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Tracing isospin with the π^-/π^+ ratio in central heavy ion collisions

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Within an isospin- and momentum-dependent hadronic transport model, we have investigated the isospin mixing with the probe of the π^-/π^+ ratio in central isospin asymmetric ^{96}Ru + ^{96}Zr collision at an incident energy of 400 MeV/u. The isospin equilibrium is not reached according to the asymmetrical distribution of the π^-/π^+ ratio with rapidity. In comparison with the nucleon observable, it suggests that the pion ratio π^-/π^+ is a promising observable to probe the relaxation of isospin degree of freedom in central heavy ion collisions without being strongly affected by the surface effect. Because of the small system size and rather strong effect of rescattering on pions, the isospin mixing shows insignificant dependence on the stiffness of the symmetry energy in the relevant colliding system.

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I. INTRODUCTION

Relaxation of the isospin degree of freedom (DOF) in heavy ion collisions (HICs) over a very wide energy range has recently attracted much attention, since it reveals not only various features of the collision dynamics, but also carries a wealth of information about the asymmetric nuclear equation of state (EOS) [1]. In HICs at Fermi energies, the various DOFs can be ordered in a hierarchical sequence according to their relaxation times, with isospin being the fastest one and used to tag the reaction time for studying the dynamic evolution of the colliding system [2,3]. By increasing the beam energy, because of the competition between Pauli blocking and preequilibrium neutron emission, the isospin relaxation time becomes longer than the thermal one above Fermi energy [4], and the nonequilibrium of the isospin DOF is observed experimentally [5]. Not only found on the beam direction, it is also found that the N/Z of the emitted light particles, which change with kinetic energy can be used as a sensitive signal for the onset of radial expansion [6]. As to the EOS, the isospin diffusion between the projectile and the target with larger N/Z asymmetry was recently measured to extract the density dependence of the symmetry energy $E_{\mathrm{sym}}(\rho)$ at subsaturation densities [7,8]. As an effective probe, it reaches consistent constraint on $E_{\mathrm{sym}}(\rho)$ with some other observables [9–12]. For a recent review, we refer the reader to Ref. [13].

At intermediately high-beam energies (e.g., hundreds of MeV/u), isospin DOF is also widely studied both experimentally and theoretically in terms of the collision dynamics and the isospin effect on the EOS. Partial transparency is model independently confirmed between the colliding nuclei by measuring the proton rapidity in Ru/Zr + Zr/Ru systems, dubbed by isospin tracer, suggesting that the global isospin equilibrium is not achieved even in the most central collisions [14]. It is further shown that the double N/P differential ratio, similar to the isospin tracer, exhibits different dependence on the symmetry energy because of the particle-emission mechanism that varies with reaction geometry [15] and beam energy [16]. Some other simulations also demonstrate that the isospin mixing depends insignificantly on the stiffness of the symmetry energy in the same system [17]. It then raises the question about the validity of using the nucleon observables mentioned earlier to probe the isospin relaxation or $E_{\mathrm{sym}}(\rho)$ in dense nuclear matter. Because of the corona effect, the nucleons at the vicinity of the surface of the projectile and the target pass each other with very low possibility of two-body collision even in very central events [18]. This effect is increasingly pronounced with decreasing the centrality or by going to the large rapidity [16]. It is not assured that the nucleons freeze-out in the dense region of the colliding system. Thus, the degree of isospin mixing seen by the nucleons depends sensitively on the geometry variation induced by the change of system size or centrality. Moreover, their memory on the information of the compressed nuclear matter is considerably distorted because of the contribution of the low-density part. Naturally, it is of interest to find an alternative observable that is less influenced by this particular effect.

Very recently, the charged pion produced in HICs at around 1 GeV/u beam energy arouses great attention in constraining the symmetry energy at suprasaturation densities [19] as well as probing the expansion dynamics [20] in HICs with large neutron excess. According to the simple isobar model, pions are mainly produced via the Δ resonance from the first-chance-independent nucleon-nucleon collisions mainly in the dense region, and the yield ratio of the charged pion is written as $\pi^-/\pi^+ = (5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2_{\mathrm{dense}}$ [21]. Therefore, the ratio π^-/π^+ effectively measures the $\langle N/Z \rangle$ of the dense region, which is more neutron rich than the colliding system because of the isospin fractionation mechanism [22,23]. Recently, the π^-/π^+ data from the FOPI Collaboration [24] were reanalyzed based on an isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, and circumstantial evidence of a soft-symmetry energy at suprasaturation densities was then reported [25], and further discussions arose on the stability of neutron stars and on the nature of gravity at very short distances [26]. Further tests of the soft-density dependence of $E_{\mathrm{sym}}(\rho)$ were soon proposed with other light cluster probes in heavy ion collisions [27]. By owning to the medium effect on the pion production and

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propagation, the π^-/π^+ ratio might change and might lead to slightly modified dependence on $E_{\mathrm{sym}}(\rho)$ [28–30]. Soon later, however, a rather stiff $E_{\mathrm{sym}}(\rho)$ was deduced with the improved isospin-dependent quantum molecular dynamics (ImIQMD) transport model by analyzing the same set of data, by drawing a totally different conclusion [31]. The elliptic flow of neutron and hydrogen isotopes suggests a moderate soft $E_{\mathrm{sym}}(\rho)$ [32]. These controversies on the $E_{\mathrm{sym}}(\rho)$ behavior for dense nuclear matter appeal for further efforts to survey the temporal and spatial evolutions of π^-/π^+ with different $E_{\mathrm{sym}}(\rho)$ in the collisions.

By observing that the π^-/π^+ ratio carries the isospin information of the colliding system, we expect that the π^-/π^+ ratio, as a function of rapidity in the isospin asymmetric collisions, may measure the degree of isospin mixing without being strongly influenced by the surface effect as with the nucleon observable because the Δ resonances, which dominate the pion source in this energy range, are produced mainly in the dense region [23]. Moreover, it is also of interest to see whether the isospin mixing is sensitively dependent on the stiffness of the symmetry energy in suprasaturation densities achievable at the relevant energy [33]. In this paper, the rapidity distribution of charged pions is investigated in Ru (Zr) + Zr (Ru) at 400 MeV/u based on an isospin- and momentum-dependent transport model IBUU04. The ratio π^-/π^+ as a function of rapidity and its dependence on the symmetry energy is studied. The correlation between the double ratio of π^-/π^+ and the ratio of proton yield as a function of rapidity in two isospin asymmetric systems is discussed.

II. MODEL DESCRIPTION

The transport model used in the present paper is IBUU04, which is based on the Boltzmann-Uehling-Uhlenbeck (BUU) model, which includes the effects of isospin and the momentum dependence in both the isoscalar and the isovector potentials. In this model, nucleons, baryon resonances, and their decay channels are all included. For the isospin-dependent elastic NN collisions, an in-medium effect is self-consistently included by adopting the scaling of nucleon effective mass in the medium. The inelastic cross sections, on the other hand, are derived from the experimental data of free space NN collisions, since the in-medium inelastic NN cross section is still controversial. Specifically, the isospin- and momentum-dependent mean-field potential is given by

$$\begin{aligned} U(\rho,\delta,\mathbf{p},\tau) ={}& A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\ &+ B\left(\frac{\rho}{\rho_0}\right)^{\sigma}(1 - x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^{\sigma}}\delta\rho_{\tau'} \\ &+ \frac{2C_{\tau\tau}}{\rho_0}\int d^3\mathbf{p}'\frac{f_\tau(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2} \\ &+ \frac{2C_{\tau\tau'}}{\rho_0}\int d^3\mathbf{p}'\frac{f_{\tau'}(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2}, \end{aligned} \qquad (1)$$

where ρ_τ and ρ'_τ denote proton ($\tau = -1/2$) or neutron ($\tau = 1/2$) density with $\tau \neq \tau'$ and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry in the nuclear medium, values of the parameters A_u, A_l, B, $C_{\tau,\tau}$, $C_{\tau,\tau'}$ and Λ can be set by fitting the moment dependence of the $U(\rho,\delta,\mathbf{p},\tau)$ to that predicted by the Gony-Hartree-Fock and/or the Brueckner-Hartree-Fock calculations. This interaction yields an incompressibility of 211 MeV for symmetrical nuclear matter at normal density. The isovector potential $(U_n - U_p)/2$ derived from ansatz (1) is momentum dependent and consists of the experimental Lane potential. The parameter x is introduced to mimic various predictions for the density dependence of the nuclear-symmetry energy $E_{\mathrm{sym}}(\rho)$ while keeping the saturation properties of symmetric nuclear matter. For a given x, one can readily calculate the symmetry energy as a function of density with $x = -1$ (1) by representing a stiff (supersoft) density dependence at $\rho > \rho_0$. Pauli blocking is taken into account in both the initialization of the colliding nuclei and the NN collisions during the transport process. More details of the model can be found in Refs. [8,19,34]. Therefore, with the isospin- and momentum-dependent single-particle potential $U(\rho,\delta,\mathbf{p},\tau)$, we can investigate the transport of the isospin DOF in heavy ion collisions quantitatively in theory.

III. RESULTS AND DISCUSSIONS

Let us first compare the simulated rapidity distribution of the charged pions with the FOPI data [35]. Figure 1 presents the rapidity spectra of (a) π^-, (b) π^+, and (c) π^-/π^+, respectively. The abscissa $Y^{(0)}$ is the scaled rapidity defined by $Y^{(0)} = y_{\mathrm{lab}}/y_{\mathrm{cm}} - 1$, where y_{lab} is the rapidity of the particle in the laboratory frame and y_{cm} is the center-of-mass rapidity. For comparison, the results of the isospin-dependent quantum molecular dynamics (IQMD) simulation, read off from Ref. [35], is also presented. Unlike the test particle method in the BUU framework, each nucleon in IQMD is initialized as a Gaussian wave packet with the width parameter L, which describes the interaction range of the particle. In this calculation, an appropriate value of $L = 4.33\ \mathrm{fm}^2$ is applied to the Ru/Zr system with total mass $A \approx 200$ because of its sensitive influence on the stability of the initialized nuclei and the flow observables at freeze-out, as demonstrated in Refs. [36,37]. Similar to the IBUU04 model, on the other hand, the pions in the IQMD model [36,38] are explicitly produced via the decay of the Δ resonances. In this IQMD calculation, only the lowest three states are included. The πN scattering is then taken into account by a modified detailed balance principle. The isospin-dependent free space NN cross sections are adopted for both elastic and inelastic scatterings. The momentum-dependent interaction, which is found to affect the freeze-out density, the nucleon and fragment emissions, the system-size dependence, and the flow observables [39–41], is incorporated by parametrizing the momentum dependence of the real part of the nucleon optical potential [36]. The stiffness of the EOS of symmetric nuclear matter shows insignificant influence on the pion yield at this energy [35]. To lessen the fluctuation caused by the uncertainty of the centrality, we fix the impact parameter at $b = 3$ fm, which corresponds to the centrality of 10%, which is obtained by using the variable E_{rat} in the experiment. The x parameter is fixed at $x = 1$. To change the x parameter does not sensitively influence the multiplicity of pions, although the ratio is found to favor a

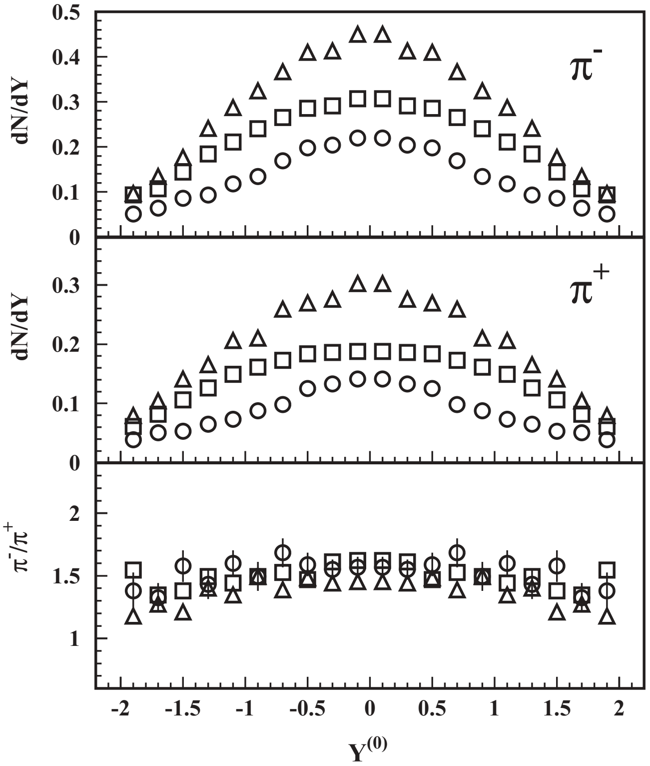

FIG. 1. Comparison of IBUU04 ($x = 1$) calculations (open circle) with data (open square) for the rapidity distributions of (a) π^-, (b) π^+, and (c) π^-/π^+ in central Ru + Ru collisions with 10% of σ_{geom} at 400 MeV/u. The IQMD simulations (open triangle) with a stiff EOS and momentum-dependent interactions are also presented. The data and the IQMD simulations are taken from Ref. [35].

soft-symmetry energy at high densities as revealed in our previous analysis [25]. It is shown in panels (a) and (b) that the FOPI data (open square) lie between the calculations within the IQMD (open triangle) and the IBUU04 (open circle). Namely, the IQMD model gives a relatively higher prediction of pion production, while the IBUU04 model underestimates the yield of the charged pions. Similarly, at 400 MeV/u, the underestimation of the pion multiplicity by the BUU-type [29] and the overestimation by the IQMD-type [36] transport models were also reported in Ref. [24]. Interestingly, it is found that the inconsistency between the model and the experimental data decreases with the system size and beam energy. In the central collision of Au + Au, the consistency is reached within 80% at 400 MeV/u and 90% at 600 MeV/u. At higher energies above 600 MeV/u up to about 1 GeV/u, the simulation results are consistent with the experimental data within the error bars as shown in Ref. [25]. A more detailed assessment of the predictive power of various transport models was made, and an overall disagreement of about 30% for the inclusive charged pion yield is found with different models [42]. Despite the total charged pion multiplicity predicted with IBUU04, which appears to be lower than the data at the beam energy considered here, the differential yield ratio of π^- and π^+ reproduces the experimental data reasonably well. Figure 1(c) presents the ratio π^-/π^+ of the IBUU04 simulation in comparison with the data and the IQMD simulations. The error bars presented in our simulation are of statistical origin only. It is shown that the simulation of IBUU04 is in good agreement with the data or the IQMD predictions. Toward midrapidity, the ratio π^-/π^+ exhibits a slight enhancement of about 20% –30% compared with the large rapidity region.

The difference of the ratio π^-/π^+ between the midrapidity and the large rapidity region is attributed to two possible reasons. First, because of the Coulomb effect, π^- experiences attraction toward the inner region in the momentum space and leads to a higher differential yield at midrapidity compared to larger rapidity. It is further found in the simulation that the Coulomb effect does not influence the total ratio π^-/π^+. If we turn off the Coulomb interaction in the model, the π^-/π^+ distribution becomes almost flat over the rapidity. Second, if a soft-symmetry energy term at high density is at work, the neutrons are attracted toward the dense region, and a more neutron-rich fireball than the system is formed in the collision. This mechanism was introduced earlier as isospin fractionation and leads to an integrated ratio π^-/π^+ that is higher than the $\langle N/Z\rangle^2$ of the system, depending on the system size and beam energy. Therefore, the pion ratio π^-/π^+, which reflects the N/Z composition of the dense region, is expected to be discernibly higher at midrapidity, which corresponds to the emitting source with high density. Nevertheless, while the Coulomb effect and the isospin fractionation tend to increase π^-/π^+ at midrapidity, the rescattering of pions in the medium is likely to broaden the rapidity distribution and to smear the difference between the midrapidity and large rapidity region.

Since the pion ratio π^-/π^+ reflects the isospin composition in the dense region where the pions are produced, it is then of interest to probe the relaxation of the isospin DOF and its dependence on $E_{\text{sym}}(\rho)$ at high densities by using the π^-/π^+ distribution as a function of rapidity in the central collisions. In this regard, we chose the isospin asymmetric colliding system ^{96}Ru + ^{96}Zr at energy $E = 400$ MeV/u. The isospin asymmetry for projectile and target is 1.18 and 1.40, respectively. The impact parameter is fixed at 1.0 fm. In the scenario of isospin transparency, a larger ratio π^-/π^+ is expected at the target rapidity region than at the projectile rapidity region, whereas in the scenario of complete isospin equilibrium, a symmetric π^-/π^+ distribution is predicted. Figure 2 presents the simulated rapidity spectra of π^-/π^+ with (a) $x = 1$ and (b) $x = 0$. The ratio in ^{96}Zr + ^{96}Ru (open circle) is obtained by reflecting the ratio in ^{96}Ru + ^{96}Zr (solid circle) with respect to the midrapidity. It is shown that the ratio π^-/π^+ exhibits the similar distribution as a function of rapidity with the experimental trend in ^{96}Ru + ^{96}Ru at the impact parameter $b = 3$ fm. The ratio reaches its maximum at midrapidity and decreases toward larger rapidities. More interestingly, it is shown that the rapidity spectrum of π^-/π^+ in the asymmetric collisions ^{96}Ru + ^{96}Zr is not symmetric with respect to midrapidity. The ratio π^-/π^+ is globally higher in the backward hemisphere than that in the forward hemisphere, which indicates the agreement with the scenario of isospin transparency predicted before. Moreover, the asymmetry of ratio on rapidity also indicates the importance of the primary correspondence of the π^-/π^+ and the local nucleonic isospin composition of the fireball rather than the Coulomb effect on the charged pions in the sense of isospin transparency.

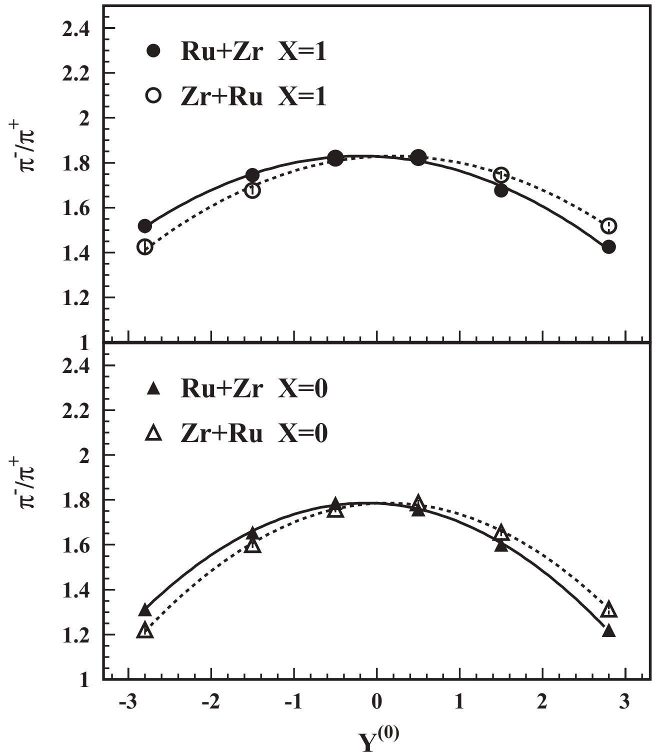

FIG. 2. π^-/π^+ ratio as a function of reduced rapidity $|y^{(0)}|$ in the IBUU04 calculation with the momentum-dependent interaction (a) $x = 1$ and (b) $x = 0$ in ^{96}Ru + ^{96}Zr (solid, calculated) and ^{96}Zr + ^{96}Ru (open, reflected by the solid symbols with respect to the midrapidity).

Otherwise, with pure Coulomb interaction, one may expect more abundant π^- in the forward hemisphere where more protons are distributed. If we reflect the calculated results in ^{96}Ru + ^{96}Zr (full circle) with respect to midrapidity to indicate the ratio spectrum in ^{96}Zr + ^{96}Ru as represented by the open circle, it is found that, in the target rapidity region, the ratio in ^{96}Ru + ^{96}Zr is higher than the reflected system, while in the projectile rapidity region, the opposite trend is observed. The difference between these two systems is increasingly pronounced when passing from midrapidity to large rapidity.

To have a quantitative estimation on the transport of isospin and its dependence on the symmetry energy at high densities, we define the double ratio of π^-/π^+ in the forward and backward regions at a given absolute value of rapidity $|y_0|$:

$$R(\pi^-/\pi^+) = \frac{\pi^-/\pi^+(y_0 < 0)}{\pi^-/\pi^+(y_0 > 0)}. \tag{2}$$

This definition is similar to $R(p)$ introduced in Ref. [35]. Figure 3 presents the distribution of $R(\pi^-/\pi^+)$ as a function of rapidity. The straight lines are the fitting to the symbols with the point (0,1) included as physically required. It is shown that the slope of $R(\pi^-/\pi^+)$ with rapidity exhibits an insignificant dependence on the symmetry energy at high densities. With a hard-symmetry energy, the double ratio $R(\pi^-/\pi^+)$ and the slope are slightly higher. The sensitivity of the dependence of $R(\pi^-/\pi^+)$ on different parameters $x = 0$ or 1 is about 2%, lower than what is predicted from systematics in Ref. [23]. The possible reasons would be that (i) the $\langle N/Z\rangle$ is lower in Ru + Zr than the systems in Ref. [23] and (ii) rescattering of pions diminishes the effect of $E_{\mathrm{sym}}(\rho)$ on the slope of $R(\pi^-/\pi^+)$ although the integrated π^-/π^+ remains unchanged. We notice that the dependence of the stopping seen by light clusters on $E_{\mathrm{sym}}(\rho)$ is also insignificant, as reported in Ref. [17].

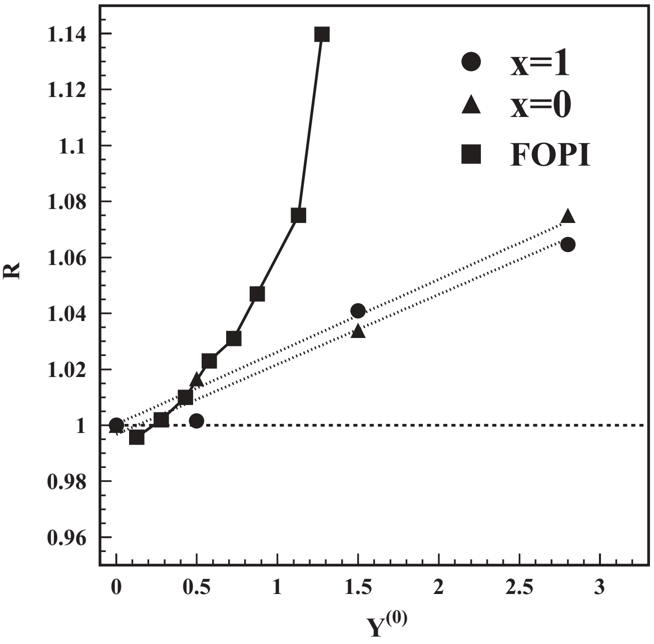

FIG. 3. $R(\pi^-/\pi^+)$ in the IBUU04 simulation with $x = 1$ (solid circle) and $x = 0$ (solid triangle) in comparison with the experimental $R(P)$ (solid square) [35] in the central ^{96}Ru + ^{96}Zr collision at 400 MeV/u.

It is interesting to compare $R(\pi^-/\pi^+)$ and $R(p)$ with a fixed formulation of NN cross section. As shown in Fig. 3, $R(P)$ and $R(\pi^-/\pi^+)$ behave very differently as a function of rapidity, although they all show an increasing trend. In the whole range of rapidity, the increasing rate of $R(\pi^-/\pi^+)$ is almost constant for pions. In addition, it is nearly the same with that of protons only in the midrapidity range ($|y^{(0)}| < 0.5$). At projectile rapidity range, however, the increasing rate of $R(p)$ becomes considerably higher than that of pions. The difference at large rapidity is attributed to the corona effect, which is seen by the protons at the vicinity of the surface but not by pions, since the latter comes from the Δ's produced mainly in the high-density region. Therefore, it suggests that the π^-/π^+ ratio as a function of rapidity is an effective signal of the isospin nonequilibrium in central HICs.

IV. SUMMARY

To summarize, with the isospin- and momentum-dependent hadronic transport model IBUU04, we simulated the yield ratio of π^-/π^+ in central collisions in ^{96}Zr(^{96}Ru) + ^{96}Ru(^{96}Zr) at 400 MeV/u. The ratio π^-/π^+ exhibits a discernible distinction in the forward and backward rapidity regimes in center of mass because of the isospin asymmetry between the project and target, suggesting that the isospin equilibrium is not reached in the collisions in agreement with the previous experimental picture from the proton tracer. Moreover, the ratio of proton yield $R(p)$ in the two isospin asymmetric systems is nearly the same with the double ratio of π^-/π^+ at the midrapidity region but becomes considerably higher at the projectile rapidity region. This is attributed to the increasing surface effect experienced by the protons with large rapidity. Thus, the pion ratio π^-/π^+ can be used to probe the isospin mixing in central collisions without being strongly distorted by the surface effect. Furthermore, it is demonstrated that the degree of isospin equilibration with π^-/π^+ is not sensitive to the symmetry energy at suprasaturation densities in the relevant system. To see the effect of $E_{\mathrm{sym}}(\rho)$, one may need heavier systems with larger isospin asymmetry between the projectile and target.

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