Meta-stable States in Quark-gluon Plasma

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Introduction

- In relativistic heavy-ion collisions, a deconfined phase of matter, quark-gluon plasma is believed to be created for high enough collision energies. With ongoing HIC programs such as LHC, the properties of this novel form of matter deep in the deconfined regime can be probed.

- In pure $SU(3)$ gauge theory, the deconfined phase of matter exists in three degenerate ground states characterised by the 3 values of the Polyakov loop, which is the order parameter for the ststem.
- However, in the presence of dynamical quarks(i.e in full QCD), the $Z(3)$ symmetry, which is a symmetry of the system in the confined phase, is broken explicitly, and hence lifts the degeneracy between the states. It should lead to meta-stable states in deconfined phase.

Introduction...

- The possible $Z(3)$ metastable states in deconfined phase may result in very interesting scenarios in both Heavy-ion collisions as well as early universe.
- In Heavy-ion collisions, during thermalization stage, the fireball could end up trapped in one of these meta-stable states, thereafter decaying to the true ground state via a first order phase transition, even before the system cools down to below T_c.
- In early universe, meta-stable phases of super-horozon sizes may form, and they decay to the ground state through bubble nucleation.

Dynamical quarks, Z(3) Symmetry and the Meta-stable states

- Consider pure $SU(N)$ gauge theory at finite temerature and their symmetries. Later, we discuss the fate of this symmetry with the inclusion of dynamical quarks.
- In this system at a temperature, $T = \beta_\tau^{-1}$, the static fundamental charges probes the dynamics of pure glue system, and are described by the Polyakov loop,

$$l(\vec{x}) = \frac{1}{N}\,\mathrm{Tr}\,P\,\exp\left[ig\int_0^{\beta_\tau} A_0(\vec{x},\tau)d\tau\right].$$

, with $\langle l(\vec{x})\rangle \Longrightarrow$ order parameter for confinement-deconfinement transition.

where, $P \Longrightarrow$ path ordering,

$g \Longrightarrow$ gauge coupling,

$A_\mu(\vec{x},\tau) = A_\mu^a(\vec{x},\tau)\lambda^a \Longrightarrow$ Vector potential

Dynamical quarks, Z(3) Symmetry....

- The gauge fields here $A_\mu(\vec{x},\tau)$ obey periodic boundary conditions in the Euclidean time direction.

  $A_\mu(\vec{x},\beta_\tau) = A_\mu(\vec{x},0)$

- These boundary conditions are maintained by a group of non-trivial gauge transformations that are periodic up to a constant twist matrix, $z \in SU(N)$,

$$g(\vec{x},\beta_\tau) = z\, g(\vec{x},0).$$

Dynamical quarks, Z(3) Symmetry....

- The matrices z form the center $Z(N)$ of the gauge group $SU(N)$, Hence, the pure $SU(N)$ gauge theory at finite temperature has the complete symmetry $\mathcal{G} \times Z(N)$, where $\mathcal{G}$ is the group of strictly periodic gauge transformations.
- However, under the global $Z(N)$ symmetry transformations, $l(\vec{x})$ transforms as

  $$l(\vec{x}) \rightarrow z\, l(\vec{x}),$$

  where,

  $$z = \exp(2\pi i n/N)\mathbf{1} \ \in \mathbf{Z(N)},$$

  ,with $n = 0.1, 2, ...(N-1)$
- The deconfined phase, characterized by $\langle l(\vec{x}) \rangle \neq 0$, corresponding to the finite free energy of an isolated heavy test breaks the symmetry spontaneously.

Effects of dynamical quarks...

- Inclusion of fermion fields in fundamental representation breaks the $Z(N)$ symmetry explicitly. The fermion fields must obey anti-periodic boundary conditions in τ,

  $$\Psi(\vec{x}, \beta_\tau) = -\,\Psi(\vec{x}, 0).$$

  These fields transforms under $SU(N)$ as,

  $$\Psi \rightarrow g\,\Psi,$$

  and breaks the $Z(N)$ symmetry explicitly.

Effects of dynamical quarks...

- The explicit breaking of $Z(3)$ symmetry by quark fields leads to one unique ground state, and (possibly) two meta-stable states in the deconfined phase. We will investigate these meta-stable states in lattice QCD simulations.

- There are studies on $Z(3)$ meta-stable states at high temerature in the presence of quarks in effective models.[Dixit etal, Ignatius etal]

- However, there are a very few lattice QCD studies indicating existence of these states in deconfined phase, with fermions in the sextet representation[Machtey etal]

Numerical method and parameters

We study the Monte-Carlo evolution of a suitably chosen initial gauge field configuration. To generate the gauge field configurations, we use the MILC code which uses the standard Hybrid R algorithm. We use similar simulation parameters as in Machtey etal.

To have the system thermalized/trapped to a meta-stable state, we have chosen the initial configuration appropriately. We did a pure gauge calculation on a lattice of size $16^3 \times 4$ near critical temerature ($\beta = \beta_c$=5.6925), starting with a "fresh lattice". We then select one configuration each for the following cases.

- $Re\,L \ll 0$ and $Im\,L \gg 0$, i.e. $\theta \simeq 2\pi/3$.
- $Re\,L \ll 0$ and $Im\,L \ll 0$, i.e. $\theta \simeq -2\pi/3$.
- $Re\,L \ll 0$ and $Im\,L \sim 0$, i.e. $\theta \simeq \pi$.[To test if a meta-stable state could exist at $\theta = \pi$]
- $Re\,L \gg 0$ and $Im\,L \sim 0$, i.e. $\theta = 0$.

Numerical method and parameters

- We use each of the above gauge configurations (one for each θ) as an initial configuration to thermalize, and calculate the Polyakov loop in presence of 2 and 3-flavor quarks for a series of β values, i.e $5.2 \leq \beta \leq 6.0$.

- We use MILC code with dynamical staggered fermion action, with quark mass $am_{u,d} = 0.01$, so that $m_{u,d}/T = 0.04$. Each gauge configuration is analysed after 10 heat-bath iterations. For each value of β, we collect 2500 gauge configurations.

- Micro-canonical time step used is $\Delta\tau \sim 0.01$, with the trajectory length, $\tau \sim 0.8$.

Results and Discussions

- In the simulations, the initial configuration thermalizes within a few hundred Monte-Carlo steps. For β values up to $\beta_m \sim 5.80$, we observed a unique final thermalized state irrespective of the initial configuration chosen.

- For higher β values, this pattern changes. For $\beta > \beta_m$ with appropriate initial configuration, we started seeing the system thermalizing to an "intermediate" state, where the Polyakov loop fluctuates around a large non-zero imaginary value, and afterwards the system makes a transition to another state, in which the real part of Polyakov loop fluctuating around a mean positive value, with the imaginary part zero.

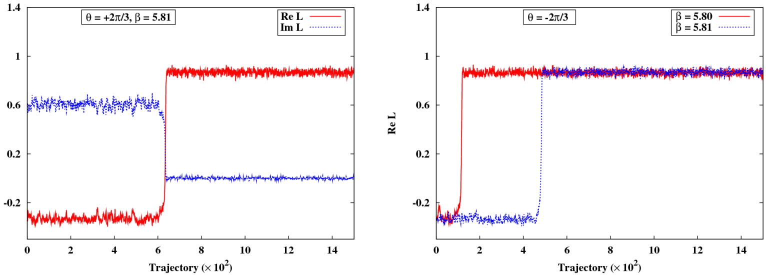
- The meta-stable states are not observed below β_m because for $\beta < \beta_m$, the thermal fluctuations are large compared to the barrier height between these states and the true ground state.

Results and Discussions

- In simulation results, higher β corresponds to higher temperature and larger quark mass, hence the barrier height between the meta-stable state and the absolute ground state increases with β value.

- In Fig. 1(b) for $\theta = -2\pi/3$, this explains why the system stays longer in the meta-stable state for $\beta = 5.81$ than $\beta = 5.80$.

Results and Discussions...

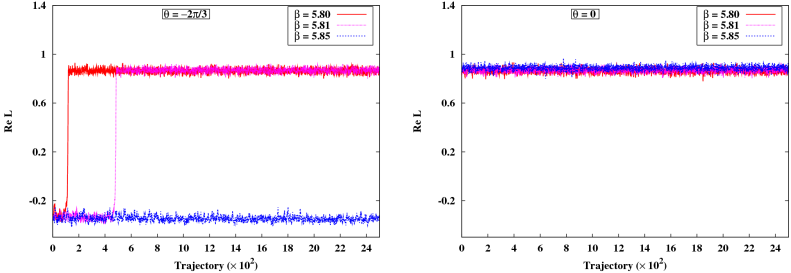


(a) (b)

Figure: (a) The fluctuations of both real and imaginary part of Polyakov loop around some mean value, (b) Real parts of Polyakov loop for two β values are plotted against trajectories.

- Here, we see that for the higher β, the meta-stable state persists longer.

Results and ...

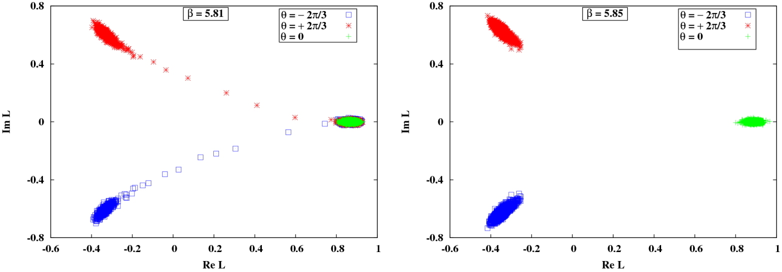


(a) (b)

Figure: Polyakov loop, *Re L* vs. no. trajectories for (a) $\theta = -2\pi/3$, and (b) $\theta = 0$ for 2-flavor case.

Here, in this figure, for $\beta = 5.85$, the meta-stable state does not decay at all within our Monte Carlo history.

Results and ...



(a) (b)

Figure: Imaginary part of Polyakov loop vs. real part for various β values.

In this figure, for $\beta = 5.85$, there are no fluctuations between different minima. With various trial configurations, we find two meta-stable states for $\theta = \pm 2\pi/3$, and one absolute ground state at $\theta = 0$.

Results and ...

- We perform simulations for 3$-$flavors of degenerate quarks. In this case, the meta-stable states appear at higher values of β_m compared to that of 2$-$flavor, with all other findings remaing similar to those of 2-flavor case. The value of β_m we get, should be the lower bound for all the quark masses for which $am_{u,d}(\beta_m) \leq 0.01$.

- We estimate the temperature T_m corresponding to β_m and am_q, from $\beta-$function which relates these bare parameters to the lattice cutoff, a. This gives us $T_m = T(\beta_m = 5.80, am_q = 0.01) = 750$ MeV, above which the meta-stable state starts appearing. There is a possibility that these states may be observable at LHC.

Summary

- We perform full QCD simulations with $N_f = 2, 3$ flavor of degenerate quarks to study meta-stable states in the neighbourhood of T_c.

- We find the temperature scale to be $T_m \gtrsim 750$ MeV (for $N_f = 2$) above which meta-stable states can appear. So, we expect that these meta-stable states may be observed at LHC.
- We discuss the possibility, that when the Universe cools down below T_m, there may be roll down and large coherent oscillations of the Polyakov loop in the region where meta-stable phase existed, which may lead to interesting consequences.