Impact of nuclear deformation on longitudinal flow decorrelations in high-energy isobar collisions

Maowu Nie,1,2 Chunjian Zhang,3 Zhenyu Chen,1,2 Li Yi,1,2 and Jiangyong Jia3,4

1Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, 266237, China
2Key Laboratory of Particle Physics and Particle Irradiation, Ministry of Education, Shandong University, Qingdao, Shandong, 266237, China
3Department of Chemistry, Stony Brook University, Stony Brook, New York 11794, USA
4Physics Department, Brookhaven National Laboratory, Upton, New York 11976, USA

Fluctuations of harmonic flow along pseudorapidity \( \eta \), known as flow decorrelations, is an important probe of the initial condition and final state evolution of the quark-gluon plasma. We show that the flow decorrelations are sensitive to the deformations of the colliding nuclei. This sensitivity is revealed clearly by comparing flow decorrelations between collisions of isobars, \( ^{96}\text{Zr}+^{96}\text{Zr} \) and \( ^{96}\text{Ru}+^{96}\text{Ru} \), which have different deformations. Longitudinal flow decorrelations in heavy-ion collisions is a new tool to probe the structure of colliding nuclei.

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I. INTRODUCTION

Azimuthal anisotropic flow \([1]\) is an important tool to study the properties of the quark-gluon plasma produced in high-energy heavy-ion collisions at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) \([2–4]\). The flow is characterized via a Fourier expansion of particle production \( dN/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi) \), where \( v_n \) and \( \Psi_n \) are the \( n^{\text{th}} \)-order of flow magnitude and phase, respectively. The dominating components \( v_2 \) (elliptic flow) \([5]\) and \( v_3 \) (triangular flow) \([6]\) have been studied extensively. They have led to constraints on both the initial condition as well as the transport properties of the QGP \([7–9]\).

One important insight realized recently is that the heavy-ion initial condition is not boost invariant in the longitudinal direction. In fact, it interpolates between projectile nucleus geometry in the forward direction and target nucleus geometry in the backward direction. These two geometries are not the same due to random fluctuations of participating nucleons, which leads to a twist in the final state event-plane angles \([10–14]\). This effects have been measured at both the LHC \([15–17]\) and RHIC \([18]\), and are well described by 3+1D event-by-event viscous hydrodynamical models \([19–25,25]\). The experimental observable for flow decorrelation is constructed from ratios of two-particle correlations

\[
r_n(\eta, \eta_{\text{ref}}) = \frac{V_{n\Delta}(\eta, \eta_{\text{ref}})}{V_{n\Delta}(\eta, \eta_{\text{ref}})}
\]

where the \( \eta_{\text{ref}} \) is the reference pseudorapidity common to the numerator and the denominator, typically chosen at forward rapidity. The decorrelation is reflected by the fact that \( V_{n\Delta}(\eta, \eta_{\text{ref}}) \neq v_n(\eta)v_n(\eta_{\text{ref}}) \), and appearing as a linear decrease of \( r_n \) as a function of \( \eta \).

The longitudinal fluctuations of the initial condition are strongly influenced by the collective structure of the colliding nuclei \([26,27]\). Most heavy nuclei are more or less deformed from spherical shape and can be described by a Woods-Saxon form:

\[
\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta,\phi))/\alpha}}
\]

\[
R(\theta, \phi) = R_0(1 + \beta_2 Y_2^2 + \beta_3 Y_3^3)
\]

where the nuclear surface \( R(\theta, \phi) \) includes quadrupole deformation \( \beta_2 \) and octupole deformation \( \beta_3 \), \( R_0 \) and \( a \) are the half-height radius and nuclear skin, respectively. Recent studies show that the \( v_n \) are strongly enhanced by \( \beta_n \), especially in the ultra-central collisions. The \( v_n \) are also influenced by the \( R_0 \) and \( a \) in the mid-central collisions \([28]\). The evidence for these influences is best revealed by ratios of \( v_n \) between two isobar collision systems with different structures. Since isobar nuclei have the same mass number but different structures, deviation from the unity of the ratio of any observable must originate from differences in the structure of the colliding nuclei, which impact the initial state of QGP and its final state evolution. One such example is the \( ^{96}\text{Zr}+^{96}\text{Zr} \) and \( ^{96}\text{Ru}+^{96}\text{Ru} \) collisions, which have shown significant departure from unity in the ratios of many observables, including \( v_2 \) and \( v_3 \) \([29]\). The structure differences between \( ^{96}\text{Ru} \) and \( ^{96}\text{Zr} \) are also expected to cause differences in the longitudinal structure of the initial condition and subsequently the flow decorrelations.

This paper studies the influence of nuclear deformation \( \beta_2 \) and \( \beta_3 \) on the flow decorrelations \( ^{96}\text{Zr}+^{96}\text{Zr} \) and \( ^{96}\text{Ru}+^{96}\text{Ru} \) collisions within a Multi-phase transport model (AMPT). We focus in particular on the ratios of the \( r_n \) between...
the two systems, which show significant deviation from unity in the presence of deformations.

II. THE AMPT MODEL

In AMPT model, the initial partons can be treated as strings in the longitudinal direction, with the fluctuation of the length of the strings, longitudinal fluctuation was naturally introduced, previous studies suggest it can well describe the flow decorrelation in heavy-ion collisions [30, 31]. We use the AMPT string melting version to simulate isobar $^{96}$Zr+$^{96}$Zr and $^{96}$Ru+$^{96}$Ru collisions at $\sqrt{s_{NN}} = 200$ GeV. The string melting version consists of four main components: Monte Carlo Glauber as initial conditions, strings and mini-jet that melt into partons from the HIJING model [32], elastic parton cascade by the ZPC model [33], a quark coalescence model for hadronization, and hadron rescatterings described by the ART model [34]. For details, see the review [35].

The Wood-Saxon parameters for the two collision systems are set with $R_0 = 5.09$ fm and $a = 0.52$ fm, the deformation parameter is set with $\beta_2 = 0.162$ and $\beta_3 = 0$ for Ru, $\beta_2 = 0.06$ and $\beta_3 = 0.2$ for Zr. The elastic parton-parton cross section is $\sigma = 3$ mb, which is also used in recent AMPT studies [36, 37].

Recent studies also suggest the neutron skin and the symmetry energy are different between $^{96}$Zr+$^{96}$Zr and $^{96}$Ru+$^{96}$Ru collisions [38, 39], for simplicity, these effects are not included in this study.

III. RESULTS AND DISCUSSIONS

The major difference between Zr+Zr and Ru+Ru in this study is the initial deformation, thus any differences in the final observable ratios between the two collision systems will directly reflect the nuclear structure. The isobar ratio is also studied in a recent study, which suggests the final state observable isobar ratio is insensitive to the final state effects, such as the shear viscosity, hadronization, and hadronic cascade [40]. Fig. 1 show $r_2$ and $r_3$ as a function of $\eta$ averaged over $0.4 < p_T < 4$ GeV for Zr+Zr and Ru+Ru collisions in two centrality intervals 0-10% and 10-40%, where reference pseudorapidity ranges are $3.1 < \eta_{ref} < 5.1$ for $r_2$ and $2.1 < \eta_{ref} < 5.1$ for $r_3$. The contributions from nonflow like dijets are expected to contribute to $r_2$ due to the small gap between $\eta$ and $\eta_{ref}$. $3.1 < \eta_{ref} < 5.1$ can significantly suppress these non-flow contributions, while $r_3$ is almost independent of reference rapidity ranges, $2.1 < \eta_{ref} < 5.1$ enables us have sufficient statistics for $r_3$ in this study. Though Ru+Ru collisions show a similar trend as Zr+Zr collisions, the differences of $r_2$ and $r_3$ between the two collision systems are still clear. For $r_2$, the difference for most central collision 0-10% is negligible, while 10-40% shows a clear difference, especially at large pseudorapidity. However for $r_3$, both 0-10% and 10-40% show clear deviation. It is worth noticing that the recent STAR preliminary results show the a similar trend [41].

To further quantify the difference, the ratio between Ru+Ru and Zr+Zr is analytically calculated in Fig. 2. $r_2$ ratio is consistent with 1 within error in 0-10%, while it shows a clear difference for 10-40%, and the difference is up to 1%. Previous study suggest the presence of $\beta_3$,Zr can significantly enhance $r_2$,Zr in mid-central collisions [37], it could be the same reason on the negligible difference in $r_2$ ratio in 0-10%. Unlike $r_2$ ratio, the $r_3$ ratio is significantly less than 1, the difference can go up to 4% in both 0-10% and 10-40%. The results suggest $r_n$ is also sensitive to the nuclear structure, and $r_n$ ratio can provide a more direct way to quantify the difference, which can be used in future experimental measurements.

The factorization ratio $r_n$ can be parametrized with a linear function: $r_n(\eta) = 1 - 2F_n \eta$, where slope parameter $F_n$ quantified the strength of flow decorrelation. Thus $F_n$ can be well extracted for each centrality interval. To better quantify the centrality dependence of $F_n$, the centrality bins are redefined with 10% interval. As in ultra-central collisions, the initial geometry will involve more nuclear deformation effect, we further ex-

![Figure 1](image-url)

Figure 1: $r_2$ (top) and $r_3$ (bottom) as a function of pseudorapidity $\eta$ in Zr+Zr and Ru+Ru collisions in 0-10% and 10-40% centralities.
Figure 2: Ratio of $r_2$ (top) and $r_3$ (bottom) between Zr+Zr and Ru+Ru collisions in 0-10% and 10-40% centralities.

Figure 3: Centrality dependence of slope parameter $F_2$ (left) and $F_3$ (right) in Zr+Zr and Ru+Ru collisions.

The impact of nuclear deformation on longitudinal flow decorrelation in Zr+Zr and Ru+Ru collisions is studied in AMPT string melting framework. With a large quadrupole deformation of Ru and large octupole deformation of Zr, clear differences in flow decorrelations are observed between the two collision systems. We further propose $r_n$ ratio to quantify the differences between the two systems, and the deviation can go up to 1% for $r_2$ in 10-40% and 5% for $r_3$ in 0-10% at large $\eta$. The slow parameter $F_n$ of $r_n$ are studied as a function of centrality. Around 10% difference is observed for $F_2$ in mid-central collisions, and up to 20% difference for $F_3$ in most central collisions. The results suggest the longitudinal dynamics are also sensitive to the nuclear structure, and it can provide further constrain on the nuclear structure in heavy-ion collisions.

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