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Publication Date
2005-10-07

Baryon-strangeness correlations: a diagnostic of strongly interacting matter

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The correlation between baryon number and strangeness elucidates the nature of strongly interacting matter. This diagnostic can be extracted theoretically from lattice QCD calculations and experimentally from event-by-event fluctuations. The analysis of present lattice results above the critical temperature severely limits the presence of $q\bar{q}$ bound states, thus supporting a picture of independent (quasi)quarks. Details may be found in [1].

1. Introduction

Recent experimental findings at RHIC as well as new results from lattice QCD have sparked an intense discussion about the nature of strongly interacting matter right above T_c. In particular the original idea of a QGP as a plasma of weakly interacting quarks and gluons has been challenged. For one, the high-T behavior of the lattice equation of state falls somewhat below that of an ideal gas of massless quarks and gluons [2], indicating that the chromodynamic plasma has a more complex structure. Furthermore, lattice QCD calculations on spectral functions [3,4] suggest the presence of bound, color-neutral states well above T_c. This has led to the suggestion that at moderate temperatures, $T \simeq 1-2\,T_c$, the system is composed of medium-modified (massive) quarks and gluons together with their (many and possibly colored) bound states [5,6].

In this contribution we want to discuss a novel diagnostic tool [1] for eluciding this issue by probing the relevant degrees of freedom and their correlations.

2. Correlation between Baryon Number and Strangeness

Let us start our argument with a simple observation: Assume that the basic degrees of freedom are weakly interacting quarks and gluons. Then strangeness is carried exclusively by the s and $\bar{s}$ quarks which in turn carry baryon number in strict proportion to their strangeness, $B_s = -\frac{1}{3}S_s$, thus rendering strangeness and baryon number strongly correlated. This feature is in stark contrast to a hadron gas. For example, at small baryon chemical potential the strangeness is carried primarily by kaons, which have no baryon number.

Let us introduce the following correlation coefficient,

$$C_{BS} \equiv -3\frac{\sigma_{BS}}{\sigma_S^2} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2} = -3\frac{\langle BS\rangle}{\langle S^2\rangle}. \tag{1}$$

which is unity for a simple QGP, or more generally, for a system where the quark flavors are uncorrelated.

In a gas of uncorrelated hadron resonances, we have

$$C_{BS} \approx 3\frac{\langle\Lambda\rangle + \langle\bar{\Lambda}\rangle + \ldots + 3\langle\Omega^-\rangle + 3\langle\bar{\Omega}^+\rangle}{\langle K^0\rangle + \langle\bar{K}^0\rangle + \ldots + 9\langle\Omega^-\rangle + 9\langle\bar{\Omega}^+\rangle}, \tag{2}$$

and the numerator receives contributions from only (strange) baryons, while the denominator receives contributions also from (strange) mesons. As a result, $C_{BS} = 0.66$ for $T = 170$ MeV and $\mu_B = 0$. On the other hand, at very high μ_B and low T, where strangeness is carried exclusively by Lambdas and Kaons, $C_{BS} \approx \frac{3}{2}$. This significant dependence of C_{BS} on the hadronic environment is in sharp contrast to the simple quark-gluon plasma where the correlation coefficient remains strictly unity at all temperatures and chemical potentials.

The correlation coefficient C_{BS} can be expressed in terms of basic quark-flavor susceptibilities

$$\chi_{ff'} = -\frac{1}{V}\frac{\partial^2 F}{\partial\mu_f\partial\mu'_f}, \quad C_{BS} = 1 + \frac{\chi_{ds} + \chi_{us}}{\chi_{ss}} \tag{3}$$

and thus is calculable in lattice QCD. As is evident from the above expression, the deviation of C_{BS} from unity is controlled by the ratio of flavor-off-diagonal over flavor-diagonal susceptibilities. Or in other words, this ratio measures the strength of flavor correlations. For the specific case of light-strange susceptibilities, the values $\chi_{ff'}$ extracted at $T = 1.5\,T_c$ by Gavai *et al.* [8], we obtain $(\chi_{us} + \chi_{ds})/\chi_{ss} = 0.00(3)/0.53(1) \ll 1$, and thus $C_{BS} \approx 1$, suggesting that the quark flavors are uncorrelated. Unfortunately, at present no results at lower temperatures for 2+1 flavor QCD are available. But since the relevant quantity is the ratio of flavor-off-diagonal over flavor-diagonal susceptibilities, similar arguments can be made in the light-quark sector only, where the necessary susceptibilities have been calculated over a wide range of temperature [7]. The relevant ratio $-2\chi_{ud}/\chi_{uu}$ is shown in Fig. 1. While the ratio is finite below T_c, consistent with the presence of correlations in a hadron gas, it drops rapidly around T_c and is consistent with zero above $T \geq 1.1T_c$ indicating that the up and down flavors are uncorrelated above this temperature.

We note that the vanishing of the off-diagonal susceptibilities, and hence the unit value of C_{BS}, does not conflict with the existence of hadron-like resonances that have been identified well above T_c [3,4], since their large masses (of more than 2 GeV) make them insignificant near T_c. Furthermore it is important to recognize that the calculated equation of state [2] indicate that the system cannot be merely an assembly of weakly interacting elementary quarks and gluons. However, the various apparently conflicting features might be reconciled if the system were to organize itself into an assembly of weakly interacting quasi-particles, such as the picture emerging from QCD by the application of re-summation techniques [9].

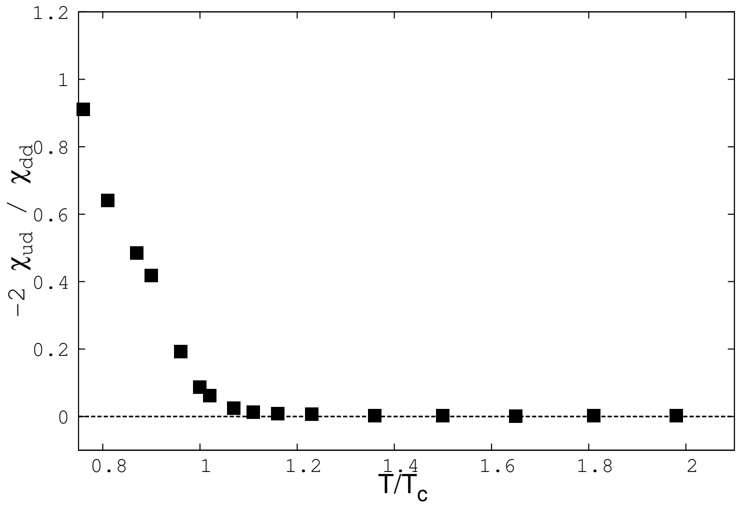

Figure 1. Ratio of off-diagonal to diagonal susceptibility as a function of temperature in 2-flavor unquenched Lattice QCD

Recently there has appeared an interesting model [5] that describes the chromodynamic system as a gas of massive quarks, anti-quarks, and gluons together with a myriad of their bound states generated by a screened Coulomb potential. In order to assess the consistency of this model with present lattice results, we estimate the ratio C_{BS} in such a scenario. Using the masses and degeneracies of the various states as given in Ref. [5] we find $C_{BS} \approx 0.62$ at $T = 1.5T_c$, which is significantly below the value of $C_{BS} \approx 1$ obtained from lattice QCD. Essential for the deviation is the presence of $q\bar{q}$-bound states in the model, which, like the mesons in the hadron gas, contribute to the denominator but not the numerator of C_{BS}. Note, that if there were as many di-quark states as quark-antiquark states, then $C_{BS} = 1$. However, this is unlikely due to the structure of the color-coulomb interaction, which favors $\bar{q} - q$ states. Also, higher order susceptibilities appear to be inconsistent with the presence of di-quark states [10,11]. In the meantime other ideas such as polymers have surfaced, which would bring the above model closer to the lattice results [12,13]. To which extend these new ideas are consistent with other correlations obtained from the lattice remains to be seen.

In principle, the correlation coefficient C_{BS} is measurable in experiment via event-by-event fluctuations [14], by evaluating

$$C_{BS} \;=\; -3\frac{\frac{1}{N}\sum_n B^{(n)}S^{(n)} - \left(\frac{1}{N}\sum_n B^{(n)}\right)\left(\frac{1}{N}\sum_n S^{(n)}\right)}{\frac{1}{N}\sum_n (S^{(n)})^2 - \left(\frac{1}{N}\sum_n S^{(n)}\right)^2}\ , \tag{4}$$

where $B^{(n)}$ and $S^{(n)}$ denote the baryon number and strangeness observed for a given event n within a central rapidity interval, $|y| < y_{\max}$. Note that this expression takes all possible correlations among the final-state hadrons into account and thus differs from the simplified form 2, which is valid for an uncorrelated hadron gas only. Since both baryon number and strangeness are conserved quantities, their correlations and fluctuations should be preserved during the expansion [15]. However, the measurement of C_{BS} requires the detection of neutrons as well as corrections for weak decays on an event-by-event basis.

3. Conclusions

We have proposed the correlation coefficient $C_{BS} = -3\sigma_{BS}/\sigma_S^2$ as a useful diagnostic tool for elucidating the character of chromodynamic matter. If baryon number and strangeness are carried by effectively independent quarks and antiquarks, then this ratio is unity for any value of the energy and baryon-number density. By contrast, it exhibits a significant dependence on the baryon density in a hadron gas and is about $\frac{2}{3}$ at RHIC. The value for C_{BS} obtained from (quenched) lattice QCD calculations are close to unity, consistent with independent quarks. The recently proposed "bound-state quark-gluon plasma", on the other hand, yields significantly lower values.

This work was supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, and by the Office of Basic Energy Sciences, Division of Nuclear Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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