Electroweak baryogenesis in presence of primordial magnetic fields

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Outline

- I. Introduction
- II. Generation of an axial asymmetry during the phase transition, in presence of hypermagnetic fields
- III. Phase Transition in presence of a hypermagnetic field
- IV. Conclusions and perspectives

I. Introduction

Baryonic Asymmetry

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

Estimation of baryonic number (WMAP):

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

I. Baryogenesis

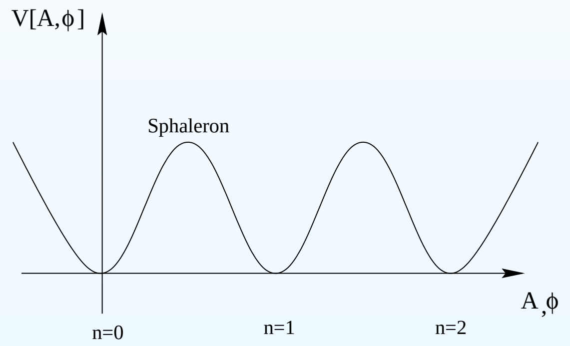
A dynamical generation of the observed asymmetry, where the Universe in an initial symmetric state evolves to an asymmetric one, was proposed by Sakharov in 1967. He established three conditions:

- 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.

I. Baryogenesis

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



- Violation of symetries C y CP gives a direction to the baryon number generation. (In the standard model, C violation comes from the existence of vector and axial currents and CP violation in CKM mass matrix)

I. Baryogenesis

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

Successful baryogenesis

- baryon asymmetry generation
- baryon asymmetry preservation

I. Baryogenesis

Violation rate of the barionic number in a comoving volume

$$\boxed{\dot{B} = -cBT \exp\left(-E_{sph}/T\right)}$$

$$\boxed{E_{sph} \sim M_W(T)/\alpha_W ; \alpha_W = g^2/4\pi ; M_W(T) = g\ vev/2}$$

In order to preserve the obtained asymmetry, the rate of the universe expansion must be greater than the rate of transition between distinct vacua

$$\boxed{\Gamma_{sph} \propto exp(-E_{sph}(T)/T) < H \sim g_\star^{1/2} T^2}$$

I. Baryogenesis

This condition leads to:

(Shaposhnikov, 1987)

$$\boxed{\left(\frac{vev}{T}\right) \geq 1.0 - 1.5}$$

but in the electroweak standard model the maximum value (with $m_H = 0$):

$$\boxed{\left(\frac{vev}{T}\right)_{MS} \leq 0.55}$$

We have to enhance this value.

I. 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: $\partial_\mu \theta \; j_B^\mu \rightarrow$ shifts the energy density of baryons relative to antibaryons)).

Then, the assymmetry 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)

I. 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.

Cosmic magnetic fields can be primordial

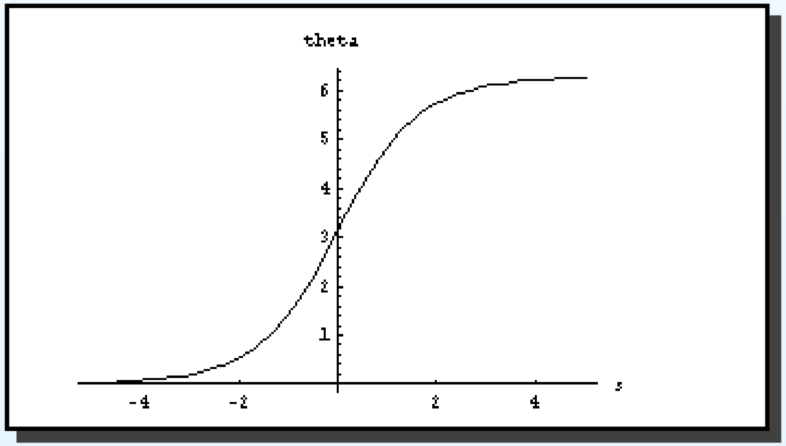
The presence of magnetic fields can change the order of the PT, enhancing its strength, as it happens in a superconductor (Meissner effect).
(Giovannini & Shaposhnikov, 1998; Elmfors & et al., 1998).

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

II. 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 thickness



II. 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

$$\left\{ i\not{\partial} - eA_\mu \gamma^\mu - m(z) \right\} \Psi = 0$$

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

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

We choose the field in the direction $\hat{z}$: $\mathbf{B} = B\hat{z}$.

II. 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 $U(1)_Y$

II. Interaction of fermions with the wall $\longrightarrow$ generation of axial asymmetry

The solutions Ψ for both equations were found (with analytical and numerical methods), for left and right modes, matching them in the bubble wall ($z = 0$).

and the coefficients of reflection and trasmission were derived, for energies near the potential barrier, for particles and anti-particles.

II. Interaction of fermions with the wall $\longrightarrow$ generation of axial asymmetry

For a left handed incident particle:

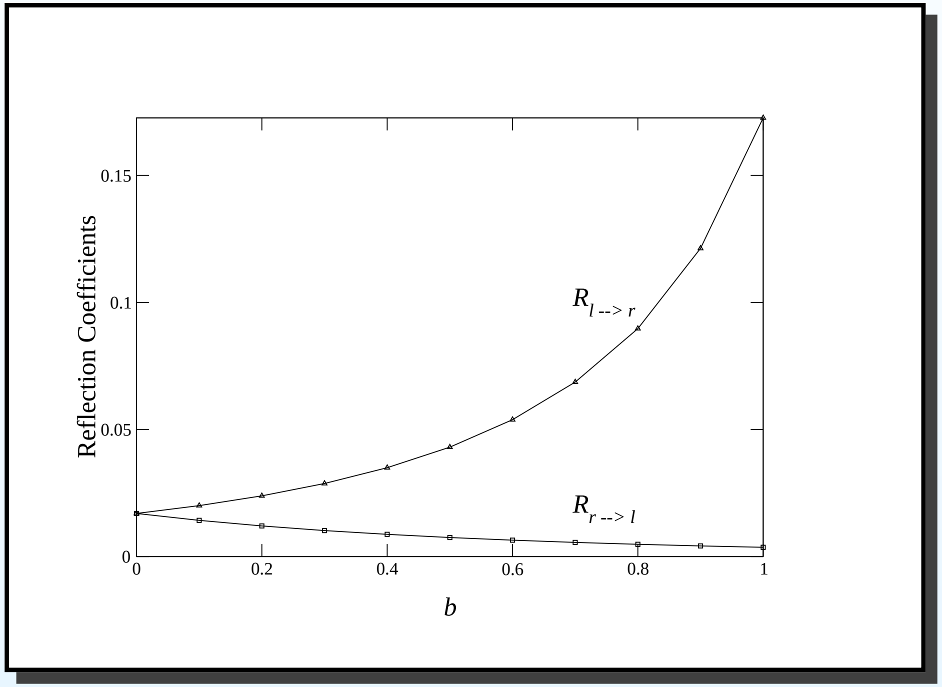
$$R_{l\to r} = -J^r_{\text{ref}}/J^l_{\text{inc}}$$

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

and for the axial conjugated process

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

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



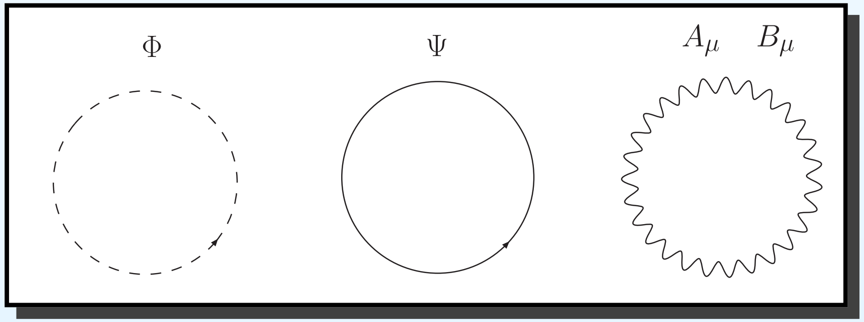
A. Ayala, G.P., G. Pallares, Phys. Rev. D 66 (2002)

Finite temperature effective potential of the standard model

The effective potential considers all the quantum corrections of the theory.

Previous work with magnetic fields: classical; to 1-loop and lattice.

- Effective potential to 1-loop



$$V(\phi_{cl}) = V^0(\phi_{cl}) - \frac{i\hbar}{2}\sum_i Tr\left[\ln(-k^2 + m_i^2(\phi_{cl}))\right]$$

III. Finite temperature effective potential of the standard model

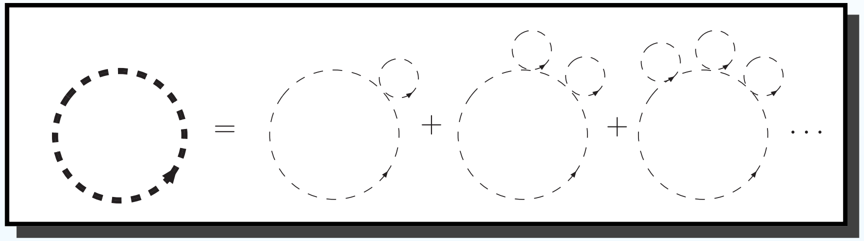
But, the next order -ring diagrams- have been shown to be necessary to have a self consistent theory (contributions of the same order than 1-loop and cancellations of some imaginary terms).

Our work:

we calculated all the corrections due to the interaction with plasma (finite temperature) and to coupling to the hypermagnetic field, up to ring diagrams

in the weak field limit $eB \ll m^2 \ll T^2$

III. Finite temperature effective potential of the standard model



$$V_{ring} = -\frac{1}{2} Tr \left[\sum_{N=1}^{\infty} \frac{1}{N} \left(-\frac{1}{k^2 - m_i^2} \Pi_i^1 \right)^N \right]$$

$$\Pi = \frac{\lambda T}{2} \sum_n \int \frac{d^3 k}{(2\pi)^3} \frac{1}{\omega_n^2 + k^2 + \Pi^1}$$

$$\Pi_\beta = \frac{\lambda T^2}{12} \left[1 - 3 \left(\frac{\lambda}{12\pi^2} \right)^{1/2} + \ldots \right]$$

$$V_{ring} = -\frac{T}{12\pi} \left[(m_i^2 + \Pi^1)^{3/2} - m_i^3 \right]$$

III. Scalar propagator with magnetic fields

Magnetic fields can be included in calculations of QFT through Schwinger's proper time method, which incorporates the effects of external magnetic fields in Green functions (from all Landau levels).

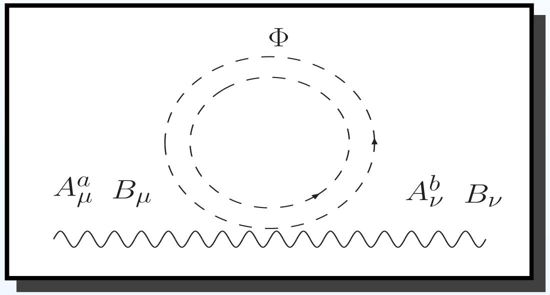
$$\boxed{iD^B(k) = \int_0^\infty \frac{ds}{\cos(eBs)} e^{-is(k_{||}^2 - k_\perp^2 \frac{\tan(eBs)}{eBs} - m^2 + i\epsilon)}}$$

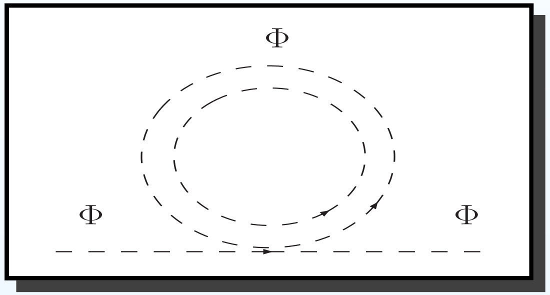
In the weak field limit $eB \ll m^2 \ll T^2$

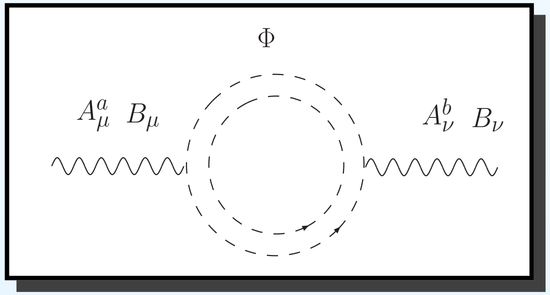
$$\boxed{\Delta(i\omega_n) = \frac{1}{\omega_n^2 + k^2 + m^2}\left[1 - \frac{(eB)^2}{(\omega_n^2 + k^2 + m^2)^2} - \frac{2(eB)^2 k_\perp^2}{(\omega_n^2 + k^2 + m^2)^3}\right]}$$

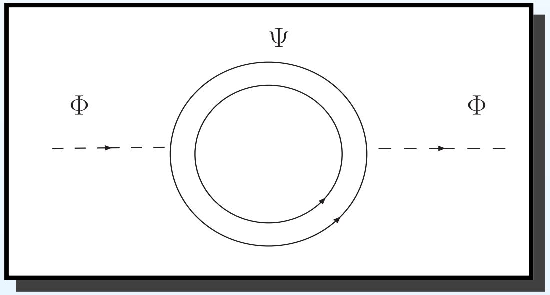
III. Effective potential with hypermagnetic field

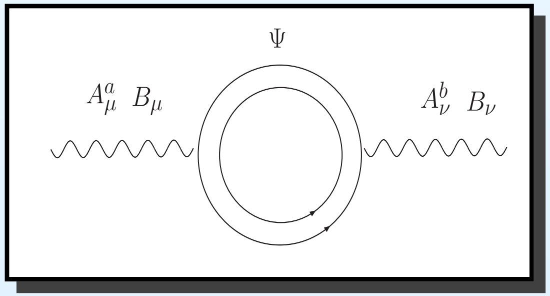
Contributions to the effective potential of the standard model that are modified by the presence of the hypermagnetic field











Symmetry breaking

$$\boxed{V_{Higgs}^{ring} = -\sum_{i=1}^{4}\{\frac{T}{12\pi}\left[(m_i^2+\Pi_1)^{3/2}-m_i^3\right]-\frac{(eB)^2\Pi_1}{192\pi}\frac{T}{(m_i^2+\Pi_1)^{3/2}}\}}$$

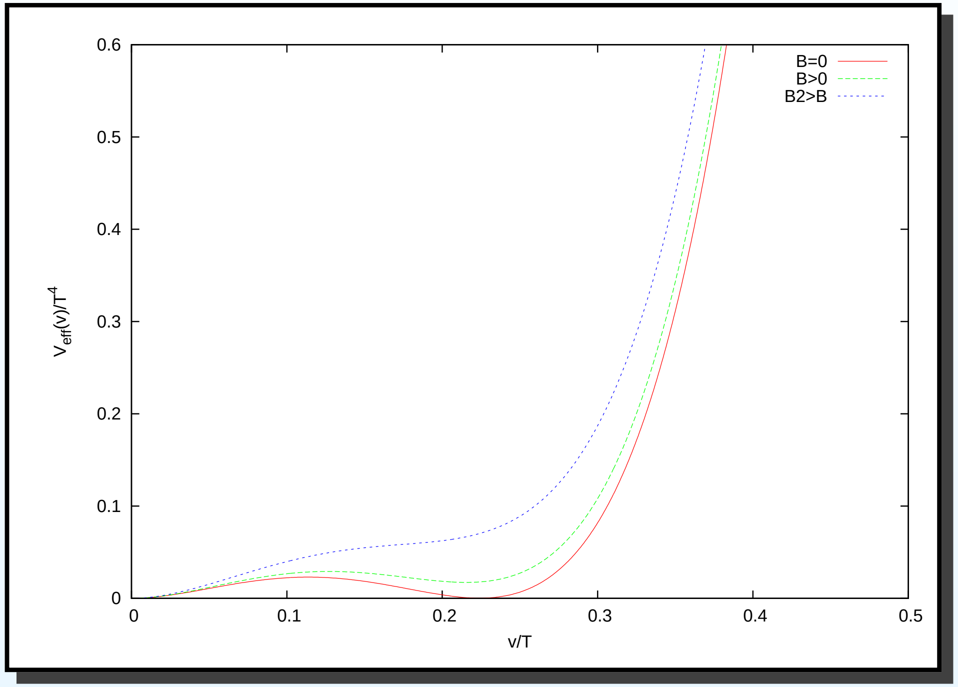
where Π_1 is the leading temperature contribution to the scalar self-energy, $\Pi_1 = \frac{T^2}{4}\{\frac{3}{4}g^2+\frac{1}{4}g'^2+2\lambda+f^2\}$.

Similar term for gauge bosons.
Relevant factor that enhances the order of the PT is $\frac{T}{\tilde{m}_i^3}$, from the tadpole diagram, since $\tilde{m}_i(v)$ is small for small values of v.

Fermions have a subdominant infrared behavior.

Symmetry breaking

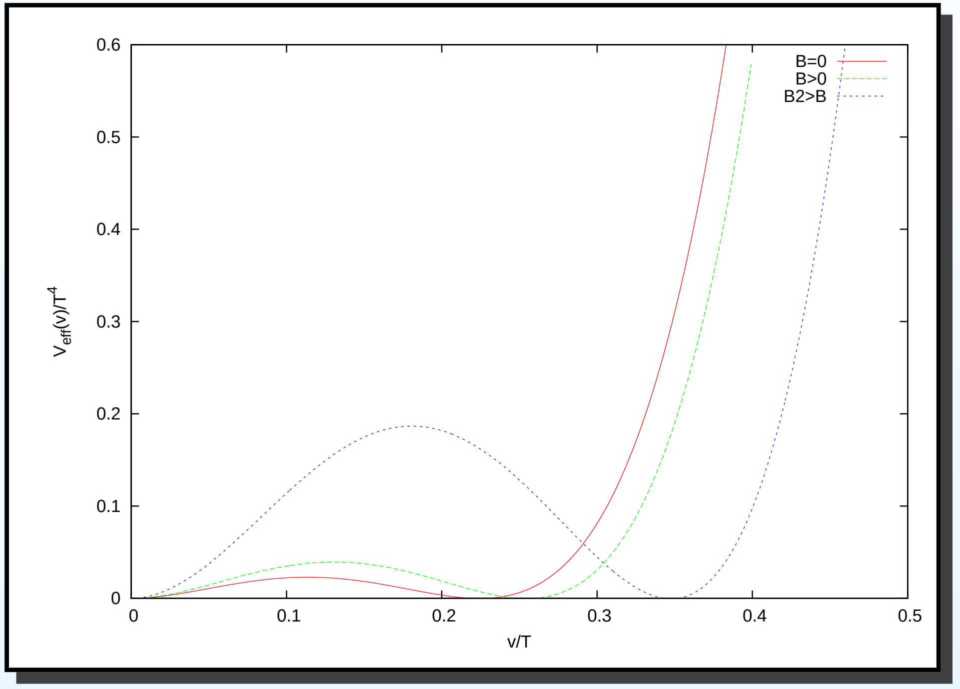
Case with hypermagnetic field, parametrized $B = b(100\ GeV)^2$, for three different strength, at the same temperature



Couplings of the standard model: $g_w = 0.637$, $g' = 0.344$, $\lambda = 0.11$, $f = 1$, $\mu = 81.6\ GeV$, $e = 0.3$

III. Symmetry breaking

Comparison of the cases $eB = 0$ and $eB \neq 0$, when the minima are degenerate.



A. Sánchez., A. Ayala, G.P., Phys. Rev. D 2007.

IV. Conclusions and perspectives

The presence of hypermagnetic primordial fields contributes to satisfy two of the three basic ingredients for baryogenesis

- It generates an axial asymmetry between the two phases, that results, in the broken phase, in a preferential direction for the transition between different topological vacua of the sphaleron, associated to the baryonic number violation

- It induces an EWPT more strongly first order, reducing the PT temparature and enhancing the ratio $\frac{vev}{T}$, as the strength of the hypermagnetic field is enhanced.

- Work with arbitrary magnetic field strength