Dynamically Integrated Transport Approach for High-Energy Nuclear Collisions at High Baryon Density

Koichi Murase,1 Yukinao Akamatsu,2 Masayuki Asakawa,2 Tetsufumi Hirano,1 Masakiyo Kitazawa,2,3 Kenji Morita,4,5 Yasushi Nara,6 Chiho Nonaka,7,8 and Akira Ohnishi9

1Department of Physics, Sophia University, Tokyo 102-8554, Japan
2Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
3J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan
4Institute of Theoretical Physics, University of Wroclaw, 50204 Wrocław, Poland
5iTHES Research Group, RIKEN, Saitama 351-0198, Japan
6Akita International University, Yua, Akita-city 010-1292, Japan
7Department of Physics, Nagoya University, Nagoya 464-8602, Japan
8Kobayashi Maskawa Institute, Nagoya University, Nagoya 464-8602, Japan
9Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

E-mail: murase@sophia.ac.jp, akamatsu@ern.phys.sci.osaka-u.ac.jp, yuki@phys.sci.osaka-u.ac.jp, hirano@sophia.ac.jp, kitazawa@phys.sci.osaka-u.ac.jp, kmorita@yukawa.kyoto-u.ac.jp, nara@aiu.ac.jp, nonaka@hken.phys.nagoya-u.ac.jp, ohnishi@yukawa.kyoto-u.ac.jp

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To explore the structure of the QCD phase diagram in high baryon density domain, several high-energy nuclear collision experiments in a wide range of beam energies are currently performed or planned using many accelerator facilities. In these experiments search for a first-order phase transition and the QCD critical point is one of the most important topics. To find the signature of the phase transition, experimental data should be compared to appropriate dynamical models which quantitatively describe the process of the collisions. In this study we develop a new dynamical model on the basis of the non-equilibrium hadronic transport model JAM and 3+1D hydrodynamics. We show that the new model reproduce well the experimental beam-energy dependence of hadron yields and particle ratio by the partial thermalization of the system in our core–corona approach.

KEYWORDS: high-energy nuclear collisions, beam energy scan, dynamical initialization, core–corona separation

1. Introduction

One of the important goals in quantum chromodynamics (QCD) is to reveal the structure of the phase diagram. The phase diagram is drawn in a plane with the horizontal and vertical axis being the temperature $T$ and the baryon chemical potential $\mu_B$, respectively. With the vanishing baryon chemical potential, the transition from a hadron gas to quark gluon plasma (QGP) is known to be crossover by lattice QCD calculations. For the finite baryon chemical potential, the phase structure is less known because such first-principles calculations are not available due to the sign problem. To explore the high baryon density domain of the phase diagram by high-energy nuclear collision experiments, Beam Energy Scan (BES) programs at the Relativistic Heavy Ion Collider (RHIC) at BNL and NA61/SHINE experiment at the Super Proton Synchrotron (SPS) at CERN are ongoing. Several future experiments such the CBM experiment at FAIR, MPD at NICA, CEE at HIAF, and a heavy-ion program at J-PARC (J-PARC-HI) are also currently planned to search a wider range of the beam energy to explore a broader region of the phase diagram. The most interesting topic in
these experiments is search of the first-order phase transition and the QCD critical point which are predicted by some theoretical models [1].

In experiments, the direct observable is just momentum distributions of final state hadrons. To reconstruct from the hadron spectra the information of the high baryon density matter created in the middle stage of collision reactions, we need an appropriate dynamical model to quantitatively describe the whole process of collision reactions in a wide range of the beam energy. We present a new method to dynamically integrate a hadronic transport model and a hydrodynamic model, which have been used in describing lower-energy and higher-energy collisions, respectively.

2. Model

In our new model, JAM+Hydro, we dynamically integrate the hadronic transport model JAM [2] and ideal hydrodynamics [3]. In the lower-energy collisions for the high baryon density region, the colliding nuclei take finite time to pass through each other, which requires a dynamical description of the initial dynamics. Here we adopt the idea of the dynamical initialization [4] in which hydrodynamics initially starts with vacuum, and then the fluids are created by source terms described by the transport model. Also, in the lower-energy collisions, the fraction of the thermalized part in the system becomes smaller. Therefore, we need to separate the thermalized part (core) and the other non-equilibrium part (corona) [5] to describe each part with an appropriate model, i.e., hydrodynamics for core and a non-equilibrium transport model for corona. In our model we make such separation in both of space and time dynamically, which we call dynamical core–corona separation. Finally the interaction between the thermalized part and the non-equilibrium part is also important. Here we need to consider the dynamical coupling of the two models whose time evolution is simultaneously solved.

The corona part of the system is described by JAM cascade, a microscopic transport model which contains the binary collisions of particles, resonance decays and string formation and fragmentation. The core part is described by ideal hydrodynamics with a phenomenological equation of state, EOS-Q [6]. The core–corona separation is controlled by two parameters, which respectively. For the source terms we consider the absorption of particles into the fluids:

\[ \frac{\partial}{\partial \mu} T_{\mu\nu}^f = J^\nu, \quad \frac{\partial}{\partial \mu} N_{\mu}^f = \rho, \]

where \( T_{\mu\nu}^f \) and \( N_{\mu}^f \) are the energy–momentum tensor and the baryon current carried by the fluid part, respectively. For the source terms we consider the absorption of particles into the fluids:

\[ J^\mu(t, r) = \frac{1}{\Delta t} \sum_i p_i^\mu G(r - r_i), \quad \rho(t, r) = \frac{1}{\Delta t} \sum_i B_i G(r - r_i), \]

where \( p_i^\mu, r_i \) and \( B_i \) denote the momentum, position and baryon number of the \( i \)-th particle, and the sum runs over the absorbed particles which decay within the time step \( \Delta t \) in the region where the energy density \( e \) satisfies \( e > e_f \). The smearing profile \( G(r) \) is given by the Lorentz contracted Gaussian profile with the width \( \sigma = 0.5 \text{ fm} \). In a corona region where \( e < e_p \), fluids are converted to JAM particles using the positive contribution of the Cooper–Frye formula:

\[ \Delta N_i = \frac{g_i}{(2\pi)^3} \int \frac{d^3 p}{E} \frac{\det(\Delta \sigma \cdot p)}{\exp[(\Delta \sigma \cdot p)/E] \pm 1}, \]

where \( \Delta \sigma_j^\mu \) is the surface element of the particlization hypersurface \( e = e_p \), the coefficients \( g_i \) and \( \mu_i \) are the spin degeneracy and the chemical potential of the \( i \)-th hadron species, respectively, and \( \pm 1 \) is + for fermions and – for bosons. In this way, we simultaneously solve the JAM cascade and ideal hydrodynamics which are dynamically coupled to each other through the source terms in the core, \( e > e_f \), and the Cooper–Frye formula in the corona, \( e < e_p \).
3. Results

![Graphs showing rapidity distributions](image)

Fig. 1. The rapidity distributions of identified hadrons are plotted for central Pb+Pb collisions at $\sqrt{s_{NN}} = 6.4$ GeV for the fluidization energy $e_f = 0.5$ (red dashed) and 1.0 GeV/fm$^3$ (blue dotted). The black solid lines and points are from JAM cascade and experimental data [7], respectively.

![Graphs showing beam-energy dependence](image)

Fig. 2. The beam-energy dependence of identified hadron yields are plotted for the fluidization energy $e_f = 0.5$ (red dashed line) and 0.8 GeV/fm$^3$ (blue dotted line). The JAM cascade results and experimental data [8] are shown by the black solid line and points, respectively.

Using the JAM+Hydro model, we performed calculations of Au+Au collisions ($\sqrt{s_{NN}} = 2.7–4.9$ GeV) and Pb+Pb collisions ($\sqrt{s_{NN}} = 6.4–17.3$ GeV) with the impact parameter $b < 4.0$ fm for 0–7% centrality at $\sqrt{s_{NN}} = 6.4–12.4$ GeV or otherwise $b < 3.4$ fm for 0–5% centrality. Figure 1 shows rapidity distributions of identified hadrons. Compared to the JAM cascade model, the rapidity distributions are improved by the JAM+Hydro model for all the hadron species. The change of the protons from the JAM cascade model to the JAM+Hydro model is small for both fluidization energy $e_f = 0.5$ and 1.0 GeV/fm$^3$, which means that the stopping power of the two nuclei is unaffected by the introduction of hydrodynamic description. We also notice that the negatively charged pions are suppressed while the strange hadrons are enhanced by the hydrodynamic evolution because the yields become closer to the equilibrium values by thermalization forced by the conversion of particles to fluids. The beam-energy dependence of identified hadron yields is shown in Fig. 2. The JAM cascade slightly overestimates pions and underestimates strange particles. This situation is resolved by the
Fig. 3. The particle ratio for positively charged kaons and pions are plotted as a function of the beam energy for each fluidization energy $e_f = 0.5$ (red dashed line), $0.8$ (purple chain line) and $1.0$ (blue dotted line) GeV/fm$^3$. The black solid line and points are from the JAM cascade and experiments [9], respectively.

JAM+hydro model, and good agreement with the data is obtained. Figure 3 shows the $K^+/\pi^+$ ratio as a function of the beam energy. The JAM+Hydro prediction is significantly improved from the JAM cascade prediction. The ratio is sensitive to the fluidization energy $e_f$ at AGS energies, and larger values of $e_f$ improve the description. The ratio at higher beam energies is not so much affected by $e_f$. Also the transverse mass spectra of identified hadrons are in good agreement with experimental data [3].

4. Summary

For high-energy nuclear collisions in a wide range of the beam energy to explore the high baryon density region of the QCD phase diagram, we developed a new dynamical model, JAM+Hydro, in which a hadronic transport model JAM and ideal hydrodynamics are dynamically integrated by putting emphasis on dynamical initialization, dynamical core–corona separation and dynamical coupling of the models. We performed calculations of central Au+Au/Pb+Pb collisions in the beam-energy range of $\sqrt{s_{NN}} = 2.7$–17.3 GeV and obtained significantly improved results of the beam-energy dependence of identified hadron yields and the particle ratio of positively charged kaons and pions, which can explain the experimental data well.

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