Impact of nuclear structure on the CME background in $^{96}\text{Ru} + ^{44}\text{Ru}$ and $^{96}\text{Zr} + ^{44}\text{Zr}$ collisions at $\sqrt{s_{\text{NN}}} = 7.7 \sim 200$ GeV from a multiphase transport model

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Impacts of nuclear structure on multiplicity ($N_{ch}$) and anisotropic flows ($v_2$ and $v_3$) in the isobaric collisions of $^{96}\text{Ru} + ^{44}\text{Ru}$ and $^{96}\text{Zr} + ^{40}\text{Zr}$ at $\sqrt{s_{\text{NN}}} = 7.7, 27, 62.4,$ and 200 GeV are investigated by using the string melting version of A MultiPhase Transport (AMPT) model. In comparison with the experimental data released by the recent STAR Collaboration, it is found that the impact of deformation on the $v_2$ difference is mainly manifested in the most central collisions, but the neutron skin effect dominates in the mid-central collisions, and these differences are magnified at lower energies.

I. INTRODUCTION

The present theories predict that a local parity ($P$) and charge parity ($CP$) violation region could be formed by strong interaction in relativistic heavy-ion collisions [1–4], where a charge number imbalance of light quark can be achieved. In the process of a non-central heavy-ion collision, the $CP$-violating region is affected by the strong magnetic field produced by high speed protons passing through [5, 6], resulting in charge separation along the magnetic field. This phenomenon is also known as the Chiral Magnetic Effect (CME) [7–11]. The confirmation of the existence of the CME will lead to a deeper understanding for QCD vacuum, it will also imply the existence of the CME-sensitive charge separation is measured in heavy-ion collisions [2, 12, 13] etc. Various chiral related phenomena and possible detectable methods have been discussed in literature, eg. [13–17]. Finding an experimental signature that can conclusively confirm the CME is one of current major challenges in heavy-ion physics.

Since the magnetic field is usually perpendicular to the reaction plane (RP, defined by the collision impact parameter and the beam momentum) in heavy-ion collisions, the CME-sensitive charge separation is measured with respect to the reaction plane, and the most widely used observable in present time is the “$\gamma$ correlator”: $\gamma_{\alpha\beta} = \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle$ [18], where $\phi_{\alpha}$ and $\phi_{\beta}$ are the azimuthal angle of charged particles of interest, and $\Psi_{RP}$ is the angle of the reaction plane. However, some non-CME signal sources (e.g. $v_2$) can also contribute to the $\gamma$, which makes it difficult to quantify the CME effect by this way [19–21].

In order to disentangle the contribution of CME from the background to $\gamma$, many ideas have been proposed, among which the isobar collisions (e.g. $^{96}\text{Ru} + ^{44}\text{Ru}$ and $^{96}\text{Zr} + ^{40}\text{Zr}$) are expected to provide the best solution to this problem. $^{96}\text{Ru} + ^{44}\text{Ru}$ and $^{96}\text{Zr} + ^{40}\text{Zr}$ have the same nucleon numbers but different charges, it is expected that different Chiral Magnetic Effect (CME) signals can be quantitatively extracted in the same flow-driven backgrounds [22, 23]. The project of $^{96}\text{Ru} + ^{44}\text{Ru}$ and $^{96}\text{Zr} + ^{40}\text{Zr}$ isobar collisions at $\sqrt{s_{NN}} = 200$ GeV was launched at RHIC in the year 2018, and the results were recently released from the STAR collaboration [4]. The isobar blind analysis in the STAR Collaboration [24] observed the significant differences in the multiplicity and flow harmonics in a given centrality between the two collision systems, suggesting that the magnitude of the CME background is different between the two species. Many studies suggested that the difference of CME backgrounds in Ru and Zr collisions was due to the differences in geometry shapes of colliding ions, such as the difference of deformation and neutron skin thickness for Ru and Zr [22, 25, 26].

In this study, the CME background difference between Ru and Zr collisions is studied by a MultiPhase Transport (AMPT) model, with three different nuclear structure parameters for Ru and Zr. Our results are compared with the experimental data to verify which description for nucleon structure of Ru and Zr is more consistent with the real nuclear structure. Further, the energy dependence of the CME background differences between Ru and Zr is studied at different energies, i.e. $\sqrt{s_{NN}} = 7.7, 27, 62.4,$ and 200 GeV, which will answer the question of what would be the background difference at lower energy.

The organization of the present paper is as follows: In Sect. 2, the general setup of the simulation on Ru + Ru and Zr + Zr collisions by AMPT is briefly introduced. In Sect. 3, the numerical results and discussion are pre-
sent, and the summary is given in Sec. 4.

II. GENERAL SETUP

A. The AMPT model

Here we choose the string melting version of the AMPT model [27, 28] to simulate Ru + Ru and Zr + Zr collisions and analyze the simulated data to discuss the CME backgrounds, which has proven effective in describing collective flow data in small and large collision systems at RHIC and LHC [29–33]. Based on the nonequilibrium transport dynamics, the AMPT model is composed of four parts: the Heavy-Ion Jet INteraction Generator (HIJING) model [34, 35] for generating the initial-state information, Zhang’s parton cascade (ZPC) model [36] for modeling partonic scatterings, the Lund string fragmentation model or a quark coalescence model for hadrons formation, and a relativistic transport (ART) model [37] for treating the hadron scatterings. In the AMPT model of string melting, the partons freeze-out according to local energy density, and the hadronization process is simulated by a naive quark coalescence model, which combines two nearest partons into a meson and three nearest quarks (anti-quarks) into a baryon (anti-baryon). The method for determining hadronic species is achieved by the flavor and invariant mass of coalescing partons.

B. Description of $^{96}_{40}$Ru and $^{96}_{40}$Zr

The spatial distribution of nucleons in the rest frame of $^{96}_{44}$Ru and $^{96}_{40}$Zr can be described by the following 2-parameter Fermi mass density of the Woods-Saxon (WS) form [22, 38, 39]:

$$\rho(r, \theta) = \frac{\rho_0}{1 + \exp \left( \frac{r-R_0(1+\beta_2 Y_2^0(\theta))}{a} \right)}, \quad (1)$$

where $r$ is radial position and $\theta$ is polar angle in spherical coordinates, $\rho_0 = 0.16 \text{ fm}^{-3}$ is the normalization factor, $R_0$ and $a$ describe the “radius” of the nucleus and the surface diffuseness parameter, respectively, and $\beta_2$ denotes the deformation of the nucleus. The $\beta_2$ values of $^{96}_{44}$Ru and $^{96}_{40}$Zr are not accurately known at present [22, 40, 41]. Here we take three sets of WS parameters to investigate the effect of nuclear structures on CME backgrounds for isobar collisions, as shown in Table I.

The parameters are arranged by the following way: Case-1, Ru ($\beta_2^{Ru} = 0.13$) has large deformation than Zr ($\beta_2^{Zr} = 0.06$); Case-2, Ru ($\beta_2^{Ru} = 0.03$), in contrast, has a smaller deformation than Zr ($\beta_2^{Zr} = 0.18$); Case-3 is based on the latest calculations of the energy density functional theory (DFT) [26, 45], which assumes that the nucleus is spherical ($\beta_2 = 0$). According to the calculation of proton and neutron distribution, it shows that the overall size of Ru is smaller than that of Zr because the neutron skin of Zr is much thicker. This allows the nucleon distributions well parameterized as a halo-type WS distribution. Figure 1 shows the distributions of charged hadron numbers from the AMPT model within $|\eta| < 0.5$ in Ru + Ru and Zr + Zr collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ for above three sets of Woods-Saxon parameters, which shows the nuclear density parameter of Case-3 gives the best description of the RHIC-STAR data [4].

| Nucleus | $R$(fm) | $a$(fm) | $\beta_2$ | $R$(fm) | $a$(fm) | $\beta_2$ |
|---------|--------|--------|--------|--------|--------|--------|
| Case-1  | 5.13   | 0.46   | 0.13   | 5.06   | 0.46   | 0.06   |
| Case-2  | 5.13   | 0.46   | 0.03   | 5.06   | 0.46   | 0.18   |
| Case-3  | 5.067  | 0.5    | 0      | 4.965  | 0.556  | 0      |

III. RESULTS AND DISCUSSION

In this section, the simulated results from the AMPT model for three nuclear density parameters of Ru + Ru and Zr + Zr collisions at $\sqrt{s_{NN}} = 7.7, 27, 62.4, \text{ and } 200 \text{ GeV}$ are presented. In this work we will show the predictions for the mean multiplicity $\langle N_{ch} \rangle$, the elliptic flow $v_2$, and the triangular flow $v_3$ of charged particles as a function of centrality in the two isobaric collision systems. The effect of initial geometry on CME background will also be discussed according to the eccentricities in Ru + Ru and Zr + Zr collisions. Note that the collision system is divided into different centralities based on the distribution of the number of charged hadrons with taking the deformation into account.

A. Mean charge multiplicity $\langle N_{ch} \rangle$

The upper panels of Fig. 2 show the mean charge multiplicity $\langle N_{ch} \rangle$ at mid-pseudorapidity ($|\eta| < 0.5$) as a function of centrality, from the string melting mode of AMPT, for three cases of the parameter settings of isobar collision systems at $\sqrt{s_{NN}} = 7.7, 27, 62.4, \text{ and } 200 \text{ GeV}$. The Ru+Ru/Zr+Zr ratio of the mean charge multiplicities is shown in the lower panels of Fig. 2. The STAR data [4] for isobar collision systems at $\sqrt{s_{NN}} = 200 \text{ GeV}$ are also shown for comparison. Our simulation results show that the mean charge multiplicity $\langle N_{ch} \rangle$ of the two isobaric systems for three cases is close to each other, which is basically consistent with the data of the STAR Collaboration at different centralities.

The Ru+Ru/Zr+Zr ratio in the bottom panel of Fig. 2 gives a clear illustration of the difference between these two isobar collisions. The ratios for the three cases are different in shape, with Case-1 and Case-2 remaining near
the unit for all centralities at different energies, Case-3 rising almost directly in proportion to the centrality at √s_{NN} = 200 GeV, which is also rising in a zigzag pattern with other energy. The shape of case-3 is the closest to the STAR measurements at √s_{NN} = 200 GeV.

B. Harmonic flow

The harmonic flow is investigated in this paper for the two isobaric collision systems, which contributes as the major background of the CME-sensitive observable, such as Δγ_{112}. The harmonic flow coefficient v_2{2} is calculated by the two-particle correlation method in the following form [4]:

\[ v_{2}^{2}(\eta) = \langle \cos(n\phi_{1} - n\phi_{2}) \rangle . \]  

(2)

Here we put a cut of Δη_{1,2} > 0.05 as did in the STAR treatment for v_2{2}. The upper panels of Fig. 3 present the AMPT results for the centrality dependence of elliptic flow v_2{2} of charged hadrons at mid-pseudorapidity (|η| < 1) with three geometry settings of isobaric collisions. It can be observed that v_2{2} for Ru + Ru and Zr + Zr are similar to each other at different energy, and the v_2{2} with three setting parameters is also close to each other. Our results are consistent with the STAR data at √s_{NN} = 200 GeV, but slightly higher than that of the STAR data in central collision.

The lower panels of Fig. 3 gave the v_2{2} ratios between Ru+Ru and Zr+Zr collisions. The centrality dependence of the ratio for the three settings are very different at √s_{NN} = 200 GeV, for case-1 (-2) decreasing (increasing) from central to peripheral collisions until about 20% centrality staying close to unit, and for case-3 showing as a bow above unit. As seen from case-1 and case-2, the deformation has a major effect on the v_2{2} ratios in central (centrality less than 20%) isobaric collision systems, which means that the larger the deformation nucleon is, the larger its v_2{2}. Comparing with the data from the STAR [4], case-1 is more consistent with it in the most central collisions and case-3 is more consistent with it in mid-central collisions. This indicates that the deformation effect is significant in the most central collisions and the neutron skin influence emerges in mid-central collisions. In other words, the deformation of 96Ru and 96Zr described by case-1 means a larger quadrupole deformation in 96Ru compared with 96Zr, and the nuclear density distribution described by case-3 suggests the two isobars have different nuclear structures as predicted by the DFT calculations.

It was also observed that the ratios of v_2{2} was mag-
nified at lower energies in isobar collisions, but the three settings have different performances at different centrality. As shown in Fig. 4(b), in the most central collisions (0-5%), the absolute value of $v_2\{2\}$ ratios is small at higher energy for Case-1 and Case-2, which means that the isobar collision at higher energy will have a smaller difference due to deformation. At the same time, the $v_2\{2\}$ ratios at different energy is almost independent of the neutron skin effect in the most central collisions. Figure 4(d) shows the $v_2\{2\}$ ratios are lower at higher energy in the mid-central collisions (20-50%) for Case-3, which means that the isobar collision at higher energy has a smaller difference due to neutron skin effect. For Case-1 and Case-2, the ratios of $v_2\{2\}$ have little difference for different energies in this centrality region, which indicates that deformation has little effect on $v_2\{2\}$ ratios in the mid-central collision. The trend of $v_2\{2\}$ ratios at different energies with different centrality reconfirms that the effect of deformation on $v_2\{2\}$ ratios mainly occurs in the most-central collisions (0-5%), and the impact of neutron skin on $v_2\{2\}$ ratios mainly happens in the mid-central collisions (20-50%).

The above results tell us that we can not get a cleaner CME background at lower energy, whereas, the differences in nuclear structure at low energy will result in a larger differences of CME background. On the other hand, perhaps the lower energy are more suitable for us to study the nuclear structure of $^{96}\text{Ru}$ and $^{96}\text{Zr}$ because of stronger signal than that at higher energy. In other words, it is worth performing a beam energy scan of isobaric collisions to constrain the nuclear structure parameters or to disclose the CME background from nuclear structure.

We also investigate the effect of second order deformation to the triangular flow $v_3\{2\}$ of charged hadrons at mid-pseudorapidity ($|\eta| < 1$) as a function of centrality at $\sqrt{s_{NN}} = 200$ GeV, as shown in Fig. 5. From the upper panels of Fig. 5, it is seen that the calculated $v_3\{2\}$ are close to the STAR data [4] for three settings, while the lower panels of Fig. 5 show no significant difference among the three different settings for $v_3\{2\}$ ratios, which seems that the nuclear structure used in this study has little effect on $v_3\{2\}$. This is consistent with the conclusion in reference [25] that the $\beta_2$ has an effect on $v_2$ but does not on $v_3$. 

FIG. 2. (Upper panels) The mean charge multiplicity $N_{ch}$ within $|\eta| < 0.5$ as a function of centrality in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 7.7, 27, 62.4,$ and 200 GeV. The STAR data [4] for isobar collisions at $\sqrt{s_{NN}} = 200$ GeV are also shown in comparison. The centrality bins are slightly horizontally moved for clarity. (Lower panels) The ratio of the mean charge multiplicity in Ru+Ru collisions to that in Zr+Zr collisions in matching centrality and energy. The above data include statistical uncertainty.
C. The initial geometry

Next, we want to find whether the differences in final state measurements due to the effects of nuclear structure are already implicit in the early stages after isobar collisions. The initial geometry of a nucleus-nucleus collision can be characterized by eccentricity, which represents the initial geometric anisotropy of the collision zone in the transverse plane (perpendicular to the beam direction). The definition of eccentricity for $n$-th harmonic in the coordinate space of the partons for a single collision event is given by following form [46, 47]

$$\varepsilon_n(P) = \frac{\sqrt{(r^n \cos(n\varphi))^2 + (r^n \sin(n\varphi))^2}}{r^{n-1}},$$  \hspace{1cm} (3)

where $r$ and $\varphi$ are the position and azimuthal angle of each parton in the transverse plane. In practice, the event averaged eccentricity coefficients $\langle \varepsilon_n(P) \rangle$ are used to characterize the initial geometry asymmetry, and we mainly focus on the $\varepsilon_2$ in this study.

The upper panels of Fig. 6 show the $\langle \varepsilon_2 \rangle$ for three cases in isobar collisions at $\sqrt{s_{NN}} = 7.7$, 27, 62.4, and 200 GeV as a function of centrality, and the $\langle \varepsilon_2 \rangle$ for three settings are close to each other at different centralities. The lower panels of Fig. 6 present the $\langle \varepsilon_2 \rangle$ ratios between Ru+Ru and Zr+Zr collisions. As expected, the shape of $\langle \varepsilon_2 \rangle$ ratios is similar to the above presented flow ratios for the three settings at different centralities, i.e. the effect of deformation on eccentricity mainly occurs in the most central collision, while the effect of neutron skin on eccentricity mainly dominates in mid-central collisions. This illustrates that part of the contribution to the difference on CME backgrounds in Ru + Ru and Zr + Zr collisions originates from the effect of nuclear structure on the initial geometry after collisions.

In addition, we can see that the shape of $\langle \varepsilon_2 \rangle$ ratio have no significant changes at different energy as shown in Fig. 7 for the centrality ranges of 0-5% and 20-50% with three settings of nuclear structure parameters. The energy independence of $\langle \varepsilon_2 \rangle$ ratios is opposite to the previous situation of $v_2$ ratios, suggesting that it is energy dependent of the transition efficiency from initial geometry asymmetry to final momentum space. And the energy dependence of the $v_2$ ratios via the transport model, such as AMPT, indicate the hydrodynamical evolution in the collisions [48–50].
IV. CONCLUSION AND OUTLOOK

The recent STAR measurement of the final state observables confirmed the differences in nuclear structure between Ru and Zr systems. By comparing the simulation results in Ru + Ru and Zr + Zr collisions from the AMPT model with the STAR data, we found that these differences can be explained by the large quadrupole deformation $\beta_2$ of $^{96}$Ru and the differences in their neutron skin. These results are consistent with previous studies [22, 25, 26, 51]. We also found the centrality dependence of the difference in final state observables between Ru + Ru and Zr + Zr collisions on nuclear structure, i.e. the effect of deformation is significant for the most central collision, however, the effect of neutron skin is dominant in mid-central collisions. This conclusion was supported more strongly by subsequent investigation on the energy dependence of $v_2$ ratios in Ru + Ru / Zr + Zr in the most central collisions and mid-centrality collisions, respectively, which is shown that both nuclear structures magnify the difference of $v_2$ in lower energy in the collision region where they dominate. The results of the energy dependence of $v_2$ ratios also indicate that it can not be achieved more clean CME backgrounds in lower energy from Ru + Ru and Zr + Zr collisions.

The study of eccentricity ratios of two systems tells us that part of the CME background difference is originated from the difference of initial geometry in Ru + Ru and Zr + Zr collisions, and the fact that eccentricity ratios are independent of energy shows that the energy dependence of the difference in $v_2$ ratio is also influenced by the dynamical evolution of the collision zone.

For future plans, it is necessary to develop a nuclear structure description for Ru and Zr that takes into account both deformation and neutron skin effects, if background differences due to the difference of nuclear structure can be more accurately predicted, we might be able to isolate this difference and get a clean signal of the CME effect. Fortunately, more precise deformation description has been tested in some work and seems successful in...
FIG. 6. (Upper panels) Eccentricity $\varepsilon_2$ for three cases in isobar collisions at $\sqrt{s_{NN}} = 7.7, 27, 62.4, \text{ and } 200 \text{ GeV}$ as a function of centrality. The solid and open symbols represent measurements for Ru+Ru and Zr+Zr collisions, respectively. The data points are shifted along the $x$ axis for clarity. (Lower panels) The ratios of $\varepsilon_2$ in Ru+Ru over Zr+Zr collisions. The statistical uncertainties are represented by lines.

describing new data of RHIC and LHC Collaboration [25, 52–54]. Our analysis also shows that background difference in isobar collisions are magnified at lower energy, as Ref. [25] pointed out that isobar collisions can be used as a precision tool to measure the shape of nuclei, this may be easier to do at lower energy.

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FIG. 7. (Upper panels) The ratios of $\langle \varepsilon_z \rangle$ in Ru+Ru over Zr+Zr collisions in the most central collisions. (Lower panels) The ratios of $\langle \varepsilon_z \rangle$ in Ru+Ru over Zr+Zr collisions in mid-central collisions. The statistical uncertainties are represented by lines.