

2 - 2 Review of Annual Progress from Nuclear Matter Phase Structure Group*

Qiu Hao and Zhang Yapeng

The Nuclear Matter Phase Structure Group at the Nuclear Matter Research Center (QMRC) is focused on investigating the phase structure of Quantum Chromodynamics (QCD) matter and studying the properties of nuclear matter under extreme conditions. To achieve these objectives, the group leverages heavy-ion collision (HIC) experiments, which enable the creation of hot and condensed nuclear matter in laboratory settings. The group's research efforts are primarily concentrated on two heavy-ion experiments: the CEE experiment at the Heavy Ion Research Facility in Lanzhou-Cooler storage Ring (HIRFL-CSR) and the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). Additionally, the group collaborates closely with a theoretical team in order to further enhance their research endeavors. In the paragraphs that follow, we briefly summarize the advancements made by both the experimental and theoretical teams in 2022.

The CSR External-target Experiment (CEE) ^[1] will be the first large-scale nuclear physics apparatus in the GeV region constructed by Chinese scientists. The CEE project includes 8 sub-detection systems, *i.e.* super-contraction dipole magnet, silicon pix based beam monitor (BM), start time detector (T0), time projection chamber (TPC), multi-wire drift chamber array (MWDC), inner and external time of flight detector (iTOF and eTOF) and zero-degree detector (ZDC), and 6 public support systems, *i.e.* data acquisition (DAQ), trigger system (Trigger), high-precision clock system (CLK), slow control (SL), technical support system and simulation and analysis software system. The CEE experiment has been under construction since 2020, and it is expected to take data in 2024. In 2022, all sub-systems of the CEE project have switched to the phase of engineering prototype, and eTOF sub-system has been in the phase of massive production. The overall mechanical design of the CEE project has been completed. The interfaces between sub-detection systems and the public technical support system, in aspects of mechanics, power, electronics, data communication, trigger and clock format, are finalized. A computing farm for the CEE experiment has been built in this year, which includes about 500 CPU cores and 2.1 PB storage space. CEE Simulation and analysis software (CeeROOT), based on FairROOT platform, is further developed. The event data model (EDM) for all sub-detectors are finalized. The renovation of the foundation and the ground wire have been finished, the gas system, cabling, control room, UPS power system will be installed or built in 2023. CEE simulation software frame has been developed and maintained by our group. The fully simulation chain of the TPC has been established. In order to improve track momentum resolution, position resolution and double-track separation capability, the shape of TPC read-out pad is optimized from rectangle shape to zigzag configuration. A tracker for the TPC including track finder and track fitting, based on the Cellular Automata (CA) algorithm and the Kalman-filter method, has been developed by our group, and it has been integrated into the CeeROOT software. The tracker can find tracks properly with MC events, with optimized track finder algorithm, the track finder speed was decreasing significantly, and its tracker finder speed is close to existing HIC experiment like the STAR experiment. Meanwhile, the TPC tracking team is still trying to further optimize the running speed and tracking efficiency of the tracker. A event plane reconstruction algorithm has been developed based on ZDC simulated data, and the event plane resolution with IQMD events can reach about 90%. Algorithms for defining the colliding centrality are developing based the conventional method of track/TOF hit multiplicities method and machine learning method. Based on the fast simulation package and IQMD data, systematic uncertainty of π^\pm yields filtered by the CEE spectrometer is investigated, it is found that π^\pm yields and their transverse momentum spectra can be properly measured within a systematic uncertainty of a few percent.

Based on the STAR experiment, our group worked on the physics topics of net-baryon fluctuation, spin physics, collective flow, hypernuclei production and so on. High-order moments of net proton number is an important observable searching for the critical point in the QCD phase diagram. A preliminary result of the high-order moments of net proton number in STAR 3.2 GeV fixed-target experiments has been obtained. we have measured the global spin alignment of ϕ and K^{*0} vector mesons in Au+Au collisions at 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4, and 200 GeV using the data from the first phase of the Beam Energy Scan (BES) program^[2], as shown in Fig. 1. We observed that the ρ_{00} of ϕ meson is unexpectedly large, while that of K^{*0} is in line with non-polarization baseline. The magnitude of ϕ meson ρ_{00} can not be explained by any conventional mechanisms but may be attributed to the influence of a vector meson strong force field. This work provides a potential new avenue for understanding the strong interaction at work at the sub-nucleon level. We have measured the transverse momentum spectra and yield of K^{*0} in Au+Au collisions at 11.5, 14.5, 19.6, 27, and 39 GeV^[3] from BES program. From the particle

ratios, K^{*0}/K and ϕ/K , we have demonstrated the dominance of re-scattering in hadronic phase of the medium at RHIC BES energies. Based on K^{*0}/K ratios, we have estimated the lower limit of lifetime hadronic phase at BES energies. The heavy ion collisions can generate an enormously large magnetic field ($eB \sim 10^{18}$ Gauss). The difference in rapidity-odd directed flow of positively and negatively charged particles (Δv_1) is an excellent probe for such strong B -field. We have reported the Δv_1 of pions, kaons and protons in isobar (Ru+Ru and Zr+Zr) collisions at 200 GeV^[4]. The negative sign of Δv_1 of protons (and kaons) at peripheral collisions may be attributed as an evidence of the strong electromagnetic field driven effects in heavy ion collisions. Recently, group number Yi Yin *et al.* predicted that difference in local polarization of Λ and $\bar{\Lambda}$ at BES energies can be used to probe a novel or baryonic Spin Hall effect (SHE)^[5]. We have reported preliminary measurement of local polarizations of Λ and $\bar{\Lambda}$ in Au+Au collisions at 19.6 and 27 GeV. Within present uncertainties, there is no indication of baryonic SHE at these energies. The analysis at lower BES energies (<19.6 GeV), where the SHE signal is expected to be stronger, is under way.

Collective flows has been commonly used for studying the properties of matter created in high-energy heavy-ion collisions, due to its high sensitivity to early stage collision dynamics. The first-order and second-order Fourier coefficient of azimuthal distributions of produced particles in HICs are called directed flow (v_1) and elliptic flow (v_2) respectively. Using the data from the STAR fixed-target Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$ and 4.5 GeV, we have extracted v_1 and v_2 of light nuclei (d, t, ${}^3\text{He}$ and ${}^4\text{He}$), and the detection efficiency correction and systematic uncertainty for the measurements are in progress. Significant directed flow of hypernuclei ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ signals were observed in fixed-target Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV for the first time. Comparing to that of light nuclei, it is found that the mid-rapidity v_1 slopes of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ follow baryon number scaling, implying that the coalescence is the dominant mechanism for these hypernuclei production in the 3 GeV Au+Au collisions. This result has been accepted by journal of Physical Review Letters. Meanwhile, direct flow of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ in fixed-target Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9, 4.5$ GeV are also in progress. An antimatter hypernucleus ${}^4_{\Lambda}\bar{\text{H}}$, composed of 4 antibaryons, has been observed via its two-body decay ${}^4_{\Lambda}\bar{\text{H}} \rightarrow {}^4\bar{\text{He}} + \pi^+$ in Au+Au, U+U, Ru+Ru, and Zr+Zr collisions with energy equal or close to 200 GeV at RHIC. Lifetimes of anti-hypernuclei ${}^3_{\Lambda}\bar{\text{H}}$ and ${}^4_{\Lambda}\bar{\text{H}}$ are measured for the first time. Data analysis including efficiency correction has finished, final results is under collaboration review. The production yield of hypernuclei ${}^4_{\Lambda}\text{He}$ was analysed in 3 GeV Au+Au collisions with its three-body decay channel of ${}^4_{\Lambda}\text{He} \rightarrow {}^3\text{He} + p + \pi^-$ in 0~50% centrality, the systematic uncertainty of this analysis is in progress (Fig. 1).

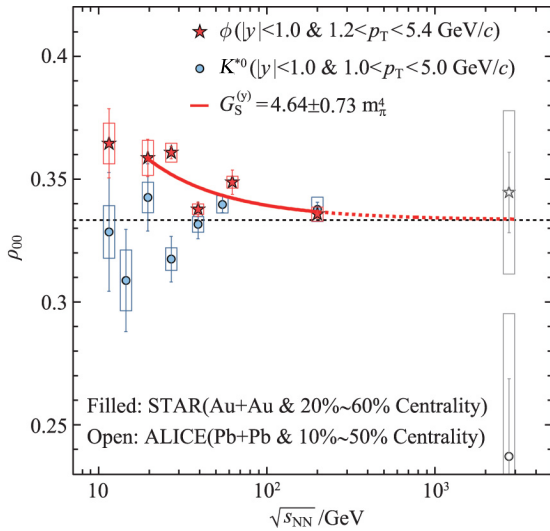


Fig. 1 (color online) Global spin alignment of ϕ and K^{*0} vector mesons in heavy-ion collisions. The measured matrix element ρ_{00} as a function of beam energy for the ϕ and K^{*0} vector mesons within the indicated windows of centrality, transverse momentum (p_T) and rapidity (y). The open symbols indicate ALICE results for Pb+Pb collisions at 2.76 TeV at p_T values of 2.0 and 1.4 GeV/c for the ϕ and K^{*0} mesons, respectively, corresponding to the p_T bin nearest to the mean p_T for the 1.0 ~ 5.0 GeV/c range assumed for each meson in the present analysis. The black dashed line represents $\rho_{00} = 1/3$.^[2]

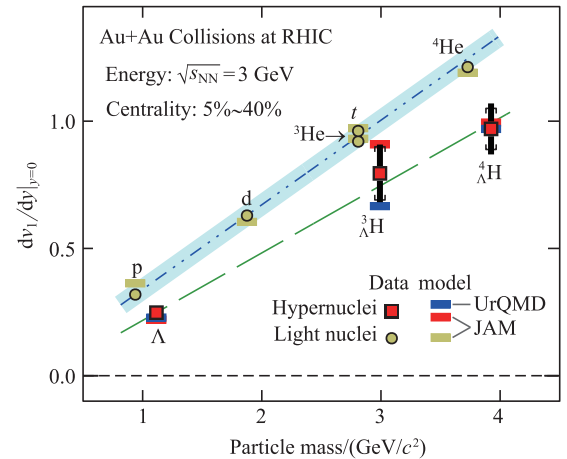


Fig. 2 (color online) Mass dependence of the mid-rapidity v_1 slope, dv_1/dy , for Λ , and from the 35% ~ 40% mid-central Au+Au collisions. The statistical and systematic uncertainties are presented by vertical lines and square brackets, respectively. The slopes of p, d, t, ${}^3\text{He}$ and ${}^4\text{He}$ from the same collisions are shown as black circles. The blue and dashed green lines are the results of a linear fit to the measured light nuclei and hypernuclei v_1 slopes, respectively. For comparison, calculations of transport models plus coalescence afterburner are shown as gold and red bars from JAM model, and blue bars from UrQMD model^[6].

On the theoretical side, we have a team focusing on the QCD phase structure and the spin polarization. We have made essential steps in studying both the spin and phase structure of QCD matter. In particular, we are the first group applying the newly developed non-equilibrium effective field theory to study the hydrodynamic fluctuations in the context of heavy-ion collisions experiments. In Ref. [2], we introduce a freeze-out procedure to convert the critical fluctuations in a droplet of quark-gluon plasma (QGP) that has, as it expanded and cooled, passed close to a posited critical point on the phase diagram into cumulants of hadron multiplicities that can subsequently be measured. In Ref. [3], we study this important mechanism for spin polarization generation that has not been systematically explored before and predict the signature of the SHE in those collisions using a (3+1) D viscous hydrodynamic model MUSIC with AMPT initial condition. We propose to use the second Fourier coefficients of the net spin polarization of Lambda hyperon as sensitive probes to search for the SHE (Fig. 2).

References

- [1] L. Lü, H. Yi, Z. Xiao, et al., *Sci. China Phys. Mech. Astron.*, 60(2017)012021.
- [2] M. S. Abdallah, *Nature*, 7947, 614(2023)244. [arXiv:2204.02302 [hep-ph]].
- [3] M. Abdallah, *Phys. Rev. C*, 107, 3(2023)034907.
- [4] [STAR], [arXiv:2304.03430 [nucl-ex]].
- [5] S. Y. F. Liu, Y. Yin, *JHEP*, 07(2021)188. doi:10.1007/JHEP07(2021)188 [arXiv:2103.09200 [hep-ph]].
- [6] [STAR], [arXiv:2211.16981 [nucl-ex]].

* Foundation item: National Natural Science Foundation of China (11927901) and MOST (2015CB856903)

2 - 3 Exploring the Phase and Spin Structure of QCD Matter*

Yin Yi

Exploration of the phase and spin structure of quantum chromodynamics (QCD) matter is one of the primary goals of the heavy-ion collision program. The intriguing hints observed in the first phase of the Beam energy scan (BES), in particular the deviations of certain measures of fluctuations from their non-critical baseline, deviations that vary non-monotonically as a function of \sqrt{s} , motivate the ongoing experimental efforts in its second, higher statistics, phase (BES II) to look for the conjectured QCD critical point. BES II data has been taken by the STAR collaboration over the course of 2019-2021 in AuAu collisions at a sequence of collision energies, which corresponds to a scan in μ_B . The data is currently being analyzed and we look forward with considerable anticipation to learning much from these measurements. Furthermore, the recent observation of Λ hyperon polarization produced in heavy-ion collisions opens a new research front in understanding spin structure of hot and dense nuclear matter.

We have made essential steps in studying both spin and phase structure of QCD matter. In particular, we are the first group applying the newly developed non-equilibrium effective field theory to study the hydrodynamic fluctuations in the context of heavy-ion collisions experiments. The non-Gaussian fluctuations of baryon density are sensitive to the presence of the conjectured QCD critical point. Their observational consequences are crucial for the ongoing experimental search for this critical point through the beam energy scan program at Relativistic Heavy Ion Collider (RHIC). In the expanding fireball created in a heavy-ion collision, critical fluctuations would inescapably fall out of equilibrium and require a systematic description within a dynamical framework. In Ref. [1], we employ newly developed effective field theory (EFT) for fluctuating hydrodynamics to study the real-time critical non-Gaussian fluctuations of a conserved charge density. In particular, we derive the evolution equations for multi-point correlators of density fluctuations and obtain the closed-form solutions with arbitrary initial conditions that can readily be implemented in realistic simulations for heavy-ion collisions. We find that non-linear interactions among noise fields, which are missing in traditional stochastic hydrodynamics, could potentially contribute to the quartic (fourth-order) fluctuations in the scaling regime even at tree level in non-equilibrium situations.