Light nuclei production as a probe of the QCD phase diagram (Phys. Lett. **B781**, 499 (2018))

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1 Abstract

It is generally believed that the quark-hadron transition at small values of baryon chemical potentials μ_B is a crossover but changes to a first-order phase transition with an associated critical endpoint (CEP) as μ_B increases. Such a μ_B-dependent quark-hadron transition is expected to result in a **double-peak** structure in the collision energy dependence of the baryon density fluctuation 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 ^{3}H yields in central heavy-ion collisions within the coalescence model for light nuclei production, we find that the relative neutron density fluctuation $\Delta\rho_n = \langle(\delta\rho_n)^2\rangle/\langle\rho_n\rangle^2$ at kinetic freeze-out indeed displays a clear peak at $\sqrt{s_{NN}} = 8.8$ GeV and a possible strong re-enhancement at $\sqrt{s_{NN}} = 4.86$ GeV. **Our findings thus provide a strong support for the existence of a first-order phase transition at large μ_B and its critical endpoint at a smaller μ_B in the temperature versus baryon chemical potential plane of the QCD phase diagram.**

2 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 collision energy dependence of 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.

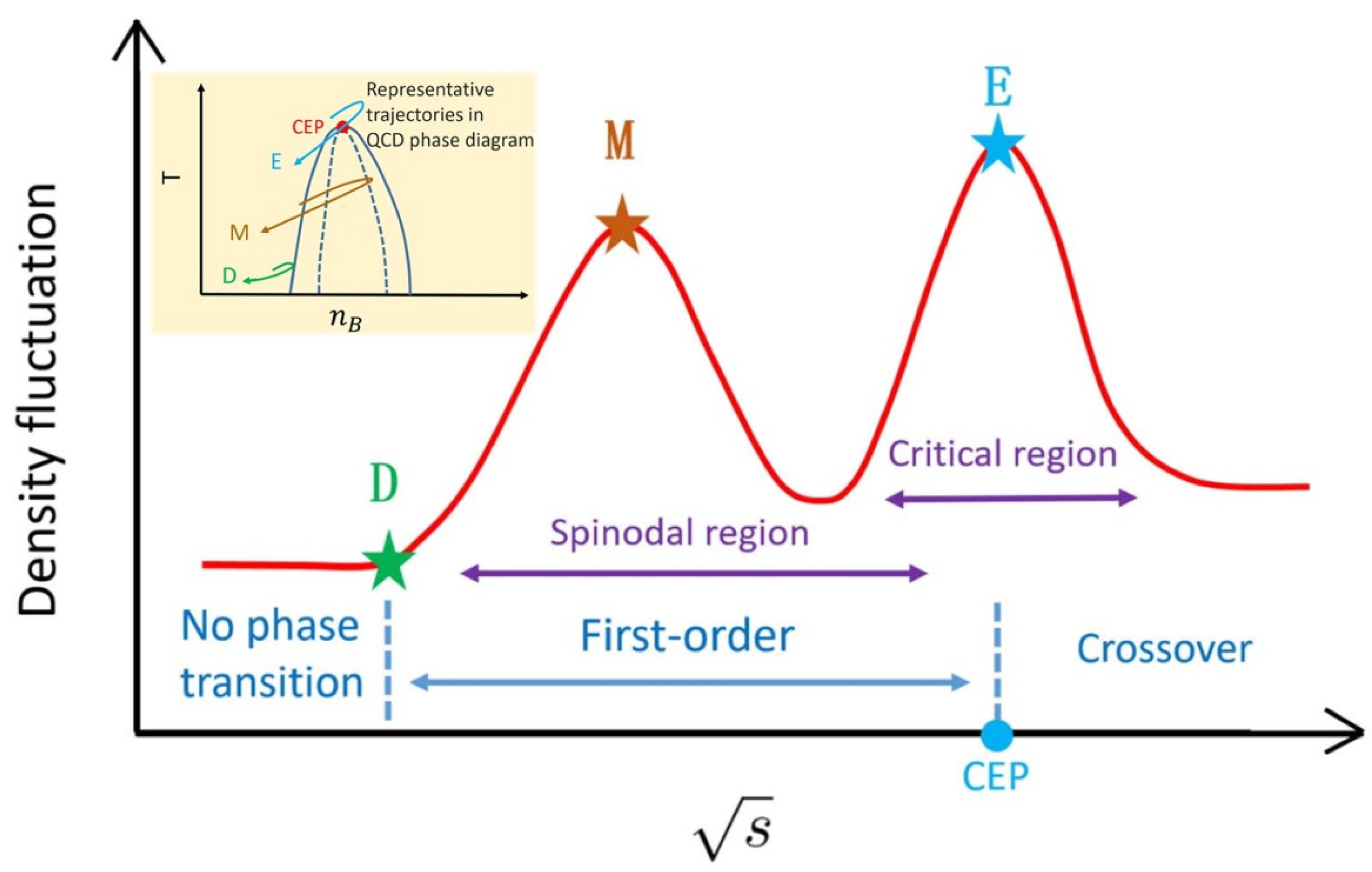

Figure 1: Schematic depiction of the collision energy dependence of density fluctuations in heavy-ion collisions together with the corresponding phase regions in the QCD phase diagram. Point 'D' indicates the beginning of first-order phase transition, 'M' denotes the maximum caused by the spinodal instability and 'E' denotes the maximum due to the CEP. The typical trajectries are also shown in the T-n_B plane of QCD phase diagram with n_B being the baryon number density.

3 Light Nuclei Production and Nucleon Density Fluctuations

Light nuclei, such as d and ^{3}H, are formed from nucleons in a very restricted phase-space volume of Δx ~2 fm and Δp ~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 $\gtrsim 2$ fm. Within a coalescence model, the the neutron and proton density correlation $C_{\rm np} = \langle\delta\rho_n\delta\rho_p\rangle/(\langle\rho_n\rangle\langle\rho_p\rangle)$ and the relative neutron density fluctuation $\Delta\rho_n = \langle(\delta\rho_n)^2\rangle/\langle\rho_n\rangle^2$ can be extracted from production of p, d and ^{3}H [1, 2], i.e.,

$$C_{\rm np} \approx 0.0019\, R_{\rm np} V_{\rm ph} N_{\rm d}/N_{\rm p}^2 - 1, \quad (1)$$

$$\Delta\rho_n \approx 3.5\,(1 + C_{\rm np})^2 N_{\rm p} N_{^3{\rm H}}/N_{\rm d}^2 - 2C_{\rm np} - 1, \quad (2)$$

with $R_{\rm np} = N_p/N_n = \langle\rho_p\rangle/\langle\rho_n\rangle$ and $V_{\rm ph} = (2\pi mT)^{3/2}V$. The ratio $R_{\rm np}$ can be estimated from the measured pion yield ratio by using the relation $N_p/N_n = (\pi^+/\pi^-)^{1/2}$ from the statistical model. The quantity $V_{\rm ph} = (2\pi mT)^{3/2}V = \lambda T_{\rm ch}^{3/2} V_{\rm ch}$ (with $T_{\rm ch}$ and $V_{\rm ch}$ being the chemical freeze-out temperature and volume, respectively) in Eq. (1) is the effective phase-space volume occupied by nucleons in the fireball at kinetic freeze-out. It is found in a transport model calculation that the value of $\lambda \approx 1.6$ is almost a constant at BES energies. With the information on $C_{\rm np}$ and $\Delta\rho_n$, we can further define the isospin density fluctuation $\Delta\rho_I$ as $\Delta\rho_I = \frac{\langle(\delta\rho_n - \delta\rho_p)^2\rangle}{(\langle\rho_n\rangle + \langle\rho_p\rangle)^2} = \frac{R_{\rm np}^2\Delta\rho_p - 2R_{\rm np}C_{\rm np} + \Delta\rho_n}{(1+R_{\rm np})^2}$.

4 Main Results

The yields dN/dy of p, d and ^{3}H are measured at AGS and SPS energies. We plot the collision energy dependence of $C_{\rm np}$, $\Delta\rho_n$ and $\Delta\rho_I$ in Fig. 2. It is seen from Fig. 2 (a) that the neutron-proton density correlation $C_{\rm np}$ has a non-monotonic behavior with a valley located at $\sqrt{s_{NN}}$ =8.8 GeV. The similar behavior of $\Delta\rho_n$ and $\Delta\rho_I$ with both peaked at $\sqrt{s_{NN}} = 8.8$ GeV in Fig. 2 (b) could be due to the same underlying physics of critical fluctuations in the vicinity of CEP. According to the universality of critical behavior, the singular parts of both $\Delta\rho_n$ and $\Delta\rho_I$ in the second-order phase transition scale with power of the correlation length l, and diverge at the CEP in the QCD phase diagram. Due to the effects of critical slowing down and dynamical expansion in heavy-ion collisions, only modest but similar enhancements of $\Delta\rho_n$ and $\Delta\rho_I$ can be developed. As a result, the non-monotonic behaviors shown in Fig. 2 are consistent with the scenario that the CEP is reached or closely approached in the produced QGP during its time evolution in central Pb+Pb collisions at around $\sqrt{s_{NN}} = 8.8$ GeV. For lower (e.g., $\sqrt{s_{NN}} = 6.3$ and 7.6 GeV) and higher (e.g., $\sqrt{s_{NN}} = 12.3$ and 17.3 GeV) energies, both $\Delta\rho_n$ and $\Delta\rho_I$ would decrease because the correlation length l quickly decreases as the evolution trajectory moves away from the CEP.

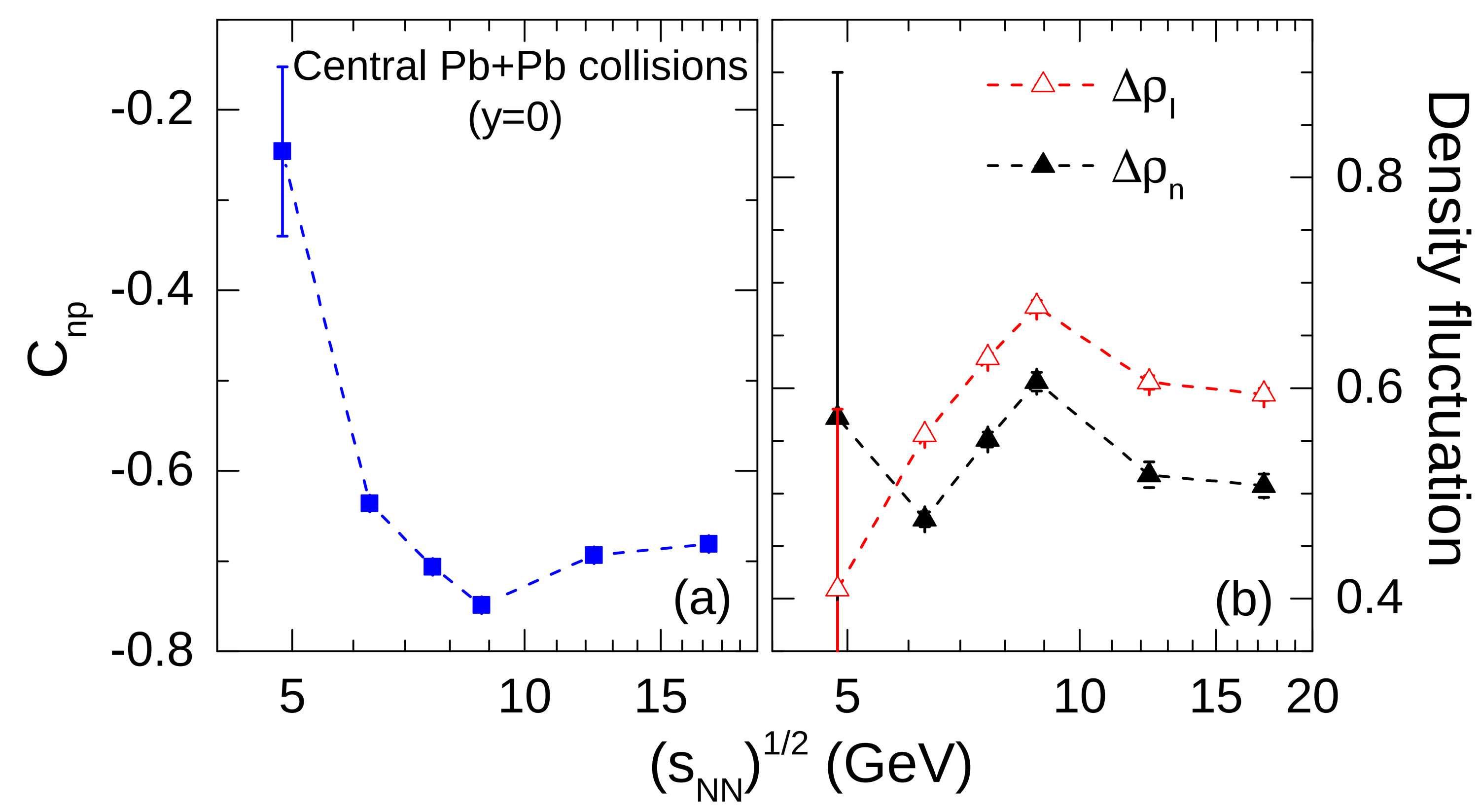

Figure 2: Collision energy dependence of the neutron and proton density correlation $C_{\rm np}$ (a) and the neutron and isospin density fluctuations $\Delta\rho_n$ and $\Delta\rho_I$ (b) in central Pb+Pb collisions at SPS energies and Au+Au collisions at AGS energies.

One can also see from Fig. 2 (b) that there is a possible strong re-increase of $\Delta\rho_n$ when the collision 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 $\Delta\rho_I$ ($C_{\rm np}$) continues to decrease (increase). This may 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 $\Delta\rho_n = \langle(\delta\rho_n)^2\rangle/\langle\rho_n\rangle^2$ at kinetic freeze-out supports the scenario depicted in Fig. 1.** But the statistical uncertainties of $\Delta\rho_n$ and $\Delta\rho_I$ at $\sqrt{s_{NN}} = 4.86$ 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 $\Delta\rho_n = \langle(\delta\rho_n)^2\rangle/\langle\rho_n\rangle^2$ at kinetic freeze-out that we have extracted from analyzing the measured yields of p, d and ^{3}H in central heavy-ion collisions at AGS and SPS energies within the coalescence model. In particular, we have found the $\Delta\rho_n$ to display a clear peak at $\sqrt{s_{NN}} = 8.8$ GeV and a possible 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

[1] K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. **B774**, 103 (2017).
[2] K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, and Z. Xu, Phys. Lett. **B781**, 499 (2018).

Acknowledgements

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