LEPTOGENESIS WITH COSMIC STRINGS

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Abstract

A new scenario for baryogenesis is described. The basic idea is that theories beyond the standard model which contain a $U(1)_{B-L}$ gauge symmetry, where $B$ and $L$ are respectively baryon and lepton numbers, predict the existence of $B - L$ cosmic strings with right-handed neutrinos trapped as transverse zero modes. Cosmic string loops lose their energy via gravitational radiation and rapidly decay releasing these right-handed neutrinos. These decay into lepton and electroweak Higgs boson producing an initial lepton asymmetry. This lepton asymmetry is then converted into a baryon asymmetry via sphaleron transitions. The minimal extension of the standard model and the minimal grand unified theory for which this scenario works are respectively $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ and SO(10).
The aim of baryogenesis is to predict the matter/anti-matter asymmetry of the Universe. This is characterised by a parameter $\eta$ which is equal to the ratio of the baryon number density to the photon number density $\eta = \frac{n_B}{n_\gamma}$ and is predicted by nucleosynthesis to be \(^1\)

$$\eta = \frac{n_B}{n_\gamma} = (2 - 7) \times 10^{-10}. \quad (1)$$

Baryogenesis scenarios have to deal with the problems of sphalerons\(^2\). Sphaleron transitions violate $B + L$ and conserve $B - L$ ($B$ and $L$ are respectively baryon and lepton numbers) and are very rapid between $10^2$ and $10^{12}$ GeV\(^3\). Since $B = \frac{(B+L)}{2} + \frac{(B-L)}{2}$ and $L = \frac{(B+L)}{2} - \frac{(B-L)}{2}$ we have:

$$<B>_{T} \simeq \beta <(B-L)>_{T} \quad \text{and} \quad <L>_{T} \simeq \gamma <(B-L)>_{T}$$

with $\beta$ and $\gamma$ close to 0.5\(^4\). Hence we see that unless the Universe started with a non-vanishing $B - L$ asymmetry, any baryon or lepton asymmetry generated at the grand unified scale will be erased by sphaleron transitions.

In 1986, Fukugita and Yanagida\(^5\) introduced then the idea of leptogenesis: a lepton asymmetry is first produced which is then converted into a baryon asymmetry via sphaleron transitions. We present here a new scenario for leptogenesis\(^6\).

The basic idea is the following. Theories beyond the standard model which contain a $U(1)_{B-L}$ gauge symmetry, predict the existence of $B - L$ cosmic strings, that are cosmic strings associated with the breaking of $U(1)_{B-L}$, as well as the existence of right-handed neutrinos acquiring a Majorana mass at the $B - L$ breaking scale. As a consequence, there are right-handed neutrinos trapped as transverse zero modes in $B - L$ cosmic string cores. Cosmic string loops loose their energy emitting gravitational radiation and rapidly decay releasing these neutrinos. These neutrinos decay producing an initial lepton asymmetry.

Cosmic strings are one dimensional topological defects which form when a gauge group $G$ spontaneously breaks down to a subgroup $H$ of $G$ if the vacuum manifold $\frac{G}{H}$ contains non contractible loops, i.e. if the first homotopy group $\pi_1(\frac{G}{H})$ is non trivial. They form, for example, when a $U(1)$ symmetry breaks down to the identity. When a gauge group $G \supset U(1)_{B-L}$ breaks down to a subgroup $H \not\supset U(1)_{B-L}$ of $G$, $B - L$ cosmic strings form. The simplest theory beyond the standard model which predicts the existence of $B - L$ cosmic strings $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ and the simplest grand unified theory is $SO(10)$.

Now the Higgs field which forms a $B - L$ string, which we call $\Phi_{B-L}$, is the same Higgs field which is used to give a superheavy Majorana mass to the right-handed neutrino. Therefore, there are right-handed neutrinos trapped as transverse zero modes\(^7\) in $B - L$ cosmic string core\(^6\). The zero mode solution can be found by solving the equations of motion for the right-
handed neutrino field:

\[ i\gamma^\mu D^\mu \nu^c - i\lambda \Phi^*_B - L \nu^c = 0. \]  

(2)

\[ \nu^c = C\gamma^7 \nu^c_{R} \] transforms as a singlet under the standard model gauge group. \( C \) is the charge conjugation matrix and \( \lambda \) is a Yukawa coupling constant. The spinor \( N = \nu_R + \nu_L^c \) is a Majorana spinor. For a straight infinite cosmic string lying along the z-axis, \( \Phi_{B-L} = f(r)e^{i\theta} \), with \( f(0) = 0 \) and \( f \rightarrow \infty \) \( M_{B-L} \), where \( M_{B-L} \) is the \( B - L \) breaking scale. The zero mode solution is then given by:

\[ N = \beta(r, \theta) \alpha(z + t) \]  

(3)

where \( \beta(r, \theta) \) is a function peaked at \( r = 0 \) which exponentially vanishes outside the core of the string, so that the fermions effectively live on the string. \( \alpha(z + t) \) which shows that the neutrinos travel at the speed of light in the \(-z\) direction, so that they are effectively massless.

On a straight string the energy to momentum relation \( E = P \) holds, we have a continuous spectrum of states and the Fermi energy \( E_F = 0 \). However, on a cosmic string loop of radius \( R \), the energy relation must be modified to:

\[ E = \left(\frac{L + \frac{1}{2}}{R}\right) = P + \frac{1}{2R}, \]  

where \( L \) is the neutrino angular momentum. The neutrino energy spectrum is then \( E = \frac{\pm(n + \frac{1}{2})}{R} \) where \( n \) is an integer, we have a discrete spectrum of states and the Fermi energy \( E_F = \frac{1}{2R} \).

When a string network forms, some closed loops are initially formed as well as infinite strings. Cosmic string loops loose their energy via gravitational radiation at a rate \( \dot{E} = -\Gamma_{\text{loops}} \frac{M_{B-L}}{M_{pl}} \) and rapidly decay. The network evolves, and more loops form via the intercommuting of long strings. A loop decays when its radius becomes comparable to its width \( \sim M_{B-L}^{-1} \). The neutrino Fermi energy is then \( E_F \sim \frac{1}{2} M_{B-L} \), which is lower than the energy needed by a neutrino to escape the string. Hence, when a cosmic string loop decays, it releases at least \( n_\nu = 1 \) heavy Majorana neutrino. This is an out-of-equilibrium process.

The released neutrinos \( N \) decay according to the two diagrams shown in figure 1, producing a lepton asymmetry. CP is violated through the one loop radiative correction involving an electroweak Higgs particle. The lepton asymmetry produced is characterised by the CP violation.
parameter\textsuperscript{9)}:
\[ \epsilon \simeq \frac{m_{D_3}^2}{\pi v^2} \frac{M_{N1}}{M_{N2}} \sin \delta, \]  
where \( m_{D_3} \) is the Dirac mass of the third lepton generation, \( v \) is the vacuum expectation value of the electroweak Higgs field, \( v = < H_{ew} > = 174 \text{ GeV} \), \( M_{N1} \) and \( M_{N2} \) are the right-handed neutrino Majorana masses of the first and second generation respectively and \( \delta \) is the CP violating phase.

The generated baryon number per comoving volume at temperature \( T \) is then given by
\[ B(T) = \frac{1}{2} \frac{N_{\nu}(t) \epsilon}{s}, \]
where \( s \) is the entropy of the Universe at time \( t \) and \( N_{\nu}(t) \) is \( n_{\nu} \) times the number density of cosmic string loops which have shrunk to a point at time \( t \).

The final baryon asymmetry is therefore a function of the cosmic string scenario parameters, of the neutrino mass matrix and of the strength of CP violation. Using the model of Copeland et al.\textsuperscript{10)} for cosmic string loop evolution, and assuming that the Dirac neutrino masses fall into a hierarchical pattern similar to that of leptons and quarks, we find:
\[ B_{\text{final}} \simeq \frac{13.8}{(0.3 \pi)^3} \frac{\nu_s}{(k - 1) k^{\frac{3}{2}} \Gamma_{\text{loops}}} \frac{M_{B-L}}{M_{pl}} \frac{m_{D_3}^2}{v^2} \frac{M_{N1}}{M_{N2}} \sin \delta \]  
where \( \nu_s \) and \( k \) are respectively related to the different length scales in the string network and to the life-time of a loop.

Fixing \( \frac{M_{N1}}{M_{N2}} = 0.1 \), assuming \( m_{D_3} = 1 - 100 \text{ GeV} \) and assuming maximum CP violation, i.e. \( \sin \delta = 1 \), we find that the parameter \( \eta \) is predicted with the \( B - L \) breaking scale in the range
\[ M_{B-L} = (1 \times 10^6 - 2 \times 10^{15}) \text{ GeV}. \]  

The minimal extension of the standard model for which this scenario works is \( SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \) and the minimal GUT is \( SO(10) \).

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