CHAPTER I
INTRODUCTION

Heavy-ion collisions offer a unique testing ground for studying the properties of nuclear matter under various conditions. Advancements in theory and experiment over several decades have led more research areas to converge on a few, or perhaps even a single, fundamental truth about the universe. The acquired knowledge and interdependent knowledge are intertwined between various fields of physics research especially between nuclear physics and astrophysics. As various puzzles from astrophysics can be solved by testing on Earth within the heavy-ion collision facilities and the nuclear physics puzzles can also be tested with observable stellar objects, e.g., neutron stars and binary neutron mergers, dark matter, and others. This leads the heavy-ion collision facilities all over the world to move their focus toward the lower energy collisions, low temperature with extreme density, in order to probe various scenarios within the QCD phase diagram especially for the existence of the critical end point and the Equation of state (EoS) which is a direct connection between the nuclear properties and the compact stellar objects like neutron stars. The Beam Energy Scan (BES) program initiated by RHIC, and upcoming experiments GSI-FAIR and HADES that are joining the efforts, are particularly designed for low energy regimes.

During this PhD studies, our colleges and me have been investigated the dynamics of the heavy-ion collisions particularly focusing on its space-time dynamics ranging from the initial stage to the final stage of the heavy-ion collisions. Together, we have published the following papers:

1. Kittiratpattana, A., Reichert, T., Steinheimer, J., Herold, C., Limphirat, A., Yan, Y., and Bleicher, M. (2022). Correcting the B_A coalescence factor at energies relevant for the GSI-HADES experiment and the RHIC Beam Energy Scan. *Phys. Rev. C*, 106(4):044905 (Kittiratpattana et al., 2022)

2. Reichert, T., Kittiratpattana, A., Li, P., Steinheimer, J., and Bleicher, M. (2023a). Probing system size dependence at high baryon density by systematic comparison of Ag+Ag and Au+Au reactions at 1.23A GeV. *J. Phys. G*, 50(2):025104 (Reichert et al., 2023a)

3. Li, P., Steinheimer, J., Reichert, T., Kittiratpattana, A., Bleicher, M., and Li, Q. (2023). Effects of a phase transition on two-pion interferometry in heavy ion collisions at $\sqrt{s_{\mathrm{NN}}} = 2.4 - 7.7$ GeV. *Sci. China Phys. Mech. Astron.*, 66(3):232011 (Li et al., 2023)

4. Kittiratpattana, A., Reichert, T., Li, P., Limphirat, A., Herold, C., Steinheimer, J., and Bleicher, M. (2023). Investigating the cluster production mechanism with isospin triggering: Thermal models versus coalescence models. *Phys. Rev. C*, 107(4):044911 (Kittiratpattana et al., 2023)

5. Reichert, T., Savchuk, O., Kittiratpattana, A., Li, P., Steinheimer, J., Gorenstein, M., and Bleicher, M. (2023b). Decoding the flow evolution in Au+Au reactions at 1.23A GeV using hadron flow correlations and dileptons. *Phys. Lett. B*, 841:137947 (Reichert et al., 2023b)

6. Kittiratpattana, A., Reichert, T., Buyukcizmeci, N., Botvina, A., Limphirat, A., Herold, C., Steinheimer, J., and Bleicher, M. (2024). Production of nuclei and hypernuclei in pion-induced reactions near threshold energies. *Phys. Rev. C*, 109(4):044913 (Kittiratpattana et al., 2024)

However, the scope of this thesis will be on the exploration and demonstration of the dynamics of heavy-ion collisions, with a particular emphasis on the interplay and the utilization between (hyper)nuclei formation and space-time evolution of the created fireball, considering the various dependencies that influence them especially toward lower energies, e.g., the beam energy, EoS, formation mechanisms, stopping power, and system size. These studies are essential to the study of QCD matter, the critical behavior, and potentially to constrain the EoS. They are reported in the following papers:

- Kittiratpattana, A., Reichert, T., Steinheimer, J., Herold, C., Limphirat, A., Yan, Y., and Bleicher, M. (2022). Correcting the B_A coalescence factor at energies relevant for the GSI-HADES experiment and the RHIC Beam Energy Scan. *Phys. Rev. C*, 106(4):044905 (Kittiratpattana et al., 2022)

- Li, P., Steinheimer, J., Reichert, T., Kittiratpattana, A., Bleicher, M., and Li, Q. (2023). Effects of a phase transition on two-pion interferometry in heavy ion collisions at $\sqrt{s_{NN}} = 2.4 - 7.7$ GeV. *Sci. China Phys. Mech. Astron.*, 66(3):232011 (Li et al., 2023)

- Kittiratpattana, A., Reichert, T., Li, P., Limphirat, A., Herold, C., Steinheimer, J., and Bleicher, M. (2023). Investigating the cluster production mechanism with isospin triggering: Thermal models versus coalescence models. *Phys. Rev. C*, 107(4):044911 (Kittiratpattana et al., 2023)

- Kittiratpattana, A., Reichert, T., Buyukcizmeci, N., Botvina, A., Limphirat, A., Herold, C., Steinheimer, J., and Bleicher, M. (2024). Production of nuclei and hypernuclei in pion-induced reactions near threshold energies. *Phys. Rev. C*, 109(4):044913 (Kittiratpattana et al., 2024)

To achieve these goals, both theoretical and simulation models are indispensable because first principle QCD calculations are computationally too expensive. These models help us understand the origin of particle formations and the space-time evolution of the systems, as well as help us interpret experimental data. This thesis employs the UrQMD v3.5 transport model for event simulations and comparing the results with findings from our assumptions and/or other models. The importance on the understanding of space-time picture of the heavy-ion collisions and the development of theoretical models as well as other prospects are introduced and discussed in Chapter II. Chapter III focuses on developments and core assumptions of various simulation models.

Ch. IV points out our aims by demonstrating the utilization of the space-time structure of the fireball and the influences from the beam energies and the EoS. The space-time dynamics in the context of beam energies are explored based on the cluster formations in Sec. 4.1. The spatial geometric coalescence model is adopted and improved to estimate the (anti)deuteron productions and to extract the space-time structure of (anti)nucleon source. The (anti)nucleon source geometries will also be tested and confirmed with the UrQMD simulation. The extracted source geometries might help in revealing the presence of critical behavior on the beam energy spectrum and provide a proper explanation for the space-time structure of nucleon and antinucleon source geometries. Additionally, the space-time structure of the fireball is further investigated on various EoS with different phase transition scenarios from the standard UrQMD EoS to the chiral mean field EoS with and without phase transition. Sec. 4.4 will illustrate not only the energy-dependence but also the density-dependent nature of the emission source geometry. The distinct critical behaviors from HBT radii and the UrQMD freeze-out time are expected and the corresponding critical density could be extracted.

The cluster formations, e.g. (anti)deuteron, from the previous chapter, have displayed some of their influences on the emission source structure which may potentially lead to the possible critical behavior of the fireball. As final stage observables, these clusters, in fact, can be also influenced by many more factors since the early stage ranging from the strangeness enhancement, the fluctuations, correlations, and initial collision geometries which all are as sensitive to the EoS and the critical behavior. They also have a direct implication for the astrophysics subjects like the neutron star structure, the early universe, and dark matter. Moreover, different assumptions on their formation mechanisms could also result in different outcomes and interpretations. Thus, all of these topics will be reviewed in detail in Ch. V.

Due to the maximum fluctuations and correlations of conserved quantities as well as the prolonging of the relaxation time, the critical behavior could be manifested by the cluster formations, particularly within the coalescence picture. The coalescence parameter reflects the emission volume with an inverse proportional relation. However, this volume is not the same as the (charged) volume from the thermal picture which scales monotonic exponentially with the beam energies. Instead, it is similar to the homogeneity volume of the HBT emission source. However, at low energies, the experimental data of B_2 and B_3 from various experiments indicate that this emission source volume behaves like the thermal volume which is unlikely. Ch. VI will address the discrepancy in coalescence parameter B_A measurements by proposing a corrected formula to account for primordial nucleons. The correction is expected to bring coalescence parameters to align with HBT predictions as a support the validity of our approach providing a consistent space-time picture.

To accurately estimate and interpret the final-stage cluster spectra from experiments, an understanding of their space-time origin and formation mechanisms is needed. There are tensions on the origin of these clusters from the two most common mechanisms, i.e., the thermal and coalescence model. A key distinction between them is the difference in space-time pictures of their occurrences. That is, the thermal model directly produces and emits clusters from the hot fireball at the chemical freeze-out together with all other particle species, while the coalescence model happens during the final stage of the collisions, kinetic freeze-out. Given our focus on the space-time dynamics of collisions, we leverage this difference and aim to resolve this tension. In Ch. VII will demonstrate how these clusters experienced the isospin equilibration from the chemical freeze-out. The isospin exchange should lead to the fluctuations of the available nucleons to coalesce in the system. Due to this, the district maxima behaviors of clusters could be expected while the grand-canonical thermal model will average out all the fluctuation and only show constant thermal yields. This will be a clear indication that the clusters must be formed later at kinetic freeze-out with the coalescence picture.

The solutions for such debate can also be investigated at different collision systems via the hypernuclei formations. The coalescence models predict a stronger suppression on the system size-dependence of the hypertrition yield ratio ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ when compared with the thermal model's. This raises the need for data at smaller system sizes. These data will not only help to pin down the cluster mechanisms between the thermal and coalescence models but also be crucial for the hypernuclei internal interactions which have a direct implication on constraining the neutrons star EoS. The investigation in Ch. VIII will provide another coalescence prediction for hypertrition yield ratio at even lower energies and smaller system sizes and point out the potential advantages of pion-induced reactions at HADES experiments for studying (hyper)nuclei formations. The UrQMD and the Statistical Multifragmentation Model (SMM) will be employed to show that (hyper)nuclei abundances in these reactions are comparable or could even be higher than those at high-energy facilities. Since the environments provided by the pion beam at HADES is conductive for (hyper)nuclei formation due to a stronger stopping power than other collision systems.