Influence of neutron skin thickness on $\pi^-/\pi^+$ ratio in Pb+Pb collisions

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Within an isospin and momentum dependent transport model IBUU11 using as an input nucleon density profiles from Hartree-Fock calculations based on a modified Skyrme-like (MSL) model, we study the influence of the uncertainty of the neutron skin thickness on the $\pi^-/\pi^+$ ratio in both central and peripheral Pb+Pb collisions at beam energies of 400 MeV/nucleon and 1000 MeV/nucleon. Within the current experimental uncertainty range of neutron skin in $^{208}$Pb, while the neutron skin effect on the $\pi^-/\pi^+$ ratio is negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions especially at 400 MeV/nucleon. Moreover, we found that while the $\pi^-/\pi^+$ ratio is larger with a softer $E_{\text{sym}}(\rho)$ in central collisions, above certain impact parameters depending on the size of the neutron skin, a stiffer $E_{\text{sym}}(\rho)$ can lead to a larger $\pi^-/\pi^+$ ratio as most of the pions are produced at densities below the saturation density in these peripheral reactions. Thus, a clear impact parameter selection is important to extract reliable information about the $E_{\text{sym}}(\rho)$ at suprasaturation densities (size of neutron skin) from the $\pi^-/\pi^+$ ratio in central (peripheral) heavy-ion collisions.

The density dependence of nuclear symmetry energy $E_{\text{sym}}(\rho)$ affects not only the structure of nuclei and neutron stars, such as the neutron skin in heavy nuclei and radii of neutron stars[1, 2], but also their reaction dynamics, such as particle production in heavy-ion collisions[3, 4] and emission of gravitational waves in spiraling neutron star binaries[10]. Thus, combining information from various laboratory experiments and astrophysical observations has the promise of mapping out accurately the currently still poorly known $E_{\text{sym}}(\rho)$ in a broad density range[11, 12]. In particular, various observables from the size of neutron skin, pygmy dipole resonance and dipole polarizability in heavy nuclei, e.g., refs. [13, 16] to the neutron/proton[17] and $\pi^-/\pi^+$[18] ratios in heavy-ion collisions have been found to be sensitive to the $E_{\text{sym}}(\rho)$ at different densities. While significant progress has been made in constraining the $E_{\text{sym}}(\rho)$ mostly around the saturation density $\rho_0$[19], much more work needs to be done to better determine the $E_{\text{sym}}(\rho)$ at both subsaturation and suprasaturation densities. For an overview of the latest status of the field, we refer the reader to the webpages of the 2013 International Collaboration in Nuclear Theory program on nuclear symmetry energy[20] and the Third International Symposium on Nuclear Symmetry Energy (Nusym13)[21].

The size of neutron skin has long been identified as one of the most promising observables to fix the $E_{\text{sym}}(\rho)$ around 0.1 fm$^{-3}$, see, e.g., Refs. [22, 27]. However, the available data obtained mostly from hadronic probes suffer from large uncertainties. For example, the experimentally measured size of neutron skin in $^{208}$Pb currently ranges from about 0.1 fm from $\pi^+$-Pb scattering to 0.33 fm from the PREX-I experiments using parity violating e-Pb scattering[28] with large error bars. For a recent review, see, e.g., Ref. [29]. Interestingly, it was shown very recently within a relativistic mean-field model[30] that a neutron skin for $^{208}$Pb as thick as 0.33 fm reported by the PREX-I experiment[28] can not be ruled out although most other studies have reported much smaller values. This situation has stimulated the renewed interest to experimentally measure more precisely the size of neutron skins in heavy nuclei. Currently, the community is waiting with much interest for the approved CREX and PREX-II experiments at JLab[31] to provide more accurate values for the neutron skin thickness in both $^{48}$Ca and $^{208}$Pb. On the other hand, at suprasaturation densities, the $\pi^-/\pi^+$ ratio in heavy-ion collisions near the pion production threshold[18] is among the most promising observables proposed based on transport model simulations by several groups. Unfortunately, the theoretical results from different models are still inconsistent and conclusions from comparisons with very limited data available remain rather controversial[32, 33]. This situation demands certainly collec-
tive efforts by the community, among other things, to quantify theoretical uncertainties associated with various model assumptions and input parameters in transport model studies of heavy-ion collisions. As a useful step towards this goal, we investigate effects of the uncertainties of the neutron skin thickness on extracting information about the high-density symmetry energy using the $\pi^-/\pi^+$ ratio in heavy-ion collisions at beam energies of 400 MeV/nucleon and 1000 MeV/nucleon within the latest version of an isospin and momentum dependent transport model IBUU11 [36].

To initialize transport models, it is necessary to know the nucleon density profiles for the two colliding nuclei. Ideally, one would like to use the same nuclear interaction to generate self-consistently the initial state phase space distributions within the reaction model itself. Practically, to our best knowledge, none of the available reaction models can describe properties of nuclei in their ground state as good as the microscopic and/or phenomenological many-body theories. Thus, most models use as input nucleon distributions predicted by nuclear structure models. While the proton distributions are constrained precisely by electron scattering experiments, the neutron density distributions are still largely unknown. Because of the diverse predictions using various interactions and many-body theories, the neutron skins for colliding nuclei used in transport models change from model to model. We investigate here how the size of neutron skin may affect the $\pi^-/\pi^+$ signal of the $E_{\text{sym}}(\rho)$ from central to peripheral heavy-ion collisions. In fact, soon after the high-energy radioactive beams become available some 25 years ago, the $\pi^-/\pi^+$ in peripheral nuclear reactions induced by rare isotopes was proposed as a sensitive measure of the size of neutron skin [47, 48]. It is thus necessary to examine the influence of the uncertainty of neutron skin thickness on the information of $E_{\text{sym}}(\rho)$ we may extract from studying the $\pi^-/\pi^+$ ratio in heavy-ion collisions. As an example, we study the $\pi^-/\pi^+$ ratio in Pb+Pb collisions from central to peripheral impact parameters at beam energies of 400 MeV/nucleon and 1000 MeV/nucleon. We will see that while the neutron skin effect on the $\pi^-/\pi^+$ ratio is found negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions especially at 400 MeV/nucleon. Moreover, although the $\pi^-/\pi^+$ ratio is larger with a softer $E_{\text{sym}}(\rho)$ in central collisions, we found that above certain impact parameters depending on the size of the neutron skin, a stiffer $E_{\text{sym}}(\rho)$ can lead to a larger $\pi^-/\pi^+$ ratio as most of the pions are created at densities below the saturation density in these peripheral reactions.

This study is carried out using the isospin dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [49] of version IBUU11 [50]. To ease the following discussions, we briefly describe here the MDI (momentum dependent interaction) model used in simulating the reaction dynamics, and the nucleon density profiles with different sizes of neutron skins used in initializing the two colliding nuclei. The momentum dependence of both the isoscalar [41, 47] and isovector [40, 46, 48] parts of the nuclear interaction is important in understanding not only many phenomena in intermediate-energy heavy-ion collisions but also thermodynamical properties of isospin-asymmetric nuclear matter [49, 51]. The MDI mean-field potential for a nucleon with momentum $\vec{p}$ and isospin $\tau$ can be written as [42]

$$U(\rho, \delta, \vec{p}, \tau) = A_u(x) \frac{\rho_{\tau}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} + B \left( \frac{\rho}{\rho_0} \right)^\sigma (1 - x \delta^2) - 8 \tau x \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0} \delta \rho_{-\tau} + \frac{2 C_{\tau,\tau}}{\rho_0} \int d^3 p' \frac{f_\tau(p')}{1 + (\vec{p} - \vec{p'})^2/\Lambda^2} + \frac{2 C_{\tau,-\tau}}{\rho_0} \int d^3 p' \frac{f_{-\tau}(p')}{1 + (\vec{p} - \vec{p'})^2/\Lambda^2}. \quad (1)$$

In the above, $\rho = \rho_n + \rho_p$ is the nucleon number density and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry of the nuclear medium; $\rho_{n(p)}$ denotes the neutron (proton) density; $\sigma$ is 1/2 for neutrons and −1/2 for protons, and $f(\vec{p})$ is the local phase space distribution function. The expressions and values of the parameters $A_u(x), A_l(x), \sigma, B, C_{\tau,\tau}, C_{\tau,-\tau},$ and $\Lambda$ can be found in Refs. [40, 52], and they lead to the binding energy of −16 MeV, incompressibility 212 MeV for symmetric nuclear matter, and symmetry energy $E_{\text{sym}}(\rho_0) = 30.5$ MeV at saturation density $\rho_0 = 0.16$ fm$^{-3}$, respectively.

![FIG. 1: (Color online) The density dependence of the symmetry energy.](image)

The MDI mean-field potential comes from Hartree-Fock calculations using a modified Gogny force including a zero-range effective three-body interaction and a finite-range Yukawa-type two-body interaction [41, 52, 53]. The variable $x$ was introduced to mimic different forms of the symmetry energy predicted by various many-body theories without changing any properties of symmetric
are the $E_{\text{sym}}(\rho)$ with $x = 1$ and $x = 0$. The density dependence of $E_{\text{sym}}(\rho)$ around $\rho_0$ is generally characterized by the slope parameter $L = 3\rho_0(dE_{\text{sym}}/d\rho)_{\rho=\rho_0}$. The softer (stiffer) $E_{\text{sym}}(\rho)$ with $x = 1$ ($x = 0$) has a value of $L = 16.4$ (62.1) MeV. Due to the well-known isospin fractionation during heavy-ion collisions, a larger value of $E_{\text{sym}}(\rho)$ at density $\rho$ generally leads to a smaller isospin asymmetry there to lower the energy of the system. Since the density reachable depends sensitively on the impact parameter and the $\pi^-/\pi^+$ is sensitive to the isospin asymmetry of the participant region, the dependence of the $\pi^-/\pi^+$ ratio on the $E_{\text{sym}}(\rho)$ is expected to be affected by the impact parameter and the size of neutron skin.

To examine effects of the neutron skin, we initialize nucleons in phase space using neutron and proton density profiles predicted by Hartree-Fock calculations based on the MSL model [54]. Different values of neutron skin thickness can be obtained by changing only the value of $L$ in the MSLO force [55] while keeping all the other macroscopic quantities the same. Shown in Fig. 2 are the density profiles corresponding to a neutron skin thickness $S$ of 0.1 and 0.3 fm in $^{208}$Pb. As one expects, the proton distributions are almost identical, while the neutrons distribute differently in the two cases considered.

Because the magnitude of isovector potentials is always much smaller than that of isoscalar potentials during heavy-ion reactions, isospin effects on reaction observables are normally very small. To exclude uncertainties of statistical nature from our physical considerations, we have performed large scale calculations with $4 \times 10^5$ events in each case reported here. Thus, in most plots the statistical error bars are smaller than the plotting symbols except in very peripheral reactions. Within the IBUU model for heavy-ion collisions up to about 1.5 GeV/nucleon, most pions are produced through the decay of $\Delta(1232)$ resonances. As discussed in detail in Ref. [18], the $(\pi^-/\pi^+)$ ratio defined as

$$\frac{\pi^- + \Delta^- + \frac{1}{2}\Delta^0}{\pi^+ + \Delta^{++} + \frac{1}{2}\Delta^+},$$

(2)

is a good measure of the symmetry energy effect during heavy-ion collisions. At the final stage, all the $\Delta$ resonances will eventually decay and the $(\pi^-/\pi^+)$ ratio naturally becomes the ratio of free pions, i.e., $\pi^-/\pi^+$. To see how the $\pi^-/\pi^+$ ratio in heavy-ion collisions depends on the impact parameter, the beam energy, and the $E_{\text{sym}}(\rho)$ for a given neutron skin thickness of 0.1 fm, we show in Fig. 3 the evolutions of the $(\pi^-/\pi^+)$ ratio from midcentral to peripheral $^{208}$Pb + $^{208}$Pb collisions at a beam energy of 400 (left) and 1000 MeV/nucleon (right), respectively. For pion production, it is known that there is no obvious impact parameter dependence from head-on to midcentral heavy-ion reactions. Consistent with previous observations from various transport model calculations, the $\pi^-/\pi^+$ ratio is larger and more sensitive to the $E_{\text{sym}}(\rho)$ near the pion production threshold. One interesting new feature seen is that the dependence of

![Graph showing neutron and proton density profiles for $^{208}$Pb with neutron skin thickness of 0.1 and 0.3 fm, respectively.](image)

**FIG. 2:** (Color online) The neutron and proton density profiles for $^{208}$Pb with neutron skin thickness of 0.1 and 0.3 fm, respectively.

![Graph showing the evolution of the $(\pi^-/\pi^+)$ ratio from central to peripheral $^{208}$Pb + $^{208}$Pb reactions at beam energies of 400 (left) and 1000 MeV/nucleon (right).](image)

**FIG. 3:** (Color online) Evolution of the $(\pi^-/\pi^+)$ ratio from central to peripheral $^{208}$Pb + $^{208}$Pb reactions at beam energies of 400 (left) and 1000 MeV/nucleon (right). The $x$ parameter is 1 (red) and 0 (black), and the size of neutron skin is 0.1 fm in all cases.
the $\pi^-/\pi^+$ ratio on the $E_{sym}(\rho)$ has a transition from midcentral to peripheral collisions. Namely, in central to midcentral collisions, a softer $E_{sym}(\rho)$ with $x = 1$ leads to a larger $\pi^-/\pi^+$ ratio than the stiffer one with $x = 0$, while it is the opposite in peripheral reactions. This is because the average density of the participant region is significantly above $\rho_0$ in central to midcentral collisions, while it becomes lower than $\rho_0$ in peripheral collisions. In the latter case, a softer $E_{sym}(\rho)$ gives a larger value of the symmetry energy and a less neutron-rich participant matter, resulting in a smaller $\pi^-/\pi^+$ ratio. This phenomena indicates that the sorting of events according to some effective impact parameter selection criteria is very important for extracting reliable information about the $E_{sym}(\rho)$ from the $\pi^-/\pi^+$ ratio in heavy ion collisions.

Since the symmetry energy effect depends sensitively on the isospin asymmetry of the participant region, we would expect that the exact impact parameter where the transition happens depends on the size of neutron skin and beam energy. We thus examine the rapidity dependence of the $\pi^-/\pi^+$ ratio using different sizes of neutron skin in $^{208}$Pb in Fig. 4 and Fig. 5 with beam energy of 400 MeV/nucleon and 1000 MeV/nucleon, respectively. It is seen that increasing the size of neutron skin reduces appreciably the $\pi^-/\pi^+$ ratio in peripheral reactions especially at a lower beam energy. Within the first-chance nucleon-nucleon collision model without considering the isospin dependence of Pauli blocking as well as the subsequent pion reabsorption and reproduction that are simulated in the transport model, one natively expects the $\pi^-/\pi^+$ ratio to increase with increasing size of neutron skin. Indeed, this is observed in the very earlier stage of the reaction. However, our transport model calculations indicate that with a thicker neutron skin the final multiplicities of both $\pi^-$ and $\pi^+$ increase in peripheral reactions due to the larger overlap and the higher density reached in the participant region. Thus the $\pi^-/\pi^+$ ratio is appreciably larger with a neutron skin of 0.1 fm than 0.3 fm for a given $x$ parameter. Compared to the 400 MeV/nucleon case, the $\pi^-/\pi^+$ ratio at 1000 MeV/nucleon is flatter in rapidity $y$ due to multiple pion production channels possible only at higher beam energies. Moreover, in peripheral reactions at 1000 MeV/nucleon the $\pi^-/\pi^+$ has a double bump structure. This is understandable since the nuclear stopping power is lower at 1000 than 400 MeV/nucleon. Thus, the Coulomb field of the spectators in peripheral collisions at 1000 MeV/nucleon leads to the well-known Coulomb peaks in the $\pi^-/\pi^+$ ratio.

As shown in Fig. 4 and Fig. 5, while the absolute effect of the neutron skin is small, it is comparable with or even larger than the effect due to the $E_{sym}(\rho)$ in peripheral collisions, especially at 400 MeV/nucleon. One can compare more quantitatively and fairly their relative effects on the $\pi^-/\pi^+$ ratio by comparing

$$F(L) = \frac{\Delta(\pi^-/\pi^+)}{\Delta L/L} \quad (3)$$

$$F(S) = \frac{\Delta(\pi^-/\pi^+)}{\Delta S/S} \quad (4)$$

where $\Delta(\pi^-/\pi^+)$ is the resulting change in the midrapidity ($|y/y_{beam}| \leq 0.5$) $\pi^-/\pi^+$ ratio due to the variation of the $L$ parameter or the size of neutron skin $S$. Presented
in Tab. I and Tab. II are the values of $F(L)$ and $F(S)$ for the reactions studied here. In central to midcentral collisions the values of $F(L)$ are much larger than that of $F(S)$, indicating that indeed the $\pi^-/\pi^+$ ratio in these reactions is an observable sensitive to the parameter $L$ with little influence from the uncertainties of the size of neutron skin. On the other hand, in peripheral collisions the $\pi^-/\pi^+$ ratio is sensitive to the variation of neutron skin thickness with small uncertainties due to our poor knowledge about the $E_{sym}(\rho)$, especially at lower beam energies.

**TABLE I:** The measure $F(L)$ ($10^{-2}$) of the symmetry energy effect on the midrapidity $\pi^-/\pi^+$ ratio in Pb+Pb reactions.

| $S$ (fm) | $E_{beam}$ (MeV) | $b$ (fm) | $\rho$ (fm) |
|----------|-----------------|----------|-------------|
| $S = 0.10$ | 400 (1000) | 34.5 (10.1) | 12.3 (0.4) |
| $S = 0.30$ | 400 (1000) | 28.8 (7.8) | 13.9 (0.9) |
| $b = 5$   | 48.4 (4.3) | 11.0 (0.4) | 22.1 (7.8) |
| $b = 7$   | 8.9 (0.2)   | 13.9 (0.9) | 25.2 (7.2) |
| $b = 9$   | 41.8 (20.6) | 33.4 (18.5) | |
| $b = 11$  | -3.9 (-6.3) | -1.9 (-5.8) | |

**TABLE II:** The measure $F(S)$ ($10^{-2}$) of the neutron skin effect on the midrapidity $\pi^-/\pi^+$ ratio in Pb+Pb reactions.

| $x = 0$   | $x = 1$   |
|-----------|-----------|
| $E_{beam}$ (MeV) | 400 (1000) | 400 (1000) |
| $b = 5$   | 48.4 (4.4) | 8.9 (0.2) |
| $b = 7$   | 11.0 (0.4) | 13.9 (0.9) |
| $b = 9$   | 22.1 (7.8) | 25.2 (7.2) |
| $b = 11$  | 41.8 (20.6) | 33.4 (18.5) |

In summary, the influence of the uncertainty of the neutron skin thickness on the $\pi^-/\pi^+$ ratio in $^{208}\text{Pb}+^{208}\text{Pb}$ collisions at beam energies of 400 and 1000 MeV/nucleon was examined within the IBUU11 transport model. While the neutron skin effect on the $\pi^-/\pi^+$ ratio is negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions especially at 400 MeV/nucleon. Moreover, it is found that while the $\pi^-/\pi^+$ ratio is higher with a softer $E_{sym}(\rho)$ in central collisions, above certain impact parameters depending on the size of neutron skin a stiffer $E_{sym}(\rho)$ can lead to a larger $\pi^-/\pi^+$ ratio. Thus, a clear impact parameter selection is important to extract reliable information about the $E_{sym}(\rho)$ at suprasaturation densities (size of neutron skin) from the $\pi^-/\pi^+$ ratio in central (peripheral) heavy-ion collisions.

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