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Antimatter in Cosmic Rays

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Abstract

We have briefly reviewed the available information on the antimatter content in the universe deduced from astronomical observations and examined some of the theories relating to symmetric cosmology, in order to understand the present universe. The importance of studying antimatter in cosmic rays has been looked into and the experiments to detect positrons, antiprotons and antinuclei have been described briefly. The results from these experiments are presented. We have discussed the interpretations of these observations critically from the point of view of antimatter content in the universe and with regard to the understanding of the propagation of cosmic rays. Some of the important implications of these results have been highlighted and the need for future investigation has been brought out.

INTRODUCTION

The positron is the first antiparticle to be discovered during the early thirties (Anderson 1933). It became clear soon that electron-positron pair production by a photon is a common electromagnetic process in nature, occurring when the photon energy is larger than the rest mass of the pair. The positron remains as a free particle until it comes in contact with an electron and annihilate when at rest into two photons of 511 keV each. This phenomenon and the observed conservation of basic quantum numbers during particle creation, imply that particles are created and destroyed in nature as particle-antiparticle pairs. Such observations confirmed the particle-antiparticle conjugation symmetry, according to which neither a particle nor its antiparticle can have a preferred position as far as the general laws of nature are concerned. When such symmetry is well preserved in microscopic phenomenon, one is inclined to believe that it should be preserved in macroscopic world as well. Eventhough the positron was known to scientists as a form of antimatter, the importance of antimatter in cosmology and in astrophysics was realised only after the discovery of the antiproton (Chamberlain et al. 1955), nearly two decades later. The obvious consequence of the conjugation symmetry immediately stimulated speculation on the antimatter content of the universe (Goldhaber 1956; Alpher and Herman 1958), namely, the existence of antinucleons in abundance equal to nucleons in the universe. However, observations indicate that this is not so. This raises an important question as to whether the universe must be symmetric, and if so, what kind of physical processes could separate matter from antimatter from an initial symmetric universe?

While particle-antiparticle symmetry and the validity of conservation laws are undeniable, it is well known that there are examples in physics that strongly violate symmetries of the underlying laws. As an example, Maxwell's equations are time-symmetric, yet physically interesting solutions are only the outgoing waves; the time symmetry of Maxwell's equations is broken by selecting solutions with appropriate boundary conditions. Similarly, while on the microscopic level, the violation of time-reversal invariance is an exceedingly small effect, macroscopic systems display a clear arrow of time. One could, therefore, visualise that it is also possible to obtain physically interesting cosmological solutions to account for the lack of symmetry in the universe from the concept of symmetric universe by choosing right kind of boundary conditions. One school believes that violation of the symmetries of the underlying physical laws is a requirement for any interesting macroscopic system and they are not concerned with the observed lack of symmetry in the universe. The other school believes that the laws of nature are as simple and symmetric as conceivable and they search for basic physical processes and boundary conditions which could produce the observed asymmetry from the basic symmetric universe.

2. OBSERVATIONAL EVIDENCE FOR ANTIMATTER

Annihilation of antinucleon ($\bar{N}$) and nucleon (N) leads to the production of π^0, π^+ and π^- in equal abundance. The neutral pion decays to two gamma rays and the end products of charged pions are electrons (e^+, e^-), electron neutrinos ($\nu_e, \bar{\nu}_e$) and muon neutrinos ($\nu_\mu, \bar{\nu}_\mu$). Gamma rays carry about a third of the total energy and can be detected easily. Therefore, detection of annihilation gamma rays from astronomical objects would be a clear signature of the existence of antimatter. In this section, we summarise the results on $\bar{N}/N$ from astronomical observations.

(1) There is direct evidence from space probes which landed on Moon, Venus and Mars without being annihilated, that these bodies of our solar system are composed of ordinary matter. Solar wind and energetic particles emitted by the Sun do not annihilate when coming in contact with space probes; this clearly indicates that the Sun is made up of matter. If any of the planets in our solar system is made up of antimatter, interactions of solar wind on its surface would make them the strongest gamma ray sources in the sky, which they are not, and therefore, one could conclude that the entire solar system consists of only matter.

(2) Matter and antimatter cannot survive in the Galaxy in the form of mixed gas component. Observationally, from galactic gamma ray background one can set an upper limit of about 10^{-15} for the fraction, of antimatter to co-exist with matter in interstellar space (Steigman 1976). However, if antimatter separated from matter during the early phase of cloud formation, then they may not come in direct contact with each other.

(3) Stars and antistars could be formed out of regions of matter and antimatter that have separated during the early phase. In the case of an antistar, its motion through interstellar medium would accrete interstellar matter, which upon annihilation, will produce gamma rays. One can use the standard accretion cross-section and calculate the rate of gamma ray production. Comparing the calculated total luminosity of the Galaxy above 100 MeV to that observed ($\approx 2 \times 10^{42}$ photons s^{-1}), one can set an upper limit of 10^{-4} for the fraction of antistars in the Galaxy (Steigman 1976).

(4) The existence of positrons can be inferred through Faraday rotation because the sense of rotation depends upon the charge state of the electrons ($e+$ or e^-) assuming that the general magnetic fields have some regularity. Faraday rotation is proportional to $<B_{11}>$ $[n(e^-)-n(e+)]$ where B_{11} is the component of magnetic field along the line of sight, and dispersion measure is proportional to $[n(e^-)+n(e+)]$. Should there be comparable numbers of matter and antimatter clouds, there would be null Faraday rotation along a line of sight. However, the magnetic field strength, deduced from the Faraday rotation measurements using the dispersion measure, is found to be consistent with that deduced from other independent methods. This indicates that interstellar space does not contain equal numbers of matter and antimatter regions.

(5) Diffuse gamma rays above 100 MeV, which is found to be nearly isotropic, can be used to set an upper limit to the amount of matter-antimatter annihilation in the intergalactic medium. Making use of the observational deduction that the observed X-ray background is the result of thermal emission from hot intergalactic gas at 10^8°K, one obtains a limit of 10^{-7} as the fraction of antimatter in the form of hot intergalactic gas (Steigman 1976). In a similar manner, an upper limit of 10^{-8} can be set by attributing the apparent flattening of the diffuse gamma ray spectrum around a few MeV, to annihilation gamma rays created and redshifted from an early epoch of red shift $z \sim 100$ (Stecker et al. 1971).

Though the above upper limits give an impression that antimatter may not exist at all, it is important to realise that these limits only tell us about the fraction of antimatter in gaseous or solid form amidst an environment of matter. On the universal scale, however, it is difficult to reject the hypothesis that they are separated in a large scale into different domains of matter and antimatter.

3. SYMMETRIC COSMOLOGICAL MODELS TO EXPLAIN THE OBSERVATION

One of the important requirements for any symmetric big bang model, which is proposed to explain the lack of antimatter, is that it should also explain the observed ratio of the number of nucleons to that of photons, $\eta = N/N\gamma$, in the present epoch. In the absence of creation and annihilation, N remains constant, and if one neglects the few photons emitted by stars etc., $N\gamma$ also remains unchanged. It is found that the value of $\eta \equiv n/n\gamma \sim 10^{-9\pm1}$ in the present epoch, the density of nucleons n being $10^{-6\pm1}$ cm^{-3}, and the photon density in the universal black body radiation being about $400 cm^{-3}$. In the early epochs, when the temperature and density were high enough, nucleon-antinucleon pairs were created and destroyed. Since baryon number $(N-\bar{N})$ is expected to be conserved, one requires for an unsymmetrical model an excess of only about 1 nucleon to exist for energy 10^9 nucleon-antinucleon pairs during the initial stages when photons and nucleons were in thermodynamic equilibrium.

In the case of simple symmetric big-bang model, equilibrium between particles and radiation was maintained by strong and electromagnetic forces at $t \lesssim 10^{-5}$ sec, which corresponds to a temperature of $KT \gtrsim 300$ MeV and density $\gtrsim 10^{15}$ $g.cm^{-3}$. So long as the equilibrium is maintained through the reaction $N+\bar{N} \rightleftharpoons \gamma + \gamma$, the ratio of N, $\bar{N}$ to photons is, as given by Steigman (1976):

$$\frac{N}{N\gamma} \approx \frac{\bar{N}}{N\gamma} \approx 2 \ (Mc^2/kT)^{3/2} \exp\ (-Mc^2/kT)$$

where M is the mass of nucleon and k the Boltzmann constant. As the temperature decreases, the creation of $N\bar{N}$ decreases and when the density becomes low, annihilation also ceases. Therefore, after a critical age of the universe, corresponding to the annihilation life time of nucleons, nucleon to photon ratio is preserved. This occurs at an age of about 2×10^{-3} sec, and a corresponding temperature $T \approx 20$ MeV. Substituting this value of the temperature in the above equation, one obtains a value of about 2×10^{-18} for η, which is about 9 orders of magnitude smaller than the value estimated from observations in the present epoch. Therefore, in order to avoid annihilation catastrophe in a symmetric model, nucleons and anti-nucleons must be separated before the universe is about one millisecond old. Early attempts to achieve this through statistical fluctuations did not succeed. Detailed studies, to effect phase transition at very high temperature and density, using some properties of high energy physics, have been evolved after Omnes (1970). A summary of these investigations have been discussed by Steigman (1976) and Stecker (1978). In the following, we shall briefly present some relevant aspects.

3.1 Omnes Model:

The main approach in Omnes Model is to show that above a critical density, when phase transition occurs, the free energy of the system, containing strongly interacting nucleons and antinucleons in thermal equilibrium, would be a minimum. This would happen only if the second virial co-efficient in the virial expansion of the free energy is positive. However, a detailed analysis of the accelerator data to derive the virial co-efficient (Bogdanova and Shapiro 1974) showed that the second virial co-efficient is indeed negative! Even if one accepts that the phase transition occurs during the very high density phase of the universe at T> 350 MeV, remixing would take place as the universe expands. In order to prevent total annihilation during this period of remixing, primordial turbulence has been invoked (Aly et al. 1974) to destroy the correlations; annihilation process can provide a continuous source for generating turbulence (Stecker and Puget 1972). Steigman (1976) has investigated the consequences of these processes from the view point of observable parameters. (a) With the uncertainties of various parameters which go into these estimates, a wide range of values can be predicted for η between 10^{-18} and 10^{-1}. (b) Annihilation leads to the distortion of the observed black body photon spectrum if the galaxy formation results from annihilation driven turbulence. (c) Most of the primordial nucleosynthesis takes place during a short period at a temtemperature $\simeq 10^{9}$ °K and if annihilation continues, it is difficult to envisage proper nucleosynthesis to take place due to the photodisintegration of deuterium.

3.2 Alfven-Klein Model:

Alfven and Klein (1962) proposed an unconventional symmetric model in which they assume that the observed part of the universe, called the Metagalaxy, is a finite region of space, having separated out from an infinite static background at a much lower density. The Metagalaxy, containing a homogeneous mixture of matter and antimatter, initially contracts, until the annihilation products exert an isotropic pressure that will halt the collapse and turn it into the observed expansion. This model cannot explain the high isotropy of the microwave background, source distribution etc. without placing the Sun at the centre of the Metagalaxy. This model not only rejects Copernican Principle but also cannot account for the black body radiation (Steigman 1974).

3.3 Grand Unified Theory and Symmetric Cosmology:

The emergence of an unified theory of weak and electromagnetic interactions and the grand unified theory with spontaneous symmetry breaking have opened up possibilities of obtaining the required amount of asymmetry in baryon number in the universe from an initial symmetric state (Weinberg 1979 and references therein). The grand unified models of elementary particle interaction suggest that during the early epoch at $T > 10^{15}$ GeV, CP (Charge Conjugation and Parrty) and baryon number (B) violating forces such as through the decay of superheavy X-boson, generated a large net baryon number. As the universe expanded, there are at least 2 ways by which the observed asymmetry could have evolved. (a) During a brief period following this epoch, B-violating forces were in equilibrium with other forces, annihilating nearly all the previously existing net baryon number and leaving the universe with the small excess of $\sim 10^{-9}$ baryon to every photon. (b) During the above brief period, even if perfect equilibrium existed leading to the annihilation of all the net baryon number, as these forces got out of equilibrium around $T \approx 10^{15}$ GeV, CP and B violating forces (through the interaction of Higgs boson) could have generated the observed baryon to photon number.

4. COSMIC RAYS AS A PROBE TO DETECT ANTIMATTER

We have described in Section 2, various methods of detecting the presence of antimatter, based on identifying either the decay products resulting from annihilation or the effect on physical processes. These have to be detected against a vast background. For instance, in the case of gamma rays, the annihilation products cannot be easily distinguished from those resulting from interaction of cosmic rays with matter; and in the Faraday rotation method, the effect of prositrons is the same as that by negatrons with the magnetic field reversed. Therefore, it may not be possible at all to obtain definitive evidence for the existence of antimatter from such observations. Detection of antimatter in cosmic rays, on the other hand, provides direct evidence for its existence outside the solar system. The main advantage of looking for antimatter in cosmic rays is that they ultimately pervade all galactic space and are not confined to the source regions. Therefore, even if antimatter cosmic ray sources are isolated from matter regions they should be present in cosmic rays.

There are 3 types of antimatter searches that have been made in cosmic rays; they are for (i) positrons, (2) antiprotons and (3) antinuclei of charge $Z \gtrsim 2$. Positrons and antiprotons have been detected in cosmic rays, but they are also created in interactions of high energy cosmic ray nuclei with interstellar gas. Thus, they will provide more information on the propagation of cosmic rays in interstellar space than on the existence of antimatter, unless the flux of the primordial component is comparable to or larger than that of the secondary products. Some of the astrophysical significance of observing cosmic ray antiprotons in relation to deuterium have been discussed elsewhere (Stephens 1978). In the case of antinuclei, only upper limits are obtained so far. In this section, we describe these measurements and discuss the implication of the results.

4.1 Positrons:

Positrons in cosmic radiation have been detected using magnet spectrometers flown at small atmospheric depths using balloons. The early measurements were carried out by the Chicago group (Fanselow et al. 1969 and the references therein) whose spectrometer consists of a permanent magnet with a bending power $\int Bdl \simeq 0.9$ kG.m, a gas Cerenkov counter to reject non-relativistic particles, spark chamber arrays to determine the trajectory, shower spark chamber to distinguish electron shower, and scintillators to define geometry and to determine the charge. Recently, superconducting magnet spectrometers with a bending power $\approx$(3-5) kG.m have been employed by scientists at Berkeley and Johnson Space Center (JSC), and some

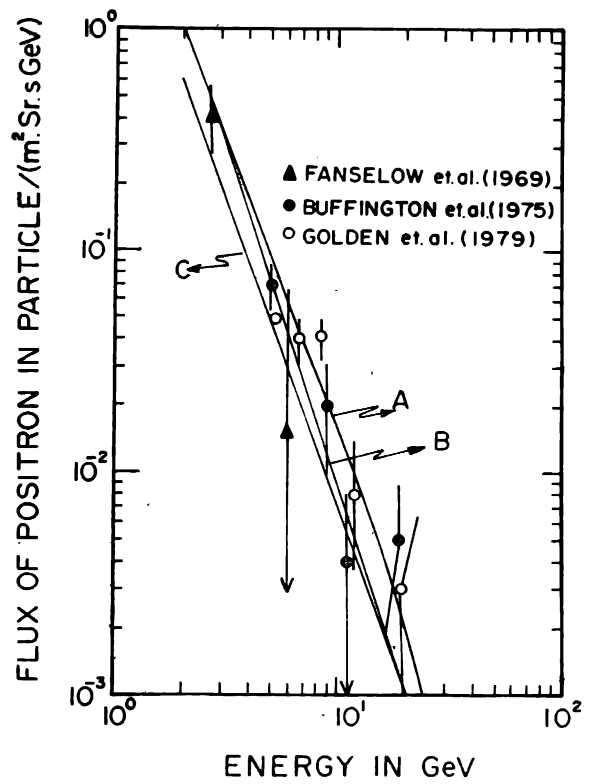

Fig. 1: Differential energy spectrum of cosmic ray positrons. The solid curves are the calculated secondary spectra for various models of cosmic ray propagation.

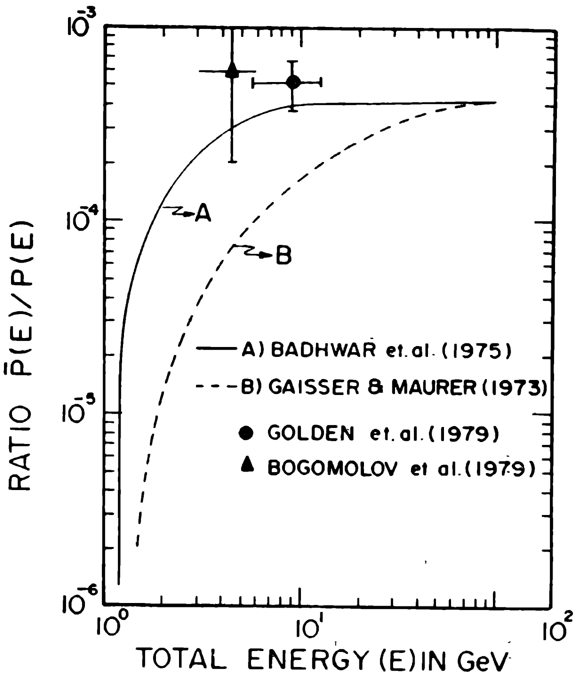

Fig. 2: The ratio of antiprotons to protons as a function of energy. The solid curves are the calculated curves based on secondary production in cosmic rays.

interesting results have been obtained above a few GeV (Buffington et al. 1975; Golden et al. 1979a). These spectrometers consist of a charge identifying module, position sensitive detector to determine the particle curvature (Berkeley used wide gap spark chambers and JSC used multiwire proportional chambers), cascade shower module (lead plate spark chamber by Berkeley and lead plate-scintillator sandwich assembly by JSC). In addition, Berkely group employed a bremsstrahlung radiator to identify positrons uniquely against the vast background of protons, whereas the JSC group utilised a gas Cerenkov counter with a threshold of Lorentz factor $\gamma_L=40$ to eliminate most of the protons below this threshold velocity and the shower profiles to distinguish positrons from the remaining protons which leaked through the gas Cerenkov counter; apart from these, a time of flight device was also used to establish the direction of motion of the particle.

The results obtained from these experiments above a GeV are plotted in Figure 1. The solid curves in this figure represent the calculated secondary positrons due to collisions of cosmic ray nuclei with interstellar gas. These curves have been estimated using the production spectrum given by Badhwar and Stephens (1977), and the leaky box model for the propagation of cosmic rays with (1) a constant life time of 10^7 yr, a mean matter traversal of 5 g.cm^{-2} of interstellar hydrogen, 4μG for galactic magnetic field, and a photon density of about 0.6 eV. cm^{-3} (Curve A) and (2) an energy dependent life time above 3 GeV of the type $(3\ \mathrm{GeV}/E)^{0.5} \times 10^7$ yr, the other parameters remaining the same as above (Curve B). Curve C is based on the nesty leaky box model (Cowsik and Wilson 1973), in which cosmic rays are confined to the source regions in an energy dependent manner, $\propto \exp(-E/7.85\ \mathrm{GeV/n})$, such that a large fraction of the matter traversed by the low energy cosmic rays are within the source regions; in the present estimate, the parameters of this model have been adjusted to 5 g.cm^{-2} of matter traversed at low energies; the life time of cosmic rays and interstellar parameters being the same as of Curve A.

One can notice from Figure 1 that Curve A steepens beyond about 20 GeV by one power as a result of the energy loss processes. Curve B steepens around 3 GeV by half power due to the energy dependent leakage life time and would meet curve A at high energies. Curve C steepens well below a GeV, because the spectrum of positrons injected into the interstellar space is steeper as they are produced by nucleons, whose energy is about 10 times the positron energy with depleted flux in the source region due to energy dependent confinement. The present uncertainties in the experimental results do not allow us to distinguish between the models represented by Curves A and B. However, the observed flux values clearly indicate that the expected positron spectrum on the basis of nested leaky box model (Curve C) is too low. This would mean that either nested leaky box model is incorrect or cosmic rays contain positrons of source origin. In the latter case, the excess of positrons cannot be attributed to the existence of antimatter in cosmic ray sources, because it is not difficult to envisage positrons to be accelerated in sources (Sturrock 1971; Jones 1979). Therefore, the detection of excess positrons in cosmic rays cannot really prove the existence of antimatter in cosmic ray sources.

4.2 Cosmic Ray Antiprotons:

When high energy cosmic ray nucleons interact with interstellar gas nucleon-antinucleon pairs are created; the effective threshold energy for this process is about 10 GeV. The created anti-neutrons decay to antiprotons. Estimates of the ratio of $\bar{p}/p$ in cosmic rays, using accelerator data, have been made and Figure 2 shows two estimates: Curve A (Badhwar et al. 1975) and Curve B (Gaisser and Maurer 1973). While these two calculations give identical results at asymptotically high energies, they differ very much at low energies. The dramatic decrease in this ratio below a few GeV results from threshold effect. One can infer from this figure that detection of antiprotons at non-relativistic energies by annihilation process is difficult unless the detector sensitivity is better than one part in 10^5. Therefore, early attempts to detect antiprotons at nonrelativistic energies failed to give useful conclusions (cf. Apparao 1967).

At relativistic energies, only two experimental groups have so far succeeded in detecting antiprotons in cosmic rays. The first experiment was carried out by the State University of New Mexico (Golden et al. 1979b) using the superconducting magnet spectrometer of the Johnson Space Center, described in the last section. In order to detect antiprotons, negatively charged and singly ionizing particles moving downward without triggering the gas Cerenkov counter (to eliminate most of the electrons, muons, pions and kaons) and showing no shower development (to eliminate electrons which leaked through the Cerenkov counter) were selected. A total of 46 antiproton candidate events were recorded in the rigidity interval 5.6 to 12.5 GV/c. After correcting for atmospheric muons, pions and kaons which leaked through the Cerenkov counter, instrumental background, albedo events and atmospheric antiprotons, the ratio of galactic antiproton to proton is estimated as $(5.2 \pm 1.5) \times 10^{-4}$; this is shown in Figure 2.

The second experiment was carried out by a Russian group (Bogomolov et al. 1979) using a permanent magnet spectrometer consisting of spark chamber arrays to obtain particle curvature, scintillation counters to determine the charge and a gas Cerenkov detector to eliminate particles with $\gamma_L >$ 6.5. The bending power of this magnet is ≈ 0.7 kG.m. From a large number of balloon flights, they have identified 2 antiprotons in the energy bin 3 GeV to 6 GeV and obtained a value of $(6 \pm 4) \times 10^{-4}$ for $\bar{p}/p$ ratio; this is also plotted in Figure 2. We briefly examine this result here. This result has not been corrected for atmospheric antiprotons and for albedo particles. Firstly, they have detected one antiproton in the energy range 1.5 to 2.5 GeV below the geomagnetic threshold, which corresponds to a flux of (0.1 ± 0.1) particle/(m^2.sr.s. GeV). Similarly, the flux of antiprotons, on the basis of the observed 2 antiprotons, in the energy range 3 GeV to 6 GeV is (0.067 ± 0.047) particle/(m^2.sr.s.GeV). An examination of the theoretical curve A in Figure 2 suggests that if the antiproton below 2.5 GeV is atmospheric, the flux above 4 GeV should also be of similar origin. Secondly, if one considers curve B, the estimated flux of atmospheric antiprotons below 2.5 GeV is very small and one may have to attribute the observed antiproton below 2.5 GeV to an albedo particle. Thus the correction due to albedo particle in this experiment could be very large. From the above two arguments and the poor statistics of 2 events, we feel that the $\bar{p}/p$ ratio from this experiment shown in Figure 2 can, if at all, be only an upper limit.

Keeping in mind the possible uncertainties in the calculations and the statistics of the experiment, one infers from Figure 2 that the observed flux of antiprotons are consistent with a secondary origin. If this be so, then the decay life time of antiprotons should be at least as large as the life time of cosmic rays in the Galaxy, i.e. $\gtrsim 10^7$yrs. This upper limit is about 9 orders of magnitude better than that determined from the storage ring experiment (Bregman et al. 1978). It has been pointed out by Golden et al (1979b) that the observed flux value is consistent with the energy dependent life time of cosmic rays in the Galaxy and not in the source regions according to the nested leaky box model (an argument similar to the one used in the case of positrons). It also shows that cosmic rays traverse the bulk of matter only after their acceleration, because of the effective threshold of 10 GeV for the production of antiprotons. Finally, if antimatter exists, the upper limit for antiprotons obtained by comparing the observed flux with curve A is consistent with the upper limits deduced from antinuclei (Table 1).

The above conclusions are based on the calculated curve of Badhwar et al (curve A). However, if one has to compare the observations with curve B, it is quite clear that there is an excess of antiprotons over that of expected secondary flux. This estimated fraction of antimatter (a few times 10^{-4}) is too large compared to the upper limits deduced from antinuclei observation. Therefore, either curve B is incorrect or one needs to look for a mechanism to enhance the flux of secondary antiprotons in cosmic rays (Szabelski et al 1980).

4.3 Antinuclei:

We inferred, from the study of positrons and antiprotons in cosmic rays, that it is difficult to obtain information on the existence of antimatter as a result of the secondary production of these particles in interstellar gas. In the case of antinuclei of charge $Z \geq 2$, the probability of producing them in high energy collisions is negligible, and their presence in cosmic rays would become a direct evidence for the acceleration of antimatter in cosmic ray sources. Further, the detection and identification of relativistic particles of $Z \geq 2$ is very reliable. Therefore, many attempts have been made in the past to look for antimatter in cosmic ray nuclei of charge $Z \geq 2$ using various kinds of detectors. The most versatile of these detectors is the one using superconducting magnet spectrometer. The spectrometer used by the Berkeley group for this purpose contained all elements described earlier except the bremsstrahlung radiator, and they were able to set upper limits to the fraction of antihelium and heavier antinuclei (Smoot et al 1975). In an earlier version of the JSC spectrometer that contained only nuclear emulsions to identify and determine the curvature, upper limits were obtained for the fraction of antinuclei of $Z \geq 3$ (Golden et al 1974). However using the later version described earlier, they were able to set better upper limits to the fraction of antihelium in cosmic rays (Badhwar et al 1978).

TABLE 1.

Antimatter Upper Limits

Rigidity Range R in GV/c	Z	Antimatter to matter ratio upper limit with 95% confidence limit	Reference
$4 \leq R \leq 33$	2	5×10^{-4}	Smoot et al (1975)
$33 \leq R \leq 100$	2	2×10^{-2}	,,
$5 \leq R \leq 10$	2	5.8×10^{-5}	Badhwar et al (1978)
$10 \leq R \leq 33$	2	1.6×10^{-4}	,,
$33 \leq R \leq 100$	2	10^{-2}	,,
$4 \leq R \leq 33$	≥ 3	8×10^{-5}	Smoot et al (1975)
$33 \leq R \leq 100$	≥ 3	6×10^{-3}	,,
$4 \leq R \leq 125$	≥ 3	5×10^{-3}	Golden et al (1974)

The upper limits obtained from these measurements are shown in Table I. One notices from this table that the best upper limits are those obtained for anti-helium by Badhwar et al (1978) of about 6×10^{-5} and for nuclei of $Z \geq 3$ by Smoot et al (1975) of about 8×10^{-5}. It is known that cosmic ray intensities have remained essentially the same over a few billion years, during which time the solar system has made many trips around the Galaxy. This suggests that the observed cosmic rays provide a fair sample of material content of the Galaxy. The upper limits obtained here then tell us that the antimatter content of the Galaxy is less than about 6×10^{-5}. In the energy region considered above, the contribution of cosmic rays from outside the Galaxy is expected to be very small, and hence, it is difficult to deduce information on the antimatter content in the universe.

5. SUMMARY AND FUTURE PROSPECTS

The following are the salient points that arise from the present discussion on the study of antimatter in cosmic rays:

(a) Astronomical observations have provided upper limits to the antimatter content in the Galaxy and in the universe, but they cannot rule out the existence of antimatter in equal abundance in isolated domains.

(b) Though the present theories of symmetric universe are not quantitative enough to be convincing, there lies a potential promise for the future from the grand unified theory to provide the framework by which one could understand the present universe.

(c) It has been shown that the observed positrons in cosmic rays do not provide evidence to the existence of antimatter in the sources. However, positron results permit us to distinguish between various models of cosmic ray propagation.

(d) There is an urgent need to improve the existing observations on positrons, and extend them reliably to lower and higher energies, in order to make definitive conclusion relating to cosmic ray propagation. These experiments have to be performed outside the terrestrial atmosphere using satellites or space probes.

(e) Recently, a finite flux of antiprotons has been discovered in cosmic rays. An important inference from this result is that the decay life time of antiprotons should be at least as large as the residence time of cosmic rays in the Galaxy ($\gtrsim 10^7$yr).

(f) If the observed antiprotons are secondary in origin, they imply, firstly, that cosmic rays traverse insignificant amount of matter during the acceleration phase, and secondly, these observations are inconsistent with the prediction of nested leaky box model for the propagation of cosmic rays. The latter conclusion is supported by positron observation also.

(g) There is a need to determine the energy spectrum of antiprotons reliably over a wide range of energies; these experiments have to be performed outside the atmosphere to eliminate the corrections due to secondary particles. The theoretical calculations should also be examined to remove the existing discrepancy between the two estimates.

(h) Antimatter observations have clearly shown that the fraction of antimatter in the Galaxy has to be $<10^{-4}$. These experiments should be pursued further on a large scale to look for antinuclei, because such observations only can establish or otherwise the existence of antimatter uniquely.

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