The Problem of Mass: Mesonic Bound States Above T_c*

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By extending the Bielefeld LGS (Lattice Gauge Simulation) color singlet interaction, we find that the masses of π, σ, ρ and a_1 excitations, 32 degrees of freedom in all, go to zero (in the chiral limit) as $T \to T_c$. This result indicates a smooth phase transition at T_c, at which from above the masses and couplings of mesons vanish à la Brown-Rho scaling. We discuss that our scenario successfully explains the STAR (STAR Collaboration) ρ^0/π^- ratio in Au-Au peripheral collisions at RHIC.

1. Introduction

The problem of mass is one of the most fundamental in physics. We now have experimental evidence that meson masses decrease by $\sim 20\%$ as the density increases to nuclear matter density. This incipient decrease has been seen in the STAR data for the ρ-meson, at a low density $\sim 0.15 n_0$, where n_0 is nuclear matter density [1]. Data on in-medium ω photoproduction in Nb measured by the CBELSA/TAPS collaboration shows this mass to decrease roughly consistently with about 15% for nuclear matter density [2]. Such decrease in mass was predicted by Brown and Rho [3]. This is well and fine for finite density, although the experiments take us up to only $\sim n_0$. However, Harada and Yamawaki [4] carrying out a renormalization group calculation in their vector manifestation show that the vector mass goes to zero at a fixed point as the temperature goes up to T_c from below.

Now the question is what happens when one approaches T_c from above. The existence of mesonic bound states has been predicted by many authors [5–7]. In this work, we discuss the masses of color-singlet mesonic bound states above T_c [8] and their implications on STAR at RHIC [9].

2. Masses of Mesonic Bound States Above T_c

The Bielefeld group [10] have carried out lattice gauge calculations to obtain the heavy quark free energy for the region of temperatures above T_c. We analyzed their results for

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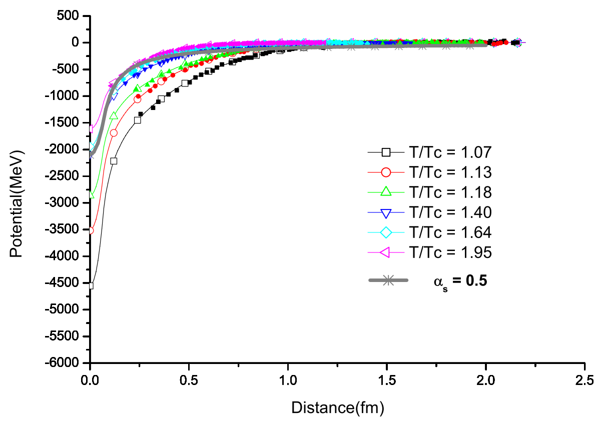

Figure 1. The potential extracted from Bielefeld lattice gauge simulation [11] (filled symbols) with $m_q = 1.4$ GeV. Thin solid lines are fitted curves and the thick solid line is for the color-Coulomb interaction with constant coupling $\alpha_s = 0.5$ [7].

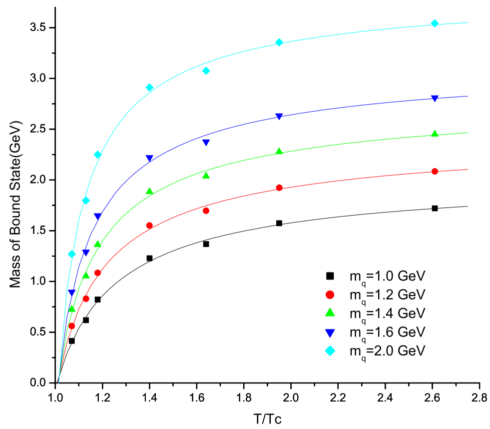

Figure 2. Mass of bound states of chirally restored SU(2) quarks and antiquarks. The fitting curves show that the mass of bound states approaches zero as T goes to T_c, independently of the thermal quark masses.

the color singlet (Coulomb) potentials [8]. The finite temperature analog of the static potential is not known and it is not clear whether at all it can be properly defined. Therefore we use the internal energy as potential in the Klein-Gordon equation. The color singlet internal energy can be derived from the free energy obtained in lattice gauge calculations:

$$V_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T} \tag{1}$$

Since we fitted the Bielefeld LGS data, final results are not sensitive to the choice of different parameterizations. In the above expression (Eq. (1)) we subtracted the value of the free energy at $r \to \infty$, namely $F_1(r = \infty, T)$. This is because we are only interested in the binding energy. The resulting potential is summarized in Fig. 1. As in Brown et al.[7], in order to enforce the asymptotic freedom at the origin, we used the molecular radius as $R \simeq \hbar/2m_q$. Inside the molecular radius we introduced the effective potential which is the same as the Coulomb potential for a uniform charge distribution [7].

Lattice calculations from the Bielefeld group [10] are the interactions between heavy quarks, so we need to add (model dependent) interactions so as to use them for the light quarks making up our mesons. Brown [12] showed that in a stationary state the E.M. interaction Hamiltonian between fermions is

$$H_{int} = \frac{e^2}{r}(1 - \vec{\alpha}_1 \cdot \vec{\alpha}_2), \tag{2}$$

where $\vec{\alpha}_{1,2}$ are velocity operators. This formula, suitably transcribed to QCD, is applicable to the system we are considering. In this paper we restrict our consideration to $T \sim T_c$. It will turn out that the mesons are essentially massless in this region. Since $\vec{\alpha}$ is essentially the helicity, we expect for the light quark potential to be

$$V_{\rm light}^{\rm eff}(T=T_c) \;=\; \begin{cases} 2V_{\rm heavy}^{\rm eff} & for \quad \vec{\alpha}_1\cdot\vec{\alpha}_2=-1 \\ 0 & for \quad \vec{\alpha}_1\cdot\vec{\alpha}_2=+1 \end{cases} \tag{3}$$

since helicity is either ± 1 near T_c.

The resulting masses of bound states are summarized in Fig. 2. As shown in the figure, the mass of bound states approaches zero as T goes to T_c, independently of the thermal quark masses. The factor of 2 introduced by the magnetic interactions is precisely the factor needed to make the (zero) masses of π and σ continuous across T_c, as dictated by chiral symmetry (since the pion mass is protected and the σ is degenerate with the pion at T_c).

3. Equilibrium Above T_c and STAR ρ^0/π^- Ratio

In a recent experiment, STAR [13] has reconstructed the ρ-mesons from the two-pion decay products in the Au + Au peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV. They find the ratio of

$$\frac{\rho^0}{\pi^-}|_{STAR} = 0.169 \pm 0.003({\rm stat}) \pm 0.037({\rm syst}), \tag{4}$$

almost as large as the $\rho^0/\pi^- = 0.183 \pm 0.001({\rm stat}) \pm 0.027({\rm syst})$ in proton-proton scattering. If one assumes equilibrium at the freezeout, then the ratio is expected to come to about $\frac{\rho^0}{\pi^-} \sim 4\times 10^{-4}$ [14].

In describing what happens as the system expands and the temperature cools from T_c down to T_{flash}, we choose the 32 degrees of freedom for the ρ, π, σ and a_1 in the $SU(4)$ multiplet (for up and down flavors) that come down from above T_c as described in [15,16]. These are the light degrees of freedom found in the quenched lattice calculation of Asakawa et al. [6] and used in [7]. We suggest that the entropy at T_c in lattice calculations correspond to that of massless bosons. Below T_c, the hadronic freedom is operative with the mesons nearly massless (due to the chiral symmetry restoration at T_c). Now in Harada-Yamawaki HLS/VM [4], near $T_c \approx 175$ MeV, the width drops rapidly as the mass drops:

$$\frac{\Gamma_\rho^\star}{\Gamma_\rho} \sim \left(\frac{m_\rho^\star}{m_\rho}\right)^3 \left(\frac{g^\star}{g}\right)^2 \Rightarrow \left(\frac{m_\rho^\star}{m_\rho}\right)^5 . \tag{5}$$

We assume that the effective gauge coupling in medium denoted g^* begins to scale only above $T_{flash} \approx T_{freezeout} \approx 120$ MeV in peripheral collisions when the soft glue has begun to melt. This is analogous to the behavior in density where it is empirically established that the scaling of g^*/g sets in only at $n \sim n_0$ [17]. With nearly zero couplings and masses, the particles stream freely without interaction until the vector mesons go about 90% on-shell at the flash temperature $T_{flash} \approx 120$ MeV at which the soft glues condensate and induce strong interactions triggering the decay into pions.

We find that in total 63 pions result at the end of the first generation from the 32 $SU(4)$ multiplet, i.e., ρ (18), a_1 (27), a_0 (4), π (3), σ (2) and $\epsilon \equiv f(1285)$ (12) where the number in the parenthesis is the number of pions emitted [9]. Excluded from the counting are the ω and η since they leave the system before decaying. Also left out are the three π^-'s coming from the ρ^0 decays which are reconstructed in the measurement. One-third of the pions counted will be π^-'s, so there will be 21 π^-'s. The original 3 ρ^0 can be reconstructed in the STAR projection chamber, so we find [9]

$$\frac{\rho^0}{\pi^-} \approx 3/21 \approx 0.14, \tag{6}$$

which is in good agreement with the observed value (4) considering that the standard scenario would be off by several orders of magnitude [14].

The factor of > 400 enhancement with respect to the equilibrium value can be understood as follows. Because of the decreased width due to the hadronic freedom, the ρ meson goes through *only one generation* before it freezes out in the peripheral collisions in STAR. But there is no equilibrium at the end of the first generation. Had the ρ possessed its on-shell mass and width with $\sim$ five generations as in the standard scenario, it is clear that the ρ^0/π^- ratio would be much closer to the equilibrium value.

4. Conclusions

By analyzing the Bielefeld lattice gauge results, we found that the masses of π and σ approaches zero at T_c from above, the resulting zero masses are continuous across T_c, as dictated by chiral symmetry (since the pion mass is protected and the σ is degenerate with the pion at T_c). We also show that the surprisingly large STAR ratio can be simply understood in terms of the (massless) hadronic degrees of freedom above T_c.

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