(NASA-TM-86156) ON THE NATURE OF THE BARYON ASYMMETRY (NASA) 15 p HC A02/MF A01 CSCL 03B
N85-14784
Unclas
G3/93 24088

NASA

Technical Memorandum 86156

ON THE NATURE OF THE BARYON ASYMMETRY

By F.W. Stecker

August 1984

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

ON THE NATURE OF THE BARYON ASYMMETRY

F. W. Stecker
Laboratory for High Energy Astrophysics
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA

Text of Invited talk given at the International Symposium on Phase Transitions in the Early Universe, Bielefeld, Federal Republic of Germany, June 1984.

To be published in Nuclear Physics B

BIBLIOGRAPHIC DATA SHEET

1. Report No. TM 86156	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ON THE NATURE OF THE BARYON ASYMMETRY		5. Report Date August, 1984
		6. Performing Organization Code 660
7. Author(s) F. W. Stecker		8. Performing Organization Report No.
9. Performing Organization Name and Address Lab. for High Energy Astrophysics		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address		
		14. Sponsoring Agency Code

15. Supplementary Notes

Text of Invited Talk Presented at the International Symposium on Phase Transitions in the Early Universe, Bielefeld, Fed. Rep. Germany, June 1984.

To be published in Nuclear Physics B

16. Abstract

I examine here the question as to whether the baryon asymmetry in the universe is a locally varying or universally fixed number. In particular, I focus on the question as to the existence of a possible matter-antimatter domain structure in the universe arising from a GUT with spontaneous CP symmetry breaking. I review the theoretical considerations and observational data and astrophysical tests relating to this fundamental question.

17. Key Words (Selected by Author(s)) particle theory, cosmology, antimatter, cosmic rays	18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UN	UN	15	

*For sale by the National Technical Information Service, Springfield, Virginia 22161

GSFC 25-44 (10/77)

ON THE NATURE OF THE BARYON ASYMMETRY

F. W. STECKER

NASA Goddard Space Flight Center
Greenbelt, MD 20771, U.S.A.

I examine here the question as to whether the baryon asymmetry in the universe is a locally varying or universally fixed number. In particular, I focus on the question as to the existence of a possible matter-antimatter domain structure for the universe deriving from a GUT with spontaneous CP symmetry breaking. I review thoeretical considerations and astrophysical data and tests relating to this fundamental question.

1. INTRODUCTION

One of the most fundamental questions in cosmology is that of the role of antimatter in the universe. This question, which is connected with that of the nature of CP symmetry breaking in the modern GUT gauge theory paradigm, should also be one of fundamental importance to physics. Yet, it has been dismissed rather superficially in much of the recent literature. In order to address this problem properly, one cannot gloss over the subtleties and look for a quick answer. It is necessary to set up a proper theoretical framework for discussion and to look for empirical tests.

2. GRAND UNIFIED THEORIES AND THE ORIGIN OF THE BARYON ASYMMETRY

The preponderance of baryons over antibaryons in the cosmic radiation provides convincing evidence that the baryons that make up the stars in our galaxy are matter and not antimatter. This asymmetry can be extended to clusters of galaxies fairly convincingly by considering the observed level of γ-ray background radiation and comparing it to theoretical calculations of annihilation radiation if galaxies and antigalaxies were mixed in virialized clusters. However, it is important to note that the observational constraints on cosmological antimatter do not extend beyond the scale of galaxy clusters[1]. Given the fact that there are $\sim10^8$ galaxy clusters in the visible universe, it follows that the observations leave open the possibility that the universe may be baryon symmetric. This possibility has various observational implications which will be discussed. Thus, the fundamental question as to whether antimatter plays an equal role with matter in the makeup of the galaxies remains unanswered, despite claims to the contrary. The choice between the two alternatives, viz., a totally baryon asymmetric universe (TAU) and a locally asymmetric universe (LAU) with overall baryon symmetry, remains one of importance to both particle physics and cosmology.

We base our discussion on a hot big-bang cosmology and the generation of a baryon asymmetry through interactions predicted by grand unified theories (GUTs) which do not conserve baryon number. Sakharov[2] showed that there are three basic conditions which must be fulfilled in order to generate a baryon asymmetry in the early universe, viz., baryon number violation, thermal disequilibrium, and CP violation. The expansion of the universe itself fulfills the thermal disequilibrium condition. The GUT interactions provide the baryon number violation in both the TAU and LAU scenarios. In fact, the critical difference between the TAU and LAU scenarios hinges on the third Sakharov condition, the nature of the CP violation. If the CP violation incorporated into the GUT Lagrangian is hard, the resulting cosmology will be of the TAU type; spontaneous soft CP violation can result in the formation of CP domains which can lead to the production of local baryon excesses and antibaryon excesses in separate regions (LAU) within the context of the standard GUT paradigm[3]. To see this more explicitly, let us consider the Weinberg[4] scenario for baryon production through the decay of superheavy gauge and Higgs bosons (X). (Numerous other authors have worked on calculations of the baryon asymmetry, some of the most extensive being given by Harvey, et al.[5] along with references to earlier work.) With this simple decay into two channels, $X \to q\ell$ (quark, lepton) and $X \to \bar{q}\bar{q}$ with branching ratios r and $1-r$ respectively, and the corresponding antiparticle decays, $\bar{X} \to \bar{q}\bar{\ell}$ and $\bar{X} \to qq$ having branching ratios $\bar{r}$ and $1-\bar{r}$, the baryon number generated in the decays is

$$\Delta B = 1/2\ [1/3r - 2/3\ (1-r) - 1/3\bar{r} + 2/3\ (1-\bar{r})] = 1/2\ (r-\bar{r}). \qquad (1)$$

If CP is conserved, $r = \bar{r}$ and no baryon excess is generated. It is also particularly important in the context of this paper to note that the sign of the CP violation determines the sign of $r-\bar{r}$ and thus the sign of the baryon excess. Thus, whether matter or antimatter is created in a given region of the universe in the early big bang depends on the sign of the CP violation parameter. In the scenarios usually considered, CP violation of one sign only is put into the model explicitly either in the Lagrangian via complex Yukawa couplings between the fermions and scalar fields, or in complex self-couplings of the scalar fields. However, it is also possible for the CP violation to arise from the mechanism of spontaneous symmetry breaking. Such a mechanism has been proposed to explain the smallness of the CP violation implied by the small electric dipole moment of the neutron.[6] Furthermore, if CP is broken spontaneously, the amount of CP violation is finite and calculable, whereas the presently popular baryon production scenarios invoke a "hard" CP violation, leading to infinite renormalizations of the CP parameters, which thus become incalculable undetermined free parameters. With spontaneous CP violation, the Lagrangian is CP invariant (the couplings are real), but the scalar fields themselves take on complex vacuum expectation values, which produce the CP violation.

This type of CP violation is, in principle, calculable. We start out with a completely CP symmetric theory, with the symmetry of the Lagrangian reflected in the state of the universe at the highest temperature. This being the case, owing to the finite age of the univere, t_U, regions separated by distances greater than $\sim ct_U$ are not, and never were during the course of the expansion, in causal contact. Thus if spontaneous symmetry breaking of CP occurred at a time t_{CP}, it would have occurred independently and with random signs in regions separated by distances larger than $\sim ct_{CP}$. We will call these "seed domains" and consider both how they arise and scenarios for their subsequent growth and evolution. This domain structure is not unlike the domain structure generated when a piece of ferromagnetic material cools without the presence of an external magnetic field. In that case, each of the domains contains atoms having their magnetic moments aligned in a given direction. On the average, there will be no preferred direction on a global scale. Analogously, one may expect that spontaneous symmetry breaking processes in the early big bang will most likely break baryon symmetry in localized regions of the universe but will preserve the overall global matter-antimatter symmetry of the initial state. Thus, present ideas of unified gauge theories with spontaneous CP symmetry breaking can lead naturally to a LAU.[3] Senjanović and Stecker have considered mechanisms of spontaneous soft CP violation within the context of the specific grand unified theories involving the SU(5) and SO(10) gauge groups.[7] They discuss two distinct classes of models, viz., those with only one source of CP violation independent of temperature for SU(5) and those in which the CP violation at the superheavy mass scale for SO(10) has nothing to do with the observed CP violation at "low temperatures" in the K^0-$\bar{K}^0$ system. They conclude that, independent of the particular model, the domain picture of the universe emerges naturally in theories of soft CP violation.

In the minimal SU(5) model with only one Higgs multiplet, CP violation has to be put in the Lagrangian "by hand" in the form of complex Yukawa couplings, since the vacuum expectation value of the Higgs field can always be redefined to be real by means of a gauge transformation. Choosing such a hard CP violation yields a baryon-photon ratio unacceptably small compared to that determined by astrophysical observation.[8] It is therefore necessary to increase the number of five-dimensional Higgs multiplets. Increasing this number to three, viz., ϕ_1, ϕ_2 and χ, results in a realistic grand unified theory based on SU(5) that allows for soft CP violation at high temperatures. Two of the Higgs fields ϕ_1 and ϕ_2 acquire vacuum expectation values with a relative phase θ that cannot be transformed away, since they carry the same U(1) quantum number. At $T \gg G_F^{-1/2} = O(M_W)$ the symmetry will still be broken, with $\langle\chi\rangle = 0$, but with $\langle\phi_1\rangle$ and $\langle\phi_2\rangle$ nonvanishing. This is because of the logarithmic temperature dependence of the coupling constants obtained from renormalization group theory. Thus, spontaneous soft CP breaking can occur at the grand unification temperatures where baryons are produced.

The Higgs potential as a function of θ can, in general, be written as

$$V(\theta) = A + B \cos\theta + C \cos 2\theta, \tag{2}$$

where A, B, and C are independent of θ. Obviously, for an appropriate range of parameters, the minimum of the Higgs potential lies at $\theta_0 \neq 0$, with $\cos\theta_0 = -B/4C$, so that we always have two solutions, θ_0 and $-\theta_0$.

The value of $r - \bar{r}$ is proportional to $\sin\theta$. Now, since $\theta = \pm\theta_0$ (the solution of the minimization of the potential), one obtains,

$$n_B/n_\gamma \propto \pm \sin\theta_0. \tag{3}$$

The renormalization group analysis suggests that the symmetry was unbroken at even higher temperatures $T > m_X \approx 10^{15}$ GeV. As the temperature decreased below the mass scale of the superheavy gauge bosons, we expect that separate domains were generated with θ_0 and $-\theta_0$ phases. From Eq. (3), this results in separate regions of matter and antimatter excesses in the universe.

A particularly promising mechanism for producing domains on an astronomically relevant scale has been suggested by Sato[9]. This mechanism depends on the fact that the expansion of the universe can be drastically altered from the standard radiation-dominated relationship if the energy density of the Higgs fields is larger than that of the thermal radiation, producing inflation of the CP domain sizes. This results in an exponential stretching of the domains of CP coherence from their initial size, provided that a first order (discontinuous) phase transition is involved. In the Sato scenario, the universe then supercools significantly below the critical temperature whereupon a rapid universal phase transition releases the energy density of the vacuum fields. The universe then reheats to temperatures where X-particles are produced, which subsequently decay to give baryon and antibaryon regions on a macroscopic scale. The regions of baryon and antibaryon excess may evolve further, possibly leading to the formation of matter and antimatter galaxies in separate regions of the universe.[10]

The symmetry breaking mechanisms which we have been discussing can lead to the formation of various topological structures such as monopoles, strings and domain walls. It has been shown that domain walls, if formed, must disappear at an early stage in order to be consistent with the observed homogeneity of the universe[11]. Vilenkin[12] has considered the dynamics of walls and strings and discussed several mechanisms for wall disappearance such as multiple symmetry breaking. He has also found that domain walls do not reflect light but do repel nonrelativistic particles. Such a repulsion might play a role in keeping matter and antimatter apart at some stage in the early universe. Using an idea reminiscent of the suggestion of Vilenkin, Kuz'min, et al.[13] have demonstrated a method by which domain walls may vanish. Choosing a model based on three Higgs multiplets, similar to that discussed previously, they show how the CP symmetry may be again restored as the universe cools, resulting in the dissipation of the domain walls.

Mohanty and Stecker have recently suggested another possible scenario where the domain walls can disappear naturally.[14] By combining the idea of a srongly interacting SU(5) phase with spontaneous CP violation, they show how the degeneracy between the two different vacua with respect to CP symmetry can be lifted dynamically before the transition from the SU(5) phase to the low energy SU(3) x SU(2) x U(1) phase is completed. The model can be extended to SO(10).

The scenario uses an extension of the model of Ref. 7 with additional heavy fermions. They have employed a Coleman-Weinberg type of Higgs potential where there is no characteristic mass term and where the perturbative potential respects the CP symmetry so that domains will be produced. The phase transition proceeds very slowly due to the flatness of the potential, and supercooling results. As the universe cools, the coupling constant grows stronger and stronger and finally we enter the regime where the non-perturbative effects come into play.

In this strong coupling regime, SU(5) instanton effects give rise to SU(5) singlet condensates of the heavy fermions of the form $\langle\bar{\Psi}_i\psi_i\rangle$. Once such condensates are formed, quadratic and cubic terms like

$$G_Y^2\, m(T)^2 e^{2i\beta}\, \mathrm{Tr}\phi^2 \propto \cos 2(\theta+\beta) \tag{4}$$

and

$$G_Y{}^3 m(T) e^{3i\beta}\, \mathrm{Tr}\phi^3 + \mathrm{h.c.} \propto \cos 3(\theta+\beta) \tag{5}$$

will be induced. Here β denotes the non-absorbable phase of the SU(5) singlet $\langle\bar{\Psi}_i\psi_i\rangle$ condensate. The phase angle β is calculable for the strongly interacting SU(5) phase and is dependent on the fermion masses as in the QCD case. Since β is non-zero, the CP degengeracy will be lifted in the presence of such an induced term in the Lagrangian. The phase β indicates the alligment of vacuum, namely in the direction of the condensates $\langle\bar{\Psi}_i\psi_i\rangle$. As the universe supercools, the direction of the CP symmetry, which is initially different in different domains, is influenced by the condensates to become effectively aligned in their direction. This is very much like the alignment of ferromagnetic domains in the presence of the external magnetic field. The same cubic term which dynamically breaks the degeneracy owing to the discrete symmetry also removes the vacuum degeneracy owing to the initial CP symmetry. As opposed to the model of Ref. 13, the Mohanty-Stecker model leaves CP broken at low energies, broken dynamically by a condensate of heavy fermion pairs. Such a scenario solves the domain wall problem by creating an energy difference between the two CP degenerate vacua, driving the phase transition to a true vacuum state of unique CP. This transition occurs at $T \ll M_{GUT}$, and it will also result in monopole suppression. This scenario also allows a sufficient baryon asymmetry to be produced in the early universe. However, in this case, this asymmetry is <u>local</u> rather than <u>universal</u> owing to the initial CP domain structure which can persist through the supercooling phase. The mechanism suggested by Sato[9] can then act to produce fossil "domains" of baryon and antibaryon asymmetry of survivable size at reheating, after the inflation of the CP domains which occurs during the supercooling phase. A specific GUT model for moderate inflation of extended topological structures has been given by Lazarides and Shafi[15]. The elimination of the CP domain wall problem allows for the possibility of a viable baryon-symmetric domain LAU cosmology.

3. POSSIBLE OBSERVATIONAL INDICATIONS OF A LAU BARYON SYMMETRIC COSMOLOGY

3.1. The Cosmic γ-Ray Background Radiation

One of the most significant consequences of baryon symmetric LAU cosmology lies in the prediction of an observable cosmic background of γ-radiation from the decay of π^0-mesons produced in nucleon-antinucleon annihilations. This is also a most encouraging aspect of this cosmology, since it satisfactorily explains the observed energy spectrum of the cosmic background γ-radiation as no other proposed mechanism does (with the possible exception of hypothetical point sources).

For high redshifts z, when pair production and Compton scattering become important, it becomes necessary to solve a cosmological photon transport equation in order to calculate the γ-ray background spectrum I(E). This integro-differential equation takes account of γ-ray production, absorption, scattering, and redshifting and is of the form

$$\frac{\partial \mathcal{I}}{\partial t} + \frac{\partial}{\partial E}\left[-EH(z)\mathcal{I}\right] = \mathcal{Q}(E,z) - \kappa_{AB}(E,z)$$
$$+ \int_{E}^{\varepsilon(E)} dE' \, \kappa_{sc}(E,z) \quad \mathcal{I}(E;\ E')\, dE'$$

where

$$\mathcal{I}(E,z) = (1+z)^{-3}\ I(E,z)$$
$$\mathcal{Q}(E,z) \equiv (1+z)^{-3}\ Q(E,z) \tag{6}$$

and $\frac{\partial}{\partial t} = -\ (1+z)\ H(z)\ \frac{\partial}{\partial z}$,

$$H(z) = H_0(1+z)(1+\Omega z)^{1/2}$$

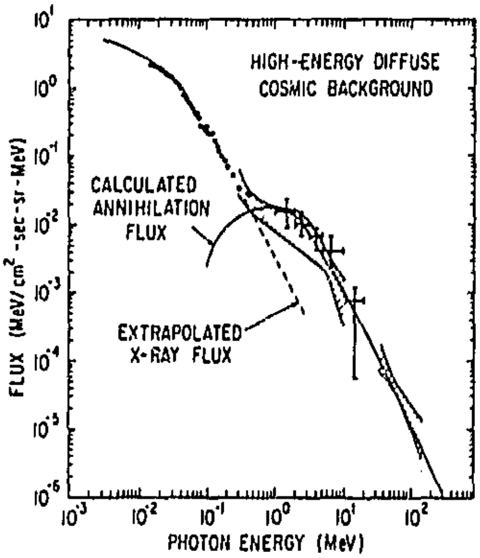

Fig. 1. The Cosmic γ-Ray Background Spectrum: Theory and Observational Data.

The second term in eq. (6) expresses energy loss from the redshift effect. The third term is the γ-ray source term from $\bar{p}p$ annihilation primarily into π^0s. The absorption term is 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. 1 shows the observational data on the γ-ray background spectrum. The dashed line is an extrapolation of the X-ray background component. The calculated annihilation spectrum[21] is also shown. The excellent agreement between the theory and the data is apparent. Other attempts to account for the γ-ray background radiation spectrum by diffuse processes give spectra which are inconsistent with the observations, generally by being too flat at the higher energies.

In Fig. 1 the spectrum is shown as an energy flux. The "bump" in the energy range of 1-10 MeV stands out clearly and can be used as prima facie evidence that a new spectral component dominates in this energy region. The energy flux in this range is a factor of 40 higher than a power law extrapolation of the X-ray component, as shown in the figure.[17]

3.2. Antimatter in the Cosmic Radiation

Measurements of cosmic-ray antiprotons can give us important information about cosmic-ray propagation and also provide a test for primary cosmological antimatter. Data on $\bar{p}$ fluxes at energies[24] above 20 GeV give measured values a factor of 4-10 above the fluxes expected for a standard "leaky box" type propagation models[18]. In fact, the $\bar{p}$ flux integrated over the observed energy range is ~ 7 times the expected flux. But what is particularly striking is that the flux observed in the 150-300 MeV range is orders of magnitude above what is expected (see Fig. 2). The reason that standard secondary $\bar{p}$ production models give a very low flux in the 150-300 MeV energy range is a basic feature of the relativistic kinematics. Antiprotons with less than ~ 1 GeV energy must be produced backward in the cms of the collision, and those with energy as low as 150-300 MeV must be produced by cosmic-ray protons significantly above threshold. Since the cosmic-ray proton energy spectrum falls off steeply with energy, the secondary $\bar{p}$ flux has a natural low-energy

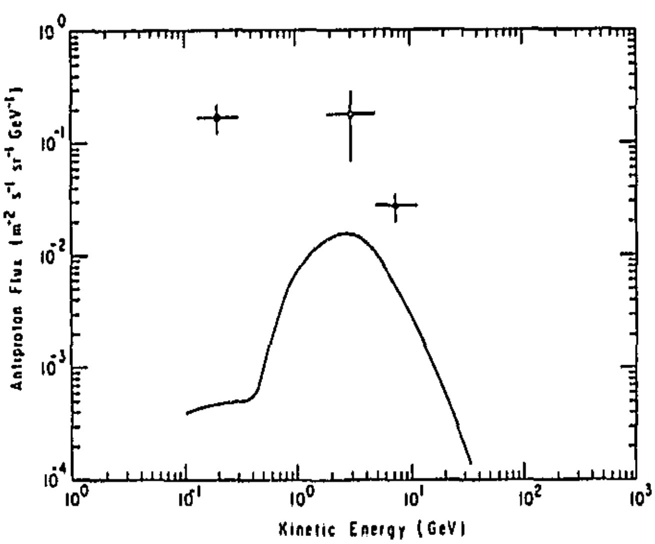

Fig. 2. Cosmic ray antiproton fluxes: Data and predictions from the standard propagation model with energy losses are shown[18].

cutoff. This leaves two explanations for the cosmic-ray $\bar{p}$'s: (1) they are extragalactic primaries, or (2) they are secondary and have undergone significant deceleration. Solar modulation effects will not produce the deceleration required by the secondary hypothesis to account for the 150-300 MeV flux[19].

An extragalactic primary flux from antimatter active galaxies could supply a $\bar{p}$ flux with a ratio $\bar{p}/p \sim 5 \times 10^{-4}$ (Ref. 19), the protons being overwhelmingly galactic in origin[20]. Furthermore, the lack of cosmic-ray $\bar{\alpha}$'s at present detection levels can plausibly be accounted for by spallation and photodisintegration in the cores of active galaxies. Estimated spallation and photodisintegration times of $\tau_{sp} \sim 0.2 - 6 \times 10^{4}$ yr and $\tau_{pd} \sim 3 \times 10^{8}$ yr are made for these sources. Finally, it is predicted that the $\bar{\alpha}/\alpha$ ratio should be determined by $\bar{\alpha}$ acceleration in normal antimatter galaxies and that the resultant flux should be in the range[19] $5\times10^{-6} \lesssim \bar{\alpha}/\alpha \lesssim 10^{-5}$. It is also estimated that extragalactic cosmic-rays can reach us by diffusion from distances of up to 500 Mpc.

Other possible explanations for the cosmic-ray $\bar{p}$ flux have recently been reviewed[18]. These alternatives appear to have serious problems. Production of $\bar{p}$'s through n-$\bar{n}$ oscillations gives a flux orders of of magnitude below the observed flux. Galactic primordial black holes are quite ad hoc. Suggestions for secondary generation and deceleration of $\bar{p}$'s in galactic cosmic-ray sources have various energetics problems.

4. FUTURE TESTS OF A LAU BARYON SYMMETRIC COSMOLOGY

Let us first consider cosmic ray spectrum and charge measurements. The measured spectrum of galactic cosmic radiation can be represented by a power law in energy of the form $KE^{-\Gamma}$ with the spectral index $\Gamma \simeq 2.75$ for several decades above the 10 GeV energy level. The source spectrum of this radiation is expected to have a lower spectral index, Γ_s of $\sim$ 2.0 to 2.2. This appears to be likely for two reasons. (1) Measurements of the ratio of secondary to primary nuclei in the cosmic radiation suggest that the mean lifetime in the Galaxy due to trapping by the tangled galactic magnetic fields falls with energy as $E^{-\delta}$ where the value[21] of δ is about 0.7. (2) If there exists a general acceleration mechanism for generating cosmic rays which acts in both galactic and extragalactic sources to give a universal source spectrum with $\Gamma \simeq 2$, as is now thought to be case with shock acceleration[22], the extragalactic cosmic ray component should reflect this source spectrum. Thus, with the antiprotons assumed to be both primary and extragalactic and the bulk of the protons assumed to be galactic, the $\bar{p}/p$ ratio should increase with energy as E^{δ}. Taking $\delta \simeq 0.7$, antiprotons could make up approximately 1% of the cosmic ray flux at an energy of $\simeq$ 500 GeV and even $\sim$ 50% at higher energies. This has important observational implications as pointed out by Stecker and Wolfendale[23]. Such an extrapolation implies that the extragalactic and galactic cosmic ray fluxes may become comparable at an energy of $\sim 10^5$ GeV, and that extragalactic particles may predominate above this energy. It is interesting to note that the resultant flattening in the spectrum occurs at this particular energy, as there have been claims[24] of a flattening in the cosmic ray spectrum as inferred from measurements of extensive air showers. Measurements of the sign of the charges of cosmic rays at the highest practical energy and the determination of the spectra of the various charged components of the cosmic radiation up to that energy will provide a test of the LAU hypothesis. Such a test requires that the detector be placed above the atmosphere so that the incoming cosmic ray nuclei can be measured directly. The sign of the charged particles (and their magnitude) may be measured by using a superconducting magnet. Such an experiment, with an attainable energy of ~ 0.5-1 TeV, could be flown aboard the Space Shuttle.

In addition, an emulsion stack experiment could be flown on a high-altitude balloon or the Space Shuttle to look for antihelium nuclei. A polar or near-polar orbit would be desirable to avoid the geomagnetic cutoff. In view of the almost impossible odds of creating a secondary ^{4}He antinucleus, the unambiguous detection of even one such particle would provide irrefutable evidence of primary cosmic ray antimatter. The extent to which a null result would disprove the hypothesis is unclear, but if $\bar{\alpha}/\alpha \ll 10^{-5}$ (the value estimated for $\bar{\alpha}$'s leaking from normal antimatter galaxies[19]), the difficulty would be severe. Suggestions to look for cosmic ray $\overline{\mathrm{Fe}}$ have also been made.[25]

Several suggestions have been made for using high-energy neutrino astronomy to look for antimatter elsewhere in the universe[26]. These suggestions are all based on the fact that cosmic ray pp and $p\gamma$ interactions favor the secondary production on π^+'s over π^-'s, whereas for $\bar{p}\bar{p}$ and $\bar{p}\gamma$ interactions the situation is reversed. The subsequent decay of the pions results in equal amounts of ν_μ's and $\bar{\nu}_\mu$'s of almost equal energies. However, π^+ decay leads to ν_e production, whereas π^- decay leads to $\bar{\nu}_e$ production. A production mechanism of particular importance in this context because of its large inherent charge asymmetry, involves the photoproduction of charged pions by ultrahigh energy cosmic rays interacting with the universal 3K blackbody background radiation. The most significant reactions occur in the astrophysical context principally through the Δ resonance channel.

There is a significant and potentially useful way of distinguishing ν_e's from $\bar{\nu}_e$'s, namely through their interactions with electrons. The $\bar{\nu}_e$'s have an enhanced cross section through resonance formation of the W^-. For electrons at rest in the observer's system, the resonance occurs for cosmic $\bar{\nu}_e$'s of energy $M_W^2/2m_e = 6.3 \times 10^3$ TeV.

The cosmic and atmospheric fluxes for $\bar{\nu}_e$'s based on cosmic ray production calculations have been given[27]. Assuming that there is no significant enhancement in the flux from production at high redshifts, the integral $\bar{\nu}_e$ spectrum from $\gamma\bar{p}$ interactions is expected to be roughly constant at 10^{-18} to 10^{-17} $\bar{\nu}_e$'s cm^{-2} sr^{-1} up to an energy of $\sim 2 \times 10^7$ TeV, above which it is expected to drop steeply. It is expected that the largest competing background flux of $\bar{\nu}_e$'s will be prompt $\bar{\nu}_e$'s from the decay of atmospherically produced charmed mesons. An acoustic deep underwater neutrino detector may provide the best hope for testing for cosmic antimatter by studying the diffuse background neutrinos.[28] The practical threshold for such devices appears to be in the neighborhood of 10^3 - 10^4 TeV. Acoustic detectors of effective volume >> 10 km^3 (10^{10} tons) may be economically feasible and event rates of $\sim 10^2$ - 10^4 yr^{-1} may be attained in time.

Future observations of angular fluctuations in the 100 MeV γ-ray background radiation using the Gamma Ray Observatory satellite could also play a key role in determining whether the flux is from point sources or more diffuse "ridges" from annihilations on the boundaries of "fossil" domains. Studies of primordial light element abundances[29] and short wavelength distortions of the cosmic far infrared background radiation[30] with the Cosmic Background Explorer satellite may also provide future tests of the nature of the baryon asymmetry of the universe.

REFERENCES

1) F. W. Stecker, Nature 273 (1978) 493; A. J. Allen, Mon. Not. R. astr. Soc. 197 (1981) 679.

2) A. D. Sakharov, JETP Lett. 5 (1967) 24.

3) R. W. Brown and F. W. Stecker, Phys. Rev. Letters 43 (1979) 315.

4) S. Weinberg, Phys. Rev. Letters 42 (1979) 850.

5) J. A. Harvey, E. W. Kolb, D. B. Reiss and S. Wolfram, Nucl. Phys. B177 (1981) 456.

6) Eg., R. N. Mohapatra and G. Senjanović, Phys. Lett 89B (1979) 57.

7) G. Senjanović and F. W. Stecker, Phys. Lett. 96B (1980) 285.

8) S. Barr, G. Segre and H. A. Weldon, Phys. Rev D20 (1979) 2949; A. Yildiz and P. Cox, Phys. Rev. D21 (1980) 906.

9) K. Sato, Phys. Lett. 99B (1981) 66.

10) F. W. Stecker and J. L. Puget, Astrophys. J. 178 (1972) 57; N. Dallaporta, L. Danese and F. Lucchin, Astrophys. Space Sci. 27 (1974) 497.

11) Ya. B. Zeldovich, I. Yu. Kobzarev and L. B. Okun, Sov. Phys. JETP 40 (1975) 1.

12) A. Vilenkin, Phys. Rev. D23 (1981) 852.

13) V. A. Kuzmin, I. E. Tkachev and M. E. Shaposhnikov, Phys. Lett. 105B (1981) 167.

14) A. K. Mohanty and F. W. Stecker, Phys. Lett. 143B (1984) 351.

15) G. Lazarides and Q. Shafi, Phys. Lett B, in press.

16) F. W. Stecker, Ref. 1.

17) F. W. Stecker, in Early Evolution of the Universe and Its Present Structure eds. G. O. Abell and G. Chincarini (Reidel, Dordrecht, 1983) pp. 437-443.

18) Data reviewed by R. J. Protheroe in Composition and Origin of Cosmic Rays ed. M. M. Shapiro (Reidel, Dordrecht, 1983) pp. 119-124.

19) F. W. Stecker, R. J. Protheroe and D. Kazanas, Astrophys. and Space Sci. 96 (1983) 171.

20) F. W. Stecker, Phys. Rev. Lett. 35 (1975) 188; D. Dodds, A. W. Strong and A. W. Wolfendale, Mon. Not. R. astr Soc. 171 (1975) 569.

21) J. F. Ormes and R. J. Protheroe, Astrophys. J. 272 (1983) 756.

22) I. Drury, W. I. Axford and D. Sommers, Mon. Not. R. astr. Soc. 198 (1982) 833.

23) F. W. Stecker and A. W. Wolfendale, Nature 309 (1984) 37.

24) J. Kempa, J. Wdowczyk and A. W. Wolfendale, J. Phys. A7 (1974) 1213.

25) S. P. Ahlen, P. B. Prince, M. H. Salamon and G. Tarlé, Astrophys. J. 260 (1982) 20.

26) J. G. Learned and F. W. Stecker in Proc. Neutrino 79 Intl. Conf. eds. A. Haatuft and C. Jarlskog (U. Bergen, Bergen, 1980) Vol. 2, pp. 461-470; V. S. Berezinsky and V. L. Ginzburg, Mon. Not. R. astr. Soc. 194 (1981) 3. R. W. Brown and F. W. Stecker, Phys. Rev. D26 (1982) 373.

27) F. W. Stecker, Astrophys. J. 228 (1979) 919.

28) Brown and Stecker, Ref. 26.

29) F. W. Stecker, Phys. Rev. Lett. 44 (1980) 1237; V. M. Chechetkin, M. Yu. Khlopov and M. G. Shapozhnikov, Rivista del Nuovo Cimento 5 (1982) No. 10.

30) F. W. Stecker and J. L. Puget, in Gamma Ray Astrophysics eds. F. W. Stecker and J. I. Trombka, U. S. Govt. Printing Office, Washington, 1973) pp. 381-384.