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Criticality of the net-baryon number probability distribution at finite density

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ABSTRACT

We compute the probability distribution $P(N)$ of the net-baryon number at finite temperature and quark-chemical potential, μ, at a physical value of the pion mass in the quark-meson model within the functional renormalization group scheme. For $\mu/T < 1$, the model exhibits the chiral crossover transition which belongs to the universality class of the $O(4)$ spin system in three dimensions. We explore the influence of the chiral crossover transition on the properties of the net baryon number probability distribution, $P(N)$. By considering ratios of $P(N)$ to the Skellam function, with the same mean and variance, we unravel the characteristic features of the distribution that are related to $O(4)$ criticality at the chiral crossover transition. We explore the corresponding ratios for data obtained at RHIC by the STAR Collaboration and discuss their implications. We also examine $O(4)$ criticality in the context of binomial and negative-binomial distributions for the net proton number.

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1. Introduction

Fluctuations of conserved charges are promising observables for exploring critical phenomena in relativistic heavy ion collisions [1–4]. A particular role is attributed to higher order cumulants of the net baryon number and electric charge fluctuations, which in a QCD medium can be negative near the chiral transition [5–7].

At physical values of quark masses, the phase transition in QCD is expected to change from a crossover transition at small values of the baryon chemical potential to a first-order transition at large net baryon densities. The first-order chiral phase transition, if it exists, then begins in a second-order critical point, the critical end point (CEP) [8]. Owing to the divergent correlation length at the CEP [7], and the spinodal phase separation in a non-equilibrium first-order transition [9], one expects large fluctuations of the net-baryon number in heavy ion collisions, at beam energies where the system passes through the first-order phase boundary or close to the CEP.

The conjectured existence of a CEP in the QCD phase diagram has so far not been confirmed by lattice QCD calculations (LQCD) [10,11]. At small values of the quark chemical potential, $\mu_q/T < 1$, LQCD exhibits a chiral crossover transition. There are indications that, in the chiral limit for light quarks, the QCD transition belongs to the universality class of 3-dimensional $O(4)$ spin systems [12,13]. Thus, a promising approach for probing the phase boundary in heavy ion collisions, is to explore the fluctuations of the chiral phase transition, assuming $O(4)$ criticality. Owing to the proximity of the chemical freeze-out to the chiral crossover at small values of the baryonic chemical potential, one may expect that the critical fluctuations are reflected in the data on conserved charges [14]. A baseline for the cumulants of charge fluctuations is provided by the hadron resonance gas (HRG) model, which reproduces the particle yields at chemical freeze-out in heavy ion collisions [15], as well as the LQCD equation of state in the hadronic phase [16,17].

At the CEP, which is expected to belong to 3d $Z(2)$ universality class, the second and higher order cumulants diverge. By contrast, at a chiral phase transition belonging to the $O(4)$ universality

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class, at vanishing baryon chemical potential, low-order cumulants remain finite, while the sixth and higher order cumulants diverge.[1] For non-zero quark masses, the divergences are replaced by a rapid variation of the cumulants near the crossover temperature, including changes of sign [18].

The fluctuations of the net-baryon number, more precisely of the net-proton number, were measured in heavy ion collisions by STAR Collaboration at RHIC [19–22]. Data on the mean (M), variance (σ), skewness (S) and kurtosis (κ) of the net-proton number were obtained in a broad energy range and for different centralities. These observables are linked to the cumulants χ_n of the net-baryon number, and are accordingly modified by the critical chiral dynamics.

The most recent STAR data show that, while the ratio $\sigma^2/M = \chi_2/\chi_1$ is consistent with the HRG result in central collisions, differences are found in the products $S\sigma = \chi_3/\chi_1$ and $\kappa\sigma^2 = \chi_4/\chi_2$. The deviations in the latter are small at the top RHIC energy, increase with the order of the cumulants at fixed collision energy, and show a non-monotonic dependence on the energy with a maximum at $\sqrt{s_{NN}} \simeq 19$ GeV. In the $O(4)$ universality class one expects[2] $\chi_4/\chi_2 < 1$, while in $Z(2)$ this ratio is expected to be larger than unity [23]. Thus, the systematics of the ratios of cumulants in central Au–Au collisions, as measured by STAR [22], indicate that the observed deviations of the net proton number fluctuations from the HRG values may be attributed to $O(4)$ criticality at the phase boundary, at least for $\sqrt{s_{NN}} \geq 19$ GeV.

The cumulants of a conserved charge are given by appropriate combinations of moments of the corresponding probability distribution. Thus, the behavior of cumulants near criticality must be reflected in the properties of the probability distribution. Moreover, it is expected that the critical behavior of the probability distribution depends on the universality class. Indeed, we have recently shown, that the structure of the probability distribution for the net baryon number depends on the properties of the critical chiral fluctuations [23,24]. In particular, we have argued, that at vanishing chemical potential, the residual $O(4)$ critical fluctuation at physical pion mass leads to narrowing of the probability distribution relative to the Skellam function. This corresponds to a negative structure of the sixth order cumulant at the chiral crossover transition [24].

In this paper, we extend our previous studies to non-zero chemical potential and propose a method for identifying the characteristic properties of the net baryon probability distribution, which are responsible for the critical behavior of the cumulants at the chiral transition. We apply this method to the net proton probability distributions obtained by the STAR Collaboration in central Au–Au collisions at $\sqrt{s_{NN}} \geq 19$ GeV. We also critically examine the question whether $O(4)$ criticality can be captured by assuming that the baryon and antibaryon multiplicities are described by binomial or negative binomial distributions.

In this paper, we show that the (suitably rescaled) ratio of the net baryon probability distribution to the corresponding Skellam function reveals the critical narrowing of the probability distribution, which is characteristic for the $O(4)$ scaling.

2. The net-baryon number probability distribution

In the grand canonical ensemble specified by temperature T, subvolume V and chemical potential μ, the probability distribution for the conserved charge N, is given by

$$P(N; T, V, \mu) = \frac{Z(T, V, N)e^{\mu N/T}}{\mathcal{Z}(T, V, \mu)}, \tag{1}$$

where the canonical partition function $Z(T, V, N)$ is obtained e.g. by a projection of the grand partition function $\mathcal{Z}(T, V, \mu)$,

$$Z(T, V, N) = \frac{1}{2\pi} \int_0^{2\pi} d\left(\frac{\mu_I}{T}\right) e^{-iN\frac{\mu_I}{T}} \mathcal{Z}(T, V, \mu = i\mu_I). \tag{2}$$

In the HRG the probability distribution of the net-baryon number is, within the Boltzmann approximation, given by the Skellam function [21,25]

$$P^S(N) = \left(\frac{b}{\bar{b}}\right)^{N/2} I_N(2\sqrt{b\bar{b}})e^{-(b+\bar{b})} \tag{3}$$

where $b = \langle N_b \rangle$ and $\bar{b} = \langle N_{\bar{b}} \rangle$ are the thermal averages of the number of baryons and anti-baryons, respectively.

The HRG model reproduces the particle yields in heavy ion collisions in a broad energy range from SIS to LHC. Furthermore, it describes the equation of state obtained in LQCD, as well as the first and second order cumulants of the net baryon number for temperatures below the chiral crossover temperature. On the other hand, as suggested in [18], the *deviation* of higher order cumulants and their ratios from the HRG results provides a potential signature for criticality at the phase boundary.

These considerations indicate, that the probability distribution of the HRG, the Skellam function, offers an appropriate baseline for $P(N)$. Indeed, for small N, where the probability distribution is fixed by the non-critical lowest order cumulants the Skellam function provides a good approximation to $P(N)$. On the other hand, for large N the two distributions differ, since the critical fluctuations modify the tail of the distribution, which in turn determines the higher cumulants. Thus, it is natural to consider the Skellam function as a reference for identifying criticality in the probability distribution of the net-baryon number [21]. Specifically, we show that the ratio of $P(N)$ to the Skellam function exposes the effect of critical fluctuations.

We extract the characteristic features of the probability distribution near the chiral crossover transition within the $O(4)$ universality class by applying the Functional Renormalization Group (FRG) approach to the quark-meson (QM) model [26–28]. The QM model exhibits the relevant chiral symmetry of QCD, and belongs to the same $O(4)$ universality class [29,30].

The Lagrangian density in the QM model reads

$$\mathcal{L} = \bar{q}\left[i\gamma_\mu\partial^\mu - g(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\right]q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 - \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4 - h\sigma, \tag{4}$$

where q and $\bar{q}$ denote the quark and anti-quark fields coupled with the $O(4)$ chiral meson multiplet $\phi = (\sigma, \vec{\pi})$. The last three terms in Eq. (4) constitute the mesonic potential with the symmetry breaking term.

The thermodynamic potential is calculated in the QM model, within the FRG approach [26]. Applying the optimized regulator to the exact flow equation for the effective average action in the local potential approximation [26], the flow equation for the scale dependent thermodynamic potential density Ω_k reads [5]

$$\partial_k\Omega_k(\rho) = \frac{k^4}{12\pi^2}\left[\frac{3}{E_\pi}\left\{1 + 2n_B(E_\pi)\right\} + \frac{1}{E_\sigma}\left\{1 + 2n_B(E_\sigma)\right\} - \frac{24}{E_q}\left\{1 - n_F\left(E_q^+\right) - n_F\left(E_q^-\right)\right\}\right], \tag{5}$$

[1] For $\mu \neq 0$, diverging cumulants appear already at third order.

[2] Although the results of [23] were obtained in the chiral limit, it is plausible that they remain valid also for physical values of the quark masses.

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