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Cosmology is often wrong but never in doubt.

L. Landau

Every man takes the limits of his own field of vision for the limits of the world.

A. Schopenhauer

1. INTRODUCTION

It has been proposed by Heisenberg (1967) and Fritzsch and Minkowski (1975) that the fundamental Lagrangian of nature should be completely symmetric and that all observed asymmetries are due to asymmetries in the vacuum state. Thus, all asymmetries would arise from spontaneous symmetry breaking of the ultimate grand unified theory. The full symmetry of the theory is expected to hold in the interactions above some critical temperature T_c. Below that critical temperature, multiple vacuum states can be arrived at by the process of spontaneous symmetry breaking. Each "state" corresponds to a unique set of vacuum expectation-values of scalar fields (or their equivalent) which, having been randomly determined through a dynamical instability, themselves determine a new, selfcontained gauge-field theory. Thus, a theory of nature is arrived at randomly from a number of equally probable theories, the original Lagrangian not having uniquely determined the "low-temperature" physics which we observe at our accelerators.

The symmetry breaking process has been compared to spontaneous magnetization of a piece of ferromagnetic material cooled below the Curie temperature. In this case, it is well known that domains are formed, each of which having its own randomly determined direction of magnetization. We are comfortable with the ferromagnetism case because we accept the fact that the original symmetry in the physics is still reflected by the fact that there is no overall preferred direction of magnetization so that, in the absence of an external magnetic field, a "large enough" sample will possess no net magnetization even though the spontaneous magnetization will be quite evident on the scale of an individual domain, destroying the symmetry locally.

It thus becomes possible to envision that in remote regions of the presently observable universe, a different self-contained field theory may hold (as defined by the set of vacuum expection values of scalar fields) or, at least, may have held at some point in the evolution of the universe. This is what the process of spontaneous symmetry breaking implies, provided that the various "domains", over which the randomly determined parameters of the broken gauge theory hold, were not in causal contact at the time the dynamical instability occurred. Because of the finite light-travel time and age of the universe at the time of symmetry breaking, we are of necessity, dealing with field theories which held over finite regions (horizon sizes) of the universe. These differences in the "laws of nature" which involve particle physics at very high energy can, for the most part, be expected to show up only locally in very subtle and sophisticated accelerator experiments, thus giving us the comfortable intuitive feeling of the uniqueness of all physical laws which has successfully guided us in the past. But the past has also taught us that intuition derived from more familiar situations (classical macrophysics, low velocity physics) can be misleading when extrapolated to less familiar, more subtle, or newly considered phenomena.

There is at least one phenomenon of truly cosmic significance for which it is clear that the concept of "locally asymmetric" physics from spontaneous symmetry breaking should be considered. That phenomenon is the scenario for the creation of "baryon asymmetries" in the early big-bang from spontaneous symmetry breaking of grand unified gauge theories. When considered in the framework described above, we see the real possibility that the created baryon asymmetries are "local" in cosmic sense; the spontaneous symmetry breaking process (in this particular case of CP symmetry) may lead to the creation of separate domains of baryon and antibaryon excess with various real observational and theoretical consequences. Indeed, as we will see, various astrophysical data such as the cosmic γ-ray background spectrum, cosmic-ray $\bar{p}$ flux measurements, recent determinations of a low primordial He abundance, and galaxy clustering can be interpreted as favoring this point of view.

2. UNIFIED GAUGE FIELD THEORIES

The various fields describing the forces of nature can be represented by the symmetries they possess in terms of the transformations of the quantum systems they produce which leave the Lagrangian invariant. The generators can be related to generalized charges. For example, in the case of QED, conservation of charge can be derived from the symmetry with respect to a one parameter phase transformation called a gauge transformation, with the generator being electric charge. The symmetry group is the unitary group U(1). The electromagnetic field $A_\mu(x)$ is introduced by requiring invariance under local gauge transformations $\lambda(x)$ and requiring that the derivatives of the charged fields transform in the same way as the fields themselves. This leads to the introduction of a gauge covariant derivative with an additional term involving eA_μ so that A_μ enters the theory through the kinetic energy term in the Larangian.

More complex gauge fields can be constructed from generators which preserve the form of the Lagrangian under more complex symmetry groups involving larger numbers of parameters, i.e., group spaces of higher dimension. These generators obey Lie algebras. An example of importance to the unified field theory of electromagnetic and weak interactions, is the gauge group SU(2), the unitary group whose fundamental representation consists of two-dimensional (traceless) matrices of determinant + 1. For this group, the generators can be represented by the familiar Pauli spin matrices. The demand for local gauge invariance under SU(2) transformations, as in the case of QED, requires the introduction of a new gauge field B_μ and coupling constant g (instead of e) in the covariant derivative.

In the electroweak theory of Glashow, Weinberg and Salam (GWS) the gauge group is a product SU(2) x U(1). In the quantum gauge theory of strong interactions, QCD (quantum chromodynamics), the generalized charges are referred to as colors. In GWS, the four transformation parameters result in the four gauge bosons γ (photon), $W^\pm$, Z^0 the heavy bosons which carry the weak charged and neutral currents. For an SU(n) theory, there are n^2-1 free parameters. In QCD or color SU(3) there are $3^2-1 = 8$ gluons which carry the force. In the simplest grand unified theory, viz. SU(5), there are a total of 24 gauge bosons, γ, $W^\pm$, Z^0, the 8 gluons and 12 new superheavy bosons, $X^{4/3}$, $Y^{1/3}$ of all three colors together with their antiparticles (Georgi and Glashow 1974). It is these bosons which are responsible for the "leptoquark" force which can transform quarks into leptons and vice versa, violating baryon number and producing an excess of matter (or antimatter) out of the primordial thermal radiation. (For further discussion, see, e.g., Stecker 1980b, Langacker 1981).

3. SPONTANEOUS SYMMETRY BREAKING

Of course, in our world of "low temperature" physics much of the symmetry of the unified theories is badly broken, leaving only $SU(3)_C$ and $U(1)_{EM}$. This is reflected in the large masses of all of the gauge bosons except γ and the gluons (which are massless) and the corresponding weakness of the weak and leptoquark interactions. The broken symmetries are incorporated into the theory by keeping the full symmetry in the Lagrangian but allowing the gauge bosons to obtain their masses "spontaneously" as the result of introducing new scalar (or "Higgs") fields which have a non-zero vacuum expectation value. One big advantage of the Higgs mechanism is that it allows the construction of a theory which is renormalizable, i.e., for which the calculations of observables give finite results. The way the Higgs mechanism works is as follows. Consider for example, a real scalar field whose contribution to the Lagrangian takes the form

$$L_s = \frac{1}{2} (\partial_\mu \phi)(\partial^\mu \phi) - V(\phi) \quad (1)$$

where the potential term is an even function $V(\phi) = V(-\phi)$. Consider, e.g., a potential of the form

$$V(\phi) = \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4 \quad (2)$$

where $\lambda > 0$ so that the energy is bounded from below. In the case $\mu^2 < 0$, $V(\phi)$ has minima at

$$\langle \phi \rangle = \pm \left(\frac{-\mu^2}{\lambda}\right)^{1/2} \equiv v \quad (3)$$

which gives, by definition, the vacuum expectation value for ϕ. The Lagrangian gives the equation of motion for scalar particles of mass $\sqrt{2\lambda}\, v$ excited near a ground state v. Note that for $\phi = \phi - v$, $V(\phi) \neq V(-\phi)$ and the symmetry is broken.

If ϕ couples to fermions with a coupling of the Yukawa form

$$L_Y = f\phi\bar{\psi}\psi \quad (4)$$

the Higgs field ϕ gives fermions masses of order fv. Thus, without explicitly introducing masses into the Lagrangian, the Higgs mechanism produces masses in the theory which are proportional to v, i.e., $m_f \sim fv$, $m_\phi \sim \sqrt{2\lambda}\, v$, $m_B \sim gv$.

For a more detailed discussion of this mechanism of spontaneous symmetry breaking, see, e.g., Albers and Lee (1973) and Beg and Sirlin (1974). So far we have spoken of vacuum expectation values $\langle\phi\rangle$ of the scalar fields in a zero-temperature theory with the symmetries of the Lagrangian broken by the Higgs mechanism. The cosmological implications come in when we consider what happens as T increases to temperatures $T \gtrsim \langle\phi\rangle$. In this case some, or all, of the symmetry in the theory may be restored (e.g. Weinberg 1974, Linde 1979) i.e., $\langle\phi\rangle_T \to 0$ for $T > T_c$ (some critical temperature) and the corresponding masses go to zero. A direct analogy can be made here with the theory of superconductivity, where the Cooper pairs play the role of Higgs particles and the photon acquires an effective mass for $T < T_c$ which disappears at $T > T_c$ (the Meissner effect). In the finite temperature case, the Higgs fields have a thermal distribution of excitations and the vacuum expectation value is replaced by the operator Gibbs average. In the simple case of equation (2) the resulting potential acquires an effective quadratic term

$$-\mu^2_{eff}(T) \simeq -\mu^2 + \sigma T^2 \quad (5)$$

and critical temperature $T_c = |\mu|\sigma^{-1/2}$ where $\mu_{eff} = 0$ in the case $\sigma > 0$. In general, σ is a function of the coupling constants of the model.

4. BARYON PRODUCTION IN THE EARLY UNIVERSE

In the early big-bang, if the dynamics of the universe is dominated by the energy density of the thermal radiation, the temperature of the universe $T \propto 1/\sqrt{t}$, where t is the age of the universe. (The exception is when the expansion is dominated by the energy density of the Higgs field. That case will be discussed later.)

The critical temperature for symmetry breaking at the electroweak level, i.e., $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ is usually considered to be of order $1/\sqrt{G_F} \simeq 300$ GeV, but as one can see from equation (5), T_c depends on the specific parameters of the theory. In fact, it is possible that $T_c >> 1/\sqrt{G_F}$ as we will discuss later. The characteristic temperature scale for grand unification is given by the energy scale at which the coupling constants for the electroweak gauge groups and strong gauge group become comparable. This is given from renormalization group theory to be of order $\sim 10^{15}$ GeV, above which for the SU(5) theory only one coupling constant, associated with this simple gauge group, exists. Thus, it is at this temperature level, $T \sim m_X$, that baryon generation processes will be of importance.

A scenario for baryon production through the decay of these superheavy gauge and Higgs bosons has been given by Weinberg (1979). He considered the decay of these "X-bosons" into two channels $X \to ql$ and $X \to \bar{q}\bar{q}$ with branching ratios r and 1-r respectively, together with the antiparticle decays $\bar{X} \to \bar{q}\bar{q}$ and $\bar{X} \to qq$ with branching ratios $\bar{r}$ and $1-\bar{r}$.

The three conditions for production of a baryon excess in the early universe are (1) baryon (quark) nonconservation, (2) nonconservation of C (charge conjugation) and CP (C x parity) and (3) thermal disequilibrium (Sakharov, 1967). We have seen that grand unification supplies condition (1). The expansion of the universe supplies condition (3). The need for condition (2) can clearly be seen in the Weinberg scenario. The baryon number generated in the X and $\bar{X}$ decays is

$$\Delta B = \frac{1}{2}\left[\frac{1}{3}r - \frac{2}{3}(1-r) - \frac{1}{3}\bar{r} + \frac{2}{3}(1-\bar{r})\right] = \frac{1}{2}(r-\bar{r}) \quad . \qquad (6)$$

If CP is conserved, $r = \bar{r}$ and no baryon excess is generated. It should also be noted that the sign of the CP violation determines the sign of $r - \bar{r}$ and therefore the sign of ΔB. Thus, whether a baryon excess or an antibaryon excess is created by this process depends on the sign of the CP violation parameter. The result is a baryon-to-photon ratio

$$\eta \equiv \frac{n_B}{n_\gamma} \sim (10^{-3}-10^{-2})\ \Delta B \qquad (7)$$

where ΔB is given by equation (6). From astrophysical observations, one obtains $10^{-10} \lesssim \eta \lesssim 10^{-8}$. Nanopoulos and Weinberg (1979) conclude that the decays of the superheavy scalar bosons are most relevant for cosmological baryon production. They estimate that $10^{-8}\ \varepsilon \lesssim \Delta B \lesssim 10^{-6}\varepsilon$. The parameter ε, is a parameter characterizing the strength of CP violation. Nanopoulos and Weinberg estimate $10^{-9} \lesssim |\eta| \lesssim 10^{-3}$ immediately after the era of baryon production, the sign being undetermined. (Numerous other authors have also worked on the problem of estimating η . See, e.g., Kolb and Wolfram, 1980a; Langacker 1981 and references therein.)

5. CP VIOLATION AND COSMOLOGICAL IMPLICATIONS

It follows from the discussions of the previous section that the sign of the baryon number excess, which determines whether matter or antimatter is created, 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 in the Lagrangian via complex Yukawa couplings between the fermions and scalar fields, i.e., L_Y of the form in equation (4) with f complex, or in complex self couplings of the scalar fields, i.e., λ complex in the potential term $\frac{1}{4}\lambda\phi^4$. 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 (Mohapatra and Senjanović 1978). 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 parameter which thus become incalculable undetermined free parameters. With spontaneous CP violation the Lagrangian is CP invariant (f and λ real), but the scalar fields themselves take on complex vacuum expectation values which produce the CP violation. In this second case, the CP violation is not put in by hand ad hoc. 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 temperatures. This being the case, owing to the finite age of the universe 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 $\sim ct_{CP}$. The symmetry of the Lagrangian becomes hidden on a small scale. However, there will be no preferred direction on a global (universal) scale. 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 an overall baryon-symmetric cosmology as suggested by Brown and Stecker (1979). Kolb (1981) has pointed out an interesting fact relevant to the question of domain size and structure from percolation theory. He notes that the effective domain size will be much larger than the causal horizon when the symmetry is broken, owing to the statistics of the problem. Thus, a spectrum of size scales will result, including large scale domain structure.

Senjanović and Stecker (1980) 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. 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 super-heavy 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 independently 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 "by hand" in the Lagrangian 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 which is unacceptably small compared to that determined by astrophysical observation (Barr, Segrè and Weldon 1979; Yildiz and Cox 1980). It is therefore necessary for consistency to increase the number of 5-dimensional Higgs multiplets. Increasing this number to three results in a realistic grand unified theory based on SU(5) which allows for soft CP violation at high temperatures. Two of the Higgs fields acquire vacuum expectation values with a relative phase which cannot be transformed away, since they carry the same U(1) quantum number. Senjanović and Stecker consider a Higgs sector with three 5-dimensional multiplets with the following pattern of symmetry breaking at the electroweak level ($T \lesssim 300$ GeV):

$$\langle\chi\rangle = \begin{pmatrix}0\\0\\0\\0\\\rho\end{pmatrix}, \quad \langle\phi_1\rangle = \begin{pmatrix}0\\0\\0\\0\\v_1\end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix}0\\0\\0\\0\\v_2e^{i\theta}\end{pmatrix} \tag{8}$$

It can be shown that at $T >> 300$ GeV the symmetry will still be broken, with $\langle\chi\rangle = 0$ but with $\langle\phi_1\rangle$ and $\langle\phi_2\rangle$ nonvanishing. This follows from having the coefficient μ_{eff} of the quadratic terms in the Lagrangian for $V(\phi_1,)$ and $V(\phi_2)$ of the form given by equation (5) with $\sigma < 0$ at $T \sim 300$ GeV. Then, noting that σ is a slowly varying function of T, owing to the logarithmic temperature dependence of the coupling "constants" (obtained from renormalization group theory), in some cases $\sigma(T)$ becomes positive for $T_c \gtrsim m_x$. Thus, spontaneous soft CP breaking at the electroweak level can be effective even at baryon production temperatures.

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

$$V(\theta) = A + B\cos\theta + C\cos 2\theta \tag{9}$$

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

The value of $r-\bar{r}$ is proportional to $\sin\theta$. Now since $\theta = \pm\theta_o$ (the solution of the minimization of the potential), one obtains from equation (7)

$$\eta \propto \pm \sin \theta_o \qquad (10)$$

The renormalization group analysis suggests the possibility that at even higher temperatures $T > m_X \simeq 10^{15}$ GeV, the symmetry was unbroken. Then as the temperature decreased below the mass scale of the superheavy gauge bosons, we expect that separate domains were generated with θ_o and $-\theta_o$ phases. Therefore from equation (10) it is obvious that one is bound to expect domains with matter and antimatter excesses in the universe. Senjanović and Stecker also considered a recently suggested model (Harvey, Ramond and Reiss 1980), based on the SO(10) grand unified theory. The idea is that a 126-dimensional representation of Higgs fields can be shown to be able to acquire a complex vacuum expectation value for a range of parameters of the Higgs potential. Therefore, one can have CP violation at the unification temperature scale completely independent of the nature of the light (electroweak) Higgs sector. (This situation is to be contrasted with the SU(5) theory, where the heavy Higgs ($\sim m_X$) sector is chosen to be a 24-dimensional, or adjoint representation, whose vacuum expectation value is always real.) Again, as in the previous example, one can show that $\pm\, \theta_o$ are solutions which minimize the potential.

6. DOMAIN GROWTH AND HORIZON GROWTH

The above discussion suggests that the initial domains were formed at a time when the temperature of the universe was comparable to the masses of the superheavy gauge or Higgs bosons involved in the symmetry breaking. A particularly promising mechanism for producing domains on an astronomically relevant scale has been suggested by Sato (1981). 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 field is larger than that of the thermal radiation.

In the early, high temperature universe, using the Robertson-Walker metric, the Einstein equations reduce to

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{\kappa}{R} + \frac{\Lambda}{3} + \frac{8\pi G\varepsilon}{3} \simeq \frac{8\pi G}{3}\,(\varepsilon_r + \varepsilon_v) \quad . \qquad (11)$$

For $\varepsilon_r >> \varepsilon_v$ with $\varepsilon_r \propto T^4$, equation (16) yields the standard result $T \propto 1/\sqrt{t}$. However, when $\varepsilon_v >> \varepsilon_r$ and for temperatures not near the critical temperatures for symmetry breaking, $\varepsilon_v(T) \simeq$ const., and it follows from equation (16) that the universe expands exponentially. This rapid expansion is a result of the large negative pressure of the vacuum (Bludman and Ruderman 1977; Kolb and Wolfram 1980b; Guth 1981). The result is an exponential stretching of the domains of CP coherence from their initial size, provided a first order (discontinuous) phase transition is involved. In the Sato scenario, the universe then supercools below T_c to a T_{c1} whereupon the transition becomes second order (continuous) or possibly driven, (<u>cf</u>. Witten 1981) whereupon a rapid universal phase transition releases an energy density ε_v. The universe then reheats to temperatures where X-particles are produced, which subsequently decay to give baryon and antibaryon asymmetries on a macroscopic scale. These exponentially stretched domains of baryon and antibaryon excess may evolve further (Omnes 1972) leading to the formation of matter and antimatter galaxies in separate regions of the universe (Stecker and Puget 1972). This picture is outlined in Figure 1.

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, which could affect the dynamics and isotropy of the universe. The problem of monopole formation has received the most attention since, for simple grand unification scenarios, the production of these particles would result in the universe having a mass density many orders of magnitude higher than astronomical observations allow (Zel'dovich and Khlopov 1978; Preskill 1979). Some suggestions for solving the monopole problem involve the exponential stretching process discussed in the last section and multiple phase transition (symmetry breaking) scenarios (Langacker and Pi 1980). The breaking of discrete symmetries can lead to domain wall formation, and it has been argued that such walls, if formed, must disappear at an early stage in order to be consistent with the observed homogeneity of the universe (Zel'dovich, Kobzarev and Okun 1974). Clearly, the exponential stretching mechanism which has been invoked to solve the monopole problem could also alleviate the wall problem while providing a mechanism for domain growth. Vilenkin (1981) has considered the dynamics of walls and strings and discussed several mechanisms for wall disappearance, one of which again involves 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 (1981), Kuz'min, Tkachev and Shaposhnikov (1981) have demonstrated a method by which domain walls may vanish. Choosing a model based on three Higgs multiplets, similar to that discussed previously, these authors show how the CP asymmetries operative at the baryon production stage may be restored as the universe cools, resulting in the dissipation of the domain walls.

7. GALAXY FORMATION

Models of galaxy formation from "primordial turbulence" have always been attractive as a way of accounting for galaxy formation as well as for observed parameters such as the angular momenta and spatial distribution of galaxies. However, in that work, turbulence was introduced in ad hoc manner and, furthermore, such turbulence would be strongly damped out in the cosmic plasma because of the very high viscosity of the blackbody radiation field which remains coupled to the plasma until the neutralization ("recombination") epoch.

In the baryon symmetric cosmology scenario, this viscous dissipation is constantly fought by continuing radiation pressure from annihilation on the boundaries of matter and antimatter regions, which regenerates the

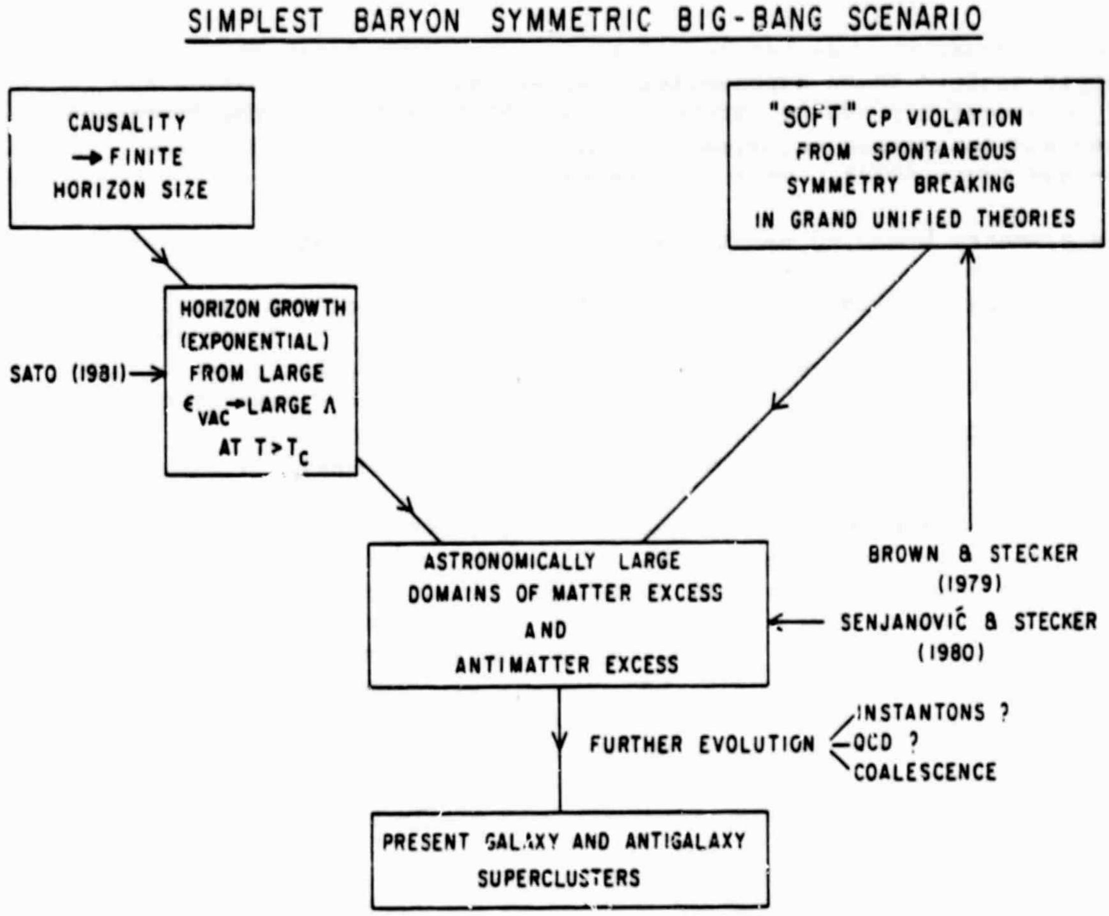

Figure 1. New framework for baryon symmetric big-bang cosmology.

turbulence. Radiation pressure from the annihilation, being directed generally away from the boundaries can drive mass fluid motions as well as causing further coalescence until the separate regions reach the size of galaxy clusters.

At the recombination epoch, the viscosity dropped drastically and the turbulent fluid motions became supersonic. Thus, both "small-scale" turbulence and density fluctuations could start to build up in the decoupled atomic fluid and later contract to form galaxies. In this scenario annihilation pressure can provide a continuous source of generating turbulence (Stecker and Puget 1972).

Barrow and Turner (1981) have proposed another scenerio for galaxy formation based on having exponential domain growth in combination with hard and soft CP violation. This picture results in a desired spectrum of isothermal fluctuations leading to galaxy formation and preserves an all matter universe which the authors desire. However, note that if we eliminate the element of hard CP violation (undesirable if only because it leads to problems with the neutron electric dipole moment) we still obtain isothermal fluctuations - but in this case we again arrive at a baryon symmetric domain cosmology.

8 THE COSMIC γ-RAY BACKGROUND RADIATION

One of the most significant consequences of baryon symmetric big-bang 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 perhaps at present the 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 determine the γ-ray background spectrum. This integro-differential equation takes account of γ-ray production, absorption, scattering, and redshifting (Stecker, Morgan and Bredekamp 1971).

Figure 2 shows the observational data on the γ-ray background spectrum. The dashed line marked X is an extrapolation of the X-ray background component. The theoretical curve marked "annihilation" is the calculated annihilation spectrum (Stecker 1978). The excellent agreement between theory and data is apparent. This striking evidence has been a prime motivation for studying BSDC. Other recent attempts to account for the γ-ray background radiation spectra by diffuse processes give spectra which are, in one way or another, inconsistent with the observations, generally by being too flat at the higher energies.

It is possible that the γ-ray background is made up of a superposition of point sources. However, since only one extragalactic source has been seen at energies above ~1 MeV, this remains a conjecture. Such a hypothesis must be tested by determining the spectral characteristics of extragalactic sources and comparing them in detail with the characteristics of the background spectrum. It presently appears, e.g., that Seyfert galaxies may have a characteristic spectrum which cuts off above a few MeV, so that they could not account for the flux observed at higher energies.

9. 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. Gaisser and Levy (1974) pointed out that observation of a cosmic $\bar{p}$ flux without the low energy cutoff characteristic of secondary antiprotons whould be a signal of a primary component of antiprotons in the cosmic rays. Buffington, Schindler and

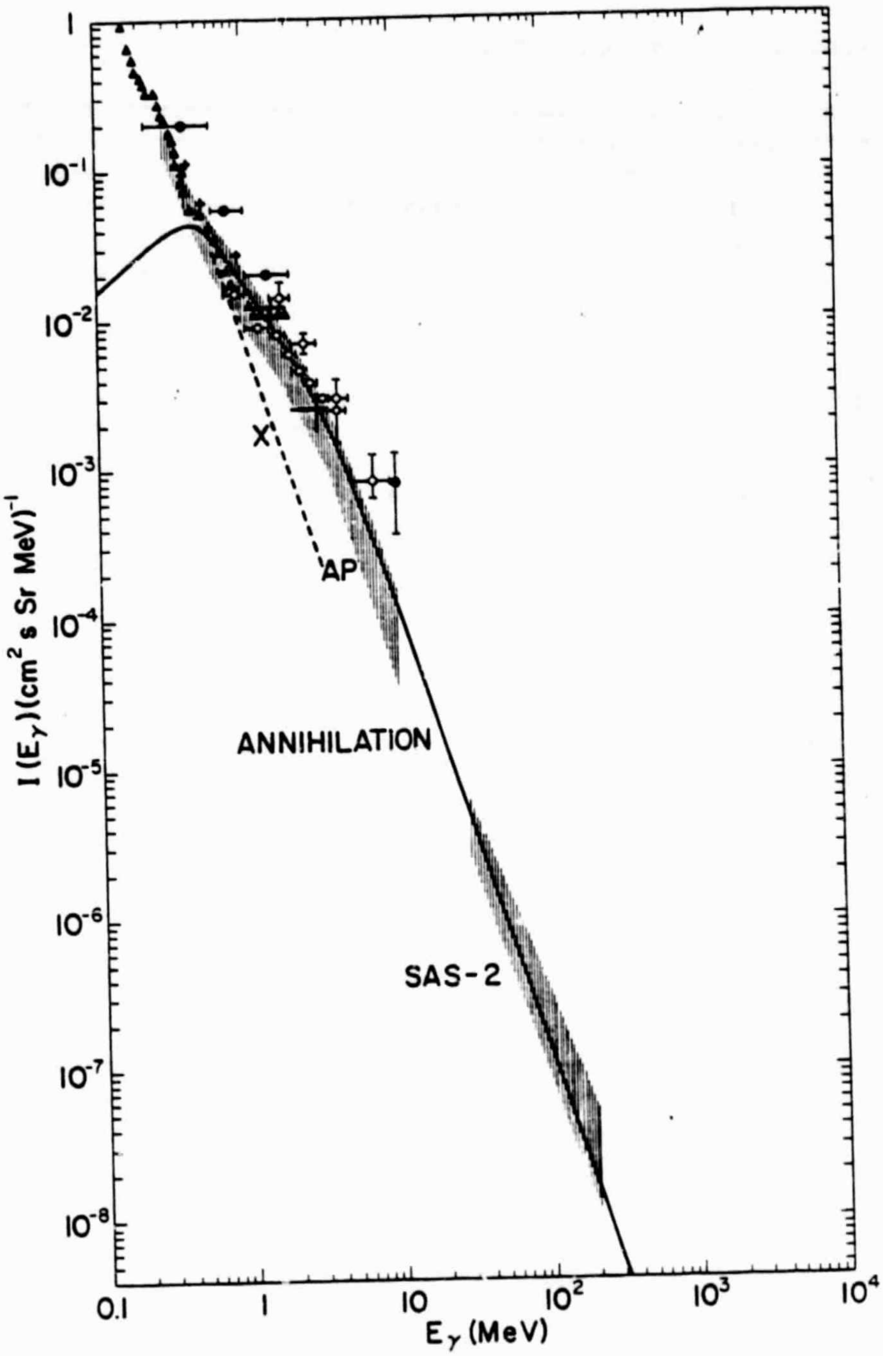

Figure 2. Data on the cosmic γ-ray background radiation from Apollo 15 and the SAS-2 satellite. Also shown are data from balloon experiments and theoretical curves.

Pennypacker (1981), observing at energies well below the secondary cutoff, appear to see just such a signal of primary antiprotons. Data on $\bar{p}$ fluxes at higher energies (Bogomolov, et al. 1979, Golden, et al. 1979) give measured values a factor of 4-10 above the fluxes expected for a standard "leaky box" type propagation model with the primaries passing through ~ 5 g/cm^2 of material (Stecker, Protheroe and Kazanas 1981 and references therein).

The magnitude of the secondary $\bar{p}$ component depends critically upon how cosmic rays are stored in and propagate through the Galaxy. The simplest model describing the propagation of cosmic rays in the Galaxy is the leaky box model. The closed galaxy model gives a higher $\bar{p}/p$ ratio than the leaky box model. In the version of the closed galaxy model proposed by Peters and Westergaard (1977) the sources of cosmic rays are located in the spiral arms of the Galaxy, from which they slowly leak out into an outer containment volume which comprises part of the disk and the surrounding halo, a region which we will refer to here collectively as "the halo". The outer boundary of the halo constitutes a closed box from which cosmic rays cannot escape. Depletion of cosmic rays in the halo is then solely due to nuclear interactions and energy losses. The halo thus contains an "old component" while the spiral arms also contain a "young component" of cosmic rays.

An important parameter of the closed galaxy model is K, the ratio of the mass of gas in the galaxy as a whole to that in the spiral arms. Peters and Westraard attempted a fit to the observed secondary to primary ratios for values of K in the range 50 to 500. The rate of production of antiprotons in the halo has been calculated for values of K ranging from 50 to 500. We show the resulting $\bar{p}/p$ ratios in Figure 3. As can be seen from the figure, the closed galaxy model predictions are compatible with the high energy data but predict a $\bar{p}$ flux which is still more than a decade below that observed by Buffington, et al.

There are various problems associated with the closed galaxy model in any case. It cannot account for the shape of the cosmic ray proton spectrum at high energies (Ormes and Balasubrahmanyan, private communication.) The model also requires confinement of a young component to a spiral arm region containing the Sun. Such a picture does not appear to be consistent with analysis of the non-thermal radio data (Price 1974; Brindle et al. 1978) or a detailed analysis of the galactic γ-ray data (Stecker 1977). Finally, it should be stressed that there are no physical reasons for arguing that the Galaxy should be substantially closed to cosmic-ray leakage.

It is difficult to see how the high flux of antiprotons below the low energy cutoff characteristic of secondary antiprotons can be explained by a secondary galactic component. Figure 3 also shows the prediction for the leaky box model. If this model provides the correct description of galactic cosmic ray confinement and propagation, then the spectrum of an additional primary antiproton component making up the deficit $\bar{p}$ flux would have roughly the same shape as the galactic proton spectrum. The ratio of

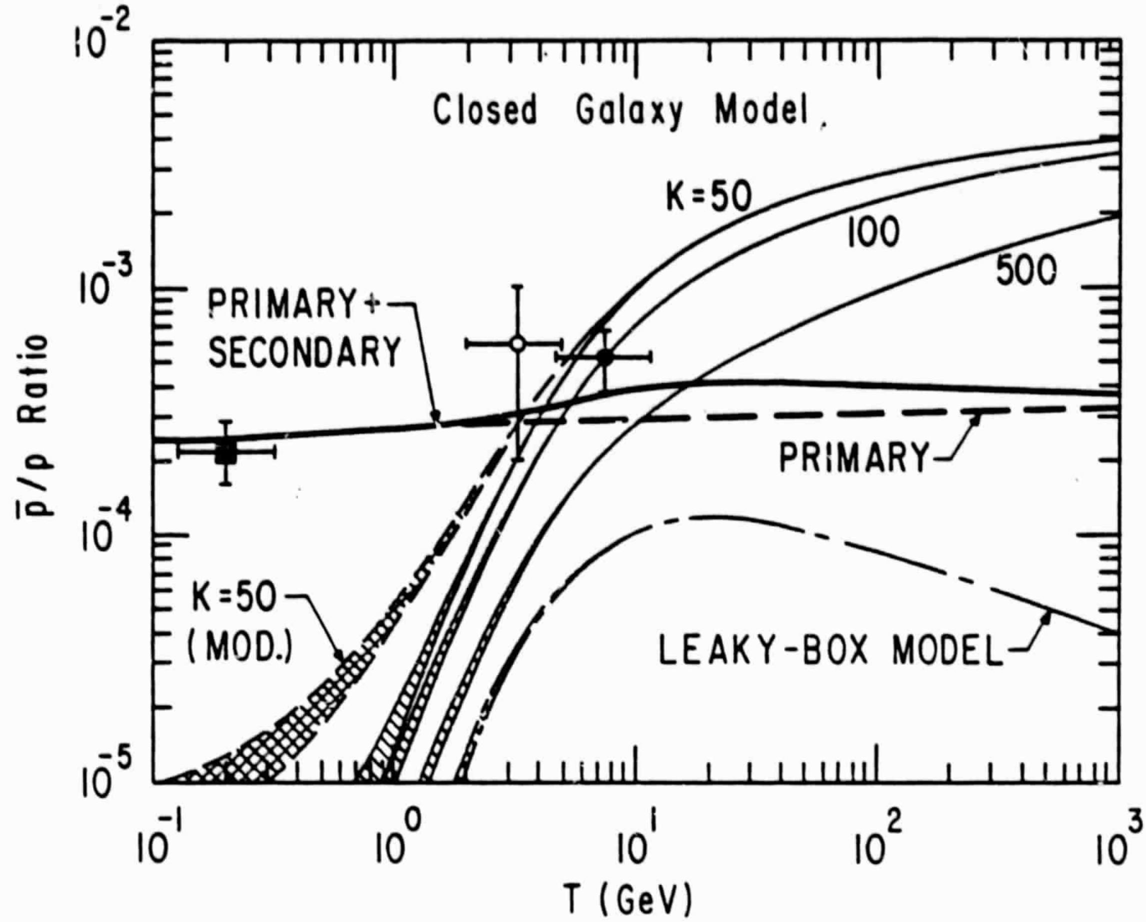

Figure 3. The predicted p̄/p ratio for the closed galaxy model and leaky box model compared with the observed ratio. The curve labled K=50 Mod indicates the effect of solar modulation with a mean energy loss of 600 MeV on the closed galaxy model prediction for K=50. Key to data: (■) Buffington, et al. (1981); (○) Bogomolov et al. (1979); (●) Golden et al. (1979). The heavy line shows the effect of adding an extragalactic p̄ component to the leaky box model prediction as discussed in the text. (From Stecker, et al. 1981).

the extragalactic p̄ flux to the galactic proton flux would then be $(3.2\pm0.7) \times 10^{-4}$. This is plotted as the heavy dashed line in Figure 3. The reduction in the p̄/p ratio below this value at low energies is due to the combined effects of "galactic modulation" (ionization energy losses, nuclear interactions and p̄ annihilation) and solar modulation. The p̄/p ratio for the sum of this extragalactic component plus the secondary (leaky box model) component is shown by the heavy line of Figure 3.

The inconsistency of the observed cosmic ray antiproton spectrum and intensity with the calculated secondary flux, as well as the fact that p̄/p= const. independent of energy, may both be indications of a possible primary extragalactic origin. Using rough energetics arguments (Ginzburg and Syrovatskii 1964) one can estimate that leakage from normal galaxies would produce an extragalactic cosmic ray component with a flux $(I_{ex}/I_{gal})_{NG} = \xi_{NG} \simeq 10^{-5}-10^{-4}$. For active galaxies, these estimates yield $\xi_{AG} \simeq 10^{-3}$. If we assume that half of the extragalactic flux is from antimatter sources, the resulting estimate for $\bar{p}/p \simeq 1/2\xi_{AG} \simeq 5\times10^{-4}$ is interestingly quite close to the measured values.

In discussing the $\bar{p}$ data, we should note the upper limits on the fluxes of antinuclei. The best 95% confidence upper limits at present are $\bar{\alpha}/\alpha \leq 1.5\times10^{-4}$ at 4.33 GeV/c (Badhwar, et al. 1978) barely consistent with $\bar{\alpha}/\alpha \simeq \bar{p}/p$, and $\bar{\alpha}/\alpha < 2.2\times10^{-5}$ in the low energy range of 130-370 MeV/nucleon (Buffington, et al. 1981) indicating that $\bar{\alpha}/\alpha < \bar{p}/p$ in this energy range. This latter upper limit is consistent with $\bar{\alpha}/\alpha = \xi_{NG}/2 = 5\times10^{-6}$ -5×10^{-5} (see above). Note that we can only argue that $\bar{\alpha}/\alpha = \bar{p}/p$ for cosmic ray poduction in normal galaxies, since we are comparing extragalactic fluxes with fluxes produced by processes in our own galaxy. It is conceivable that cosmic-ray α's produced in the cores or jets of active galaxies are broken up by collisions with matter or photons. Thus, the observed $\bar{p}$'s could come from active antimatter galaxies without accompanying $\bar{\alpha}$'s, but with the expected $\bar{\alpha}/\alpha \sim 10^{-5}$ from normal antimatter galaxies. In this case, future cosmic-ray experiments may soon detect $\bar{\alpha}$'s! Antimatter active galaxies containing regions of high photon or matter density may not be detectable as γ-ray sources, however, they may be directly determined to be antimatter sources through their production of cosmic ray $\bar{\nu}_e$'s (Learned and Stecker 1979).

In a matter-antimatter symmetric domain cosmology it is posible for the helium formed in the first three minutes of the big-bang to have been partially or totally destroyed by photodisintegration by annihilation γ-rays. This process has been suggested to account for the recent observations of low He abundances in less evolved galaxies, implying a low value for the primordial helium abundance as compared to theory (Stecker 1980a, 1981). If this is indeed the case, active galaxies and quasars during the "bright phase" (Berezinsky and Smirnov 1975) may have had very little He to accelerate.

Let us now consider the propagation of extragalactic cosmic rays. Not much is known regarding the physical parameters involved and one has to resort to rough estimates. A diffusion model can be considered as a first approximation to the problem (Ginzburg and Syrovatskii 1964). The mean distance cosmic rays diffuse in time t_u is $\langle R\rangle \simeq (2Dt_u)^{1/2}$ where $D = (1/3)\,\ell v$ is the diffusion coefficient and $t_u \sim 10^{10}$ years. Since $v \sim 10^{10}$ cm s^{-1} the largest uncertainty lies with the determination of the length scale. The length ℓ is of the order of the scale of inhomogeneity of the intergalactic magnetic field, which is not less than the intergalactic particle mean free path, i.e. $\ell \gtrsim (n\sigma)^{-1}$. In an ionized gas with $T \sim 10^6$-10^8K and $n_e \sim 10^{-7}$-10^{-5} cm^{-3}, the corresponding lower limit for the mean diffusion distance is then in the range 0.5 to 500 Mpc. Thus, extragalactic cosmic rays can reach our galaxy in a Hubble time from other clusters or superclusters which may consist of antimatter galaxies and contain cosmic ray sources. The estimates are admittedly quite uncertain, especially since they depend on the topology of intergalactic field lines which the cosmic rays follow, since their gyroradii are expected to be small compared to ℓ. (See also Kiraly, these proceedings.)

10. "CELL" STRUCTURE OF THE UNIVERSE

Not only do galaxies form clusters, but also these clusters of galaxies are not uniformly distributed; they cluster into superclusters. Between the superclusters are large voids--regions with a very low (possibly zero) space density of galaxies (Joeveer and Einasto 1978; Gregory and Thompson 1978; Chincarini and Rood 1979; Shanks, these proceedings). The existence of these holes is the kind of structure which can arise from a BSDC. The cosmic background γ-radiation originating from supercluster boundary annihilations should exhibit angular fluctuations which can best be studied with a high-resolution detector such as the 100 MeV spark chamber detector proposed for a future satellite "Gamma Ray Observatory".

11. FUTURE TESTS USING HIGH ENERGY COSMIC RAY NEUTRINOS

Several suggestions have been made recently for using high-energy neutrino astronomy to look for antimatter elsewhere in the universe (Learned and Stecker 1979; Berezinsky and Ginzburg 1981, Stecker and Brown 1981). These suggestions are all based on the fact that cosmic ray pp and pγ interactions favor the secondary production of 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 channels because of the steepness of the ultrahigh energy cosmic ray spectrum.

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 (resonance) through formation of weak intermediate vector bosons such as 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 for $M_W \simeq 80$ GeV corresponding to $\sin^2\theta_W \simeq 0.23$ in the GWS model.

If one entertains the possibility of higher mass intermediate vector bosons, $\bar{\nu}_e + e^- \rightarrow B^-$, and correspondingly higher resonance energies, a feasible test for cosmic antimatter may be at hand.

The cosmic and atmospheric fluxes for $\bar{\nu}_e$'s, based on cosmic ray production calculations have been given by Stecker (1979). 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 ~ 2 X 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. A cosmic $\bar{\nu}_e$ signal may be heavily contaminated by prompt atmospheric $\bar{\nu}_e$'s at the W resonance energy. The cosmic flux is expected to dominate the higher energies so that the existence of higher mass bosons B^- may be critical to any proposed test for cosmic antimatter using diffuse fluxes (Brown and Stecker 1981, Stecker and Brown 1981). (There is now experimental evidence for M_W > 100 GeV as suggested by composite models (Fitzsch, these proceedings.))

An acoustic deep underwater neutrino detector may provide the best hope for testing for cosmic antimatter by studying the diffuse background neutrinos. The practical threshold for such devices appears to be in the neighborhood of 10^3 - 10^4 TeV (Bowen and Learned 1979). For higher mass resonances B^-, the relevant neutrino resonance energy $E^B \propto M_B^2$ and the effective detection volume $V_{eff} \propto M_B^6$. Considering that the incident flux is expected to be roughly constant up to energies ~ 2 X 10^7 TeV, one gains much in looking for higher mass resonances at higher energies. Acoustic detectors of effective volume >> 10 km^3 (10^{10} tons) may be economically feasible and event rates of ~ 10^2 - 10^4 yr^{-1} may be attained in time.

The asymmetry in the production of charged pions in matter versus antimatter sources is reflected in cosmic-ray pp and $\overline{pp}$ interactions as well as pγ and $\bar{p}\gamma$ interactions. Through the principal decay mode, this asymmetry is again reflected in a ν_e - $\bar{\nu}_e$ asymmetry and thus in the characteristics of events produced in deep underwater neutrino detectors. For ν-sources, these effects may be measurable at energies ~ 1-10 TeV with optical detectors (Learned and Stecker 1979). The possibility that pγ and $\bar{p}\gamma$ interactions in quasars and active galaxies would produce significant fluxes of $\bar{\nu}_e$'s , detectable through the W^- resonance, has been suggested by Berezinsky and Ginzburg (1981) as a way of looking for cosmic antimatter. Hopefully, this interesting suggestion will be explored in more detail as our understanding of the nature of cosmic ray production in compact objects increases.

12. CONCLUSION

In grand unified theories, a scenario has been developed for the evolution of the early universe wherein the matter which eventually forms the galaxies arises as a "baryon excess" owing to baryon number non-conserving interactions at ultrahigh energies. This scenario requires that CP symmetry be broken. Although the nature of CP breaking, even at low energies, has not yet been established, there are several reasons to prefer spontaneous CP symmetry breaking. Aside from the philosophical consistency with the whole concept of spontaneous symmetry breaking which is the key to unified gauge theories, there are several important technical reasons (beyond the scope of this paper) for suspecting that CP is broken spontaneously. This mechanism explains naturally why CP violation is small (a problem with the alternative Kobayashi-Maskawa model of explicit hard CP violation). It leads in a natural way to natural flavor conservation (a generalization of the GIM mechanism). It provides a solution to the strong CP problem as well (e.g. Mohapatra and Senjanović 1978).

Spontaneous breaking of CP leads to a domain structure in the universe with the domains evolving into separate regions of matter excess and antimatter excess. The creation of these excesses subsequent to a period of exponential horizon growth (a dynamical effect of the Higgs fields) can result in a universe in which matter galaxies are formed in some regions and antimatter galaxies are formed in others. There is no need for a separation mechanism since the regions containing the excesses come into being as separate regions. There are advantages in this model in explaining various astrophysical data such as the cosmic γ-ray background spectrum, cosmic ray $\bar{p}$ flux measurements, a low primordial He abundance and strong galaxy clustering. (It should, of course, be kept in mind that all present scenarios for the early big-bang based on present specific grand unification models have problems with topological singularities and that these ideas may be drastically revised if it becomes necessary to attribute a composite nature to quarks and leptons.)

It should be kept in mind that any positive observational data (e.g., cosmic-ray $\bar{p}$'s, $\bar{\alpha}$'s, $\bar{\nu}_e$'s) supporting the existence of large amounts of antimatter in the universe will be evidence of the spontaneous nature of CP violation at high energies, in accord with our earlier discussion. Thus, astrophysical tests which can distinguish between an all matter cosmology and a baryon symmetric domain cosmology can tell us something important and fundamental about the nature of particle physics at extremely high energies. (See also Stecker 1978, 1980b.)

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