Effect of Pre-fragment Decay on Collective Flow and Nuclear Stopping Power in Intermediate-Energy Heavy-Ion Collisions

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Abstract

Light particle production in heavy-ion collisions plays an important role in extracting information on the nuclear equation of state. Based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model and utilizing the statistical decay model GEMINI++ to handle the decay of pre-excited fragments, we investigate the influence of pre-fragment decay on the collective flow of light particles and nuclear stopping power in Au+Au collisions at intermediate energies. The study reveals that, due to memory effects, daughter nuclei from pre-fragment decay in heavy-ion collisions inherit partial dynamical properties of their parent nuclei, and incorporating pre-fragment decay leads to a better description of experimental data, with this effect's influence on observables diminishing as collision energy increases. The results demonstrate that pre-fragment decay and light particle production in heavy-ion collisions exert certain influences on observables sensitive to the nuclear equation of state. Careful consideration is necessary when employing these observables to extract information on the nuclear equation of state.

Full Text

Abstract

In heavy ion collisions (HICs), the production of light particles plays an important role in extracting information about the equation of state (EoS) of nuclear matter. Based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model, we investigated the effect of sequential decay on the collective flows and nuclear stopping power of light particles in Au+Au collisions at intermediate energies, using the statistical decay model GEMINI++ to process the secondary decay of primary fragments. It is found that, due to the memory effect, the daughter nuclei produced by decay inherit part of the dynamic

information of the parent nucleus. Experimental data can be better described by considering sequential decay, and the influence of this decay on observables weakens with increasing collision energy. The results highlight that sequential decay and the production of light particles in HICs have an obvious effect on observables sensitive to the EoS, and these effects should be carefully considered when using these observables to extract information about the EoS.

Introduction

The study of dense nuclear matter properties is one of the most important topics in nuclear physics, and heavy ion collision (HIC) experiments are the only effective means to produce dense nuclear matter in terrestrial laboratories [1-6]. However, the timescale of ion collisions is extremely short, with intermediate-energy HICs lasting only tens to hundreds of fm/c. Consequently, direct measurement of dense nuclear matter is currently impossible with existing technology. To investigate the dynamical behavior of HICs, experiments can only capture information about reaction products in the final state using detectors, such as momentum distributions of free nucleons and fragments, to infer properties like velocity, energy, and trajectory of reaction products, thereby analyzing the collision dynamics. Generally, we can simulate HICs using transport models and compare simulation results with experimental data to extract information about the nuclear matter equation of state [7-11].

Transport models widely used for intermediate-energy HICs can be broadly divided into two categories: the Boltzmann-Uehling-Uhlenbeck (BUU) model [2] and the Quantum Molecular Dynamics (QMD) model [3,12]. After decades of continuous development and improvement, they have been extensively employed to simulate HICs and extract nuclear structure and dense nuclear matter properties, such as the nuclear matter equation of state, symmetry energy, and two-body scattering cross-sections [13-20].

During transport model simulations of HICs, most models cannot directly produce fragments and require clusterization models to construct final-state fragments before analyzing observables of light particles and comparing them with experimental values to extract nuclear matter properties. However, pre-fragments obtained from transport models combined with clusterization models are typically in excited states, whereas fragments in real HICs undergo de-excitation over relatively long timescales before reaching detectors. Therefore, at relatively low collision energies, the excitation energy of pre-fragments from theoretical simulations is comparable to the beam energy, and we must pay attention to the effect of pre-fragment de-excitation on final observables [21-25].

On the other hand, underestimation of light fragment yields is a long-standing problem in transport model simulations of intermediate-energy HICs [26], and various theoretical methods have been proposed to address it. These include using statistical decay models to handle final-state fragment construction and de-excitation, such as 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], based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model and using a phase-space clusterization model while ignoring the decay of pre-excited fragments, we could reasonably reproduce collective flow results for free protons and deuterons from INDRA and FOPI experiments, although the description of α-particles showed large discrepancies. To better describe collective flow distributions of light particles and investigate the effect of decay on light particle observables in intermediate-energy HICs, this work employs the statistical model GEMINI++ to describe the decay of pre-excited fragments.

This paper uses the dynamical transport model UrQMD to simulate intermediate-energy HICs and the statistical model GEMINI++ to handle pre-fragment decay, investigating the effects of pre-fragment decay on light particle yield distributions, collective flows, and nuclear stopping power. The paper is organized as follows: Section 2 describes the theoretical models and observables, Section 3 presents results and discussion, and Section 4 provides a summary.

2.1 Dynamical Model: UrQMD

The UrQMD model is a transport model for microscopic non-equilibrium dynamics [36-40], where each nucleon is represented by a Gaussian wave packet with a fixed width. In Au+Au collisions, the wave packet width parameter is rr = 2 fm^2, and the temporal evolution of each nucleon's coordinates and momenta follows Hamilton's canonical equations. The total Hamiltonian includes kinetic energy and nucleon-nucleon effective interaction potential , which comprises the Skyrme potential term , Coulomb energy Coul, and momentum-dependent potential term md:

$$= + + \text{Coul} + \text{md}$$

To better simulate intermediate-energy HICs, this work adopts the Skyrme energy density functional used in the improved QMD (ImQMD) model [41-42] to construct the mean field. The local and momentum-dependent terms are expressed as:

$$,\text{md} = \quad ,\text{md r},$$

$$\text{sur,iso} [(\quad - \quad)]^2 + \gamma + 1 \ \text{sym}(\ (\ )^2 + \text{sym}(\ ) \ + \ \text{sym}($$

$$\text{md} = {}^3 {}_1 {}^3 {}_2 \ (\ , \ {}_1) \ (\ , \ {}_2) \ \text{md}(\ {}_{12})$$

$$\text{md}(\ {}_{12}) = \ \text{md} \ln^2(1 + \ \text{md} \ {}^2{}_{12}) + \ ,$$

where $= (\text{n} - \text{p}) / (\text{n} + \text{p})$ is the isospin asymmetry, p is the proton density, and n is the neutron density. In this work, the saturation density of nuclear matter is ${}_0 = 0.16\ \text{fm}^{-3}$, and the potential parameters are $\alpha = -393$ MeV, $\beta =$

320 MeV, $\gamma = 1.14$, sur = 19.5 MeV fm^2, sur,iso = −11.3 MeV fm^2, sym = 20.4 MeV, sym = 10.8 MeV, sym = −9.3 MeV, = 1.3, md = 1.57 MeV, md = 500 (GeV/)$^{-2}$, and = 0. These parameter settings correspond to a soft momentum-dependent equation of state (SM-EoS) with a nuclear matter incompressibility coefficient of $_0$ = 200 MeV and a symmetry energy slope parameter of = 80.95 MeV.

For nucleon-nucleon elastic cross-sections, medium modification effects are considered through a density- and momentum-dependent parameterization correction factor (,) multiplied by the free nucleon-nucleon cross-section free to obtain the in-medium nucleon-nucleon elastic cross-section [40,43-44]:

in-medium = (,) × free

(,) = + (1−) ^{1}+(NN/ $_0$) $_0$− $_0$ + $_0$, for NN > 1 GeV/ NN 1 GeV/

The parameters are set to $_0$ = 1, = 1/6, = 1/3, $_0$ = 0.3 GeV/ , and = 8, where NN is the relative momentum of the two nucleons in their center-of-mass frame.

Furthermore, since nucleons are fermions obeying the Pauli exclusion principle, Pauli blocking effects must be considered in collision processes [22,43]. If the final-state phase space is unoccupied, the scattering is successful with probability (1−), otherwise it is blocked. The phase space densities of outgoing particles in nucleon-nucleon collisions are and :

/ = ( )^3 − (r / − r) − (p / − p)

Here denotes nucleons of the same type surrounding the outgoing particle. A nucleon-nucleon collision occurs only when both conditions are satisfied:

2 (block = 1 − (1 −)(1 −) < ,

where r and p are the relative distance and relative momentum between nucleon and (the same condition applies for nucleon), and is a random number between 0 and 1.

For final fragment construction, we employ the isospin-dependent minimum spanning tree algorithm (iso-MST) [45-48]. When the relative distance between nucleon pairs is less than $_0$ and the relative momentum is less than $_0$ = 0.25 GeV/ , these nucleons belong to the same cluster. Since there is no Coulomb interaction between neutron-neutron and neutron-proton pairs, they may belong to the same fragment due to attractive forces even when their separation is larger than that of proton-proton pairs. Therefore, the distance threshold for proton pairs is smaller than for other nucleon pairs, with values of $_0$ = 2.8 fm and $_0$ = 3.8 fm. While this improvement cannot completely solve the light fragment yield problem, using these parameters provides a relatively good description of collective flow data and two-particle correlation effects in HICs [35,40,49-51]. $_0$ = $_0$

2.2 Statistical Decay Model: GEMINI++

Due to GEMINI's problem of underestimating low-energy particle yields, Charity et al. further developed the GEMINI++ model by improving decay channels for excited fragments and correcting transmission coefficients [30,52]. This model is a Monte Carlo-based statistical decay model [30,52] commonly used to simulate decays during excited fragment de-excitation, including light particle evaporation, symmetric and asymmetric fission, and other possible two-body decay modes. It has been widely used to describe de-excitation of pre-fragments in low-, intermediate- [53-62], and high-energy [63-65] HICs. In this work, the parameters used in GEMINI++ are the default values [52,61,66], with shell-corrected level density parameters of $_0 = 7.3$ MeV and $_\infty = 12$ MeV.

The model includes four basic inputs: mass number , charge number , excitation energy *, and angular momentum of the excited nucleus. The excitation energy can be obtained from the difference between the binding energy of the pre-fragment and the experimentally measured ground-state binding energy:

$$^* = \text{excited bind} - \text{ground}$$

where ground can be obtained from the AME2020 atomic mass evaluation data tables [67-68], and for unknown nuclei beyond the data tables, the ground-state binding energy can be calculated using the liquid-drop model [69-71]. When the excitation energy is less than or equal to zero, the pre-fragment is considered to be in its ground state and no decay is considered. The angular momentum of pre-fragments can be obtained from classical mechanics:

$$= \Sigma \ \mathrm{r} \ \times \mathrm{p} \ ,$$

where r and p are the coordinate and momentum vectors of the -th nucleon in the pre-fragment. It has been verified that including angular momentum contributions does not significantly affect the results.

2.3 Observables

In this work, we mainly discuss the effects of pre-fragment decay on collective flows and nuclear stopping power of light particles. The commonly used directed flow $_1$ and elliptic flow $_2$ in collective flows are defined as [72]:

$$_1 = \ / \ , \ _2 = \ (^2 \ - \ ^2)/ ^2 \ ,$$

where and are particle momenta along the direction (impact parameter) and direction, respectively, is the momentum along the beam direction , and the transverse momentum is $= \sqrt{(^2 \ + \ ^2)}$. The brackets denote averaging over observed particles in all events.

Nuclear stopping power is typically characterized by the quantities proposed by the INDRA collaboration [73] and the FOPI collaboration [74]:

$$= \Sigma \ / \ \Sigma \ _\parallel,$$

where (‖) is the transverse (longitudinal) energy in the center-of-mass frame, and the sum includes all considered particles. Particles have rapidities and in the and directions, respectively, with corresponding variances ^{2} and ^{2} . The rapidity is defined as:

$$, = ½ \ln[(+ ,)/(- ,)]$$

The rapidity magnitude of the projectile nucleus is = ½ ln[(+)/(−)], and the reduced rapidities of particles in the and directions are defined as $^0 =$ / and $_0 =$ / , all in the center-of-mass frame.

3.1 Yield Distribution

Figure 1 [Figure 1: see original paper] (color online) shows the charge multiplicity distribution in central Au+Au collisions (= 0-2 fm) at a beam energy of 150 MeV/nucleon at 200 fm/ , comparing results before and after including decay with INDRA experimental data [26]. The blue hollow circles show results without decay, green solid triangles show results with decay, and red stars show experimental measurements. It can be seen that after including decay of excited pre-fragments, the yields of fragments with > 2 are overall suppressed due to decay of heavy fragments and become closer to experimental values, while the yields of particles with $= 1$ and $= 2$ are enhanced and can reasonably describe the experimental yield of $= 2$ particles.

Furthermore, Figure 2 [Figure 2: see original paper] shows the rapidity distributions of hydrogen isotopes (, ,) and helium isotopes (^{3}He and ^{4}He) yields in Au+Au collisions at 150 MeV/nucleon with impact parameter = 0-2 fm. The blue dashed lines show results without decay, green solid lines show results with decay, and the left, middle, and right panels show results at = 200, 250, and 300 fm/ , respectively. When including secondary decay of pre-excited fragments, the yields of and increase slightly, while the yield enhancement for helium isotopes is particularly significant. However, the rapidity distribution of is almost unaffected, because has a larger binding energy per nucleon and is less likely to decay, and heavy pre-excited fragments preferentially emit ^{3}He (with smaller binding energy per nucleon) rather than when evaporating light nuclei of the same mass. As shown in Figure 1, heavy fragments decay into lighter fragments, leading to increased light particle yields. Therefore, after including decay, the yields of ^{3}He and ^{4}He increase by factors of 1.4 and 4.9, respectively (at = 200 fm/). In QMD-type transport model calculations, light particle yields (especially ^{3}He and ^{4}He) are typically underestimated compared to experimental values. In our previous study [42], UrQMD model calculations gave…

[References section continues with the provided bibliography]

Note: Figure translations are in progress. See original paper for figures.