CHAPTER IX
SUMMARY

In this thesis, we emphasize the importance of the understanding of the space-time picture of heavy-ion collision dynamics (as highlighted in Ch. II) which is helpful for the search of a potential critical point and constraining the EoS for neutron stars. These two topics are some of the main efforts for most of the future facilities, especially the BES program and GSI-FAIR and HADES. Various theoretical and simulation models are important tools for describing the physics and properties of the medium. Ch. III provides a brief introduction of transport, hydrodynamics, and hybrid models. The corresponding assumptions and advantages of these models are covered. For a microscopic treatment with realistic correlations and fluctuations, we adopt the UrQMD v3.5 transport model for event simulations and for the whole thesis.

The space-time structure of the fireball is explored by demonstrating the interplay between the coalescence parameter B_2 and the (anti)nucleon source geometries in Sec. 4.1 of Ch. IV. By adopting the Mrówczyński's spatial coalescence model, we investigate the (anti)deuteron production and extract the (anti)nucleon source radii r_0 and r_* by fitting the (anti)deuteron formation rate with the available coalescence parameter data B_2 and $\overline{B_2}$ from NA49 to STAR. The simulations from the cascade UrQMD v3.5 transport model show agreement with our (anti)nucleon source geometries, in which the antinucleon source suffers from the $N\overline{N}$-annihilation at the center. The comparison of r_0/r_* from both models shares a similar trend. However, the r_0/r_* from our model exhibits a sign for critical behavior from the observed local maxima of both antinucleon source radii at $\sqrt{s_{NN}} = 27$ GeV. This finding also indicates that the (anti)nucleon emission source V_{source} of the coalescence model is not the same as the thermal (charged) volume V_{chem}, which always scales with the collision energy. This motivates us to further investigate and compare the effects of different critical behaviors on the emission source.

Since the interpretation of extracted (anti)nucleon sources is similar to the HBT source volume, we utilize two-pion HBT interferometry to study the source volume in Sec. 4.4, particularly the effects of different EoS with and without phase transition for the neutron star-like medium, i.e., HADES to STAR energies. We begin our investigation by showing that the impact from the Coulomb potential is minimal and negligible around these energies, where the strong interaction is dominant. The simulation results from the CMF_PT2 EoS are the only EoS that exhibits critical behavior from the phase transition, where the nuclear density for the phase transition to occur in this energy range is around $\rho_B/\rho_0 \leq 4 - 5$. The emission time distribution from the UrQMD v3.5 transport model further supports this critical behavior of CMF_PT2 by extending the freeze-out time distribution of the π^- toward the cascade's at higher energies. This indicates that the HBT radii are sensitive and can be used to test and constrain the EoS.

The space-time structure of emission sources is usually related to the coalescence parameters which are measured by either the HBT method or the cluster yields. However, in order to correctly estimate cluster formations and interpret the experimental data, we need to have a clear understanding of their origins and their implications to the whole space-time dynamics of the collisions. Ch. V details various possible cluster formation mechanisms and also highlights hypernuclei formation which shares a similar basis with normal cluster formation.

We continue our discussion on the emission source volume toward even lower collision energies. It is well known and has been clarified in this thesis how the coalescence parameter is inversely proportional to the emission source $B_A \propto \left(1/V\right)^{A-1}$, which is again equivalent to the volume of homogeneity of the HBT volume. However, the HBT prediction drops at lower energies, showing a discrepancy with the increasing B_A from the experiments. To solve this disagreement, we demonstrate in Ch. VI that the measurements of B_A from all experimental facilities are obtained from the estimated final state neutrons, e.g., $B_2 \simeq d/p^2_{\text{final}}$, which is justified only at high energies. We propose to make adjustments to B_A measurements by calculating the correct distributions of primordial protons and neutrons, e.g., $B_2 \simeq d/\left(pn\right)_{\text{prim}}$. By validating our formula with the simulated events from the UrQMD v3.5 transport model, our corrected B_A indeed aligns with the emission volume predicted by the HBT method, providing a consistent picture of the emission source.

One of the most debated concepts in cluster formation is which mechanism is realized in nature, especially the controversial interpretation of cluster formation within the thermal model. In Ch. VII, we propose an approach, based on the different distinct space-time pictures, to distinguish between the thermal (chemical freeze-out) and coalescence (kinetic freeze-out) model in order to solve this tension. By using the isospin triggering $\Delta Y_\pi = \left(Y_{\pi^-} - Y_{\pi^+}\right)$, the results from the UrQMD v3.5 transport model agree with our theoretical estimates as the simulated deuterons, tritons, and ^{3}He all show their maxima indicating the ΔY_{π}-dependent. This is a clear illustration that the coalescence mechanism, which occurs at the kinetic freeze-out, is sensitive to the isospin fluctuations and thus is responsible for the cluster formation.

Another difference between the thermal model and coalescence model is also apparent in the system size-dependence of the hypertriton ratio, ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$. The coalescence model predicts a stronger suppression than the canonical thermal model. Also, the study of the critical behavior and the constraint for the low energy EoS (neutron star conditions) involve not only normal nuclei but also hypernuclei and their interactions, e.g., YN$-$ and/or YYN$-$interaction. Hence, our last Ch. VIII begins by highlighting the need for low energy and a small system for hypernuclei formation. We employ the UrQMD v3.5 transport model to simulate the same collisions of $\pi^{-} + \mathrm{C}$ and $\pi^{-} + \mathrm{W}$ at $p_{lab} = 1.7$ GeV as at HADES and contrast the results with the SMM model for the (hyper)nuclei formation. We found that the extrapolation fit function needs to be adjusted due to the residue protons sitting in the target region, which is outside of the detector acceptance. The light nuclei rapidity distributions further show that the incoming pions can only knock one or two nucleons off the target region, which is a favorable condition for cluster formation or fragmentation. This is further supported by the integrated total yields that (hyper)nuclei, produced with pion-induced reactions, are comparable and even higher than those at p+A and A+A collisions. These indicate that the pion beam at HADES provides a conductive environment to explore these rare probes. Finally, we end our investigation by showing that the ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ from pion-induced reactions could indeed provide a new measurement at a lower system size and also exhibit a strong suppression following the prediction of the coalescence model.