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Waves in magnetized quark matter

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Abstract

We study wave propagation in a non-relativistic cold quark-gluon plasma immersed in a constant magnetic field. Starting from the Euler equation we derive linear wave equations and investigate their stability and causality. We use a generic form for the equation of state, the EOS derived from the MIT bag model and also a variant of the this model which includes gluon degrees of freedom. The results of this analysis may be relevant for perturbations propagating through the quark matter phase in the core of compact stars and also for perturbations propagating in the low temperature quark-gluon plasma formed in low energy heavy ion collisions, to be carried out at FAIR and NICA.

Keywords: Quark-gluon plasma; Non-relativistic Euler equation; QCD; MIT bag model

1. Introduction

There is a strong belief that quark gluon plasma (QGP) has been formed in heavy ion collisions at RHIC and at LHC [1,2]. Deconfined quark matter may also exist in the core of compact stars [3]. Waves may be formed in the QGP [4–6]. In heavy ion collisions waves may be produced, for example, by fluctuations in baryon number, energy density or temperature caused by inhomogeneous initial conditions [7]. Furthermore, there may be fluctuations induced by energetic partons, which have been scattered in the initial collision of the two nuclei and propagate through the medium, loosing energy and acting as a source term for the hydrodynamical equations.

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In [5] we have studied wave propagation in cold and dense matter both in a hadron gas phase and in a quark gluon plasma phase. In deriving wave equations from the equations of hydrodynamics, we have considered both small and large amplitude waves. The former were treated with the linearization approximation while the latter were treated with the reductive perturbation method. Linear waves were obtained by solving an inhomogeneous viscous wave equation and they have the familiar form of sinusoidal traveling waves multiplied by an exponential damping factor, which depends on the viscosity coefficients. Since these coefficients differ by two orders of magnitude, even without any numerical calculation we concluded that, apart from extremely special parameter choices, in contrast to the quark gluon plasma there will be no linear wave propagation in a hadron gas.

In this work we will investigate the effects of a magnetic field on wave propagation in a quark gluon plasma. We shall focus on the stability and causality of these waves. A natural question is "how does the magnetic field affect stability and causality of density waves ?". We will try to answer this question in a, as much as possible, model independent way.

Our conclusions should apply to the deconfined cold quark matter in compact stars and to the cold (or slightly warm) quark gluon plasma formed in heavy ion collisions at intermediate energies, to be performed at FAIR [8] or NICA [9].

In what follows we will carry out a wave analysis which is very frequently used in hydrodynamcis [10]. We will be able to see if the presence of a magnetic field modifies the conclusions reached in [5].

2. Hydrodynamics in an external magnetic field

We shall consider the non-relativistic Euler equation [11] with an external magnetic field $\vec{B}$. The three fermions species (three quarks) have negative or positive charges and due to the external magnetic field they may assume different trajectories [12,13]. As a consequence we must apply the multifluid approach [12,13], which consists in writing one Euler equation for each quark $f = u, d, s$:

$$\rho_{m\,f}\left[\frac{\partial \vec{v_f}}{\partial t} + (\vec{v_f}\cdot\vec{\nabla})\vec{v_f}\right] = -\vec{\nabla} p + \rho_{c\,f}\Big(\vec{v_f}\times\vec{B}\Big) \tag{1}$$

where $\rho_{m\,f}$ and $\rho_{c\,f}$ are the mass and charge density of the quarks of flavor f respectively. We employ natural units ($\hbar = c = 1$) and the metric used is $g^{\mu\nu} = \text{diag}(+,-,-,-)$.

When we employ the multifluid approach, we are effectively using the approximation of weak interactions between the fluid constituents. In principle in an ideal QGP the interaction between the quark and gluon constituents is weak. In the presence of a strong magnetic field the interaction is even weaker, since the coupling constant decreases with increasing B field [14]. We will work with three equations of state. In the first two of them there is no interaction between the constituents. They are compatible with the multifluid approach. In the third one (called "mean field QCD") we have interactions, but the coupling constant is not large. What justifies the mean field approximation is the high density of sources. So we assume that in all our calculations we are in the weak coupling regime and hence we can borrow all the techniques and approximations (including the multifluid approach) from the plasmas known in electrodynamics.

In what follows we will consider quark matter with three quark flavors: up (u), down (d) and strange (s). As it is usually studied in [15], such quark matter may exist in compact stars. The charges are: $Q_u = 2\,Q_e/3$, $Q_d = -\,Q_e/3$ and $Q_s = -\,Q_e/3$, where $Q_e = 0.08542$ is the abso-