Chiral asymmetry during the EWPT from CP-violating scattering off bubble walls

ISMD 2017

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September 11, 2017

Problems that *matter*

Error 404: Antimatter not found

In the early Universe, an asymmetry was created and matter dominated over antimatter through some mechanism if one assumes initial symmetry.

Primordial Magnetic Fields

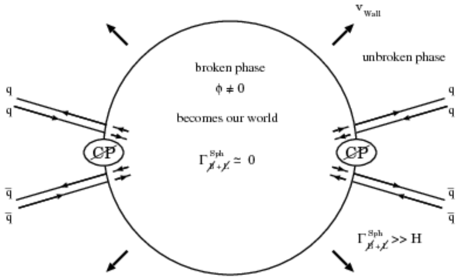
It is an experimental fact that intergalactic magnetic fields are present. They are relatively weak but their existance remains a puzzle and one needs a model to understand how were they generated. They could have influenced the formation of galaxies among other things.

Sakharov conditions

- Baryon number violation: If the baryon number was conserved, there must have been a primordial baryon asymmetry.
- C and CP violation: If these were not the case, one could proof that any process that generates an excess of baryons would have an antibaryon counterpart.
- Departure from thermal equilibrium: Otherwise the system would be stationary.

EWPT

- In a first order EWPT, the condition of departure from thermal equilibrium is met.
- In a first order phase transition, one has nucleation of bubbles; inside the bubble there is a stable phase and a metastable phase inside.
- Compared to boiling water, instead of air bubbles, one has true vaccum bubbles where the Higgs vev is different from zero.



Violation of CP during the EWPT

With Sakharov conditions in mind, a model with a CP violation source is provided. This comes in the form of a complex phase in the mass.

A complex mass

$$m(z) = m_0 e^{i\phi} \Theta(z).$$

We start off a Lagrangian

$$\mathcal{L} = i\bar{\Psi}\gamma^\mu \partial_\mu \Psi - m^*(z)\bar{\psi}_R \psi_L - m(z)\bar{\psi}_L \psi_R$$

and using E-L, one obtains the Dirac eq.

$$\left\{ i\gamma^\mu \partial_\mu - m^*(z)\frac{1}{2}(1-\gamma_5) - m(z)\frac{1}{2}(1+\gamma_5) \right\} \Psi = 0,$$

Solving the Dirac equation

In the symmetric phase (outside the bubble) $z < 0$,

$$[E^2 + d_z^2]\Phi^1_+(z) = 0,$$
$$[E^2 + d_z^2]\Phi^1_-(z) = 0,$$

and in the broken phase $z > 0$ (inside the bubble),

$$[E^2 - m_0^2 + d_z^2]\Phi^1_+(z) = 0,$$
$$[E^2 - m_0^2 + d_z^2]\Phi^1_-(z) = 0,$$

with solutions

$$\Phi^1_\pm(z) = A_\pm e^{iEz} + B_\pm e^{-iEz}.$$

and

$$\Phi^1_\pm(z) = F_\pm e^{i\sqrt{E^2-m_0^2}z} + G_\pm e^{-i\sqrt{E^2-m_0^2}z}.$$

Transmission coefficients

$$T^L = \frac{1}{E\left(E+\sqrt{E^2-m_0^2}\right)^2}\cdot\left[m_0^3\sin\phi\cos\phi\right.$$

$$\left.+\sqrt{E^2-m_0^2}\left(E+\sqrt{E^2-m_0^2}\right)(E+m_0\sin\phi)\right]$$

$$T^R = \frac{1}{E\left(E+\sqrt{E^2-m_0^2}\right)^2}\cdot\left[-m_0^3\sin\phi\cos\phi\right.$$

$$\left.+\sqrt{E^2-m_0^2}\left(E+\sqrt{E^2-m_0^2}\right)(E-m_0\sin\phi)\right]$$

- There is a term that depends (periodically) on ϕ.
- When $\phi = (2n+1)\pi/2$, the asymmetry is maximal.

Transmission coefficients: dependance on the angle

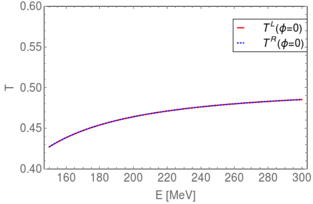
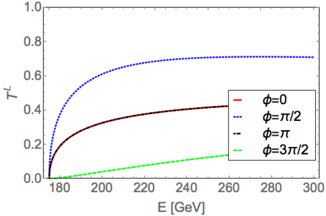
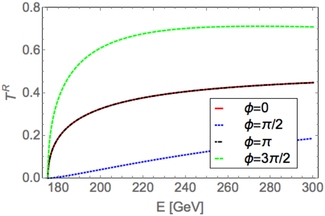


Figure: Transmission coefficients for $\phi = 0$.





- There is a different transmission for T_L and T_R depending on the phase ϕ.

Consequences and perspectives

- One has asymmetry between left and right modes.
- For fermions with an electric charge q_f, a local transverse current is generated.
- The intensity of the current can be quantified in terms of the $T^L - T^R$ difference.

With the help of Ampère's law,

$$\nabla \times \vec{B} = 4\pi \vec{J} + \frac{\partial \vec{E}}{\partial t},$$

one can see that a magnetic field can be generated even with the absence of $\frac{\partial \vec{E}}{\partial t}$.

Conclusions

- With a complex phase that induces CP violation during the EWPT, one obtains a different behavior between chiral modes.
- Such behavior creates an electric current that in turn generates a magnetic field.