Strangeness at High Temperatures: From Hadrons to Quarks

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(Received 3 May 2013; revised manuscript received 2 August 2013; published 23 August 2013)

Appropriate combinations of up to fourth order cumulants of net strangeness fluctuations and their correlations with net baryon number and electric charge fluctuations, obtained from lattice QCD calculations, have been used to probe the strangeness carrying degrees of freedom at high temperatures. For temperatures up to the chiral crossover, separate contributions of strange mesons and baryons can be well described by an uncorrelated gas of hadrons. Such a description breaks down in the chiral crossover region, suggesting that the deconfinement of strangeness takes place at the chiral crossover. On the other hand, the strangeness carrying degrees of freedom inside the quark gluon plasma can be described by a weakly interacting gas of quarks only for temperatures larger than twice the chiral crossover temperature. In the intermediate temperature window, these observables show considerably richer structures, indicative of the strongly interacting nature of the quark gluon plasma.

DOI: 10.1103/PhysRevLett.111.082301 PACS numbers: 11.10.Wx, 11.15.Ha, 12.38.Aw, 25.75.Nq

Introduction.—Strangeness has played a crucial role [1] in the experimental and theoretical investigations of the deconfined phase, namely, the quark gluon plasma (QGP) phase, of quantum chromodynamics (QCD) at high temperatures. Experimental results from the Relativistic Heavy Ion Collider and the Large Hadron Collider suggest that the QGP has been created during the highly energetic collisions of heavy nuclei [2]. Experimental results showing enhanced production and large collective flow of strange hadrons [3] strongly indicate that deconfined strange quarks existed inside the QGP, despite the absence of real strange quarks within the initially colliding nuclei. However, theoretical understanding of the deconfinement of strangeness remains unclear. *A priori*, it is not unreasonable to expect that the heavier strange quark may not be largely influenced by the chiral symmetry of QCD and the deconfinement of the strange quarks may not take place at the chiral crossover temperature (T_c). Based on the observations that, compared to the light up and down quarks, the net strange quark number fluctuations [4,5] show a much smoother behavior across the chiral crossover region, it has been suggested [6] that the deconfinement crossover for the strange quarks may take place at a temperature larger than T_c. Consequently, strange hadronic bound states may exist inside the QGP for temperatures $T \gtrsim T_c$ [7].

Moreover, the nature of the deconfined QGP for moderately high temperatures also remains elusive. An intriguing open question is whether in this temperature regime the QGP is a strongly coupled medium lacking a quasiparticle description [2] or consists of other degrees of freedom such as colored bound states [8] or massive colored quasiparticles [9]. Knowledge regarding the behavior of strangeness carrying degrees of freedom (sDoF) in the QGP is essential to answering this question.

It is well known [10,11] that the quantum numbers, such as the baryon number (B), electric charge (Q), and strangeness (S), can be probed using the fluctuations and correlations of these quantities. We construct observables from combinations of up to fourth order cumulants of net strangeness fluctuations and their correlations with net baryon number and electric charge fluctuations that probe the sDoF in different temperature regimes. We calculate these observables using state-of-the-art lattice QCD (LQCD) simulations and compare our results with the hadron gas description at lower temperatures and with the weakly interacting quark gas description at higher temperatures.

Strangeness in a gas of uncorrelated hadrons.—For an uncorrelated gas of hadrons, e.g., the hadron resonance gas (HRG) model [12], the dimensionless partial pressure $P_S \equiv (p - p_{S=0})/T^4$ of all the strange hadrons is given by

$$\begin{aligned} P_S^{\mathrm{HRG}}(\hat{\mu}_B, \hat{\mu}_S) = {} & P^{\mathrm{HRG}}_{|S|=1,M} \cosh(\hat{\mu}_S) \\ & + P^{\mathrm{HRG}}_{|S|=1,B} \cosh(\hat{\mu}_B - \hat{\mu}_S) \\ & + P^{\mathrm{HRG}}_{|S|=2,B} \cosh(\hat{\mu}_B - 2\hat{\mu}_S) \\ & + P^{\mathrm{HRG}}_{|S|=3,B} \cosh(\hat{\mu}_B - 3\hat{\mu}_S), \end{aligned} \tag{1}$$

within the classical Boltzmann approximation. In the temperature range 130 MeV $\lesssim T \lesssim$ 200 MeV relevant for our discussion, the Boltzmann approximation gives at most 3% corrections to the full HRG model results for all the susceptibilities involving strangeness considered here and hence is well justified. Here, $\hat{\mu}_{B/S} = \mu_{B/S}/T$ are the

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dimensionless baryon and strangeness chemical potentials. $P^{\rm HRG}_{|S|=1,M}$ is the partial pressure of all $|S|=1$ mesons and $P^{\rm HRG}_{|S|=i,B}$ are the partial pressures of all $|S|=i$ ($i=1,2,3$) baryons, for $\mu_B=\mu_S=0$. For simplicity, we have set the electric charge chemical potential $\hat{\mu}_Q=0$.

To investigate the sDoF, we will use the dimensionless generalized susceptibilities of the conserved charges

$$\chi^{XY}_{mn}=\frac{\partial^{(m+n)}[p(\hat{\mu}_X,\hat{\mu}_Y)/T^4]}{\partial\hat{\mu}^m_X\partial\hat{\mu}^n_Y}\Bigg|_{\vec{\mu}=0}, \quad (2)$$

where $X,Y=B,S,Q$ and $\vec{\mu}=(\mu_B,\mu_S,\mu_Q)$. We also use the notations $\chi^{XY}_{0n}\equiv\chi^Y_n$ and $\chi^{XY}_{m0}\equiv\chi^X_m$.

Using the two strangeness fluctuations (χ^S_2, χ^S_4) and the four baryon-strangeness correlations ($\chi^{\rm BS}_{11}$, $\chi^{\rm BS}_{13}$, $\chi^{\rm BS}_{22}$, $\chi^{\rm BS}_{31}$) up to fourth order, we have a set of six susceptibilities that can be used to construct observables that project onto the four different partial pressures in an uncorrelated hadrons gas introduced in Eq. (1):

$$M(c_1,c_2)=\chi^S_2-\chi^{\rm BS}_{22}+c_1v_1+c_2v_2, \quad (3)$$

$$B_1(c_1,c_2)=\tfrac{1}{2}(\chi^S_4-\chi^S_2+5\chi^{\rm BS}_{13}+7\chi^{\rm BS}_{22})+c_1v_1+c_2v_2, \quad (4)$$

$$B_2(c_1,c_2)=-\tfrac{1}{4}(\chi^S_4-\chi^S_2+4\chi^{\rm BS}_{13}+4\chi^{\rm BS}_{22}) + c_1v_1+c_2v_2, \quad (5)$$

$$B_3(c_1,c_2)=\tfrac{1}{18}(\chi^S_4-\chi^S_2+3\chi^{\rm BS}_{13}+3\chi^{\rm BS}_{22}) + c_1v_1+c_2v_2. \quad (6)$$

The combination $c_1v_1+c_2v_2$ spans a two-dimensional plane in the six-dimensional space of susceptibilities on which the partial pressure $P^{\rm HRG}_S$ vanishes identically when the sDoF are described by a gas of uncorrelated hadrons, irrespective of their masses. The two additional free parameters c_1 and c_2 can thus be used to construct observables that have an identical interpretation in the uncorrelated hadron gas but differ under other circumstances, for instance, in a medium where the sDoF are carried by quark-like quasiparticles. For v_1 and v_2, we choose the following combinations:

$$v_1=\chi^{\rm BS}_{31}-\chi^{\rm BS}_{11}, \quad (7)$$

$$v_2=\tfrac{1}{3}(\chi^S_2-\chi^S_4)-2\chi^{\rm BS}_{13}-4\chi^{\rm BS}_{22}-2\chi^{\rm BS}_{31}. \quad (8)$$

Since in a hadron gas the baryonic sDoF are associated with $|B|=1$, the baryon-strangeness correlations differing by even numbers of μ_B derivatives are identical, giving $v_1=0$. v_2 can be rewritten as the difference of two operators [13], each of which corresponds to the partial pressure of all strange hadrons in an uncorrelated hadron gas, leading to $v_2=0$. Thus, for a classical uncorrelated hadron gas such as the HRG model, $M(c_1,c_2)\to P^{\rm HRG}_{|S|=1,M}$ and $B_i(c_1,c_2)\to P^{\rm HRG}_{|S|=i,B}$ ($i=1,2,3$), independent of the values of c_1 and c_2. For asymptotically high temperatures, i.e., when the sDoF are noninteracting massless quarks, these observables will generically attain different values for different combinations of (c_1, c_2).

Strangeness near the chiral crossover.—Here, we investigate to what extent sDoF are described by an uncorrelated hadron gas in the vicinity of the chiral crossover temperature $T_c=154(9)$ MeV [14]. The LQCD results for the susceptibilities were obtained for two different lattice spacings (a) corresponding to temporal extents $N_\tau=1/aT=6$ and 8 using $\mathcal{O}(a^2)$ improved gauge and highly improved staggered quark [15] discretization schemes for $(2+1)$ flavor QCD. The up and down quark masses correspond to a Goldstone pion mass of 160 MeV, and the strange quark mass is tuned to its physical value. The susceptibilities were measured on 3000–8000 gauge field configurations, each separated by 10 molecular dynamics trajectories, using 1500 Gaussian random source vectors for each configuration. Further details of the LQCD computations can be found in Refs. [5,14]. Although the LQCD results presented here are not obtained in the limit of zero lattice spacing, the effects of continuum extrapolations are known to be quite small for our particular lattice discretization scheme, especially in the strangeness sector [5]. This will also be substantiated by the very mild lattice spacing dependence of our results going from the $N_\tau=6$ to the $N_\tau=8$ lattices. Thus, we expect that the continuum extrapolated results will not alter the physical picture presented in this Letter.

In Fig. 1, we show the LQCD results for the two combinations v_1 and v_2, defined in Eqs. (7) and (8), that vanish identically in an uncorrelated hadron gas. The LQCD data for these two quantities are consistent with zero up to T_c and show rapid increase towards their noninteracting massless quark gas values above the T_c region. In Fig. 1, we also show the difference between the quadratic (χ^B_2) and the quartic (χ^B_4) baryon number fluctuations that also receive contributions from the light up and down quarks. In an uncorrelated gas of baryons, the difference $\chi^B_2-\chi^B_4$ also vanishes identically, owing to the fact that all baryon number carrying degrees of freedom are associated with $|B|=1$. The LQCD results for this quantity are also consistent with such a hadronic description up to T_c, showing rapid departures above the T_c region. All these results indicate that until the chiral crossover, the sDoF are in accord with that of the uncorrelated gas of hadrons, and such a description breaks down within the chiral crossover region. Since v_1 is the analog of $\chi^B_2-\chi^B_4$ in the strange baryon sector, the fact that both quantities have similar temperature dependence shows that the behavior of the sDoF around the chiral crossover region is rather akin to the behavior of degrees of freedom involving the light quarks. Note that the vanishing values of these observables at low temperatures are independent of the mass spectrum of the hadrons, as long as they are uncorrelated and the

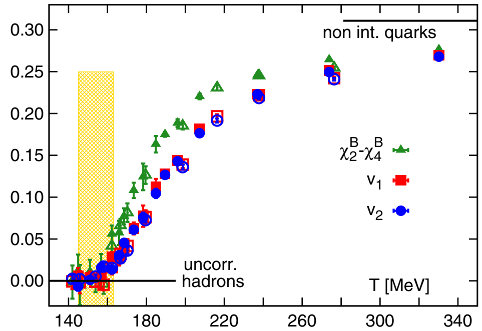

FIG. 1 (color online). Two combinations v_1 and v_2 [see Eqs. (7) and (8)] of strangeness fluctuations and baryon-strangeness correlations that vanish identically if the sDoF are described by an uncorrelated gas of hadrons. Also shown is the difference of quadratic and quartic baryon number fluctuations $\chi_2^B - \chi_4^B$. This observable also vanishes identically when the baryon number carrying degrees of freedom are described by an uncorrelated gas of strange as well as nonstrange baryons. The shaded region indicates the chiral crossover temperature $T_c = 154(9)$ MeV [14]. The lines at low and high temperatures indicate the two limiting scenarios when the DoF are described by an uncorrelated hadron gas and a noninteracting massless quark gas, respectively. The LQCD results for the $N_\tau = 6$ and 8 lattices are shown by the open and filled symbols, respectively.

Boltzmann approximation is well suited. It reflects that the relevant degrees of freedom carry integer strangeness $|S| = 0, 1, 2, 3$ and integer baryon number $|B| = 0, 1$.

In Fig. 2, we study the partial pressures of the strange hadrons using the LQCD results for the four combinations $M(c_1, c_2)$, $B_1(c_1, c_2)$, $B_2(c_1, c_2)$, and $B_3(c_1, c_2)$ [see Eqs. (3)–(6)], each for three sets of (c_1, c_2). One of the combinations corresponds to $c_1 = c_2 = 0$ and thus represents the basic projection onto a given strangeness sector in an uncorrelated hadron gas. The other two parameter sets for (c_1, c_2) are chosen to produce widely different values for these observables in a noninteracting massless quark gas at asymptotically high temperatures. From Fig. 1, it is obvious that they are identical at low temperatures. Up to T_c, independent of (c_1, c_2), these four quantities individually agree with the partial pressures of the $|S| = 1$ mesons and the $|S| = 1, 2, 3$ baryons when one uses the actual vacuum mass spectrum of the strange hadrons in an uncorrelated hadron gas. Specifically, $M(c_1, c_2)$, $B_1(c_1, c_2)$, $B_2(c_1, c_2)$, and $B_3(c_1, c_2)$ reproduce the HRG model results for $P^{\rm HRG}_{|S|=1,M}$, $P^{\rm HRG}_{|S|=1,B}$, $P^{\rm HRG}_{|S|=2,B}$, and $P^{\rm HRG}_{|S|=3,B}$, respectively [16]. As can be seen from the insets of Fig. 2, such a description of the LQCD results breaks down within the T_c region for each of the meson and baryon sectors. Above T_c, all these quantities show a smooth approach towards their respective noninteracting, massless quark gas values, depending on the values of c_1 and c_2.

Strangeness in the quark gluon plasma.—To investigate whether the sDoF in the QGP can be described by weakly interacting quasiquarks, we study correlations of net strangeness fluctuations with fluctuations of net baryon number and electric charge. Such observables were studied in Refs. [10,18] for the second order correlations. We extend these correlations up to the fourth order. If the sDoF are weakly or noninteracting quasiquarks, then strangeness $S = -1$ is associated with the fractional baryon number $B = 1/3$ and electric charge $Q = -1/3$, giving

$$\frac{\chi_{mn}^{\rm BS}}{\chi_{m+n}^{S}} = \frac{(-1)^n}{3^m} \quad \text{and} \quad \frac{\chi_{mn}^{\rm QS}}{\chi_{m+n}^{S}} = \frac{(-1)^{m+n}}{3^m}, \tag{9}$$

where $m, n > 0$ and $m + n = 2, 4$.

In Fig. 3, we show the LQCD results for these ratios scaled by the proper powers of fractional baryonic and

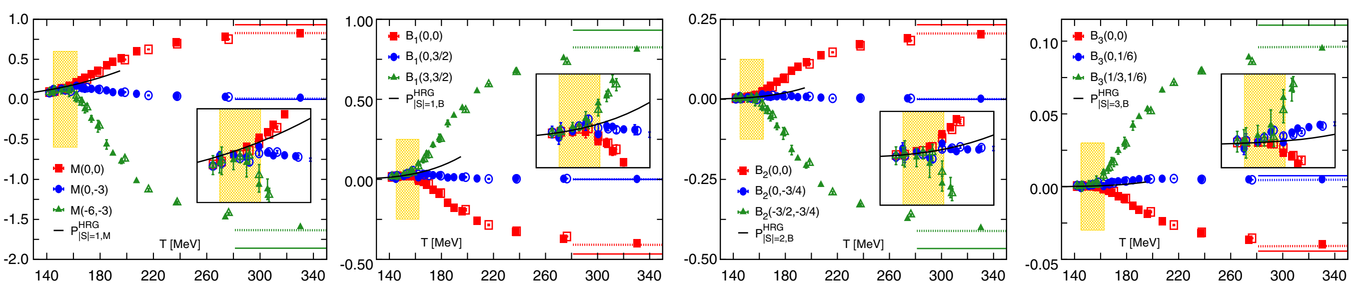

FIG. 2 (color online). Four combinations [see Eqs. (3)–(6)] of net strangeness fluctuations and baryon-strangeness correlations $M(c_1, c_2)$, $B_1(c_1, c_2)$, $B_2(c_1, c_2)$, and $B_3(c_1, c_2)$ (from left to right), each for three different sets of (c_1, c_2). Up to the chiral crossover temperature $T_c = 154(9)$ MeV [14] (shown by the shaded regions), independent of (c_1, c_2), these combinations give the partial pressures of $|S| = 1$ mesons ($P^{\rm HRG}_{|S|=1,M}$) and $|S| = 1, 2, 3$ baryons ($P^{\rm HRG}_{|S|=1,B}$, $P^{\rm HRG}_{|S|=2,B}$, $P^{\rm HRG}_{|S|=3,B}$) in an uncorrelated gas of hadrons having masses equal to their vacuum masses, i.e., in the HRG model (indicated by the solid lines at low temperatures). Above the T_c region, such a hadronic description breaks down (shown in the insets) and all the combinations smoothly approach towards their respective, (c_1, c_2)-dependent, high temperature limits (indicated by the solid horizontal lines at high temperatures) described by the noninteracting massless strange quarks. The dotted horizontal lines at high temperatures depict the perturbative estimates (see the text) for all these observables obtained using one-loop resummed HTL calculations [19]. The LQCD results for the $N_\tau = 6$ and 8 lattices are shown by the open and filled symbols, respectively.

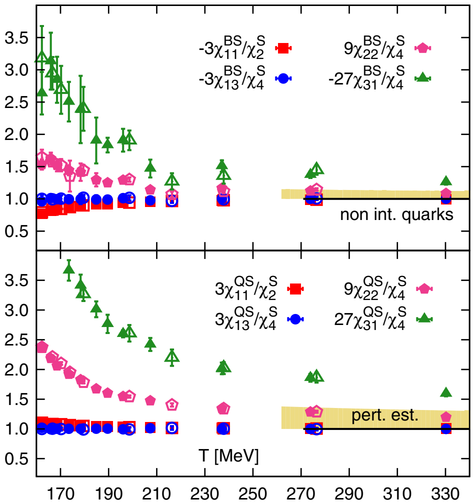

FIG. 3 (color online). Baryon-strangeness (top) and electric charge-strangeness correlations (bottom), properly scaled by the strangeness fluctuations and powers of the fractional baryonic and electric charges [see Eq. (9)]. In the noninteracting massless quark gas, all these observables are unity (shown by the lines at high temperatures). The shaded regions indicate the range of perturbative estimates (see the text) for all these observables obtained using one-loop resummed HTL calculations [19]. The LQCD results for the $N_\tau = 6$ and 8 lattices are shown by the open and filled symbols, respectively.

electric charges. The shaded regions at high temperatures indicate the ranges of values for these ratios as predicted for the weakly interacting quasiquarks from the resummed hard thermal loop (HTL) perturbation theory at the one-loop order [19], using one-loop running coupling obtained at the scales between πT and $4\pi T$. The ratios of the second order correlations χ_{11}^{BS}/χ_2^S and χ_{11}^{QS}/χ_2^S are much closer to those expected for weakly interacting quasiquarks, differing only at a few percent level for $T \sim 1.25T_c$. Previous LQCD studies [4,5,20] also showed similar results, suggesting that sDoF in the QGP can be described by weakly interacting quasiquarks even down to temperatures very close to T_c. However, our results involving correlations of strangeness with higher powers of baryon number and electric charge clearly indicate that such a description in terms of weakly interacting quasiquarks can only be valid for temperatures $T \gtrsim 2T_c$. While the HTL perturbative expansion for ratios involving one derivative of the baryonic or electric charges (i.e., χ_{11}^{XS}/χ_2^S and χ_{13}^{XS}/χ_4^S, $X = B, Q$) starts differing from the noninteracting quark gas limit at $\mathcal{O}(\alpha_s^3 \ln\alpha_s)$ [21], the same happens for those involving higher derivatives of the baryonic or electric charges (i.e., χ_{22}^{XS}/χ_4^S and χ_{31}^{XS}/χ_4^S, $X = B, Q$) starts at $\mathcal{O}(\alpha_s^{3/2})$ [19], α_s being the strong coupling constant. Thus, the enhancement of the higher order electric charge- or baryon-strangeness correlations is probably expected within the regime of validity of the weak coupling expansion. Apart from the charge- or baryon-strangeness correlations presented here, at the fourth order, there are three more susceptibilities involving derivatives with respect to all B, Q, and S, namely, χ_{ijk}^{BQS} with $i, j, k > 0$ and $i + j + k = 4$. These baryon-charge-strangeness correlations can also be used in a similar manner to simultaneously probe both B and Q associated with the sDoF. We have studied these quantities, too, and arrived at the same conclusion regarding the validity of the weakly interacting quark gas picture at high temperatures. Also note that the high temperature behavior of the quantities depicted in Fig. 2 reaffirms our conclusion that the weakly interacting quark gas picture can only be valid for $T \gtrsim 2T_c$. For temperatures beyond the validity of the weak coupling expansion, it would be interesting to see whether such enhancements indicate a strongly coupled QGP [22] without quasiparticles or signal the presence of colored bound states [8] and/or density-dependent massive quasiparticles [23].

Conclusions.—The LQCD results presented in this Letter show that until the chiral crossover temperature T_c, the quantum numbers associated with the sDoF are consistent with those of an uncorrelated gas of hadrons. Furthermore, up to T_c, the partial pressures of the strange mesons and baryons are separately in agreement with those obtained from the uncorrelated hadron gas using vacuum masses of the strange hadrons. Such a hadronic description of the sDoF breaks down in the chiral crossover region. Moreover, the behavior of the sDoF around T_c is quite similar to that involving the light up and down quarks. Altogether, these results suggest that the deconfinement of strangeness seemingly takes place at the chiral crossover temperature. On the other hand, our LQCD results involving correlations of strangeness with higher powers of baryonic and electric charges for $T > T_c$ provide unambiguous evidence that the sDoF in the QGP can become compatible with the weakly interacting quark gas only for $T \gtrsim 2T_c$. For the intermediate temperatures $T_c \lesssim T \lesssim 2T_c$, strangeness is nontrivially correlated with the baryonic and electric charges, indicating that the QGP in this temperature regime remains strongly interacting.

This work has been supported in part through Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy, through the Scientific Discovery through Advanced Computing (SciDAC) Program funded by the U.S. Department of Energy, Office of Science, Advanced Scientific Computing Research and Nuclear Physics, the BMBF under Grant No. 05P12PBCTA, the DFG under Grant No. GRK 881, the EU under Grant No. 283286, and the GSI BILAER Grant. Numerical calculations have been performed using the USQCD GPU Clusters at JLab, the Bielefeld GPU Cluster, and the NYBlue at the NYCCS. We also thank Nvidia for supporting the code development for the Bielefeld GPU Cluster.

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