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Insight into the magnetic response of hadron gas using non-extensive statistics

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Non-central heavy-ion collisions at ultra-relativistic energies are unique in generating magnetic fields of significant strength in the laboratory. The short-lived magnetic field created at the early stages of this type of collision could impact the system's thermodynamic and transport properties of final state dynamics. In this work, we analyze the bulk thermodynamic observables such as energy density(ϵ), pressure(P), entropy density(s), as well as second-order quantity like the speed of sound (c_s^2) of a hadron gas in the presence of an external static magnetic field utilizing thermodynamically consistent non-extensive Tsallis statistics at zero chemical potential, $\mu = 0$. Further, such a system's magnetization(M) is also investigated. This analysis reveals an interplay of the diamagnetic and paramagnetic aspects of the system in the presence of the external magnetic field of distinct strengths for non-central heavy-ion collisions as one moves from RHIC to the LHC energies.

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1. Introduction

The law of electrodynamics states that the electric charge in a uniform motion can produce electric and magnetic fields (B). Likewise, the fast and oppositely directed motion of the colliding beams carrying a large positive electric charge (or spectator protons) in the non-central relativistic heavy-ion collisions can produce an electromagnetic field [1–3], which provides us a unique tool to probe and understand the Quantum Chromodynamics (QCD) phase diagram for a wide range of temperatures (T) and baryon-chemical potential (μ_B). The experiments like Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), where heavy-ions are collided to investigate the resultant QCD matter, the maximum magnetic field generated can be of the order; $B \sim (m_\pi^2) \sim 10^{18}$G [4] and $B \sim (15m_\pi^2)$ respectively, where m_π denotes the mass of a pion [5, 6]. The electromagnetic field created in a heavy-ion collision is perhaps the strongest magnetic field ever created in nature. Thus, it is important to study the effect of the magnetic field on the hot and dense matter formed in such collisions to understand the QCD phase diagram. In the presence of an external magnetic field, the energy of the neutral and charged particle are respectively given by [7–10],

$$E_{i,n} = \sqrt{p^2 + m_i^2} \tag{1}$$

$$E_{i,c}(p_z, k, s_z) = \sqrt{p_z^2 + m_i^2 + 2|e_i|B(k + 1/2 - s_z)}. \tag{2}$$

We have estimated the thermodynamic variables such as energy density (ϵ), pressure (P), entropy density (s), magnetization (M), and squared speed of sound (c_s^2) for charged and neutral particles in the presence of a strong magnetic field at zero chemical potential, $\mu = 0$, in non-extensive statistics. The details of the work can be found in Ref. [10].

2. Results and Discussion

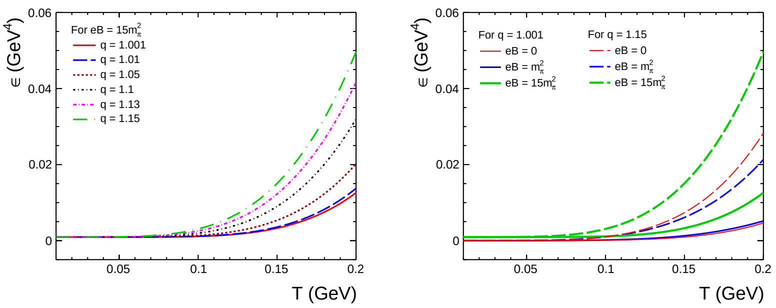

Figure 1: (Color online) The left panel illustrates the variation of a hadron gas's total energy density as a function of temperature for different non-extensive parameter values at a constant magnetic field $eB = 15m_\pi^2$. The right panel represents the variation of total energy density at various strengths of magnetic fields and distinct values of q [10] .

The left panel of fig. 1 illustrates the variation of a hadron gas's total energy density as a function of temperature for distinct non-extensive parameter values at a constant magnetic field $eB = 15m_\pi^2$. We observed that energy density monotonically increases with an increase in temperature for all q-values. A finite energy density is observed at low temperatures because of vacuum contribution. The right panel of fig. 1 represents the variation of total energy density at various strengths of magnetic fields and extreme values of q to see the competing effects of an external magnetic field and the non-extensive parameter as a function of temperature. The energy density rises with an increase in the magnetic field for $q = 1.001$ and $q = 1.15$ at the low-temperature regime. Whereas, at a more significant temperature regime, the energy density of the system with an external magnetic field $eB = m_\pi^2$ is lower than that of the system in the absence of an external magnetic field. The result is encouraging because this behavior is noticed when the system is away from equilibrium.

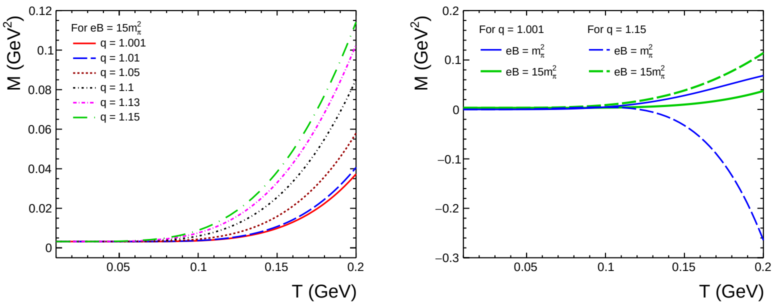

Figure 2: (Color online) The left panel represents the variation of magnetization of a hadron gas as a function of temperature for different values of the non-extensive parameter at a constant magnetic field $eB = 15m_\pi^2$. The right panel represents the variation of magnetization at different strengths of magnetic fields and for distinct values of non-extensive parameter q [10].

The left panel of fig. 2 represents the variation of magnetization of a hadron gas as a function of temperature for distinct values of the non-extensive parameter at a constant magnetic field $eB = 15m_\pi^2$. A finite magnetization is observed at lower temperatures because of vacuum contribution and gradually increases with an increase in temperature for all q-values. When the system is near equilibrium, the magnetization of the system is lower for lower q-values,. As the q-value increases, the magnetization of the system rises at all temperatures. The right panel of fig. 2 illustrates the variation of magnetization at distinct magnetic fields for systems near and away from equilibrium. For $q = 1.001$ values, the magnetization of the system with a lower external magnetic field is higher for all temperatures. However, the magnetization of the system with an external magnetic field $eB = m_\pi^2$ is negative for $q = 1.15$, implying that the system has diamagnetic behavior. Further, for $eB = 15m_\pi^2$, the system shows positive magnetization suggesting that the system has paramagnetic behavior. For peripheral heavy-ion collisions, with the increased system center-of-mass energy from RHIC to the LHC, the system undergoes a diamagnetic to paramagnetic transition.

The left panel of fig. 3 represents the variation of pressure, and the right panel of fig. 3 represents entropy density as a function of temperature in a magnetized hadron gas for various q-values. The magnetic field corresponds to LHC *i.e* $eB = 15m_\pi^2$, both the pressure and the entropy density of the system increase with an increase in temperature for all the q-values. A finite pressure is observed

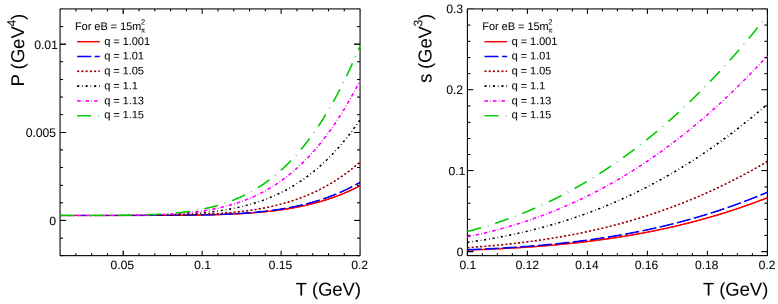

Figure 3: (Color online) The left and the right panel represents the variations of total pressure and the entropy density as a function of temperature in a magnetized hadron gas for distinct values of non-extensive parameter q, respectively [10].

at zero temperature because of the vacuum contribution of the particles considered in this study. In fig. 4, we have calculated the squared speed of sound, (c_s^2), for a magnetized hadron gas as a

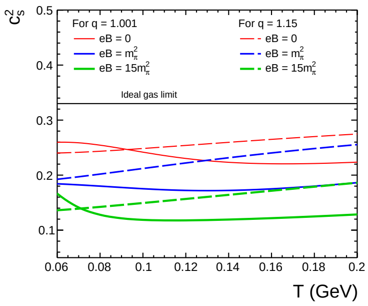

Figure 4: (Color online) The squared speed of sound of hadron gas as a function of temperature for different q-values for different strengths of an external magnetic field [10].

function of temperature for various q-values under distinct strengths of the external magnetic field ($eB = 0, m_\pi^2$ and $15m_\pi^2$. For $q = 1.001$, the squared speed of sound in all the external magnetic fields decreases with an increase in temperature. (c_s^2) is the highest in the absence of an external magnetic field for a system near equilibrium. However, when the system is away from equilibrium, *i.e* for $q =$ 1.15, we observe the (c_s^2) increases for all the cases of external magnetic fields. The magnetic field appears to lower the speed of sound in the medium at all temperatures.

3. Summary

In summary, we found a diamagnetic to paramagnetic transition for the system in the behavior of non-central heavy-ion collisions as one moves from RHIC to the LHC energies. Such an observation is never made so far and perhaps needs more investigations. We have also investigated the squared speed of sound of a hadron gas under an external magnetic field. We observe the value of c_s^2 besides respecting the Stefan-Boltzmann limit of 1/3, asymptotically decreases with an increase in magnetic field strength. Hence, the system is more interactive in a finite magnetic field.

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