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The cosmic QCD phase transition with dense matter and its gravitational waves from holography

M. Ahmadvand, K. Bitaghsir Fadafan *

Faculty of Physics, Shahrood University of Technology, P.O. Box 3619995161, Shahrood, Iran

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ABSTRACT

Consistent with cosmological constraints, there are scenarios with the large lepton asymmetry which can lead to the finite baryochemical potential at the cosmic QCD phase transition scale. In this paper, we investigate this possibility in the holographic models. Using the holographic renormalization method, we find the first order Hawking–Page phase transition, between the Reissner–Nordström AdS black hole and thermal charged AdS space, corresponding to the de/confinement phase transition. We obtain the gravitational wave spectra generated during the evolution of bubbles for a range of the bubble wall velocity and examine the reliability of the scenarios and consequent calculations by gravitational wave experiments.

1. Introduction

Cosmological Phase Transitions (PTs) in the early universe have played significant roles in the universe that we can see at the present time. The last PT at which quarks and gluons are confined is the phase transition of Quantum Chromodynamics (QCD) which occurred around 10^{-5} secs after the big bang. The theory of QCD describes strong nuclear interactions. Despite other theories in the standard model of particle physics, QCD is strongly-coupled at low energy and cannot be described by perturbative methods, though at high energy it is an asymptotic freedom theory. For light quarks, the QCD Lagrangian has an approximate symmetry called chiral symmetry, which is spontaneously broken, in the QCD vacuum. Chiral condensate as the order parameter of this PT becomes non-zero in the broken phase, and pseudo-Goldstone pions and conservation of the baryon number are remainders of this spontaneously broken symmetry. Furthermore, there is another approximate symmetry, the global Z(3) center symmetry which is spontaneously broken under the de/confinement PT, for heavy quarks. For this PT, the expectation value of Polyakov loop is the relevant order parameter, which can be obtained from the heavy quark potential [1,2].

If a PT is first order, it gives rise to non-equilibrium events, the nucleation and growth of bubbles. Two degenerate states with minimum free energy are separated by the bubbles. The vacuum energy of the system causes bubbles to expand and collide with each other. The spherical symmetry of the bubbles is broken and parts of the energy can create Gravitational Waves (GWs) in the spacetime [3]. The process of the bubble collision can also produce bulk motion which itself is taken into account as another source for GWs through sound waves [4] and Magnetohydrodynamic (MHD) turbulence [5] in the plasma. Due to the weakness of gravitational interactions and least attenuation of GWs, the detection of their signal gives us important information from early epochs of the universe.

At the energies which the two mentioned aspects of the QCD PT occur, the theory is strongly-coupled, thus perturbative expansions cannot be applied. Lattice QCD as a numerical method can help to understand these phenomena. In this approach, it is shown that for $2+1$ intermediate bare quark masses (2 light quarks, up and down, and 1 heavier quark, strange) with negligible baryochemical potential, PT is not first order but a crossover [6], whereas for so heavy, static quarks or pure gauge theory, PT is first order [7]. However, for the finite baryochemical potential, this method suffers from the sign problem related to the complexity of fermion determinant [8].

Here, we focus on the de/confinement aspect of the PT at the finite baryochemical potential. The baryochemical potential depends on baryon and lepton asymmetries and for tiny baryon and lepton asymmetries it would vanish. However, a large lepton asymmetry can be supported in the early universe [9]. This finite baryochemical potential can be justified in late leptogenesis scenarios [10],

* Corresponding author.
E-mail addresses: ahmadvand@shahroodut.ac.ir (M. Ahmadvand), bitaghsir@shahroodut.ac.ir (K. Bitaghsir Fadafan).

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which are compatible with BBN and CMB constraints. The large lepton asymmetry is expected to be in the neutrino chemical potential [9] and can be proposed in the models with the dark matter neutrino candidate [11].

In this work, we use AdS/QCD approach to explaining the de/confinement PT. The conjecture of gauge/gravity as an extension to AdS/CFT correspondence has been a useful technique describing a strongly-coupled gauge theory by a gravitational theory in a higher dimensional spacetime [12]. Deriving universal properties of these theories, such as the ratio of the shear viscosity of the hot plasma to the entropy density, is one of the issues handled through these dualities [13]. People also tried to address QCD PT features within this context. In [14], it is shown that there is a correspondence between the first order Hawking–Page (H–P) PT and the de/confinement PT for compact boundaries. Also, for non-compact boundaries with the removed small radius region of AdS space, [15] found the H–P PT.

The study of GWs from the cosmological QCD PT using the gauge/gravity duality was initiated in [16]. In that paper, we studied the cosmological QCD PT considering gluodynamics and zero baryochemical potential. We used AdS/QCD models to find the corresponded H–P PT and calculated the GW spectra radiated during the PT. In this paper, we are interested in studying holographically the cosmological deconfinement transition with possible finite baryochemical potential. Taking quark degrees of freedom into account leads to adding an abelian gauge field on the gravity side. (For the holographic QCD by considering finite chemical potential see [17–19].) Within hard and soft wall models [20,21] we here apply the holographic renormalization [22] to find the H–P PT, between Reissner–Nordström AdS black hole (RN AdS BH) and thermal charged AdS (tc AdS).

For zero baryochemical potential, the temperature at the PT is determined by a special horizon radius which is fixed by IR cut-off in the models [15]. However, as we will see, in the case of finite baryochemical potential, temperature depends on baryochemical potential as well. Therefore, to specify temperature and baryochemical potential at the transition, we also investigate the string configuration based on the expectation value of Polyakov loop as the order parameter during the PT. Finally, we extend our approach in [16] and study the spectrum of the GWs radiated during the de/confinement PT from these models for three different ranges of the bubble wall velocity. Detecting the signal of these GWs allows testing our results.

This paper is organized as follows: In the next section we explain properties of distinct sources for GWs generated from a first order PT. In section three, we study Hawking–Page phase transition in the AdS/QCD models and find the Gravitational wave spectrum for three different regimes of the bubble wall velocity. In the last section, we summarize the results.

2. Gravitational waves of a first order phase transition

As mentioned before, during a first order cosmological PT occurring in a thermal bath, bubbles are nucleated and because of the vacuum energy released from the initial phase, bubbles expand. In the hydrodynamical description of the bubble evolution, the bubble velocity, v_b, is an important parameter which affects the GW generation of this process. Two modes of the bubble wall velocity are classified, the bubble front moving with subsonic velocity, deflagration, and supersonic velocity, detonation. For small bubble wall velocities, the big contribution for the GW energy density is not expected since the energy almost thermalize the fluid. However, for relativistic velocities, the imprint of GW sources of PTs can be traced. If the wall velocity is held at a relativistic velocity, the role of the fluid is very important and the GW contribution comes from sound waves and MHD turbulence. In the case which bubbles can run away without a bound, the energy of the runaway bubbles cannot be ignored and three sources of GWs coexist [23,24]. In the following, we explain how to calculate the contribution of each source.

2.1. Bubble collision

After bubble nucleation and expansion, they collide with each other and the fraction of the latent heat of the system in the thermal bath is converted to GWs. The GW generated from the bubble collision is simulated by the envelope approximation [25] so that the anisotropic transverse component of the energy-momentum of uncollided bubble envelope, resulted from the broken spherical symmetry of a colliding bubble, is taken into account.[1] Numerical fits give this GW energy density as

$$h^2\Omega_{en}(f) = 3.5\times 10^{-5}\Big(\frac{0.11 v_b^3}{0.42+v_b^2}\Big)\Big(\frac{H_*}{\tau}\Big)^2\Big(\frac{\kappa\alpha}{1+\alpha}\Big)^2 \times\Big(\frac{10}{g_*}\Big)^{\frac{1}{3}} S_{en}(f), \tag{1}$$

where the spectral shape of the GW is [27]

$$S_{en}(f) = \frac{3.8(\frac{f}{f_{en}})^{2.8}}{1+2.8(\frac{f}{f_{en}})^{3.8}}. \tag{2}$$

The present red-shifted peak frequency is given by

$$f_{en} = 11.3\times 10^{-9}[\mathrm{Hz}]\Big(\frac{0.62}{1.8-0.1v_b+v_b^2}\Big)\Big(\frac{\tau}{H_*}\Big)\Big(\frac{T_*}{100\ \mathrm{MeV}}\Big) \times\Big(\frac{g_*}{10}\Big)^{\frac{1}{6}}. \tag{3}$$

The spectrum is almost a function of f^3 for small frequencies and f^{-1} for frequencies larger than the peak frequency. Also, α is the vacuum energy density to the thermal energy density ratio,

$$\alpha = \frac{\epsilon_*}{\frac{\pi^2}{30}g_* T_*^4}, \qquad \epsilon_* = \Big(-\Delta F(T) + T\frac{d\Delta F(T)}{dT}\Big)\Big|_{T=T_*}. \tag{4}$$

ΔF is the free energy difference between two phases and T_* is the temperature at which the PT takes place. Also, κ is the fraction of the vacuum energy converted into the kinetic energy of the bubbles and τ^{-1} is the duration of the PT. Moreover, the Hubble parameter is given by

$$H_* = \sqrt{\frac{8\pi^3 g_*}{90}}\frac{T_*^2}{m_{pl}}, \tag{5}$$

where g_* denotes the number of effective relativistic degrees of freedom, which is almost 10 at the QCD PT, and $m_{pl} = 1.22\times 10^{22}$ MeV is the Planck mass.

2.2. Sound waves and MHD turbulence

After bubbles collided, the fraction of the energy is transformed into the plasma motion, κ_v. This kinetic energy of the plasma generates MHD turbulence, as a Kolmogorov turbulence, which induces GW radiation. Furthermore, as proposed in [4], the compression waves in the fluid, sound waves, can be another source

[1] For an analytic approach see [26].