Probing neutron-skin thickness with free spectator neutrons in ultracentral high-energy isobaric collisions

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We show that the yield ratio of free spectator neutrons produced in high-energy 96Zr+96Zr to 96Ru+96Ru collisions is a clean probe of the neutron-skin thickness of colliding nuclei and the slope parameter L of the symmetry energy. The idea is demonstrated based on the proton and neutron density distributions via a state-of-the-art Skyrme-Hartree-Fock-Bogolyubov calculation. Among spectator nucleons given by the Glauber model, free spectator neutrons include those from direct production that survive from clusterization as well as those from deexcitation of heavy clusters described by the popular GEMINI model. More free neutrons are produced in collisions of 96Zr nucleus due to its larger neutron skin, compared to those produced in collisions of 96Ru nucleus with a smaller neutron skin. The difference of the free spectator neutron yield is further increased with the increasing difference of the neutron-skin thickness between 96Zr and 96Ru with a larger L value, and the increase in ultracentral collisions is particularly insensitive to model details and experimental uncertainties. Since the production of free spectator neutrons is not affected by the complicated dynamics in the mid-rapidity region, the ratio of their multiplicities in ultracentral isobaric collisions is a robust observable for constraining the neutron skin and L value.

Introduction. The distributions of protons and neutrons in heavy nuclei are the primary probes of the nuclear interaction as well as the nuclear matter equation of state (EOS) [1, 2], particularly the symmetry energy that describes how the energy per nucleon changes with the neutron-proton asymmetry [3]. In heavy neutron-rich nuclei, the excess neutrons are pushed out to form a neutron skin, with its thickness Δrnp, defined as the difference between the neutron and proton root-mean-square (RMS) radii. The value of Δrnp is a robust probe of the slope parameter L of the symmetry energy [4–9]. Besides its relevance in nuclear structure, the measurement of Δrnp and the subsequent determination of L are important in understanding many interesting phenomena in both astrophysics [10, 11] and nuclear reactions [12].

In the past decades, various methods have been used to measure Δrnp, including hadron-nucleus scatterings [13–18], photon-nucleus scatterings [19], and, particularly, parity-violating electron-nucleus scatterings [20, 21], the data from which has induced considerable attention [22] and debate [23, 24]. Recently, it is realized that the huge amount of particles produced in high-energy heavy-ion collisions at \(\sqrt{s_{NN}} \geq 100\) GeV can be used to determine the density distribution of colliding nuclei [25–27], includ-

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Most observables in heavy-ion collisions utilize particles produced near the mid-rapidity region, the descrip-
tion of which requires sophisticated modeling of the full space-time dynamics and properties of the QGP. In this Letter, we propose the ratio of the number of free spectator neutrons \( N_n \) in isobar systems, easily measurable by the zero-degree calorimeters (ZDC) [30], as a clean and complementary probe of the neutron-skin thicknesses of \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \). In ultracentral collisions (UCC), most free spectator nucleons, outside the overlap region, originate from the surface of the nuclei (see cartoon in Fig. 1). In high-energy heavy-ion collisions, these free neutrons, captured by the ZDC, are casually disconnected from the matter produced by the participating nucleons. The \( N_n \) is sensitive to the \( \Delta r_{np} \), i.e., a larger \( \Delta r_{np} \) in \(^{96}\text{Zr} \) than in \(^{96}\text{Ru} \) is expected to give a larger \( N_n \) in \(^{96}\text{Zr}+^{96}\text{Zr} \) collisions than in \(^{96}\text{Ru}+^{96}\text{Ru} \) collisions. The free spectator neutrons can be produced either directly or from the deexcitation of charged nucleon clusters. Despite being measured routinely in heavy-ion experiments, the distribution of \( N_n \) is mostly used to estimate the event centrality or the reaction plane [37, 38].

Our study is the first to use the \( N_n \) to probe the collective structure of colliding nuclei. The recent STAR paper [30] has observed a significant enhancement of the neutron skin in isobar systems, easily measurable by the zero-degree calorimeters (ZDC) [30], as a clean and complementary probe of the neutron-skin thicknesses of \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \) collisions relative to \(^{96}\text{Ru}+^{96}\text{Ru} \) collisions, providing a clear motivation for our study.

![FIG. 1. (top) Side view of central collisions of \(^{96}\text{Zr} \) with a larger neutron skin and \(^{96}\text{Ru} \) with a smaller neutron skin. The directly-produced spectator neutrons and those from the deexcitation of charged clusters go to the ZDC down the beamline. The free protons and remaining charged clusters are bent away by beam optics. (bottom) Density profiles of neutrons and protons for \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \) from spherical SHF calculations using different slope parameters \( L \) of the symmetry energy.](image)

**Method.** We generate the spatial distributions of neutrons and protons in the initial \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \) using the Skyrme-Hartree-Fock (SHF) model [39], where the 10 parameters in the Skyrme interaction can be expressed analytically in terms of 10 macroscopic quantities including \( L \). The model allows us to vary \( L \) while keeping the other parameters fixed at their empirical values [39] that give a reasonable description of global nuclear structure data. Based on the Skyrme interaction, the energy-density functional can then be obtained using the Hartree-Fock method, and the single-particle Hamiltonian is obtained using the variational principle. Solving the Schrödinger equation gives the wave functions of constituent neutrons and protons and thus their density distributions. As an essential ingredient for the description of open shell nuclei, the paring correlations have also been incorporated in above standard procedure, and this is called the Skyrme-Hartree-Fock-Bogolyubov (SHFB) method [40]. The effects of axial symmetry deformation are included in the SHFB calculation using the cylindrical transformed deformed harmonic oscillator basis. An analysis on the ratio of \( v_2 \) and \( v_3 \) in the isobaric collisions favors \( \beta_2 = 0.16 \) for \(^{96}\text{Ru} \) and \( \beta_2 = 0.06 \) and \( \beta_3 = 0.20 \) for \(^{96}\text{Zr} \) [31]. We will compare results from spherical and deformed density distributions, and will show later that the results are relatively insensitive to the deformation parameters. The bottom panels of Fig. 1 show the density profiles of \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \) from spherical SHF calculations, from which we obtain \( \Delta r_{np} = 0.147 \text{ fm} \) in \(^{96}\text{Zr} \) and \( 0.028 \text{ fm} \) in \(^{96}\text{Ru} \) for \( L = 30 \text{ MeV} \), and \( \Delta r_{np} = 0.231 \text{ fm} \) in \(^{96}\text{Zr} \) and \( 0.061 \text{ fm} \) in \(^{96}\text{Ru} \) for \( L = 120 \text{ MeV} \), respectively. The influence of nuclear deformation on \( \Delta r_{np} \) for a given \( L \) is found to be less than 8%. The charge radii for \(^{96}\text{Zr} \) and \(^{96}\text{Ru} \) in different cases are consistent with the experimental data [41] within 1.5%.

The \(^{96}\text{Zr}+^{96}\text{Zr} \) and \(^{96}\text{Ru}+^{96}\text{Ru} \) collisions are simulated using a Monte-Carlo Glauber model. In each collision event, the colliding nuclei are placed at a random impact parameter and their orientations are uniformly randomized. The coordinates of neutrons and protons are sampled according to the density distributions obtained from the SHFB calculation, while their momenta are sampled in the isospin-dependent Fermi sphere according to the local densities of neutrons and protons. The nucleon-nucleon inelastic cross section are chosen to be \( 42 \text{ mb} \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). From this, the participant nucleons and spectator nucleons are identified. The quantities associated with participant matter, such as the number of participating nucleons and nucleon-nucleon collisions, are calculated for each event. The distribution of these quantities are then used in a fit to the measured distribution of charged-particle multiplicity \( N_{ch} \), according to the experimental procedure [30]. The quantities associated with spectator matter, in particular the \( N_n \), to be determined below, can then be correlated with \( N_{ch} \), similar to that from the experimental analysis.

The spectator matter are further grouped into charged clusters and free nucleons. Nucleons close in phase space, i.e., with the distance \( \Delta r < \Delta r_{\text{max}} = 3 \text{ fm} \) and relative momentum \( \Delta p < \Delta p_{\text{max}} = 300 \text{ MeV}/c \), are assigned to the same cluster [42]. Here \( \Delta r_{\text{max}} \) and \( \Delta p_{\text{max}} \) represent the scale of maximum distance and relative momentum between neighboring nucleons in the clusters, respectively.
The deexcitation of heavy clusters with \( A \geq 4 \) are handled by the GEMINI model [43, 44], which requires as inputs the angular momentum and the excitation energy of the cluster. The angular momentum of the cluster is calculated by summing those from all nucleons with respective to their center of mass (C.M.), while the energy of the cluster is calculated from a simplified SHF energy-density functional [39], with the neutron and proton phase-space information obtained from averaging over parallel events [45, 46] for the same impact parameter and collision orientation. Based on the same ground-state-nucleon phase-space information, the binding energy per nucleon obtained from this method for most nuclei, including \(^{90}\text{Ru}\) and \(^{96}\text{Zr}\), are found to agree with the SHFB calculation within \( \pm 1 \) MeV, therefore justifying this approach. The excitation energy is then calculated by subtracting from the calculated cluster energy the ground-state energy of known nuclei taken from Ref. [47]. For clusters with compositions absent in Ref. [47], an improved liquid-drop model [48] is employed to calculate their ground-state energies.

For spectator nucleons that do not form heavy clusters \((A \geq 4)\), they could still coalesce into light clusters with \( A \leq 3 \), i.e., deuterons, tritons, and \(^3\text{He}\), and the formation probabilities are calculated according to the following Wigner functions [49, 50] in their C.M. frame, i.e.,

\[
 f_d = 8g_d \exp \left( -\frac{\rho^2}{\sigma_d^2} - p^2 \frac{\sigma_d^2}{\sigma_d^2} \right),
\]

\[
 f_{i/\text{He}} = 8^2 g_{i/\text{He}} \exp \left[ - \left( \frac{\rho^2 + \lambda^2}{\sigma_{i/\text{He}}^2} - (p_{\rho}^2 + p_{\lambda}^2) \frac{\sigma_{i/\text{He}}^2}{\sigma_{i/\text{He}}^2} \right) \right],
\]

with \( \tilde{\rho} = (\tilde{r}_1 - \tilde{r}_2)/\sqrt{2} \), \( \tilde{p}_\rho = (\tilde{p}_1 - \tilde{p}_2)/\sqrt{2} \), \( \lambda = (\tilde{r}_1 + \tilde{r}_2 - 2\tilde{r}_3)/\sqrt{6} \), and \( \tilde{p}_\lambda = (\tilde{p}_1 + \tilde{p}_2 - 2\tilde{p}_3)/\sqrt{6} \) being the relative coordinates and momenta. \( g_d = 3/4 \) and \( g_{i/\text{He}} = 1/4 \) are the statistical factor for spin 1/2 proton and neutron to form a spin 1 deuteron (spin 1/2 triton/\(^3\)He). The width of the Wigner function is chosen to be \( \sigma_d = 2.26 \) fm, \( \sigma_{1/2} = 1.59 \) fm, and \( \sigma_{i/\text{He}} = 1.76 \) fm, consistent with the radius of deuterons, tritons, and \(^3\)He [51], respectively. All possible combinations of neutrons and protons are considered in forming light clusters, and this approach has been shown to describe the production of light clusters in both low- and high-energy [52] heavy-ion collisions. The total free spectator neutrons are composed of the residue neutrons that have not coalesced into light clusters and those from the deexcitation of heavy clusters.

**Validation with experimental data.** To validate the method and the values of \( \Delta r_{\text{max}} \) and \( \Delta \rho_{\text{max}} \) described above, we performed an analysis of \( \text{Au}+\text{Au} \) collisions at \( \sqrt{s_{NN}} = 130 \) GeV, for which the experimental data on \( N_n \) as a function of \( N_{ch} \) exists [53]. The quadrupole deformation is chosen to be \( \beta_{2\text{Au}} = 0.15 \) [54, 55] and the nucleon-nucleon inelastic cross section is taken to be 40 mb. The values of \( N_n \) as a function of \( N_{ch} \) from our calculation are compared with experimental data in Fig. 2. Here our main focus is on UCC region \((N_{ch} > 700)\), where the results are not affected by uncertainties of cluster deexcitations and other physics processes. A smaller \( \Delta r_{\text{max}} \) would imply that nucleons in the nuclear surface, enriched with neutrons, can only combine with close-by nucleons to form clusters. Therefore one expect more residue free neutrons, compared to the case with a larger \( \Delta r_{\text{max}} \). We see that the value of \( \Delta r_{\text{max}} = 3 \) fm achieves the best description of the experimental data [53]. We checked that the results are not sensitive to the value of \( \Delta \rho_{\text{max}} \) within its reasonable range.

**Predictions for the isobar systems.** Figure 3 displays the overall isospin asymmetry \( \delta_{\text{spectator}} \) of the spectator matter as a function of \( N_{ch} \). Due to the presence of neutron skin (see Fig. 1), the spectator matter becomes more neutron rich in more central collisions. Most of the increase, by about 50%, happens over the 0–5% centrality range \((N_{ch} = 250–400)\), implying that the \( \delta_{\text{spectator}} \) in the
UCC region is much more sensitive to the neutron skin. Furthermore, the more neutron-rich $^{96}\text{Zr}+^{96}\text{Zr}$ system has an overall larger $\delta_{\text{spectator}}$ value than the $^{96}\text{Ru}+^{96}\text{Ru}$ system. Most importantly, for a larger $L$ value and therefore a larger neutron skin, the $\delta_{\text{spectator}}$ in central collisions is greatly enhanced. When $L$ increases from 30 to 120 MeV, $\delta_{\text{spectator}}$ in the UCC region increases by about 0.040 in the more neutron-rich $^{96}\text{Zr}+^{96}\text{Zr}$ system compared to about 0.015 in the less neutron-rich $^{96}\text{Ru}+^{96}\text{Ru}$ system. Inclusion of nuclear deformation reduces slightly compared to about 0.015 in the less neutron-rich $^{96}\text{Zr}+^{96}\text{Zr}$ system. The cluster deexcitations contribute with and without considering the deexcitations of heavy clusters to the isobar systems. The cluster deexcitations contribute with and without considering the deexcitations of heavy clusters is no longer the main contribution to $N_{\text{spectator}}$, since the nuclear deformation, combined with random collision orientation, smears the radial distribution of the spectator protons and neutrons. But such effect is subdominant compared to the influence of $L$.

Figure 4 (a) shows the number of free neutrons $N_{n}$ with and without considering the deexcitations of heavy clusters in spectator matter via the GEMINI model in the isobar systems. The cluster deexcitations contribute significantly to $N_{n}$ in non-central collisions but are less important in the UCC region of $N_{\text{ch}}>340$ or centrality range 0−0.2%, where $N_{n}$ with and without deexcitations agree with each other, showing that the deexcitation of heavy clusters is no longer the main contribution to $N_{n}$ there. On the other hand, we note that among spectator nucleons that do not form heavy clusters, about 0.8−1.4 neutrons, dependent on $N_{\text{ch}}$, may coalesce into light clusters. The larger $\Delta\tau_{\text{np}}$ associated with $L=120$ MeV leads to systematically a larger $N_{n}$, compared with $L=30$ MeV. The $N_{n}$ in a single collision system is susceptible to theoretical and experimental uncertainties, such as clusterization algorithm, excitation energy, or detector efficiency, etc. In contrast, the ratio of $N_{n}$ in ultracentral $^{96}\text{Zr}+^{96}\text{Zr}$ to $^{96}\text{Ru}+^{96}\text{Ru}$ collisions, as shown in the lower panels of Fig. 4, is rather insensitive to the uncertainties mentioned above. We predicts a ratio of $N_{n}$ in the UCC region at around 1.27 for $L=30$ MeV and 1.31 for $L=120$ MeV, respectively. The $L$ effect is not small if the values are compared with the baseline ratio ($\sim1.08$) of the total neutron numbers in the two collision systems.

The shaded bands in the ratio represent uncertainties from the calculation of the excitation energy ($\pm1$ MeV per nucleon) of clusters: a higher excitation energy generally leads to more free nucleons. The ratio in the UCC region of $N_{\text{ch}}>340$ is clearly insensitive to this uncertainty. Ratios of $N_{n}$ in the UCC region for $L=60$ and 90 MeV are also plotted in Fig. 4 (c) and (d), which show a linearly increasing trend of the ratio with increasing $L$.

The recent STAR paper [30] indeed acknowledged a significant enhancement of $N_{n}$ in $^{96}\text{Zr}+^{96}\text{Zr}$ collisions relative to $^{96}\text{Ru}+^{96}\text{Ru}$ collisions, as measured by the ZDC. It would be exciting to compare our predicted ratio to the future measurement to provide a quantitative constraint on the neutron skin and $L$ value.

The right panels of Fig. 4 show corresponding results including effects of nuclear deformation. In the UCC region of $N_{\text{ch}}>340$, the values of $N_{n}$ are found to decrease by up to 20% compared to the spherical case, and the ratio of $N_{n}$ changes by about 0.01 when nuclear deformation is enabled, which is about 25% effect compared to the difference between $L=30$ and 120 MeV. This shows that the potential change to the $N_{n}$-ratio associated with uncertainties in the deformation is a subleading effect, and is controllable once the deformation is known in prior.

**Summary and outlook.** We show that the yield ratio of free spectator neutrons produced in ultracentral high-energy isobaric collisions, avoiding the complex dynamics for observables at midrapidities, is a clean probe of the neutron-skin thickness $\Delta\tau_{\text{np}}$ of colliding nuclei and the slope parameter $L$ of the symmetry energy. We illustrate this idea by using a Glauber model for $^{96}\text{Zr}+^{96}\text{Zr}$ and $^{96}\text{Ru}+^{96}\text{Ru}$ collisions, where proton and neutron distributions in $^{96}\text{Zr}$ and $^{96}\text{Ru}$ are provided by the Skyrme-Hartree-Fock-Bogolyubov calculation, and free spectator neutrons are produced either from the deexcitation of heavy clusters in spectator matter or direct ones that have not coalesced into light clusters. The coalescence parameters for the formation of heavy clusters are tuned to describe the measured free spectator neutron yield $N_{n}$ at large charged-particle multiplicities in Au+Au collisions at $\sqrt{s}_{NN}=130$ GeV. The values of $N_{n}$ are predicted to be larger in $^{96}\text{Zr}+^{96}\text{Zr}$ than in $^{96}\text{Ru}+^{96}\text{Ru}$ collisions due to the larger $\Delta\tau_{\text{np}}$ in $^{96}\text{Zr}$ than in $^{96}\text{Ru}$. This difference further increases when a larger $L$ value is used. We found that the ratio of $N_{n}$ in ultracentral $^{96}\text{Zr}+^{96}\text{Zr}$ to $^{96}\text{Ru}+^{96}\text{Ru}$ collisions are free from the uncertainties of cluster deexcitations and is relatively insensitive to the nuclear deformation. This ratio is also expected to largely cancel experimental errors, therefore making it an...
clean probe of the $\Delta r_{np}$ of colliding nuclei. The present study can be generalized to any two colliding systems with similar mass number but different isospin asymmetries such as those along an isotonic chain, for which the sensitivity of the $N_p$-ratio to $\Delta r_{np}$ and $L$ is expected to increase with increasing difference in their isospin asymmetries. For a single colliding system, such as Au+Au or Pb+Pb, we found that the yield ratio of free spectator neutrons over free spectator protons is also an excellent probe of $\Delta r_{np}$ and $L$. The free spectator protons can be measured by instrumenting the forward region with dedicated detectors, see, e.g., Ref. [56]. Such study is in progress.

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