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Fluctuations in non-ideal pion gas with dynamically fixed particle number

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Abstract

We consider a non-ideal hot pion gas with the dynamically fixed number of particles in the model with the $\lambda\phi^4$ interaction. The effective Lagrangian for the description of such a system is obtained after dropping the terms responsible for the change of the total particle number. Reactions $\pi^+\pi^- \leftrightarrow \pi^0\pi^0$, which determine the isospin balance of the medium, are permitted. Within the self-consistent Hartree approximation we compute the effective pion mass, thermodynamic characteristics of the system and the variance of the particle number at temperatures above the critical point of the induced Bose–Einstein condensation when the pion chemical potential reaches the value of the effective pion mass. We analyze conditions for the condensate formation in the process of thermalization of an initially non-equilibrium pion gas. The normalized variance of the particle number increases with a temperature decrease but remains finite in the critical point of the Bose–Einstein condensation. This is due to the non-perturbative account of the interaction and is in contrast to the ideal-gas case. In the kinetic regime of the condensate formation the variance is shown to stay finite also.

Keywords: Pion gas; Bose–Einstein condensation; Fluctuations

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1. Introduction

Multitude of pions is produced in central ultra-relativistic nucleus–nucleus collisions at SPS, RHIC and LHC energies [1–5]. Because of the kinematical separation of the light meson component or hadronization of quark–gluon plasma, a pion-enriched system can be formed at midrapidity. Spectra of produced pions are approximately exponential at intermediate transverse momenta, $m_\pi \lesssim p_T \lesssim 7\,m_\pi$, here and below $m_\pi = 139\,\mathrm{MeV}$ is the pion mass, and $\hbar = c = 1$. Therefore, one may assume that the pions stem from a hot fireball characterized by a temperature $T(\vec{r}, t)$ and density $n(\vec{r}, t)$, which expands until a thermal freeze-out, cf., e.g., the analysis [6] performed for higher SPS energies. The fit of the particle yields to the data shows that even at LHC energies the temperature at the chemical freeze-out proves to be rather low, $T_{\mathrm{ch}} \simeq 155\,\mathrm{MeV}$ [7]. The chemical non-equilibrium analysis of the LHC data on mean particle multiplicities [8] shows that the temperature at the hadronization, $T_{\mathrm{h}} \simeq T_{\mathrm{ch}}$, might be even lower, 140–145 MeV. The thermal freeze-out temperature for hadrons is expected to be still lower, $T_{\mathrm{th}} \sim 100$–$120\,\mathrm{MeV}$ as was evaluated in [9–12] for energies under consideration. Estimates [13] show that at temperatures $T \lesssim 130$–$140\,\mathrm{MeV}$, the rate of pion absorption becomes smaller than the rate of pion rescattering. This implies that the total pion number can be considered as dynamically fixed during the subsequent fireball expansion before the thermal freeze out [14]. The time scale of chemical equilibration for $T \simeq 100$–$120\,\mathrm{MeV}$, is estimated to be much longer, $\tau_{\mathrm{ch}} \sim 100\,\mathrm{fm}$ [15,10] (these evaluations were performed for high SPS energies), than that of thermal equilibration, $\tau_{\mathrm{th}} \sim$ few fm, and the typical time of the fireball expansion, $\tau_{\mathrm{exp}} \sim 10$–$20\,\mathrm{fm}$ [16,12] for the collision energies under consideration.

At energies under consideration the measured p_T spectra show an enhancement at low transverse momenta, e.g. see [17], which is attributed to a feed-down from resonance decays and a non-zero value of the pion chemical potential. Already the first descriptions of pion spectra for collisions at $200A\mathrm{GeV}$ in the blast wave-model showed that the chemical potential of magnitude ~ 120–$130\,\mathrm{MeV}$ is required [18–20]. The recent fit [21] for collisions with $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ obtained the chemical potential of pions $\mu \simeq 134.9\,\mathrm{MeV}$ that is just 80 keV below the mass of the neutral pion. Such a proximity of the pion chemical potential to the critical value of the Bose–Einstein condensation in the ideal gas inspires speculations that the Bose–Einstein condensate (BEC) can be indeed formed in nucleus–nucleus collisions. Although it was demonstrated in [22] that the chemical potential cannot reach the critical value in the course of the quasi-equilibrium isentropic fireball expansion, non-equilibrium overcooling effects [23–25] may provide a mechanism to drive pions to the BEC. The condensation can also occur because of an additional injection of non-equilibrium pions from resonance decays [26], decomposition of a “blurred phase” of hot baryon-less matter [27], sudden hadronization of supercooled quark–gluon plasma [28] or a decay of the transient BEC of gluons or glueballs pre-formed at an initial stage in a heavy-ion collision, cf. [29–33]. The ALICE collaboration reports a large coherent emission of pions from multi-pion correlation studies [34]. The fraction of coherent pions coming from this fit is as large as $23\% \pm 8\%$. The non-equilibrium parameters obtained in analysis require that about 5% of pions are in the BEC [35]. For a discussion of a possibility of an occurrence of BEC in heavy-ion collisions at high energies with LHC detectors we cite recent review [36].

The presence of a phase transition (of the second or first order) implies an increase of fluctuations near the critical point, as a general property manifested in various critical opalescence phenomena, cf. [37]. The proximity of the system created in nucleus–nucleus collisions to the Bose–Einstein condensation was argued in [38,41,35] to reveal itself through a divergence of the normalized variance. The results were derived for an ideal pion gas in the thermodynami-

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