Axial charge segregation during a first order phase transition in the presence of hypermagnetic fields

Collaboration: Alejandro Ayala, Gabriel Pallares, UNAM, 2002

Centro Tecnológico, FES Aragón, UNAM

Abstract

We study the scattering of fermions off a finite width kink wall during the electroweak phase transition in the presence of a background hypermagnetic field.
We derive and solve the Dirac equation for such fermions and compute the reflection and transmission coefficients for the case when the fermions move from the symmetric to the broken symmetry phase.
We show that the chiral nature of the fermion coupling with the background field in the symmetric phase generates an axial asymmetry in the scattering processes.
We briefly discuss possible implications of such axial charge segregation for baryon number generation.

Outline

- I. Introduction
    - Ia- Baryonic Asymmetry
    - Ib- Baryogenesis
    - Ic- Magnetic/hypermagnetic fields
    - Id- Non-local baryogenesis
- II. Generation of an axial asymmetry during the phase transition, in presence of hypermagnetic fields
    - IIa- First order phase transition
    - IIb- Movement equation for fermions in each phase
    - IIc- Interaction of fermions with the wall
    - IId- Generation of axial asymmetry
- IV. Discussion and conclusions

Ia- Baryonic Asymmetry

The Universe lacks of antimatter, or there are significant domains consisting of antimatter

Estimation of baryonic number (WMAP):

$$\boxed{B = n_B/s \sim (6.1^{+0.3}_{-0.2}) \times 10^{-10} \; ; \; n_B = n_b - n_{\bar{b}}}$$

Ib- Baryogenesis

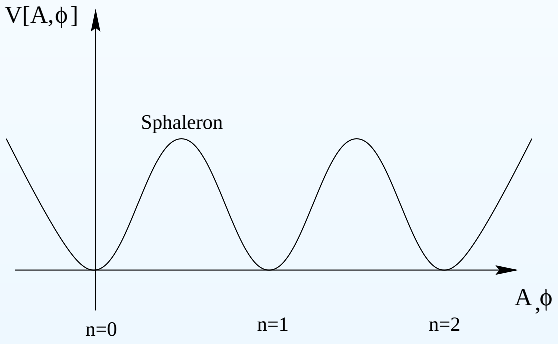
A dynamical generation of the observed asymmetry, where the Universe in an initial symmetric state evolves to an asymmetric one, was proposed by Sakharov in 1967. He established three conditions:

- Non-conservation of baryonic number
- Breaking of symmetry between particles and antiparticles (C and CP symmetries violation)
- Deviation from thermal equilibrium

The standard model of weak interactions fulfills the three conditions during the electroweak phase transition, although too weakly.

Ib- Baryogenesis

- The transition between different topological vacua of the theory generates baryonic number.



- Violation of C and CP symmetries gives a direction to the baryon number generation.

Ib- Baryogenesis

- A first order phase transition $\longrightarrow$ out of equilibrium conditions.

Successful baryogenesis

- baryon asymmetry generation
- baryon asymmetry preservation

Ic- Magnetic/hypermagnetic fields

For temperatures above the EWPT, the magnetic field corresponds to the group $U(1)_Y$ with the hypercharge as the coupling constant (*hypermagnetic* field). The hypercharge of left and right handed fermions are different.

Magnetic fields seem to be pervading the entire universe: they have been observed in galaxies, clusters, intracluster medium and high-redshift objects. Their origin is uncertain, being one of the possibilities that they are primordial.

The presence of magnetic fields can change the order of the PT, enhancing its strength, as it happens in a superconductor (Meissner effect).

(Giovannini & Shaposhnikov, 1998; Elmfors et al., 1998; Sanchez, Ayala & Piccinelli, 2007) .

But also, the barriers of the sphaleron energy are lowered by magnetic fields, due to the spaleron dipole moment (Comelli et al., 1999).

Id- Non-local baryogenesis

It is not necessary that CP violation and (anomalous) baryon violation occur in a single process at a single space-time point.

A CP violating charge asymmetry can be generated in the bubble wall and transported back in the symmetric region by particle reflection off the bubble wall.

CP violating phase in the scalar potential of a two doublets Higgs model. (Coupling of the fermionic hypercharge current to scalar fields: $\partial_\mu \theta \; j_B^\mu \longrightarrow$ shifts the energy density of baryons relative to antibaryons)).

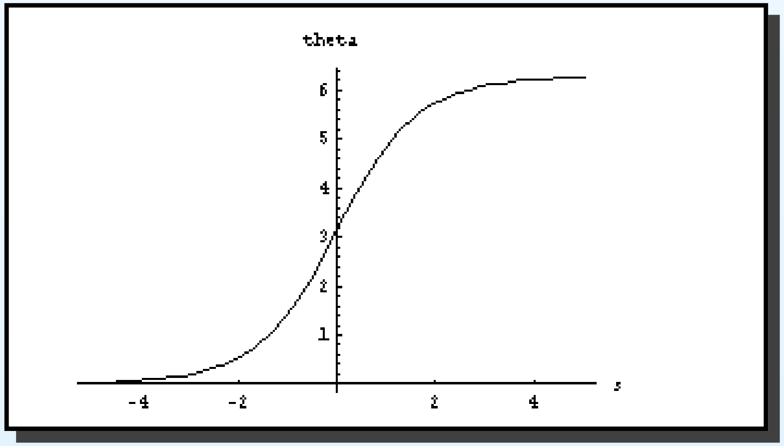
Then, the asymmetry in hypercharge will result in baryon assymmetry, in the symmetric phase, where B violating processes are not suppressed, and finally passes into the expanding bubbles of the broken phase.

(Cohen, Kaplan & Nelson, 1991, 1992)

IIa- First order phase transition

Coexistence of two phases: bubbles of true vacuum in a background of false vacuum.
Structure of the wall ?

Thin wall, with degenerated minima in the two phases
$\varphi(x) = 1 + \tanh(x)$
with $x = \frac{\delta\ T}{\sqrt{2\lambda}}\ z$
$\sqrt{2\lambda}/(\delta\ T)$ is the bubble wall thickness,
being λ and δ parameters of the effective, finite temperature, Higgs potential.



IIb- Movement equation for fermions in each phase

Fermionic modes are coupled differently to the magnetic field in the symmetric and the broken phase.

In the broken phase, the Dirac equation for a charged fermion

$$\left\{ i\partial\!\!\!/ - eA_\mu\gamma^\mu - m(z) \right\}\Psi = 0$$

$A^\mu = (0, \mathbf{A})$: fourvector potential,(with null temporal component, in reference system of the wall)

We choose it in order that the direction of the field will be: $\mathbf{B} = B\hat{z}$.

The fermion mass $m(z)$ is proportional to the expectation value in vacuum of the Higgs field.

IIb- Movement equation for fermions in each phase

Before the PT, the coupling is chiral, Dirac equation for axial fermions, with hypermagnetic field

$$\begin{aligned} (i\not{\partial} - \frac{y_L}{2} g' \not{A})\Psi_L - m(z)\Psi_R &= 0 \\ (i\not{\partial} - \frac{y_R}{2} g' \not{A})\Psi_R - m(z)\Psi_L &= 0 \end{aligned}$$

$y_{R,L}$: right and left handed hypercharges,
Ψ_R and Ψ_L are the right and left handed modes respectively for the spinor Ψ
g': coupling constant of $U(1)_Y$

IIc- Interaction of fermions with the wall

The solutions Ψ for both equations were found (with analytical and numerical methods), for left and right modes, matching them in the bubble wall ($z = 0$).
Since in the broken symmetry phase there is no propagating component corresponding to the Z^0,
b' is related to b and Weinberg's angle θ_W by $b' = \frac{b}{\cos\theta_W}$
(which in turn implies $eb' = g'b$)

The coefficients of reflection and trasmission were derived, for energies near the potential barrier, for particles and anti-particles. They were built from reflected, transmitted and incident currents of each type.
For a given spinor wave function Ψ, the current normal to the wall is given by

$$J = \Psi^\dagger \gamma^0 \gamma^3 \Psi \, . \qquad (1)$$

IIc- Interaction of fermions with the wall

The interaction of fermions with the wall generates an axial asymmetry between the two phases

In next figure we show the coefficients $R_{l\to r}$ and $R_{r\to l}$ as a function of the magnetic field parameter b ($b \equiv B\left(\frac{T\delta}{\sqrt{2\lambda}}\right)^{-2}$).

We explicitly work with the top quark since, being the heaviest particle in the broken phase, it has the largest yukawa coupling. ($m_0 = 175GeV$; $y_R = 4/3$, $y_L = 1/3$ and a value of $g' = 0.344$, as appropriate for the EWPT epoch.)

IId- Generation of axial asymmetry

For a left handed incident particle:

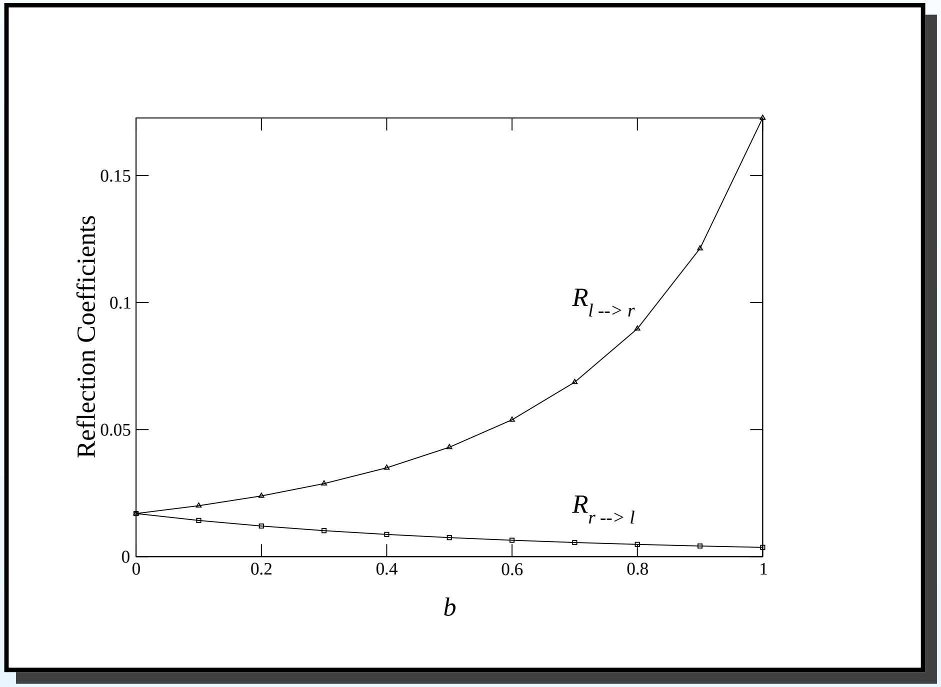
$$R_{l\to r} = -J^r_{\rm ref}/J^l_{\rm inc}$$

$$T_{l\to l} = J^l_{\rm tra}/J^l_{\rm inc}$$

and for the axial conjugated process

$$R_{r\to l} = -J^l_{\rm ref}/J^r_{\rm inc}$$

$$T_{r\to r} = J^r_{\rm tra}/J^r_{\rm inc}$$



A. Ayala, G.P., G. Pallares, Phys. Rev. D 66 (2002)

IId- Generation of axial asymmetry

We work at an energy slightly larger then the height of the barrier in order to avoid the exponential damping of the transmitted waves.

Notice that the difference grows with increasing field strength

For an incident wave coupled with $y_L(y_R)$, the fact that the differential equations mix up the solutions means that the reflected wave will also include a component coupled with $y_R(y_L)$.

III. Discussion and Conclusions

- The presence of hypermagnetic primordial fields provides a mechanism to produce an axial charge segregation in the scattering of fermions off the true vacuum bubbles. It is a consequence of the chiral nature of the fermion coupling to hypermagnetic fields in the symmetric phase.

- This asymmetry, built on either side of the wall, is dissociated from non-conserving baryon number processes and can subsequently be converted to baryon number in the broken symmetry phase where sphaleron induced transitions are taking place with a large rate. This mechanism -*non-local baryogenesis*- in the absence of the external field, can only be realized in extensions of the SM where a source of *CP* violation is introduced *ad hoc* into a complex, space-dependent phase of the Higgs field.

III. Discussion and Conclusions

- We have computed explicitly transmission and reflection coefficients for the axial modes incident on the wall from the symmetric phase. Since these are related to the corresponding coefficients for fermions incident from the broken symmetry phase by *CPT* and Unitarity, we find that the axial charge segregation still happens when taking into account also this process. We also emphasize that, under the very general assumptions of *CPT* invariance and unitarity, the total axial asymmetry (which includes contributions both from particles and antiparticles) is quantified in terms of the particle (axial) asymmetry, resulting in a total contribution that is the double of the one we have calculated.

III. Discussion and Conclusions

- It can be checked that $R_{r \to l} + T_{r \to r} = 1$ and $R_{l \to r} + T_{l \to l} = 1$ within the numerical precision of the calculation, which means that the analysis respects unitarity.

- Finally, the relation between this axial asymmetry and CP violation can be understood as the result of mixing two levels: right- and left-handed quarks coupled to an external hypermagnetic field. When the two chirality modes interact only with the external field, they evolve separately.It is the scattering with the bubble wall that allows a finite transition probability from one mode to the other. *CP* is violated in the process because *C* is conserved but*P* is violated.