Light nuclei production as a probe of the QCD phase diagram

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Abstract

It is generally believed that the quark-hadron transition at small values of baryon chemical potentials \(\rho_B\) is a crossover but changes to a first-order phase transition with an associated critical end-point (CEP) as \(\rho_B\) increases. Such a \(\rho_B\)-dependent quark-hadron transition is expected to result in a double peak structure in the correlation function due to the first-order phase transition in heavy-ion collisions with one at lower energy due to the spinodal instability during the first-order phase transition and another at higher energy due to the critical fluctuations in the vicinity of the CEP. By analyzing the data on the \(p_d\) and \(H\) yields in central heavy-ion collisions within the coalescence model for light nuclei production, we find that the relative neutron density fluctuation \(\Delta N_n = \frac{\langle p_d N_n \rangle}{\rho_B} - 1\) at kinetic freeze-out indeed displays a clear peak at \(\sqrt{s_{NN}} = 8.8\ GeV\) and a possible strong re-enhancement at \(\sqrt{s_{NN}} = 9.0\ GeV\). Our findings thus provide a strong support for the existence of a first-order phase transition at large \(\rho_B\) and its critical endpoint at a smaller \(\rho_B\) in the temperature versus baryon chemical potential plane of the QCD phase diagram.

1 Introduction

Searching for the CEP and locate the phase boundary in the QCD phase diagram is the main motivation for the heavy-ion collision experiments being carried out in RHIC/BES, FAIR, NICA, and NA61/SHINE. In the present study, we propose a new scenario depicted in Fig. 1 that there should be a double-peak structure in the correlation function due to the baryon density fluctuation in heavy-ion collisions, with the lower energy one due to the spinodal instability associated with a first-order quark-hadron phase transition and the higher energy one induced by the second-order phase transition at the CEP.

2 Light Nuclei Production and Nucleon Density Fluctuations

Light nuclei, such as \(d\) and \(H\), are formed from nucleons in a very restricted phase-space volume of \(\Delta B \sim 2\ fm\) and \(\Delta \rho \sim 0.1\ GeV\) and their production in heavy-ion collisions can thus be used as an ideal probe of the local nucleon density fluctuations at scales \(\lesssim 2\ fm\). Within a coalescence model, the neutron and proton density correlation \(C_{np} = \langle n \cdot p \rangle / \langle \rho_N \cdot \rho_p \rangle\) and the relative neutron density fluctuation \(\Delta N_n = \langle n \rangle / \rho_n - 1\) can be extracted from production of \(p_d\) and \(H\) [1, 2], i.e.,

\[ C_{np} \approx 0.0010 \times \frac{R_{pp} V_p \rho_B N_p^2}{N_n^2} - 1, \]

\[ \Delta N_n \approx 3.5 \times \frac{1 + C_{np}^2 N_p^2 N_n^2}{2 C_{np}^2 - 1}. \]

One can also see from Fig. 2 (b) that there is a possible strong re-increase of \(\Delta N_n\) when the energy is decreased from \(\sqrt{s_{NN}} = 6.3\ GeV\) to \(4.86\ GeV\), which could be a result of the spinodal instability as shown in Fig. 1. In contrast, the \(\Delta \rho_p\) (\(\Delta N_p\)) continues to decrease (increase). This may be due to the fact that the effect of spinodal instability in the isospin density is not as strong as that in the baryon density for heavy-ion collisions at AGS/SPS energies. Hence the collision energy dependence of the relative neutron density fluctuation \(\Delta N_n = \langle n \rangle / \rho_n\) at kinetic freeze-out supports the scenario depicted in Fig. 1. But the statistical uncertainties of \(\Delta N_n\) and \(\Delta \rho_p\) at \(\sqrt{s_{NN}} = 8.86\ GeV\) are large, and more precise measurements are extremely important to confirm the present conclusion.

5 Conclusions

- We have proposed a double-peak structure in the collision energy dependence of the baryon density fluctuation in heavy-ion collisions as a probe to the structure of the QCD phase diagram, with the lower energy one due to the spinodal instability associated with a first-order quark-hadron phase transition and the higher energy one induced by the second-order phase transition at the CEP.
- This double-peak structure seems to be supported by the collision energy dependence of the relative neutron density fluctuation \(\Delta N_n = \langle n \rangle / \rho_n\) at kinetic freeze-out that we have extracted from analyzing the measured yields of \(p_d\) and \(H\) in central heavy-ion collisions at AGS and SPS energies within the coalescence model. In particular, we have found the \(\Delta \rho_p\) to display a clear peak at \(\sqrt{s_{NN}} = 8.8\ GeV\) and a strong re-enhancement at \(\sqrt{s_{NN}} = 4.86\ GeV\), suggesting that the CEP could have been reached or closely approached in central Pb+Pb collisions at \(\sqrt{s_{NN}} = 8.8\ GeV\) and the first-order phase transition could have occurred in central Au+Au collisions at \(\sqrt{s_{NN}} = 4.86\ GeV\).

References


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