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Measuring neutron skin by grazing isobaric collisions

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Neutron skin thickness ($\Delta r_{\rm np}$) of nuclei and the inferred nuclear symmetry energy are of critical importance to nuclear physics and astrophysics. It is traditionally measured by nuclear processes with significant theoretical uncertainties. We recently proposed an indirect measurement of the $\Delta r_{\rm np}$ by charged hadron multiplicities in central isobaric collisions at relativistic energies, which are sensitive to nuclear densities. In this paper we propose a direct measurement of the $\Delta r_{\rm np}$ by using net-charge multiplicities in ultra-peripheral (grazing) collisions of those isobars, under the assumption that they are simple superimposition of nucleon-nucleon interactions. We illustrate this novel approach by the TRENTO and URQMD models.

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Nuclei are bound states of protons and neutrons by the overall attractive nuclear force. The nuclear strong force is isospin symmetric, however, because of Coulomb interactions, heavy nuclei usually need more neutrons than protons to remain stable. The root-mean-square radius of neutron distribution in a heavy nucleus is thus larger than that of the proton distribution. The difference is referred to as the the neutron skin thickness, $\Delta r_{\rm np} \equiv r_n - r_p$ [1]. With more neutrons comes the penalty symmetry energy associated with the asymmetry between the proton and neutron numbers. By measuring the $\Delta r_{\rm np}$, one gains valuable information about the nuclear symmetry energy. Of particular interest is the symmetry energy density slope parameters L at the nuclear saturation density ρ_0 [2–5] and L_c at the critical density $\rho_c \approx 0.11$ fm^{-3} [6].

The $\Delta r_{\rm np}$ has traditionally been measured by low-energy electron and hadron scatterings off nuclei [3, 4, 7–9]. Because of the inevitable uncertainties in modeling the strong interaction of the scattering processes in quantum chromodynamics (QCD) [10], large uncertainties on the L and L_c persist. Void of the strong interaction uncertainties, parity-violating scattering processes with electrons [11, 12] and neutrinos [13], sensitive to the neutral current, have been measured. The latest result from the Lead Radius Experiment (PREX-II) on the ^{208}Pb, $\Delta r_{\rm np} = 0.283 \pm 0.071$ fm [14, 15], still has a large statistical uncertainty. This leads to $L_c = 71.5 \pm 22.6$ and $L = 105 \pm 37$ MeV[16], compared to $L = 75 \pm 25$ MeV[17] from traditional scattering experiments, where the uncertainty is dominated by statistical one in the former and systematic one in the latter. Efforts combining the PREX-II and astro-nuclear observations may improve the L_c and L constraints [18].

Recently we have proposed to use the ratio of charged hadron multiplicities ($N_{\rm ch}$) in most central collisions of isobars ($^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr) at the Relativistic Heavy Ion Collider (RHIC) to help constrain the $\Delta r_{\rm np}$ [19]. This exploits the sensitivity of particle production to nucleon density distribution, which differs slightly between Ru and Zr because of their different $\Delta r_{\rm np}$ values. Note that $N_{\rm ch}$ is isospin insensitive; it is essentially the same among pp, pn, and nn interactions at high energies (see Table I). Our idea in Ref. [19] probes the nucleon density and in turn the neutron's knowing the precisely measured proton's; it does not directly probe the neutron density.

The nucleon density difference is of course also present in peripheral collisions but there, the $N_{\rm ch}$ sensitivity to $\Delta r_{\rm np}$ is weak (see Fig. 4 of Ref. [20] where the isobar difference is only 2%). However, those ultra-peripheral collisions, where the nuclei are only grazing each other, must have very different mixture of participant protons and neutrons, and therefore likely yield significantly different net-charge numbers (ΔQ). This is obvious especially for the case of full acceptance with exact charge conservation, in which a proton releases one net-charge number, while the contribution from neutrons is none. This difference should also manifest in limited-acceptance midrapidity detectors. By measuring ΔQ in those grazing collisions, one could in principle determine the difference in the numbers of protons and neutrons participating in those collisions, which is *directly* sensitive to $\Delta r_{\rm np}$.

To make our idea more concrete, we list in Table I the ΔQ (and $N_{\rm ch}$ as well as the net-proton number ΔB_p) in minimum bias pp, pn, and nn interactions at $\sqrt{s} = 200$ GeV, simulated by the PYTHIA event generator [21, 22] (version 8.240). We used Monash tune [23] which was based on the LHC data (we will discuss this particular point at end of the paper). The acceptance cuts for ΔQ are $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/c, and we have excluded the (anti-)protons with $p_T < 0.4$ GeV/c (where the protons are strongly contaminated by background in experiments [24]). The $N_{\rm ch}$ is from $|\eta| < 0.5$ and $0.2 < p_T < 2$ GeV/c (as usually done in experiment). The ΔQ differs sig-

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TABLE I: The midrapidity charged hardon multiplicity $N_{\rm ch}$ ($|\eta| < 0.5$), the net-charge ΔQ, and net-proton ΔB_p within $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/c (excluding protons and antiprotons from $p_T < 0.4$ GeV/c) in minimum bias pp, pn, and nn interactions at $\sqrt{s} = 200$ GeV by PYTHIA (version 8.240, Monash tune [23]).

PYTHIA	$N_{\rm ch}$	ΔQ	ΔB_p
p+p	3.487	0.0793	0.0158
p+n	3.485	0.0255	0.0144
n+n	3.483	−0.0279	0.0130

nificantly between pp and nn interactions, whereas the ΔB_p is almost the same. The charge difference in the initial baryons that have transported to midrapidity is transferred nearly entirely to mesons. This difference will imprint in peripheral nucleus-nucleus (AA) collisions, the magnitude of which depends on the $\Delta r_{\rm np}$. If a peripheral AA collision is a simple superimposition of nucleon-nucleon (NN) interactions, then one can predict ΔQ in AA by those in NN collisions as

$$\Delta Q_{AA} \propto q_{AA}\Delta Q_{pp} + (1 - q_{AA})\Delta Q_{nn}\,, \qquad (1)$$

where q_{AA} is the fraction of protons among the participant nucleons. The proportionality (normalization) factor is simply the number of NN collisions. We have taken $\Delta Q_{pn} = (\Delta Q_{pp} + \Delta Q_{nn})/2$ which is a good assumption as seen in Table I, we have also verified this in the Hijing model [25, 26] and the URQMD model [27, 28]. One can have a similar equation for ΔB_p, but since ΔB_p are almost the same among pp, pn and nn interactions it is of little use for our purpose.

Now consider the isobar collisions of Ru+Ru and Zr+Zr at $\sqrt{s_{\rm NN}} = 200$ GeV. The ΔQ ratio in Ru+Ru over Zr+Zr collisions, under the superimposition assumption, is

$$R_{\Delta Q} \equiv \frac{\Delta Q_{\rm RuRu}}{\Delta Q_{\rm ZrZr}} = \frac{q_{\rm RuRu} + \alpha/(1-\alpha)}{q_{\rm ZrZr} + \alpha/(1-\alpha)}\,, \qquad (2)$$

where $\alpha \equiv \Delta Q_{nn}/\Delta Q_{pp}$ is the ΔQ ratio in nn to pp interactions; PYTHIA gives $\alpha \simeq -0.352$. The overall $q_{\rm RuRu}$ and $q_{\rm ZrZr}$ values for the whole nuclei are 44/96 and 40/96, respectively; they would give $R_{\Delta Q} \simeq 1.267$. Of course, the simple superimposition assumption breaks down in non-peripheral collisions because of nuclear effects. However, the assumption should be good for grazing AA collisions, where one expects Eq. (2) to be valid. The general idea to probe $\Delta r_{\rm np}$ by $R_{\Delta Q}$ is that a sizeable $\Delta r_{\rm np}$ will make the q_{AA} decrease dramatically with increasing impact parameter (b) in those grazing collisions. The $\Delta r_{\rm np}$ of ^{96}Zr is significantly larger than that of ^{96}Ru, so the $R_{\Delta Q}$ ratio amplifies the $\Delta r_{\rm np}$ sensitivity. The $\Delta r_{\rm np}$ of both nuclei are controlled by the L_c parameter, thus a measurement of $R_{\Delta Q}$ can determine its value.

Following our previous work [19, 29], we examine four sets of ^{96}Ru and ^{96}Zr nuclear densities from energy density functional theory (DFT). One is the standard Skyrme-Hartree-Fock (SHF) model (see, e.g., Ref. [30]) using the well-known interaction set SLy4 [31, 32]. The other is the extended SHF (eSHF) model [33, 34] with three sets of interaction parameters, denoted as Lc47, Lc20 and Lc70, corresponding to $L_c = 47.3$, 20 and 70 MeV [35], respectively, all with the symmetry energy $E_{\rm sym}(\rho_c) = 26.65$ MeV [6]. The Lc47 set is the best fit to data on the nuclear masses and electric dipole polarizibility in ^{208}Pb [6], and the other two are to explore the effects of the symmetry energy (and neutron skin) variations.

With a given nuclear density, one can calculate the q_{AA} parameter in Ru+Ru and Zr+Zr collisions as a function of b (and $N_{\rm ch}$). We use the TRENTO model [36] to do that. In TRENTO particle production is related to the reduced thickness, $N_{\rm ch} \propto T_R(p; T_A, T_B) \equiv [(T_A^p + T_B^p)/2]^{1/p}$ [36, 37]. We use the parameter $p = 0$ (i.e., $N_{\rm ch} \propto \sqrt{T_A T_B}$), a gamma fluctuation parameter $k = 1.4$, and a Gaussian nucleon size of 0.6 fm, which were found to well describe the multiplicity data in heavy ion collisions [36, 37]. The $q_{\rm RuRu}$ and $q_{\rm ZrZr}$ from TRENTO calculations are shown in Fig. 1. They are sensitive to the $\Delta r_{\rm np}$ and thus the L_c parameter, and decrease with decreasing $N_{\rm ch}$ in peripheral collisions. Both these features indicate the effect of $\Delta r_{\rm np}$ on $R_{\Delta Q}$. The sensitivity is larger in Zr+Zr than Ru+Ru collisions because of the larger $\Delta r_{\rm np}$ of Zr.

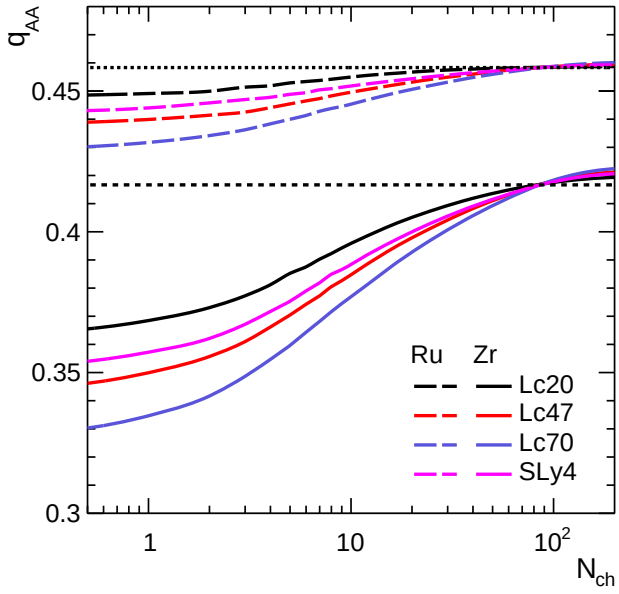


FIG. 1: (Color online). The proton fractions q_{AA} among participant nucleons as function of charged hadron multiplicity $N_{\rm ch}$ calculated by TRENTO with the ^{96}Ru and ^{96}Zr nuclear densities from eSHF (Lc20, Lc47, Lc70) and SHF (SLy4). The dotted and dashed lines indicate the overall values of 44/96 and 40/96 of the entire Ru and Zr nuclei, respectively.

With those ratios and the α value, the $R_{\Delta Q}$ can be obtained by Eq. (2) directly. Figure 2 shows the $R_{\Delta Q}$ as a function of $N_{\rm ch}$ using $\alpha = -0.352$ from PYTHIA (Table I, the dashed curve using another alpha value will be discussed later). The differences among the nuclear densities are obvious at small $N_{\rm ch}$. While the calculated $R_{\Delta Q}$ is unlikely correct at large $N_{\rm ch}$ because of the invalid assumption of simple NN superimposition for those non-peripheral AA collisions, the $R_{\Delta Q}$ for grazing collisions with small $N_{\rm ch}$ should be robust and can be used to determine

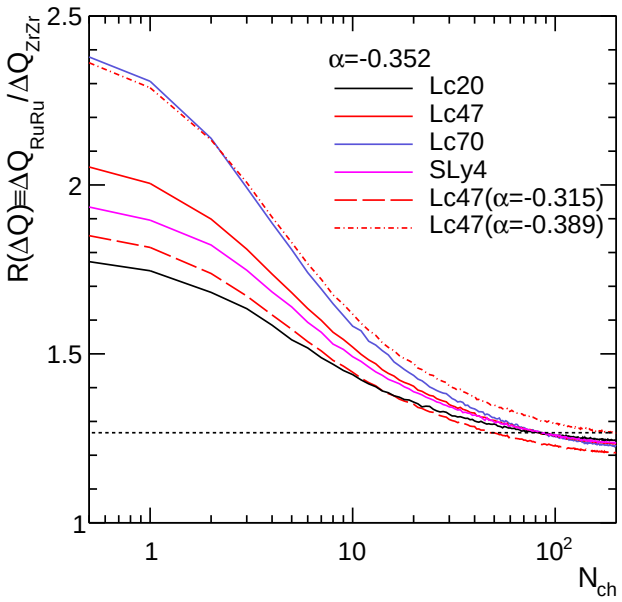


FIG. 2: (Color online). $R_{\Delta Q}$ as function of $N_{\rm ch}$ by Eq. (2) with $\alpha = -0.352$ from PYTHIA and the q_{AA} from TRENTO in Fig. 1 with four DFT densities (solid curves). The dashed (dash-dotted) curve uses $\alpha = -0.315$ (-0.389) with the Lc47 density. The dotted line indicates the overall value of 1.267.

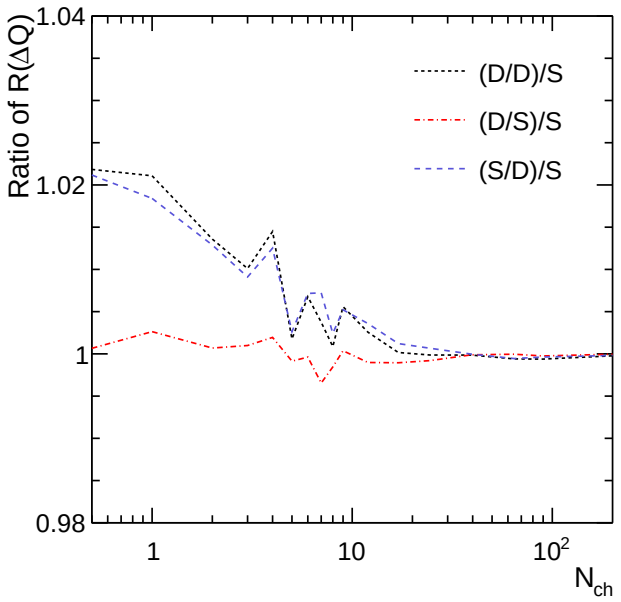


FIG. 3: (Color online). Effect of nuclear quadrupole deformity on the $R_{\Delta Q}$, shown by its relative deviation from the spherical case.

the $\Delta r_{\rm np}$ and thus the L_c parameter. We note that the α value is obtained from minimum bias NN interactions. However, a grazing AA collision with a particular $N_{\rm ch}$ value selects biased underlying NN interactions, especially when $N_{\rm ch}$ is small. We have verified that the ΔQ_{pp} and ΔQ_{nn} do indeed depend on $N_{\rm ch}$ of NN collisions, however their ratio α is insensitive to $N_{\rm ch}$. Using a constant α in Eq. (2) is, therefore, justified.

The DFT densities we used have assumed spherical nuclei without considering the possible deformation in their calculations. Their experimental measurements of the quadrupole deformation parameter are also uncertain, ranging from $\beta_2 = 0.053$ to 0.158 for Ru and from 0.08 to 0.217 for Zr [38]. To test the sensitivity of our results to nuclear deformation, we follow Ref. [39] using the Woods-Saxon parameterization $\rho(r,\theta) \propto [1+\exp([r - R(1+\beta_2 Y_2^0(\theta))]/a)]^{-1}$ with $\beta_2 = 0.16$ fixed and the R and a reproducing the first and second radial moments of the DFT-calculated spherical proton and neutron densities of SHF/SLy4. The changes in $R_{\Delta Q}$ from the spherical case are shown in Fig. 3 for the three combinations of deformed/spherical Ru and Zr nuclei. The effect is only a couple of percent, leading possibly to less than 5 MeV uncertainty in the extracted L_c parameter. This small effect is not a surprise because the $R_{\Delta Q}$ is sensitive only to the relative proton/neutron composition on the nuclear surface, which is not sensitive to nuclear deformation.

Next we examine our idea using a dynamical model. We use the URQMD (Ultra relativistic Quantum Molecular Dynamics, v3.4) [27, 28] as it have been widely used to study the conserved charge number and its fluctuations in heavy ion collisions [40, 41]. We simulate events within $b \in [7, 20]$ fm since we focus only on peripheral collisions. The same acceptance cuts have been applied as done in PYTHIA simulations. Figure 4 shows $R_{\Delta Q}$ as a function of $N_{\rm ch}$. Similar splittings are found at low $N_{\rm ch}$ as in Fig. 2. URQMD simulations of NN interactions indicate $\alpha = -0.344$. Using this α value, the predicted curves by Eq. (2) are superimposed in Fig. 4. The curves can fairly well describe the URQMD data. This indicates that the grazing collisions in URQMD, with $N_{\rm ch} \lesssim 10$, are indeed simple superimposition of NN interactions. This is not surprising as only a few nucleons participate in such a grazing AA collision so any nuclear effect would be negligible. At higher $N_{\rm ch}$ the URQMD data points deviate from the curves, presumably because those collisions are not simple NN superimpositions any more. It may also be viewed as that the effective α in central AA collisions, because of nuclear effects, is very different from the one calculated using single NN interactions.

The large differences among the nuclear densities are mostly due to the negative value of α as mentioned before. We note that a larger p_T cut on (anti)proton makes α more negative, e.g., $\alpha = -0.416$ with $p_T > 0.8$GeV/c on (anti)proton, which may make the $R_{\Delta Q}$ more sensitive to $\Delta r_{\rm np}$. However, excluding any "net-charge" will weaken the correlation between the initial protons from the incoming nuclei and the final-state net-charge observable, which would introduce stronger model dependence. We also note that the finite negative α value is not merely because we exclude the (anti)proton with $p_T < 0.4$GeV/c; we have checked that without any p_T cut, the α value is -0.370 at mid-rapidity ($|\eta| < 1.0$). In our URQMD simulations, the hyperon decays are not included. The hyperon decays can introduce net-charge because of the combined effect of the finite acceptance (which does not always cover both

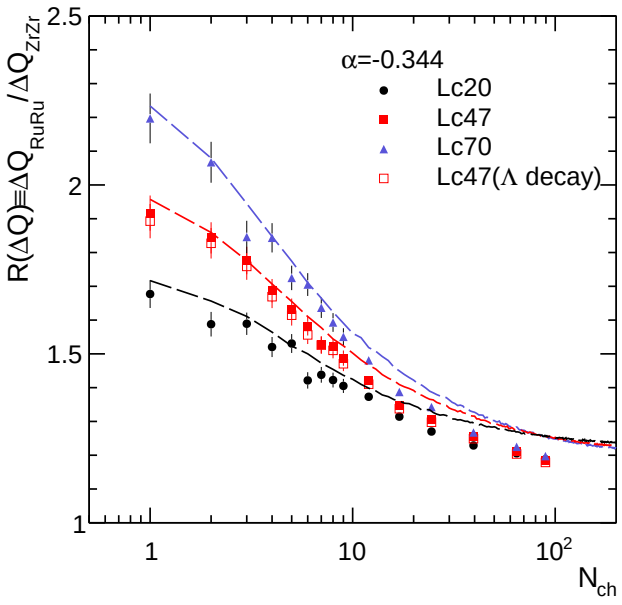


FIG. 4: (Color online). $R_{\Delta Q}$ for $b \in [7, 20]$fm as function of $N_{\rm ch}$ ($|\eta| < 0.5$) simulated by URQMD with DFT nuclear densities from eSHF (Lc20, Lc47, Lc70). The ΔQ is calculated from $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/c excluding the (anti-)protons with $p_T < 0.4$ GeV/c. The open red squares show a calculation for the Lc47 case including Λ-hyperon decays. The curves are Eq. (2) with $\alpha = -0.344$ from URQMD NN interactions and the q_{AA} from TRENTO in Fig. 1.

daughter particles from the decay) and the asymmetry of those decays. We have calculated the effect of Λ decays for the Lc47 case, and found that the effect is negligible (see the open red squares in Fig.4).

We have simulated ∼450 million URQMD events for each isobar system in Fig. 4. They give a statistical uncertainty on L_c of roughly 9 MeV using data points at $N_{\rm ch} \lesssim 10$. It should be noted that our proposal requires measurements of ultra-peripheral collisions which are often difficult because of trigger inefficiencies in experiment, increasing in severity with decreasing $N_{\rm ch}$. Over 2 billion minimum bias events have been collected at RHIC for each isobar system; they would likely give similar statistics to our simulated URQMD sample, given the typical experimental trigger inefficiency. Thus, the statistical uncertainty on the extracted L_c using isobar data is expected to be ∼10 MeV. Since our $R_{\Delta Q}$ observable is a ratio of two isobar systems, many experimental systematic effects cancel and would unlikely contribute a significant part to the overall experimental uncertainty. We note that the electromagnetic interactions could affect the proposed method. However, in experiment, one can avoid electromagnetic interactions by triggering on minimum bias hadronic interactions only.

Our idea relies on the state of the art DFT calculation and the assumption of simple NN superimposition for grazing isobar collisions. The theorectical uncertainty from the former may be gauged by the two parameter sets of SLy4 and Lc47 shown in Fig. 2, corresponding to similar L_c values. Their difference would give an uncertainty of ∼6 MeV. This is rather modest compared to the substantial uncertainties from QCD modeling of traditional scattering observables. Another theoretical uncertainty on density distributions comes from nuclear deformation; this is insignificant as indicated by Fig. 3.

The assumption of simple NN superimposition should be rather robust for grazing heavy ion collisions over a wide range of relativistic energies. We have focused on $\sqrt{s_{\rm NN}} = 200$ GeV in this study because the isobar collision data recently taken at RHIC were at this energy [42]. We note that isospin-sensitive observables, such as the π^+/π^- ratio, have been proposed long ago to probe high-density symmetry energy in low energy nuclear collisions (not particularly in grazing collisions) [43]. In our study of grazing AA collisions, the NN information imprint in ΔQ is carried over by the α parameter. The α value we used in this study comes from a particular tune of PYTHIA and URQMD. It is used only to illustrate our proposed method; its value should be taken with caution. For example, PYTHIA6 (version 6.416) tuned to RHIC data [44] would give $\alpha = -0.315$, the result of which with the Lc47 density is shown by the dashed curve in Fig. 2. Hijing gives $\alpha = -0.389$ which is shown by the dash-dotted curve in Fig. 2 for Lc47. This would result in an uncertainty on L_c comparable to the range of the parameter sets in Fig. 2 (which was constrained from traditional scattering measurements). The determination of the α parameter is therefore essential. The ΔQ data in pp interactions are abundant, that in nn is experimentally not available. While nn interactions are hard to perform, their information may be indirectly accessed by proton-deuteron and/or deuteron-deuteron collisions, yet to be conducted. In addition, one may gain valuable information on the α parameter from existing p-Au and d-Au data at RHIC. Provided that the α parameter can be determined relatively precisely, our proposal will likely result in a L_c value with an overall uncertainty of 10-15 MeV. This would be a substantial complement to traditional methods with the present overall ∼20 MeV uncertainty [16].

In summary, we demonstrate that the net-charge ratio $R_{\Delta Q}$ in isobar $^{96}_{44}$Ru+$^{96}_{44}$Ru over $^{96}_{40}$Zr+$^{96}_{40}$Zr collisions can be predicted from those in pp and nn interactions under the assumption that nucleus-nucleus AA collisions are a simple superimposition of nucleon-nucleon NN interactions. We show using the URQMD model that this assumption is valid for ultra-peripheral (grazing) collisions with $N_{\rm ch} \lesssim 10$ within the midrapidity range of $|\eta| < 0.5$. The predicted $R_{\Delta Q}$ depends on the proton and neutron densities, particularly on the neutron skin thickness $\Delta r_{\rm np}$. The $R_{\Delta Q}$ measurement in grazing isobar collisions, together with density functional theory DFT calculations of nuclear densities, can therefore determine the $\Delta r_{\rm np}$, and in turn the symmetry energy density slope parameter L_c.

We have previously proposed [19] an indirect observable, the $N_{\rm ch}$ ratio in central isobar collisions, to probe the $\Delta r_{\rm np}$. This observable is isospin insensitive and is based on the fact that particle production in relativistic heavy ion collisions depends on the total nuclear (proton+neutron) density which has some sensitivity to the $\Delta r_{\rm np}$. The $R_{\Delta Q}$ observable proposed here is isospin sensitive, directly related to the $\Delta r_{\rm np}$. It is based on the

simple superimposition of NN interactions for those grazing AA collisions, and depends on the difference (proton – neutron) density which is highly sensitive to the $\Delta r_{\rm np}$. Combining these two observables shall yield stringent constrains on the $\Delta r_{\rm np}$, and thus the L_c parameter.

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