BARYOGENESIS THROUGH GRADUAL COLLAPSE OF VORTONS

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Abstract

We evaluate the matter-antimatter asymmetry produced by emission of fermionic carriers from vortons which are assumed to be destabilized at the electroweak phase transition. The velocity of contraction of the vorton, calculated through the decrease of its magnetic energy, originates a chemical potential which allows a baryogenesis of the order of the observed value. This asymmetry is not diluted by reheating if the collapse of vortons is distributed along an interval of $\sim 10^{-9}$ sec.

1 Introduction

The matter-antimatter asymmetry in the universe is one of the well established facts of cosmology. There are many possible mechanisms to generate this baryonic density due to phenomena which presumably occurred in the first fraction of second after the big-bang but all of them suffer some criticism. They include also methods involving cosmic strings or other topological defects produced in some of the phase transitions produced in the universe.

In this work we present a baryogenesis model based on possibly very abundant closed cosmic strings called vortons stabilized by superconducting currents, which might lose this stability at the electroweak phase transition. The distinctive feature of our mechanism is that we follow

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the process of contraction of vortons and that we assume that they do not destabilize all at the same time.

In Section 2 we give a survey of the baryogenesis methods which have some connection with our proposal. In Section 3 we briefly describe vortons and their relationship with Grand Unified Theories (GUT). Section 4 reminds the instantaneous decay of vortons and the reheating which causes the dilution of matter-antimatter asymmetry. In Section 5 we present our scenario of gradual decay of vortons indicating how the reheating problem may be solved. Section 6 contains the details of the calculation of the contraction velocity which, for the case of charged carriers, is based on the decrease of the associate magnetic energy. In Section 7 we evaluate by tunneling the probability of emission of carriers which gives way to the asymmetry produced by each vorton. Section 8 shows how the variation of magnetic field due to contraction produces a chemical potential which allows our baryogenesis to be of the order of the expected one. Section 9 contains some conclusions.

2 Methods to generate matter - antimatter asymmetry

From the nucleosynthesis of light elements there is a constraint for the baryonic density which, related to entropy density to give an invariant value, is [\(n_B/s = 10^{-11} - 10^{-10}\).

To explain this asymmetry, if one starts from a symmetric universe, three conditions are required [\(n_B/s = 10^{-11} - 10^{-10}\), i) non-conservation of baryonic number, ii) violation of C and CP to distinguish particle from antiparticle, iii) period of non-equilibrium to allow different number of particles and antiparticles.

The method of baryogenesis closest to experimental verification is that which corresponds to the electroweak phase transition [\(n_B/s = 10^{-11} - 10^{-10}\)] provided it is a first-order one. Expanding bubbles of the broken-symmetry phase would produce in its wall a chemical potential due to the variation of a CP violating phase \(\theta\) compared to the external symmetric medium, where the active sphalerons would generate the baryonic density. The latter would not be erased because the bubble expansion would include it in the broken-symmetry phase where sphaleron processes are very slow. Due to the rate of sphaleron transitions in the high-temperature phase one would obtain

\[
\frac{n_B}{s} \simeq \frac{\alpha_w^4}{g^*} \Delta \theta ,
\]

where the weak coupling is such that \(\alpha_w \simeq 10^{-3}\) and the number of zero-mass modes at the electroweak temperature \(T \sim 100\text{GeV}\) is \(g^* \simeq 100\). Therefore the observed asymmetry is reproduced if \(\Delta \theta \sim 10^{-2}\). However this mechanism with Standard Model ingredients is not possible because the phase transition turns out to be of second order for the experimental bound on the Higgs mass and the CP violation is not enough.

A solution which would include not too high-energy elements beyond the Standard Model is afforded by the Minimal Supersymmetric Standard Model. But this model would be severely constrained because to give an enough first-order phase transition the Higgs boson should be light \(m_H < 100\text{GeV}\) as well as the stop \(m_{\tilde{t}} \leq 200\text{GeV}\), and to allow a large enough variation...
of the CP violation parameter without entering in conflict with the neutron electric dipole moment the lower generations of squarks should be very heavy[?], though this last condition might be relaxed[?].

On the other extreme of the energy range, a possibility of baryogenesis would be given by the decay of GUT Higgs and gauge bosons which should be produced out of equilibrium requiring \( T \sim 10^{16} \text{GeV} \). The generated baryonic density would be

\[
\frac{n_B}{s} \sim \frac{\varepsilon}{g^*}
\]

where, with the asymmetry produced by one of these superheavy particles \( \varepsilon \sim 10^{-8} \), there would be agreement with the expected value.

A problem is here that at these extremely high temperatures magnetic monopoles would have been produced with the consequent overclosure of the universe density, as well as very heavy cosmic strings which might originate undesirable inhomogeneities. It is anyhow difficult to explain such high T from the reheating at the end of inflation, unless the non-linear quantum effects of preheating give way to an explosive heavy particle production out of equilibrium[?].

### 3 Cosmic strings and vortons

Cosmic strings are topological defects which appear in a phase transition when an abelian symmetry additional to the standard model is broken. To avoid the monopole problem we may assume that the universe reached a temperature for which the GUT symmetry G was already broken

\[
G \to SU(3)_C \times SU(2)_L \times U(1)_Y \times \tilde{U}(1) .
\]

If at a slightly lower temperature, let us say \( 10^{15} \text{GeV} \), also the symmetry \( \tilde{U}(1) \) is broken the cosmic strings will be produced[?]. They will become superconducting[?] depending on the group G and the details of the Higgs mechanism for the breaking of \( \tilde{U}(1) \). A superconducting current will appear for those fermionic carriers which acquire mass due to the coupling with a Higgs field which winds the string and originates zero modes inside it. The superconducting current classically stabilizes closed loops through a number \( N \) related to the angular momentum due to the carriers inside them.

It is not necessary that the carriers are charged[?]. In fact if \( G = SO(10) \) the only particle which acquires mass at the \( \tilde{U}(1) \) phase transition is \( \nu_R \) which may have a zero mode inside the string. On the other hand if \( G = E_6 \) several fermions acquire mass at the \( \tilde{U}(1) \) breaking and some of them, which may give superconducting currents, are charged and with baryonic number.

For normal cosmic strings it is interesting[?] that if the emission of superheavy bosons at present time is normalized to explain the flux of ultra-high energy cosmic rays, their decay in the past may give the expected baryogenesis provided that the asymmetry per particle is six orders of magnitude higher than that necessary in Eq.(3).

The stabilized superconducting closed loops are called vortons[?]. Their number density, mass, length and quantum decay probability depend on the coincidence or not of the scales of
string formation and appearance of superconductivity in them\[?\]. If both scales coincide at \(m_x\) the vorton density is

\[ n_v \simeq \left( \frac{m_x}{m_{pl}} \right)^{\frac{3}{2}} T^{3}, \]

its energy \(E_v \simeq N m_x\), radius \(R \simeq N m_x^{-1}\) and \(N \sim 10\) if \(m_x \sim 10^{15}\)GeV. If the superconductivity scale is smaller than the formation one, the density is smaller and vortons are more stable for quantum decay.

The density Eq.(5) overcloses the universe in a way similar to that of monopoles, if there is not a collapse of vortons for some reason. If this is produced at high energy when the carriers are \(\nu_R\), a lepton asymmetry appears which may be converted into baryon asymmetry by sphaleron processes to give the expected value with adequately large CP violation parameter\[?\]. Alternatively, if superconductivity appears at much lower temperature, i.e. at the supersymmetric scale \(\sim 1\)TeV, there are models predicting that vortons which subsequently decay below the electroweak temperature may release baryonic charge in agreement with the expected one\[?\], again assuming an adequate CP violation factor.

It must be noted that if the scales of formation and superconductivity coincide and the vorton density is decreased for some process to be constrained by the critical density of universe, the quantum decay probability might be enough to explain the high energy cosmic rays\[?\].

4 Instantaneous decay of vortons at the electroweak transition

Trying to include as few ingredients as possible, we will adopt the point of view that vortons have obtained the superconducting property at the same scale of formation, and that they lose their stability at the well established electroweak transition. This may occur if, due to the new Higgs mechanism at this scale, the zero modes acquire a small mass\[?\]. It is not required that the transition is of first order.

If vortons disappear instantaneously, since they contain roughly \(N\) heavy bosons the produced baryonic density is

\[ \frac{n_B}{s} = \left( \frac{m_x}{m_{pl}} \right)^{\frac{3}{2}} \frac{N \xi}{g^*}, \]

which will be very small if the asymmetry due to each particle \(X\) is of the same order of that of GUT bosons assumed in Eq.(3).

Furthermore, since vortons behave as non-relativistic matter, its density which is very small at formation becomes equivalent to that of radiation at \(T \sim 10^{6}\)GeV and dominates on it by 6 orders of magnitude at the electroweak scale. Therefore if at this temperature vortons transform instantaneously into light particles, i.e. radiation, there will be a reheating according to

\[ \rho_v (T_{EW}) = N m_x \left( \frac{m_x}{m_{pl}} \right)^{\frac{3}{2}} T_{EW}^{3} = \rho_R (T_{reh}) = g^* T_{reh}^{4}, \]
which gives $T_{reh} \approx 10^7 \text{GeV}$.

This instantaneous reheating would produce an increase of the entropy density of $(\frac{T_{reh}}{T_{EW}})^3 \approx 10^9$ times with the corresponding dilution of the baryogenesis of Eq.(6) in the same factor.

According to this scenario the universe would be initially dominated by radiation, then from $T \sim 10^8 \text{GeV}$ to $T_{EW}$ by vortons and after the reheating to $T_{reh}$ again by radiation till $t \sim 10^{11} \text{ sec.}$ when finally non-relativistic matter takes over.

5 Gradual collapse of vortons

The alternative that we wish to present corresponds to the plausible situation that vortons are not destabilized all at the same time when reaching the electroweak temperature. Due to the Higgs mechanism that will be working in this phase transition, we expect a probability that a vorton loses its zero modes and starts its collapse. Without attempting to calculate this probability for destabilization, we remark that the temperature will remain constant at $T_{EW} \sim 100 \text{GeV}$ if vortons decay during an interval such that the universe expands its scale from $a_1$ to $a_2$ when all is transformed to radiation

$$a_1^3 N m_x \left(\frac{m_x}{m_{pl}}\right)^{\frac{3}{2}} T_{EW}^3 = a_2^3 g^* T_{EW}^4.$$ (8)

The space scale would therefore increase in two orders of magnitude and, using $\frac{a_1}{a_2} = \left(\frac{t_1}{t_2}\right)^{\frac{3}{2}}$, if the process starts at $t_1 \sim 10^{-12} \text{ sec}$ it would be completed at $t_2 \sim 10^{-9} \text{ sec}$. The advantage is now that the total increase of entropy, which is similar to that of instantaneous destabilization, is distributed in a larger volume. Baryogenesis would not be diluted at the beginning of the interval but only at the end with a factor $\left(\frac{a_2}{a_1}\right)^3$ so that the average dilution would be $\sim \frac{1}{2}$. It is reasonable to think that the collapse of vortons keeps the temperature constant because as soon as there is a tendency to reheating the symmetry is restored and the destabilization of vortons stops.

Furthermore, we will follow the contraction of each vorton obtaining baryogenesis not by the presumably small asymmetry in the decay of bosons X, but from the emission of charged baryonic carriers during the collapse. The resulting asymmetry per vorton may turn out to be larger due to the chemical potential which will appear in the wall of the vorton because of the non-equilibrium process of contraction, resulting in a different emission of fermions and antifermions.

6 Velocity of contraction during vorton decay

The evaluation of the velocity of contraction of the vorton after its destabilization at the electroweak temperature is crucial for determining the non-equilibrium process.

One possibility of calculation, which may be applied to the case of neutral carriers, is to consider that stabilization is abruptly lost at $T_{EW}$ so that the string contracts due to a constant tension $\mu \sim m_x^2$. If the string mass were constant and the initial radius is $R = \frac{N}{m_x}$, the relation between the velocity and each radius $r$ would be
\[ v^2 \simeq 2 \frac{R - r}{R}. \] (9)

Considering that the vorton mass decreases linearly with its radius in the rest frame, including the Lorentz factor and being at the initial stage of the contraction when the iterative approximation may be used, the velocity turns out to be

\[
v = \frac{1}{\sqrt{2}} \arctan \frac{\sqrt{2}N}{m_xt} \left[ 1 - \left( \frac{m_xt}{N} \right)^2 \right]^{\frac{1}{2}} + 2 \arcsin \left( \frac{m_xt}{N} \right) - 3 \frac{2\sqrt{2}}{2} \ln \left( \frac{m_xt + \sqrt{2}N \left[ 1 - \left( \frac{m_xt}{N} \right)^2 \right]^{\frac{1}{2}}}{m_xt - \sqrt{2}N \left[ 1 - \left( \frac{m_xt}{N} \right)^2 \right]^{\frac{1}{2}}} \right) - \frac{\pi}{2\sqrt{2}}. \] (10)

To have the relation between velocity and radius which replaces Eq.(9), \( v \) of Eq.(10) should be integrated on time. It is clear that \( v \) will vary from 0 to 1 when \( r = 0 \) so that the time of collapse will be \( t_c \geq \frac{N}{m_x} \).

For charged carriers, in which we are more interested, the velocity of contraction may be calculated in an easier way. We consider the decay of a vorton as a succession of transitions between superconducting states of numbers \( N, N-1,... \) keeping the value of the current \( I \). Looking at a classical average, one will see a loop with increasing contraction velocity with the corresponding relativistic factor in its mass which will be compensated by the decrease of the magnetic energy that is defined in the broken-symmetry phase.

The balance for the vorton when its radius is \( r \) and the associated magnetic field is \( B \) compared with the initial one \( B_i \), will be

\[
\frac{r}{R} N m_x \left( \frac{1}{\sqrt{1 - v^2}} - 1 \right) = \frac{1}{2} \int d\rho \left( B_i^2 - B^2 \right). \] (11)

Since in general we will expect

\[
\frac{1}{2} \int d\rho \ B^2 = k \ I^2 \ r \] (12)

and being \( I = \frac{N}{2\pi R} \), we will have

\[
1 - v^2 = \frac{1}{\left( 1 + \frac{k_i R - k_f r}{4\pi^2 r} \right)^2}, \] (13)

where the coefficient \( k_f \) at the end of the collapse may be different from the initial one \( k_i \).

At the beginning, when \( R - r \) is small and \( k_i = k_f \)

\[
v^2 \simeq \frac{k_i}{2\pi^2} \frac{R - r}{R}, \] (14)

which is analogous to the previous estimation due to constant tension. For \( r \to 0 \) the velocity Eq.(13) will tend to 1.

An important ingredient for our evaluation of baryogenesis will be the calculation of the coefficients \( k \).