The QCD Phase Transition in the Early Universe

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Introduction

From the microwaves background radiation and the light element abundances from big bang nucleosynthesis one knows that the ratio of baryon to photon number is tiny: $n_B/n_γ \sim μ/T \sim 10^{-10}$. In standard cosmology one concludes that the early universe was hot enough to keep baryon number conserved during the epoch of baryogenesis.

Little Inflation at Phase Transition

What would happen if the early universe passes through a first order QCD phase transition?

A first order phase transition allows for a false metastable vacuum state where the universe could be trapped for some time → Inflationary Phase.

The baryon to photon ratios before and after the inflationary period should scale with the ratio of the scale parameters cubed as entropy is produced during reheating while baryon number is conserved so that

\[
\frac{n_B}{n_γ} \sim \left(\frac{μ}{T}\right)^3.
\]

The final ratio should be $10^{-9}$ as observed. So we need just a boost of $X = \ln(n_B/n_γ) / \ln(10) \sim 7$, i.e. seven e-folds, to get an initial ratio of $(μ/T)_0 = O(1)$.

Our scenario [1] is as follows:

- The early universe is at large baryochemical potentials $μ/T \gtrsim 1$ initially.
- The early universe reaches the first order phase transition line of QCD at high baryochemical potentials and is trapped in the false vacuum.
- The inflationary period starts with supercooling and dilution with $μ/T \rightarrow \text{const}.
- The decay to the true vacuum state will release latent heat, so that the universe is reheated to $T \rightarrow T_r$.
- Due to the entropy produced during the transition the final baryon to photon ratio is given by $μ/T \sim 10^{-10}$.
- Finally, the universe evolves along the standard cosmological path.

The path through the QCD phase diagram for the little inflation scenario is depicted in Fig. 1.

Cosmological Implications

There are observable differences between the Little Inflation scenario and the standard model of cosmology [1, 4].

Large Scale Structures

- Density and pressure perturbations depend on the energy density, pressure and speed of sound during inflation.
- The little inflationary epoch modifies the large-scale structure power spectrum responsible for galaxy formation. Here we show the typical mass scale of globular clusters ($\sim 10^7 M_☉$) [4].

Potential Barrier and Nucleation

- An important issue of this approach is the stability of the barrier between the quark and hadron phase up to very low temperatures $T \rightarrow 0$.

This is indeed the case in chiral models of QCD including gluonic degrees of freedom in the form of a dilaton field [2].

We use the model of Ref. [3] for different bag constants.
- The surface tension needed for nucleation to fail, so that the nucleation time scale exceeds the expansion time, is $124\text{ MeV}/\text{fm}^2$ [4].

Ref. [5] give possible ranges of $μ/T \sim 10^{-8}$ to $10^{-10}$ at very high densities.

- After some supercooling inflation comes to an end and the phase transition to the true minimum occurs.

This could either take place due to a strong drop in the surface tension or even due to a complete vanishing of the barrier between the two phases in the effective potential (spinodal decomposition).

Strong sensitivities of nucleation rates on the surface tension have been also found for high-density matter as encountered in the interior of neutron stars or in core-collapse supernovae [6].

Summary and Outlook

The QCD phase transition can be probed by cosmological observations: by the gravitational wave background, by large-scale structure formation, and by dark matter properties. The scenario needs to be treated in a field theoretical approach incorporating chiral symmetry and the Polyakov loop. The cosmological signals depend on

- Potential barrier → inflation, nucleation timescales
- Equation of state, speed of sound → structure formation
- Trace anomaly → gravitational wave spectrum

Gravitational waves

- Even for standard cosmology the gravitational spectrum will have a step due to the QCD crossover transition [4], see Fig. 2.
- Due to the inflationary period primordial gravitational waves are highly suppressed [4].
- During a first order transition, bubble collisions and turbulences are a source of gravitational radiation [8].

(Extra)Galactic Magnetic Fields

- Seeds of (extra)galactic magnetic fields can be generated by charged bubble collisions during the phase transition.
- A first order QCD phase transition in the early universe would provide a possible explanation of those cosmological magnetic fields [9].

Dark Matter

- The cold dark matter density is diluted by the same factor as the baryon number density, i.e. by up to a factor $10^{-3}$.
- One needs a lower WIMP annihilation cross section to explain the present cold dark matter relic density. That can be probed at the LHC.

References
