## **CONTENTS**

|      |       |   | Page |
|------|-------|---|------|
| ABS  | TRACT | Г IN THAI   | 1    |
| ABS  | TRACT | Γ IN ENGLISH  | II   |
| ACK  | NOWL  | LEDGEMENTS  | III  |
| CON  | ITENT | ·<br>S  | IV   |
| LIST | OF F  | IGURES  | VI   |
| CHA  | PTER  | t .   |      |
| I    | INTF  | RODUCTION   | 10   |
| II   | LITE  | RATURE REVIEW   | 12   |
|      | 2.1   | Heavy-ion collision                                       | 12   |
|      | 2.2   | Quantum chromodynamics phase transition                   | 13   |
|      | 2.3   | Equation of state: EoS                                    | 15   |
|      | 2.4   | Correlations and fluctuations                             | 18   |
|      | 2.5   | Experimental results                                      | 19   |
|      | 2.6   | Light nuclei production                                   | 20   |
|      |       | 2.6.1 Coalescence model                                   | 21   |
|      |       | 2.6.2 Thermal model                                       | 22   |
|      | 2.7   | Fluctuations in coordinate vs. momentum space             | 23   |
| Ш    | RESE  | EARCH METHODOLOGY   | 25   |
|      | 3.1   | The UrQMD transport model                                 | 25   |
|      | 3.2   | Implementation of a phase transition in UrQMD             | 26   |
|      | 3.3   | Light nuclei production in UrQMD                          | 27   |
|      |       | 3.3.1 Deuteron production                                 | 27   |
|      |       | 3.3.2 Triton and helium-3 production                      | 28   |
|      |       | 3.3.3 Helium-4 production                                 | 28   |
|      | 3.4   | UrQMD simulation  | 29   |
|      | 3.5   | Data analysis   | 29   |
|      |       | 3.5.1 Propagation of the light nuclei in coordinate space | 31   |
| IV   | RESU  | JLTS AND DISCUSSION                                       | 32   |
|      | 4.1   | Time evolution in light nuclei multiplicities             | 32   |

# CONTENTS (Continued)

|     |       |   | Page |
|-----|-------|---|------|
|     | 4.2   | Time evolution in cumulant ratios of the light nuclei | 32   |
|     | 4.3   | Cumulant ratios in different rapidity windows         | 39   |
|     | 4.4   | Light nuclei ratios                                   | 48   |
| ٧   | CON   | CLUSION   | 51   |
| REF | ERENC | ES  | 52   |
| CUR | RICUL | LUM VITAE   | 58   |

# LIST OF FIGURES

| rigu | re   | age |
|------|--|-----|
| 2.1  | The space-time diagram of heavy-ion collision (Braun-Munzinger et al., 2019).                        | 13  |
| 2.2  | The phase diagram of quarks and gluons. The diagram displays the current                             |     |
|      | knowledge and assumptions on possible states that quarks and gluons                                  |     |
|      | can become as function of temperature ${\cal T}$ and baryon density (image by                        |     |
|      | Jan Steinheimer)   | 14  |
| 2.3  | The proton cumulant ratio $C_4/C_2$ in two beam energy scan phases BES-I                             |     |
|      | and BES-II at RHIC in different centralities under AuAu collision within                             |     |
|      | rapidity range $\left y\right  < 0.5$ (image taken from the Quark Matter 2025 in                     |     |
|      | Frankfurt by Zachary Sweger, Wed, P35)   | 19  |
| 2.4  | Beam energy dependence of the scaled cumulant $K_3/K_2$ in different                                 |     |
|      | centralities including a comparison with the STAR data (Adamczewski-                                 |     |
|      | Musch et al., 2020)  | 20  |
| 2.5  | Double ratio of triton (t), proton (p) and deuteron (d) as a function of                             |     |
|      | coupling strength with the case of first-order phase transition (blue solid                          |     |
|      | star) and crossover (red open star) (Sun, Ko, et al., 2021)  | 21  |
| 2.6  | Corrected scaled variance $\tilde{\omega}_y$ as a function of fixed acceptance fraction $\alpha_y$ . |     |
|      | The bands correspond to the beam energies $\sqrt{s_{NN}}$ . The limiting cases                       |     |
|      | of coordinate space are shown in red band, labeled $\tilde{\omega}_{coord}$ (Kuznietsov              |     |
|      | et al., 2024)  | 24  |
| 3.1  | Time evolution in pressure and baryon density at $T=0$ between the                                   |     |
|      | two scenarios: the CMF EoS with no phase transition (orange line) and the                            |     |
|      | phase transition EoS (blue line). The red shading area refers to a region                            |     |
|      | where the pressure gradient is negative: the spinodal region (Savchuk                                |     |
|      | et al., 2023).   | 27  |

# LIST OF FIGURES (Continued)

| Figu | ire  | Page |
|------|--|------|
| 3.2  | Beam-energy dependence of the deuteron to proton ratio from the UrQMD                                |      |
|      | simulation (solid lines), thermal model fit (dotted lines). The symbols of                           |      |
|      | different styles denote the experimental data from the corresponding                                 |      |
|      | collaborations: SIS (triangle down), E802 (hexagon), PHENIX (triangles up),                          |      |
|      | NA49 (blue diamonds), STAR (circles), ALICE (pentagon), E814 (square).                               |      |
|      | The blue horizontal line represents the UrQMD+hydro result on the d/p                                |      |
|      | ratio at 2.76 TeV and the green horizontal line represents the UrQMD                                 |      |
|      | result of the $rac{ar{d}}{ar{p}}$ ratio in Si+Au collisions at $E_{	extsf{lab}}=14.6~A$ GeV (Sombun |      |
|      | et al., 2019)  | 30   |
| 4.1  | Time evolution in light nuclei multiplicities (proton (red), deuteron (purple),                      |      |
|      | triton (green), $^3He$ (orange), $^4He$ (blue) at $E_{\mathrm{lab}}=2.0~A\mathrm{GeV}$ (upper plot)  |      |
|      | and $3.0\ A{\rm GeV}$ (lower plot). The plots display the multiplicities within the                  |      |
|      | spherical volume with radius 2 fm centered at the origin from UrQMD                                  |      |
|      | calculations with phase transition (dashed lines) and with a crossover                               |      |
|      | (solid lines)  | 33   |
| 4.2  | Time evolution in light nuclei multiplicities (proton (red), deuteron (purple),                      |      |
|      | triton (green), $^3He$ (orange), $^4He$ (blue) at $E_{ m lab}=2.0~A{ m GeV}$ (upper plot)            |      |
|      | and $3.0\ A {\rm GeV}$ (lower plot). The plots display the multiplicities at mid-                    |      |
|      | rapidity $ y  \leq 0.5$ from the same calculations   | 34   |
| 4.3  | Time evolution of the scaled variance of the multiplicities of baryons                               |      |
|      | (grey), protons (red) and light nuclei (deuterons (purple), tritons (green),                         |      |
|      | $^3He$ (orange), $^4He$ (blue)) at $E_{ m lab}=2.0~A$ GeV (upper plot) and $3.0~A$ GeV               |      |
|      | (lower plot) within a spatial volume. The UrQMD calculations were carried                            |      |
|      | out using a CMF equation of state (EoS) that includes either a first-order                           |      |
|      | phase transition (dashed lines) or a smooth crossover (solid lines). A                               |      |
|      | distinct enhancement in the baryon cumulants is observed during the                                  |      |
|      | phase transition   | 35   |

# LIST OF FIGURES (Continued)

| Figur | ·e  | Page |
|-------|---|------|
| 4.4   | Time evolution of the scaled variance of the multiplicities of baryons  |      |
|       | (grey), protons (red) and light nuclei (deuterons (purple), tritons (green),                                  |      |
|       | $^3He$ (orange), $^4He$ (blue)) at $E_{ m lab}=2.0~A{ m GeV}$ (upper plot) and $3.0~A{ m GeV}$                |      |
|       | (lower plot) within the rapidity interval $-0.50 \leq y \leq 0.50$ from the                                   |      |
|       | same UrQMD calculations with the phase transition EoS. During the phase                                       |      |
|       | transition, free protons and other nuclear clusters are only slightly affected.                               | 36   |
| 4.5   | Time evolution of the skewness of the multiplicities of baryons (black),                                      |      |
|       | protons (red) and light nuclei (deuterons (purple), tritons (green), $^3He$                                   |      |
|       | (orange), $^4He$ ) at $E_{ m lab}=2.0~A{ m GeV}$ (upper plot) and $3.0~A{ m GeV}$ (lower plot).               |      |
|       | The plots show the results within a spatial volume. UrQMD calculations  |      |
|       | were conducted using a CMF EoS incorporating either a first-order phase                                       |      |
|       | transition (dashed lines) or a smooth crossover (solid lines)   | 37   |
| 4.6   | Time evolution of the skewness of the multiplicities of baryons (black),                                      |      |
|       | protons (red) and light nuclei (deuterons (purple), tritons (green), $^3He$                                   |      |
|       | (orange), $^4He$ ) at $E_{\mathrm{lab}}=2.0~A\mathrm{GeV}$ (upper plot) and $3.0~A\mathrm{GeV}$ (lower plot). |      |
|       | The plots show the results within the rapidity range $ y  \leq 0.50$ from the                                 |      |
|       | same UrQMD calculations with the phase transition EoS   | 38   |
| 4.7   | Scaled variance as a function of rapidity window of the baryons (black),                                      |      |
|       | protons (red) and deuterons (purple) at the time 8 fm/c and 50 fm/c   |      |
|       | $E_{\mathrm{lab}} = 2.0~A \mathrm{GeV}$   | 40   |
| 4.8   | Scaled variance as a function of rapidity window of the baryons (black),                                      |      |
|       | protons (red) and deuterons (purple) at the time 8 fm/c and 50 fm/c   |      |
|       | $E_{\mathrm{lab}} = 3.0~A \mathrm{GeV}$   | 41   |
| 4.9   | Scaled variance as a function of rapidity window of tritons (green), $^3He$                                   |      |
|       | (orange) and $^4He$ (blue) at the time 8 fm/c and 50 fm/c $E_{\mathrm{lab}}=2.0~A\mathrm{GeV}$                | 42   |
| 4.10  | Scaled variance as a function of rapidity window of tritons (green), $^3He$                                   |      |
|       | (orange) and $^4He$ (blue) at the time 8 fm/c and 50 fm/c $E_{\rm lab}=3.0~A{\rm GeV}$                        | 43   |
| 4.11  | $S\sigma$ as a function of rapidity window of the baryons (black), protons (red)                              |      |
|       | and deuterons (purple) at the time 8 fm/c and 50 fm/c $E_{lab} = 2.0$ AGeV                                    | 44   |

# LIST OF FIGURES (Continued)

| Figur | Figure   |    |
|-------|--|----|
| 4.12  | $S\sigma$ as a function of rapidity window of the baryons (black), protons (red)                       |    |
|       | and deuterons (purple) at the time 8 fm/c and 50 fm/c $E_{ m lab}=3.0~A{ m GeV}$                       | 45 |
| 4.13  | $S\sigma$ as a function of rapidity window of tritons (green), $^3He$ (orange) and                     |    |
|       | $^4He$ (blue) at the time 8 fm/c and 50 fm/c $E_{\mathrm{lab}}=2.0~A\mathrm{GeV}~\dots$                | 46 |
| 4.14  | $S\sigma$ as a function of rapidity window of tritons (green), $^3He$ (orange) and                     |    |
|       | $^4He$ (blue) at the time 8 fm/c and 50 fm/c $E_{\mathrm{lab}}=3.0~A\mathrm{GeV}~\dots$                | 47 |
| 4.15  | Time evolution of double ratios $\frac{(t)(p)}{d^2}$ and $\frac{(He4)(p)}{(He3)(d)}$ for corresponding |    |
|       | energies of $2.0~A{\rm GeV}$ (blue) and $3.0~A{\rm GeV}$ (pink) in coordinate space                    | 49 |
| 4.16  | Time evolution of double ratios $(t*p)/d^2$ and $(^4He*p)/(^3He*d)$ for                                |    |
|       | corresponding energies of $2.0\ A{\rm GeV}$ (purple) and $3.0\ A{\rm GeV}$ (yellow) in                 |    |
|       | momentum space. The gray bands correspond to the results from the                                      |    |
|       | STAR experiment of Au+Au at $E_{\rm lab}=3.0~A{\rm GeV},0-10\%$ centrality. The                        |    |
|       | data is taken from figure 16 (b) in (Abdulhamid et al., 2024)  | 50 |