Effect of a primordial magnetic field on a warm inflation scenario

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Magnetic fields

- The Universe is magnetized in a wide range of spatial scales.
- The presently observed cosmic magnetic fields could have a primordial origin.
- It is important to take into account the magnetic field effect when addressing early universe events:
  - Cosmic phase transitions.
  - Inflationary process.
  - Particles decay process.

Inflation

- Early models of inflation -supercooled models- assumed very little interaction of the inflaton with all other fields until the reheating process, at the end of inflation.
- In warm inflation[1], the inflaton is assumed to interact with other fields in a continuous and more natural way.
- A successful implementation of this model is embedded in the framework of supersymmetry.
- It rests on a two-step process of radiation production,

$$\phi \to \chi \to yy,$$

where ϕ is the inflaton, χ an intermediary heavy field and y the light sector, composed of fermions ψ_y and scalars y.

[1] A. Berera, Phys. Rev. D **71**, 023514 (2005).

Warm Inflation

- The model requires a dissipative component Γ of sizable strength as compared to the expansion rate of the universe.
- This additional dissipation, responsible for producing radiation, modifies the equation of motion for the inflaton ϕ:

$$\ddot{\phi} + (3H + \Gamma_{\phi})\dot{\phi} + V_{T,\phi} = 0$$

where H is the Hubble parameter and V_T is the inflaton effective potential. Warm inflation requires $\Gamma > 3H$.

Warm Inflation

The superpotential that involves all the interactions of the inflaton and the intermediate field χ reads[2]

$$W = g\Phi\Lambda^2 - g\Phi X^2 - hXY_1Y_2,$$

where Y are the light superfields coupled to X, the heavy sector. g and h are coupling constants ($\sim \mathcal{O}(0.1)$) and Λ is a mass scale (up to $\sim \mathcal{O}(10^{11} GeV^4)$).
Note that if the heavy field is charged then the following relation holds

$$q_X = q_{Y_1} - q_{Y_2}$$

with q_i the charge of each particle.

[2] L. M. Hall and I .G. Moss, Phys. Rev. D **71**, 023514 (2005).

Effective potential

The contribution to the inflaton effective potential coming from the heavy charged particles up to one loop reads[3],

$$V^1(\phi) = V^1_\chi + V^1_{\psi_\chi}.$$

$$V^1(\phi) \quad = \quad \frac{4}{2}\int \frac{d^4p}{(2\pi)^4}\left(\ln D_B^{-1}(p)\right) - \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\ln Det(S_B^{-1}(p)),$$

where D and S are the propagators of boson and fermion, respectively.
In the presence of an external and uniform magnetic field B, which defines the z-direction, the above expressions become

$$\begin{aligned} D_B(p) &= \int_0^\infty \frac{ds}{\cos q_\chi Bs}\exp\left\{is(p_{||}^2 - p_\perp^2\frac{\tan q_\chi Bs}{q_\chi Bs} - m_\chi^2 + i\epsilon)\right\}, \\ S_B(p) &= \int_0^\infty \frac{ds}{\cos q_\chi Bs}\exp\left\{is(p_{||}^2 - p_\perp^2\frac{\tan q_\chi Bs}{q_\chi Bs} - m_{\psi_\chi}^2 + i\epsilon)\right\} \\ &\quad \times\left[(m_{\psi_\chi} + \not{p}_{||})e^{iq_\chi Bs\sigma_3} - \frac{\not{p}_\perp}{\cos q_\chi Bs}\right], \end{aligned}$$

with s the Schwinger proper time parameter, $(a\cdot b)_{||} \equiv a_0b_0 - a_3b_3$, $(a\cdot b)_\perp \equiv a_1b_1 + a_2b_2$ and σ_3 the third Pauli matrix. q_χ denotes the charge associated to the heavy superfield fermion or boson components.

[3] G.P. & A. Sánchez, Phys. Rev. D 106, 043511 (2022).

Effective potential

Once the integration over the momentum is carried out, and all divergent terms are isolated, the effective potential can be written as

$$V^1(\phi) \quad = \quad V_0^1 + V^1_{q_\chi B^2} + V^1_{df},$$

with

$$V_0^1 \quad = \quad \frac{1}{8\pi^2}\int_0^\infty \frac{ds}{s^3}\left\{e^{-sm_\chi^2} - e^{-sm^2_{\psi_\chi}}\right\}$$

$$V^1_{q_\chi B^2} \quad = \quad -\frac{1}{8\pi^2}\int_0^\infty \frac{ds}{s}\left\{e^{-sm_\chi^2} + 2\ e^{-sm^2_{\psi_\chi}}\right\}\frac{(q_\chi B)^2}{6}$$

$$\begin{aligned} V^1_{df} \quad = \quad & \frac{1}{8\pi^2}\int_0^\infty \frac{ds}{s^3}\left\{e^{-sm_\chi^2}\left[\frac{q_\chi Bs}{\sinh(q_\chi Bs)} - 1 + \frac{1}{6}(q_\chi Bs)^2\right]\right. \\ & \left. - e^{-sm^2_{\psi_\chi}}\left[\frac{q_\chi Bs}{\coth(q_\chi Bs)} - 1 - \frac{1}{3}(q_\chi Bs)^2\right]\right\}, \end{aligned}$$

where the masses m_χ and m_{ψ_χ} keep track of the bosonic and fermionic sectors, respectively.

Thermal masses

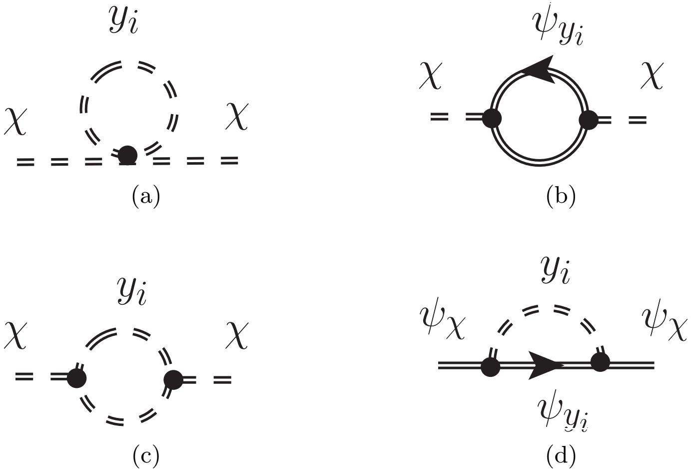

Figure: Feynman diagrams that account for the interaction between heavy and light fields at one-loop, where double lines indicate that the charged particles are dressed with the magnetic field effects. Continuous lines indicate fermionic fields, ψ_χ and ψ_{y_i}, and dashed lines indicate bosonic fields, χ and y_i.

Thermal masses

The main divergences cancel out (from SUSY) and the remaining ones are due to the soft SUSY breaking term, defined as the slight difference between the fermion and boson masses, that is

$$\begin{aligned} m_\chi^2(T,B) &= 2g^2\phi^2 + m_b^2(T,B) + M_s^2, \\ m_{\Psi_\chi}^2(T,B) &= 2g^2\phi^2 + m_f^2(T,B), \end{aligned}$$

where $m_b^2(T,B)$ and $m_f^2(T,B,r)$ are the one loop self-energy corrections to the fermion and boson masses, respectively, that have to be calculated in a thermal magnetized bath.
By imposing that the effective potential lower value be zero at $\phi = \phi_0$, with ϕ_0 the inflaton vev, that is

$$V_\chi^1(\phi,T,B)\big|_{\phi=\phi_0} = 0$$

and

$$\frac{\partial}{\partial\phi}V_\chi^1(\phi,T,B)\bigg|_{\phi=\phi_0} = 0,$$

we carried out the renormalization.

Magnetic masses

Since the external magnetic field is felt by the heavy sector, it must represent the highest physical scale for the light particles, that can be considered as constrained into the Lowest Landau Level (LLL) (neglecting the T contribution).

$$m_\chi^2(B) \approx M^2 - \frac{4}{\pi^3}\frac{h^2 q_1 q_2 B}{q_\chi} \ln\left(\frac{q_1 B}{m_1 m_2}\right), \tag{1}$$

with $M^2 = 2g^2\phi^2$.

$$m_{\psi_\chi}^2(B) = M^2 + \frac{h^2 q_1 q_2 B}{\pi^3 q_\chi} \ln\left(\frac{q_1 B}{m_2^2}\right). \tag{2}$$

The magnetic field introduces an additional SUSY breaking (from the different signs).

Effective potential

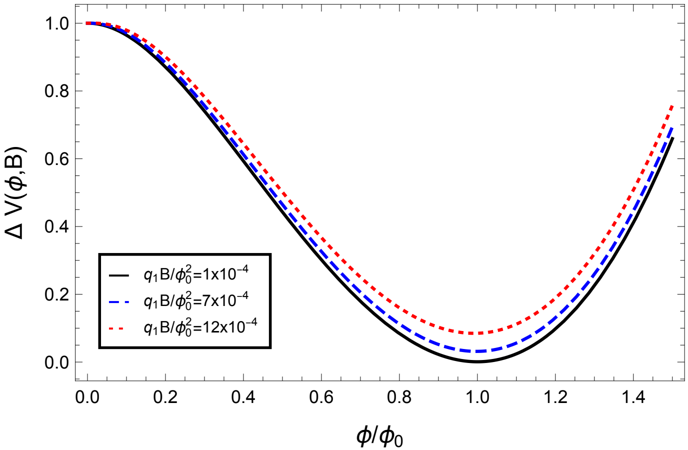

Figure: Effective potential normalized by $\mathcal{V}(0,0)$, for different magnetic field strengths for $M_s/\phi_0 = 0.05$, $m_1/\phi_0 = 10^{-3}$, $m_2/\phi_0 = 5\times10^{-3}$, $g = 0.1$ and $h = 0.1$.

where $\Delta\mathcal{V}(\phi,B) \equiv \frac{V^{(1)}(\phi,T,B) - V^{(1)}(0,T,B)}{V^{(1)}(0,0,0)} + 1.$

Magnetic effect on decay width

To calculate the charged scalar particle decay width we made use of the optical theorem, which relates the self-energy imaginary part with the decay width, as follows

$$\Gamma(l) = -\frac{\mathrm{Im}(\Sigma(l))}{l_0}.$$

We get

$$\Gamma^B(l) = \frac{2h^2}{\pi^2}\frac{q_1 q_2}{q_\chi}B\frac{(l_{||}^2 - m_1^2 - m_2^2)\theta(l_{||}^2 - (m_1+m_2)^2),}{l_0\sqrt{(l_{||}^2 - (m_1+m_2)^2)(l_{||}^2 - (m_1-m_2)^2)}}$$

In vacuum, the decay width, reads

$$\Gamma(l) = \frac{h^2}{4\pi}\frac{(l^2 - m_1^2 - m_2^2)\sqrt{(l^2 - (m_1+m_2)^2)(l^2 - (m_1-m_2)^2)}}{l_0 l^2}\theta(l^2 - (m_1+m_2)^2).$$

Magnetic effect on decay width

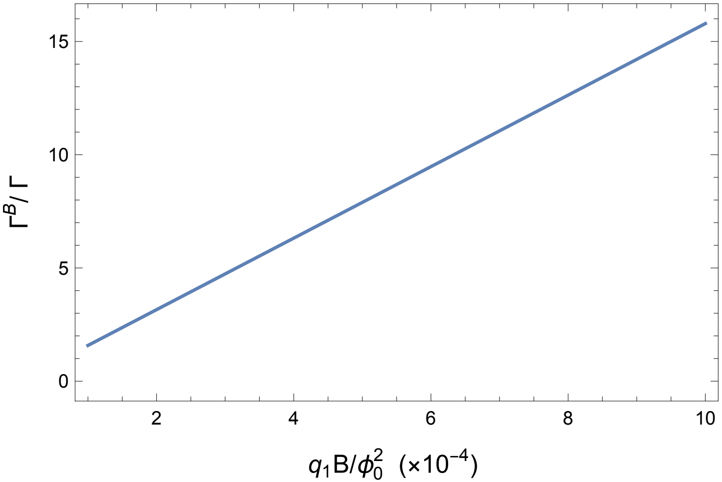

Figure: Decay width ratio Γ^B/Γ, of a heavy charged scalar into two light charged fermions, for different magnetic field strengths, for $M_s/\phi_0 = 0.05$, $m_1/\phi_0 = 10^{-3}$, $m_2/\phi_0 = 5 \times 10^{-3}$, $g = 0.1$. The magnetic field enhances this process.

Slow-roll parameters

The slow-roll conditions can be verified through the parameter

$$\epsilon = \frac{m_P^2}{16\pi}\left(\frac{V'}{V}\right)^2$$

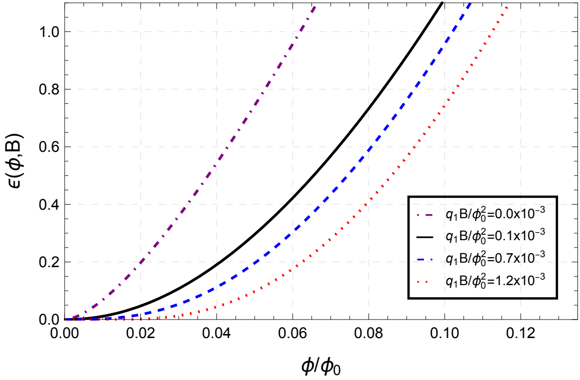

Figure: Slow-roll parameter ϵ for different magnetic field strengths with $M_s/\phi_0 = 0.05$, $m_1/\phi_0 = 10^{-3}$, $m_2/\phi_0 = 5\times10^{-3}$, $g = 0.1$ and $h = 0.1$.

Final remarks

- In this work we have studied the effects that a possible primordial magnetic field can have on the inflaton potential, taking as the underlying model a warm inflation scenario and considering that all fields interacting with the inflaton field are charged.
- We found that the magnetic field effect on the effective potential is to make it less steep as compared with the vacuum case, showing that magnetic fields do not spoil the inflationary process.
- This statement is supported by the behavior shown by the slow-roll ϵ-parameter as a function of the magnetic field.
- We have estimated the magnetic field effect on the decaying process of the heavy particles, in one channel. More work has to be done.

Thank you! // Grazie!

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