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Research Article

Nuclear Stopping in Central Au+Au Collisions at RHIC Energies

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Nuclear stopping in central Au+Au collisions at relativistic heavy-ion collider (RHIC) energies is studied in the framework of a cascade mode and the modified ultrarelativistic quantum molecular dynamics (UrQMD) transport model. In the modified mode, the mean field potentials of both formed and "preformed" hadrons (from string fragmentation) are considered. It is found that the nuclear stopping is increasingly influenced by the mean-field potentials in the projectile and target regions with the increase of the reaction energy. In the central region, the calculations of the cascade model considering the modifying factor can describe the experimental data of the PHOBOS collaboration.

1. Introduction

The study of strongly interacting matter at extreme temperatures and densities is provided a chance by heavy-ion collisions at ultrarelativistic energies [1–5]. In particular, the study of transport phenomena is majorly important to the understanding of many fundamental properties [6, 7]. The quark-gluon plasma (QGP) is expected to form at ultrarelativistic energies. Many microscopic transport models have been used to study the properties. The motivation is to provide a satisfied description of final-state hadron production for accurate and comprehensive simulations used in modern particle and nuclear physics experiments [8].

The main purpose of this work is to extract the information on nuclear stopping by comparison of the pseudorapidity distributions of charged particles from a transport-model simulation with data. This goal can be achieved by studying the pseudorapidity distribution of charged particles from central Au+Au collisions at relativistic heavy ion collider (RHIC) energies, within a transport model, the ultrarelativistic quantum molecular dynamics (UrQMD) model. And the modifying factor is considered in this cascade mode. This method is advantageous to directly compare existing data, and it can describe the experimental data very well.

2. Ultrarelativistic Quantum Molecular Dynamics Transport Model

The UrQMD model is a microscopic many-body transport approach and can be applied to study proton-proton (pp), proton-nucleus (pA), and nucleus-nucleus (AA) interactions over an energy range from the heavy-ion synchrotron (SIS) to RHIC. This transport model is based on the covariant propagation of color strings, constituent quarks, and diquarks (as string ends) accompanied by mesonic and baryonic degree of freedom [9]. In present model, the subhadronic degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [10–12], which are dominant at the early stage of heavy ion collisions (HICs) with high super proton synchrotron (SPS) and RHIC energies.

2.1. The Mean-Field Treatments. The UrQMD model is based on parallel principles as the quantum molecular dynamics (QMD) model; hadrons are represented by Gaussian wave packets in phase space and the phase space of hadron i is propagated according to Hamilton's equation of motion [13],

$$\dot{\vec{r}}_i = \frac{\partial H}{\partial \vec{p}_i}, \qquad \dot{\vec{p}}_i = -\frac{\partial H}{\partial \vec{r}_i}. \tag{1}$$

Here, $\vec{r}$ and $\vec{p}$ are the coordinate and momentum of the hadron i, respectively. The points on the coordinate and momentum represent the coordinate and momentum for the time derivative. The Hamiltonian H consists of the kinetic energy T and the effective interaction potential energy U,

$$H = T + U. \tag{2}$$

In the standard UrQMD model, the potential energy U includes the two-body and three-body Skyrme-, Yukawa-, Coulomb-, and Pauli-terms [13, 14],

$$U = U_{\text{sky}}^{(2)} + U_{\text{sky}}^{(3)} + U_{\text{Yuk}} + U_{\text{Cou}} + U_{\text{pau}}. \tag{3}$$

In the modified version of UrQMD (based on the version 3.3), the following two terms are further added: (1) the density-dependent symmetry potential term U_{sym} and (2) the momentum-dependent term U_{md} [15]. In this work, the soft momentum dependent (SM) equation of state (EoS) is used, which is described in [16]. The Yukawa-, Pauli-, and symmetry-potentials of baryons become negligible, while the Skyrme- and the momentum-dependent parts of potentials still influence the whole dynamical process of HICs above the 2A GeV [17]. During the formation time, the "preformed" particles (string fragments that will be projected onto hadron states later on) are usually treated to be free-streaming, while reduced cross sections are only included for leading hadrons. Recently, the mean-field potentials for both formed and "preformed" particles are considered for a better understanding of Hanbury-Brown-Twiss (HBT) time-related puzzle [18] and nuclear stopping [19]. In this paper, the pseudorapidity distribution about charged particles at RHIC energies will be shown. And the relativistic effect on the relative distance and the relative momentum and a covariance-related reduced factor used for the update of potentials [17, 20] are considered in calculations.

2.2. The Modifying Factor for the UrQMD Calculations. It is known that the calculation results of the UrQMD model about the (pseudo)rapidity distribution of charged particles are somewhat larger than that of the experimental data [9, 19, 21, 22]. So, in this work, the modifying factor for the UrQMD calculations is led in, and it is marked as α which multiplies directly the pseudorapidity distribution ($dN_{\text{ch}}/d\eta$) of charged particles as the renormalization. At RHIC energies, this factor increases with the increase of the reaction energy.

3. Nuclear Stopping at RHIC Energies

At RHIC energies, as the pseudorapidity distribution of charged particles in the transverse direction has not been provided by experimental physicists, we study the nuclear stopping with the longitudinal pseudorapidity distribution. Figures 1, 2, and 3 depict the pseudorapidity distributions of charged particles for central Au+Au collisions (<6% of total cross section σ_T) at RHIC, respectively. The experimental data (circles) of charged particles produced in Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4, 130, and 200 GeV are taken from [23, 24]. The curves are our calculated results with different treatments shown in the panels. In the calculations, besides a cascade mode shown in the panel, we also show the results with potentials of both formed and "preformed" hadrons ("pf-part and f-B SM-EoS") in the panel. Cross sections used in the model are not modified by the nuclear medium in this energy region.

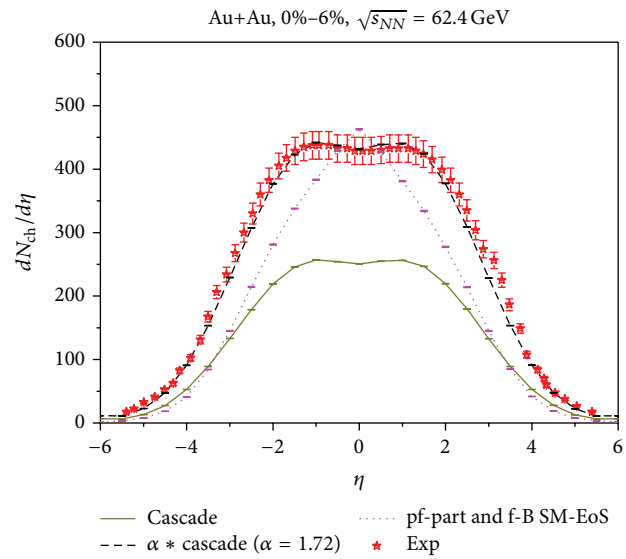

Figure 1: Charged particle pseudorapidity distributions for central Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 GeV. Calculations with cascade and with potentials ("pf-part and f-B SM-EoS") are shown by the curves. Experimental data taken from the PHOBOS collaboration [23] are represented by scatters.

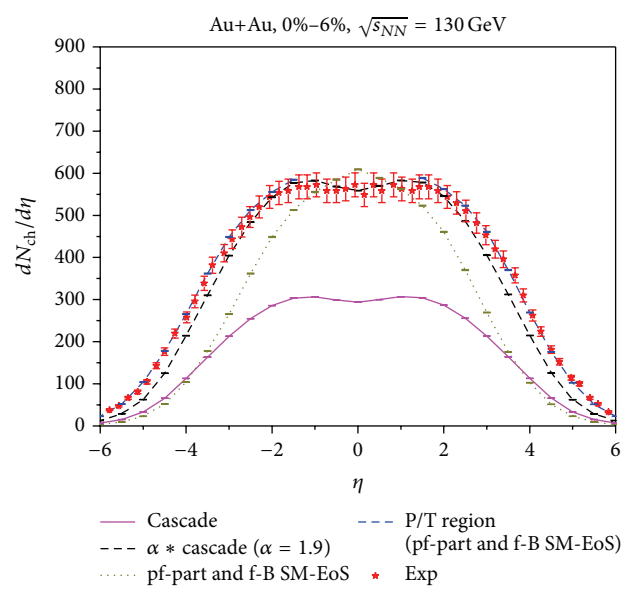

Figure 2: Charged particle pseudorapidity distributions for central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV. Calculations with cascade and with potentials ("pf-part and f-B SM-EoS") are shown by the curves. Experimental data taken from the PHOBOS collaboration [24] are represented by scatters.

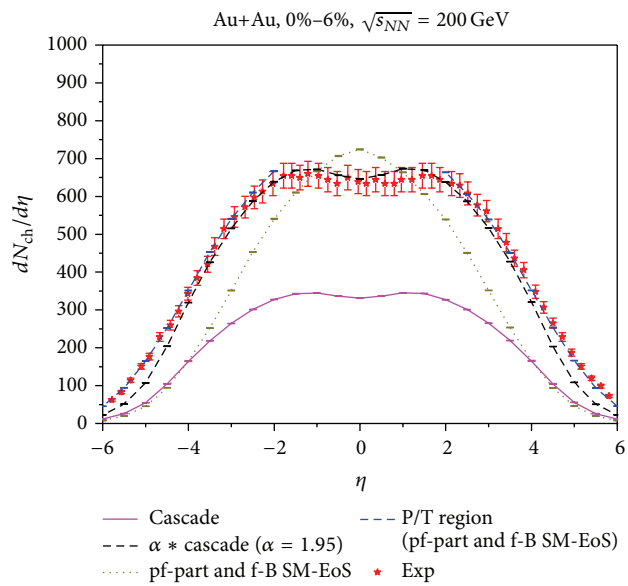

Figure 3: Charged particle pseudorapidity distributions for central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Calculations with cascade and with potentials ("pf-part and f-B SM-EoS") are shown by the curves. Experimental data taken from the PHOBOS collaboration [24] are represented by scatters.

In Figure 1 ($\sqrt{s_{NN}}$ = 62.4 GeV), it is found that the shape of the pseudorapidity distributions of measured charged particles is similar to the cascade calculations at $\sqrt{s_{NN}}$ = 62.4 GeV, but the results have only a half of the experimental data. The calculations with potentials give a Gaussian-like distribution, and they cannot describe the pseudorapidity distribution of charged particles completely. When the modifying factor is imported in the cascade calculations, it can describe well the experimental data. At this center-of-mass energy, the value of α is 1.72 with χ^2 per degree of freedom (χ^2/dof) being 1.04.

In Figure 2 ($\sqrt{s_{NN}}$ = 130 GeV), the curves and scatters are similar to Figure 1. But the difference is that the cascade calculations cannot describe the experimental data, even if the modifying factor is imported in the cascade calculations. When the value of α is 1.9 with χ^2/dof being 0.33, the cascade results are according to the experimental data at $(-1.5) < \eta < (1.5)$. We define this region as central region. The left of central region is called target region, and the right is called projectile region. At this energy, the reaction principle of the projectile (or target) region and central region is very different. So in this work, we consider that the calculations with potentials in the regions of $(-6.0) \leqslant \eta \leqslant (-0.5)$ and $(0.5) \leqslant \eta \leqslant (6.0)$ are moved horizontally to both sides, respectively. In other words, the calculations of pseudorapidity distribution in the target region are moved to left side, and the corresponding values of η reduce one. In a similar way, the calculations in the projectile region are moved to right side, and the corresponding values of η are plus one. In this figure, it can be seen that the calculations of the UrQMD model in view of this method are in keeping with the experimental data as well.

In Figure 3 ($\sqrt{s_{NN}}$ = 200 GeV), the curves and scatters are similar to Figure 2, and the processed method is also the same as Figure 2. But the value of α is 1.95 with χ^2/dof being 0.52, and the cascade results are according to the experimental data at $(-2.0) < \eta < (2.0)$. The processing method is similar to Figure 2. In this figure, the calculations of pseudorapidity distribution in the region of $(-6.0) \leqslant \eta \leqslant (-1.0)$ are moved to left side, and the corresponding values of η reduce one. In a similar way, the calculations in the region of $(1.0) \leqslant \eta \leqslant (6.0)$ are moved to right side, and the corresponding values of η are plus one. In this figure, it can be seen that the calculations of the UrQMD model in view of this method are in keeping with the experimental data as well.

From these three figures, it is known that the value of modifying factor increases with the increase of reaction energy. At RHIC energies, with the growth of reaction energy, the regions are enlarging which is affected by the potentials of both formed and "preformed" hadrons. At $\sqrt{s_{NN}}$ = 62.4 GeV, since the reaction energy is not large enough, the impact of the mean-field potentials is not necessary to be considered in this reaction energy. In other words, there is no obvious difference between the projectile (target) and central regions. When the reaction energy is taken $\sqrt{s_{NN}}$ = 130 GeV, a lot of energy is gathered, and the QGP has been formed in the central region. In this region, the calculations of cascade UrQMD model can describe the experimental data very well. A fraction of energy is left in the projectile or target region, so we need to consider the impact of the mean-field potentials, like in Figure 2. At $\sqrt{s_{NN}}$ = 200 GeV, it is similar to the case in Figure 2. The only different thing is that the central region is enlarged comparing with the Figure 2. When the QGP has been formed, the pseudorapidity distribution of charged particles will not be affected by the mean-field potentials.

4. Summary and Outlook

In summary, we have presented the pseudorapidity distribution of charged particles for central Au+Au reactions at RHIC energies. The UrQMD transport model (version 3.3) with the cascade mode and the modified mode (considering the potentials of both formed and "preformed" hadrons) has been used in all calculations. Based on this model we have investigated the effect of mean-field potentials on nuclear stopping. It is found that nuclear stopping is increasingly influenced by the mean-field potentials in the projectile and target regions with the increase of reaction energy. Since most of the incident energy is concentrated in the central region, the calculations of the cascade model considering the modifying factor can describe the experimental data in the projectile and target region. In conclusion, our combined calculations with the cascade mode and the modified mode in the different regions can give the agreement between calculation results and the experimental data. But the intrinsic reaction mechanism has yet to be studied in depth.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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