of the last generation of classical balloon flights (the MASS experiment); the most ambitious initiative to search for antimatter (the ASTROMAG-WIZARD experiment on the Space Station) and, finally, a particularly significant future option (the detector on polar orbit).

5˙1. *Future experimental programs. The experiment* MASS. – The MASS (matter-antimatter space spectrometer) apparatus is a second-generation detector, able in principle to solve the problem of the presence of low-energy (≤ 1 GeV) antiprotons, which is still open because of the contradiction between the existent experimental data, as we have seen previously.

The apparatus (fig. 26) is composed of track detection chambers, time-of-

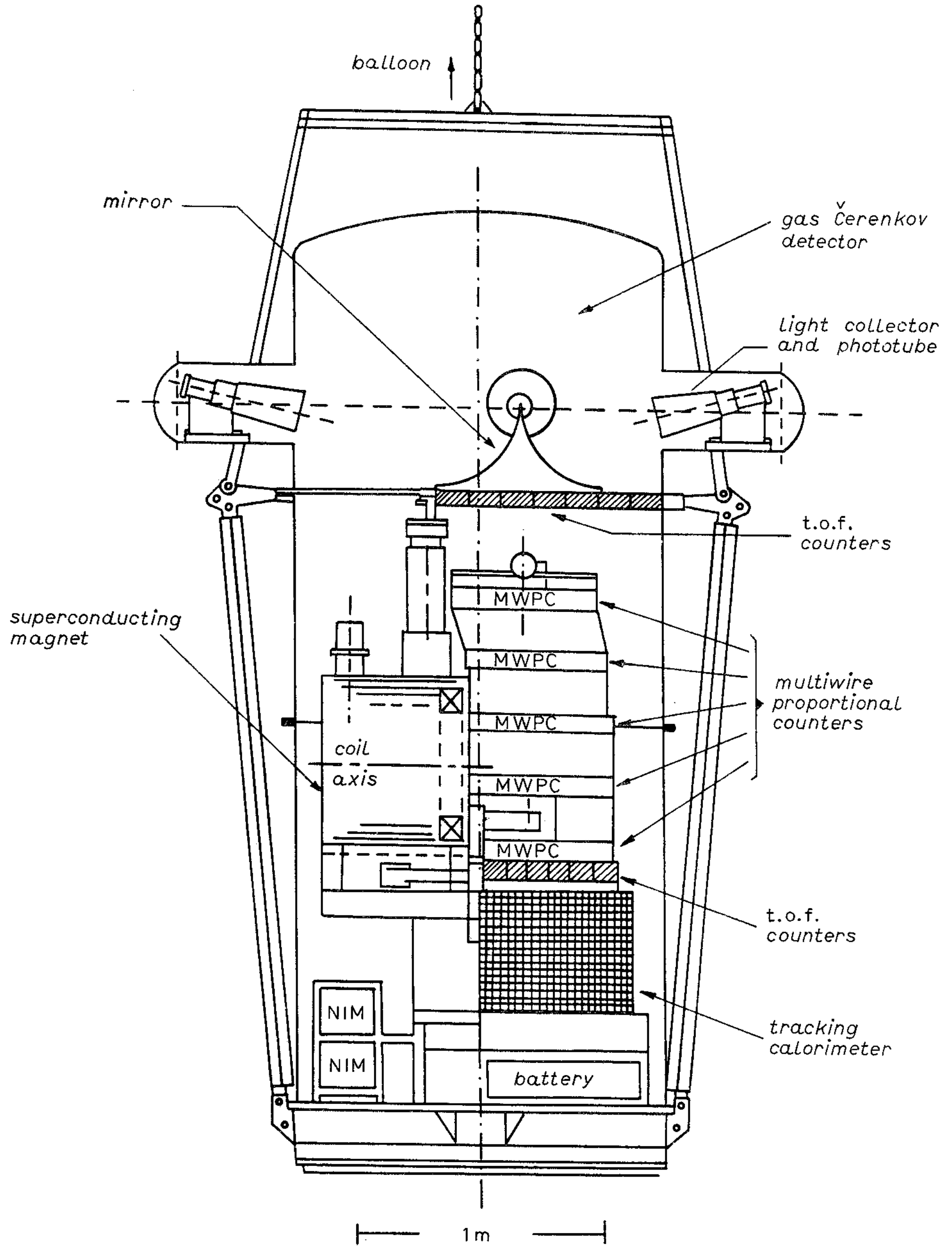

Fig. 26. – Set-up of the apparatus MASS for the balloon flight.

flight, superconducting magnet, Čerenkov, and is basically the same apparatus of Golden [92] used to collect the data already presented in sect. 3˙3 but with an important upgrading: a fifty-plane tracking calorimeter, made by 3200 brass streamer tubes coupled with an equal number of strips for the induced signals, that seems the best device to work in connection with a magnetic spectrometer, in order to detect cosmic antiprotons [93].

The special features of an apparatus designed for balloon flights place several constraints that must be taken into account in the design and construction of the calorimeter; the most important are due to the total weight that can be carried, to the dimensions of the whole apparatus and to the limitations on power consumption. Moreover, the peculiarity of the experimental search of antiprotons in cosmic-rays puts some specific requirements that have to be fulfilled with a calorimeter providing not only an energy measurement, but also an accurate reconstruction of the annihilation vertex and of the outcoming tracks. In fact, an antiproton annihilation at rest takes place with a typical pattern, the annihilation star, in which the tracks outcoming from the vertex show an isotropic configuration due to momentum conservation; another configuration is also possible, the annihilation in flight, in which secondary particles are boosted in the forward direction. Therefore, the detection of an energy deposit greater than the kinetic energy of the incoming particle (the $\bar{\mathrm{p}}$ annihilation contributes with two proton masses to the total energy) and the visualization (by means of track fitting algorithms) of a simultaneous annihilation star would be clear $\bar{\mathrm{p}}$ signatures, especially for low-momentum incoming particles.

The whole apparatus is designed to work transported by a flying balloon at an altitude of about 45 km, in a Canadian area closest as possible to the magnetic north-pole to minimize the geomagnetic cut-off due to the terrestrial field.

The aim of the experiment MASS is to get a clear antiparticle signature (for its completeness, the apparatus is able to detect antiprotons and positrons using much information: time of flight, charge, tracks, momentum, energy released, topology) coupled with a good statistics due to the dimensions which are quite big for a balloon-borne experiment ($(3 \times 1 \times 1)\,\mathrm{m}^3$) for a total weight of ~ 2.5 t). In this way, the MASS collaboration hopes to get the best possible measurement for a balloon-borne apparatus: to confirm or to disprove the $\bar{\mathrm{p}}$ presence at low energy and check some of the theoretical models before that the Space Station will be operative.

5˙2. *The* ASTROMAG-MAS *experiment on the Space Station.* – Unlike the MASS balloon detector, the ASTROMAG-MAS experiment [94] is a completely new opportunity for a much more powerful apparatus. Placed on a 28° degree orbit at an altitude of about 500 kilometers, the Space Station (fig. 27) will allow the installation of the ASTROMAG facility.

The ASTROMAG facility (essentially a superconducting magnet) will be the core of two experiments: MAS (matter-antimatter spectrometer) reviewed in

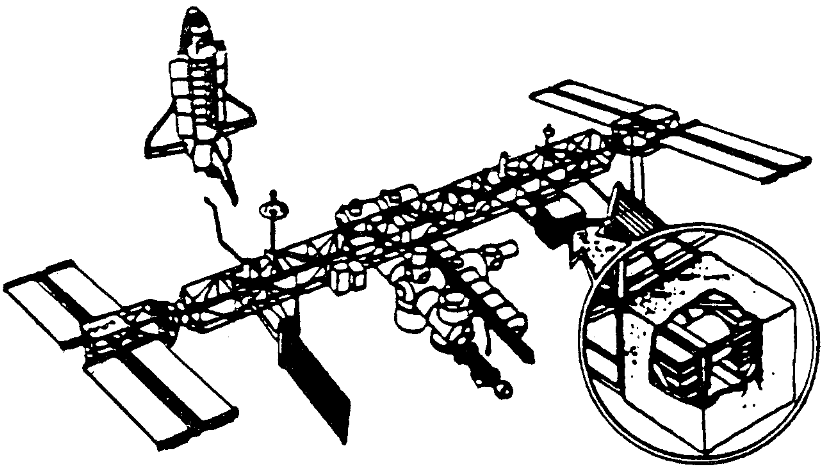

Fig. 27. – Schematic view of the position of ASTROMAG on the Space Station.

this paper, and CRIS (cosmic-rays isotope spectrometer) placed on the other side of the magnet (fig. 28).

For MAS experiment an apparatus called WIZARD [95] has been proposed.

Primary goal of the WIZARD apparatus will be to try to answer the question of the degree to which the universe contains antimatter. But the apparatus is a general-purpose one able to search for many phenomena.

Experimentally this is the WIZARD program:

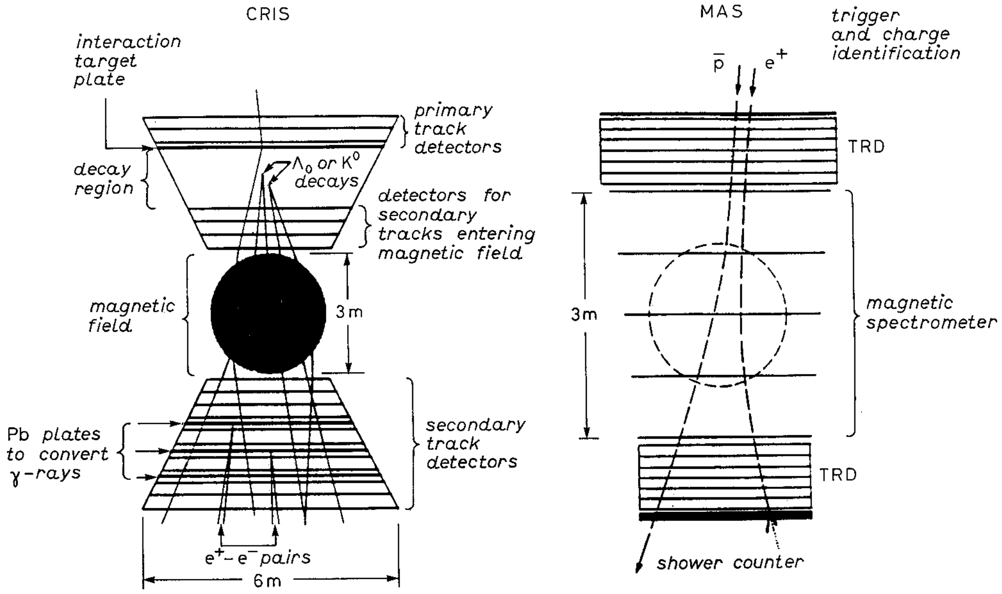

Fig. 28. – Layout of CRIS and MAS apparatus for ASTROMAG.

1) Search for antinuclei (galactic or extragalactic) with a never achieved before sensitivity.

2) Confirmation and search for the origin of the overabundances of antiprotons in cosmic rays.

3) Search for the possible confirmation of the hypothesis related to the dark matter, like photino annihilation, studying the antiproton spectrum.

4) Search for possible confirmations of exotic processes like the evaporation of primordial black holes or the antigalaxies contribution studying the antiproton and positron spectrum.

5) Search for production mechanisms of positrons and antiprotons in nucleon interactions taking place in interstellar medium and in cosmic-ray sources.

Schematically, the WIZARD apparatus will be optimized for the measurement of protons, antiprotons, electrons and positrons, but it will be suitable also to measure high-energy gamma-rays, light nuclei and antialphas.

The apparatus will be composed by a transition radiation detector, a tracking chamber system, a shower counter and scintillation counters; the geometric factor is about $0.1\,\mathrm{m}^2\,\mathrm{sr}$ for a $R_{\max} > 2\,\mathrm{TV}$.

To give an idea of the technological improvements that such a kind of apparatus also achieves, we will briefly describe the main features of the calorimeter.

The identification of positrons and their separation from protons and light nuclei requires a well-segmented calorimeter. The calorimetric measurement with tracking capability in order to give the annihilation pattern is also a powerful tool in the search for antimatter in space. Moreover, a good energy-resolution calorimeter extends the gamma-ray search to those γ that have not been converted in the upper part of the magnetic telescope. Silicon detector technology can be an ideal tool for these purposes [96]. The electromagnetic calorimeter foreseen for WIZARD has to cover an area of $\sim(1 \times 1)\,\mathrm{m}^2$. The weight limitation ($\sim 1\,\mathrm{t}$) allows a maximum thickness of ~ 10 radiation lengths (X_0) using lead absorber. The silicon detectors constitute the sensitive planes of the calorimeter. The planes are realized connecting the silicon strip wafer (SSW) in order to build X and Y planes. The connection of the SSW is done through a Kapton printed board electrically connected by pressure to the strip in order to avoid delicate bounds. The optimization of the sampling layers and of the dimension of the strip is done on the basis of the power and read-out constraints. The number of channels will be kept below 10^4 to stay in the power limits. The dimension of the strip will vary from $\sim 2\,\mathrm{mm}$ at the calorimeter entrance to $(3 \div 4)\,\mathrm{mm}$ after the shower maximum ($\sim 5X_0$). Considering a sampling step of 1/3 of radiation length X_0 the silicon detector planes will be 30 for the total thickness of $10\,X_0$. The X and Y planes will be alternate every 1/3 of X_0. The first fifteen planes ($5X_0$) will be equipped with 2 mm strips and the remaining with $(3 \div 4)$ mm strips. An accuracy of $\sim 5\,\mu$m can be achieved for position measurements carried out by strip silicon detectors.

The electronic read-out will be done with VLSI preamplifer sampler and hold circuit available in chips of 128 channels. Zero suppression and logic decision before trasmission will be done with local intelligence realized with microprocessor. Silicon calorimeters are used in places where special conditions have to be fulfilled (presence of magnetic field, tight-space requirement, vacuum, etc). The feasibility and the advantages of a large Si calorimeter for future high-energy hadron machines, such as the large hadron collider (LHC) at CERN and the superconducting super collider (SSC) in the USA, are under study, and experimental tests are being carried out by several collaborations.

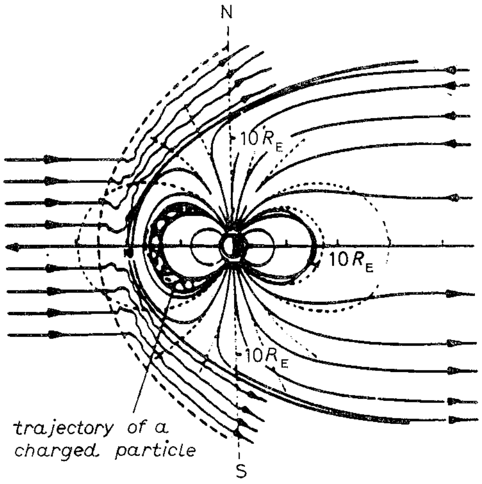

Fig. 29. – Trajectories of charged particles in the terrestrial magnetic field.

5·3. *A future option: the polar detector?* – ASTROMAG will be a very powerful multi-purpose apparatus and a fundamental step in antimatter search mainly because of its capability to take data for years instead of days as in balloon-borne experiments. But ASTROMAG yet is not the best that can be done for specific antimatter research because of the orbit. In fact, owing to the 28° inclination of the space station, the geomagnetic cut-off due to the magnetic terrestrial field (fig. 29) makes the study of the low-energy regions of the spectrum ($< (3 \div 4)$ GeV/nucleon) for antiproton and antihelium impossible. Now there are reasons to prefer to search for antimatter at low energy because of both physics and technology.

The physical reasons are related to the $\bar{\text{p}}$ production mechanism and to the $\overline{\text{He}}$ abundance. There should not be secondary antiprotons produced by colliding protons below $\sim 1.1\,\text{GeV/c}$ due to kinematics (unless energy degradation mechanisms occur), so that low-energy $\overline{\text{p}}$ would be produced by one or more of the exotic mechanisms presented before. For the hypothetic $\overline{\text{He}}$ (that can be only primary) its rarity suggests to extend the research in the low-energy region under the hypothesis that the $\overline{\text{He}}$ flux decreases increasing the energy. The technological reason is also very important being related to the necessity of detecting an eventual $\overline{\text{He}}$ with no ambiguity at all because its rarity makes it impossible to get a significant statistics. Now a low-energy antihelium is more easily detectable in comparison with a more energetic one because:

i) the annihilation star can be fully contained in a tracking calorimeter showing its clear signature;

ii) it is easier to make a significant comparison between the low momentum detected by a magnetic spectrometer and the much higher energy released in the calorimeter (due to the contribution of the annihilation).

Thus, the full containment (possible only at low energy) makes the experimenters sure of the signature even if very few $\overline{\text{He}}$ are detected (in fact even the detection of a single $\overline{\text{He}}$ would be a major result).

From these considerations it comes out that an apparatus able to cover a great energy range from 1 to 500 GeV using WIZARD-like detectors (TRD, $\mathrm{d}E/\mathrm{d}x$, magnetic field) for more energetic particles and a tracking silicon calorimeter for the less energetic ones, placed in a polar orbit to reduce the cut-off, would be the best for systematic antimatter research.

Another possibility (depending on launch availability) could be an apparatus placed in a very high orbit, away from 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 (European Space Agency and National Space Agencies like the Italian ASI) to deal with, getting the goal to use European launchers and satellites to achieve very significant results, possibly in close cooperation with American partners.

6. – Conclusions.

The question of what amount of primary antimatter exists in the universe is still open. At the present stage of the research, no claims for a really well established scenario can be accepted, because of the incertitude of the very few existent experimental data.

In fact, we can speculate, with some experimental arguments, only about our galaxy or, maybe, about our cluster of galaxies, while the extrapolations over greater dimensions are still very difficult. Nevertheless, the very useful theoretical work of many physicists has led to pictures of the highest interest (concerning the mechanisms of propagation, the exotic hypothesized sources, the existence of new elementary particles and new cosmological scenarios) in such a way that new experiments, discriminating between models, can lead to radical and very interesting changements in our conception of the physical world.

What we need now are experimental data and the next $(10 \div 12)$ years will maybe provide a beginning of solution, but we need also to understand more and more about our «observable» universe and, first of all, if it is coincident or not with the universe conceived in the traditional philosophical way as the «whole».

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G. Strinati – Application of the Green's functions method for the study of the optical properties of semiconductors.
I. R. Yukhnovs'kii – Solution of the three-dimensional Ising model for description of the second-order phase transition.
N. Kim, G. C. La Rocca, S. Rodriguez and F. Bassani – Inversion asymmetry and magneto-optics in zinc-blende semiconductors.
R. Badii – Conservation laws and thermodynamic formalism for dissipative dynamical systems.

FORTHCOMING PAPERS (in alphabetical order)

M. BATTEZZATI – The Legendre transformation and complementary relations for second-order Hylleraas-type homogeneous functionals.

D. BOYANOVSKY and C. M. NAON – An introduction to conformal invariance in quantum field theory and statistical mechanics.

R. BRUZZESE, A. SASSO and S. SOLIMENO – Multiphoton excitation and ionization of atoms and molecules.

I. L. BUCHBINDER, S. D. ODINTSOV and I. L. SHAPIRO – Renormalization group approach to quantum field theory in curved space-time.

P. CHIAPPETTA – High-energy precision tests beyond standard model.

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G. P. FILIPPOV – Microscopic theory of collective resonances of light nuclei.

P. FURLAN, G. M. SOTKOV and I. T. TODOROV – Two-dimensional conformal quantum field theory.

P. GIANNOZZI, G. GROSSO and G. PASTORI PARRAVICINI – Theory of electronic states in lattices and superlattices.

L. REGGIANI and V. MITIN – Recombination and ionization processes at impurity centres in hot electron semiconductor transport.

C. ROSSETTI – On the bound states of power law central potentials.

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