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Date: 2023-06-02T00:00:00+00:00

Abstract

In this study, the rapidity distribution, collective flows, and nuclear stopping power in 197Au+197Au collisions at intermediate energies were investigated using the ultrarelativistic quantum molecular dynamics (UrQMD) model coupled with the GEMINI++ code. The UrQMD model was employed to simulate the dynamic evolution of heavy-ion collisions, while the GEMINI++ code was utilized to simulate the decay of primary fragments produced by UrQMD. The calculated results were compared with experimental data from INDRA and FOPI. It was found that the rapidity distribution, collective flows, and nuclear stopping power were influenced to a certain extent by the decay of primary fragments, particularly at lower beam energies. Moreover, the experimental data for collective flows and nuclear stopping power at the investigated beam energies were better reproduced when the sequential decay effect was included.

Full Text

Effects of Sequential Decay on Collective Flows and Nuclear Stopping Power in Heavy-Ion Collisions at Intermediate Energies

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In this study, the rapidity distribution, collective flows, and nuclear stopping power in ^{197}Au + ^{197}Au collisions at intermediate energies were investigated using the ultrarelativistic quantum molecular dynamics (UrQMD) model with GEMINI++ code. The UrQMD model was adopted to simulate the dynamic evolution of heavy-ion collisions, whereas the GEMINI++ code was used to simulate the decay of primary fragments produced by UrQMD. The calculated results were compared with the INDRA and FOPI experimental data. It was found that the rapidity distribution, collective flows, and nuclear stopping power were affected to a certain extent by the decay of primary fragments, especially at lower beam energies. Furthermore, the experimental data of the collective flows and nuclear stopping power at the investigated beam energies were better reproduced when the sequential decay effect was included.

Keywords: Heavy-ion collisions · Sequential decay effect · Collective flow · Nuclear stopping power

INTRODUCTION

Understanding the properties of dense nuclear matter is a central topic in basic research on heavy-ion collisions (HICs), as this represents the only terrestrial method for creating dense nuclear matter in the laboratory [1–5]. However, the typical timescale for the existence of this dense nuclear matter is extremely short (less than or on the order of a few fm/c) [6], making direct measurement of its properties currently impossible. Consequently, the fundamental properties of dense nuclear matter are typically inferred by comparing experimental data with transport model simulations [7–11]. As powerful tools for investigating the dynamics of nonequilibrium systems at intermediate energies, two classes of transport models—the Boltzmann–Uehling–Uhlenbeck (BUU)-type [1] and quantum molecular dynamics (QMD)-type models [2] along with their updated versions—have been extensively employed to simulate HICs and extract information about the structure of initial nuclei and the properties of the created dense nuclear matter, such as the nuclear equation of state, nuclear symmetry energy, and in-medium nucleon-nucleon cross section [12–17].

Both BUU- and QMD-type models primarily consist of three components: the initialization of projectile and target nuclei, the mean-field potential for each particle, and the two-body scattering (collision term). Different techniques are typically used to treat these three components in different models. To establish a theoretical systematic error that quantifies the model dependence of transport predictions and to disentangle the causes of different predictions, the Transport Model Evaluation Project (TMEP) has recently been performed [18–22].

After simulating the dynamical process of HICs within transport models, an afterburner is usually employed for fragment formation, which can then be used to construct observables for comparison with experimental data to extract information about nuclear matter. However, the fragments formed are typically excited and cannot be detected experimentally as such. In experiments, the detected particles have undergone long-term de-excitation. Therefore, greater emphasis should be placed on the effect of de-excitation in the treatment of afterburners, particularly for studying HICs at Fermi energies where the beam energy is comparable to the excitation energy [23–25].

The underestimation of light fragment yields (e.g., ^{3}H, ^{3}He, and ^{4}He) in HICs at intermediate energies is a long-standing problem in transport model simulations, and numerous techniques have been developed to address it [26], including the statistical multifragmentation model (SMM) [27, 28], the statistical evaporation model (HIVAP) [29], the statistical model GEMINI [30], and the Simulated Annealing Clusterization Algorithm (SACA) [31, 32]. In our previous studies [33–35], using the conventional phase space coalescence model "Minimum Spanning Tree" (MST) [36–38] and disregarding the decay of excited primary fragments from the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model simulation, we found that experimental data for the collective flow of protons and deuterons at INDRA and FOPI energies could be reasonably reproduced, whereas those for α particles differed from experimental data. To improve the description of light cluster production and explore the influence of sequential decay on observables in HICs at intermediate energies, we employed the statistical code GEMINI++ to describe the decay of primary fragments.

In this study, we calculated the rapidity distributions and collective flows of free protons and light clusters, as well as the nuclear stopping power, using the UrQMD model both with and without sequential decay. The remainder of this paper is organized as follows. Section II provides the relevant descriptions of the transport model, statistical model, and observables. The calculation results are presented and discussed in Section III. Finally, a summary and outlook are provided in Section IV.

II. MODEL DESCRIPTION AND OBSERVABLES

A. Dynamical Model: UrQMD

The UrQMD model [39–42] is a typical transport model used for microscopic many-body nonequilibrium dynamics. In this model, each nucleon is represented by a Gaussian wave packet of width L. Empirically, L = 2 fm^2 is chosen to simulate Au+Au collisions. The coordinates and momenta of each nucleon are propagated using Hamilton's equations of motion. The total Hamiltonian of the system H consists of the kinetic energy T and the effective interaction potential energy U, which includes the Skyrme potential energy U_ , Coulomb energy U_{Coul}, and momentum-dependent potential energy U_{md}:

$$\langle H \rangle = T + U_\rho + U_{Coul} + U_{md}.$$

To study HICs at intermediate energies, the Skyrme energy density functional was introduced in the same manner as in the improved quantum molecular dynamics (ImQMD) model [43, 44]. The local and momentum-dependent potential energies can be written as:

$$U_{\rho,md} = \int u_{\rho,md}\, dr$$

where

$$u_\rho = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^\gamma} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur,iso}}{2\rho_0}[\nabla(\rho_n - \rho_p)]^2 + \rho\epsilon_{sym}(\rho)\delta^2$$

with

$$\epsilon_{sym}(\rho) = A_{sym}\left(\frac{\rho}{\rho_0}\right) + B_{sym}\left(\frac{\rho}{\rho_0}\right)^\eta + C_{sym}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}$$

and

$$u_{md} = \frac{t_{md}}{\rho_0}\ln^2\left[1 + a_{md}(p_i - p_j)^2\right]\rho^2.$$

Here, δ = (_n - _p)/(_n + _p) denotes the isospin asymmetry defined by the neutron (_n) and proton (_p) densities. In the present work, the normal nuclear matter density $_0$ = 0.16 fm^{-3}, α = -393 MeV, β = 320 MeV, γ = 1.14, g_{sur} = 19.5 MeV fm^2, g_{sur},iso = -11.3 MeV fm^2, A_{sym} = 20.4 MeV, B_{sym} = 10.8 MeV, C_{sym} = -9.3 MeV, = 1.3, t_{md} = 1.57 MeV, and a_{md} = 500 (GeV/c)$^{-2}$ are chosen, corresponding to a soft and momentum-dependent (SM) equation of state with incompressibility K$_0$ = 200 MeV and symmetry-energy slope parameter L = 80.95 MeV, which are in their commonly accepted regions [42, 45–49].

In this work, the in-medium nucleon-nucleon (NN) elastic cross section is considered as the product of a density- and momentum-dependent medium correction factor F(, p) times the free nucleon-nucleon cross section σ_{free}^{NN}, which is available from experimental data:

$$\sigma_{in-medium} = F(\rho, p) \times \sigma_{free}^{NN},$$

where

$$F(\rho,p)=\begin{cases} f_0, & p_{NN}>1\text{GeV}/c,\\ \lambda+(1-\lambda)e^{\zeta\rho/\rho_0}-\frac{f_0}{1+(p_{NN}/p_0)^\kappa}+f_0, & p_{NN}\le 1\text{GeV}/c. \end{cases}$$

The parameters $f_0 = 1$, $\lambda = 1/6$,   = 1/3, $p_0 = 0.3$ GeV/c, and   = 8 were adopted, with p_{NN} being the momentum in the two-nucleon center-of-mass frame. More detailed studies regarding the effects of F(, p) parameters on various observables can be found in Refs. [41, 42, 50]. In addition to the in-medium NN cross section, Pauli blocking plays an important role in determining the collision rate. The Pauli blocking treatment follows the same procedure described in Refs. [19, 41] and involves two steps. First, the phase space densities f_i and f_j of the two outgoing particles for each NN collision are calculated:

$$f_{i,j}=\sum_k \frac{1}{(2\pi\hbar)^3}\exp\left[-\frac{(r_{i,j}-r_k)^2}{2\sigma_r^2}\right]\exp\left[-\frac{(p_{i,j}-p_k)^2\cdot 2\sigma_r^2}{\hbar^2}\right].$$

Here, σ_r denotes the width parameter of the wave packet; σ_r^2 = 2 fm^2 is used in this work. The index k represents nucleons of the same type around the outgoing nucleon i (or j). The following two criteria were simultaneously considered:

$$P_{block}=1-(1-f_i)(1-f_j)<\xi,$$

where r_{ik} and p_{ik} denote the relative distance and momentum between nucleons i and k. The above conditions are also applied to nucleon j. The symbol   denotes a random number between 0 and 1.

Additionally, the isospin-dependent minimum spanning tree (iso-MST) algorithm was used to construct clusters [36–38]. Nucleon pairs with relative distances smaller than R_0 and relative momenta smaller than $P_0 = 0.25$ GeV/c are considered bound in a fragment. Here, R_{pp}^{0} = 2.8 fm and R_{nn}^{0} = 3.8 fm are used for proton-proton and neutron-neutron (neutron-proton) pairs, respectively. A fairly good agreement between recently published experimental data (including collective flows, nuclear stopping power, and Hanbury–Brown–Twiss interferometry) and UrQMD model calculations was achieved with appropriate choices of the above parameters [35, 42, 45, 51, 52].

B. Statistical Model: GEMINI++

The statistical GEMINI++ decay model [30, 53] is a Monte Carlo method for simulating the decay of excited fragments, which includes light particle evaporation, symmetric and asymmetric fission, and all possible binary-decay modes. It has been widely used to treat the de-excitation of primary fragments in studies of nuclear reactions at low and intermediate energies [23, 25, 54–60] and high energies [61–63]. The parameters of the shell-smoothed level density in GEMINI++ were set to their default values: k_0 = 7.3 MeV and k_∞ = 12 MeV. A more detailed discussion of the GEMINI++ parameters can be found in Refs. [53, 60, 64].

There are four inputs for the GEMINI++ code (with default parameter settings): the mass number A, charge number Z, excitation energy E*, and angular momentum L of the primary fragment. After the UrQMD transport and iso-MST coalescence processes, the excitation energy of a fragment is calculated as:

$$E^* = E_{bind}^{excited} - E_{bind}^{ground},$$

where E_{bind}^{excited} is the binding energy of the primary fragment (the sum of the potential and kinetic energies of all nucleons belonging to the fragment), and E_{bind}^{ground} is the binding energy of the ground state obtained from the nuclear data table AME2020 [65, 66]. When the excitation energy of the fragment was less than or equal to zero, it was regarded as a bound state and did not decay further. The angular momentum of the primary fragments was calculated using classical mechanics:

$$\vec{L} = \sum_i \vec{r}_i \times \vec{p}_i,$$

where r_i and p_i are the coordinate and momentum vectors, respectively, of the i-th nucleon in the primary fragments in the fragment's center-of-mass frame. The total angular momentum is the sum over all nucleons in the primary fragments. We verified that the results remained almost unchanged if the contribution of angular momentum in GEMINI++ was not included.

C. Observables

In this study, we focus on collective flows and nuclear stopping power, which are commonly used observables for investigating the properties of dense nuclear matter. The directed flow (v_1) and elliptic flow (v_2) are defined as [67]:

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle,$$

where p_x and p_y are the two components of the transverse momentum p_t = √(p_x^2 + p_y^2). Angle brackets indicate the average over all considered particles from all events.

The nuclear stopping power R_E, which characterizes the transparency of the colliding nuclei, can be defined as [68]:

$$R_E = \frac{\sum E_\perp}{\sum E_\parallel},$$

where E_ (E_) is the center-of-mass transverse (parallel) energy, and the sum runs over all considered particles.

Another quantity, var_{tl}, is also widely used to measure stopping power and was proposed by the FOPI Collaboration [69]:

$$var_{tl} = \frac{\langle y_x^2 \rangle}{\langle y_z^2 \rangle},$$

where y_x^2 and y_z^2 are the variances in the rapidity distributions of particles in the x and z directions, respectively.

III. RESULTS AND DISCUSSIONS

A. Rapidity Distribution

The rapidity distributions of hydrogen isotopes (Z = 1) and helium isotopes (^{3}He and ^{4}He) in ^{197}Au + ^{197}Au collisions at E_{lab} = 40 MeV/nucleon and impact parameter b = 5.5–7.5 fm are shown in Fig. 1 [Figure 1: see original paper]. The left, middle, and right panels display the calculated results when the switching time of the UrQMD model was set to 200 fm/c, 250 fm/c, and 300 fm/c, respectively. When considering the decay of excited primary fragments, the yields of Z = 1 particles are slightly increased, whereas those of ^{3}He and ^{4}He clusters are clearly enhanced. The yields of ^{3}He and ^{4}He are approximately 1.5 and 6 times greater than those obtained from simulations without sequential decay.

It is well known that the yields of light clusters such as ^{3}He and ^{4}He obtained using QMD-type codes are significantly smaller than experimentally measured yields. As discussed in our previous work [44], the yield of ^{3}He calculated using the UrQMD model was approximately three times lower than the experimental data. The inclusion of GEMINI++ improved the description of light cluster production to some extent; however, the yields of light clusters were still underestimated. Additionally, the inclusion of GEMINI++ may have led to an overestimation of free nucleon yields. To further address these issues, additional factors should be considered, such as the spin degree of freedom and the dynamical production process [7].

B. Collective Flows

The collective flows of Z = 1 particles as functions of reduced rapidity y_0 in ^{197}Au + ^{197}Au collisions at E_{lab} = 40 MeV/nucleon are shown in Fig. 2 [Figure 2: see original paper] (directed flow v_1 [left panel] and elliptic flow v_2

[right panel]). The simulations were stopped at 200 fm/c. Clear differences are observed in the distributions of collective flows between simulations with and without considering the decay of primary fragments, particularly for the elliptic flow v_2 from peripheral (b = 5.5–7.5 fm) collisions. As shown in Fig. 1, the difference in yields of Z = 1 particles between simulations with and without sequential decay arises from particles produced by the decay of heavier excited primary fragments. These heavier excited primary fragments are typically produced at target/projectile rapidity; thus, the directed flow at target/projectile rapidity is significantly affected by sequential decay. Increasing the impact parameter results in more large-mass primary fragments being produced, making the effects of sequential decay on collective flows more evident.

To quantitatively evaluate the influence of sequential decay on collective flows, we calculated the v_1 slope (top panels) and v_2 (bottom panels) at mid-rapidity for Z = 1 particles (left panels) and free protons (right panels) at different stopping times and compared them with experimental data, as shown in Fig. 3 [Figure 3: see original paper]. The slope of directed flow v_{11} and elliptic flow v_{20} at mid-rapidity were extracted by assuming:

$$v_1(y_0) = v_{10} + v_{11} \cdot y_0 + v_{13} \cdot y_0^3,$$
$$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2 + v_{24} \cdot y_0^4,$$

in the range $|y_0| < 0.4$, following the same procedure as in the experimental reports [69–71]. The left panels show results from simulations at E_{lab} = 50 MeV/nucleon, while the right panels show results at E_{lab} = 400 MeV/nucleon. There is an obvious difference in v_{11} and v_{20} between simulations with and without considering the decay of primary fragments at E_{lab} = 50 MeV/nucleon. When the decay of primary fragments is included, the value of v_{11} decreases while that of v_{20} increases, bringing both closer to the experimental data. This can be understood from the fact that both directed and elliptic flows are stronger for large-mass fragments [33, 69, 70]. The decay of fragments is isotropic within the fragment's center-of-mass frame in the statistical model. Thus, the light nuclei produced from the decay of primary fragments retain information about the primary fragments. Furthermore, at E_{lab} = 50 MeV/nucleon, v_{11} first decreases with time and then saturates (increases) after 200 fm/c in simulations without (with) the sequential decay effect. This can be explained by the competition between sequential decay and dynamical effects. At approximately t = 150 fm/c, nucleons are located in a low-density environment where final-state interactions are attractive, leading to a decrease in v_{11}. When GEMINI++ is considered at t = 300 fm/c, only a few large-mass fragments can emit hydrogen isotopes, and the effect of sequential decay on v_{11} gradually weakens. A comparison of sequential decay effects at E_{lab} = 50 MeV/nucleon with those at E_{lab} = 400 MeV/nucleon shows that sequential decay effects are more pronounced at lower beam energies, which is understandable because more large-mass fragments that contribute to light cluster production are formed at lower beam energies.

The beam energy dependence of v_{11} (top panel) and v_{20} (bottom panel) for semi-central ^{197}Au + ^{197}Au collisions is shown in Fig. 4 [Figure 4: see original paper]. The value of v_{11} from simulations without sequential decay is higher than the experimental data at lower energies. When sequential decay is included, v_{11} is reduced and v_{20} is enhanced at low energies, consistent with the results shown in Fig. 3. Both v_{11} and v_{20} are considerably closer to the experimental data for all investigated energies. Moreover, the effects of sequential decay on collective flows decrease with increasing beam energy. With higher beam energy, the reaction becomes more violent and the multiplicities of large-mass primary fragments decrease.

For a systematic investigation of sequential decay effects on collective flows, we calculated the transverse 4-velocity (u_t^0) dependence of v_1 for light charged particles in semi-central ^{197}Au + ^{197}Au collisions at E_{lab} = 120, 150, and 250 MeV/nucleon, both with and without considering the decay of primary fragments, and compared them with experimental data [69], as shown in Fig. 5 [Figure 5: see original paper]. The effects of sequential decay on $v_1(u\_t^0)$ for particles with mass number A < 4 are relatively weak, affecting v_1 only at low u_t^0. When the sequential decay effect is considered, v_1 of α particles is significantly influenced and can reasonably reproduce the experimental data at higher u_t^0. This is because including the decay of excited primary fragments enhances the multiplicity of α particles, as shown in Fig. 1. The α particles produced by the decay of excited primary fragments exhibit a large flow effect because they inherit the flow information of the primary fragments. The remaining discrepancies in u_t^0-dependent v_1 of light clusters may be due to simplifications in the initial wave function of particles (nucleons and possible clusters) and quantum effects in two-body collisions, as well as the lack of a dynamical production process, which requires further investigation [7].

C. Nuclear Stopping Power

Nuclear stopping power characterizes the transparency of colliding nuclei and provides insight into the equilibration rate of the colliding system. Thus, it is meaningful to explore the effects of sequential decay on nuclear stopping power. The yield distributions of deuterons and ^{4}He clusters as functions of reduced longitudinal (y_z/y_{pro}) and transverse (y_x/y_{pro}) rapidities for central ^{197}Au + ^{197}Au collisions at E_{lab} = 40 MeV/nucleon, with and without sequential decay, are shown in Fig. 6 [Figure 6: see original paper]. The calculated values of R_E are indicated in each panel and are slightly decreased—that is, the nuclear stopping power is reduced when sequential decay is considered. Notably, the values of R_E are only weakly influenced by sequential decay; however, the yield spectrum of each particle is obviously affected, particularly for ^{4}He clusters. In conjunction with Fig. 1, we conclude that sequential decay has a strong effect on particle yields and yield distributions, but only weakly influences nuclear stopping power because the de-excitation of primary fragments in the GEMINI++ code is isotropic.

The nuclear stopping power R_E (E_{lab} = 40 MeV/nucleon, left panel) and var_{tl} (E_{lab} = 400 MeV/nucleon, right panel) for free protons from central (b = 0–2 fm) ^{197}Au + ^{197}Au collisions, calculated at different stopping times, are shown in Fig. 7 [Figure 7: see original paper]. Similar to the collective flows shown in Fig. 3, the effects of sequential decay on nuclear stopping power are more obvious at lower energies than at higher energies. In all cases, the results saturated and were close to or covered by the experimental data above 200 fm/c.

Fig. 8 [Figure 8: see original paper] shows the degree of nuclear stopping (R_E or var_{tl}) in central ^{197}Au + ^{197}Au collisions as a function of beam energy. It is clear that both R_E and var_{tl} decrease and are much closer to the experimental data when the GEMINI++ code is applied, and the difference in nuclear stopping power values gradually disappears with increasing beam energy. With the same impact parameter (centrality), more violent reactions occur at higher beam energies, producing fewer heavily excited primary fragments. The difference with free protons is that they are produced from the decay of heavy excited primary fragments, which usually have weak stopping power (smaller values of R_E and var_{tl}) [73, 74]. As a result, the nuclear stopping power was slightly reduced by including the GEMINI++ code.

IV. SUMMARY AND OUTLOOK

In summary, we investigated the effects of sequential decay of excited primary fragments on the rapidity distribution, collective flows of light nuclei, and nuclear stopping power in Au+Au collisions at intermediate energies. Primary fragments were produced using the UrQMD model, and sequential decay of the excited primary fragments was performed using the GEMINI++ code. We observed that the sequential decay of excited primary fragments has a clear influence on rapidity distributions and collective flows but relatively weakly affects stopping power. This is due to the memory effect: light particles produced from the sequential decay of excited primary fragments inherit the collective properties of the primary fragments. Furthermore, the sequential decay effects gradually decreased with increasing beam energy because fewer large-mass fragments that can emit light particles were produced at higher beam energies. More importantly, the ability to reproduce the relevant experimental data at the investigated energies was improved to a certain extent by including sequential decay effects.

These results are meaningful for extracting the properties of nuclear matter by comparing transport model calculations with experimental data. The effects of secondary sequential decay on observables, such as the N/Z ratios and elliptic flow ratios of neutrons versus hydrogen isotopes, will be discussed in future publications.

ACKNOWLEDGEMENTS

The authors acknowledge support from the computing server C3S2 at Huzhou

University. This work is partly supported by the National Natural Science Foundation of China (Nos. U2032145 and 11875125) and the National Key Research and Development Program of China under Grant No. 2020YFE0202002.

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