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CP violations in the Universe

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Abstract The origin of the asymmetry between matter and antimatter that is evident in our part of the Universe is one of the open questions in cosmology, because the CPT symmetry between matter and antimatter seems to be absolutely conserved at microscopic level. We repeat here the classical proofs which exclude the viability of a Universe baryon symmetric on the average, or the observed asymmetry as an initial conditions. The current understanding is that the asymmetry should have been dynamically generated before nucleosynthesis, by B, C, and CP violating processes, acting out of thermodynamical equilibrium, as suggested by Sakharov in the 70's. The physical realizations of these conditions would be possible, in principle, also in the framework of the Standard Model of elementary particles, but the present limits on the mass of the higgs particle exclude this possibility. Finally we present the model of baryogenesis through leptogenesis, which is allowed by a minimal extension of the Standard Model, which has the appeal of being testable in future long-baseline neutrino oscillation experiments.

Key words: Cosmology: early universe, elementary particles

1 INTRODUCTION

One of the many providential circumstances about our Universe is its (at least local) "baryon asymmetry", or, in other words, the fact that in our environment all the massive objects are made of positive protons and negative electrons. The question which immediately follows is why it is so, given the complete equivalence between matter and antimatter established by the CPT theorem, which states that any local quantum field should be symmetric respect to the successive application of a charge conjugation $\widehat{C} \equiv q \rightarrow -q$, a parity reflection $\widehat{P} \equiv \mathbf{r} \rightarrow -\mathbf{r}$ and a time reversal $\widehat{T} \equiv t \rightarrow -t$ as a direct consequence of Lorentz invariance. A testable prediction of the CPT symmetry is the fact that any particle X has an antiparticle $\overline{X}$ with same mass $m_X = m_{\overline{X}}$, same total decay width $\Gamma_X = \Gamma_{\overline{X}}$ and same but opposite charge $Q_X = -Q_{\overline{X}}$. The most accurate test performed (Hagiwara et al. 2002) shows that the mass difference $|m_{K^0_L} - m_{\overline{K}^0_L}| \leq 4.4 \times 10^{-19}$ GeV at 90% C.L., while we have from precision measurements (Yamaguchi et al. 2003) of the mass of antiprotons $|m_p - m_{\overline{p}}| \leq 2 \times 10^{-8}$ GeV at 90% C.L.

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A consequence of the CPT theorem is that the e.m. appearance of galaxies made of antimatter would be exactly the same of that of ordinary galaxies. In fact Dirac concluded his Nobel lecture in 1933 saying:

> *"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."*

Even if astronomical observations cannot exclude at the moment (DeRujula 1997) that we live in an elegantly baryon symmetric Universe, consisting of large islands of matter and antimatter as supposed by Dirac, γ-ray astronomy has given the evidence that antimatter is not present inside a distance of at least 20 Mpc, because, as shown in Fig. 1, no indication of matter-antimatter annihilation radiation con be observed in the emission above 100 MeV from the Virgo cluster.

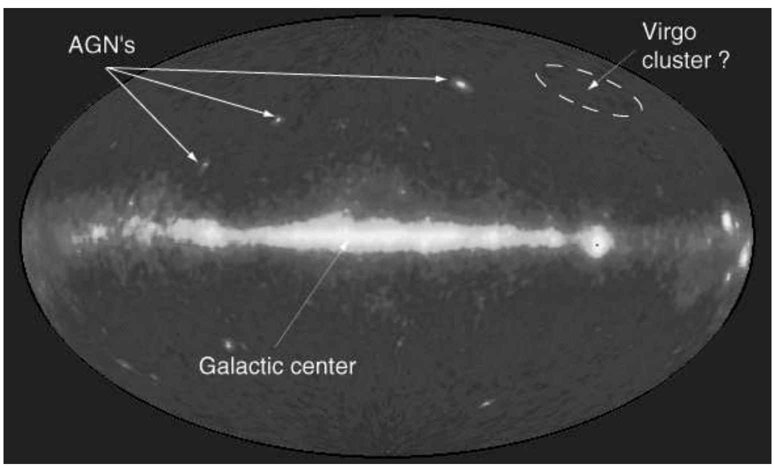

Figure 1 EGRET all-sky gamma-ray survey above 100 MeV.

Recent observations (Uzan et al 2003) favor a value $\Omega_0 = 1.04^{+0.02}_{-0.04}$ very close to a flat Universe (see also talks by Panagia and by Colafrancesco in these proceedings). The present baryon abundance Ω_B is estimated from several type of measurements to be $\Omega_B\, h^2 = 0.024 \pm 0.0001$ (Spergel et al. 2003), completely compatible also with the value required for the synthesis of light elements (Burles et al. 2001). This converts into an extremely small baryon to photon ratio

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} = 6.5^{+0.4}_{-0.3} \times 10^{-10}\,, \tag{1}$$

constant since the time of nucleosyntesys ($t \approx 1$ s). The smallness of this ratio could suggest trivial explanations such as the effect of local fluctuations or the effect of initial conditions. Both this explanations have unsurmountable difficulties (see e.g. the classical review of Steigman 1976), that I will discuss in§2 and §3.

The idea of dynamical generation of baryon asymmetry in the initially symmetric universe, that I will discuss in §4, due to the violation of the symmetry between matter and anti-matter at microscopic level, was pioneered by Sakharov (1967) soon after the discovery by Christenson et al (1964) of the CP violating in weak interactions. As we will show in §4 in addition to the CP symmetry, also baryon number and charge conservation should be violated. Therefore the most likely framework in which baryogenesis could take place was that of the Grand Unified Theories (GUT), which predict baryon violations. In fact for a rather long time it has been thought that the observed baryon was to be interpreted as an evidence for the validity of the GUT. However this explanation is now considered to be in conflicts with an inflationary initial stage of the Universe.

In §5 we will present the alternative to the failure of GUT baryogenesis proposed by Kuzmin et al. (1985) that the Sakharov scenario could have been realized before the Electro-Weak (EW) phase transition, in the framework of the Standard Model (SM) of elementary particles. But also in this case there is a general consensus that this is unlikely, due to the experimental lower limit to the mass of the higgs particle.

Among the many other suggested mechanisms that imply an extension of the SM (for a recent review see e.g. Dine & Kusenko 2003) we have chosen to discuss in §6 the baryogenesis through leptogenesis mechanism, proposed by Fukugita & Yangita (1986), because it appear at the moment it has the particular appeals to be experimentally testable by accelerator experiments.

2 CAN THE UNIVERSE BE BARYON SYMMETRIC ?

We will start considering the evolution of particles density in the early Universe, when it was radiation dominated and its scale factor evolved as $R \propto t^{1/2}$. In the radiation dominate era most of the particles were in thermodynamical equilibrium with the photons by reactions of the type $X + \gamma \leftrightarrows X + \gamma$, thus the energy density of the Universe can be parameterized with the formula

$$\rho = \frac{\pi^2}{30} N(T) T^4 , \tag{2}$$

where $N(T)$ is the effective number of degrees of freedom of the cosmic plasma. The energy density of non relativistic particles is exponentially suppressed,

$$N(T) = \left[\sum_{m_i \leq T} g_i + \frac{7}{8} \sum_{m_j \leq T} g_j \right] . \tag{3}$$

The statistical weight g will be $g = 2J + 1$ for massive fields or particles with spin J, 2 for massless fields with spin and 0 for massless scalar fields. Inserting Eq. (2) into the Friedmann-Lemaïtre equation (Hagiwara et al. 2002) we have immediately

$$H = \frac{\dot{R}}{R} = 1.66 \sqrt{N(T)} \frac{T^2}{M_{Pl}} , \tag{4}$$

where where $M_{Pl} = G_N^{-1/2} = 1.22 \times 10^{19}$ GeV, is the Planck mass. Deriving $R \propto t^{1/2}$ we have $t = (2H)^{-1}$ or

$$t = \frac{0.3}{\sqrt{N(T)}} \frac{M_{Pl}}{T^2} . \tag{5}$$

In Fig. 2 we have plotted $N(T)$ as a function of the temperature, which finally depends on the mass spectrum allowed by Particle Physics. The solid line shows the prediction of the Standard Model, which can be considered well founded up to temperatures of $\mathcal{O}(100)$ GeV. The dashed line represents the mass spectrum of the supersymmetric extension of the SM, the lower without and higher with GUT.

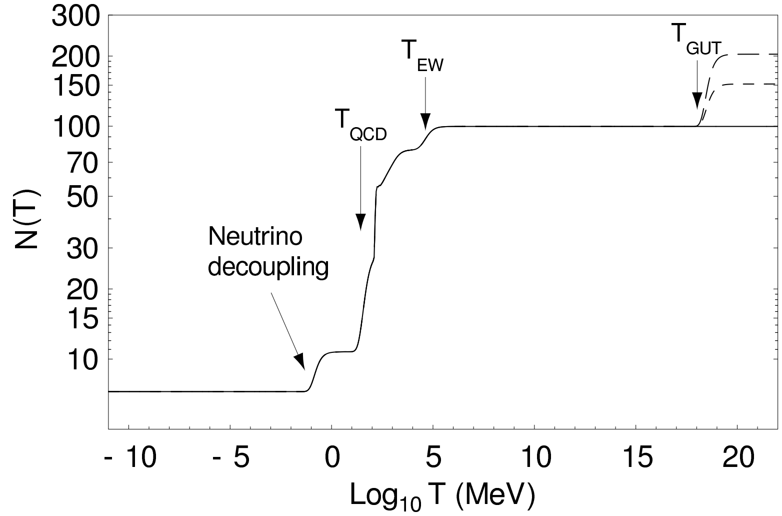

Figure 2 Effective number of degrees of freedom of the cosmological plasma before nucleosynthesis, as a function of the temperature. The arrows show some of the relevant temperatures at which we expect a sharp change of the physical regime in the plasma, due to the physics of particles interactions.

However the smoothness of the space-time expansion, given by Eq. (5) is very misleading. Even if it does not have a large impact on the rate of expansion, the change of physical conditions of the cosmic plasma in the radiation dominated era is extremely dramatic, with an increasing complexity towards higher temperatures which is not included in simple d.o.f. counting. It is well understood, for example, that at a temperature of the order of $T > T_{QDC} \approx 150$ MeV the quarks are no longer confined into hadrons, therefore the plasma is a mixture of quarks and gluons almost free, which is indicated as the Quark Gluon Plasma (QGP) (see e.g. Schwarz 1998), a new state of matter never directly observed up to now, which appears in Eq. (5) simply as a smooth change under the square root from $N(T < T_{QCD}) = 17.25$ to $N(T > T_{QCD}) = 61.75$. It is worth noticing in this context that the physics that we apply to the cosmic plasma has been learned from high energy particles collision. The difference at least in principle is that the high temperature plasma created during these collisions is very far from thermodynamical equilibrium, therefore the extrapolation to the actual physics of cosmic plasma could be uncertain.

In this section we want to explore the possibility that the local baryon asymmetry could have been originated by a statistical fluctuation of the baryon antibaryon pairs created in the reaction $B\overline{B} \leftrightarrows \gamma\gamma$. The number density of baryon-antibaryon pairs in equilibrium with the radiation at a temperature T will be obtained integrating the Boltzmann-Vlasov equation

$$\frac{dn_B}{dt} + 3\,H\,n_B = -(n_B - n_B^{eq})\;\langle\sigma_{B\overline{B}}\,v\rangle\;n_{\overline{B}}^{eq}\,, \tag{6}$$

where $\langle \sigma_{B\overline{B}}\, v\rangle$ is the thermally averaged rate of the annihilation reaction $B\overline{B} \leftrightarrows \gamma\gamma$ and $n_B^{eq} = n_{\overline{B}}^{eq}$ is the integral of the Fermi-Dirac distribution. In the non-relativistic limit $T < 1$ GeV we have

$$n_B^{eq} = n_{\overline{B}}^{eq} \simeq \frac{1}{\sqrt{2}\,\pi^{\frac{3}{2}}}\,(m_p\, T)^{\frac{3}{2}}\; e^{-m_p/T}\,. \tag{7}$$

As long as $\Sigma_{B\overline{B}}\, n_{\overline{B}}^{eq} \gg H$ we have the chemical equilibrium $n_B = n_B^{eq}$, but when $\Gamma_{B\overline{B}}\, n_{\overline{B}}^{eq} \approx H$ the density of both baryons and anti-baryons will decrease with the expansion $\propto R^{-3}$. Due to entropy conservation, the baryon fraction n_B/n_γ will remain frozen from now on. The freeze out temperature T_f will be the solution of the equation $H(T_f) = \Gamma_{B\overline{B}}\, n_{\overline{B}}^{eq}(T_f)$. The thermally averaged annihilation rate is $\Gamma_{B\overline{B}} \approx m_\pi^{-2}$, then solving numerically this equation we have $T_f =$ 25 MeV. The relic density of baryons produced in chemical equilibrium will be $n_B/n_\gamma \approx 10^{-18}$. From statistical fluctuations one would expect $N_B - N_{\overline{B}} \approx \sqrt{N_B}$ but inside the causal radius of the Universe at freeze out temperature $L \leq H(T_f)^{-1}$, (Cohen et al. 1998). Applying Eq. (5) we have $L \approx 600$ km thus the total amount of matter enclosed in the local matter bubble could be of the order of $M \approx \frac{\delta n_B}{n_B}\, 10^5\, M_\odot$, which is excluded by direct observations.

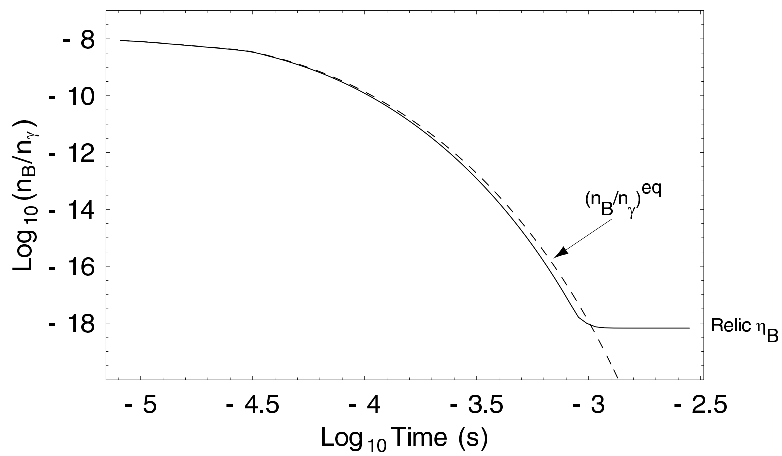

Figure 3 Solution of the Boltzmann-Vlasov equation for a baryon symmetric Universe (solid line). The dashed represents the equilibrium density.

Therefore an initially baryon symmetric Universe could evolve into a locally baryon asymmetric one, with the observed baryon antibaryon segregation, only if, as suggested by Omnès (1969), an unknown mechanism could separate matter from antimatter on a scale larger then the casual horizon at the freeze out, but clearly the more reasonable alternative is to admit that the local baryon asymmetry was preexisting time of the freeze $t_f \simeq 10^{-3}$ s.

3 COULD BARYON ASYMMETRY BE AN INITIAL CONDITION ?

The naîve extrapolation of the radiation dominated era to $t \to 0$ leads to an unphysical singularity $\rho \to \infty$. This extrapolation loose any significance when $t \simeq M_{Pl}^{-1}$ because at this point we expect the gravitational field to be quantized. The Plank mass scale was proposed by Planck (1899), soon after having discovered the quantum of action $\hbar$, as a phenomenological constant derived from the black body radiation spectrum, as a possible natural unit for the mass. Planck's proposal was not at all justified in the physics of his time, and the smallness of this units made it totally unsuited to be used in the practical world. On the contrary we know now that if a particle with mass M_{Pl} it has a Schwarzchild radius $r_S = 2\,M_{Pl}^{-1}$ while its Compton wavelength is only $r_C = M_{Pl}^{-1}$, therefore it will appear under any aspect like a black hole. According to theory, a black hole of mass M_{Pl}, because of quantum effects, emits Hawking radiation like a black body, and evaporate completely its rest-mass energy M_{Pl}, via Hawking radiation (Jacobson 1995) in a time $t_{Pl} = M_{Pl}^{-1}$, in agreement with the Heisenberg's principle $\Delta E\,\Delta t \geq 1$. This implies that a temperature $T > M_{Pl}$ cannot be observed because it is realized at $t < M_{Pl}^{-1}$.

According to quantum field theory, empty space is filled with quantum fluctuations of all types of physical fields, therefore the energy density of the Universe for $t \simeq M_{Pl}^{-1}$ is a stochastic variable with average value $\mathcal{O}(M_{Pl}^4)$. This is the scenario for the starting of the chaotic inflation proposed by Linde (1983), where the dominant field at $t \approx M_{Pl}^{-1}$ was a massive scalar field with lagrangian density

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m^2\,\phi^2\,, \tag{8}$$

where $m \ll M_{PL}$ is the mass of the field. From this lagrangian we can obtain the energy-stress tensor in the canonical form

$$T_{\mu\nu} = \partial_\mu\phi\,\partial_\nu\phi - g_{\mu\nu}\mathcal{L}\,. \tag{9}$$

For a perfect fluid it is $T_{\mu\nu} = \mathrm{diag}\,(\rho, p, p, p)$, therefore we can identify

$$\begin{aligned} \rho &= T_{00} = \tfrac{1}{2}\dot{\phi}^2 + \tfrac{1}{2}(\nabla\phi)^2 + \tfrac{1}{2}m^2\,\phi^2\,, \\ p &= \tfrac{1}{3}(T_{11} + T_{22} + T_{33}) = \tfrac{1}{2}\dot{\phi}^2 - \tfrac{1}{2}(\nabla\phi)^2 - \tfrac{1}{2}m^2\,\phi^2\,, \end{aligned} \tag{10}$$

where for an homogeneous field (at least for $R \leq H^{-1}$) the space derivatives vanish. The condition required for a DeSitter type of expansion $\rho \simeq$ const is $p \simeq -\rho$. Comparing with Eq.ns (10) we see that this implies $\dot{\phi} \ll m\,\phi$, which is called the slow-rollover condition. In this case from the Friedmann-Lemaitre equation we have

$$H \simeq \sqrt{\frac{4\pi}{3}}\,\frac{m\,\phi}{M_{Pl}}\,, \tag{11}$$

causing an exponential expansion $R \propto e^{\int H dt}$. The conservation of energy can be put in the form:

$$\ddot{\phi} + 3\,H\dot{\phi} + m^2\,\phi = 0 \tag{12}$$

resembling the equation of a damped harmonic oscillator, with a friction term $3\,H\,\dot{\phi}$. Initially when the field is $\phi \geq M_{Pl}/3\pi$, the field decreases as $\phi \propto e^{-3\int H dt}$. When the field ϕ becomes sufficiently small it begins to oscillate around $\phi = 0$. As any rapidly oscillating classical field, it looses its energy to radiation and pairs of particles that come to a state of thermal equilibrium at a temperature $T_{reh} \simeq \sqrt{\Gamma\,M_{Pl}}$ where Γ is the decay width of the field to radiation and particles. From this time on, the corresponding part of the universe can be described by the standard hot universe theory. In realistic versions of inflationary theory the duration of the exponential expansion could be as short as 10^{-35} s, but H could be extremely large. Uzan et al. (2003) observed that if one takes literally the WMAP best fitted value $\Omega_0 = 1.02 \pm 0.02$ (Bennett et al. 2003) it indicates (at 1 σ) that the universe could have a slightly positive curvature. The expansion needed to obtain $\Omega_0 \geq 1.05$ (excluded at 95% C.L. from WMAP data) is $e^{\int H dt} \geq \mathcal{O}(10^{28})$. we have two difficulties that as far as we know quantum gravity

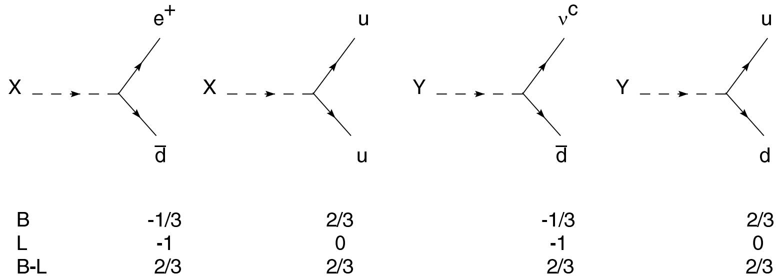

Figure 4 Coupling of the GUT vector bosons to quark and leptons.

does not conserve $\overline{B}$, as could be theoretically predicted by process involving BH evaporation (Upadhyay et al. 1999). In fact the weak and strong nuclear forces are carried by massive fields, which are set to zero at the event horizon, so black holes cannot have neither baryon number nor lepton number. It means that if a BH has been formed by matter with net baryon charge, it should likely loose this charge in the gravitational collapse.

Therefore even if we assume that a net baryon number N_B was preexisting to the onset of inflation, it will be conserved in the expansion, but the initial entropy $S_{in} \simeq (M_{Pl}/m)^3$ will be increased by a factor $e^{3\int H dt} \geq \mathcal{O}(10^{84})$, diluting the asymmetry N_B/S to an extremely low level.

4 GUT BARYOGENESYS

Sakharov (1967) soon after the discovery by Christenson et al. (1964) of the CP violating decay $K_L^0 \rightarrow \pi\,\pi$ proposed that an initially baryon-symmetric Universe could acquire a baryon asymmetry as an effect of CP violations. In fact the generation of a matter-antimatter asymmetry in the early Universe starting with symmetric initial conditions, is impossible if CP symmetry is not violated, because in this case a mixture of a particle A, kept in chemical equilibrium with its antiparticle $\overline{A}$ by the reaction $A\overline{A} \leftrightarrows \gamma\gamma$ will produce the same amount of matter and antimatter. Electromagnetic and strong interactions are invariant respect to $\widehat{C}$, $\widehat{P}$, and their product $\widehat{C}\widehat{P}$, therefore no baryon asymmetry can be originated from these type of interactions. Instead it was experimentally demonstrated by Wu et al. (1957) that the weak interactions do not conserve the $\widehat{P}$ symmetry. Before 1964 it was common wisdom to think that CP symmetry should hold also for weak interactions, until it has been shown experimentally (Hagiwara et al. 2002) that the widths of the decay $K^0 \rightarrow l^+\nu_l\pi^-$, is larger by 0.3% than its $\widehat{C}\widehat{P}$-conjugated $\overline{K}^0 \rightarrow l^-\overline{\nu}_l\pi^+$. Similar deviations are observed in the decay of the mesons with beauty (Aubert et al. 2001, Abe et al. 2001).

It is worth noticing however that the CP violation cannot produce a baryon over antibaryon excess if the baryon number is not violated in the same decay. This is the reason why CP violation can be studied experimentally at low energies only in meson system which have $B = 0$ in decays that have only leptons antileptons pair and mesons in the final state, because at low energies the baryon and lepton number appear to be conserved quantities. This has been for a long time a weak point in the Sakharov mechanism.

Ten years after the Sakharov paper, the $SU(5)$ model of Grand Unification Theory (GUT) was proposed by Georgi & Glashow (1974), renewing the interest in baryogenesys. In this theory quarks and leptons are in the same multiplet, so do exist interactions that couples quarks and leptons, which could induce baryon number violating processes, such as, for example, the proton decay $p \to e^+ \pi^0$. As shown in fig. 4 this interactions are mediated by two "leptoquark" vector bosons X and Y carrying baryon number B and lepton number L, such as to have $B-L = 2/3$. Obviously the masses m_X and m_Y must both be very large, in order to justify the fact that the lifetime of the proton is many order of magnitude greater then the Hubble time, and the search for proton decay as well as any other search for baryon number violating processes has given negative results (Hagiwara et al. 2002). Moreover in the decay of the X and Y bosons CP violations are also predicted as a consequence of the mixing of quarks, the same mechanism that leads to violate CP symmetry in the Standard Model.

To be more quantitative, if GUT's are true at very high temperatures each type of leptoquark X and Y will be pair created and decay into the channels shown in fig. 4. If for example we consider a leptoquark X with widths parameterized as

$$\begin{array}{ll} \Gamma(X \to q\,q) = (1+\epsilon_q)\Gamma_q & \Gamma(X \to q\,\bar{l}) = (1-\epsilon_l)\Gamma_l \\ \Gamma(\overline{X} \to \overline{q}\,\overline{q}) = (1-\epsilon_q)\Gamma_q & \Gamma(\overline{X} \to \overline{q}\,l) = (1+\epsilon_l)\Gamma_l \end{array} \tag{13}$$

where q is any quark and l any lepton. The constraint due to the discrete symmetries are

- If baryon number is conserved $\Gamma_q = 0$
- If CP symmetry is conserved $\epsilon_q = \epsilon_l = 0$
- If CPT is conserved it would be $\Gamma_X = \Gamma_{\overline{X}}$, a condition fulfilled if $\epsilon_q \Gamma_q = \epsilon_l \Gamma_l$.

If the particles X and $\overline{X}$ are pair created at a temperature $T \approx m_X$ by the reaction $X\,\overline{X} \leftrightarrows \gamma\,\gamma$ all the leptoquark will decay before annihilating, because the rate of annihilation will be $\langle \sigma_{X\overline{X}}\, v \rangle \approx \alpha_X^2\, T^3/m_X^2$, while the decay width, averaged over the relativistic time dilation will be $\Gamma_X \approx \alpha_X\, m_X^{/} \sqrt{T^2 + M_X^2}$ where $\alpha_X < 1$ is the coupling constant. In each decay of a pair $X\overline{X}$ we have a net baryon number increase

$$\Delta B = \frac{\frac{4}{3}\epsilon_q\,\Gamma_q - \frac{2}{3}\epsilon_l \Gamma_l}{\Gamma_X} = \frac{2}{3}\,\frac{\epsilon_q\,\Gamma_q}{\Gamma_X}\,, \tag{14}$$

where we have taken into account that any quark carries a baryon number $B = 1/3$.

Therefore the evolution for the number densities will be a set of coupled Boltzmann-Vlasov equations, which are written using the variables $\eta_X = n_X/n_\gamma$ and $\eta_B = (n_B - n_{\overline{B}})/n_\gamma$ (Kolb & Wolfram 1980):

$$\begin{aligned} \dot{\eta}_X \; &\simeq \; -\Gamma_X \left\{ (\eta_X - \eta_X^{eq}) + \Delta_B\, \eta_B\, \eta_X^{eq} \right\} \\ \dot{\eta}_B \; &\simeq \; \Delta_B\, \Gamma_X\, (\eta_X - \eta_X^{eq}) - 2\,\eta_B \left\{ \Gamma_X\, \eta_X^{eq} + n_\gamma \langle \sigma_{qq\to\overline{q}\,\overline{q}} v \rangle \right\} \end{aligned} \tag{15}$$

where η_X^{eq} is the equilibrium density ratio, obtained integrating the Bose-Einstein distribution, and $\langle \sigma_{qq\to\overline{q}\,\overline{q}} v \rangle$ of the baryon violating reaction $qq \to \overline{q}\,\overline{q}$ mediated by a virtual GUT boson, which we have assumed to be $\langle \sigma_{qq\to\overline{q}\,\overline{q}} v \rangle \approx \alpha_X^2\, T^2/(T^2 + M_X^2)^2$.

Numerical solutions of the Eq.ns (15) are shown in Fig. 5. The relic baryon asymmetry originated by this process is

$$\eta_B \approx \mathcal{O}\left(10^{-2}\right)\, \Delta B\,, \tag{16}$$

therefore the observed value of the present baryon asymmetry $\eta_B \simeq 6.5 * 10^{-10}$ is obtained assuming that CP violations are in the range $\epsilon \approx \mathcal{O}(10^{-6})$ and $\Gamma_q/\Gamma_X \approx$ few percent.

However the decay of the X bosons can take place only at an age of the Universe $t \geq \Gamma_X^{-1}$ and for the mechanism to be effective in producing a sizeable baryon asymmetry, it should take place when the temperature is $T \approx \mathcal{O}(M_X)$. Combining these two constraints we have

$$M_X \geq \; N(T)^{-\frac{1}{2}}\, \alpha_X\, M_{Pl} \approx \alpha_X\, 10^{17}\ \mathrm{GeV}\,, \tag{17}$$

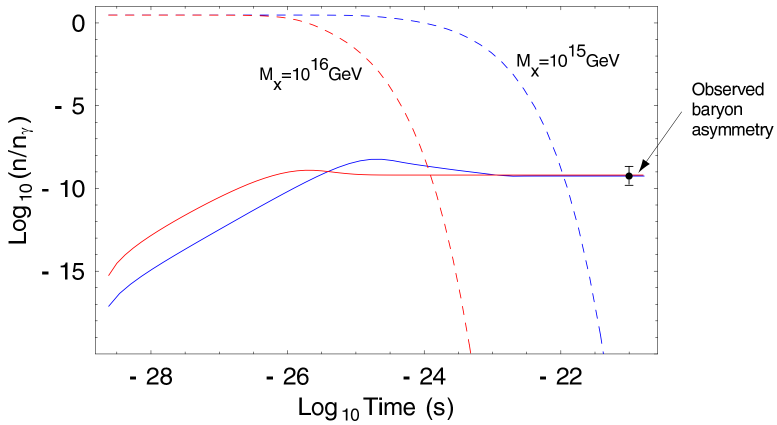

Figure 5 Solution of the Boltzmann-Vlasov equation for an initially baryon symmetric Universe (solid line). The dashed lines represents the equilibrium density, while solid lines are the B-asymmetry originated by the decay of GUT bosons.

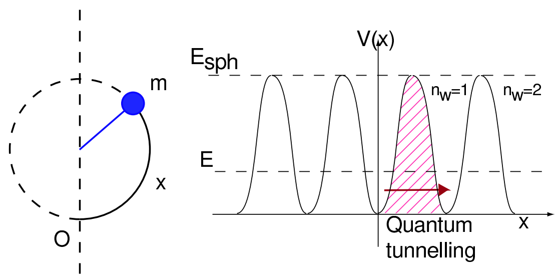

Figure 6 In the Standard Model transition $\Delta B = \Delta L = \pm 3$ which violates $B + L$, but conserve $B - L$ are mediated spontaneously by a field configuration called "sphaleron", as tunnelling transition between different vacua.

which predicts a proton lifetime of

$$\tau_p \simeq \tau_\mu \left(\frac{m_\mu}{m_p}\right)^5 \left(\frac{M_X}{M_W}\right)^4 \simeq 10^{34} \left(\frac{m_X}{10^{16}\ \mathrm{GeV}}\right)^4 \text{ years}, \tag{18}$$

not in conflict with the experimental limit $\tau_p \geq 1.6 \times 10^{33}$ years at 90% C.L. (Shiozawa et al 1998). But this requires that the reheating of the Universe after inflation, during the reheating phase is expected to be in the range of 10^{14} GeV otherwise too many relics such as monopoles or gravitinos would be created in contrast with observations (see e.g. Riotto & Trodden 1999).

5 ELECTROWEAK BARYOGENESYS

As an interesting alternative to the suspected failure of GUT baryogenesys, Kuzmin et al. (1985) examined the possibility that the violations of baryon number, predicted in the Standard Model at very high temperature could produce the observed baryon asymmetry. 'tHooft (1976) proved that in the electroweak unified model $B - L$ is always conserved, while $B + L$ violating

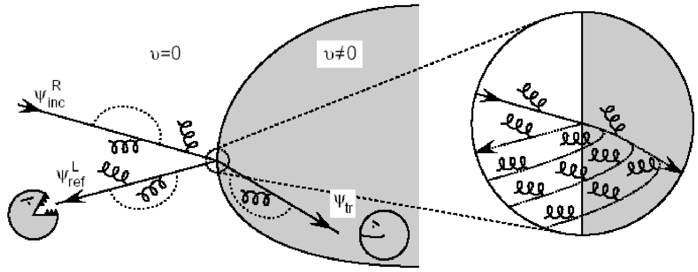

Figure 7 Artistic view from Gavela et al. (1994) of the selective reflection mechanism in the walls of EW bubbles. The hungry "pacman" represents rapid sphalerons processes. The wiggly lines stand for collisions with thermal gluons. Only electroweak loops are depicted, represented by dotted lines.

processes with the selection rule $\Delta B = \Delta L = \pm 3$ could be predicted. At temperatures $T \leq T_{\rm EW}$ these types of transition are strongly suppressed, but at high temperatures the rate will be $\Gamma_{\rm sph} \simeq \alpha_W T$ (Rubakov & Shaposhnikov 1996) where $\alpha_W = \alpha/\sin^2\theta_W \simeq 1/30$. Applying Eq. (4) we have that $B+L$ violating processes are in thermal equilibrium, $\Gamma_{\rm sph}(T) \geq H(T)$, for $T \leq T_{\rm max}$ where

$$T_{\rm max} \simeq N(T)^{-\frac{1}{2}} \alpha_W M_{Pl} \approx 10^{12} \text{ GeV}, \tag{19}$$

as confirmed by recent lattice calculations (Moore 2000). The Boltzmann-Vlasov equation Eq. (6) is in this case

$$\frac{dn_B}{dt} = \frac{dn_L}{dt} \simeq -\Gamma_{\rm sph}(n_B + n_L) \tag{20}$$

where is $\frac{dn_B}{dt} = \frac{dn_L}{dt}$ a consequence of the $B-L$ conservation. The solution to this equation will be

$$n_B = \frac{1}{2}(n_B - n_L)_{T_{\rm max}} + \frac{1}{2}(n_B + n_L)_{T_{\rm max}}\, e^{-\Gamma_{\rm sph}/2H} \tag{21}$$

where we have used $t = (2H)^{-1}$. Thus we have that in practice no baryon asymmetry could exist before the EW phase transition, if as expected $n_B = n_L$ at the end of inflationary expansion.

Therefore only at $T \approx T_{\rm EW}$ the violation of the CP symmetry could operate to produce a baryon asymmetry. However in the SM CP-symmetry is violated by the CKM mechanism, discussed in §4. However at high temperatures the CKM mechanism of CP violation is strongly suppressed, due to the smallness of mass difference between the light quarks. In fact the CP violation is possible via the CKM mechanism only because quarks having the same electrical charge have different masses. At high temperature the mass difference becomes negligible, therefore we have that the CP violation is very small, being at $T \simeq 100$ GeV of the order of $\epsilon \approx \mathcal{O}(10^{-19})$. (Jarlskog 1985).

However the situation could be quite different if the phase transition from a symmetric EW vacuum to the ordinary vacuum is a first order phase transition (Farrar & Shaposhnikov 1993). In this case the transition is not homogenous but proceed by nucleation of bubbles of the spontaneously broken symmetric phase, in which we can assume that $T \leq T_{\rm EW}$, and $B+L$ violating reactions are suppressed, embedded in a symmetric vacuum with $T \geq T_{\rm EW}$ where $B+L$ violating reactions occur at fast rate. In this situation we can expect that the CP violations will originate a difference in the reflection and transmission coefficients of the quarks

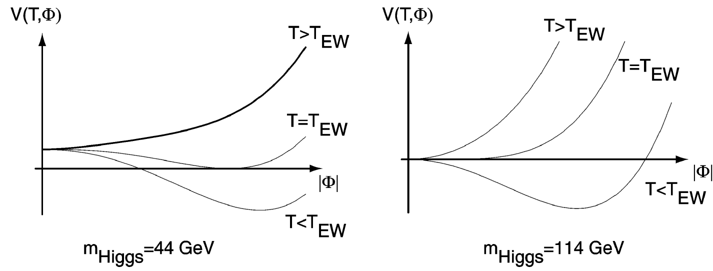

Figure 8 Behavior of the Higgs potential in the Standard Model at finite temperature around $T \approx T_{\rm EW}$ transition for two different masses of the higgs particle.

and anti-quarks by the walls of the bubbles, as schematically shown in the cartoon of Fig. 7. This could originate a a baryon asymmetry inside the bubbles, which expands and coalesce until they fill the entire Universe. Whether or not this mechanism could produce the observed asymmetry has been questioned (see e.g. Huet & Sather 1995 or Gavela et al. 1994), but more conclusively is the fact that it is now generally accepted that the EW phase transition is not first order. In Fig. 8, we have plotted the potential $V(T,\Phi)$ for two different masses of the Higgs field. It is clear from this figure that the transition is sharper for a low Higgs mass. Therefore the lower limit to the mass of the Higgs boson set by the LEP2 experiments (Barate et al. 2003) $m_H \geq 114$ GeV excludes this mechanism.

6 BARYOGENESYS THROUGH LEPTOGENESYS

The failure of the EW baryogenesis has as the consequence that we have to find an explanation to the observed baryon asymmetry in some extension of the SM. The possibility that the baryon asymmetry could be produced by the baryon number violating reactions, is contained in the Eq. (21) which we have derived in the previous section. Fukugita & Yanagita (1986) proposed that at a temperature $T \geq T_{\rm max}$ a lepton excess could be produced, for example by lepton number violating GUT processes. This approach is very interesting in the light of present evidence for neutrino masses and oscillations (Frampton et al. 2002).

As a matter of fact neither cosmology nor experiments can exclude the existence of heavy right-handed neutrinos with mass much greater than $M_Z/2$, predicted by GUT's. Since lepton number is violated the right-handed neutrinos can be majorana type particles, which means in practice particles that are indistinguishable from their anti-particles, such as happens for the neutral pion. The "seesaw mechanism" (see e.g. Akhmedov et al. 1999 and references therein) provides a very natural and attractive explanation of the smallness of the neutrino The smallness of left-handed neutrino masses as inferred from the oscillations of solar and atmospheric neutrinos masses, being the mass matrix of left-handed neutrinos

$$m_L = -m_D\, M_R^{-1}\, m_D^T\,, \tag{22}$$

where m_D is the ordinary mass matrix of dirac particles, and M_R the mass matrix of right-handed majorana particles. Assuming a minimal extension of the SM the quark sector will be unchanged, while to the lepton sector will be added three singlet right-handed neutrinos N_i. The terms of of the mass matrix will be of the order $m_L \approx m^2/M$ where m are the eigenvalues of the dirac mass of the charge 2/3 quarks and M the typical mass of right-handed neutrinos. The largest mass of left-handed neutrinos should be of the order of m_t^2/M. From the best fit

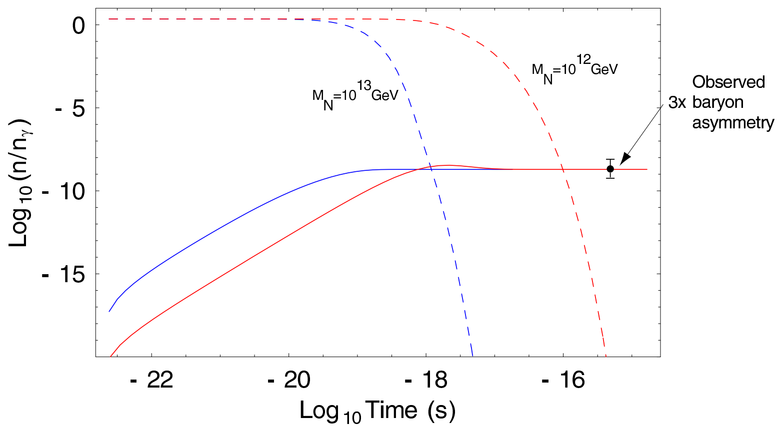

Figure 9 Solution of the Boltzmann-Vlasov equation for an initially baryon and lepton symmetric Universe. The dashed lines represents the equilibrium density, while solid lines are the L-asymmetry originated by the decay of heavy majorana neutrinos.

of all combined data on the oscillation of atmospheric neutrinos it is obtained (Fornengo et al. 2000) $\Delta m^2_{\rm atm} = 3 \times 10^{-3}$ eV^2, if we assume that $\Delta m^2_{\rm atm} \approx (m_t^2 - m_c^2)^2/M^2$ we obtain a value of $M \approx 10^{12}$ GeV/c^2. Therefore if heavy right-handed neutrinos do exist, their majorana mass allowed in GUT's must be very large and their decay at $T \approx T_{\rm max}$ should take place when they are not in thermodynamical equilibrium, respecting the third Sakharov's condition for generation of baryon asymmetry.

In this situation an initial lepton asymmetry will be originated by CP violation which makes the two decay channel of the right handed neutrinos $N \to l^- + h^+$ and $N \to l^+ + h^-$ asymmetrical with

$$\Gamma[N \to l^- + h^+] = \frac{1}{2}\,(1+\epsilon)\,\Gamma \quad \text{and} \quad \Gamma[N \to l^+ + h^-] = \frac{1}{2}\,(1-\epsilon)\,\Gamma\,, \tag{23}$$

where Γ is the total width and $\epsilon \ll 1$ the amount of CP violation. The thermodynamics of these decays is very similar to the one done for the decay of the GUT bosons in §4 (Pilaftsis 1998, Buchmuller et al 2003). Typical numerical solutions of the Boltzmann-Vlasov coupled equations is shown in Fig. 9. Also in this case we have that the lepton asymmetry will be

$$\eta_L \approx \mathcal{O}(10^{-2})\,\epsilon\,. \tag{24}$$

Even if the initial baryon number $B = 0$ initially at $T > T_{\rm max}$ we have $B - L = -L_{ini}$, then the fast sphaleron baryon number violating transitions can produce excess baryons, in order to keep $B-L$ constant. Taking into account the conservation of chemical potentials, of charge and of hypercharge (see e.g. Pilaftsis 1998) we arrive to the conclusion that the baryon number at the end of the EW phase transition will about 1/3 of the conserved $B - L$ initial value, which secure the result that this mechanism can produce the observed asymmetry if the CP violation amount is $\epsilon \approx \mathcal{O}(10^-8)$.

However in order to establish that the observed baryon asymmetry was produced in this way, it is necessary to demonstrate that both the sign and the absolute value of the CP violations are the correct ones (Frampton et al. 2002). What is extremely interesting about this mechanism is the fact that it is possible to establish a link between the amount of CP violations required by successful leptogenesys and the difference $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$ in the probability the oscillation of low energy neutrinos (Endoh et al 2003), which can be tested in long-baseline accelerator experiments.

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