Search for the chiral magnetic effect in collisions between two isobars with nuclear structures

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Isobar collisions which were thought with a same background and different magnetic fields provide an opportunity to verify the chiral magnetic effect (CME) in relativistic heavy-ion collisions. However, the first result from the RHIC-STAR isobar experiment did not observed the CME signal, but discovered that the backgrounds are different between $^{96}_{44}$Ru + $^{96}_{44}$Ru and $^{96}_{40}$Zr + $^{96}_{40}$Zr collisions. We test eighteen cases of Woods-Saxon parameter settings resulted from different nuclear deformation or nuclear structure effects using a multiphase transport model. We find out that seven cases can reasonably reproduce three reference ratios measured by the STAR experiment. With considering both the halo-type neutron skin structure and CME-like charge separation, we demonstrate that it is difficult for the CME observables ($\Delta\delta$, $\Delta\delta$ ratio, $\Delta\gamma$ and $\Delta\gamma/\nu_2$ ratio) to distinguish the presence or absence of the CME, if the CME strength is weak in isobar collisions. It is because the final state interactions significantly weaken the initial CME signal, resulting in non-linear sensitivities of the CME observables to the CME strength. Therefore, more sensitive observables are required to search for the possible small CME signal in isobar collisions.

I. INTRODUCTION

A deconfined QCD matter with quark and gluon degrees of freedom, the quark-gluon plasma (QGP), is believed to be created in the early stage of relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) \cite{1, 2} and at the Large Hadron Collider (LHC) \cite{3}. On the other hand, some studies have shown an extremely strong magnetic field can be generated in the early stage of QGP evolution \cite{4–9}. Thus relativistic collisions provide a suitable environment for some novel chiral anomalous phenomena, such as chiral magnetic effect (CME) \cite{10–12}, and chiral magnetic wave (CMW) \cite{13, 14}. The efforts to search for these phenomena have been the focus of research for nearly a decade, because it may reveal new knowledge related to the local charge-parity violation in strong interactions and the topological fluctuations of the QCD vacuum.

The researches of the CME have been in rapid development, although the backgrounds for searching the CME cause serious difficulties \cite{15–19}. It has been first proposed that the CME could be observed by measuring the $\gamma$ correlator \cite{20}. By assuming the CME background is charge-independent, the difference $\Delta\gamma$ between the opposite sign (OS) and the same sign (SS) is expected to reflect the CME signal. The positive $\Delta\gamma$ has been observed by both RHIC-STAR \cite{21, 22} and LHC-ALICE experiments \cite{23}, which is consistent with the CME expectation. Unfortunately, the real situation is complicate because some backgrounds can also cause a positive $\Delta\gamma$, such as the resonance decays \cite{24} and local charge conservation \cite{25}, which makes the matter more difficult to observe a weak CME signal under a dominant background \cite{26}. Therefore, the isobar program of $^{96}_{44}$Ru + $^{96}_{44}$Ru and $^{96}_{40}$Zr + $^{96}_{40}$Zr collision by the RHIC-STAR experiment was expected to solve this problem because the two isobar systems have a same nucleon number but different proton numbers \cite{27}. Isobar collisions are expected to produce a same background but different magnetic

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fields, which should make the CME observable ratio of Ru + Ru to Zr + Zr greater than unity [28–31]. However, the recent blind analysis carried by the five STAR experimental analysis groups has consistently shown that the ratios of the CME observables between the two isobar collisions are less than unity [32], which announced that no predefined CME signal so far has been observed in the isobar program.

The backgrounds for the two isobar collisions are different in fact, since the differences of charged-particle multiplicity and collective flow between the two isobar collisions have been observed by STAR [32]. To explain the source of the differences, different nuclear deformations or nuclear structures have been used. As shown in Refs. [33–35], the neutron-skin effect, quadruple and octupole deformations are needed to be taken into account to explain the measured differences, which supports the existence of neutron-skin structure and nuclear deformation in the two isobar nuclei [36–39]. In other words, their nucleon density distributions should be described by a deformed Woods-Saxon (WS) form with some proper deformation parameters considering these effects. It has been proposed that the isobar collision experiment provides a new experimental way to study nuclear deformation and nuclear structure [40, 41]. In this work, we first try to find the best setting of WS parameters which can reproduce the STAR isobar data, then constraint the strength of possible CME signal in Ru + Ru and Zr + Zr collisions at \( \sqrt{s} = 200 \) GeV by using a multiphase transport (AMPT) model including both the signal of chiral magnetic effect and the good setting of WS parameters.

The paper is organized as follows. First, we introduce and test different nuclear geometry configurations of isobar nuclei using the AMPT model to find which cases are good ones in Sec. II. Then we introduce the AMPT model with including the CME and the CME observable of interest in Sec. III. In Sec. IV, we present our results about the CME observable and compare them with the STAR data. Finally, we draw conclusions in Sec. V.

II. INTRODUCING GEOMETRY CONFIGURATIONS OF ISOBAR NUCLEI

The AMPT model is a hybrid transport model which mainly includes four parts [42]: HIJING model for the initial condition, Zhang’s parton cascade for the evolution of partonic stage, quark coalescence model for the hadronization and the ART model for hadron rescatterings. The nucleons inside colliding nuclei are initialized at the initial stage by the HIJING model.

To model nucleons inside \(^{96}_{44}\)Ru and \(^{96}_{40}\)Zr, the spatial distribution of nucleons in the rest frame can be written in the WS form in spherical coordinates,

\[
\rho(r, \theta) = \rho_0 / \{1 + \exp[(r - R(\theta, \phi))/a]\}, \tag{1}
\]

\[
R(\theta, \phi) = R_0[1 + \beta_2 Y_{2,0}(\theta, \phi) + \beta_3 Y_{3,0}(\theta, \phi)], \tag{2}
\]

where \(\rho_0\) is the normal nuclear density, \(R_0\) is the radius of nucleus, \(a\) is the surface diffuseness parameter, and \(\beta_2\) and \(\beta_3\) are the quadrupole and octupole deformities of nucleus. We try to find all available settings of isobar geometry deformation parameters on the market, as shown in Table I. There are fifteen cases of settings which will be tested in our work. The deformation parameter settings Case 1 and Case 2 are obtained from the experimental measurement [43–46]. The old Case 1 and old Case 2 [30] are actually from Case 1 and Case 2, but the corresponding parameters were tuned to make sure the consistency between the model simulation and the experimental measurement [47]. The Case 3 and Cases 7-10, skin-type and halo-type cases are taken from Xu’s work [33] which considers the neutron-skin effect and/or a nuclear quadrupole deformity into the WS distribution with the TRENTO model. The Cases 4-6 are taken from Jia’s recent researches [35, 48], among which the Case 4 and Case 5 can well reproduce some experimental results. Meanwhile, the Case 6 is also from Ref. [49]. The Case 11 is taken from Ref. [50] which
TABLE I. The different cases of Woods-Saxon parameter settings tested in the AMPT model.

| Case 1 [43–45] | Case 2 [43, 44, 46] | Case 3 [33] | old Case 1 [30, 47] | old Case 2 [30, 47] |
|----------------|---------------------|-------------|---------------------|---------------------|
| R₀  a  β₂     | R₀  a  β₂           | R₀  a  β₂   | R₀  a  β₂           | R₀  a  β₂           |
| ⁹⁶Ru 5.085 0.46 0.158 | ⁹⁶Ru 5.085 0.46 0.053 | ⁹⁶Ru 5.067 0.500 0.00 | ⁹⁶Ru 5.13 0.46 0.13 | ⁹⁶Ru 5.13 0.46 0.03 |
| ⁹⁶Zr 5.020 0.46 0.80 | ⁹⁶Zr 5.020 0.46 0.217 | ⁹⁶Zr 4.965 0.556 0.00 | ⁹⁶Zr 5.06 0.46 0.06 | ⁹⁶Zr 5.06 0.46 0.18 |

| Case 4 [48] | Case 5 [48] | Case 6 [35, 49] | Case 7 [33] | Case 8 [33] |
|----------------|-------------|-----------------|-------------|-------------|
| R₀  a  β₂  β₃   | R₀  a  β₂  β₃ | R₀  a  β₂  β₃   | R₀  a  β₂   | R₀  a  β₂   |
| ⁹⁶Ru 5.09 0.46 0.162 0 | ⁹⁶Ru 5.09 0.46 0.154 0 | ⁹⁶Ru 5.09 0.52 0.154 0 | ⁹⁶Ru 5.065 0.485 0.16 | ⁹⁶Ru 5.085 0.523 0   |
| ⁹⁶Zr 5.09 0.52 0.060 0.2 | ⁹⁶Zr 5.09 0.52 0.060 0.2 | ⁹⁶Zr 5.09 0.52 0.060 0.2 | ⁹⁶Zr 4.961 0.544 0.16 | ⁹⁶Zr 5.021 0.523 0   |

| Case 9 [33] | Case 10 [33] | Case 11 [50] | skin-type [33] | halo-type [33] |
|--------------|--------------|--------------|----------------|---------------|
| R₀  a  β₂    | R₀  a  β₂    | R₀  a  β₂    | R₀  a  β₂      | R₀  a  β₂      |
| ⁹⁶Ru n 5.075 0.505 0 | ⁹⁶Ru p 5.060 0.493 0 | ⁹⁶Ru n 5.015 0.574 0 | ⁹⁶Ru p 4.915 0.521 0 | ⁹⁶Ru p 4.915 0.521 0 |
| ⁹⁶Zr n 5.015 0.574 0 | ⁹⁶Zr p 4.915 0.521 0 | ⁹⁶Zr p 4.915 0.521 0 | ⁹⁶Zr p 4.915 0.521 0 | ⁹⁶Zr p 4.915 0.521 0 |

introduced a deformed setting for Ru and a neutron-skin effect for Zr. Note that in the recent blind analysis, the STAR collaboration has tabled Case 1 to Case 3, and found that the Case 3 is the best one of the Cases 1-3. In addition, we will also study the Cases 1-3 with a fixed $\beta_3 = 0.235$. Therefore, we have eighteen cases of deformation settings in total.

In order to determine which case(s) is (are) good geometry setting(s) for the two isobar nuclei, we will test if the above cases of WS parameters can produce reasonable ratios of Ru to Zr in the charged-particle multiplicity distribution, average number of charged particles and elliptic flow $v_2$, as shown in Figs. 1-3 (1 million minimum-bias events for each case), respectively. Figure 1 shows the ratios of the charged-particle multiplicity ($N_{ch}$) distribution in Ru + Ru collisions to that in Zr + Zr collisions from eighteen cases of WS parameters compared to the STAR data. It is obvious that the ratios from Case 1, old Case 2, Case 8, and Case 11 are less than unity for high $N_{ch}$, different from the experimental result which is above one. For the other cases, they can basically reproduce the experimental data, i.e. the ratio is close to unity for low $N_{ch}$, but greater than unity for high $N_{ch}$. In addition, Fig. 1(d) shows the results from Cases 1-3 but with an octupole deformation parameter of $\beta_3=0.235$ for Zr. We see that with the octupole deformation, the ratio of $N_{ch}$ distribution gets larger than unity for high $N_{ch}$ for the Case 1. This indicates the octupole deformation for Zr decreases the yield of charged particles in central Zr + Zr collisions. However, the Cases 2 and 3 are less affected by the octupole deformation. Overall, the old Case 1, Case 1 with $\beta_3$, Cases 2-3 without and with $\beta_3$, Cases 4-7, Cases 9-10, skin-type case, halo-type case can reproduce the STAR measured ratio of charged-particle multiplicity distribution.

Next we check if they can reproduce the centrality dependence of the ratio of the average number of charged particles $\langle N_{ch} \rangle$ in Ru + Ru collisions to that in Zr + Zr collisions. Same as the STAR,
FIG. 1. The ratios of the charged-particle multiplicity distribution ($|\eta| < 0.5$) in Ru + Ru collisions to that in Zr + Zr collisions from the AMPT model using eighteen cases of Woods-Saxon parameter settings, in comparison with the experimental data [32].

FIG. 2. The centrality dependences of the ratio of the average number of charged particles ($|\eta| < 0.5$) in Ru + Ru collisions to that in Zr + Zr collisions from the AMPT model using eighteen cases of Woods-Saxon parameter settings, in comparison with the experimental data [32].

we use the multiplicity distribution of all charged particles within the pseudorapidity window of $|\eta| < 0.5$ to define centrality bins. In Fig. 2(a)-(c), we can see that the ratios in Case 3, Case 4, Case 5, Case 7, Case 9, Case 10, and halo-type case increases from central to peripheral centrality bin, which are consistent with the STAR measurement. If considering the additional effect of octupole deformation into the Cases 1-3, Fig. 2(d) shows that the ratio will change slightly for central collisions but remain unchanged for peripheral collisions. Overall, the Case 3 without and with $\beta_3$, Cases 4-5, Case 7, Cases 9-10, halo-type case can reproduce the centrality dependence of the ratio of average number of charged particles between the two isobar collisions measured by STAR.

At last, we check if these cases can reproduce the centrality dependence of the ratio of elliptic flow in Ru + Ru collisions to that in Zr + Zr collisions. Same as the STAR, we use two-particle correlation method to calculate the elliptic flow $v_2$ and the charged particles under kinetic cuts of $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/c. From Figs. 3(a)-(c), we find that the ratios of $v_2(2, |\Delta\eta| > 1)$ from the Cases 3-5, Case 7, Cases 9-10, skin-type and halo-type cases can describe the experimental
FIG. 3. The centrality dependences of the ratio of $v_2(2,|\Delta\eta>1)$ in Ru + Ru collisions to that in Zr + Zr collisions from the AMPT model using eighteen cases of Woods-Saxon parameter settings, in comparison with the experimental data [32].

data. In terms of the effect of octupole deformation, Fig. 3(d) shows that the finite $\beta_3$ decreases the ratio of $v_2(2,|\Delta\eta>1)$ especially for central collisions.

According to the above performance of all cases, we can see Cases 3-5, Case 7, Cases 9-10 and the halo-type case are good cases, if we define the criterion for a good case as whether it can reproduce the above three kinds of ratios simultaneously. It is worth noting that the Cases 4-6 and the effect of $\beta_3$ have been studied in detail in Refs. [35, 48, 51], and their recent study suggested that the ratios calculated at the same $N_{ch}$ provide a better baseline for the non-CME background [52]. For simplicity, we choose the halo-type neutron skin case for doing our following study related to the CME.

III. INTRODUCING AND OBSERVING THE CME

Previously, we have introduced a CME-like charge separation into the initial stage of parton cascade in the AMPT model, and the detail can be seen in Ref. [53]. By tuning the percentage $f$ of how many quarks join the charge separation\(^1\), the signal strength of the CME can be controlled in the AMPT model. The percentage $f$ is defined as,

$$f = \frac{N_{f^+} - N_{f^-}}{N_{f^+} + N_{f^-}},$$

\(^1\)Note that because the AMPT model includes only the degrees of freedom for quarks, the $f$ is an approximate percentage.
and \( \delta_{\alpha\beta} = \langle \cos(\phi_{\alpha} - \phi_{\beta}) \rangle \), where \( \phi_{\alpha\beta} \) are the azimuthal angles of charged particles and \( \Psi_{\text{RP}} \) is the reaction plane angle [22, 23, 54]. A more positive \( \Delta\gamma \) or more negative \( \Delta\delta \) corresponds to a stronger CME, as expected by the CME [31]. To cancel out the background contribution, we further obtain the observable of the \( \Delta\gamma/v_2\{\text{EP}\} \) ratio between two isobar collisions to compare with the STAR measurement, where the elliptic flow \( v_2\{\text{EP}\} \) is calculated with respect to the event plane \( \Psi_{\text{EP}} \) [55, 56].

IV. RESULTS AND DISCUSSIONS

Before studying the CME observables, we need to make sure the ratios of the charged-particle distribution and \( v_2\{2, |\Delta\eta| > 1\} \) have no big change if the CME signal is introduced into the AMPT model. Figure 4 shows the above three criterion ratios for the AMPT model without the CME and with different strengths of the CME, in comparison with the experimental data [32]. This indicates that the introduction of the initial CME signal into collisions between two isobars with halo-type neutron skin structures has little effect on the three reference ratios. Therefore, the AMPT model with the halo-type of Woods-Saxon parameter setting provides a good baseline to study the CME in isobar collisions.

The centrality dependences of \( \Delta\delta \) for the two isobar collisions from the AMPT model without the CME and with different strengths of the CME are shown in Fig. 5(a), and compared with the experimental data. For central and mid-central collisions, the AMPT model without the CME or with a small strength of the CME can reproduce the experimental data, but underestimates the data if the CME strength is larger than \( f = 5\% \), because the CME tends to reduce \( \Delta\delta \). However, all the AMPT results fail to describe \( \Delta\delta \) for the most peripheral collisions. The centrality dependences of the ratio of \( \Delta\delta \) for the two isobar collisions are presented in Fig. 5(b). The AMPT results without the CME and a CME strength of \( f = 2\% \) are closer to the data than those with larger CME strengths, indicating that the CME strength is very small if any in isobar collisions.

The centrality dependences of \( \Delta\gamma \) for the two isobar collisions from the AMPT model without the CME and with different strengths of the CME are shown in Fig. 6(a), and compared with the experimental data. We find that the AMPT results overestimate the experimental data if the
FIG. 5. The centrality dependences of $\Delta\delta$ (a) and the ratio of $\Delta\delta$ in Ru + Ru collisions to that in Zr + Zr collisions (b) from the AMPT model with different strengths of the CME, in comparison with the experimental data [32].

strength of the CME is $f = 7.5\%$ or $f = 10\%$ for mid-central collisions. However, the results for $f = 2\%$ or $f = 5\%$ are almost as same as that without the CME ($f = 0$), all of which can well describe the experimental data. This is consistent with the previous findings that the CME observable $\gamma$ has a nonlinear sensitivity to the strength of the CME signal, as the final state interactions significantly weaken the initial CME signal [29, 53, 57].

Finally, the centrality dependences of the ratio of $\Delta\gamma/\nu_2\{EP\}$ between two isobar collisions are presented in Fig. 6(b). The ratios for $f = 7.5\%$ and $10\%$ look too large to describe the experimental data, especially for the centrality bin of 20-50%. Compared to the experimental data, no CME or a small CME strength is favored in order to reproduce the data. However, it is difficult to distinguish no CME from a small strength of the CME, because the ratios from $f = 0$, $2\%$ and $5\%$ agree with each other in our limited statistics ($\sim 30$ million minimum- bias events for each case). This indicates that the initial CME signal is absent or small in isobar collisions. Therefore, searching for possible small CME signals in isobar collisions requires more sensitive observables.

V. CONCLUSIONS

We test eighteen cases of Woods-Saxon parameter settings which consider either nuclear deformation or nuclear neutron-skin effect for Ru + Ru and Zr + Zr collisions at $\sqrt{s} = 200$ GeV, using the AMPT model. Only seven of the eighteen cases (Case 3, Case 4, Case 5, Case 7, Case 9, Case 10, and halo-type case) can reasonably reproduce the experimental ratios of charged-particle multiplic-
FIG. 6. The centrality dependences of $\Delta \gamma$ (a) and the ratio of $\Delta \gamma/v_2\{\text{EP}\}$ in Ru + Ru collisions to that in Zr + Zr collisions (b) from the AMPT model with different strengths of the CME, in comparison with the experimental data [32].

ity distribution, average number of charged particles and elliptic flow, which demonstrates that the nuclear deformation and structure information have a non-negligible impact. Isobar collisions can serve for further research of nuclear deformation or nuclear neutron-skin structure, which currently has important implications for both nuclear structure and nuclear astrophysics.

We choose the halo-type case to study the CME using the AMPT model with different strengths of the CME. The measured $\Delta \delta$, $\Delta \gamma$, $\Delta \delta$ ratio, and $\Delta \gamma/v_2\{\text{EP}\}$ ratio can be reproduced by the AMPT model without the CME or with a small strength of the CME. On the other hand, they can not be described by the AMPT model with a stronger strength of the CME. This indicates that the initial CME signal in isobar collisions is absent or small in isobar collisions. It could be due to the fact that the final state interactions significantly weaken the initial CME signal, resulting in the non-linear sensitivity of the CME observables. Therefore, more sensitive observables are required for searching for the possible small CME signal in isobar collisions.

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