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Deconfinement transition at high isospin chemical potential and low temperature

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Abstract

We consider QCD with two degenerate flavors of light quarks (up and down) at asymptotically high isospin (μ_I) with zero baryon chemical potential (μ_B) and calculate for the first time a quantitative expression for the critical temperature of the deconfinement transition in this regime. At high isospin chemical potential and sufficiently low temperatures this theory becomes equivalent to a pure Yang–Mills theory and accordingly has a first order deconfinement phase transition. Although this was conjectured in a seminal paper by Son and Stephanov in the year 2001, the critical temperature of this deconfinement phase transition was not computed. This paper computes the energy scale associated with this transition as a function of the chemical potential μ_I by relating the parameters of the equivalent Yang–Mills theory to those of the underlying theory. We also relate the equation of state in one strongly interacting regime of QCD namely at finite isospin density to that in pure Yang–Mills, with the latter being amenable to straightforward numerical calculation. Our results for the critical temperature of deconfinement transition can be compared with future lattice calculations.

Keywords: Isospin chemical potential; Phase transition; Critical temperature; Equation of state

1. Introduction

One of the goals of modern nuclear physics is to understand the rich structure of the QCD phase diagram at finite density and temperature. This is because various such phases of matter can

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be realized in nature under different circumstances. The core of neutron stars and the evolution of the early universe are two of the most prominent examples where a knowledge of the phase diagram would help our understanding.

It is very difficult to get a handle on this problem starting directly from QCD. Accordingly it is useful to learn what we can from regimes which are tractable even when they are not of direct phenomenological relevance. In this paper we focus on the low temperature regime of two-flavor QCD with zero baryon chemical potential and very large isospin chemical potential. The study of this regime was originated by Son and Stephanov [1,2] who noted that in the limit of extreme isospin chemical potentials this theory became equivalent to a pure Yang–Mills theory. This implies among other things that unlike at zero chemical potential the theory has a first-order deconfining transition. Although, the first order deconfinement transition at high isospin chemical potential was conjectured by Son and Stephanov, the critical temperature for this deconfinement transition has not been calculated before. This paper, relates the properties of this emergent Yang–Mills theory to the parameters of the underlying theory and calculates the critical temperature of this first order deconfinement transition.

One exciting feature of this analysis is that we can relate the equation of state at large isospin chemical potential and low temperature to the equation of state of pure Yang–Mills theory. Since the equation of state of the pure Yang–Mills theory is computable using numerical studies on a lattice with relatively modest resources, this means that the equation of state of QCD at large isospin chemical potential and low temperatures is effectively computable with modest resources — including a computation of the critical temperature of the first order transition.

To put this problem in context, it is useful to recall that considerable progress has already been made in mapping the phase diagram both in isospin density vs temperature plane and baryon density vs temperature plane. The biggest hurdle impeding progress in this effort is the strength of the QCD coupling constant at moderate energy scales. A significant portion of the phase diagram which corresponds to observable phenomena such as the dynamics at the core of the neutron stars or the heavy ion collisions is inaccessible to perturbation theory calculations as the theory is strongly coupled in this regime. In order to circumvent this difficulty numerical calculations using lattice have been employed and this has been remarkably successful in some cases. One such success story was in cosmology, where it answered questions relating to whether the universe went through a phase transition while passing from a quark gluon plasma phase to a hadronic phase at temperatures around 150 MeV. This problem was satisfactorily handled by finite temperature lattice QCD and it was concluded that the universe did not go through a QCD phase transition but a crossover as it cooled [3,4]. But lattice QCD fails at finite baryon chemical potential at low temperature. The reason behind this is that the fermion determinant in the presence of a chemical potential for the quark number becomes complex, which causes lattice algorithms involving the method of important sampling to break down. This is known as the sign problem [5–8]. But an understanding of this regime of the phase diagram is absolutely necessary for neutron star physics. This is because the mass-radius relation and the transport properties of a neutron star are determined by the phase of matter at the core where baryon density is high and the temperatures are low [9–13]. Efforts have been made to explore the finite baryon density regime using Nambu–Jona-Lasinio model [14–18], quark–meson model [19], Polyakov loop extended Nambu–Jona-Lasinio model [20–24], Polyakov loop extended quark–meson model [25,26]. But these models are not very rigorous. Since the temperatures of interest are very low, and degrees of freedom involved are fermionic, Fermi liquid theory of nucleons, which is a theory of nucleon quasi particle excitations about the Fermi surface is used to make predictions for baryon densities that correspond to a Fermi energy of 100 MeV. Very high baryon density and