PROCEEDINGS OF SCIENCE

Production of Entropy at the Chiral Phase Transition from Dissipation and Noise

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Several ongoing theoretical and experimental projects are exploring the possibility of a QCD critical point and phase transition. Here, we propose to study the production of entropy as a signature for a first-order chiral phase transition. Based on the linear sigma model, we couple the order parameter sigma to a quark fluid to describe the nonequilibrium cooling of the fireball in a heavy-ion collision. We estimate the relative increase in entropy per baryon number S/N to reach its largest value of up to 130% for a first-order phase transition at low beam energies. The lifetime of the quark-gluon plasma (QGP) at different types of transition is also investigated.

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1. Introduction

QGP is known as a state of matter in quantum chromodynamics (QCD) which resembles the universe shortly after the Big Bang and is nowadays created in heavy-ion experiments at RHIC and the LHC. One of its characteristic features is the restoration of chiral symmetry which is spontaneously broken in the QCD ground state. Lattice QCD is investigating fluctuations of conserved charges to identify crossover transition, first-order phase transition, and critical point (CP) in the QCD phase diagram [1]. Experimentally, net-proton cumulants have been reported by STAR where especially $\kappa\sigma^2$ of the net-protons shows some interesting non-monotonic behavior as a function of $\sqrt{s}$ and takes some high value of around 3.5 after widening the p_T range of acceptance [2, 3]. In this work, we study the production of entropy during a first-order phase transition as a possible experimental signal, similar to what was suggested for detecting a nuclear liquid-gas transition [4].

In previous works, it was shown that the dissipation and fluctuation of the sigma field as well as a delay in the relaxational process of the critical mode leads to an increasing entropy [5], in particular at a first-order phase transition. This is a universal feature of a nonequilibrium transition and independent of the particular choice of order parameter. Here, we are going to apply Nonequilibrium Chiral Fluid Dynamics (NχFD) [6, 7, 8, 9, 10, 11] to investigate the evolution of the critical $k = 0$ mode of the chiral order parameter field coupled to the longitudinal Bjorken-type expansion of a quark-antiquark fluid. The NχFD model has been studied extensively in the past providing a self-consistent description of critical slowing down near a CP and the spinodal decomposition around the first-order phase transition. Here, we also use this model to estimate the lifetime of the QGP in a heavy-ion collision. A possible first-order phase transition would prolong the lifetime in the mixed phase which would e.g. reflect in a higher number of thermal photons from the QGP in the detector. Results on this are also relevant for the future experimental facilities FAIR [12] and NICA [13].

2. Chiral Bjorken dynamics

In this section, we will briefly summarize the equations of the NχFD based chiral Bjorken model introduced in [5]. The linear sigma model gives us features of a chiral crossover transition for small baryochemical potentials μ_B and a CP and first-order phase transition at large μ_B. The Lagrangian density of this model is

$$\mathscr{L} = \overline{q}\left(i\gamma^\mu\partial_\mu - g\sigma\right)q + \frac{1}{2}\left(\partial_\mu\sigma\right)^2 - U(\sigma)\ , \tag{2.1}$$

$$U(\sigma) = \frac{\lambda^2}{4}\left(\sigma^2 - f_\pi^2\right)^2 - f_\pi m_\pi^2\sigma + U_0\ . \tag{2.2}$$

with standard parameters and the light quark fields $q = (u, d)$. The quark-meson coupling g is fixed by the nucleon mass given by $g\langle\sigma\rangle \simeq 940$ MeV in vacuum. The Langevin equation describes the time propagation of order parameter σ,

$$\ddot{\sigma} + \left(\frac{D}{\tau} + \eta\right)\dot{\sigma} + \frac{\partial\Omega}{\partial\sigma} = \xi\ . \tag{2.3}$$

Here, the dot refers to the derivative with respect to proper time τ and $D = 1$ in the Hubble-term for a longitudinal expansion in the z-direction. The potential $\Omega = U + \Omega_{q\bar{q}}$ contains the mean-field quark-antiquark contribution. A damping coefficient η arises from $\sigma \leftrightarrow q\bar{q}$ reaction. Choosing $\eta = 0$ will give unphysical oscillations of the σ-field. The stochastic noise ξ is assumed to be white and Gaussian. The dynamically generated energy of a constituent quark with momentum p is $E = \sqrt{p^2 + g^2\sigma^2}$. The energy-momentum tensor for the quark fluid part is assumed to be an ideal fluid with energy-momentum tensor $T_q^{\mu\nu} = (e+p)u^\mu u^\nu - pg^{\mu\nu}$ while a source term, the energy-momentum tensor of the field T_σ, is derived from the equation of motion of σ. Finally, we have a continuity equation for the hydrodynamics,

$$\partial_\mu T^{\mu\nu} = 0, \tag{2.4}$$

$$\partial_\mu T_q^{\mu\nu} - \partial_\mu T_\sigma^{\mu\nu} = 0 \; . \tag{2.5}$$

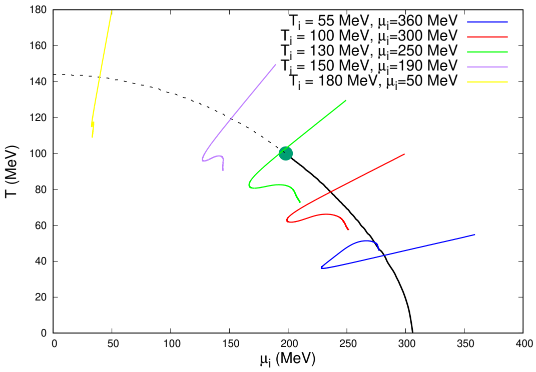
With $p = -\Omega$, the entropy density at time τ is given by re-arrangement of standard thermodynamic relations,

$$s = \frac{e + p - \mu n}{T} \; . \tag{2.6}$$

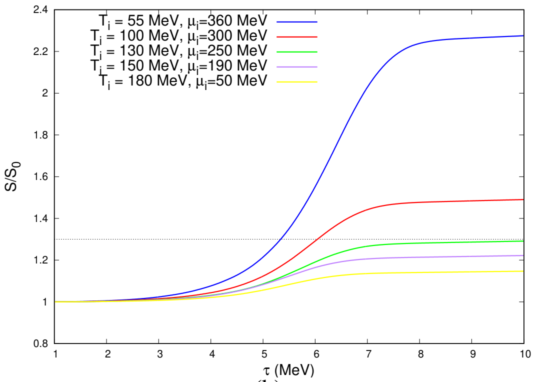
3. Entropy production from dissipation and noise

It has been shown that Eq. (2.3) with and without dissipation and noise results in different amounts of entropy production. The order parameter σ is not able to follow the rapid change in temperature during the expansion of the plasma. During this period, some extra entropy is generated in the nonequilibrium scenario.

In this section, we are going to focus on the effect of latent heat which is a main characteristic for the first-order phase transition and increases with increasing μ_B. We will see that the latent heat is correlated to the evolution of the entropy. We define initial conditions (T_i, μ_i) MeV such that we can study several scenarios of evolutions to pass through the crossover, CP and the first-order phase transition. The simulation time begins after an assumed thermalization time $\tau = 1$.



(a)



(b)

Figure 1: (a) Event-averaged trajectories for our initial conditions. The solid-line represents the first-order phase transition. The dot is at the CP, and the dashed line represents the crossover. (b) The corresponding relative entropy increase. The dashed line indicates a value of $S/S_0 = 1.3$ or 30% entropy production at a CP transition.

The trajectories for these events are shown in Fig. 1(a). The first remarkable thing to observe is a reheating process after passing through the crossover. Normally, such an effect will occur after a supercooled stated in a first-order phase transition. After the decay of the high-temperature phase, a large amount of energy dissipates into the fluid and consequently T increases. At a first-order phase transition, the effect is significantly stronger and has also been found before in inhomogeneous media [9]. We see that the strength in reheating depends on the initial condition which is experimentally related to the beam energy.

Fig. 1(b) shows the evolution of S/S_0, the increase in entropy relative to the initial entropy of the medium $S_0 \equiv S(\tau = 0)$. We see a clear trend for the final relative entropy. The entropy increases stronger at a first-order phase transition than for a crossover. At a first-order phase transition, we see an increase of up to 130% or a final entropy which is about 2.3 times higher than the initial entropy. For a crossover, on the other hand, less than 30% entropy increase are observed. Furthermore, the increase depends on how close the initial condition is to the phase boundary, with a higher expansion rate resulting in a larger increase in S as shown in [5]. This effect is relevant for experimental efforts as it will be visible in an enhancement of pion number or of the pion-to-proton ratio as a function of $\sqrt{s}$.

4. QGP lifetime

We try to calculate the lifetime of the QGP from the chiral Bjorken model. The QGP after the collision spends some time being a supercooled QGP propagating further near the first-order phase transition before hadronization sets in. The system then starts to reheat via releasing the stored latent heat. Interestingly, if this effect is strong enough, the medium can reheat back into the spinodal region before the freeze-out as seen from the trajectories in the previous section. This leads to the expectation of a prolonged lifetime of the QGP in comparison to a pure crossover scenario in the T-μ plane. This would be reflected in a higher amount of produced thermal photons in the detector.

Figure **??** illustrates the time of a QGP or mixed phase in the trajectories obtained from our calculations. The evolution through the spinodal region of the first-order phase transition yields a lifetime which is about 2 fm longer compared to a crossover or CP transition. We note, however, that due to the nonequilibrium nature, there is no unambiguous way to define this quantity. Alternatively, one could look at the evolution of the chiral order parameter or include the Polyakov loop as an order parameter for the deconfinement transition to characterize the presence of a QGP.

5. Conclusions

We have studied within the nonequilibrium chiral Bjorken model the coupled evolution of the zero mode of the chiral order parameter σ together with the longitudinal expansion of a hot and dense fluid of quark matter. The entropy significantly increases up to 130% at a first-order phase transition and less than 30% in the absence of the latent heat at a crossover. We found a clear reheating behavior for both crossover and first-order phase transition which might cause additional thermal background in heavy-ion collisions. The first-order phase transition causes a

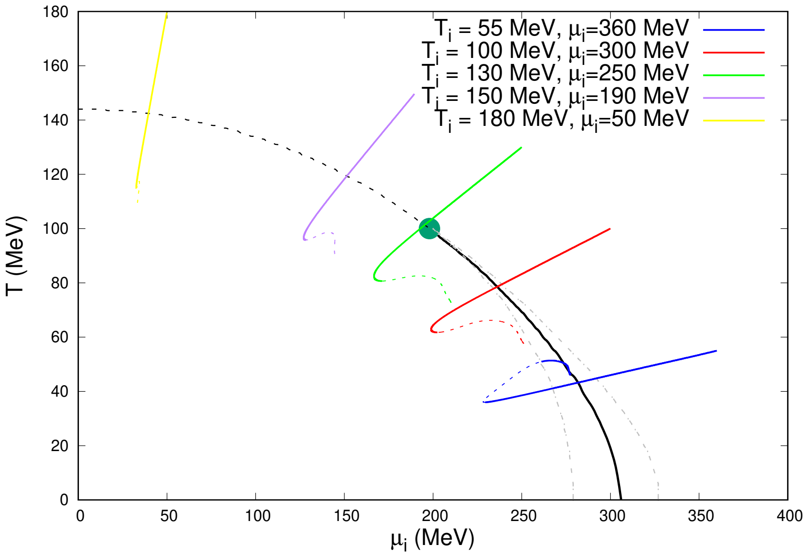


Figure 2: The QGP phase of trajectories of the medium in phase diagram. The grey dashed lines delineate the spinodal region. The colored solid lines indicate the QGP phase during the evolution, the colored dashed lines represent the hadronic phase.

longer lifetime of the QGP, roughly estimated to extend around 2 fm compared to an evolution without spinodal region.

Acknowledgments

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