Anisotropic flow of strange and multi-strange hadrons in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC

Vipul Bairathi (for the STAR Collaboration)\textsuperscript{a,∗}
\textsuperscript{a}Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
E-mail: vipul.bairathi@gmail.com

We present elliptic flow of strange and multi-strange hadrons ($K_0^0$, $\Lambda$, $\bar{\Lambda}$, $\phi$, $\Xi^-$, and $\Xi^+$) at mid-rapidity in isobar collisions ($^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr) at $\sqrt{s_{NN}} = 200$ GeV. The transverse momentum ($p_T$) dependence of elliptic flow ($v_2$) is presented for minimum bias and various collision centrality intervals. We studied the number of constituent quark (NCQ) scaling of $v_2$ in these isobar collisions. Average elliptic flow ($\langle v_2 \rangle$) has been observed to increase from central to peripheral collisions. The ratio of $\langle v_2 \rangle$ between isobar species shows a deviation from unity that is consistent with the difference in nuclear structure and deformation in these species. A system size dependence of $v_2$ is also observed among isobar, Cu+Cu, Au+Au, and U+U systems.

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1. Introduction

Several studies in relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) [1-4] and the Large Hadron Collider (LHC) [5-7] suggest the formation of an exotic state of matter called the quark-gluon plasma (QGP) [8]. One of the key observables in these studies is azimuthal anisotropic flow of produced particles which indicates hydrodynamic and collective behavior of the strongly interacting matter during the collision. Such an observable measures the anisotropy in event-by-event azimuthal angle distribution of produced particles relative to the collision plane. It arises due to spatial anisotropy of the initial overlap geometry of the colliding nuclei as a consequence of inhomogeneous initial energy deposition and fluctuations of nucleon positions in heavy-ion collisions. The initial spatial anisotropies are converted into final state momentum anisotropies through strong rescatterings among partons during the early stages prior to hadronization, and among produced hadrons at the later stages. The anisotropic flow is an important tool to explore the properties of the QGP matter formed in the relativistic heavy-ion collisions.

2. Data analysis

In the year 2018, the STAR experiment at RHIC collected data by colliding isobar species Ru+Ru and Zr+Zr at $\sqrt{s_{NN}} = 200$ GeV. It is dedicated to measure the charge separation along the magnetic field, driven by a phenomenon called the Chiral Magnetic Effect (CME) [9]. It was realized that the two isobars have different deformation parameters and flow measurements are highly sensitive to them. More importantly, measurements of strange and multi-strange hadrons flow is an excellent probe for understanding the initial state anisotropies due to their small hadronic interaction cross-section compared to light hadrons. Therefore, a systematic study of anisotropic flow of strange and multi-strange hadrons could be crucial to understand the effect of initial states in the isobar collisions.

Anisotropic flow is quantified via the Fourier decomposition of the particle azimuthal angle distribution with respect to the event plane angle. The azimuthal dependence of the particle yield can be expanded in terms of a Fourier series [10]:

$$\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y) \cos[n(\phi - \Psi_n)] \right),$$

where $\phi$, $p_T$, and $y$ are the particle’s azimuthal angle, transverse momentum, and rapidity, respectively, and $\Psi_n$ is the orientation of the $n^{th}$-order event plane. The second order Fourier coefficient $v_2$, known as elliptic flow, is particularly sensitive to the initial geometry of the collisions and the properties of the medium in the heavy-ion collisions.

In these proceedings, we report $v_2$ of $K^0_S$, $\Lambda$, $\bar{\Lambda}$, $\phi$, $\Xi^-$, and $\Xi^+$ in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. A total of $\sim$650 M minimum bias good events out of the total 1.8 B (2 B) events of Ru+Ru (Zr+Zr) collisions are used for this analysis. The above hadrons are reconstructed using the invariant mass technique through their hadronic decay channels. The combinatorial background is constructed using a track rotation method for weakly decaying hadrons, while for $\phi$-mesons event mixing technique is used [11, 12].
η-sub event plane method with a η-gap of 0.1 between the two sub-events (-1 < η < -0.05 and 0.05 < η < 1.0) has been used to calculate $v_2$ of these hadrons [10].

3. Results

3.1 $p_T$ dependence of $v_2$

![Figure 1](a.png)

**Figure 1**: $v_2$ as a function of $p_T$ for strange and multi-strange hadrons at mid-rapidity in minimum bias Ru+Ru collisions (left panel) and Zr+Zr collisions (right panel) at $\sqrt{s_{NN}} = 200$ GeV.

Figure 1 shows $p_T$ dependence of strange and multi-strange hadrons $v_2$ for minimum bias Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. At low $p_T$, $v_2$ follows a particle mass dependence, indicating hydrodynamic behavior of the medium but interestingly at intermediate $p_T$, $v_2$ follows the particle type dependence (baryon vs meson) which suggests the formation of a QGP medium in the isobar collisions at $\sqrt{s_{NN}} = 200$ GeV. The same particle mass and type dependence of $v_2$ is observed for all the other centrality intervals.

3.2 Centrality dependence of $v_2$

Figures 2 and 3 show $v_2(p_T)$ of strange and multi-strange hadrons for various centrality intervals in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. A clear centrality dependence is observed for all the measured particle species in both the isobar collisions. The $v_2$ magnitude increases from central to peripheral collisions.

Figure 4 shows $p_T$-integrated $v_2$ of strange hadrons as a function of centrality in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. The ratio of $v_2$ in Ru+Ru to Zr+Zr collisions is also shown in the bottom panels of Fig. 4 and fitted with a constant polynomial function for mid-central collisions (20-50%). About $\sim 2\%$ deviation from unity with a significance of 6.25σ for $\Lambda(\bar{\Lambda})$ and 1.83σ for $K^0_S$ is observed, which is consistent with the expectation from the difference between the nuclear structures of the two isobar nuclei [9].

3.3 NCQ scaling

Figure 5 shows $v_2$ of strange and multi-strange hadrons scaled by the number of constituent quarks $n_q$ in minimum bias Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are presented as a function of transverse kinetic energy to remove the effect of particle mass at low $p_T$. It is defined as $KE_T = m_T - m_0$, where $m_T$ is the transverse
mass ($\sqrt{p_T^2 + m_0^2}$) and $m_0$ is rest mass of the particle. The $v_2$ of strange and multi-strange hadrons follows the number of constituent quarks (NCQ) scaling in both the collision systems. The NCQ scaling of $v_2$ suggests a formation and collective behavior of the QGP medium. It also indicates that the quark coalescence is the dominant mechanism of particle production.
A nisotropic ow in isobar collisions
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Figure 4: $p_T$-integrated $v_2$ vs centrality for strange hadrons at mid-rapidity in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. The ratio of $v_2$ between Ru and Zr is also shown in the bottom panels. The error bars represent statistical and systematic uncertainties added in quadrature.

Figure 5: NCQ scaled $v_2$ vs transverse kinetic energy ($KE_T/n_q$) at mid-rapidity in minimum bias Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV. The bands represent systematic uncertainties.

3.4 System size dependence

Figure 6 shows $v_2$ of strange hadrons in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV compared to the published results from the STAR experiment at RHIC in Cu+Cu, Au+Au, and U+U collisions [13-15]. A system size dependence of $v_2$ is observed for $p_T$ above $\sim 1.5$ GeV/c. The $v_2$ seems to follow the hierarchy $v_2^Cu < v_2^{Ru/Zr} < v_2^{Au} < v_2^{U}$. Its magnitude increases with increase in the system size.

4. Summary

We reported transverse momentum dependence of elliptic flow of $K_s^0$, $\Lambda$, $\bar{\Lambda}$, $\phi$, $\Xi^-$, and $\Xi^+$ in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV for minimum bias (0-80%) and in three centrality intervals (0-10%, 10-40%, and 40-80%). A clear centrality dependence of $v_2$ is observed in the isobar collisions. We observed a particle mass hierarchy of $v_2$ which suggests hydrodynamic behavior at low $p_T$. A baryon-meson splitting at intermediate $p_T$ suggests particle type dependence of $v_2$. Elliptic flow of strange and multi-strange hadrons follows the NCQ scaling, further indicating quark coalescence as the dominant particle
production mechanism and the collectivity of the medium. Ratio of $p_T$-integrated $v_2$ for strange hadrons between the two isobar collisions shows a deviation from unity. We also observed a system size dependence of the $v_2$. These measurements could shed light on the effect of deformation and collision geometry on anisotropic particle production in relativistic heavy-ion collisions.

References