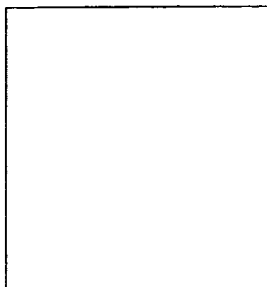


# THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

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I will give here an overview of the present observational and theoretical situation regarding the question of the matter-antimatter asymmetry of the universe and the related question of the existence of antimatter on a cosmological scale. I will also give a simple discussion of the role of  $CP$  violation in this subject.

## 1 Introduction

One of the most fundamental questions in cosmology is that of the role of antimatter in the universe. This question, which is intimately connected to the question of the nature of  $CP$  violation at high energies, is the important subject of this conference. It is a question for theorists, but ultimately as in all scientific endeavours, a question which must be answered empirically if possible.

The discovery of the Dirac equation<sup>1</sup> placed antimatter on an equal footing with matter in physics and opened up speculation as to whether there is an overall balance between the amount of matter and the amount of antimatter in the universe. The hot big bang model of the universe added a new aspect to this question. It became apparent that in a hot early epoch of the big bang there would exist a fully mixed dense state of matter and antimatter in the form of leptonic and baryonic pairs in thermal equilibrium with radiation. As the universe expanded and cooled this situation would result in an almost complete annihilation of both matter and antimatter.

The amount of matter and antimatter expected to be left over in an expanding universe can be calculated from the proton-antiproton annihilation cross section. Antinucleons “freeze out” of thermal equilibrium when the annihilation rate becomes smaller than the expansion rate of the universe. This would have occurred when the temperature of the universe dropped below  $\sim 20$  MeV. The predicted freeze out density of both matter and antimatter is only about  $4 \times 10^{-11}$  of the closure density of the universe (*i.e.*,  $\Omega_{baryon} = 4 \times 10^{-11}$ )<sup>2</sup>.

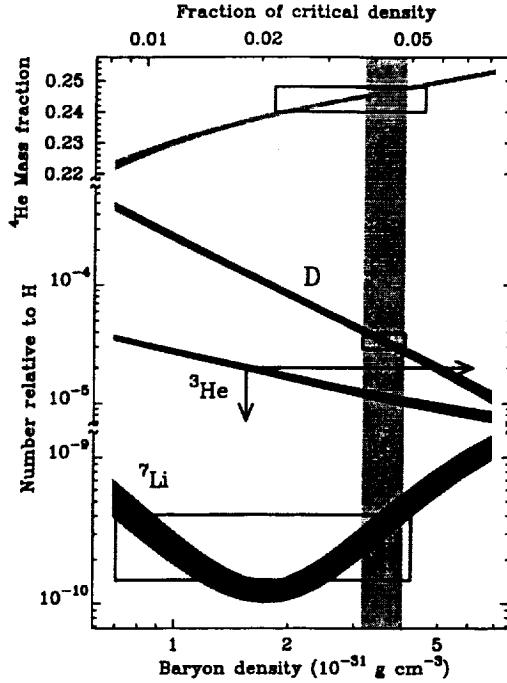


Figure 1: Predicted abundances of light nuclides from big-bang nucleosynthesis. <sup>6</sup>

On the other hand, big-bang nucleosynthesis calculations <sup>3</sup> and studies of the anisotropy of the 2.7 K cosmic background radiation <sup>4</sup> have indicated that baryonic matter makes up about 4% of the closure density of the universe, (*i.e.*,  $\Omega_{baryon} \simeq 4 \times 10^{-2}$ ) as shown in Figure 1. Thus, there is a nine order of magnitude difference between the simple big-bang prediction and the reality of the amount of baryonic matter which is found in the universe and which makes up the visible matter in galaxies as well as the matter in you and me. Clearly, there is something missing. It was elegantly shown by Sakharov <sup>5</sup> that what is missing is the breaking of symmetries. In order to make an omelet you have to break some eggs; in order to make a universe you have to break some symmetries. It is in this context that the question of the nature of the violation of  $CP$  symmetry arises.

## 2 The Sakharov Conditions (and Beyond).

Sakharov showed that three conditions are necessary in order to create the appropriately significant concentration of baryons in the early universe. They are:

- Violation of Baryon Number,  $B$
- Violation of  $C$  and  $CP$
- Conditions in which Thermodynamic Equilibrium does not Hold

The first condition is satisfied in grand unified theories (GUTs) in which strong and electroweak interactions are unified and quarks and leptons are placed in the same multiplet representations. It is also satisfied in electroweak theory through the sphaleron mechanism (see next section).

The second condition involves the nature of  $CP$  violation ( $CPV$ ). We know that  $CP$

is violated at low energies in  $K^0$  mixing and decay<sup>7</sup> and in  $B^0$  mixing<sup>8</sup>. These processes are a major subject of this meeting. The creation of matter and antimatter asymmetries in the universe (baryogenesis) involves the nature of  $CP$  violation at high energies. As will be discussed in the next section, the standard  $SU(3) \times SU(2)_L \times U(1)_Y$  model cannot account for baryogenesis at high energies. This implies that there is no obvious relationship between the low energy  $CPV$  which has been observed in the laboratory and which can be described by the CKM (Cabibbo-Kobayashi-Maskawa)<sup>9</sup> matrix and that which must account for baryogenesis.

The third condition of non-equilibrium can be supplied at the GUT scale by the expansion of the universe. Owing to this expansion, below the GUT temperature,  $CP$  violating decays of leptoquarks or GUT-Higgs bosons cannot be balanced by their inverse reactions. At the electroweak scale, things are different (see next section).

The three Sakharov conditions are part of the recipe for making our universe omelet. However, the nature of the  $CPV$  is also important. If it is spontaneous  $CPV$ <sup>10</sup>, followed by a period of moderate inflation<sup>11</sup>, one can generate astronomically large domains of  $CP$  violation of opposite sign. In principle, subsequent baryogenesis can lead to separate regions containing matter galaxies and antimatter galaxies respectively (see section 4).

### 3 Baryosynthesis

#### 3.1 Different Baryogenesis Scenarios

As we have already mentioned, baryon number is naturally violated in grand unified theories. It is also violated in the  $SU(3) \times SU(2)_L \times U(1)_Y$  standard model (SM) because in this model gauge invariant chiral currents are not conserved owing to the Adler-Bell-Jackiw anomaly.<sup>12</sup> As a result of this anomaly, together with the fact that weak gauge bosons couple only to left handed quarks and leptons, it can be shown that the SM conserves  $(B - L)$  but violates  $B$  and  $L$  separately. At electroweak unification scale temperatures  $T_{EW} \sim 100$  GeV, SM  $B$  and  $L$  violation can occur freely through “sphaleron” transitions between topologically distinct vacuum states with neighboring winding numbers.<sup>13</sup> This transition process is suppressed at temperatures much less than  $T_{EW}$  by an exponential barrier penetration factor.

However, at a temperature  $T_{EW} \sim 100$  GeV, the expansion of the universe is too slow relative to the weak and electromagnetic interaction rates for Sakharov’s out-of-equilibrium condition to hold. The weak interaction rate,  $\Gamma_{weak}$  is proportional to  $\sigma_{weak} \simeq G_F^2 T^2$  times the particle density  $n$ , where  $G_F \simeq 10^{-5}$  GeV<sup>-2</sup>. Here, we adopt natural units ( $\hbar/2\pi = c = k = 1$ ) with the temperature in GeV. With these units, within an order of magnitude, the particle density,  $n \sim T^3$  and the rate of expansion of the universe  $H \sim T^2/M_{Planck}$  in the radiation dominated era. The ratio,

$$\frac{\Gamma_{weak}}{H} \sim G_F^2 M_{Planck} T_{EW}^3 \sim 10^{15}.$$

For electromagnetic interactions, this ratio is even larger. Thus, the expansion of the universe is much too slow to break thermal equilibrium.

For effective baryogenesis to occur, Sakharov’s condition of thermal non-equilibrium must be adequately met by another means. This requirement is satisfied if the Higgs fields undergo a strongly first order phase transition when the electroweak symmetry is broken.<sup>13</sup> In order for such a phase transition to occur, lattice simulations have shown that the required SM Higgs mass must be less than  $\sim 72$  GeV.<sup>14</sup> However, lower limits on the mass of the electroweak Higgs boson obtained at LEP indicate that  $m_H \geq 110$  GeV.<sup>15</sup> This precludes the required phase transition in the case of the SM. However, it has been proposed that extensions of the SM with extra Higgs fields may work.<sup>16</sup>

In any case, it is doubtful whether the  $CPV$  described by the CKM matrix plays a role at high temperatures in the early universe or is related to the  $CPV$  needed for baryogenesis. It has been shown that the  $CPV$  provided by the CKM matrix cannot produce a large enough baryon asymmetry because, owing to GIM suppression<sup>17</sup>, its contribution to baryon number violation only arises at the three loop level.<sup>18</sup> It is more likely that  $CPV$  involving GUT scale mechanisms comes into play. These mechanisms can also involve the Higgs sector.

### 3.2 Example: The Weinberg Scenario

A simple scenario for baryon production from superheavy particle decay which can serve as an illustration of baryogenesis was given by Weinberg<sup>20</sup>. Weinberg's GUT-inspired X particles decay *via* two channels with baryon numbers  $B_1$  and  $B_2$  and branching ratios  $r$  and  $1 - r$ . The antiparticles decay with baryon numbers  $-B_1$  and  $-B_2$  with the same total rate, but with different branching ratios  $\bar{r}$  and  $1 - \bar{r}$ . The mean net baryon number produced is then

$$\Delta B = (1/2)(r - \bar{r})(B_1 - B_2).$$

The baryon to photon ratio produced is estimated by Weinberg to be two to three orders of magnitude below  $\Delta B$ . This factor is arrived at by noting that all of the particle densities started out equal in thermal equilibrium and taking account of the fact that it is the surviving baryon to entropy ratio which is conserved during the subsequent expansion of the universe and that the entropy at the time of baryogenesis, *i.e.*, the GUT era, was larger by roughly  $10^2 - 10^3$ , counting the additional degrees of freedom supplied by the particles of mass  $m \ll M_{GUT}$ .

As an even simpler example than the above one, consider a GUT leptoquark boson with the decay modes  $X \rightarrow ql$  with branching ratio  $r$  and  $X \rightarrow \bar{q}\bar{l}$  with branching ratio  $(1 - r)$ . Then  $\Delta B = (1/2)(r - \bar{r})$ . If  $CP$  is not violated, then  $r = \bar{r}$  and  $\Delta B = 0$ . Thus, we require  $CP$  violation. But, also note that the *sign* of  $\Delta B$  depends on the *sign* of  $CP$  violation. This will be a critical point in the next section.

It has been pointed out that since the sphaleron mechanism conserves  $(B - L)$  (see above), any baryosynthesis involving a GUT gauge group containing a  $U_{B-L}$  symmetry as a subgroup which is unbroken above the GUT scale will be washed out at the electroweak level by sphaleron interactions.<sup>13</sup> Recently, models have been proposed where lepton number is violated at the GUT scale and then, as the universe cools, baryon number is generated through the sphaleron mechanism.<sup>19</sup> However, even more recently, Weinberg-type processes involving GUT particle decay have been resurrected in scenarios involving Majorana neutrinos.<sup>21</sup>

Other discussions of baryogenesis mechanisms are given by Dolgov and Berezhiani in these proceedings.

## 4 A Locally Asymmetric Domain Cosmology

If  $CPV$  is predetermined, then only matter will remain in the present universe. We can refer to this case as a "global" matter-antimatter asymmetry. If, on the other hand,  $CPV$  is the result of spontaneous symmetry breaking, domains of positive and negative  $CPV$  may result<sup>10</sup>. In the case of spontaneous  $CPV$ , the Lagrangian is explicitly  $CP$  invariant, but at the symmetry breaking phase transition a  $CP$  invariant high temperature vacuum state undergoes a transition to a state where the vacuum solutions break  $CP$  either way.<sup>10 22 23</sup> This mechanism may be compared to the spontaneous formation of ferromagnetic domains when a piece of unmagnetized iron cools below the critical temperature in the absence of a magnetic field. Although there is no preferred direction of magnetization, individual domains acquire random local directions of magnetization.

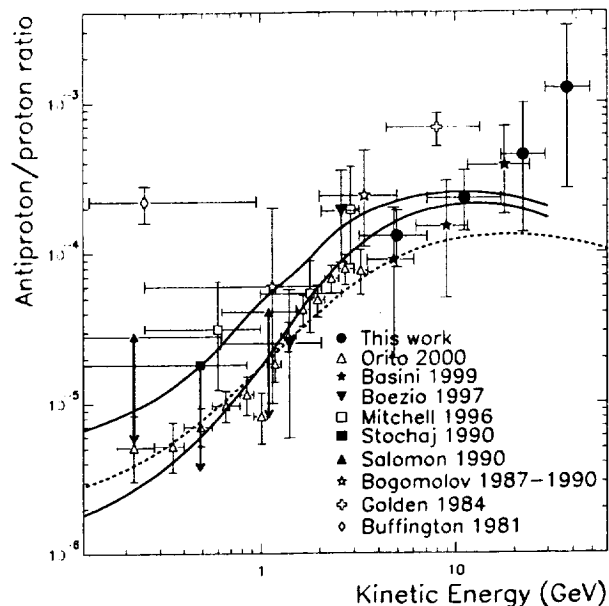


Figure 2: Measured cosmic ray  $\bar{p}/p$  flux ratios and limits as a function of energy.<sup>29</sup>

If the  $CP$  domain structure is stretched to astronomical size by a subsequent period of moderate inflation<sup>11</sup>, then, following baryogenesis, baryons may survive as galaxies in some regions of the universe and antibaryons may survive as antigalaxies in other regions. In this case, we have a “local” matter-antimatter asymmetry instead of a global one. We will refer to this possibility as a “locally asymmetric domain cosmology (LADC).” Following baryogenesis, the walls of the initially  $CP$  symmetric vacuum between the positive and negative  $CP$  domains must vanish because they are quite massive and could eventually dominate the evolution of the universe, in conflict with observations.<sup>24</sup> Various mechanisms have been proposed to accomplish this.<sup>25 26</sup><sup>27</sup> The imprint of the  $CP$  domains remains as “fossil” baryon and antibaryon “domains”.<sup>a</sup>

Unfortunately, we cannot aim the Hubble Space Telescope at distant galaxies in order to find antimatter galaxies. Antimatter galaxies will look exactly the same as matter galaxies. This is because the photon is its own antiparticle. However, we can look for other clues. Searches have been made for antimatter in the cosmic radiation and for the indirect traces of cosmic matter-antimatter annihilation in the extragalactic  $\gamma$ -ray background radiation. The results of these searches will be discussed in the next two sections.

## 5 Antimatter in the Cosmic Radiation

Many measurements have been made of antiprotons in the cosmic radiation. A recent compendium of measurements of the  $\bar{p}/p$  flux ratios as a function of energy is given in Figure 2. This figure also shows curves of the predicted flux ratios obtained by calculating the production of secondary antiprotons from galactic cosmic ray interactions with interstellar gas nuclei. As the figure indicates, the present measurements up to  $\sim 40$  GeV are consistent with secondary production. (See also the paper of Coutu in these proceedings.<sup>30</sup>)

There have been no antihelium nuclei detected in the cosmic radiation. Recent limits on the antihelium-helium ratio are shown in Figures 3 and 4.

<sup>a</sup>A cosmological model where antimatter plays a minor role has also been considered more recently.<sup>28</sup>

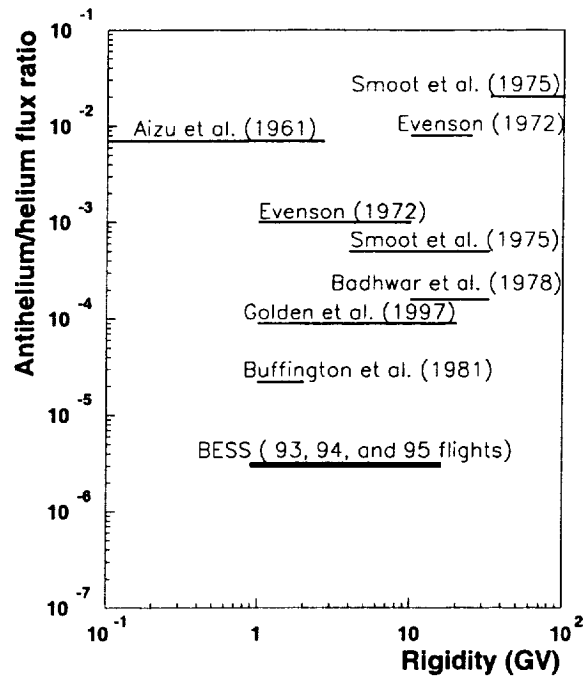


Figure 3: Observational limits on the flux ratio of  $\bar{\alpha}/\alpha$  as a function of energy. <sup>31</sup>

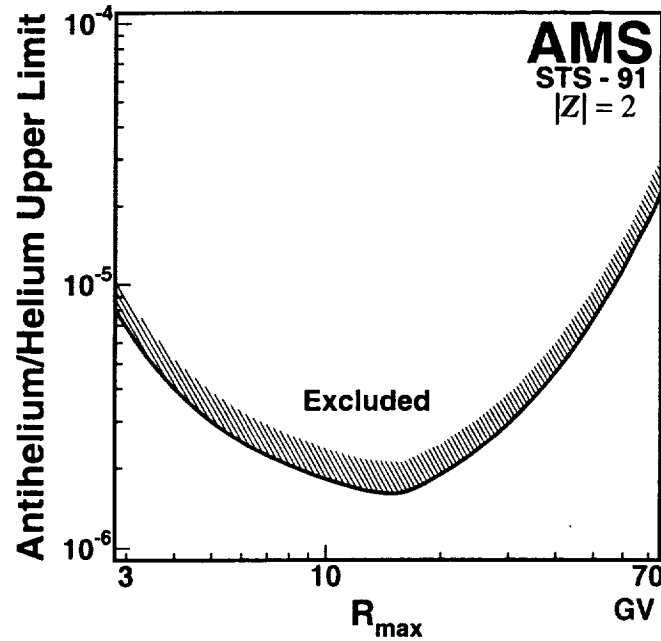


Figure 4: Recent upper limits on the flux ratio of  $\bar{\alpha}/\alpha$  as a function of energy obtained by the Alpha Magnetic Spectrometer (AMS) detector. <sup>32</sup>

Thus, there is no evidence for extragalactic antimatter in the low energy cosmic rays. This is, of course, direct evidence against the existence of significant antimatter in our own galaxy since galactic  $\gamma$ -ray observations indicate that cosmic rays diffuse throughout our galaxy.<sup>33</sup> Studies of secondary nuclides produced by cosmic ray interactions with interstellar gas also indicate diffusion of cosmic rays throughout the galaxy.<sup>34</sup>

As indicated in Figures 3 and 4, the most stringent limits on cosmic ray  $\bar{\alpha}$ 's are at very low energy. The limits get worse as the energy goes up because of the decrease in detector sensitivity owing to the smaller bending of high energy particles (and antiparticles) in the magnetic field of the detectors.

Stecker and Wolfendale<sup>35</sup> have shown that the ratio of extragalactic cosmic rays to galactic cosmic rays should increase with energy owing to the fact that the escape rate of galactic cosmic rays from the galaxy increases with energy. In addition, there is a significant question as to whether extragalactic cosmic rays can enter the galaxy owing to the presence of a galactic wind. Ahlen *et al.*<sup>36</sup> have estimated that the galactic wind could reduce the low energy component of the extragalactic cosmic ray flux by more than an order of magnitude. Thus, a better test for extragalactic antimatter would come with the measurement of cosmic rays at much higher energies. There is also the question as to whether cosmic rays can diffuse and propagate to Earth from the distances of tens of Mpc required by the LADC models (see next section).

## 6 The MeV Gamma Ray Background Test

Perhaps the most significant and potentially observable consequence of LADC is the prediction of a  $\gamma$ -ray background from the annihilation of matter and antimatter taking place at the boundaries between matter and antimatter regions. In fact, the possibility that this effect could explain the multi-MeV background observations was the original motivation for the author's work on this topic.<sup>39</sup>

Another prediction of the LADC is that the  $\gamma$ -ray background radiation from boundary annihilations would not really be isotropic. There would be a structure of  $\gamma$ -ray "ridges" produced and these ridges would be more pronounced at energies near 100 MeV than at MeV energies.<sup>37</sup>

The source of the MeV-range background radiation is still a mystery. It has been suggested that redshifted line emission from extragalactic supernovae can explain part of the flux<sup>40</sup>. However, such radiation is limited to the energy range below 3.5 MeV and therefore cannot account for all of the flux. Another suggestion has been the superposition of MeV emission tails from active galaxies<sup>41</sup>. In this regard, it should be noted that previously flown  $\gamma$ -ray telescopes were not sensitive enough to determine if such non-thermal multi-MeV  $\gamma$ -ray tails are produced by individual active galaxies. The theoretical situation regarding the origin of the multi-MeV  $\gamma$ -ray background is therefore unclear at this point.

The observational situation is summarized in Figure 5. The two results from Apollo 16 and 17 and Comptel both involved the difficult determination of a subtraction of the flux of  $\gamma$ -rays produced in the detector and surrounding material which was much larger than the true signal itself. Of course, in such a case, there is always the danger of oversubtraction as well as under-subtraction. The result is that the two data sets are, in some places, more than an order of magnitude in disagreement.

Based on preliminary Apollo 15 data, Stecker and Puget<sup>42</sup> estimated the size of the fossil matter and antimatter domains to be of the order of 10 Mpc, *i.e.*, at least the size of galaxy superclusters. Using the method of Stecker *et al.*<sup>39</sup>, Cohen *et al.*<sup>43</sup> estimated a fossil domain size of at least 1 Gpc. Neither of these papers took account of the possibility that a magnetic field which might be generated parallel to boundary might inhibit the diffusion of particles across the boundary and decrease the estimated annihilation rate.

A new dedicated satellite MeV  $\gamma$ -ray detector is required to clarify the observational situation

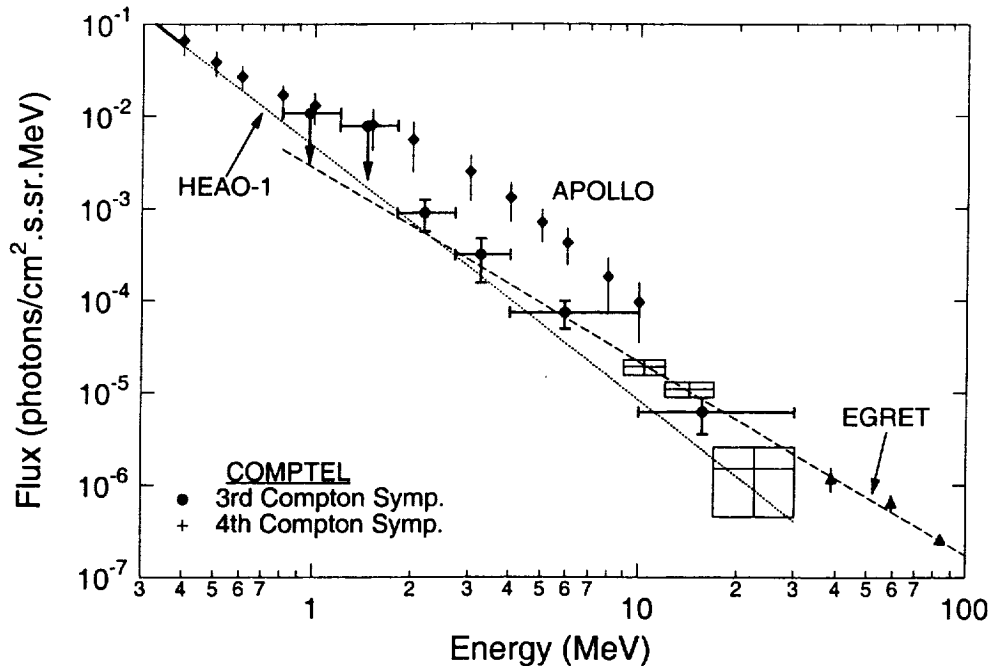


Figure 5: A compilation of diffuse  $\gamma$ -ray background measurements as a function of energy. <sup>38</sup>

and to determine the flux and spectrum of  $\gamma$ -rays in this critical energy range. The satellite should be light-weight and contain only the MeV detector and no other experiments in order to minimize the mass in which cosmic rays can induce intrinsic MeV photon production. It should be also flown in a region far from the Earth's radiation belts, since such radiation induces intrinsic MeV photon production within the satellite and detector.

## 7 Conclusions

The fact that simple hot big bang "freeze out" calculations predict a baryon density in the universe which is nine orders of magnitude too low indicates that  $B$ ,  $C$  and  $CP$  symmetries must be broken in the early universe at times corresponding to a temperature greater than 20 MeV, the simple freeze-out temperature for nucleons and antinucleons. The violation of these symmetries, especially  $CP$ , and their consequences for cosmology are the subject of this meeting. If  $CP$  violation is predetermined, than only matter will remain in the present universe. If, on the other hand,  $CP$  violation ( $CPV$ ) is the result of spontaneous symmetry breaking, domains of positive and negative  $CPV$  may result. If this domain structure is stretched to astronomical size by a subsequent period of moderate inflation, then fossil baryons may survive as galaxies in some regions of the universe and fossil antibaryons survive as antigalaxies in other regions. We have referred to this possibility as "locally asymmetric domain cosmology (LADC)." A longer period of inflation would result in the entire visible universe being in one domain region.

As of this writing, there is no evidence for large scale extragalactic antimatter and, by inference, for LADC. Cosmologically significant sub-galaxy size antimatter regions are ruled out by their potential effect on big-bang nucleosynthesis. <sup>44</sup> Significant antimatter in our own galaxy is ruled out by low energy cosmic ray measurements. Although presently unclear,  $\gamma$ -ray background measurements indicate that in a LADC cosmology, the size of the separate regions of matter and antimatter must be at least of galaxy supercluster extent.

However, in the present search for cosmological antimatter, absence of evidence is not necessarily evidence of absence. A dedicated MeV background satellite detector experiment designed



to be as clean from radiation induced intrinsic contamination as possible would help to clarify the situation. A possible determination of departures from isotropy at 20 MeV by the GLAST (Gamma Ray Large Area Telescope) satellite, to be launched in 2006, may provide another test. However, this test is compromised by the real possibility that the 20 MeV background may be dominated by unresolved blazars<sup>45</sup>. Another interesting test would be to look for departures from isotropy in the cosmic background radiation caused by the interactions of high energy electrons from the decay of  $\pi^\pm$ 's produced by annihilation at the boundaries of matter and antimatter regions.<sup>46</sup>

## 8 A Final Thought

I stated in the introduction section that the question of the existence of antimatter in the universe, as with all fundamental physics questions, in the end must be answered empirically. The discovery of even one "gold plated" antihelium nucleus in the cosmic radiation could change our whole outlook on this question. I remark that a fish called the coelacanth was believed to have become extinct 65 million years ago until one was discovered in the 1930s. The discovery of an antihelium "helicanth" would have a much more profound effect on science.

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