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Isospin symmetry breaking and Baryon-Isospin correlations in effective mean field models.

Abhijit Bhattacharyya
University of Calcutta, Kolkata
E-mail: abphy@caluniv.ac.in

Sanjay K. Ghosh
Center for Astroparticle Physics & Space Science, Bose Institute, Kolkata
E-mail: sanjay@jcbose.ac.in

Anirban Lahiri
Tata Institute of Fundamental Research, Mumbai
E-mail: anirbanlahiri.physics@gmail.com

Sarbani Majumder*
Saha Institute of Nuclear Physics, Kolkata, India.
E-mail: sarbanimajumder@gmail.com

Sibaji Raha
Center for Astroparticle Physics & Space Science, Bose Institute, Kolkata
E-mail: sibaji@jcbose.ac.in

Rajarshi Ray
Center for Astroparticle Physics & Space Science, Bose Institute, Kolkata
E-mail: rajarshi@jcbose.ac.in

A study of the 1+1 flavor system of strongly interacting matter in terms of the Polyakov−Nambu−Jona-Lasinio model is presented. It is found that though the small isospin symmetry breaking brought in through unequal light quark masses is too small to affect the thermodynamics of the system in general, it may have significant effect in baryon-isospin correlations and have a measurable impact in heavy-ion collision experiments.

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*speaker

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1. Introduction

Quantum Chromodynamics (QCD) is the formulation for first principle studies of strongly interacting matter. Along with the local color symmetry, the quark sector has few global symmetries also. In the chiral limit for two light flavors u and d, we have global vector and axial vector symmetry $SU_V(2)\otimes SU_A(2)$. For non-zero quark masses, the axial symmetry $SU_A(2)$ is explicitly broken, while for non-zero quark mass difference vector (isospin) symmetry $SU_V(2)$ is explicitly broken. Apart from the quark mass difference, ISB effects may be brought in by electromagnetic contributions as well.

Some Lattice QCD investigation of the effect of unequal quark masses was done in Ref.[1]. Recently in Ref.[2, 3] the effect of ISB on different hadronic observables were studied. Within the framework of chiral perturbation theory the isospin breaking effect in quark condensates has been studied considering $m_u \neq m_d$ and electromagnetic corrections as well, where an analysis of scalar susceptibilities [4, 5] is given. In effective mean field model like Nambu−Jona-Lasinio (NJL) model, both of the above-mentioned effects have been incorporated [6] to study the influence of the isospin symmetry breaking on the orientation of chiral symmetry breaking. In the present work we describe the first case study of ISB effect on fluctuations and correlations of strongly interacting matter within the framework of the Polyakov loop enhanced Nambu−Jona-Lasinio (PNJL) model. We discuss the possible experimental manifestations of the ISB effects based on quite general considerations in the limit of small current quark masses.

2. Formalism

Here we use the form of the 2 flavor PNJL model with the Lagrangian as in Ref.[7, 8];

$$\begin{aligned}\mathscr{L}_{PNJL} = &-\ \mathscr{U}\,[\Phi[A],\bar{\Phi}[A],T] + \bar{\psi}(\not{D} - \hat{m})\psi \\ &+\ G_1[(\bar{\psi}\psi)^2 + (\bar{\psi}\vec{\tau}\psi)^2 + (\bar{\psi}i\gamma_5\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] \\ &+\ G_2[(\bar{\psi}\psi)^2 - (\bar{\psi}\vec{\tau}\psi)^2 - (\bar{\psi}i\gamma_5\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2]\end{aligned} \tag{2.1}$$

$\mathscr{U}\,[\Phi[A],\bar{\Phi}[A],T]$ is the effective potential expressed in terms of traced Polyakov loop Φ and its charge conjugate $\bar{\Phi}$. Here we shall consider a mass matrix of the form:

$$\begin{aligned}\hat{m} &= m_1 1\!\!1_{2\times2} - m_2\tau_3 \\ &= \begin{pmatrix} m_1 - m_2 & 0 \\ 0 & m_1 + m_2 \end{pmatrix} \equiv \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}.\end{aligned}$$

where, $1\!\!1_{2\times2}$ is the identity matrix in flavor space and τ_3 is the third Pauli matrix. Here m_u and m_d are the current masses of the u and d quarks respectively. While a non-zero m_1 breaks the chiral $SU_A(2)$ symmetry explicitly a non-zero m_2 does the same for the isospin $SU_V(2)$ symmetry. We have restricted ourselves to $G_1 = G_2 = G$ which implies $m_2 = (M_d - M_u)/2$, where M_u and M_d are the constituent masses of the u and d quarks respectively. Deriving the thermodynamic potential from Lagrangian, different charge susceptibilities can be obtained from corresponding chemical potential derivative of thermodynamic potential.

3. Off-diagonal Susceptibilities for $\mu_B = 0$

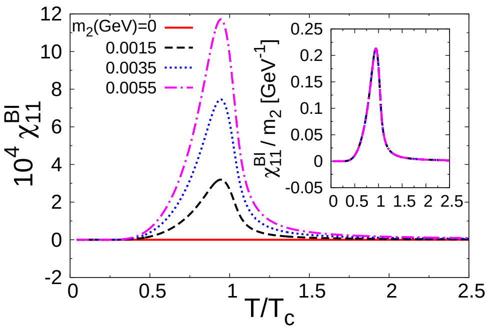

Figure 1: Second order off-diagonal susceptibility in $B-I$ sector at $\mu_B = 0$.

In Fig.1 the second order off-diagonal susceptibility χ_{11}^{BI}, is shown for different values of m_2. As expected we find $\chi_{11}^{BI} = 0$ for $m_2 = 0$. For non-zero m_2 we find χ_{11}^{BI} to have non-zero values that change non-monotonically with the increase in temperature.

An exciting feature observed here is that there is an almost linear scaling of χ_{11}^{BI} with m_2. This is shown in the inset of Fig.1.

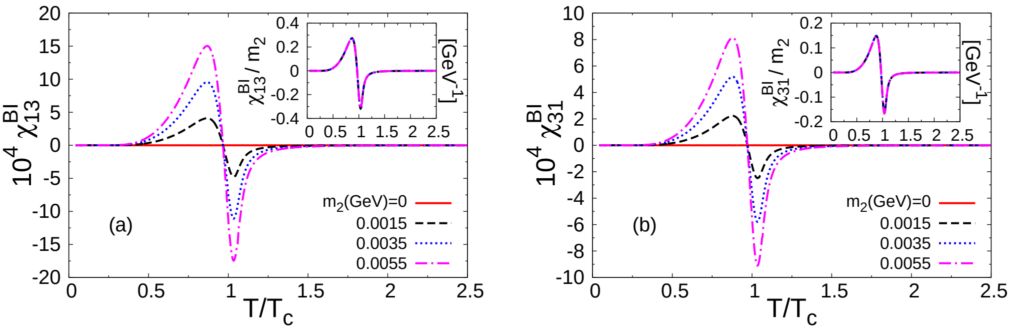

Figure 2: Behavior of 4th order off diagonal susceptibility for different m_2.

The fourth order off-diagonal susceptibilities in the $B-I$ sector are χ_{13}^{BI}, χ_{31}^{BI} and χ_{22}^{BI}. The m_2 dependence of χ_{22}^{BI} was found to be insignificant. For $\mu_B = 0$, the T dependence for the other two susceptibilities along with their m_2 scaling is shown in Fig.2.

We can express different $B-I$ correlators in terms of those in the flavor space. The flavor diagonal susceptibilities can be expanded in a Taylor series of the quark masses around $m_u = m_d = 0$. From this one is able to undestand the presence of m_2 scaling for some correlators. The detail analysis is shown in [9].

4. Off diagonal Susceptibilities for $\mu_B \neq 0$

Here we show the variation of χ_{11}^{BI} with μ_B for four different temperatures. The features vary widely over the different ranges of temperature and chemical potential. At $T \sim 2T_c$, χ_{11}^{BI} is positive, and slowly decreases with increasing μ_B. Close to T_c, χ_{11}^{BI} drops sharply to zero, becomes negative and then again slowly approaches zero. Going down somewhat below T_c there is an initial increase in χ_{11}^{BI} for some range of μ_B, and thereafter it follows the behavior at T_c. Finally at very low temperatures the change in sign of χ_{11}^{BI} is marked by a discontinuity, arising due to a first order phase boundary which exists in this range of T and μ_B.

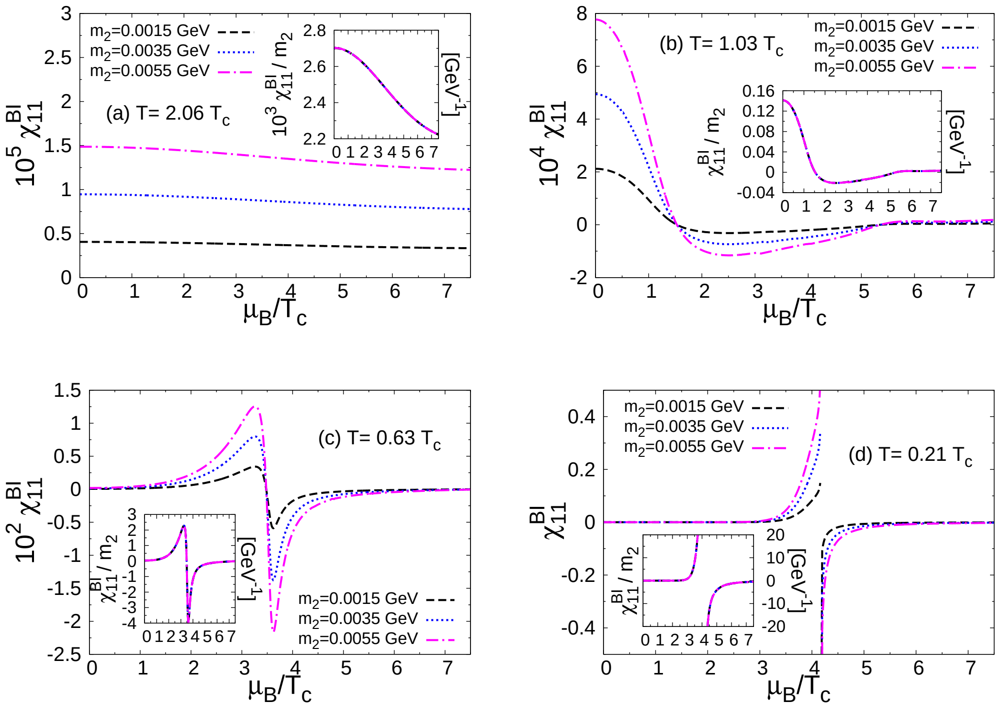

Figure 3: χ_{11}^{BI} along baryon chemical potential at different temperatures.

These various features can be understood by expressing $\chi_{11}^{BI} = \frac{\partial}{\partial \mu_B}(\frac{\partial P}{\partial \mu_I}) = (\frac{\partial n_I}{\partial \mu_B})$, where n_I is the isospin number density [9].

5. Further implications of ISB in Heavy Ion Collisions

Correlation between conserved charges, is an experimentally measurable quantity obtained from event-by-event analysis in heavy-ion collisions [10]. To compare with experiments it is often useful to consider ratios such as $\mathrm{R}_2 = \chi_{11}^{BI}/\chi_2^B = \mathrm{C}_{BI}/\mathrm{C}_{BB}$ [10, 11]. Here $\mathrm{C}_{XY} = \frac{1}{N_E}\sum_{i=1}^{N_E} X_i Y_i - (\frac{1}{N_E}\sum_{i=1}^{N_E} X_i)\cdot(\frac{1}{N_E}\sum_{i=1}^{N_E} Y_i)$, where N_E is the total number of events considered and X_i and Y_i are the event variables corresponding to the conserved charges in a given event i. Ratios of this kind are practically useful in eliminating uncertainties in the estimates of the measured volume of the fire-ball. The temperature variation of R_2 obtained here is shown in Fig.4. It decreases monotonically and approaches zero above T_c. This is expected as the baryon number fluctuation increases much more rapidly than the $B-I$ correlation below T_c, and thereafter χ_{11}^{BI} goes to zero while χ_2^B attains a non-zero value. The m_2 scaling that we observed for χ_{11}^{BI} or R_2 is most likely model independent as it is expected on very general grounds for small current quark masses as discussed above. Therefore, at any temperature and chemical potential, one can use the m_2 scaling to estimate the mass asymmetry of constituent fermions in a physical system as,

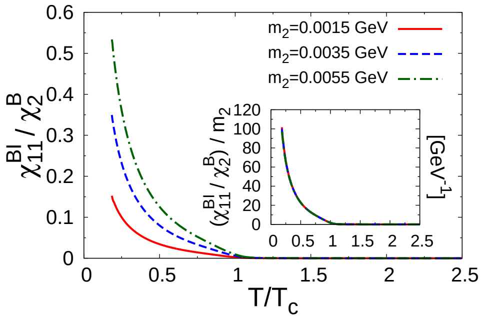

Figure 4: Ratio of B−I correlation to baryon number fluctuation at $\mu_B = 0$.

$$m_2{}^{\mathrm{expt}} = \frac{\mathrm{R}_2^{\mathrm{expt}}(T,\mu_B)}{\mathrm{R}_2^{\mathrm{th}}(T,\mu_B)} \times m_2{}^{\mathrm{th}} \tag{5.1}$$

where, ‘expt’ and ‘th’ denotes the experimentally measured and theoretically calculated values of the corresponding quantities respectively. To the best of our knowledge this is the first theoretical attempt which indicates that quark mass asymmetry in thermodynamic equilibrium can be directly measured from heavy-ion collision experiments.

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