Azimuthal Asymmetry of Pion-Meson Emission around the Projectile and Target Sides in Au+Au Collision at 1A GeV postprint

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Date: 2023-06-20T00:00:00+00:00

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Full Text

Preamble

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(Received 24 April 2015)

Abstract

The ratio of the number of emitted pions from the target side to that from the projectile side at target rapidity within the reaction plane is investigated for the study of pion dynamics using an isospin-dependent quantum molecular dynamic model. The results show that high-energy pions are emitted preferentially towards the target side and, therefore, freeze out at the early stage of the collision. By contrast, low-energy pions are emitted predominantly in the opposite direction, which means they are emitted at a later stage. This argument is based on the shadowing effect caused by the interaction of pions with spectator matter in peripheral collisions at target or projectile rapidities. This phenomenon disappears in central collisions or at midrapidity due to the weaker shadowing effect. The calculated ratios are also compared with experimental data.

PACS: 25.75.Dw, 25.75.Ld, 24.10.Lx
DOI: 10.1088/0256-307X/32/6/062501

Introduction

High-energy heavy ion collisions (HIC) provide an ideal tool to study the state of nuclear matter at higher energy densities. Due to the fast process of the collision, one can only detect particles at the freeze-out stage while information about the early stage of HIC might be missed. To investigate the properties of nuclear matter at high density in the compression stage, one must find probes that are sensitive to the properties of this dense matter to gain information about nuclear matter under high-density conditions. The pion meson, which is the most abundantly produced particle at relativistic energies, is an interesting probe of the hot and dense hadronic matter in heavy ion collisions. Some observables have been found to be sensitive to the nuclear equation of state (EOS), among which the pion multiplicity is one. Meanwhile, experimental data from π analysis of streamer chamber events at the BEVALAC were available and used to obtain EOS information through comparison with dynamical models.

One interesting observable, the azimuthal anisotropy of pion emission in asymmetric heavy ion reactions, was experimentally investigated by Gosset et al., who observed a preferential emission of charged pions away from the interaction zone towards the projectile side. This result can be attributed to stronger pion absorption by the heavier spectator remnant—an effect of shadowing by large spectator nuclei. One observable for characterizing this quantitative anisotropy uses the ratio of the number of pions emitted to the projectile side versus that to the target side within the reaction plane; however, there have been few theoretical studies to date. In this work, we study this ratio of pion emission for Au+Au collisions at 1A GeV using a transport model, namely isospin-dependent quantum molecular dynamics (IQMD), and attempt to compare with available data.

Model Description

The quantum molecular dynamics (QMD) model is a transport model based on many-body theory that describes heavy ion collisions from low energies (dozens of MeV) to relativistic energies. The IQMD model was extended from QMD by incorporating isospin effects. Over the past decades, many applications have been successfully performed in nuclear physics studies using IQMD. For instance, IQMD has been successfully applied to treat collective flow, multifragmentation, isospin effects in HIC, transport coefficients in HIC, giant monopole resonance, giant and pygmy dipole resonances, symmetry energy, and strangeness production. In addition, the nuclear modification factor and radial flow of protons for Au+Au collisions at 1A GeV have been simulated with the IQMD model, demonstrating that a soft equation of state with momentum-dependent interaction (MDI) can provide an excellent description of the data. In this context, we adopt the same soft EOS with MDI for the current simulation of projectile-target azimuthal asymmetry of pion emission in Au+Au collisions at 1A GeV. For details of the model, one can refer to Refs. [11,24,25].

Simulation and Analysis Methods

To provide direct insight into heavy ion collision evolution at 1A GeV Au+Au, we display Fig. 1 [Figure 1: see original paper] showing density contours for an impact parameter of 7 fm at 5, 10, 15, 20, 25, and 30 fm/c after time zero (the time instant when both nuclei have a distance projected to the beam axis of 2 times the nuclear radius) from our IQMD simulation. These different snapshots correspond to the effect of pion shadowing by spectator matter at different stages of the collision.

In the early phase of the collision, for instance at 5 fm/c in Fig. 1, pions detected around target rapidity (i.e., at backward angles as indicated by the arrows in Fig. 1) will be shadowed by the projectile spectator on one side and therefore exhibit flow to the other side. This apparent pion flow can serve as a potentially powerful tool for exploring nuclear dynamics and the equation of state of nuclear matter. In contrast, if pions freeze out at a late stage of the collision, say after 15 fm/c in Fig. 1, they will be shadowed (at target rapidity) by the target spectator, resulting in an anti-flow-like configuration. Meanwhile, in a middle stage (e.g., 10 fm/c in Fig. 1), particles could be emitted azimuthally symmetrically around the projectile-target sides. This anti-flow behavior of pions is found to be pronounced in peripheral Au+Au collisions and vanishes in central collisions. More details of flow and anti-flow can be found in Ref. [28] for Au+Au reactions at 1.15A GeV.

Theoretical studies of pion flow in the symmetric Au+Au system have been presented by Bass et al. for 1A GeV and by Li for 0.6–1.6A GeV. New theoretical studies can also be found in a recent ImQMD calculation.

Pions are formed by the decay of the Δ resonance (i.e., $\Delta \to N\pi$) in the energy region of about 1A GeV in the IQMD model. After pions are produced, either free or bound in a delta, they may be reabsorbed by another nucleon forming a Δ which may be absorbed in an inelastic collision, or they may decay again producing another pion through: (i) absorption: $\pi\mathrm{N} \to \Delta$, $\Delta\mathrm{N} \to \mathrm{NN}$; and (ii) scattering (resorption): $\pi\mathrm{N} \to \Delta \to \pi\mathrm{N}$.

Figure 2 [Figure 2: see original paper] shows the transverse momentum (pT) spectra of charged pions under minimum bias trigger conditions at midrapidity from IQMD simulations together with experimental data from the FOPI collaboration. The slopes of our simulation are in good agreement with the experimental data for both positive and negative pions. In the low transverse momentum region, the different trend of pions is attributed to the Coulomb potential of charged pion interactions.

For our analysis, it is convenient to transform from coordinates (pz, pT,) to spherical coordinates (p, ,), where   is the polar angle,   is the azimuthal angle between the transverse momentum vector pT and the px-axis (which lies in the reaction plane and is perpendicular to the beam axis), and   is the angle between the total momentum vector and the pz axis.

As in the experimental approach, we determine collision centrality using the charged particle multiplicity distribution in the IQMD model for Au+Au collisions with a minimum-bias impact parameter distribution at 1A GeV incident energy. To enable quantitative comparison with experimental data, the charged particle multiplicity distribution is constructed in our simulation, requiring a multiplicity number greater than two obtained with one particle in the large polar-angle range (12° ≤ lab ≤ 48°) triggered with another particle in the small polar-angle range (lab = 44° ± 4°). Figure 3(a) [Figure 3: see original paper] shows that peripheral collisions are strongly suppressed by this trigger condition. As shown in the figure, we select peripheral collisions corresponding to 65$±5±$4% centrality, matching the experimental conditions. Figure 3(b) [Figure 3: see original paper] shows the correlation between multiplicity and impact parameter under the above trigger condition in the IQMD model calculation.

To simulate an event-by-event analysis of heavy-ion reactions at 1A GeV as in the experiment, it is necessary to define a general reference frame for each event. The event-plane method uses the event-plane angle determined from the observed collective flow itself as the approximate reaction plane. The event plane angle is given as   = arctan(Qy/Qx), where Qy = Σi ωi cos(i) and Qx = Σi ωi sin(i), with the sum running over all particles used in the reconstruction of the event plane. Here i and ωi are the azimuthal angle and weight for particle i. We choose ωi = pt for rapidity Yi > 0.3 and ωi = -pt if Yi < -0.3. Figure 4 [Figure 4: see original paper] shows the   distribution within the polar angle range 0.5° ≤ lab ≤ 5°. Most particles emitted in this angular range are spectator particles, and their phase space information is used to reconstruct the event plane. Once the event plane angle is available, the observed azimuthal angle   for each particle with respect to the event plane can be calculated by   = i - .

In previous works, observation of azimuthal anisotropy with preferential emission of pions perpendicular to the reaction plane has been reported—the so-called squeeze-out behavior. This phenomenon occurs in the mid-rapidity interaction zone where particles favor emission out-of-plane, while in-plane emission is hindered due to the shadowing effect of projectile and target spectators.

Results

The spectra of emitted pions can be obtained in the later stage of collisions, i.e., at 100 fm/c in the present simulation. The ratios of these pion spectra as a function of transverse momentum pT can be directly obtained for peripheral (left panels) or near-central (right panels) collisions at target rapidity (upper panels) or midrapidity (bottom panels), as shown in Fig. 5 [Figure 5: see original paper]. The results are also compared with experimental data from the Kaon Spectrometer at the heavy-ion synchrotron SIS at GSI (Darmstadt) in the figure. The trend of our simulation and the experimental data are quite similar.

In Fig. 5(a), high-energy pions above pT of 0.5 GeV/c are preferentially emitted toward the side of the target spectator. In contrast, low-energy pions are slightly preferentially emitted toward the side of the projectile spectator. This finding shows that high-energy pions are shadowed by the projectile spectator, whereas low-energy pions are shadowed by the target spectator. In Fig. 5(b), the asymmetry gradually weakens in near-central collisions at target rapidity. This is consistent with Ref. [1], which proposed that the shadowing effect is found only in peripheral Au+Au collisions and is strongly reduced for near-central collisions. We also find that for both near-central and peripheral collisions at midrapidity, the measured ratios are close to 1, as expected for symmetric systems, as shown in Figs. 5(c) and 5(d).

Next, we discuss in more detail by comparing the yield of pions emitted in-plane to those emitted perpendicular to the reaction plane. Figure 6 [Figure 6: see original paper] shows the ratios Nπ(0)/Nπ(90) and Nπ(180)/Nπ(90) as a function of pT in peripheral collisions at target rapidity. Again, the data are compared with our simulation. The ratios are both less than unity, which indicates that the transition of the ratio Nπ(0)/Nπ(180) (Fig. 5(a)) is not caused by enhanced pion emission but rather by losses due to absorption or rescattering. By comparing Fig. 5(a) with Fig. 6, we can extract information on the emission time of pions as a function of their momentum. The ratio shows no asymmetry (Nπ(0)/Nπ(180)   1) at pT   0.5 GeV/c in Fig. 5(a), whereas it clearly shows that both ratios of Nπ(0)/Nπ(90) and Nπ(180)/Nπ(90) at both projectile and target sides are less than 1 in Figs. 6(a) and 6(b). This finding shows that pions are shadowed by both the target and projectile spectators when emitted at about 10 fm/c (see Fig. 1). In the high transverse momentum region (above pT of 0.5 GeV/c), the ratio drops with increasing transverse momentum for pions emitted toward the projectile side (Fig. 6(a)), while the opposite trend is observed on the target side (Fig. 6(b)). This observation demonstrates that high transverse momentum pions are emitted at an early stage—earlier than 10 fm/c in the present simulation. In contrast, low transverse momentum pions preferentially freeze out at later times.

Summary

In summary, we have investigated pion emission in peripheral and near-central Au+Au collisions at 1A GeV with the IQMD model. First, we compared the transverse momentum (pT) spectra of charged pions obtained by the IQMD model with FOPI experimental data and found good agreement. Then, we studied the ratio of the number of emitted pions from the target side to that from the projectile side at target rapidity within the reaction plane. We observed an obvious reduction of high-pT pion emission at the projectile side and a slight reduction of low-pT pion emission at the target side. These results stem from the projectile spectator shielding high-energy pions on the projectile side, which means high-energy pions are emitted in the early phase of the collision. However, low-energy pions are shadowed by the target spectator and therefore freeze out at later times.

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