Nuclear Science and Techniques (2023) 34:80
https://doi.org/10.1007/s41365-023-01231-1

RESEARCH HIGHLIGHT

# Searching for QCD critical point with light nuclei

**Che Ming Ko**[1]

Received: 3 May 2023 / Revised: 3 May 2023 / Accepted: 11 May 2023 / Published online: 31 May 2023


## Abstract

Density fluctuations and correlations due to a first-order quark-gluon plasma to hadronic matter phase transition and its critical end point, if they remain present after the hadronic evolution in a heavy ion collisions, can lead to an enhanced production of light nuclei in these collisions. This would then result in a non-monotonic collision energy dependence of the yield ratio $N_\mathrm{t}N_\mathrm{p}/N_\mathrm{d}^2$ of proton number $N_\mathrm{p}$, deuteron number $N_\mathrm{d}$, and triton number $N_\mathrm{t}$. Measurements of this yield ratio as a function of collision energy thus provides the possibility to probe the equation of state of strong-interaction matter and its phase diagram.

Studying the properties of baryon-rich quark-gluon plasma (QGP) is the main focus of the beam energy scan (BES) experiments [1–3] at the Relativistic Heavy Ion Collider (RHIC) as well as at the future Facility for Antiproton and Ion Research (FAIR) and the Nuclotron-based Ion Collider Facility (NICA). There have been many theoretical studies on the QCD phase diagram and its structure, based on, for example, the lattice QCD [4], holographic models [5], and effective field theories [6]. Also, the QCD phase diagram has been explored in the hydrodynamic framework by the BEST Collaboration [7] and used in machine learning methods to study its effects in heavy ion collisions [8]. In particular, using the hydrodynamic [9–12] or transport [13] model with an equation of state that has a first-order partonic to hadronic matter phase transition, it has been shown that the produced matter in heavy ion collisions could be mechanically unstable due to the spinodal instability associated with the first-order phase transition. This would then lead to an amplification of the density inhomogeneity, and the resulting density fluctuations could enhance the production of composite particles, such as hadrons and nuclei, which can then be used as a signal of the first-order phase transition. For example, using a partonic transport model based on a three-flavor Nambu-Jona-Lasinio (NJL) model [14, 15] for Au+Au collisions with the initial quark temperature and density in the spinodal region of the corresponding strong-interaction QCD phase diagram, it was shown in Ref. [13] that the quark density fluctuation after the evolution would be larger for the case with a first-order chiral phase transition than for the case without a first-order chiral phase transition in the equation of state. These results are illustrated in panels (b) and (a) of Fig. 1, respectively.

Also shown in Fig. 1 are the light nuclei produced from the hadronic matter resulting from the clumping quark matter after hadronization and further evolution as well as their yield ratio $\mathcal{O}_\text{p-d-t} = N_\mathrm{t}N_\mathrm{p}/N_\mathrm{d}^2$, where $N_p$, $N_\mathrm{d}$, and $\mathrm{N}_\mathrm{t}$ denote, respectively, the proton, deuteron, and triton numbers. According to Ref. [16], where the coalescence model [17–20] is used for light nuclei production, this yield ratio is related to the neutron relative density fluctuation $\Delta n = \langle(\delta n)^2\rangle/\langle n\rangle^2$, with $\langle n\rangle$ and $\langle(\delta n)^2\rangle$ being the average neutron density and its variance, respectively, by $\mathcal{O}_\text{p-d-t} \approx \frac{1}{2\sqrt{3}}(1+\Delta n)$. One thus expects an enhanced $\mathcal{O}_\text{p-d-t}$ if the neutron density fluctuation remains present at the kinetic freeze-out of produced hadronic matter. A similar density fluctuation effect on the yield ratio $\mathcal{O}_\text{p-d-t}$ also holds if deuteron and triton are produced thermally or statistically at the kinetic freeze-out of the hadronic matter [21, 22]. It was further argued in Ref. [23] that the critical fluctuations in the vicinity of the critical end point (CEP) of a first-order phase transition could also lead to an enhancement of the yield ratio $\mathcal{O}_\text{p-d-t}$ as shown in Ref. [24]. An enhanced $\mathcal{O}_\text{p-d-t}$ has also been interpreted as a signal for the CEP according to Refs. [25, 26], which showed that light nuclei production would be enhanced as a result of their increased binding energies when the attractive part of nucleon-nucleon

✉ Che Ming Ko
ko@comp.tamu.edu

[1] Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843-3366, USA

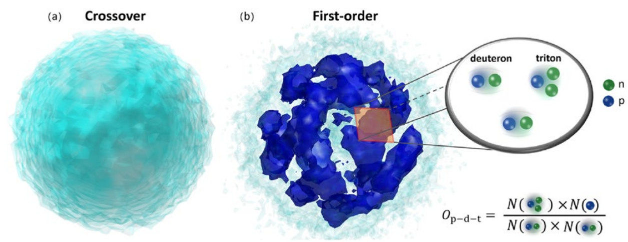


**Fig. 1** (Color online) Density distribution of strongly interacting matter in a heavy ion collision after its expansion for the cases of crossover transition (panel **a**) and first-order chiral phase transition (panel **b**). Also shown for illustration of the latter case are deuterons and tritons produced from the density fluctuating hadronic matter and their yield ratio $\mathcal{O}_{\text{p-d-t}} = N_t N_p / N_d^2$, which depends on the magnitude of neutron density distribution as discussed in the text

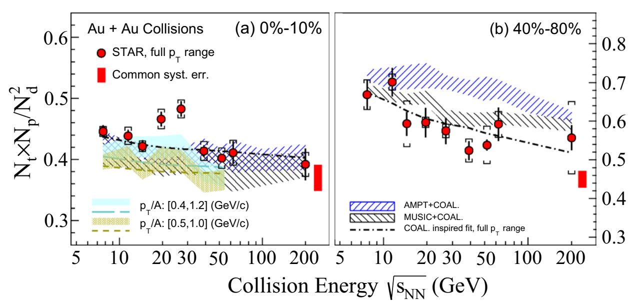


**Fig. 2** (Color online) Collision energy, $p_T$ dependence of the yield ratio $N_t N_p / N_d^2$ in Au+Au collisions at RHIC for 0%-10% central (left panel) and 40%-80% peripheral (right panel) collisions. Dashed lines are the coalescence baselines obtained from the coalescence-inspired fit. Shaded areas denote the calculations from the MUSIC+UrQMD hybrid [32] and the AMPT [33] model. Taken from Ref. [34]

potential due to the $\sigma$ meson exchange becomes deeper because of its decreasing mass as the system is close to the CEP. Reviews on this very interesting topic of the relation of light nuclei and the related topic of net baryon number fluctuations to the QCD phase transition can be found, respectively, in Ref. [27] and Refs. [28–30]. For a recent review on experimental study of the QCD phase diagram in relativistic heavy ion collisions, it can be found in Ref. [31].

Recently, the STAR Collaboration has published in Physical Review Letters [34] the yield ratio $\mathcal{O}_{\text{p-d-t}}$ from the data measured during the first phase of BES experiments. This result is based on the analysis led by Daniel Cebra, Matthew Harasty, Hui Liu, Xiaofeng Luo, Nu Xu, Ning Yu, and Dingwei Zhang. As shown in Fig. 2 for Au+Au collisions in the center-of-mass energy range of $\sqrt{s_{\text{NN}}} = 7.7 - 200$ GeV, this yield ratio is enhanced at 19.6 and 27 GeV in the most central collisions, although it shows a monotonic collision energy dependence. This result has been compared with theoretical predictions of the coalescence model for deuteron and triton production based on kinetically freeze-out protons and neutrons from microscopic models for relativistic heavy ion collisions. The latter include the hybrid model based on the (3+1)D viscous hydrodynamic model MUSIC for the quark-gluon plasma and the UrQMD transport model for the hadronic matter [32, 35] as well as a multiphase transport (AMPT) model that includes both the partonic and hadronic phases [33]. With a smooth crossover transition between the quark-gluon plasma and hadronic matter, an essentially collision energy independent $\mathcal{O}_{\text{p-d-t}}$ is predicted by these models for both peripheral and central Au+Au collisions. There have been attempts to extend the study of Ref. [13] based on the NJL model for the quark matter to include its hadronization and the evolution of the resulting hadronic matter via the AMPT model [21, 36]. These studies have shown that the quark density fluctuation can largely survive hadronization but the hadron density fluctuation is somewhat washed out by their scatterings. The resulting yield ratio $\mathcal{O}_{\text{p-d-t}}$ from the nucleon coalescence model based on kinetically freeze-out nucleons can, however, still be enhanced if the system goes through the spinodal region of the QCD phase diagram from the NJL model. Because of the low critical temperature and high baryon chemical potential in the NJL model, the enhanced $\mathcal{O}_{\text{p-d-t}}$ only happens in central Au+Au collisions at center-of-mass energies lower than where the peak is seen in the STAR data. More realistic models for the QCD equation of state are thus needed in this transport model study. These equations of state can also be used in the MUSIC+UrQMD hybrid model to study the collision energy dependence of $\mathcal{O}_{\text{p-d-t}}$ and to extract the critical temperature and baryon chemical potential from the STAR data.

Besides the yield ratio $\mathcal{O}_{\text{p-d-t}}$, there are other yield ratios of light nuclei that are also sensitive to nucleon density fluctuations and can be used to probe the QCD phase diagram. For example, the yield ratio $\frac{N_\alpha N_p}{N_{^3\text{He}} N_d} \approx \frac{2\sqrt{2}}{9\sqrt{3}}(1 + \Delta p)$ is sensitive to the proton density fluctuation $\Delta p$ [24] and also to the closeness to the critical point [37]. To avoid the smearing effect of hadronic scatterings on the nucleon density fluctuations and to directly probe the large density fluctuation during the quark to hadronic matter first-order phase transition, one can consider the yield ratio of hadrons, such as $\frac{N_p N_{\bar{K}^0}}{N_{\pi^+} N_\Lambda}$ and $\frac{N_{K^+} N_{\Xi^-}}{N_\phi N_\Lambda}$, which can be shown to be sensitive to the up quark and strange quark density fluctuations, respectively, if they are produced through quark coalescence [38, 39] and their numbers do not change during the hadronic evolution as in the statistical hadronization model [40, 41]. It is worthwhile to mention that in intermediate-energy nuclear collisions, density fluctuations of produced warm nucleonic matter can be used to study the nuclear liquid–gas phase transition [42] and light nuclei produced in these collisions can be employed to probe the density dependence of nuclear symmetry energy [43, 44], which has importance implications in both nuclear structure and nuclear astrophysics.

**Acknowledgements** The author thanks Xioafeng Luo, Yugang Ma, and Kaijia Sun for comments and suggestions, and also to Kaijia Sun for the preparation of Fig. 1. His work is supported by the U.S. Department of Energy under Award No. DE-SC0015266.

## References

1. L. Adamczyk et al., Energy dependence of moments of net-proton multiplicity distributions at RHIC. Phys. Rev. Lett. **112**, 032302 (2014). https://doi.org/10.1103/PhysRevLett.112.032302
2. L. Adamczyk et al., Beam energy dependence of moments of the net-charge multiplicity distributions in Au+Au collisions at RHIC. Phys. Rev. Lett. **113**, 092301 (2014). https://doi.org/10.1103/PhysRevLett.113.092301
3. X. Luo, Q. Wang, N. Xu et al., *Properties of QCD Matter at High Baryon Density* (Springer, New york, 2022). https://doi.org/10.1007/978-981-9-4441-3
4. H.T. Ding, S.T. Li, J.H. Liu, Progress on QCD properties in strong magnetic fields from lattice QCD. Nucl. Tech. (in Chinese) **46**, 040008 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040008
5. Z.R. Zhu, Y.Q. Zhao, D.F. Hou, QCD phase structure from holographic models. Nucl. Tech. (in Chinese) **46**, 040007 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040007
6. Y.L. Du, C.M. Li, C. Shi et al., Review of QCD phase diagram analysis using effective field theories. Nucl. Techn. (in Chinese) **46**, 040009 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040009
7. Y. Yin, The best framework for exploring the QCD phase diagram: progress summary. Nucl. Tech. (in Chinese) **46**, 040010 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040010
8. F.P. Li, L.G. Pand, X.N. Wang, Application of machine learning to the study of QCD transition in heavy ion collisions. Nucl. Tech. (in Chinese) **46**, 040014 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040014
9. J. Steinheimer, J. Randrup, Spinodal amplification of density fluctuations in fluid-dynamical simulations of relativistic nuclear collisions. Phys. Rev. Lett. **109**, 212301 (2012). https://doi.org/10.1103/PhysRevLett.109.212301
10. J. Steinheimer, J. Randrup, Spinodal density enhancements in simulations of relativistic nuclear collisions. Phys. Rev. C **87**, 054903 (2013). https://doi.org/10.1103/PhysRevC.87.054903
11. J. Steinheimer, J. Randrup, V. Koch, Non-equilibrium phase transition in relativistic nuclear collisions: importance of the equation of state. Phys. Rev. C **89**, 034901 (2014). https://doi.org/10.1103/PhysRevC.89.034901
12. C. Herold, M. Nahrgang, I. Mishustin et al., Formation of droplets with high baryon density at the QCD phase transition in expanding matter. Nucl. Phys. A **925**, 14–24 (2014). https://doi.org/10.1016/j.nuclphysa.2014.01.010
13. F. Li, C.M. Ko, Spinodal instabilities of baryon-rich quark matter in heavy ion collisions. Phys. Rev. C **95**, 055203 (2017). https://doi.org/10.1103/PhysRevC.95.055203
14. N.M. Bratovic, T. Hatsuda, W. Weise, Role of vector interaction and axial anomaly in the PNJL modeling of the QCD phase diagram. Phys. Lett. B **719**, 131–135 (2013). https://doi.org/10.1016/j.physletb.2013.01.003
15. K. Xu, M. Huang, Qcd critical end point and baryon number fluctuation. Nucl. Tech. (in Chinese) **46**, 040005 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040005
16. K.J. Sun, L.W. Chen, C.M. Ko et al., Probing QCD critical fluctuations from light nuclei production in relativistic heavy-ion collisions. Phys. Lett. B **774**, 103–107 (2017). https://doi.org/10.1016/j.physletb.2017.09.056
17. S. Butler, C.A. Pearson, Deuterons from high-energy proton bombardment of matter. Phys. Rev. **129**, 836–842 (1963). https://doi.org/10.1103/PhysRev.129.836
18. A. Schwarzschild, C. Zupancic, Production of tritons, deuterons, nucleons, and mesons by 30-GeV protons on A-1, Be, and Fe targets. Phys. Rev. **129**, 854–862 (1963). https://doi.org/10.1103/PhysRev.129.854
19. R. Bond, P.J. Johansen, S.E. Koonin et al., Breakup densities of nuclear fireballs. Phys. Lett. B **71**, 43–47 (1977). https://doi.org/10.1016/0370-2693(77)90735-3
20. H. Sato, K. Yazaki, On the coalescence model for high-energy nuclear reactions. Phys. Lett. B **98**, 153–157 (1981). https://doi.org/10.1016/0370-2693(81)90976-X
21. K.J. Sun, C.M. Ko, F. Li et al., Enhanced yield ratio of light nuclei in heavy ion collisions with a first-order chiral phase transition. Eur. Phys. J. A **57**, 313 (2021). https://doi.org/10.1140/epja/s10050-021-00607-4
22. L.L. Zhu, B. Wang, M. Wang et al., Energy and centrality dependence of light nuclei production in relativistic heavy-ion collisions. Nucl. Sci. Tech. **33**, 45 (2022). https://doi.org/10.1007/s41365-022-01028-8
23. K.J. Sun, L.W. Chen, C.M. Ko et al., Light nuclei production as a probe of the QCD phase diagram. Phys. Lett. B **781**, 499–504 (2018). https://doi.org/10.1016/j.physletb.2018.04.035
24. K.J. Sun, F. Li, C.M. Ko, Effects of QCD critical point on light nuclei production. Phys. Lett. B **816**, 136258 (2021). https://doi.org/10.1016/j.physletb.2021.136258
25. E. Shuryak, J.M. Torres-Rincon, Baryon clustering at the critical line and near the hypothetical critical point in heavy-ion collisions. Phys. Rev. C **100**, 024903 (2019). https://doi.org/10.1103/PhysRevC.100.024903
26. E. Shuryak, J.M. Torres-Rincon, Baryon preclustering at the freeze-out of heavy-ion collisions and light-nuclei production. Phys. Rev. C **101**, 034914 (2020). https://doi.org/10.1103/PhysRevC.101.034914
27. K.J. Sun, L.W. Chen, C.M. Ko et al., Light nuclei production and QCD phase transition in heavy-ion collisions. Nucl. Tech. (in Chinese) **46**, 040012 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040012
28. Q. Chen, G.L. Ma, J.H. Chen, Transport model study of conserved charge fluctuations and QCD phase transition in heavy-ion collisions. Nucl. Tech. (in Chinese) **46**, 040013 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040013
29. X. Luo, N. Xu, Search for the QCD critical point with fluctuations of conserved quantities in relativistic heavy-ion collisions at RHIC : an overview. Nucl. Sci. Tech. **28**, 112 (2017). https://doi.org/10.1007/s41365-017-0257-0
30. S.J. Wu, H.C. Song, Critical dynamical fluctuations near the QCD critical point. Nucl. Tech. (in Chinese). **46**, 040004 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040004
31. Y. Zhang, D.W. Zhang, X.F. Luo, Experimental study of the QCD phase diagram in relativistic heavy-ion collisions. Nucl. Tech. (in Chinese) **46**, 040001 (2023). https://doi.org/10.11889/j.0253-3219.2023.hjs.46.040001
32. W. Zhao, C. Shen, C.M. Ko et al., Beam-energy dependence of the production of light nuclei in Au + Au collisions. Phys. Rev. C **102**, 044912 (2020). https://doi.org/10.1103/PhysRevC.102.044912
33. K.J. Sun, C.M. Ko, Light nuclei production in a multiphase transport model for relativistic heavy ion collisions. Phys. Rev. C **103**, 064909 (2021). https://doi.org/10.1103/PhysRevC.103.064909
34. M.I. Abdulhamid, B.E. Aboona, J. Adam et al., Beam energy dependence of triton production and yield ratio ($N_t \times N_p/N_d^2$) in Au+Au collisions at RHIC. Phys. Rev. Lett. **130**, 202301 (2023). https://doi.org/10.1103/PhysRevLett.130.202301
35. W. Zhao, K.J. Sun, C.M. Ko et al., Multiplicity scaling of light nuclei production in relativistic heavy-ion collisions. Phys. Lett.

B **820**, 136571 (2021). https://doi.org/10.1016/j.physletb.2021.136571

36. K.J. Sun, W.H. Zhou, L.W. Chen, et al., Spinodal enhancement of light nuclei yield ratio in relativistic heavy ion collisions. arXiv:2205.11010
37. E. Shuryak, J.M. Torres-Rincon, Light-nuclei production and search for the QCD critical point. Eur. Phys. J. A **56**, 241 (2020). https://doi.org/10.1140/epja/s10050-020-00244-3
38. C.M. Ko, Theoretical perspective on strangeness production. EPJ Web Conf. **171**, 03002 (2018). https://doi.org/10.1051/epjconf/201817103002
39. T. Shao, J. Chen, C.M. Ko et al., Probing QCD critical fluctuations from the yield ratio of strange hadrons in relativistic heavy-ion collisions. Phys. Lett. B **801**, 135177 (2020). https://doi.org/10.1016/j.physletb.2019.135177
40. A. Andronic, P. Braun-Munzinger, J. Stachel, Hadron production in central nucleus?nucleus collisions at chemical freeze-out. Nucl. Phys. A **772**, 167 (2006). https://doi.org/10.1016/j.nuclphysa.2006.03.012
41. J. Cleymans, H. Oeschler, K. Redlich et al., Comparison of chemical freeze-out criteria in heavy-ion collisions. Phys. Rev. C **73**, 034905 (2006). https://doi.org/10.1103/PhysRevC.73.034905
42. C. Liu, X.G. Deng, Y.G. Ma, Density fluctuations in intermediate-energy heavy-ion collisions. Nucl. Sci. Tech. **33**, 52 (2022). https://doi.org/10.1007/s41365-022-01040-y
43. L.W. Chen, C.M. Ko, B.A. Li, Light cluster production in intermediate-energy heavy ion collisions induced by neutron rich nuclei. Nucl. Phys. A **729**, 809 (2003). https://doi.org/10.1016/j.nuclphysa.2003.09.010
44. L.W. Chen, C.M. Ko, B.A. Li, Light clusters production as a probe to the nuclear symmetry energy. Phys. Rev. C **68**, 017601 (2003). https://doi.org/10.1103/PhysRevC.68.017601