Measurement of global spin alignment of vector mesons at RHIC*

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We report the measurements of spin alignment (ρ_{00}) for K^{*0}, $\overline{K^{*0}}$, K^{*+}, and K^{*-} vector mesons in RHIC isobar collisions (Zr+Zr and Ru+Ru) at $\sqrt{s_{\rm NN}} = 200$ GeV. We observe the first non-zero spin alignment for $K^{*\pm}$ in heavy-ion collisions. The $K^{*\pm}$ ρ_{00} is about 3.9σ larger than that of K^{*0}. The observed difference and the ordering between $K^{*\pm}$ and K^{*0} are surprising, and require further inputs from theory. When comparing between the isobar and Au+Au collisions, no significant system size dependence in K^{*0} ρ_{00} is observed within uncertainties.

1. Introduction

In the initial stage of a non-central heavy-ion collisions (HIC), a large orbital angular momentum (OAM) is imparted into the system. The magnitude of such OAM can be $\sim bA\sqrt{s_{\rm NN}} \sim 10^4\hbar$, where b is the impact parameter and A is the mass number of the collision species [1]. A part of OAM transferred to the Quark Gluon Plasma (QGP) medium can polarize quarks and anti-quarks due to "spin-orbit" interaction and hence induce a non-vanishing polarization for hadrons with non-zero spin [2]. The incoming charged spectators in HIC can also induce a large but short lived electromagnetic field ($eB \sim 10^{18}$ Gauss) [3]. Such a strong B-field can also polarize both quarks and anti-quarks due to its coupling with the intrinsic magnetic moment. The measurement of spin polarization can not only offer insights into the initial orbital angular momentum interactions and magnetic field, but also serve as an experimental probe to understand the response of QGP medium under these extreme initial conditions. The measurement of significant non-zero polarization of Λ hyperons by STAR collaboration offered

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first experimental evidence of the presence of vorticity of the QGP medium induced by the initial angular momentum, while a hint of difference between Λ and $\overline{\Lambda}$ spin polarization at RHIC presents an opportunity to probe the initial B field [4]. The spin alignment is quantified by 00^{th} element of the spin density matrix, ρ_{00}, and can be measured from the angular distribution of the decay daughter of the vector meson [5]:

$$\frac{d\text{N}}{d\cos\theta^*} \propto \Big((1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\Big), \tag{1}$$

where θ^* is the angle between the polarization axis and momentum direction of the daughter particle in the rest frame of its parent. For global spin alignment, the polarization axis is chosen as the direction perpendicular to the reaction plane, which can be correlated with both the OAM and the B-field. The value of ρ_{00} is expected to be $\frac{1}{3}$ in absense of spin alignment, while a deviation of ρ_{00} from $\frac{1}{3}$ indicates a net spin alignment.

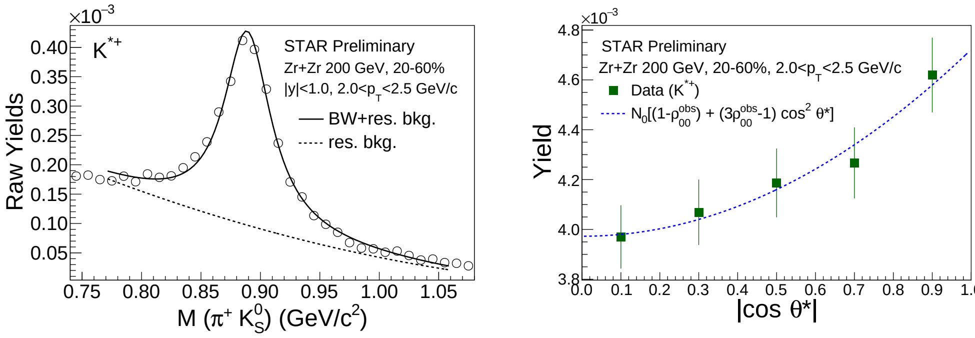

Fig. 1. Left: $K^{*+}(\rightarrow \pi^+ + K^0_{\text{S}})$ invariant mass distribution for $2.0 < p_{\text{T}} < 2.5$ GeV/c in 20-60% Zr+Zr collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. Right: efficiency and acceptance corrected K^{*+} yield as a function of $|\cos\theta^*|$ in 200 GeV Zr+Zr collisions.

At present, the available physics mechanisms that can cause spin alignment are the followings: (i) the polarized quarks induced by vorticity can hadronize via coalescence mechanism. It can make ρ_{00} smaller than $\frac{1}{3}$ [2, 6]; (ii) the ρ_{00} induced by the B-field can be either larger or smaller than $\frac{1}{3}$. The expected deviation due to vorticity and B-field is $\rho_{00} - \frac{1}{3} \sim 10^{-5}$ [6]; (iii) the electric field can give a positive contribution with $\rho_{00} - \frac{1}{3} \sim 10^{-4}$ [6]; (iv) the fragmentation of polarized quarks can make either positive or negative contribution with $\rho_{00} - \frac{1}{3} \sim 10^{-5}$ [2]; (v) local spin alignment, helicity polarization, and turbulent color field can also make ρ_{00} smaller than $\frac{1}{3}$ [7]; (vi) A fluctuating strong force field of vector meson can cause the ρ_{00} to be larger than $\frac{1}{3}$ with a deviation ~ 0.1, which is an order of magnitude large compared to more conventional mechanisms [8]. The study of ρ_{00} of various vector meson species can thus elucidate our understanding of different mechanisms causing spin alignment. Furthermore, the neutral and charged vector mesons ($K^{*0}(d\bar{s})$ and $K^{*+}(u\bar{s})$) have similar mass, but the magnetic moments of their constituent quarks differ by about a factor of five ($\mu_d \sim -0.97\mu_{\rm N}$, $\mu_u \sim 1.85\mu_{\rm N}$). Hence, the magnetic field driven contribution to the ρ_{00} of neutral and charged K^* is expected to be different.

The recent measurements of ρ_{00} of ϕ and K^{*0} vector mesons from the 1^{st} phase of RHIC Beam Energy Scan (BES-I) Au+Au collisions revealed a surprising pattern [13]. While the K^{*0} ρ_{00} is largely consistent with $\frac{1}{3}$, the ϕ mesons show a large positive deviation ($\rho_{00} > \frac{1}{3}$) with 8.4σ significance when ρ_{00} is integrated within the range $\sqrt{s_{\rm NN}} = 11.5-62.4$ GeV for $1.2 < p_{\rm T} < 5.4$ GeV/c in 20-60% Au+Au collisions. Such a large positive deviation at mid-central collisions pose challenges to more conventional physics mechanisms, while the polarization induced from a fluctuating ϕ-meson vector field can accommodate the large positive signal [8]. Moreover, the $p_{\rm T}$ and centrality differential measurements of ϕ and K^{*0} ρ_{00} in BES-I energy range also show non-trivial patterns [13].

2. Analysis method

This proceedings report the first ρ_{00} measurements of charged $K^{*\pm}$ along with neutral K^{*0} ($\overline{K^{*0}}$) vector mesons in RHIC isobar collisions of ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr species at $\sqrt{s_{\rm NN}} = 200$ GeV [9]. The $K^{*0}(\overline{K^{*0}})$ and $K^{*+}(K^{*-})$ are reconstructed via $K^{*0}(\overline{K^{*0}}) \to \pi^- + K^+(\pi^+ + K^-)$ and $K^{*+}(K^{*-}) \to \pi^+ + K^0_{\rm S}(\pi^- + K^0_{\rm S})$ respectively. The minimum-bias (MB) events are collected via a coincidence between the Vertex Position Detectors (VPD) located at $4.4 < |\eta| < 4.9$. For analysis, the vertex position along the beam ($V_{\rm z,TPC}$) and radial direction (V_r) are required to be within $-35 < V_{\rm z,TPC} < 25$ cm and $V_r < 5$ cm respectively with a coordinate system at the center of Time Projection Chamber (TPC). We analyzed about 1.8 and 2.0 billion good MB events for Ru+Ru and Zr+Zr collisions, respectively. The charged particle tracking is performed using the TPC. The collision centrality is determined from the number of charged particles within $|\eta| < 0.5$, and using a Monte Carlo Glauber simulation [10]. The second order event plane ($\Psi_{2,\rm TPC}$) is reconstructed using the tracks inside TPC [11]. In isobar collisions, the typical $\Psi_{2,\rm TPC}$ resolution achieved in mid-central collisions is $R_{2,\rm TPC} \sim 64\%$. The decay daughters of K^* are identified using the specific ionization energy loss in TPC gas volume and the velocity of particles measured by the TOF detector. The $K^0_{\rm S}$ mesons are selected via a weak decay topology. For charged $K^{*\pm}$ reconstruction, only the $K^0_{\rm S}$ candidates within $0.48 < M(\pi^+\pi^-) < 0.51$ GeV/c^2 are considered. The combinatorial background is estimated from a track rotation technique, in which one of the daughter track is rotated by 180° to break the correlation among the pairs originating from same parent particle. Then, the invariant mass signal is obtained by subtracting the combinatorial background. The K^* signal is fitted with a Breit-Wigner distribution and a second-order polynomial function to take care of residual background.

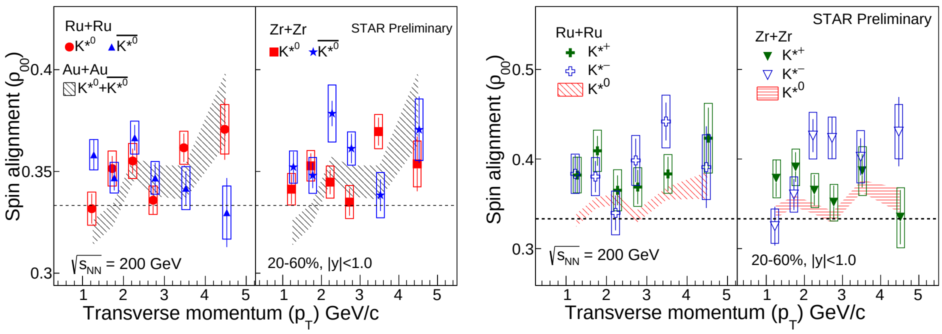

Fig. 2. Left: $\rho_{00}(p_{\mathrm{T}})$ for K^{*0} and $\overline{K^{*0}}$ in isobar collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Results are compared with that from 200 GeV Au+Au collisions [13]. Right: Comparison of $\rho_{00}(p_{\mathrm{T}})$ between $K^{*\pm}$ and K^{*0} in 200 GeV isobar collisions.

The left panel in Fig. 1 presents the K^{*+} signal for $2.0 < p_{\mathrm{T}} < 2.5$ GeV/c in 20-60% Zr+Zr collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The yield is estimated by integrating residual background subtracted signal within the range: $m_0 \pm 3\Gamma$, where m_0 and Γ are the invariant mass peak position and width of K^*. The yield is obtained in five $|\cos\theta^*|$ bins where θ^* is the angle between $\Psi_{2,\mathrm{TPC}}$ and momentum of daughter kaon (pion) in parent K^{*0} ($K^{*\pm}$) rest frame. The detector acceptance and efficiency correction factors are obtained using a STAR detector simulation in GEANT3. The right panel in Fig. 1 presents efficiency and acceptance corrected K^{*+} yield as a function of $|\cos\theta^*|$ for $2.0 < p_{\mathrm{T}} < 2.5$ GeV/c in 20-60% Zr+Zr collisions. The yield versus $|\cos\theta^*|$ distribution is then fitted with Eq.1 and the extracted ρ_{00} (called ρ_{00}^{obs}) is corrected for event plane resolution using: $\rho_{00} = \frac{1}{3} + \frac{4}{1+3R_{2,\mathrm{TPC}}}(\rho_{00}^{\mathrm{obs}} - \frac{1}{3})$ [12].

3. Results

The left panel of Fig. 2 presents the p_{T} dependence of ρ_{00} for K^{*0} and $\overline{K^{*0}}$ at mid-rapidity ($|y| < 1.0$) in 20-60% central Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The ρ_{00} between the particle and anti-particle species are consistent within errors. These results are compared with that from 200 GeV Au+Au collisions [13]. The ρ_{00} between isobar and Au+Au collisions are consistent within uncertainties across the measured p_{T} region in mid-central collisions. The right panel of Fig. 2 shows a comparison of $\rho_{00}(p_{\mathrm{T}})$ among neutral and charged K^* species in isobar collisions. The ρ_{00} for charged $K^{*\pm}$ are systematically larger than the neutral K^{*0} across the measured p_{T} region. The left panel of Fig. 3 presents the ρ_{00} as a function of average number of participants ($\langle N_{\mathrm{part}}\rangle$) for K^{*0} and $\overline{K^{*0}}$ for $1.0 < p_{\mathrm{T}} < 5.0$ GeV/c in 200 GeV Ru+Ru and Zr+Zr collisions. These results are compared with that from 200 GeV Au+Au collisions [13]. The K^{*0} ρ_{00} is larger than $\frac{1}{3}$ at smaller $\langle N_{\mathrm{part}}\rangle$. It is smaller than $\frac{1}{3}$ at large $\langle N_{\mathrm{part}}\rangle$, which can have contributions from the local spin alignment [7]. At a similar $\langle N_{\mathrm{part}}\rangle$, the ρ_{00} between small system isobar and large system Au+Au are comparable within uncertainties.

The right panel of Fig. 3 summarizes the p_{T}-integrated ρ_{00} for K^{*0}, $\overline{K^{*0}}$, K^{*+} and K^{*-} in 20-60% isobar collisions. These results are compared with $(K^{*0}+\overline{K^{*0}})$ ρ_{00} from Au+Au collisions [13]. This is the first observation of $K^{*\pm}$ ρ_{00} to be larger than $\frac{1}{3}$ in heavy-ion collisions. Moreover, the p_{T}-integrated ρ_{00} reveals a clear ordering between neutral and charged K^* species in isobar collisions, with the charged species is about 3.9σ larger than the neutral ones. Due to the interaction between the B-field and the magnetic moment of the constituent quarks, one naively expects the K^{*0} ρ_{00} to be larger than that of $K^{*\pm}$ [6]. But the observed ordering between K^{*0} and $K^{*\pm}$ is opposite to such naive expectation. Although the reason behind a difference between K^{*0} and $K^{*\pm}$ ρ_{00} is not understood yet, but these species might have different contribution from the vector meson strong force field. More inputs from theory are required to better understand the underlying physics mechanisms.

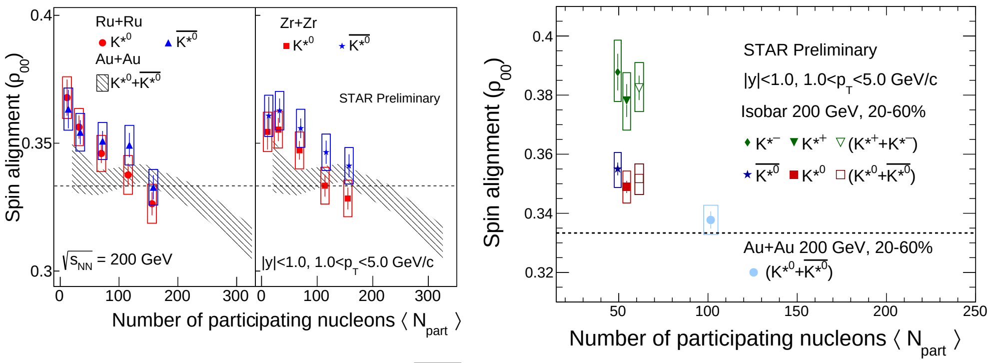

Fig. 3. Left: $\rho_{00}(\langle N_{\mathrm{part}}\rangle)$ for K^{*0} and $\overline{K^{*0}}$ in isobar collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Right: p_{T} integrated ρ_{00} for K^{*0}, $\overline{K^{*0}}$, K^{*+} and K^{*-} in 20-60% 200 GeV isobar collisions. Results are compared with K^{*0} in 200 GeV Au+Au collisions [13].

4. Summary and conclusion

In summary, the measurements of ϕ and K^{*0} ρ_{00} in Au+Au collisions from RHIC BES-I reveal a surprising pattern with a large positive deviation from $\frac{1}{3}$ for ϕ mesons and no obvious deviation for K^{*0}. At present, a fluctuating vector meson strong force field can accommodate the large positive deviation for ϕ mesons, while more theory inputs are needed for K^{*0}. The recent high statistics RHIC isobar collision (Ru+Ru and Zr+Zr) data offer a new opportunity to extend the measurement of ρ_{00} for K^{*0}, $\overline{K^{*0}}$, K^{*+}, and K^{*-} vector mesons with high precision. We observe the first non-zero spin alignment for $K^{*\pm}$ in heavy-ion collisions. The $K^{*\pm}$ ρ_{00} is larger than that of K^{*0} for 20-60% central isobar collisions. The current large deviation of $K^{*\pm}$ ρ_{00} and its ordering with K^{*0} is surprising, and opposite to the naive expectation from B-field. These results pose challenges to current understanding and inputs from theory are required to interpret the ρ_{00} results from isobar data.

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