Spin polarization and alignment in heavy-ion collisions

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Abstract. We report the measurements of global spin polarization of hyperons (P_Λ) from FAIR, RHIC and LHC energies. The P_Λ continues to follow an increasing trend at $\sqrt{s_{\rm NN}} < 7.7$ GeV indicating that enormous vorticity prevails even in hadronic dominant region. New measurements of local spin polarization ($P_{z,2}$) from isobar collisions follow the same pattern observed in previous RHIC and LHC energies. An observable motivated by predicted baryonic Spin Hall Effect, the net local polarization ($P^{\rm net}_{z,2}$), show a negative value in Au+Au collisions at $\sqrt{s_{\rm NN}} = 19.6$ and 27 GeV. The first P_z measurement with respect to third order harmonic in 200 GeV RHIC isobar collisions shows a non-zero sine modulation, indicating the presence of complex vortical structure in the medium. Surprising new patterns of spin alignment (ρ_{00}) for various vector mesons (K^{*0}, $K^{*\pm}$, ϕ and J/ψ) emerged at both RHIC and LHC energies. The large deviation in ρ_{00} of several species poses challenge to the theory.

1 Introduction

In non-zero impact parameter heavy-ion collisions, a very large orbital angular momentum (OAM $\sim 10^5 - 10^7\hbar$) is expected in the centroid of the participant matter [1]. The part of OAM transferred to the Quark Gluon Plasma (QGP) can polarize quarks (anti-quarks) due to "spin-orbit" coupling [2]. Further, the polarization of quarks are translated into the polarization of produced hadrons with non-zero spin along the OAM via hadronization processes. In the initial stage, we also expect a large magnetic field ($B \sim 10^{18}$ Gauss) [3], which can induce different spin polarization for quarks (anti-quarks) with different magnetic moments. Thus, through the polarization measurements we can search for the signatures of initial OAM interactions and B-field. These measurements help understand the response of QGP medium under these extreme initial conditions and also provide a unique opportunity to probe the spin dynamics of QGP.

2 Spin polarization of hyperons

Using the parity violating weak decay of hyperons, the global polarization ($P_{\rm H}$) can be measured from the angular distribution of the daughter baryon in parent hyperon's rest frame [4]. In 2007, the STAR experiment set an upper limit on P_Λ ($< 2\%$) in 200 GeV Au+Au collisions [5]. A breakthrough happened when STAR reported the first evidence of positive Λ and $\bar{\Lambda}$ spin polarization in heavy ion collisions from the RHIC Beam Energy Scan (BES) program. Under the assumption of local thermal equilibrium and based on hydrodynamic model,

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the polarization data averaged over all the BES energies resulted in a vorticity of about $(9 \pm 1) \times 10^{21}\ /s$. This suggests the most vortical fluid ever created in a laboratory experiment [6]. In the BES measurements, $P_{\bar{\Lambda}}$ is consistently larger than P_{Λ} across the beam energies. Due to opposite sign of their magnetic moment, such a splitting in polarization is expected from the B-field. Nevertheless, the precision is not sufficient for a clear conclusion. Subsequently, a precise non-zero P_{Λ} along with differential measurements of P_{Λ} as a function of collision centrality, transverse momentum and rapidity are reported at the top-RHIC energy [7]. The increase of P_{Λ} from central to peripheral collisions is consistent with expectation from the vorticity of the medium. Later, the ALICE experiment at LHC reported P_{Λ} consistent with zero within uncertainties [8]. Recently, the P_{Λ} measurements are extended in the lower beam energy by the fixed target set up at STAR [9] and HADES [10]. A significant P_{Λ} of about 5% is observed at these energies. The P_{Λ} follows a monotonically increasing trend from 5.02 TeV down to 2.4 GeV as shown in Fig. 1. Various transport and hydrodynamic models can successfully capture this energy dependence trend. The monotonic increase of P_{Λ} is understood as an interplay of shear flow and baryon stopping. There are scenarios, e.g, migration of polarization to forward rapidity and lifetime of the QGP etc can also contribute to P_{Λ}. Recent model calculations suggested that $P_{\Lambda} \sim 0$ at $\sqrt{s_{NN}} = 2m_N$. The monotonic rise of P_{Λ} at $\sqrt{s_{NN}} < 7.7$ GeV and a clear increase of P_{Λ} from central to peripheral collisions, in a hadronic dominant matter, is indeed surprising. It is an open question to the community, how the hadron gas can support such enormous vorticity? More experimental measurements and inputs from theory are needed for a better understanding.

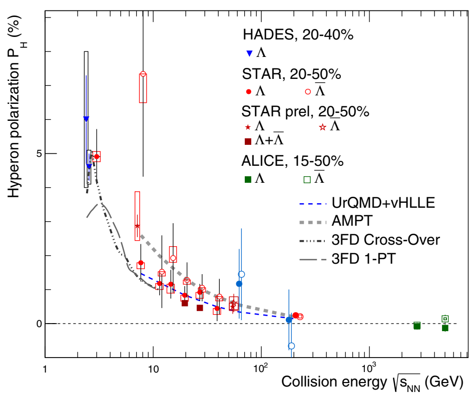

Figure 1. Beam energy dependence of global spin polarization of Λ and $\bar{\Lambda}$ hyperons [5–10]. Experimental measurements are compared to several models.

2.1 Global spin polarization in isobar collisions

The recent high statistics 200 GeV isobar collisions (${}^{96}_{44}$Ru+${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr) [11] at RHIC offer new opportunities for polarization measurements. Due to larger proton numbers, the Ru+Ru is expected to have larger initial B-field than the Zr collisions. Thus the measurement P_{Λ} and $P_{\bar{\Lambda}}$ polarization in isobar collisions can probe the initial B-field. Furthermore, several model calculations predicted a collision system size dependence in P_{Λ} ($P_{\Lambda}^{\mathrm{O+O}} > P_{\Lambda}^{\mathrm{Ru+Ru}} > P_{\Lambda}^{\mathrm{Au+Au}}$) [12]. The isobar data can be used to test such dependencies.

The STAR collaboration reported P_{Λ} and $P_{\bar{\Lambda}}$ from isobar collisions [17]. As shown in Fig. 2, the P_{Λ} ($P_{\bar{\Lambda}}$) in isobar collisions followed same centrality dependence observed in previous Au+Au collisions. No polarization difference is observed between Λ and $\bar{\Lambda}$ or between the isobar collisions species within the current precision. However, the results from RHIC BES-II are expected to provide a precision to probe the *B*-field. No obvious system size dependence in P_{Λ} ($P_{\bar{\Lambda}}$) is observed when isobar results are compared to large system Au+Au collisions at a same collision centrality. Results from a smaller system collision (O+O) data can provide more insights into the system size dependence of P_{Λ}. The STAR reported a first time non-zero polarization for Ξ and Ω hyperons in 200 GeV Au+Au collisions, which reinforces the global nature of spin polarization in heavy-ion collisions [13]. More precise measurements of Ξ and Ω polarization in future RHIC runs can help testing the species dependent splitting of polarization due to different spin and magnetic moments.

2.2 Local spin polarization of hyperons in isobar collisions

Recently it is understood that the collective flow in conjunction with the vorticity of the medium can induce a novel longitudinal polarization (P_z) along the beam direction [14]. The first non-zero sine modulation of P_z for Λ ($\bar{\Lambda}$) hyperons with respect to second order flow harmonics (Ψ_2) is observed in 200 GeV Au+Au collisions by STAR [15]. Although many hydrodynamic and transport models do excellent job in capturing the beam energy dependence of the global hyperon polarization, they failed to explain the pattern in P_z with proper sign, which is termed as a “sign-puzzle”. Later the same pattern in P_z is also seen in 5.02 TeV Pb+Pb collisions at LHC by ALICE [16]. Recently there are many theoretical developments in addressing this puzzle. It is understood that the addition of a “shear term” can explain the correct sign of P_z [18].

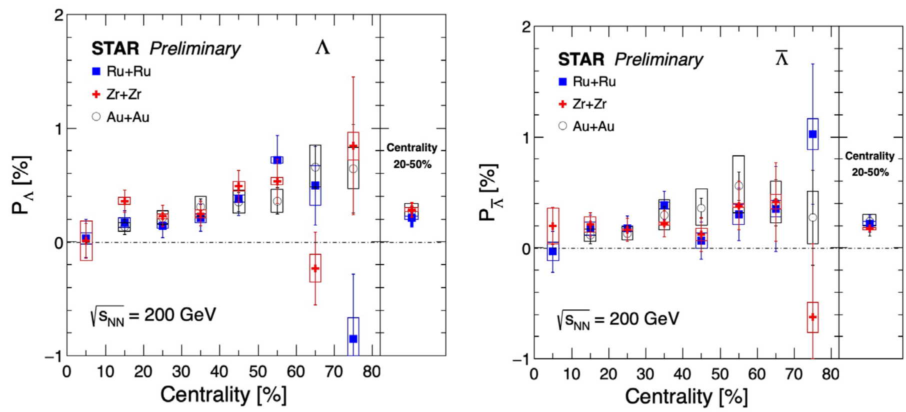

Figure 2. Centrality dependence of global spin polarization of Λ (left) and $\bar{\Lambda}$ (right) in isobar (Ru+Ru and Zr+Zr) collisions. Results are compared with the same from Au+Au collisions [17].

STAR reported P_z with respect to second order harmonics ($P_{z,2}$) from the isobar collision [17]. The left panel in Fig. 3 presents the comparison of isobar results with the same from Au+Au collisions at 200 GeV [15] and Pb+Pb collisions at 5.02 TeV [16]. There are some hints of system size dependence but no obvious energy dependence in $P_{z,2}$ is observed. These measurements in isobar collisions are also extended with respect to third order harmonics ($P_{z,3}$) for the first time and a significant non-zero sine modulation in polarization is observed [17]. Both $P_{z,2}$ and $P_{z,3}$ show a similar centrality dependence trend, however $P_{z,3}$ is systematically smaller than $P_{z,2}$ in peripheral collisions. These local polarization measurements can provide informations on the complex vortical structures, constrain on initial conditions and transport parameters in many models.

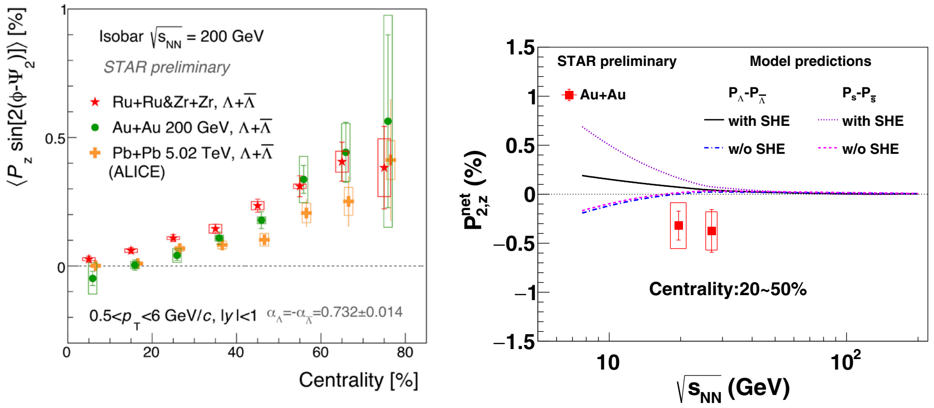

Figure 3. Left: Centrality dependence of local spin polarization ($P_{z,2}$) of Λ hyperons in Ru+Ru, Zr+Zr, Au+Au and Pb+Pb collisions. Right: Beam energy dependence of net local polarization ($P^{\rm net}_{z,2}$) of Λ and $\bar{\Lambda}$. Results are compared with model predictions.

Recently, it is predicted that the gradient of baryonic chemical potential ($\nabla\mu_B$) can cause a difference in P_z for Λ and $\bar{\Lambda}$ ($P^{\rm net}_{z,2}$). Having similarity with a spin phenomena in condensed matter physics, it is termed as baryonic Spin Hall Effect (SHE) [19]. It is predicted that the effect of SHE could be more prominent at lower beam energy (larger baryonic chemical potential) and it could produce a positive monotonically increasing $P^{\rm net}_{z,2}$ with decrease in beam energy. On the contrary, absence of SHE is predicted to generate a similar monotonic pattern but with a negative sign in $P^{\rm net}_{z,2}$. Abundant production of Λ ($\bar{\Lambda}$) and a large baryonic chemical potential provide an ideal environment to look for such novel effects at the RHIC BES range. The STAR experiment reported the net local polarization $P^{\rm net}_{z,2}$ in mid-central Au+Au collisions at 19.6 and 27 GeV as shown in right panel of Fig. 3 [20]. The sign of $P^{\rm net}_{z,2}$ is negative and consistent with absence of SHE. The P_z measurements from lower beam energies ($\sqrt{s_{NN}}$ < 19.6 GeV) will be useful in testifying the presence of SHE.

3 Spin alignment of vector mesons

The spin alignment of vector mesons can provide informations complementary to hyperon spin polarization. The global spin alignment is quantified by the diagonal element of the unity trace Hermitian spin density matrix. Among diagonal elements, only the 00$^{\rm th}$ component (called ρ_{00}) can be measured from the angular distribution (θ^*) of the decay daughter of the vector meson with respect to the polarization axis. The ρ_{00} is expected to be $\frac{1}{3}$ in absence of spin alignment. Any deviation of ρ_{00} from $\frac{1}{3}$ indicates that there is a net spin alignment. In 2008, the measurements from 200 GeV Au+Au collisions by STAR resulted a null ρ_{00} for K^{*0} and ϕ mesons with a large uncertainty [21]. Recent measurements by ALICE in mid-central Pb+Pb collisions at LHC energies indicate that the K^{*0} ρ_{00} significantly smaller than $\frac{1}{3}$ in the low $p_{\rm T}$ region, while the same for ϕ mesons is consistent with $\frac{1}{3}$ within uncertainty [22]. At low $p_{\rm T}$, there is a clear centrality dependence observed for both K^{*0} and ϕ. While the same measurements in p+p collisions at LHC yielded null deviations in ρ_{00}. The ρ_{00} in Pb+Pb collisions is observed to be an order of magnitude larger than the naive expectation from Λ polarization. The STAR collaboration reported of ϕ and K^{*0} ρ_{00} from the Beam Energy Scan [23]. The BES data reveals a surprising pattern. At mid-central collisions, while the ϕ ρ_{00} is significantly larger than $\frac{1}{3}$, the K^{*0} ρ_{00} is consistent with $\frac{1}{3}$ within uncertainties. The large signal for ϕ mesons can not be accommodated by conventional sources of polarization, e.g. vorticity of the medium, electromagnetic field etc. Polarization by a fluctuating vector meson strong force field can explain the large deviation for ϕ mesons in mid-central collisions [24]. The high statistics isobar data from STAR allows a precision measurement of ρ_{00} for K^{*0} and $K^{*\pm}$ and presented in left panel in Fig. 4. Due to a factor of five difference in magnetic moments of K^{*0} and $K^{*\pm}$ one naively expects K^{*0} ρ_{00} being larger than $K^{*\pm}$ due to its coupling with B-field. But surprisingly $K^{*\pm}$ ρ_{00} is observed to be larger than K^{*0} in isobar collisions. The behind such an ordering is not understood yet and require more inputs from theory.

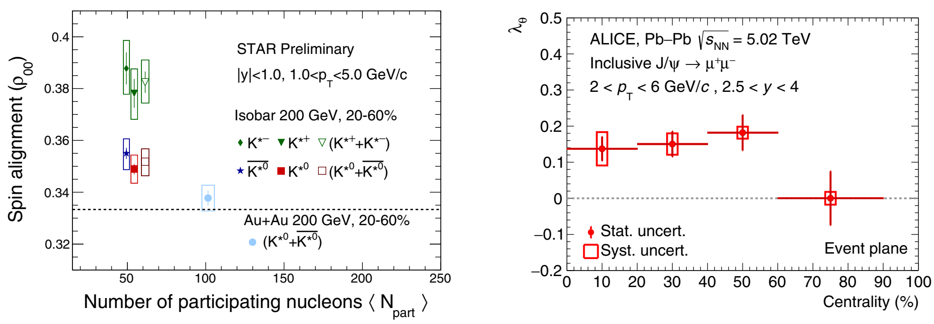

Figure 4. Left: Spin alignment (ρ_{00}) of K^{*0} ($\overline{K}^{*0}$) and $K^{*\pm}$ vector mesons in isobar (Ru+Ru and Zr+Zr) collisions. Results are compared with the same from Au+Au collisions. Right: Centrality dependence of spin polarization ($\lambda_\theta \propto (3\rho_{00} - 1)/(1 - \rho_{00})$) of J/$\psi$ in Pb+Pb collisions at 5.02 TeV [25].

Recently, the ALICE reported the first observation of J/Ψ spin polarization in di-muon channel at forward rapidity. The right panel in Fig. 4 presents the spin polarization parameter λ_θ ($\propto (3\rho_{00} - 1)/(1 - \rho_{00})$) as a function of centrality in Pb+Pb collisions at 5.02 TeV [25]. On the contrary to ρ_{00} of ϕ and K^{*0} near mid-rapidity, the J/ψ ρ_{00} (translated from λ_θ) at forward rapidity is larger than $\frac{1}{3}$. This is surprising and inputs from theory are needed for an explanation.

4 Summary

In summary, the spin polarization of hyperons across FAIR, RHIC and LHC energies established the global nature of hyperon spin polarization in heavy-ion collisions. More precise and differential measurements will provide more insights and constrain various models. Future P_Λ measurements at the low energy will reveal whether or not there is any vanishing polarization. A precise measurements of local spin polarization (P_z) of hyperons are carried out from RHIC to LHC. These results pose challenge to many theories and provide informations on the complex structure of vortices in heavy ion collisions. These measurements are generating discussions of emerging spin phenomena (such as Shear Induced Polarization, baryonic Spin Hall Effect) and help develop spin hydrodynamics, spin kinetic theories etc.

Measurements of spin alignments of vector mesons across RHIC and LHC is very surprising and puzzling. The observation of opposite sign of ρ_{00} deviations among different species requires more inputs from theory for better understanding of the data.

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