

CONTENTS

	Page
ABSTRACT IN THAI	I
ABSTRACT IN ENGLISH	III
ACKNOWLEDGEMENTS	V
CONTENTS	VII
LIST OF TABLES	X
LIST OF FIGURES	XI
LIST OF ABBREVIATIONS	XXII
 CHAPTER	
I INTRODUCTION	1
II PROSPECTS OF HEAVY-ION COLLISIONS	6
2.1 Exploring the QCD Phase Diagram	6
2.1.1 The Development of Models and Equation of State	6
2.1.2 Beam Energy Scan and Low Energy Regime	13
2.2 Space-Time Evolution	15
III MODELLING HEAVY-ION COLLISIONS	18
3.1 Transport models	19
3.2 Boltzmann(Vlasov)-Uehling-Uhlenbeck (B(V)UU) approach	19
3.3 Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model	24
3.3.1 Initialization	24
3.3.2 Propagation and Collision	26
3.3.3 (Hyper)nuclei Formation Routine	29
3.4 Hydrodynamics Models	30
3.5 Hybrid Models	32
IV EXPLORING THE SPACE-TIME STRUCTURE OF THE FIREBALL	36
4.1 (Anti)deuteron formation rate and source geometry	37
4.1.1 Mrówczyński Density Function	38
4.2 Energy Dependence of Formation Geometry	40
4.3 Validation with UrQMD	43
4.4 HBT Correlation	47

CONTENTS (Continued)

	Page
4.4.1 Two-Particle Correlations	48
4.5 Simulation set-ups and EoS	52
4.6 Two-Pion HBT Analysis	54
4.7 Effect of the EoS with Phase Transition	57
4.8 Space-time Structure from HBT radii	58
V REVIEWS ON (HYPER) (LIGHT) NUCLEI	64
5.1 Role of (Hyper)Nuclei Formation	64
5.1.1 Hypernuclei	68
5.2 Cluster Formation Mechanisms	69
5.2.1 Thermal productions	69
5.2.2 Coalescence Model	72
Simple Momentum Coalescence	73
Analytic Coalescence Models	76
Wigner's Function	78
5.2.3 Dynamical Model	79
5.2.4 Multifragmentation	82
VI CORRECTING B_A COALESCENCE FACTOR	85
6.1 Problems with B_A	86
6.2 Reconstructing Primordial Protons and Neutrons	87
6.2.1 Rapidity Distribution	87
6.2.2 p_T Distribution	90
6.2.3 Estimating B_2 and B_3	93
VII INVESTIGATING CLUSTER PRODUCTION MECHANISMS	99
7.1 Thermal vs Coalescence	99
7.2 Isospin triggering	100
7.2.1 Simple estimates	101
7.3 Qualitative Estimates	103
7.3.1 Freeze-out time distributions	104
7.4 Light cluster yields versus isospin fluctuation	105

CONTENTS (Continued)

	Page
VIII RESULTS IN PION INDUCED REACTIONS	109
8.1 The needs and potential of small collision systems	109
8.2 Model Setup	112
8.3 Proton and Λ Baryon Production	113
8.4 (Light) Nuclei distributions	118
8.5 (Hyper) Nuclei distribution	123
8.6 Fragments of larger mass numbers	125
IX SUMMARY	130
REFERENCES	134
CURRICULUM VITAE	170

LIST OF TABLES

Table		Page
3.1	Table of Baryons.	28
3.2	Table of Mesons.	28
3.3	The numerical coalescence parameters of UrQMD v3.5.	30
6.1	The B_2 values calculated final state protons and both primordial protons and neutrons at $p_T/A = 0.0$ GeV at midrapidity $ y \leq 0.5$. The calculation is extracted from 0 — 10% central Au+Au collisions at kinetic beam energies from $E_{\text{beam}} = 0.3A$ to 40A GeV.	96
6.2	The B_3 values calculated final state protons and both primordial protons and neutrons at $p_T/A = 0.0$ GeV at midrapidity $ y \leq 0.5$. The calculation is extracted from 0 — 10% central Au+Au collisions at kinetic beam energies from $E_{\text{beam}} = 0.3A$ to 40A GeV.	96

LIST OF FIGURES

Figure		Page
2.1	The compilation of the predicted location of the QCD critical point from various models, mainly chiral models and lattice QCD (Stephanov, 2006). Black points represent chiral model predictions. Green points indicate lattice predictions. The two dashed lines are the slopes corresponding to $dT/d\mu_B^2$ of the transition line at $\mu_B = 0$. The red circles denote the freeze-out points for heavy ion collisions at corresponding center-of-mass energies in GeV per nucleon.	12
2.2	QCD diagram with BES program and various facilities (Collaboration, 2014).	14
2.3	Space-Time Evolution (Braun-Munzinger and Dönigus, 2019). . .	16
4.1	The schematic picture of the geometric coalescence model for (anti)deuteron formation if the two (anti)nucleons are close enough in phase-space. A_p and A_T are the incoming projectile and target nucleons and X represents the particles that carry the rest momenta of the system. (Left) The nucleon emission source is a whole spherical with radius r_0 . (Right) the survived antinucleons are emitted only on a spherical shell radius r_0 as the $N\bar{N}$ annihilations destroy most of the antinucleon at the center radius r_*	38
4.2	The antideuteron formation according to the source bulk radius r_0 with varying suppression radii r_*	41
4.3	The energy dependence coalescence parameters B_2 for deuterons (left) and \bar{B}_2 antideuterons (right) from various experiments ranging from $\sqrt{s_{NN}} = 4.7 - 200$ GeV. The black lines show the B_2 and \bar{B}_2 fits using the extracted radii r_0 and r_* according to the formation rate in Eq. (4.7)	41
4.4	The emission source radius r_0 of deuteron (solid black lines) and the suppression region of antideuteron source r_* (dash-dotted line) as a function of energy	42

LIST OF FIGURES (Continued)

Figure		Page
4.5	The normalised (anti)nucleon distribution in transverse plane r_T at $\sqrt{s_{NN}} = 11.5$ GeV (left panel) and $\sqrt{s_{NN}} = 200$ GeV (right panel). The black solid line represents the nucleon distribution and antinucleon distribution is depicted with the dotted line.	44
4.6	The energy dependence of the fitted (anti)nucleon source radii is illustrated. The solid circles represent the whole nucleon source radius r_0 . The extracted source radii of antinucleons are depicted with square symbols. The outer source radius of antinucleons r_0 is represented by the full symbols, while the inner source radius of the suppression region r_* is indicated by the open symbols.	45
4.7	The energy dependence of the r_*/r_0 ratio of antinucleon source from Mrówczyński coalescence model (red star symbol) and UrQMD simulation (blue square symbol) at central 0 — 10% Au+Au collisions.	46
4.8	The diagram of particle detection. Particle 1 and particle 2 are emitted, with a four-momentum p_1 and p_2 , at points a and b respectively. Then they are detected by detectors A and B. If the particles are identical, we also need to consider the cases where the particles propagate indistinguishably into the detectors as illustrated with the dashed lines.	48
4.9	The comparison of the density dependent potential V (a) and the pressure p (b) from different the CMF EoS scenarios. CMF_PT2 EoS and CMF_PT3 EoS both are incorporated with a phase transition as well as instability region indicated by local maximum and minimum. The simple CMF EoS corresponds to a smooth crossover transition (Li et al., 2023).	53

LIST OF FIGURES (Continued)

Figure		Page
4.10	<p>Comparison of k_T dependence of pion HBT radii showing the effect of Coulomb interactions. Panels (a), (b), and (c) display the R_0, R_S, and R_L radii, respectively, and panel (d) shows the ratio R_0/R_S of the π-source from central (0 — 10%) Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV. Red star symbols depict the results from the HADES experiments (Adamczewski-Musch et al., 2019). Black dotted lines indicate the UrQMD simulation results without Coulomb potential (w.o. Coul.), blue dashed lines show the UrQMD simulation results with Coulomb potential for baryons only (with Coul. (B)), and pink solid lines depict the UrQMD simulation with the full Coulomb potential for all hadrons (with Coul. (B+M)). . . .</p>	55
4.11	<p>The transverse momentum (k_T) dependence of the HBT radii, R_0 (left panels), R_S (middle panels), and R_L (right panels), for 0 — 10% central Au+Au collisions at $\sqrt{s_{NN}}$ ranging from 2.4 GeV (top panels) to 7.7 GeV (bottom panels). Experimental data are denoted by star symbols from HADES, E895, E866, and STAR collaborations (Lisa et al., 2000; Lisa et al., 2005; Adamczyk et al., 2015; Adamczewski-Musch et al., 2019; Adamczewski-Musch et al., 2020; Adam et al., 2021). The UrQMD simulations are represented by lines: the cascade mode (black line with square), hard EoS (blue line with circle), and soft EoS (pink line).</p>	56

LIST OF FIGURES (Continued)

Figure		Page
4.12	Comparison of the collision energy dependence of the (top panel) R_0/R_S ratio and (bottom panel) $R_0^2 - R_S^2$ for cascade (black line with squares) and various EoS models (hard EoS: blue line with circles, CMF EoS: green line, CMF_PT2 EoS: orange dotted line, CMF_PT3 EoS: pink dashed line) with available experimental data (Lisa et al., 2000; Lisa et al., 2005; Adamczyk et al., 2015; Adamczewski-Musch et al., 2019; Adamczewski-Musch et al., 2020; Adam et al., 2021).	61
4.13	The freeze-out time distribution of π^- from 0 — 10% Au+Au collisions with the different EoS; Cascade mode (solid black line), Hard EoS (solid blue line), CMF EoS (green dashed line), CMF_PT2 EoS (solid orange line), and CMF_PT3 EoS (pink dash-dotted line)	62
4.14	(a) The corresponding mean π^- emission time $\langle t \rangle$ and (b) transverse radii r_T at freeze-out as a function of collision energies calculated from different EoS.	63
5.1	The schematic for a particle production from a thermal model. A projectile A_p and a target nucleus A_T exchange energy and momentum upon collision. All particles X, p and n, are emitted directly from the fireball including the composited particle d. This hadronization occurs at chemical freeze-out. The figure is adopted from Ref. (Kapusta, 1980)	70
5.2	The comparison between thermal predictions and the measured (anti)nuclei production on the energy spectrum. The figure is adopted from Ref. (Dönigus, 2020)	72
5.3	The schematic for a particle production and cluster formation from a colliding projectile nucleus A_p and a target nucleus A_T . In the coalescence model, the free streaming neighbor of p and n pair after flying a certain distance will coalesce and form a deuteron outside of the fireball. The rest of the momentum is represented by X. This coalescence process happens at kinetic freeze-out. The figure is adopted from Ref. (Kapusta, 1980) . . .	73

LIST OF FIGURES (Continued)

Figure		Page
5.4	The invariant cross section of π^- , K^- , \bar{p} and \bar{d} from Si+Al, Si+Cu, and Si+Au collisions. The solid-line represents the \bar{d} 's predicted by coalescence model. The measured \bar{d} and the instrumental upper limit are represented by the square open symbol at 6.1 GeV and down arrow symbols (Aoki et al., 1992).	77
5.5	The Comparison of the tp/d^2 ratio from two cluster formation mechanisms of thermal (dashed line) and simple coalescence model (solid line) with experimental data (symbols).	81
5.6	Different statistical ensembles used for describing the breakup of a nuclear system with partition f (Bondorf et al., 1995; Fai and Randrup, 1983; Gross, 1984).	83
6.1	Coalescence parameter B_A measured by experiments (Braun-Munzinger and Dönigus, 2019) and predicted by HBT (Adamczyk et al., 2015) as a function of center-of-mass energy $\sqrt{s_{NN}}$ [GeV].	86
6.2	Rapidity distribution comparison of protons and light nuclei in 0 — 10% Au+Au collisions at $E_{beam} = 1.23A$ GeV. Simulated primordial protons (red circles), simulated final state protons (red dashed lines), and reconstructed primordial protons (red solid lines) are contrasted alongside the rapidity distributions of deuterons (green diamonds), tritons (cyan crosses), and ^3He nuclei (yellow hexagons).	88
6.3	Rapidity distribution of simulated (symbols) and reconstructed (lines) proton and neutron at central Au+Au collisions $E_{beam} = 1.23A$ GeV. (Left panel) The comparison for the simulated and reconstructed primordial proton (red) and neutron (blue) rapidity based on Eq. (6.2) and Eq. (6.8). (Right panel) The comparison for the simulated and reconstructed final neutron rapidity based on Eq. (6.9).	91

LIST OF FIGURES (Continued)

Figure		Page
6.4	Invariant p_T spectra of d (green diamonds with dotted line), t (cyan pluses with dotted line), ^3He (yellow hexagons with dotted line), the primordial proton (full red circles) and neutron (full blue squares) from the simulations. While, the reconstructed primordial protons and neutrons are shown with solid red and solid blue lines respectively. The calculations are done at mid-rapidity in central Au+Au reactions at $E_{\text{beam}} = 1.23\text{A GeV}$	92
6.5	(Left panel) The Rapidity distributions of the neutron/proton ratio (full black line), and the integrated $\Delta_{\text{iso}}^{\text{prim}}$ (dashed line). (Right panel) The transverse momentum distributions of the primordial neutron/proton ratio (full black line), and the integrated $\Delta_{\text{iso}}^{\text{prim}}$ (dashed line). Both from UrQMD for $0 - 10\%$ central Au+Au reactions at $E_{\text{beam}} = 1.23\text{A GeV}$	93
6.6	The scaled transverse momentum p_T/A -dependence of the coalescence parameter B_2 (left panel) and B_3 (right panel) calculated using the final state nucleons and reconstructed primordial nucleons from UrQMD for $0 - 10\%$ central Au+Au reactions at $E_{\text{beam}} = 1.23\text{A GeV}$	94

LIST OF FIGURES (Continued)

Figure		Page
6.7	The figure caption describes the beam energy dependence of B_2 extracted at $p_T/A = 0$ GeV in mid-rapidity $ y \leq 0.5$ for 0 — 10% central Au+Au collisions. Left panel: The dashed red line illustrates the original calculation of B_2 using the final state proton square, while the solid red line shows the corrected B_2 calculated by the product of reconstructed primordial protons and neutrons. Right panel: the original B_3 of tritons and ^3He , calculated from the final state proton cubic square, are depicted by the blue dashed line and green dotted line while the corrected B_3 of tritons and ^3He , using our reconstructed primordial protons and neutrons, are shown as the blue solid line and the green dash-dotted line, respectively. Experimental data (Wang et al., 1995; Ambrosini et al., 1998; Armstrong et al., 1999; Ahle et al., 1999; Barrette et al., 2000; Armstrong et al., 2000; Afanasiev et al., 2000; Bearden et al., 2002; Anticic et al., 2004; Anticic et al., 2016; Botvina et al., 2021) are denoted by symbols, while the dash-dotted black line represents the volume extracted from HBT results from STAR (Adamczyk et al., 2015).	97
7.1	The theoretical estimation of the deuteron d (pink full line), triton t (blue dashed line), and ^3He (orange dotted line) production according to the Eq. (7.6)- (7.8) for central Au+Au reactions as a function of ΔY_π	103
7.2	Freeze-out time distribution of nucleons (full black line), pions (dashed black line), deuterons (dotted pink line), tritons (dotted blue line), and ^3He (dotted orange line).	104
7.3	Deuteron yield as a function of ΔY_π for Au+Au reactions. The UrQMD results are shown by red circles. The estimated yield, Eq. (7.7), is represented by the full red line. Left: Results at $\sqrt{s_{NN}} = 3$ GeV. Right: Results at $\sqrt{s_{NN}} = 7.7$ GeV.	105

LIST OF FIGURES (Continued)

Figure		Page
7.4	The ΔY_π dependent of triton (blue squares and dashed blue line) and ^3He (orange triangles and dotted orange line) yields. The UrQMD results are shown by symbols. The estimated yields, Eqs. (7.7) and (7.8), are represented by the lines. Left: Results at $\sqrt{s_{\text{NN}}} = 3$ GeV. Right: Results at $\sqrt{s_{\text{NN}}} = 7.7$ GeV	106
7.5	Distribution of cluster yields on the ΔY_π spectrum is normalized to unity at $\Delta Y_\pi = 39$. The symbols represent simulation results from various collision energies ranging from $E_{\text{lab}} = 1.23A$ GeV to $E_{\text{lab}} = 40A$ GeV in ultra-central Au+Au reactions from UrQMD. Left: Deuteron distribution. Right: Triton and ^3He distribution.	107
8.1	ALICE measurements in p + Pb (in red) and Pb + Pb collisions (Adam et al., 2016) (in blue) as a function of mean charged-particle multiplicity and the predictions from canonical statistical hadronization (excluded volume) (Vovchenko et al., 2018a) and coalescence models are shown (Sun et al., 2019). The figure is adopted from Ref. (Acharya et al., 2022)	110

LIST OF FIGURES (Continued)

Figure		Page
8.2	<p>The transverse momentum (p_T) spectra of protons produced in minimum bias $\pi^- + C$ (left panel) and $\pi^- + C$ (right panel) collisions at various rapidity bins ($0 \leq y < 0.1$ to $0.9 \leq y < 1.0$) as measured by the UrQMD model (v3.5). The p_T spectra are represented by differential cross sections ($d^2\sigma/dp_T dy$) in units of $[\mu b/(\text{GeV}\Delta y)]$. The curves for each rapidity bin are consecutively multiplied by a factor of 10 from bottom to top for better visualization. Solid lines with symbols depict the UrQMD simulation results, while open symbols represent recent HADES experimental measurements (Yassine et al., 2023). The lower panel shows the relative deviation (percentage difference) between the UrQMD simulations and the corresponding experimental data for each rapidity bin.</p>	114
8.3	<p>The upper panel displays the transverse momentum (p_T) spectra of Λ hyperons produced in minimum bias $\pi^- + C$ (left) and $\pi^- + C$ (right) collisions at various rapidity bins ($0 \leq y < 0.15$ to $0.9 \leq y < 1.05$) as calculated by the UrQMD model (v3.5). The p_T spectra are represented by differential cross sections ($d^2\sigma/dp_T dy$) in units of $[\mu b/(\text{GeV}\Delta y)]$. The curves for each rapidity bin are consecutively multiplied by a factor of 100 for improved visualization (bottom to top). Solid lines with symbols depict the UrQMD simulations, while open symbols represent recent HADES experimental measurements (Yassine et al., 2023). The lower panel presents the relative deviation (percentage difference) between the UrQMD simulations and the corresponding experimental data for each rapidity bin</p>	115

LIST OF FIGURES (Continued)

Figure		Page
8.4	The differential cross section with respect to the rapidity $d\sigma/dy$ $[\mu\text{b}/\Delta y]$ of protons (red), Λ 's (orange), and Ξ 's (black) from minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{C}$ (right panel) collisions. The UrQMD results are shown as colored lines with symbols, while the open black symbols depict the recent HADES measurements (Yassine et al., 2023). The blue line with crosses shows the experimental fit function for the p_T extrapolation.	117
8.5	The transverse momentum differential cross section $d^2\sigma/dp_T dy$ in $[\mu\text{b}/(\text{GeV}\Delta y)]$ of deuterons as a function of transverse momentum in different rapidity bins (from $0 \leq y < 0.1$ to $0.8 \leq y < 0.9$, the curves are successively multiplied by factors of 100 from bottom to top) for minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{C}$ (right panel) collisions from UrQMD.	119
8.6	The transverse momentum differential cross section $d^2\sigma/dp_T dy$ in $[\mu\text{b}/(\text{GeV}\Delta y)]$ of tritons as a function of transverse momentum in different rapidity bins (from $0 \leq y < 0.1$ to $0.5 \leq y < 0.6$, the curves are successively multiplied by factors of 100 from bottom to top) for minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{C}$ (right panel) collisions from UrQMD.	120
8.7	The transverse momentum differential cross section $d^2\sigma/dp_T dy$ in $[\mu\text{b}/(\text{GeV}\Delta y)]$ of ^3He as a function of transverse momentum in different rapidity bins (from $0 \leq y < 0.1$ to $0.5 \leq y < 0.6$, the curves are successively multiplied by factors of 100 from bottom to top) for minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{C}$ (right panel) collisions from UrQMD.	121
8.8	The rapidity differential cross section $d\sigma/dy$ in $[\mu\text{b}/\Delta y]$ of deuterons (orange), tritons (green), ^3He (blue) and ^4He (red) as a function of the rapidity for minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{C}$ (right panel) collisions from UrQMD (v3.5) as denoted by dashed lines with symbols and from statistical multifragmentation model (SMM) as denoted by solid lines without symbols.	122

LIST OF FIGURES (Continued)

Figure		Page
8.9	The differential cross section with respect to transverse momentum $d^2\sigma/dp_T dy$ [$\mu\text{b}/(\text{GeV}\Delta y)$] of ${}^3\text{He}$ (blue line with squares) and $\text{N}\Xi$ (black triangles) from UrQMD results at mid-rapidity minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{W}$ (right panel) collisions. The dashed line indicates the extrapolated fit of $\text{N}\Xi$	123
8.10	The differential cross section with respect to rapidity $d\sigma/dy$ [$\mu\text{b}/\Delta y$] of $\text{N}\Lambda$ (blue), $\text{NN}\Lambda$ (green), ${}^3_\Lambda\text{H}$ (red), ${}^4_\Lambda\text{H}$ (orange), ${}^4_\Lambda\text{He}$ (pink), and $\text{N}\Xi$ (black) from minimum bias $\pi^- + \text{C}$ (left panel) and $\pi^- + \text{W}$ (right panel). The UrQMD results are denoted by dashed lines with open symbols, while the results from the statistical multifragmentation model (SMM) are denoted by solid lines with full symbols.	124
8.11	The mass number distribution of the integrated cross section of light nuclei (full symbols: $Y=0$) and hypernuclei (single-strange as open symbols: $Y=1$) production with different charges Z (denoted by the color) from SMM analysis of the UrQMD data at minimum bias $\pi^- + \text{C}$ and $\pi^- + \text{C}$ collisions.	126
8.12	The comparison in the yield ratio of the hypertriton (${}^3_\Lambda\text{H}/(\Lambda + \Sigma^0)$) as a function of the mean charged particles multiplicity with various models. Our analysis for $\pi^- + \text{C}$ (green line) and $\pi^- + \text{C}$ (black line) is presented alongside data from p+Pb and Pb+Pb. The figure also includes predictions from two models: the thermal-statistical model denoted by CSM Thermal-FIST (dotted line) (Vovchenko et al., 2018a) and the previous UrQMD-hybrid coalescence model (coloured lines with symbols (Sun et al., 2019)). Finally, brown diamonds represent experimental measurements by the ALICE collaboration (Acharya et al., 2022).	127

LIST OF ABBREVIATIONS

AGS	Alternating Gradient Synchrotron
ALICE	A Large Ion Collider Experiment
BNL	Brookhaven National Laboratory
BES	Beam Energy Scan
BUU	Boltzmann-Uehling-Uhlenbeck
CBM	Compressed Baryonic Matter
CMF	Chiral Mean Field
EoS	Equation of State
FAIR	Facility for Antiproton and Ion Research
FOPI	Forschungszentrum für Atomphysik und Institut für Nuklearphysik
GiBUU	Giessen Boltzmann-Uehling-Uhlenbeck
GSI	Gesellschaft für Schwerionenforschung
HADES	High Acceptance Di-Electron Spectrometer
HBT	Hanbury-Brown Twiss
LHC	Large Hadron Collider
PHSD	Parton-Hadron-String Dynamics
QCD	Quantum Chromodynamics
QGP	Quark Gluon Plasma
QMD	Quantum Molecular Dynamics
RHIC	Relativistic Heavy Ion Collider
SIS	Schwerionen Synchrotron
SMM	Statistical Multifragmentation Model
SHM	Statistical Hadronization Model
STAR	Solenoidal Tracker at RHIC
UrQMD	Ultra-relativistic Quantum Molecular Dynamics
VUU	Vlasov-Uehling-Uhlenbeck