Shedding Light on Pion Production in Heavy-Ion Collisions and Its Application to Neutron Star Matter Properties

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Abstract

Within the framework of the quantum molecular dynamics transport model, the pion production and constraint of the high-density symmetry energy in heavy-ion collisions near threshold energy have been thoroughly investigated. The energy conservation in the decay of resonances and reabsorption of pions as well as in the inelastic nucleon-nucleon and nucleon-resonance collisions are taken into account. The isospin diffusion in the low-density region ($0.2\rho_0$ - $0.8\rho_0$) and high-density region ($1.2\rho_0$ - $1.8\rho_0$) is investigated by analyzing the spectra of neutron/proton and π^-/π^+ ratios in the isotopic reactions of ^{132}Sn + ^{124}Sn and ^{108}Sn + ^{112}Sn at the incident energy of 270 MeV/nucleon, in which the symmetry energy manifests the opposite effect in the different density domain. The controversial conclusion of the π^-/π^+ ratio for constraining the high-density symmetry energy by different transport models with the FOPI data has been clarified. A soft symmetry energy with the slope parameter of $L(\rho_0) = 42 \pm 25$ MeV by using the standard error analysis within the range of 1σ is obtained by analyzing the experimental data from the SπRIT collaboration. The neutron stars with the maximal mass of 2 $M_\odot$ and radius of 11-13 km are obtained with the constrained symmetry energy.

Full Text

Preamble

Shedding Light on Pion Production in Heavy-Ion Collisions and Application to Neutron Star Matter Properties

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Within the framework of the quantum molecular dynamics transport model, pion production and constraints on high-density symmetry energy in heavy-ion collisions near threshold energy have been thoroughly investigated. For the first time, energy conservation in resonance decay and pion reabsorption, as well as in inelastic nucleon-nucleon and nucleon-resonance collisions, has been taken into account. Isospin diffusion in the temporal evolution for different baryon-density regions (0.2(cid:26)0 - 0.8(cid:26)0) and (1.2(cid:26)0 - 1.8(cid:26)0) is systematically investigated by analyzing kinetic energy spectra of the neutron/proton ratio and (cid:25)−/(cid:25)+ ratios in the isotopic reactions 132Sn + 124Sn and 108Sn + 112Sn at an incident energy of 270 MeV/nucleon. The controversial conclusion regarding the (cid:25)−/(cid:25)+ ratio for constraining high-density symmetry energy from different transport models using FOPI data—known as the “pion puzzle”—has been clarified through complementary isospin observables. A soft symmetry energy with a slope parameter of L((cid:26)0) = 42 (cid:6) 25 MeV is obtained through standard error analysis within the 1(cid:27) range by analyzing experimental data from the S(cid:25)RIT collaboration.

Neutron stars with maximal masses of 2 M and radii of 11–13 km are obtained using the symmetry energy constrained from double ratio spectra of (cid:25)−/(cid:25)+ in isotropic reactions.

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I. INTRODUCTION

Heavy-ion collisions at intermediate energies create extreme conditions of high density, high temperature, and high isospin asymmetry, providing an excellent environment for exploring the properties of dense nuclear matter. Particle production in these collisions carries information about hot and compressed nuclear matter. Pion mesons have attracted particular attention as probes of dense matter since Yukawa predicted them as mediators of the strong interaction force [**?**] and they were subsequently discovered in cosmic-ray experiments [**?**]. Today, pions can be produced in laboratories through various reactions, including heavy-ion collisions, photon-, lepton-, and hadron-induced reactions, and electron-positron collisions. Particles produced in the GeV energy range reveal information about high-density nuclear matter and may be modified by the nuclear medium [**?**].

The nuclear equation of state (EOS) is expressed as the energy per nucleon of nuclear matter:

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

in terms of baryon density $\rho = \rho_n + \rho_p$ and relative neutron excess $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$, where $E_{sym}(\rho)$ is the symmetry energy \cite{4–6}. The symmetry energy at subsaturation density has important applications in understanding the structure of weakly bound nuclei, nucleon-nucleon correlations, and the pasta structure of neutron stars, and has been extensively investigated through various approaches including Pygmy dipole resonance, heavy-ion collisions, fast fission, and electron-nucleus scattering \cite{7–16}. High-density symmetry energy relates to compact star phenomena such as phase transitions, binary neutron star mergers, and tidal deformation \cite{17–22}, but remains poorly understood. To extract the density dependence of symmetry energy, new experiments are being conducted at facilities worldwide, including the Radioactive Isotope Beam Facility (RIBF) in Japan [?], the Rare Isotope Science Project in Korea (RAON) [?], the Facility for Rare Isotope Beams (FRIB) in the USA [?], and the Cooling Storage Ring (CSR) and High Intensity Accelerator Facility (HIAF) in China [?].

Numerous experimental data on pion production in heavy-ion collisions have been obtained, including from BEVALAC with the Berkeley Streamer Chamber [?, ?], DIOGENE at the Saturne synchrotron in Saclay [?], the FOPI collaboration at beam energies from 0.4A to 1.5A GeV at Gesellschaft für Schwerionenforschung [?], HIRFL-CSR in Lanzhou [?], and the SπRIT collaboration at RIKEN for 132Sn + 124Sn and 108Sn + 112Sn reactions at 270A MeV [?]. However, contradictory conclusions about constraining high-density symmetry energy were obtained by analyzing FOPI data on the $\pi-/\pi+$ excitation function with different transport models [?, ?], creating the "pion puzzle." Near threshold energy, pions are primarily produced via Δ(1232) resonance decay. Pion transport in heavy-ion collisions is modified in the nuclear medium through the pion-nucleon potential, in-medium cross sections, threshold energy, resonance decay width, and reabsorption processes via πN Δ reactions. The influence of the π potential on pion dynamics has been investigated using transport models \cite{35–42}. Recently, uncertainties in transport model observables for heavy-ion collisions have been discussed by the Transport Model Evaluation Project (TMEP) [?, ?]. More sophisticated investigations of pion production are still needed, incorporating isospin-, density-, and momentum-dependent pion-nucleon potentials, resonance-nucleon interactions, in-medium resonance properties, and threshold energy corrections. A unified description of symmetry energy effects on neutron/proton and $\pi-/\pi+$ spectra would help deepen understanding of experimental data.

In this work, pion production in isotopic nuclear reactions near threshold energy and its relationship to high-density symmetry energy are investigated using the Lanzhou quantum molecular dynamics (LQMD) transport model. The article is organized as follows: Section II briefly introduces the theoretical approach, Section III presents calculated results, and Section IV provides a summary and perspective on future experiments.

II. THEORETICAL APPROACH

In the LQMD transport model, the production of resonances, hyperons, and mesons is coupled to meson-baryon and baryon-baryon collisions, through which nuclear dynamics in heavy-ion collisions and hadron-induced reactions have been extensively investigated \cite{14, 45–47}. The temporal evolution of nucleons and nucleonic resonances is described by Hamilton's equations of motion under self-consistently generated two-body and three-body potentials with Skyrme effective interactions. The symmetry energy comprises three parts: kinetic energy from Fermi motion, local density-dependent interaction, and momentum-dependent potential:

$$E_{sym}(\rho) = \frac{\pi^2\rho)^{2=3}}{} + E_{sym}^{loc}(\rho) + E_{sym}^{mom}(\rho). \tag{1}$$

The stiffness of symmetry energy is adjusted by:

$$E_{sym}^{loc}(\rho) = C_{sym}(\rho/\rho_0)^{(cid:13)_s}.$$

The parameter C_{sym} is 52.5 MeV, and the stiffness parameter $(cid:13)_s$ is adjusted to obtain different density dependencies of symmetry energy. Values of 0.3, 1, and 2 correspond to soft, linear, and hard symmetry energy, with slope parameters $L(\rho_0) = 3\rho_0 dE_{sym}(\rho)/d\rho|_{(cid:26)=(cid:26)_0}$ of 42, 82, and 139 MeV, respectively. As shown in Fig. 1 Figure 1: see original paper, all cases yield symmetry energy at saturation density ($\rho_0 = 0.16$ fm^{-3}) of 31.5 MeV. The different slopes influence the neutron/proton ratio and neutron star mass-radius relations. Hard symmetry energy ($L = 139$ MeV) creates more repulsive forces for neutrons in neutron-rich matter, leading to lower neutron/proton ratios in high-density domains but larger free neutron/proton ratios. Symmetry energy dominates isospin diffusion in heavy-ion collisions, creating isospin density differences. Larger neutron/proton ratios in the density regime $1.2 \leq \rho/\rho_0 \leq 1.8$ with soft symmetry energy are obtained in the temporal evolution of 132Sn+124Sn, particularly for kinetic energies above 100 MeV, as shown in Fig. 1(b). Supra-saturation densities of $1.2 \leq \rho/\rho_0 \leq 1.8$ for protons and neutrons are accumulated from averaged temporal evolution based on local density formation in heavy-ion collisions. The stiffness of symmetry energy might be constrained by isospin observables from different density regions.

Reaction channels for pion production from resonance decay and direct processes such as Δ(1232), N*(1440), N*(1535), etc., are included in the model as follows [**?**]:

$$\Delta \leftrightarrow N\pi, \quad N^* \leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s\text{-state}).$$

Nucleon-nucleon (resonance) and pion-nucleon collisions are treated as stochastic, isotropic scattering during the temporal evolution. Momentum-dependent decay widths are implemented for $\Delta(1232)$ and N*(1440) resonances, with elementary cross sections taken from parameterized formulas calculated by the one-boson exchange model [?]. A constant width of* $\Gamma = 150$ *MeV is used for* $N(1535)$ decay. Elastic scatterings in nucleon-nucleon, nucleon-resonance ($NR \to NR$), and resonance-resonance ($RR \to RR$) collisions, along with inelastic collisions of nucleon-resonance ($NR \to NN$, $NR \to NR'$) and resonance-resonance channels ($RR \to NN$, $RR \to NR$, $RR \to RR'$, where R and R' are different resonances), are included. The direct process $NN \leftrightarrow NN\pi$(s-state) contributes roughly 15% of pion yields, with cross sections taken from the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) transport model [**?**].

Pion transport in nuclear medium is also described by Hamiltonian equations of motion:

$$V_{Coul} + \omega(p_i, \rho_i).$$

The Coulomb interaction is given by V_{Coul} with $r_{ij} = |r_i - r_j|$. Here N_M and N_B are the total numbers of mesons and baryons (including charged resonances), respectively. Note that pions have $\tau_z = -1, 0,$ and 1 for π^+, π^0, and π^-, respectively [**?**]. The isoscalar part $\omega_{isoscalar}$ is estimated by the Δ-hole model [**?**, **?**].

Energy balance in resonance decay and pion reabsorption in nuclear medium is satisfied by the relation $R \leftrightarrow N\pi$ (where R is a resonance):

$$R + p_R^2 + U_R(\rho, \delta, p_R) = N + (p_R - p_{(cid:25)})^2 + U_N(\rho, \delta, p) + \omega_{(cid:25)}(p_{(cid:25)}, \rho) + V_{Coul}^{(cid:25)N}.$$

Here p_R and $p_{(cid:25)}$ are the momenta of the resonance and pion, respectively. The term V_{Coul} contributes only for charged channels $\Delta^0 \leftrightarrow \pi^- + p$ and $\Delta^{++} \leftrightarrow \pi^+ + p$, with no effect for channels involving π^0 and neutron production. The optical potential can be evaluated from the in-medium energy:

$$V_{opt}^{(cid:25)}(p, \rho) = \omega_{(cid:25)}(p, \rho) - (m_{(cid:25)}^2 + p^2)^{1/2}.$$

U_R and U_N are single-particle potentials for resonance and nucleon, respectively. The vacuum spectral function for resonance production and decay is used. Similarly, energy conservation is treated for resonance production and direct s-state creation, e.g., for collisions with local baryon density ρ and isospin asymmetry δ:

$$N + p_{N1}^2 + U_N(\rho, \delta, p_1) + R + U_R(\rho, \delta, p_R) + N + p_{N2}^2 + U_N(\rho, \delta, p_2) = N + {p'}^2 + U_N(\rho, \delta, p')$$

for the channel $NN \leftrightarrow NR$ with momentum conservation $p_1 + p_2 = p_R + p'$. For example, the $\Delta(1232)$ optical potential is calculated via the nucleon optical potential:

$$U_{\Delta^-} = U_n, \quad U_{\Delta^{++}} = U_p, \quad U_{\Delta^+} = U_{\Delta^0} = \frac{U_n + U_p}{2},$$

where U_n and U_p are single-particle potentials for neutrons and protons. The N*-nucleon potential is taken to be the same as the nucleon-nucleon potential. The density-, isospin-, and momentum-dependent single-nucleon potential is:

$$U_{(cid:28)}(\rho,\delta,p)=\alpha+E^{loc}_{sym}(\rho)\delta^2)^{(cid:13)}\rho\delta^2+E^{loc}_{sym}(\rho)\rho\frac{\partial\rho_{(cid:28)}}{\partial p'}f_{(cid:28)}(r,p)[\ln(\epsilon(p-p')^2+1)]^2C_{(cid:28);(cid:28)}C'$$

Here $\tau\neq\tau'$, $\partial\delta^2/\partial\rho_n=4\delta\rho_p/\rho^2$, and $\partial\delta^2/\partial\rho_p=-4\delta\rho_n/\rho^2$. The nucleon effective (Landau) mass in nuclear matter with isospin asymmetry $\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$ is calculated through the potential as:

$$|1+m_{(cid:28)}|=\frac{m_{(cid:28)}}{|p|}\left|\frac{dU_{(cid:28)}}{dp}\right|$$

with free mass $m_{(cid:28)}$ at Fermi momentum $p=p_F$. Parameters α,β,γ, and ρ_0 are set to -215.7 MeV, 142.4 MeV, 1.322, and 0.16 fm^{-3}, respectively. $C_{(cid:28);(cid:28)}=C_{mom}(1+x)$, $C'_{(cid:28);(cid:28)}=C_{mom}(1-x)$ $(\tau\neq\tau')$, and isospin symbols $\tau(\tau')$ represent protons or neutrons. Values of 1.76 MeV and 5×10^{-4} c^2/MeV^2 are taken for C_{mom} and ϵ, yielding an effective mass $m^*/m=0.75$ in nuclear matter at saturation density for symmetric matter. The parameter x represents isospin splitting strength with value -0.65, producing mass splitting m^*_p in nuclear medium. An incompressibility modulus $K=230$ MeV for isospin-symmetric nuclear matter is obtained at saturation density.

Recently, the influence of the pion potential on pion dynamics in heavy-ion collisions has been extensively investigated with different transport models \cite{38–41, 53–55}. The meson is taken as a point particle, and Coulomb interaction between mesons is neglected due to their limited numbers compared to baryons.

The pion energy in nuclear medium comprises isoscalar and isovector contributions:

$$\omega_{(cid:25)}(p_i,\rho_i)=\omega_{isoscalar}(p_i,\rho_i)+C_{(cid:25)}\tau_z\delta(\rho/\rho_0)^{(cid:13)(cid:25)}.$$

Here the isovector coefficient $C_{(cid:25)}=\rho_0\bar{h}^3/(4f^2_{(cid:25)})=36$ MeV, isospin asymmetry $\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$, and isospin splitting parameter $(cid:13)_{(cid:25)}=2$.

III. RESULTS AND DISCUSSION

Isospin diffusion in heavy-ion collisions is associated with gradients of isospin density $(\rho_n-\rho_p)$ and symmetry potential $U_{sym}=(U_n(\rho,\delta,p)-U_p(\rho,\delta,p))/2\delta$, where symmetry energy significantly influences nucleon rearrangement during nuclear evolution. Neutron and proton density distributions vary with reaction system evolution, and the neutron/proton ratio differs across density ranges. To extract high-density symmetry energy, observables emitted from high-density domains in nuclear collisions are needed. While the neutron/proton ratio directly probes high-density symmetry energy, detecting high-statistics neutrons experimentally remains challenging.

We calculated kinetic energy spectra of the free neutron/proton (N/Z) ratio produced in 132Sn+124Sn and 108Sn+112Sn collisions at 270A MeV for different symmetry energy stiffness values, as shown in Fig. 2 [Figure 2: see original paper]. Free nucleons are identified via the minimum spanning tree (MST) procedure with relative distance $r_0 = 3$ fm and relative momentum $p_0 = 200$ MeV/c in phase space [**?**]. Hard symmetry energy with $L = 139$ MeV clearly leads to larger N/Z ratios, particularly above 100 MeV for neutron-rich systems. This result is consistent with Fig. 1(b), arising from more repulsive neutron interactions in dense neutron-rich matter for hard symmetry energy. More free neutrons are created with hard symmetry energy, opposite to findings in Fermi-energy heavy-ion collisions [**?**]. This conclusion aligns with IBUU04 calculations, where stiffer symmetry energy in high-density regions enhances the free neutron/proton ratio [**?**]. Identifying measurable quantities to constrain high-density symmetry energy is crucial, such as $\pi-/\pi+$, K0/K+, $\Sigma-/\Sigma+$, etc.

Symmetry energy, as a major component of the nuclear equation of state, significantly influences neutron star mass-radius relations, maximum mass, quark-gluon plasma to hadron phase transitions, and rare isotope nuclear structure. High-density symmetry energy behavior from pion production in heavy-ion collisions has been extensively studied via transport models including isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) and relativistic Vlasov-Uehling-Uhlenbeck (RVUU) \cite{54, 57–59}. Recently, the SπRIT collaboration at RIKEN measured transverse momentum spectra of pions produced in isotopic reactions [**?**, **?**]. We systematically analyzed pion production within the LQMD transport model, implementing energy conservation in resonance decay and reabsorption for the first time. The density profile of primordial pions in 132Sn+124Sn collisions at 270A MeV is shown in Fig. 3 [Figure 3: see original paper]. The black solid line denotes total pion production ($\pi-$ + $ $0 + $\pi+$), while red-dashed and blue-dotted-dashed lines represent $\pi-$ and $\pi+$, respectively. Although many pions are produced in low-density regions, pions at suprasaturation densities remain appreciable. Low-density pions mainly arise from rescattering processes (πN Δ(1232) and Δ(1232)N NN) [**?**]. Therefore, to extract high-density symmetry energy information, final pions from different density ranges must be distinguished. The $\pi-/\pi+$ ratio of primordial pions without rescattering approximately satisfies the quadratic relation from statistical models: $\pi-/\pi+ = (5\mathrm{n}^2+\mathrm{np})/(5\mathrm{p}^2+\mathrm{np})$ $(\mathrm{n}/\mathrm{p})^2$ [**?**].

To clarify the density range of primordial pions, Fig. 4 [Figure 4: see original paper] shows kinetic energy spectra of the $\pi-/\pi+$ ratio selected in density regions $0.2 \leq \ /_0 \leq 0.8$ and $1.2 \leq \ /_0 \leq 1.8$. Symmetry energy effects are opposite in different density domains: larger $\pi-/\pi+$ ratios with hard symmetry energy in low-density regions, but lower values at high densities. Moreover, the average $\pi-/\pi+$ ratio in the low-density region ($0.2 \leq \ /_0 \leq 0.8$) is close to the square of the N/Z ratio (2.43) of the reaction system, while the $\pi-/\pi+$ ratio in the high-density region approximates the average N/Z value (1.56) at kinetic energies below 100 MeV. Consequently, the $\pi-/\pi+$ ratio from total pion multiplicities cannot distinguish high-density symmetry energy effects. The pion density profile is influenced by rescattering cross sections and pion transport in nuclear medium, which may differ across transport models despite similar total pion multiplicities. Kinetic energy or transverse momentum spectra of $\pi-/\pi+$ ratios with rapidity and azimuthal emission cuts may serve as probes for constraining high-density symmetry energy.

The phase-space distribution of emitted particles in heavy-ion collisions is influenced by in-medium properties including rapidity, transverse momentum, kinetic energy, and invariant mass spectra. Figure 5 [Figure 5: see original paper] compares pion potential and threshold correction effects in 132Sn+124Sn and 108Sn+112Sn collisions at 270A MeV. Energy conservation in pion and resonance production relates to mean-field potentials of nucleons, pions, and resonances. Inclusion of energy conservation via Eqs. (7) and (8) enhances high-momentum pion production, as energetic pions are created to satisfy energy conservation in resonance decay (Eq. 7) for cases with threshold correction but without π potential (blue-dashed line). The V_{Coul} term in Eq. (7) has negligible contribution to pion transverse momentum spectra from Coulomb interactions between $\pi-$ and protons or $\pi+$ and protons from resonance decay. The pion-nucleon potential reduces pion yields due to attractive interactions, particularly for $\pi+$ production. Experimental transverse momentum spectra from the SπRIT collaboration [**?**] are nicely reproduced when including both energy conservation relations and pion potentials. Symmetry energy effects are also analyzed in Fig. 6 [Figure 6: see original paper], showing pronounced effects on $\pi-$ production where soft symmetry energy enhances yields. $\pi+$ spectra depend weakly on symmetry energy stiffness because proton-proton and proton-neutron collisions are minimally influenced by symmetry energy in neutron-rich systems. The $\pi-/\pi+$ ratio is enhanced with symmetry energy $L = 42$ MeV, consistent with high-density results in Fig. 4(b). High-transverse-momentum pions (above 150 MeV/c) are mainly produced in high-density zones and may probe high-density symmetry energy.

The single $\pi-/\pi+$ ratio in 132Sn+124Sn and 108Sn+112Sn reactions at 270A MeV is shown in Fig. 7 [Figure 7: see original paper]. Soft symmetry energy with $L = 42$ MeV better reproduces SπRIT data [**?**], particularly for the neutron-rich 132Sn+124Sn system. These results are self-consistent with free neutron/proton ratio kinetic energy spectra in Fig. 2, where hard symmetry energy yields larger neutron/proton ratios. Symmetry energy effects are more pronounced in neutron-rich systems compared to neutron-poor systems like 108Sn+112Sn. To eliminate Coulomb effects and reduce uncertainties, we analyzed double ratios (DRs) in isotopic reactions, defined as $DR(n/p) = (n/p)^{free}_{132Sn+124Sn}/(n/p)^{free}_{108Sn+112Sn}$ and $DR(\pi^-/\pi^+) = (\pi^-/\pi^+)_{132Sn+124Sn}/(\pi^-/\pi^+)_{108Sn+112Sn}$. This method has been used to constrain subsaturation-density symmetry energy and isospin splitting of nucleon effective mass [?]. Symmetry energy effects are pronounced at high kinetic energies (high transverse momenta) in isotopic reactions, as shown in Fig. 8 [Figure 8: see original paper], specifically for $E_{kin} > 100$ MeV or $p_T > 150$ MeV/c. The double ratio of neutron/proton shows more obvious symmetry energy effects than $\pi-/\pi+$, but with larger DR values for pion production. These complementary observables demonstrate that DRs at high kinetic energy or transverse momentum may probe high-density symmetry energy. The slope parameter $L(\rho_0) = 42 \pm 25$ MeV is obtained using standard error analysis within the 1σ range. Due to mixing of pions from high and low densities, symmetry energy effects on DR spectra are reduced at low p_T, but at high transverse momentum ($p_T \geq 150$ MeV/c) DRs exhibit significant sensitivity to high-density symmetry energy with approximately 20% differences.

It is noted that dcQMD calculations yield a constraint of 42 MeV $< L <$ 117 MeV. Unlike the dcQMD model, we fixed the isospin splitting of nucleon effective mass $m_p^*/m_n = 0.04$ at isospin asymmetry $\delta = 0.2$ and saturation density. dcQMD calculations show that hard symmetry energy with $L(\rho_0) = 151$ MeV yields larger single $\pi-/\pi+$ ratios and DRs at high transverse momenta, possibly due to larger pion-nucleon scattering cross sections and dominant low-density pion contributions to transverse momentum spectra. Compared to our previous results for constraining high-density symmetry energy from pion production [?], the current LQMD model includes isospin-, density-, and momentum-dependent nucleon-nucleon and pion-nucleon potentials, energy conservation for resonance production and reabsorption via $NN \leftrightarrow NR$, and energy conservation for pion production and reabsorption via $R \leftrightarrow \pi N$. These modifications are essential for transverse momentum spectra near threshold energies.

Symmetry energy effects on $DR(n/p)$ and $DR(\pi^-/\pi^+)$ spectra are opposite in high kinetic energy or transverse momentum regions: hard symmetry energy yields larger $DR(n/p)$ but smaller $DR(\pi^-/\pi^+)$ values, complementarily demonstrating that high-transverse-momentum pions ($p_T \geq 150$ MeV/c) are primarily produced in high-density domains. These results are self-consistent with kinetic energy spectra of single $(\mathrm{n/p})_{free}$ and $\pi-/\pi+$ ratios in high-density regions.

The neutron star mass-radius relation is influenced by density-dependent symmetry energy and isospin-symmetric nuclear matter properties. The maximum neutron star mass relates to nuclear matter incompressibility and hyperon-nucleon interaction potential stiffness [?]. Figure 9 [Figure 9: see original paper] compares pressure density dependence and neutron matter mass-radius relations for different symmetry energy slope parameters. The symmetry energy constraint from SπRIT pion production data yields a maximum mass of 2.0 M and radius of 11–13 km (blue lines in Fig. 9(b)). Strange neutron stars with mass 2.76 M and radius 15 km are obtained with hard symmetry energy ($L = 139$ MeV). These results are consistent with NICER observations of PSR J0030+0451 and J0740+6620. Symmetry energies with slope parameters $L = 35, 42, 53,$ and 67

MeV produce the same maximum neutron star mass but different radii. Note that our calculations include only neutrons, protons, electrons, muons, and neutrinos as neutron star constituents. Properties of symmetric nuclear matter and hyperon components also affect the mass-radius relation.

IV. CONCLUSIONS

In summary, isospin diffusion in isotopic reactions 132Sn + 124Sn and 108Sn + 112Sn at 270 MeV/nucleon is thoroughly investigated within the LQMD transport model. Symmetry energy exhibits opposite contributions to N/Z and $\pi-/\pi+$ ratios in low-density versus high-density domains. Hard symmetry energy enhances the free nucleon N/Z ratio but reduces N/Z and $\pi-/\pi+$ ratios in high-density regions. Pion production in heavy-ion collisions spans the entire density range, with most pions created in dilute nuclear matter due to rescattering processes between pions, resonances, and nucleons. Symmetry energy stiffness significantly affects $\pi-$ transverse spectra but weakly impacts $\pi+$ production. The pion optical potential is evident in high-momentum regimes, influencing both $\pi-$ and $\pi+$ spectra. Systematic analysis of symmetry energy and pion-nucleon potential effects at densities around $1.5\rho_0$ yields soft symmetry energy with slope parameter $L(\rho_0) = 42 \pm 25$ MeV (stiffness coefficient $(cid:13)_s = 0.3$) consistent with SπRIT data. Additional experiments are needed for complementary constraints on high-density symmetry energy, including collective flows and differential flows of pions, and energy spectra of triton/^{3}He ratios. Neutron stars with maximum mass 2 M and radius 11–13 km obtained from pion-data-constrained symmetry energy are consistent with NICER observations of PSR J0030+0451 and J0740+6620.

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