Evolution of critical fluctuations in a heavy-ion collision scenario

Christoph Herold\textsuperscript{a}, Marlene Nahrgang\textsuperscript{b}, Chinorat Kobdaj\textsuperscript{a}, Ayut Limphirat\textsuperscript{a}, Yupeng Yan\textsuperscript{a}

\textsuperscript{a}School of Physics, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
\textsuperscript{b}SUBATECH, UMR 6457, Universite de Nantes, Ecole des Mines de Nantes, IN2P3/CNRS, 4 rue Alfred Kastler, 44307 Nantes cedex 3, France

Abstract

We study fluctuations of the sigma field and the net-baryon number on the crossover side of the critical point within the model of nonequilibrium chiral fluid dynamics (\(N_\chi FD\)). Herein, the sigma field as the chiral order parameter is propagated explicitly and coupled to a fluid of quarks. Before investigating these fluctuations in an expanding nonequilibrium medium, we scrutinize the \(N_\chi FD\) model by comparing cumulants of the sigma fluctuations in a thermalized box to (ratios of) susceptibilities as they are obtained from derivatives of the grand canonical potential. The dynamically determined cumulants follow the trend of the thermodynamic susceptibilities. In an expanding inhomogeneous medium, however, the behavior of the fluctuations is shown to be different as a result of memory effects.

Keywords: nonequilibrium phase transition, critical fluctuations, dynamical symmetry breaking

1. Introduction

Heavy-ion collision experiments aim at studying strongly interacting matter at extreme temperatures and densities. Of special interest are the chiral phase transition and in particular the location of the critical point (CP). By measuring fluctuations of the net-proton number [1, 2], experimentalists search for non-monotonic behavior as a function of beam energy that might possibly reveal the existence of a critical region [3, 4, 5, 6].

Even though one commonly expects a rapid thermalization of the quark-gluon plasma produced after a collision, equilibration times diverge near a CP [7] and memory effects have to be taken into account [8]. We address these issues with our model of nonequilibrium chiral fluid dynamics (\(N_\chi FD\)). Here, the sigma field as the chiral order parameter is propagated via a Langevin equation and selfconsistently coupled to a locally thermalized heat bath of quarks [9]. The model has proven successful in describing relevant nonequilibrium effects like critical slowing down [10, 11, 12] and spinodal decomposition [13, 14]. Recently, we have emphasized the importance of including critical fluctuations into dynamical models to be able to describe non-monotonic net-proton fluctuations [15].

In the work presented here, we study the evolution of the chiral order parameter in an expanding medium, resembling the situation after the collision of two heavy nuclei. We evaluate the effective kurtosis \(\kappa \sigma^2\) as a function of the freeze-out energy density and compare this to \(\kappa \sigma^2\) in equilibrium as well as to the corresponding thermodynamic susceptibility.

Available online at www.sciencedirect.com

Nuclear Physics A 967 (2017) 828–831

0375-9474/© 2017 The Author(s). Published by Elsevier B.V.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
2. Model description

We study fluctuations during the fluid dynamical evolution in a heavy-ion collision starting form a quark-meson model with Lagrangian

\[ \mathcal{L} = \bar{q} \left( i \gamma^\mu \partial_\mu - g_q \sigma \right) q + \frac{1}{2} \left( \partial_\mu \sigma \right)^2 - U_\sigma . \]  

(1)

We include only light quarks, so \( q = (u, d) \). The quark masses are dynamically generated by the chiral condensate \( \sigma \), thus allowing us to fix the coupling parameter \( g_q = 3.37 \) from the nucleon mass in the ground state. The potential \( U(\sigma) \) is used in its standard version, see e.g. [14].

The grand canonical potential in mean-field approximation reads \( \Omega = \Omega_{\bar{q}q} + U_\sigma \) with the quark contribution

\[ \Omega_{\bar{q}q} = -2N_fN_cT \int \frac{d^3p}{(2\pi)^3} \left\{ \ln \left[ 1 + e^{-E_q - \mu_T} \right] + \ln \left[ 1 + e^{-E_q + \mu_T} \right] \right\} , \]

(2)

where \( E_q = \sqrt{p^2 + m^2_q} \). Note that the potential explicitly depends on temperature \( T \) and quark chemical potential \( \mu = \mu_B/3 \). As we have shown earlier in [14], the critical exponent in mean-field changes from \( \gamma = 1/2 \) at the CP to \( \gamma = 2/3 \) at the spinodals of the first-order phase transition, signaling a change in universality class.

The curvature of the grand canonical potential in equilibrium gives the mass of the sigma field which equals the inverse correlation length,

\[ m^2_\sigma = \frac{1}{\xi^2_{eq}} \left. \frac{\partial^2 \Omega}{\partial \sigma^2} \right|_{\sigma = \langle \sigma \rangle} . \]

(3)

As we are mainly interested in the impact of nonequilibrium effects, we propagate the order parameter \( \sigma \) explicitly via a stochastic Langevin equation of motion [9, 11, 12, 14],

\[ \partial_\mu \partial^\mu \sigma + \eta_\sigma(T, \mu) \partial_t \sigma + \frac{\delta \Omega}{\delta \sigma} = \xi , \]

(4)

where the friction coefficient \( \eta \) accounts for damping in the thermalized heat bath of quarks and the stochastic noise field \( \xi \) describes the back-reaction to the fields. The noise field has a vanishing expectation value \( \langle \xi(t, \vec{x}) \rangle = 0 \) and fluctuates according to the dissipation-fluctuation relation

\[ \langle \xi(t, \vec{x})\xi(t', \vec{x'}) \rangle \xi = \delta(t - t') \delta(\vec{x} - \vec{x'}) \eta_\sigma \eta_\sigma \coth \left( \frac{m_\sigma}{2T} \right) . \]

(5)

We avoid any dependence on the lattice spacing and choice of discretization [16] by coarse-graining the field \( \sigma \) over the spatial extension of the equilibrium correlation length as given in Eq. (3).

The \( T \)- and \( \mu \)-dependent damping coefficient \( \eta_\sigma \) is given by the expression

\[ \eta_\sigma = \frac{12g^2}{\pi} \left[ 1 - 2n_F \left( \frac{m_\sigma}{2} \right) \right] \left( \frac{m^4_\sigma}{4} - m^2_q \right)^{3/2} . \]

(6)

With increasing correlation length near the CP, the damping coefficient approaches zero as is also evident from the vanishing mass of the sigma field which makes a decay of a sigma into a quark-antiquark pair kinematically impossible.

The pressure of the quark fluid in local thermal equilibrium is given by the negative grand canonical potential,

\[ p(T, \mu; \sigma) = -\Omega_{\bar{q}q} . \]

(7)

Energy-momentum and baryon number are conserved via
دریافت فوری

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات