Searches for Cosmic Antimatter

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Abstract

We know from experimental high energy physics that whenever matter is created, an equal amount of antimatter is also created. However, we live in a large region of the universe where the antimatter can not constitute more than a very small fraction of the total mass. The cosmic antimatter problem has been addressed since the beginning of modern cosmology, but no definite answer has been formulated despite of the several approaches that can be found in the literature. In this chapter we will make a historical review and we will focus on the experimental techniques that has been proposed to reveal directly and indirectly the presence of cosmic antimatter in the universe. Indirect searches can be carried on with the measurements of the electromagnetic radiation in the microwave and gamma-ray range, and of the neutrino flavour, whereas direct searches lay on the measurement of the cosmic rays and probe shorter distances. Finally, the current limits on the cosmic antimatter to matter ratio are compared to the sensitivity of future experiments.

1 Introduction

The discovery of “antiparticle” solutions of the Dirac’s equation in 1929 was followed in 1932 by the experimental discovery of the positron by Blackett and Occhialini. With the development of the accelerator physics, it was experimentally established that whenever we create new particles in laboratory, they come in two different forms that are well balanced, generically called “matter” and “antimatter”.

In particular, the creation (and the annihilation) of fermions is governed by few conservation laws, the baryonic and leptonic numbers conservation being the most important ones. These laws say that if we create fundamental fermions, each with a positive baryonic (or leptonic) number, in the same reaction other fermions will be created, each with negative baryonic (or leptonic) number, in order to keep the total baryonic and leptonic
numbers constant\(^1\). In the simplest case, this means that we cannot create a single fermion: we must create a couple of particle and antiparticle at least.

When we think about the creation of the present universe, our first attempt would lead naturally to a symmetric cosmology in which matter and antimatter are present in the same amount, but astrophysical measurements say that we live in a big domain that seems to be completely made of matter. Of course, the possibility exists that the universe is symmetric on average, consisting of a collection of homogeneous domains separated by “walls” filled with radiation only. An important point is then the estimation of the domain size. If they are of the scale of galaxies or galaxy clusters, we may detect antimatter cosmic rays (CR) coming from the nearest domain. On the other hand, if some antistar exists in our Galaxy we may even detect antimatter nuclei with \(Z \geq 2\).

Nevertheless, antimatter cosmic rays do exist and are detected. The two species already measured are antiprotons and positrons: they can be produced by the CR interactions in the inter-stellar medium (ISM) or in the Earth atmosphere, and they might have a cosmic origin or even be produced by the annihilation of exotic particles, not present in the Standard Model. However, the existing measurements do not provide strong hints for primary origin: they are fully consistent with the secondary production. On the other hand, the detection of one anti-helium nucleus would be a striking evidence for the existence of anti-stars in our Galaxy, because the probability to produce the anti-alpha particle among the secondaries is negligible.

\section{Antimatter}

What the word \textit{antimatter} means is not simple, thus we start from its constituents: the \textit{antiparticles}. If all the characteristics of an elementary particle (i.e. a particle without any internal structure), like its mass, charge and spin are known, then its associated antiparticle is like its specular image: it has the same mass, but opposite charge and spin. The best example is given by the electron (with negative unit electric charge) and its antiparticle, the positron (with positive charge), whose annihilation at rest is responsible of the well known 511 keV emission line.

\subsection{CPT theorem}

In modern physics, particles (and antiparticles) are described by the Relativistic Quantum Theory of Fields, in which a couple of field operators are capable of destroying or creating one particle of each kind in every given state. One can switch between a particle and the associated antiparticle using the \textit{charge conjugation} operator \(C\):

\[ C : \psi(\mathbf{r}, t) \rightarrow \psi^*(\mathbf{r}, t) \]  

\(^1\)In the Standard Model of fundamental interactions, the three lepton numbers associated to the electron, muon and tau leptonic doublets are separately conserved.
where $\psi(r,t)$ represents a particle quantum field and $\bar{\psi}(r,t)$ is the corresponding antiparticle field.

There are two other important discrete operators: the time reversal operator $T$ and the parity operator $P$ (the spatial inversion):

\[
T : t \rightarrow -t \\
P : r \rightarrow -r .
\]

Even though in general there is no exact symmetry with respect to these operators, the CPT theorem says that every relativistically covariant quantum field theory, that admits a minimum energy state and obeys the principle of microcausality (requiring that independent measurements can always be done on two spacetime points which are outside each other’s light cone), is invariant under the action of $C$, $P$ and $T$ together, without any dependence from the order they are applied.

The strict correspondence between particles and antiparticles is a result of the CPT symmetry. In particular, the fact that their masses are exactly equal is due to the commutative property between $CPT$ and the Hamiltonian operator. In addition the $CPT$ composite operator is antiunitary: “it relates the S-matrix$^2$ for an arbitrary process to the S-matrix of the inverse process with all spin three-components reversed and particles replaced with antiparticles” (quoted from Weinberg [1995], p. 183). This means that the following two probability amplitudes are equal (an overline denoting antiparticles):

\[
A(a_1 + a_2 + \ldots \rightarrow b_1 + b_2 + \ldots) = \\
A(\bar{a}_1 + \bar{a}_2 + \ldots \rightarrow \bar{b}_1 + \bar{b}_2 + \ldots) 
\] (2)

(2)

The demonstration of this theorem can be found in the books by Itzikson and Zuber [1985] and Weinberg [1995], for example).

2.2 Anti-systems

The existence of antiparticles, obtained making $C$ acting upon particles, does not guarantee the existence of bound systems made with antiparticles. In other words, the presence of the $C$ symmetry alone does not imply that our system can simply be replaced by another system with antiparticles in place of particles: to obtain the anti-system we do need the more complex $CPT$ symmetry, that involves also the spatial and temporal reflections, changing indeed the dynamics of the system (not only its composition).

The antimatter is formed by compound systems like anti-atoms, that are made of a cloud of positrons surrounding a nucleus containing antiprotons and antineutrons. Due to the $C$ invariance of the electromagnetic interactions, all chemical interactions would be the same as ordinary matter, allowing for macroscopic antimatter agglomerates.

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\footnote{In Quantum Field Theory, the scattering process is modeled as a very short and intense interaction, that is able to change the particle state from the initial free motion to a generally different final state (again a free wave). The S-matrix contains the probability amplitude of the transition from any initial state to all the final states, thus representing the most complete description of the scattering process itself.}
However, one important point is that the electroweak and strong interactions appear neither to be symmetric with respect to the C and P operators, nor to the composite operator CP, as found by Cronin and Fitch in 1964 (for the references to original works, see Weinberg [1995] or Maiani and Ricci [1996] and references therein).

The experimental discovery of the antimatter, in the sense of bound systems of antiparticles, was done in 1965 by A. Zichichi and his collaborators at CERN [Massam et al. 1965] and by S. Ting and his collaborators at Brookhaven [Dorfan et al. 1965]: these groups independently discovered the simplest antinucleus, the antideuteron. In 1996 the simplest antiatom, the antihydrogen, was obtained and studied at CERN and at FERMILAB (see Blanford et al. 1997 and references therein).

3 Cosmic antimatter

As far as high energy physics experiments are concerned, matter and antimatter are created exactly in the same amount: the CPT symmetry holds up to a level of $10^{-12}$, electronic lepton number violations may occur only below $10^{-12}$ (whereas the limit on the total lepton number, including all families, is below $10^{-10}$), and the experimental tests on baryon conservation imply that violations (if any) must be below $10^{-6}$ [Hagiwara et al. 2002].

What about the matter we see in the universe? If we think that the conservation laws hold true during all the history of the universe, we must admit that somewhere there should be the antimatter that balances the matter we are consisting of. If the conservation laws were valid for the whole universe life, then it is important to explain the presence of non annihilated matter.

On the other hand, we could state that the baryonic and leptonic numbers were not conserved in the past, i.e. that unknown physical processes may have happened during the first phases of the universe evolution. Three conditions were formulated by Sakharov [1967], in order to have a non symmetric baryogenesis: (1) non conservation of the baryonic number $B$ and (2) non conservation of $C$ and $CP$ during a phase in which (3) the cosmic evolution was out of thermodynamic equilibrium.

Today we can evaluate the ratio between the cosmic background radiation (CBR) photons and the nucleons (plus antinucleons) number as $\eta \approx 6 \times 10^{-10}$ [Hagiwara et al. 2002]. The CBR is the result of the annihilation of particles and antiparticles (assumed to be in a nearly perfect thermal equilibrium in the very early phase of the universe) when the temperature became low enough to break the equilibrium between radiation and fermions. If all the matter in the universe is of a kind only, then $\eta$ is the relative difference between the amount of matter and antimatter at the epoch in which the radiation uncoupled from the fermions. On the other hand, if the symmetry is conserved, $\eta$ is the value of the local fluctuation in the quantity of matter and antimatter in that epoch.

The modern picture of cosmic evolution (see for example the recent review by Stecker [2002]) is based on the idea that the universe expansion had a very fast acceleration, the so-called “inflation” [Guth 1981, Linde 1982], during which a very small (at the quantum scale) bubble was stretched so much that today it has the dimensions of the visible universe. The
baryogenesis locally met the Sakharov’s conditions, and inflation has probably enlarged homogeneous domains made of matter or antimatter up to scales comparable with the size of the visible universe, as supported by recent simulations \cite{Cohen1998}.

### 3.1 Can total annihilation be avoided?

The Standard Model of fundamental interactions and the Big Bang cosmological model, when no inflation is considered, unavoidably lead to the prediction of exponential drop of any inhomogeneity: the equilibrium between the total amount of matter and antimatter in the universe should be perfect. However, observations show that we live inside a (quite large) homogeneous domain made of matter. The non zero value of $\eta$ is a problem\footnote{Well, we do need this theoretical problem, to exist.}: if the universe is made of matter only (plus the radiation) we have to understand the mechanism that produced such a little asymmetry; if the universe is symmetric, we have to understand how fluctuations could survive and generate the observable structures.

The first attempt to answer to the latter question was due to \cite{Alfven1965}. He considered an “ambiplasma” (a fully ionized plasma consisting of protons, antiprotons, electrons and positrons) and the possible formation of homogeneous cells separated by the radiation emitted from “leidenfrost”\footnote{“Leidenfrost” is the German term used to indicate the process in which the water drops “bounce” upon a hot layer without touching it, sustained by their own vapor pressure.} layers in which all the annihilations happen. \cite{Omnnes1971} found that this layer is stable when the magnetic field is negligible: the annihilations cannot disrupt the separation walls. In addition, \cite{Stecker1972} showed that the perturbations induced by the annihilations could be compatible with galaxy formation, which would be triggered by the generated turbulence inside a matter (or antimatter) domain, whose scale has to be that of a galaxy cluster.

\cite{Unno1974} applied these results to a specific case, trying to explain quasars as super massive stars composed of matter and antimatter. If the antimatter is a little fraction of the total mass, they showed that it would constitute a domain surrounded by the matter and separated by a leidenfrost layer, like a bubble inside a star.

To explain how the leidenfrost layer can be able to keep separate matter and antimatter, \cite{Aly1978} computed the annihilation rate at the boundary in 3 cases: radiative and plasma eras of Big Bang model, strong magnetic field, two intergalactic hot domains. In the meanwhile, \cite{Lehnert1977,Lehnert1978} showed that at interstellar densities no well defined boundary can form in presence of neutral gas or in a unmagnetized fully ionized plasma. Only a magnetized ambiplasma could produce a leidenfrost layer, whose thickness is proportional to $BT^{1/2}$: for $10^5 < T < 10^8$ K and $B = 10^{-8}$ T, the wall thickness is about $10^7$ m.

Thus the walls are very thin (of the order of magnitude of the Earth diameter) and practically invisible for distant observers. In analogy with the geomagnetic field structure, that has well defined zones separated by current and neutral sheets that can be detected only by spacecrafts traversing them, \cite{Alfven1973} pointed out that the whole space is likely subdivided in cells.
A recent analysis from Dolgov [2001] emphasized that the behavior of the domain walls could be different from the leidenfrost process, or more precisely it could be the opposite: instead of repulsion, the layer could attract matter and antimatter towards the annihilation region. Actually, because electrons, positrons and neutrinos have larger mean free paths than the domain walls thickness, the energy and pressure density of the annihilation region decreases, increasing the diffusion of matter and antimatter towards each other and amplifying the efficiency of the annihilation.

However, in the framework of the inflation (for a review, see for example Liddle [2001]) the problem may even be ill-posed, because the size of any conceivable antimatter domain would have been enlarged so much that the domain boundaries are well beyond the radius of the visible universe.

### 3.2 Antimatter domains

It seems possible that mechanisms exist that could produce the formation of separated homogeneous domains during the cosmic evolution, thus allowing the visible universe to be matter-antimatter globally symmetric. This is an important point, because it does not require any conservation law breaking, but we need an estimation of the domain dimensions. In addition the possibility exists to have antimatter confined into condensed bodies like antistars in our Galaxy.

#### 3.2.1 Uniform domains

Steigman [1976] considered homogeneous and uniform domains filled with matter or antimatter and concluded that they should be at least of the scale of galaxy clusters, due to the constraints coming from the measured gamma-ray flux. The diffuse gamma-ray background flux with energy $E > 100$ MeV, of the order of $10^{-5}$ cm$^{-1}$ sr$^{-1}$ s$^{-1}$, was used by Steigman to infer upper limits for the antimatter fraction in the Local Cluster. For the hot H II intergalactic medium, his upper limit is $\sim 10^{-7}$, while inside our Galaxy the limits are more stringent: $10^{-15}$ for galactic clouds and inter-cloud medium, $10^{-10}$ in the halo.

Steigman estimated that the minimum distance to antimatter domains has to be 10 Mpc, but Cohen et al [1998] imposed a much stronger limit, under the assumption of a baryo-symmetric universe, concluding that the antimatter domains have to be very distant from us, at least few Gpc (hence they could be outside our visible universe). The key point is the smoothness of the cosmic microwave background (CMB) radiation, that requires density fluctuations below $10^{-4}$ at scales larger than 15 Mpc, thus implying that, if existing, matter and antimatter domains must be in close contact. But the annihilations products will carry away very efficiently the energy from the contact region, because electrons, positrons and neutrinos have larger mean free paths than the domain walls thickness. Hence the energy and pressure density of the annihilation region decreases, increasing the diffusion of matter and antimatter towards each other and amplifying the efficiency of the annihilation (in contrast with the leidenfrost process) Dolgov [2001].
Had this processes happened after the hydrogen recombination, the domain walls regions would have been strong gamma-ray sources, producing detectable non-uniformities in the extragalactic gamma-ray spectrum \cite{Gao1990}. Non-observation of this background means that any antimatter region must be near or beyond the horizon. If the annihilation took place before the hydrogen recombination, there would be some effect on the CMB energy spectrum, which must be below the sensitivity of present data \cite{Dolgov2001}.

\textbf{Dolgov} \cite{Dolgov2001} reviewed few different models, among which it appears that a viable model that could account for the existence of domains smaller than the visible universe is based on \textquote{isocurvature fluctuations}: the initial baryon/antibaryon asymmetry was zero and started to rise only relatively late, due to fluctuations in the baryons density. Baryon (antibaryon) rich regions cooled faster and diffusing photons from hotter regions had the effect to drag those regions away, thus providing a way to get separated matter and antimatter domains. In this model the annihilations could be weak enough to create a universe consisting of possibly large domains separated by thin baryon and antibaryon voids. Again, how large are those domains?

\subsection*{3.2.2 Non-uniform domains}

The upper limits on the fraction of cosmic antimatter are not so stringent, if the possibility that it is localized into small domains is considered \cite{Chechetkin1982}. \textbf{Khlopov} \cite{Khlopov1998} showed that the minimum size for such domains is that of a globular cluster (about 1 kpc): smaller regions have been annihilated during the cosmic evolution. The mass of these domains would have probably been condensed into anti-stars during the galaxy formation, hence the best place to look for an antimatter globular cluster is the bulge of our Galaxy, where old first-generation stars are found.

A cosmological model which is able to produce small (\textasciitilde 1 kpc) antimatter domains was proposed by \textbf{Khlopov} \textit{et al.} \cite{Khlopov2000}, who considered a rather narrow time slice for baryogenesis. Their mechanism of spontaneous baryogenesis implies the existence of a complex scalar field carrying baryonic charge with explicitly broken $U(1)$ symmetry, coexisting with the inflaton field. During the inflation, the phase of the complex field behaves as a Nambu-Goldstone boson, and quantum fluctuations induce different phase tilts in different regions of the universe. When the energy is sufficiently low, the field \textquote{rolls down} the potential and start oscillating, creating baryons and antibaryons with a proportion which depends on the phase tilt. If the baryogenesis happen at the beginning of the inflation, one unavoidable ends with uniform domains which are enlarged so much that they are today larger than the visible universe. However, if it takes place (not much) later, the final scale of antimatter domains can be at the same time larger than the minimum (\textasciitilde 1 kpc) and smaller enough not to produce any signature in the CMB spectrum. The result of this model is a non-balanced amount of matter and antimatter in the visible universe, in which the small antimatter domains contain a very small fraction of the total mass.
3.2.3 Condensed bodies

The diffuse cosmic gamma-rays background cannot put an equally stringent limit to the amount of condensed antimatter bodies, like anti-stars or anti-planetoids. Steigman [1976] inferred for the number of antistars an upper limit of $10^7$ in our Galaxy (i.e. $10^{-4}$ of the total stars number). This not so stringent limit arises from the fact that antimatter confined into compact structures like antistars is well separated from the matter environment and is able to survive longer than in gas clouds.

An antistar is not expected to be a strong gamma-ray emitter, at least if it does not cross a galactic cloud neither it impacts on other condensed bodies. Dudarewicz and Wolfendale [1994] give as lower limit on the distance of the nearest antistar only about 30 pc, and give a $10^{-3}$ upper limit on the fraction of antistars in M31. However, they emphasize that the fraction could be of order unity at the Hubble radius, having superclusters and anti-superclusters sufficiently well separated, in order to restore the matter-antimatter global symmetry, even though they conclude that a perfect symmetry appears very improbable.

Khlopov [1998] suggested the possibility that antimatter stars could have survived since the beginning of galaxy formation: they should be searched for in the globular clusters. In fact, condensation of an antimatter domain cannot form an astronomical object smaller than a globular cluster, and the formation of isolated antistars in the surrounding matter is impossible, since the necessary thermal instability would finally favor the total annihilation. Thus antistars can form in an antimatter domain only, and they must constitute today a whole antimatter globular cluster at least.

In this case, several antistars in the Galaxy could be found in the roughly spherical globular clusters halo around the Galactic center, that contains old first-generation stars. The number of globular clusters is $\sim 10^2$ and each cluster contains about $10^6$ old stars. In addition, the antistars are well separated from the rest of the Galaxy, and the upper limit of $10^{-7}$ calculated by Steigman under the assumption of a uniform distribution may be well underestimated.

The upper limit to the total mass of one antimatter globular cluster in our Galaxy, was estimated to be of the order of $10^5 M_\odot$ by Belotsky et al. [1998], who then computed a maximum fraction of antimatter to matter in cosmic rays of order of $10^{-6}$. Because current limits on the anti-helium to helium ratio are at the level of $10^{-7}$, one would today estimate as $\sim 10^4 M_\odot$ the total mass of an antimatter domain, in the hypothesis that it belongs to the Galaxy.

Signatures of an antimatter globular cluster inside our Galaxy would be the presence of $^3\text{He}$ and $^4\text{He}$ in the cosmic radiation, and the flux of gamma-rays coming from the annihilation of the emitted antiprotons with the ISM. Actually, such annihilation would happen practically at rest, and produce neutral pions among secondary particles. The decay of $\pi^0$ would lead to a bump of the diffuse gamma-ray spectrum at about 70 MeV, which is compatible with EGRET data [Golubkov and Khlopov 2000].
4 Searches for cosmic antimatter signatures

There are few ways in which cosmic antimatter may show itself. Indirect ways, which are now considered, are based on the detection of annihilation radiation in the gamma-ray regime and in the CMB spectrum, on the measurement of the helicity of photons and neutrinos emitted during non CP invariant processes. The direct way (section 5) is the detection of antinuclei among cosmic rays.

4.1 Collision of matter-antimatter bodies

Sofia and Van Horn [1974] considered the collision between a star and antimatter “chunks” ($m \sim 10^{12}$ kg) and found that the annihilations due to the stellar wind are not important and that the annihilation rate is limited by the rate at which the matter is swept out by the chunk due to the stellar radiation. Thus the impact with the star cannot be avoided and the chunk penetrates into the star for $\sim 10^6$ m before eventually evaporating completely.

The chunk would become a hot and expanding antimatter bubble that would return to the stellar surface due to buoyancy in $\sim 10^2$ s. Annihilations produce charged and neutral pions, and they decay to electrons/positrons of 50–70 MeV and gamma-rays of $\sim 70$ MeV (“prompt” photons). The photons produced inside the star suffer $\sim 10$ scatterings prior to escape, degrading to energies of hundreds of keV. The inverse Compton scattering of those $e^+/e^-$ in the stellar atmosphere ($\sim 10^4$ K) will produce a number of $\sim 60$ keV photons with time constant of $\sim 10^3$ s (“delayed” photons).

The signature of such a collision would then be a precursor burst emission line at $\sim 0.5$ MeV ($e^+/e^-$ annihilation) with a $\sim 70$ MeV continuum lasting 0.1–1 s, followed by the main annihilation burst at $\sim 100$ keV (10–100 s) and by the inverse Compton photons ($E \lesssim 100$ keV, $\tau \sim 10^3$ s). This signature is not very different from the time evolution of many gamma-ray bursts (GRB).

The cross section for the chunk capture with relative velocity $v$ at infinite by a star with mass $M$ and radius $R$ is $\sigma \sim \pi(2GMR)/v^2$. A star like the Sun, for $v \sim 10^4$ m s$^{-1}$ has $\sigma \sim 10^{23}$ m$^2$, and during 1 year sweeps up a volume $V = \sigma vt \sim 10^{34}$ m$^3$. In the Galactic disk, a sphere of radius 100 pc ($V = 10^{56}$ m$^3$) contains about $10^5$ stars, then there will be a collision every $\sim 10^{15}$ years (much greater that the Universe age).

A similar way was followed by Sofia and Wilson [1976], who considered the collision between antimatter asteroids and the Sun, while Alfvén [1979] considered star-antistar collisions, possibly ending in “ambistars”, i.e. stars with matter and antimatter whose annihilations contribute with the thermonuclear fusion processes to the total emitted power.

The collision with small ($r < 10$ km) bodies in the Solar system and the encounter of clouds with antimatter clouds were considered by Rogers and Thompson [1980, 1982]. They found that very small antimatter objects in the Solar system would produce a gamma-ray flux of the order of $10^{-10}$ cm$^{-2}$ s$^{-1}$, too low to be detectable. In addition, different clouds will not merge. Instead a thin “leidenfrost” layer will form ($\sim 10^9$ m, compared to $\sim 10^{15}$ m scale length for clouds), and annihilation will burn only a very small ($\sim 10^{-12}$) fraction of the total mass, resulting in less severe constraints for gamma-rays emission than
those considered by [Steigman 1976] (but this argument may not be valid, as [Dolgov 2001] pointed out). [Fargion and Khlopov 2001] considered antimatter meteorites in the solar system, obtaining a limit of \(10^{-9} - 10^{-8}\) on the antimatter to matter ratio.

Actually all the interactions between antistars and the matter in our Galaxy are very weak until they remain in a bound system like a globular cluster (this is indeed the reason why they could have survived until now). Thus it make sense [Foschini 2001] to consider the possibility that antistars escape from their cluster, wander through the Galaxy and possibly interact with the galactic matter.

Following [Binney and Tremaine 1987], a star (or antistar) can escape from a cluster in two ways: *ejection*, in which the escape speed is gained in a single close encounter with another star, and *evaporation*, in which several distant encounters produce a gradual velocity increase. The former process is negligible when compared to the latter, whose characteristic time can be roughly estimated as \(t_{ev} \approx 100 t_{re}\), where the mean relaxation time \(t_{re} = (3 \times 10^7) - (2 \times 10^{10})\) years for a globular cluster.

We can compute the number of stars in a cluster as:

\[N(t) = N_0 \exp \left( -t/t_{ev} \right) \tag{3}\]

and the time \(t_1\) elapsed before one star can escape is found by solving the equation \(N_0 - N(t) = 1\), that is:

\[t_1 = -t_{ev} \ln \left[ (N_0 - 1)/N_0 \right] \tag{4}\]

The number of stars in a globular cluster is \(N_0 \sim 10^6\), hence we get \(t_1 = (3 \times 10^3) - (2 \times 10^6)\) years.

Because this time is much shorter than the age of the Galaxy, it is very likely that, if at least one of the galactic globular clusters is made of antimatter, there are many (possibly hundreds) antistars wandering in the roughly spherical volume in the center of the Galaxy occupied by the globular clusters.

Those antistars may interact with a matter cloud, star or smaller compact body. An important effect that has to be considered when gaseous material is accreting into an antistar is that the equilibrium between the gravitational and radiation pressure is reached at higher power than the “Eddington luminosity”

\[L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \text{ erg s}^{-1} \tag{5}\]

\((M_\odot = 2 \times 10^{30} \text{ kg is the solar mass})\) because when annihilation photons are considered, the Thomson cross section \(\sigma_T\) has to be substituted with the relativistic Klein-Nishina formula: the cross section, for photon energies much higher than the electron rest mass energy \(m_e c^2 = 511\text{ keV}\), can be approximated by

\[\sigma_{KN} \approx \frac{\pi r_e^2}{\epsilon} \left( \ln 2\epsilon + \frac{1}{2} \right), \ \epsilon \gg 1 \tag{6}\]

where \(r_e = 2.82 \times 10^{-15} \text{ m}\) is the classical electron radius and \(\epsilon = (\hbar \omega)/(m_e c^2)\) is the ratio between the photon energy and the electron rest mass energy. For 50–70 MeV photons,
typically produced by the decay chains of the charged and neutral pions arising from the nucleon/antinucleon annihilation, the Klein-Nishina formula gives for the cross section 46–61 smaller values than the classical Thomson value \( \sigma_T = \frac{8\pi r_e^2}{3} = 0.665 \times 10^{-28} \text{ m}^2 = 0.665 \text{ barn} \).

The annihilation photons would then escape almost freely from the accretion disk, taking away a considerable fraction of the total emitted energy: the net effect is that the power emitted by a matter-accreting antimatter-star can become much greater than the usual accretion case, especially in the gamma-ray regime, where normal stars have negligible emission.

On the other hand, the rare star/antistar head-on collisions would produce an intense energy release for few seconds, due to the surface annihilations, before merging and reaching a (probably super-Eddington) stationary luminosity [Foschini 2001]. These close encounters may appear as galactic GRB and, in the very rare case of a complete mixing, they might produce an “ambistar” fueled by antiproton-proton annihilations, a blue supergiant with strong \( \gamma \)-ray emission.

Hence, a possible search for matter-antimatter accretion systems could be carried on by comparing optical, X-ray and \( \gamma \)-ray luminosities of Galactic sources: the signature would be an excess of emitted power in the \( \gamma \)-ray range.

4.2 Polarization of electromagnetic emission

With a completely different approach, Cramer and Braithwaite [1977] stressed out that in addition to direct annihilation, antistars may be distinguishable by the polarization properties of their electromagnetic emission. In fact the ordinary thermonuclear reactions which occur in stars systematically convert protons into neutrons through the weak-interaction process of \( \beta^+ \) decay and electron capture.

When positrons \( (\beta^+) \) are emitted, they are preferentially in a “right” elicity state of strength \( v/c \). Their bremsstrahlung emission is then preferentially right-circularly polarized. The same is true also for the forward going annihilation photon. In antistars, antiprotons are converted into antineutrons, producing electrons in a “left” elicity state. The photons produced by those electrons are then preferentially left-circularly polarized.

During normal star processes, the photons loose the initial polarization state while diffusing out of the star, but during a supernova explosion the photons produced by the \( ^{56}\text{Ni} \) decay chain could be detectable. \( ^{56}\text{Ni} \) decays by electron capture to \( ^{56}\text{Co} \), which decays by electron capture or positron decay to \( ^{56}\text{Fe} \). The emitted positrons will radiate through bremsstrahlung polarized photons at the surface of the ejected material. These gamma-rays may then escape and be detectable. Hence, a measurement of their degree of polarization could tell us the nature of their origin.

Two effects can be exploited to measure the polarization of a \( \gamma \)-ray photon beam: Compton scattering and pair production. The differential Compton cross section of a
linearly polarized beam is:

\[ \frac{d\sigma}{d\Omega} = \frac{r_e^2 \beta^2}{2} \left( \frac{\beta}{\beta} - 2 \sin^2 \theta \cos^2 \phi \right) \]  

where \( \theta \) is the scattering angle from the incident photon direction, \( r_e \) is the classical electron radius and \( \beta \) is the ratio between the scattered and incident photon energy. The polarization is detected by the difference between the number of photons with a given azimuthal angle \( \phi \) and the number of photons scattered in perpendicular directions. Using a two-dimensional germanium strip device to measure the energy and the position of each interaction, Kroeger et al. [1998] proposed a small detector (with geometrical acceptance of few tens of cm\(^2\) sr) whose sensitivity is peaked roughly at 100–200 keV (maximum efficiency of order of 10%).

The azimuthal dependence of the cross section for electron/positron production can be written

\[ \sigma(\psi) = \frac{\sigma_0}{2\pi} \left( 1 + PR \cos 2(\psi - \psi_0) \right) \]  

where \( \psi - \psi_0 \) is the relative angle between the pair plane and the incident electric field vector, \( \sigma_0 \) is the total cross section, \( P \) is the fractional polarization, and \( R \sim 1 \) is a numerical factor expressing the inherent asymmetry of the process. This process is useful for polarization measurements above few tens of MeV, if the detector can measure the initial part of the track of two leptons: the pair produced by the incident photon must be able to propagate without being affected by the Coulomb scattering in order to find the plane defined by electron and positron tracks with good angular resolution. A possibility is to use a low density gas filling a large volume and position sensitive pixels with very small pitch (~100 \( \mu \)m) [Bloser et al. 2003].

4.3 Effects on the cosmic microwave background radiation

The most favored baryogenesis scenario today is based on a very non-uniform distribution of matter and antimatter, the latter forming very small domains (see §3.2.2). To obtain small islands of antimatter, the baryogenesis should have been happened in a small time window during inflation: a very early process would have produced too large domains, whereas they have disappeared if produced too late.

The minimum scale \( R_c \simeq (10^{-5}–10^{-4}) \zeta^{-1}(z/z_{rec})^{1/2} r_h(z_{rec}) \), where \( \zeta \) is the ratio between the anti-baryon density inside the region and the baryon density outside, and \( r_h(z_{rec}) \) is the horizon scale at the recombination [Naselsky and Chiang 2004]. At the recombination era \( t_{rec} \simeq \frac{3}{5}(\Omega_m H_0^2)^{-1/2} z_{rec}^{3/2} \), where \( z_{rec} \sim 10^3 \), \( H_0 = 100h = 73 \pm 3 \) km s\(^{-1}\) Mpc\(^{-1}\) is the present value of the Hubble parameter and \( \Omega_m = 0.127^{+0.007}_{-0.013} \) is the fraction of the universe mass density due to baryons and dark matter. At this time, the total baryonic mass is of the order of \( 10^{19} M_\odot \), and the antimatter domains could have masses of the order of \( (10^4–10^7)M_\odot \).

On the other hand, had antimatter domains occupied a non negligible volume fraction at the nucleosynthesis epoch (at \( t \simeq 300-1000 \) s), the light elements abundances would have
been different from present values (which satisfy all predictions of the Standard Big Bang Nucleosynthesis model).

Matter-antimatter annihilation right before and during hydrogen recombination would distort the CMB spectrum in different ways, depending on the epoch and on the spatial distribution of the antimatter domains. In particular, a non uniform distribution would have induced structures in the CMB polarization map. The physical processes relating the annihilation to the CMB photons are bremsstrahlung and inverse Compton scattering of $e^+/e^-$ produced by the annihilation, and electromagnetic cascades initiated by the high energy annihilation charged products.

### 4.4 Supernovae neutrinos

Finally, Barnes et al. (1987) suggested that the initial neutrino bursts from a supernova could reveal whether the source is made of matter or antimatter. In the first 2–10 ms the neutronization reaction $e^- + p \rightarrow \nu_e + n$ produces a $\sim 10^{52}$ erg burst of $\sim 10$ MeV neutrinos, whose flux cuts off abruptly when the infalling matter achieves sufficient density to trap them. This dense infalling matter comes to thermal equilibrium, in which all neutrino flavours are produced. Neutrinos and antineutrinos, approximatively in the same number, carry away 99% of the binding energy of the newly formed neutron star.

The electron neutrinos (and antineutrinos) suffer more scatterings than muon and tau neutrinos, and escape with a mean energy of $\approx 10$ MeV, roughly half than the muon and tau neutrinos mean energy. On the other hand, the produced $\nu_e$ (and $\bar{\nu}_e$) number is roughly twice the $\nu_\mu$ or $\nu_\tau$ numbers. The net effect is that the energy of thermal neutrinos is equally divided among the three flavours.

In water Čerenkov detectors, like Kamiokande, SuperK and IMB, all neutrino flavours may interact by $\nu/e$ scattering, while electron antineutrinos have an additional channel, the inverse $\beta$-decay on the hydrogen nuclei (the interaction cross section for oxygen is negligible): $\bar{\nu}_e + p \rightarrow e^+ + n$.

The ratio between the $\nu_e$ emitted during the burst phase and the number expected from the thermal phase is $r = 0.01–0.03$ and the expected counting rate for the 10 MeV electron neutrinos and the 20 MeV muon and tau neutrinos follows the proportion:

$$\bar{\nu}_e p : (\text{all thermal } \nu, \bar{\nu}) e : (\text{burst } \nu_e) e = 10 : 1.1 : 3.3r . \quad (9)$$

If the progenitor star is made of antimatter, an important difference arises with this picture: the initial burst is due to the antineutronization reaction $e^+ + \bar{p} \rightarrow \bar{n} + \bar{\nu}_e$ and the burst contains electron antineutrinos rather than neutrinos. The $\bar{\nu}_e$ cross section in water is 18 times higher than the $\nu_e$ one, and the proportion (9) has to be replaced with:

$$\bar{\nu}_e p : (\text{all thermal } \nu, \bar{\nu}) e : (\text{burst } \bar{\nu}_e)p = 10 : 1.1 : 60r . \quad (10)$$

Thus (6–20)% of all observed events from an antimatter supernova are expected to occur within the first few milliseconds. In addition, the ($\bar{\nu}_e$) reaction produces electrons with nearly isotropic cross section, while the elastic scattering ($\nu_e e$) is peaked forward. Hence
the expected signature for an antimatter source is an initial burst in a water Čerenkov detector with isotropic distribution.

From supernova SN 1987A, located in the Large Magellanic Cloud at ~ 55 kpc from Earth, 11 and 8 events were registered by Kamiokande II and IMB respectively. Due the too low statistics, it is impossible to distinguish between the expected ~ 2 (\(\bar{\nu}_e p\)) events in case of antimatter star and the expected ~ 0.1 (\(\nu_e e\)) events corresponding to a matter progenitor star. The first event registered by Kamiokande is forward peaked and if it is attributed to the burst it may prove that SN 1987A was produced by a matter progenitor star (see Barnes et al. [1987] and references therein).

5 Direct detection

As we have seen, indirect evidences of cosmic antimatter might be found in the measurements of neutral particles (photons and neutrinos): low-energy photons of the CMB would carry on information about the antimatter distribution in the early phase of cosmic evolution (§4.3), whereas high-energy photons might reveal the presence of antimatter in the modern era. In particular, ambistars (§4.1) would appear as normal stars with excess of emission power in the gamma-ray regime, whose formation could be preceded by a gamma-ray burst, whereas antistar explosions would emit high-energy photons with a different polarization state (§4.2) and a large number of antineutrinos (§4.4).

However, direct detection of CR antihelium nuclei would be the most compelling indication of the existence of cosmic antimatter: \(^4\text{He}\) could be of primordial origin or even be produced by the antiproton fusion in the core of an antistar. Antihydrogen is of course expected as the most abundant element of antimatter domains, but secondary \(^\bar{p}\) production in CR interactions with ISM is an overwhelming source of background for any conceivable cosmic antimatter search. The measurements of positrons are even less significative for this search, because positrons (and electrons) are commonly produced during the CR propagation in the ISM, and in addition they loose energy very rapidly, making impossible to probe distances of cosmological interest.

Khlopov [1998] suggested the possibility that antimatter globular clusters could have survived since the beginning of galaxies formation. The idea that one antimatter globular cluster may be present in our Galaxy refreshed the interest into the possible observation of cosmic antimatter effects.

There are several possible ways in which such an antimatter globular cluster could manifest itself: its e.m. emission may show anomalous circular polarization at all wavelengths, unrelated to any linear polarization which may be present (§4.2); their antistar wind would hardly produce detectable reactions with the galactic ISM but they may interact with matter clouds, stars or smaller bodies (§4.1). But the most important effect may be the detection of antinuclei with \(Z > 2\), that were produced only in negligible quantities during the primordial nucleosynthesis.

If a non zero amount of antimatter did survive the primordial annihilation, it is reasonable to expect that its composition will be similar to that of ordinary matter. Hence,
we may think about cosmic antimatter domains as composed by protons, positrons, anti-helium nuclei, few isotopes of antihydrogen and antihelium, with negligible quantities of heavier antinuclei.

Antistars could have formed inside antimatter domains exactly in the same way as ordinary stars formed in matter domains. Thus we may expect that nuclear reactions happen inside antistars, similar (apart from photon polarization and antineutrino production, as seen in §4.2 and §4.4) to “normal” reactions: proton-proton and C-N-O chains.

As for matter domains which contains stars and galaxies, antimatter nuclei would be injected in the ISM, where they would be accelerated as cosmic rays, and a fraction of them (that depends on particle momentum and distance from us) could escape from those domains and reach our Galaxy, where they would continue to diffuse for a long time before annihilation can happen, because the interaction length ($\sim 60 \text{ g/cm}^2$) for protons and antiprotons) is greater than the escape length ($\sim 5 \text{ g/cm}^2$). If anti-stars exist in the Galaxy, the probability to detect antimatter cosmic rays is of course larger.

Thus, a finite probability exists that cosmic ray detectors in the Solar system may reveal cosmic antimatter. Actually, such instruments would certainly detect antiparticles produced by the interactions of cosmic rays with the interstellar medium. This background can be completely overwhelming for certain kinds of cosmic antiparticles, but this is not the case for antihelium and heavier antinuclei.

### 5.1 Positrons and antiprotons

Protons are the most abundant particles among cosmic rays, and CR electrons are about 1% of protons. Very likely their antiparticles would be the most abundant species in antimatter domains, and we may expect that they would constitute the greatest antimatter fraction among cosmic rays detected on the Earth.

Other sources of antiprotons and positrons are the reactions of cosmic rays with the interstellar medium. In fact, among the secondary particles produced by energetic inelastic scatterings between two protons (the most abundant species both in CR and ISM) or a proton and a nucleus, the most abundant ones are mesons, like pions and kaons, and antiprotons. In addition, while neutral pions decay into energetic photons ($E_{\gamma} = 70 \text{ MeV}$ in their center of mass system), charged pions decay into muons and electron-positron pairs (also produced by muon decays), so that the secondary production of antiprotons and positrons is a quite common process.

Like electrons, positrons have short radiation length and suffer heavy energy losses during propagation in the ISM, hence there is no possibility that CR positrons be of cosmic origin: they are produced by the interactions of cosmic rays with the interstellar medium.

On the other hand, antiproton production is hardly disfavoured for energies below 2 GeV for kinematical reasons, so that the secondary antiproton spectrum should have a characteristic peak around 2 GeV (for higher energies, it is the primary proton spectrum that goes down as $\sim E^{-2.8}$, while the $\bar{p}$ production yield is almost constant). Thus, cosmic antiprotons (and antiprotons from exotic sources as dark matter particle annihilation...
5.2 Antihelium and antinuclei

Helium is the second most abundant species in the universe: about 25% of the total baryonic mass, and about 20% of CR particles are He nuclei. $^4$He nuclei can be of cosmic origin (produced during primordial nucleosynthesis) or of stellar origin (produced by the proton-proton and C-N-O nuclear chains). After their acceleration, helium nuclei propagate through the Galaxy for a time similar to the proton propagation time (about $2 \times 10^7$ years), and may interact with the interstellar medium, producing $^3$He isotopes by spallation.

Similarly, we expect that the greatest fraction of CR antinuclei (after antiprotons) is constituted by antihelium isotopes. Actually, the possible detection of $\bar{\text{He}}$ would be a striking demonstration that antimatter plays a cosmic role, as annihilation remnants wandering...
Figure 2: Experimental results on the CR antihelium-to-helium flux ratio \cite{Buffington1981, Golden1997, Badhwar1978, Alcaraz1999, Sasaki2001}.

through the Galaxy or in form of antistars: the secondary production probability of $^3\text{He}$ by cosmic ray interactions with the ISM was estimated to be of order $10^{-13}$ \cite{Chardonnet1997} and the probability for secondary $^4\text{He}$ is much lower.

While antihelium may be of cosmic or (anti-)stellar origin, the detection of antinuclei could be explained only as a demonstration that antistars do exist in our Galaxy (or in some nearby galaxy). Among the possible isotopes, the best candidates for this antimatter search are $^{12}\text{C}$, $^{14}\text{N}$ and $^{16}\text{O}$, because they are the most probable production results (after $^4\text{He}$) of nuclear reactions fueling antistars.

Figures 2 and 3 show the experimental upper limits found by balloon and space experiments on the cosmic ray anti-helium to helium flux ratio and antimatter (i.e. antinuclei) to matter flux ratio, respectively.

6 Summary and perspectives

The problem of the possible existence of primordial antimatter is still open, despite of the several attempts that has been tried out in the past 40 years. From the theoretical point of view, the alternatives are:
1. symmetric cosmology with matter/antimatter fluctuations either on small scales, producing homogeneous galaxy clusters, or on very small scales, that could lead to the formation of clusters of antistars;

2. symmetric cosmology with matter/antimatter fluctuations on scales that became larger than the size of galaxy clusters, and may be even larger than the visible universe;

3. asymmetric scenario involving possibly new and unknown aspects of the fundamental interactions, that were important during the early stages of the cosmic evolution and produced a $\sim 10^{-10}$ excess of particles over antiparticles.

From the experimental point of view, in the first case we have chances to find evidence of the existence of cosmic antimatter either indirectly, looking at the gamma-ray measurements, or directly, using accurate cosmic ray spectroscopy techniques. The direct detection of antinuclei is out of the possibility of cosmic ray experiments in the second scenario, whereas gamma-ray and neutrino searches can still be carried on. Of course, in the last possibility nothing more than lower limits on the size of our homogeneous domain.
can be found by astrophysics experiments: only laboratory evidence of new physics could give hints on asymmetric cosmologies.

The different experimental techniques that will be shortly reviewed are based on the direct detection of antinuclei among cosmic rays, or on measurements of the gamma-ray polarization and of the neutrino flavour during supernova events.

## 6.1 Cosmic ray experiments

The direct detection of antinuclei, that requires a magnetic spectrometer to distinguish between positive and negative charge, will be possible only below 1 TeV/nucleon with present and approved future experiments: BESS Polar [Nozaki 2004] with long duration balloon flights will reach a $\text{He}/\text{He}$ sensitivity of less than $10^{-7}$; PAMELA [Adriani et al. 2002] and AMS-02 [Aguilar et al. 2002] with longer satellite missions will reach sensitivities of the order of $10^{-8}$ and $10^{-9}$, respectively. The discovery of antihelium nuclei would be a very strong suggestion that antistars do exist in our Galaxy (in this energy range the curvature radius of a charged particle is too small to have a non negligible escape probability). Hence direct searches will be useful only to test the hypothesis of a symmetric cosmology with matter/antimatter fluctuations on very small scales.

In order to test the hypothesis of fluctuations on larger scales, one must rely on measurements of neutral particles, that are not deflected by magnetic fields and follow the shortest path from the source to the observer. For example, a possible search for matter-antimatter accretion systems could be carried on, as explained in §4.1, by comparing the power emitted in the optical, X-ray and $\gamma$-ray ranges.

## 6.2 Gamma-ray polarimetry

In §4.2 we saw that the polarization of $\gamma$-ray photons emitted in supernova explosion is expected to be different for matter and antimatter progenitors. In addition, nearly all emission mechanisms can produce linearly polarized emission, though the polarization angle and the degree of polarization depend on the source physics and geometry.

Synchrotron radiation, produced by relativistic electrons spiraling around magnetic field lines, and curvature radiation, produced by lower energy electrons following curved magnetic field lines, produce linearly polarized emission whose polarization angle traces the field direction and the degree of polarization is independent from the energy. On the other hand, Compton scattering of $\gamma$-rays on ambient electrons produces radiation whose polarization degree depends on the energy and scattering angle. These processes are expected to dominate the high-energy radiation of gamma-ray pulsars, gamma-ray bursts, supernova remnants and active galactic nuclei [Bloser et al. 2003].

Recently, the first astrophysics measurement of $\gamma$-ray polarization has been reported by the RHESSI experiment [Coburn and Boggs 2003], even though other authors stated that a re-analysis of the same data shows no polarization at all [Rutledge and Fox 2004].

Though the IBIS instrument on INTEGRAL [Winkler 2004] has some polarization sensitivity, the next generation experiments AGILE [Mereghetti et al. 1999] and GLAST...
will have a negligible sensitivity to the polarization of gamma-rays. However, a number of new detectors has been recently proposed to carry on polarization measurements of astrophysical sources. In addition to the two proposed detectors mentioned in §4.2, other examples are: GRAPE, using low-Z organic scintillators surrounded by high-Z inorganic scintillators to detect Compton scattering of 30–300 keV photons; POLAR, a bundle of plastic scintillator “spaghetti” operating in the 10-300 keV range; NeXT/SGD, with CdTe and Si semiconductor technology, in the 0.1–10 MeV range. High energy photons polarimetry is likely to be one of the most exciting frontiers in astronomy for the near future.

### 6.3 Cosmic microwave background measurements

CMB measurements made by WMAP during the first year do not show any evidence for antibaryon contamination, and can only be used to infer limits on the parameters of cosmic evolution models, as shown by Naselsky and Chiang. Results from the three years data set are currently being published, and suggest that CMB temperature, polarization and small-scale structures fit into a six-parameters cosmological model, together with light-element abundances, large-scale structure observations and the supernova luminosity to distance relationship. The best values for the cosmological power-law flat $\Lambda$CDM model are: $\Omega_m h^2 = 0.127^{+0.007}_{-0.013}$ (matter and dark matter density), $\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$ (baryon density), $h = 0.73 \pm 0.03$ km s$^{-1}$ Mpc$^{-1}$ (Hubble parameter), $n_s = 0.951^{+0.015}_{-0.019}$ (slope of the scalar perturbation spectrum), $\tau = 0.09 \pm 0.03$ (optical depth), $\sigma_8 = 0.74^{+0.05}_{-0.05}$ (amplitude of fluctuations).

Actually, it seems that there is no evidence for antimatter effects. However, the future Planck mission will study anisotropies and polarization structures of the CMB with unprecedented accuracy and the antimatter signatures could be within its sensitivity.

### 6.4 Neutrino experiments

The exciting results of supernova neutrino measurements in 1987, that opened the field of “neutrino astronomy”, were obtained by experiments that have been built for other purposes (in particular for the search of possible proton decays). On the other hand, the main issue of neutrino physics in the last dozen years is bound to the neutrino oscillations: the measurements of the differences between the squared masses of the mass eigenstates, that are different from the flavor eigenstates, reached better and better precisions.

The next generation neutrino detectors can be grouped in two sets: the big water/ice Čerenkov detectors and the magnetic calorimeters. The latter will be able to distinguish

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5$\Lambda$CDM is a cosmological model with cold dark matter and a dominant contribution from the “vacuum constant” $\Lambda$.

6For a review of past, present and future neutrino detectors, see http://neutrinooscillation.org
between the different leptons produced by the interactions of neutrino fluxes emitted by particle accelerators. Hence, they will be able to measure the flavor of the incident neutrinos, that can be compared to the known flavor of neutrinos produced by the particle beams. This is very important to understand the details of neutrino oscillations, but it is also very useful for neutrino astronomy.

In particular, supernova explosions, whose progenitor was an antimatter star, differ significantly from those produced by matter stars (see §4.4): the initial neutrino burst is due to the antineutronization reaction, that produces $\bar{\nu}_e$ instead of $\nu_e$. Hence a flux of neutrinos generated by the explosion of antimatter stars will produce positrons through the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$, whereas neutrinos produced by matter supernovae will create electrons ($\nu_e + n \rightarrow e^- + p$) in the detectors. Inside a magnetic field, electrons and positrons will be curved in opposite directions, allowing for a good discrimination between the two cases. The drawback of these detectors is that, because the neutrino incident beam has known energy and direction, their angular acceptance is quite narrow compared to water Čerenkov detectors, hence the supernova detection probability is lower. However, since the expected interaction rate is quite low, these detectors might have the possibility to be triggered also by off-beam events, in order to study atmospheric and astrophysical neutrinos.

Acknowledgments

The author wishes to thank Pavel Naselsky, Floyd W. Stecker and Maxim Khlopov for their suggestions and corrections to the first draft of this work.

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