Global polarization of Ξ and Ω hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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(STAR Collaboration)
Global polarization of Ξ and Ω hyperons has been measured for the first time in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The measurements of the Ξ⁻ and Ξ⁺ hyperon polarization have been performed by two independent methods, via analysis of the angular distribution of the daughter particles in the parity violating weak decay \( \Xi^{-} \to \Lambda + \pi^{-} \), as well as by measuring the polarization of the daughter Λ-hyperon, polarized via polarization transfer from its parent. The polarization, obtained by combining the results from the two methods and averaged over Ξ⁻ and Ξ⁺, is measured to be \( \langle P_\Xi \rangle = 0.47 \pm 0.10 \) (stat.) \( \pm 0.23 \) (syst.)% for the collision centrality 20%-80%. The \( \langle P_\Xi \rangle \) is found to be slightly larger than the inclusive Λ polarization and in reasonable agreement with a multi-phase transport model (AMPT). The \( \langle P_\Xi \rangle \) is found to follow the centrality dependence of the vorticity predicted in the model, increasing toward more peripheral collisions. The global polarization of Ω, \( \langle P_\Omega \rangle = 1.11 \pm 0.87 \) (stat.) \( \pm 1.97 \) (syst.)% was obtained by measuring the polarization of daughter Λ in the decay \( \Omega^{-} \to \Lambda + K \), assuming the polarization transfer factor \( C_{\Omega\Lambda} = 1 \).

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Global polarization of spin \( s = 1/2 \) Ξ⁻ and Ξ⁺ hyperons, as well as spin \( s = 3/2 \) Ω hyperons in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

Hyperon weak decays present the most straightforward possibility for measuring the polarization of the produced particles [11]. In parity-violating weak decays the daughter-particle distribution in the rest frame of the hyperon directly depends on the hyperon polarization:

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{p}_B^*\right),
\]

where \( \alpha_H \) is the hyperon decay parameter, \( \mathbf{P}_H^* \) is the hyperon polarization, and \( \hat{p}_B^* \) is the unit vector in the direction of the daughter baryon momentum, both in the parent rest frame denoted by an asterisk.

The polarization of the daughter baryon in a weak decay of a spin 1/2 hyperon is described by the Lee-Yang formula [12–14] in terms of the three parameters \( \alpha \) (parity violating part), \( \beta \) (violation of the time reversal symmetry), and \( \gamma \) (satisfying \( \alpha^2 + \beta^2 + \gamma^2 = 1 \)). For a particular case of \( \Xi^{-} \to \Lambda + \pi^{-} \) decay it reads:

\[
\mathbf{P}_\Lambda^* = \left(\frac{\alpha_{\Xi} + \mathbf{P}_\Xi^* \cdot \hat{p}_\Lambda^*}{1 + \alpha_{\Xi}}\right) \mathbf{P}_\Lambda^* + \beta_{\Xi} \mathbf{P}_\Xi^* \times \hat{p}_\Lambda^* + \gamma_{\Xi} \hat{p}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{p}_\Lambda^*),
\]

where \( \hat{p}_\Lambda^* \) is the unit vector of the Λ momentum in the \( \Xi \) rest frame. Averaging over the angular distribution of the Λ in the rest frame of the \( \Xi \) given by Eq. 2 yields

\[
\mathbf{P}_\Lambda^* = C_{\Xi-\Lambda} \mathbf{P}_\Xi^* = \frac{1}{3} \left(1 + 2 \gamma_{\Xi}\right) \mathbf{P}_\Xi^*.
\]

Using the measured value for the \( \gamma_{\Xi} \) parameter [14, 15], the polarization transfer coefficient for \( \Xi^{-} \to \Lambda \) decay is:

\[
C_{\Xi-\Lambda} = \frac{1}{3} (1 + 2 \times 0.916) = +0.944.
\]
The polarization of the daughter baryon in a two particle decay of spin 3/2 hyperon, \( \Omega \rightarrow \Lambda + K \), is also described by three parameters \( \alpha_\Omega \), \( \beta_\Omega \), and \( \gamma_\Omega \) [16]. The decay parameter \( \alpha_\Omega \), determines the angular distribution of \( \Lambda \) in the \( \Omega \) rest frame and is measured to be small [15]: \( \alpha_\Omega = 0.0157 \pm 0.0021 \); this makes it practically impossible to measure the \( \Omega \) polarization via analysis of the daughter \( \Lambda \) angular distribution. The polarization transfer in this case is determined by the \( \gamma_\Omega \) parameter via [16–18]:

\[
P_\Lambda^* = C_{\Omega-\Lambda} \mathbf{P}_\Omega^* = \frac{1}{2} (1 + 4\gamma_\Omega) \mathbf{P}_\Omega^*.
\] (6)

The time-reversal violation parameter \( \beta_\Omega \) is expected to be small. This combined with the constraint that \( \alpha^2 + \beta^2 + \gamma^2 = 1 \) limits the unmeasured parameter to \( \gamma_\Omega \approx \pm 1 \), resulting in a polarization transfer \( C_{\Omega-\Lambda} \approx 1 \) or \( C_{\Omega-\Lambda} \approx -0.6 \).

Our analysis is based on the data of Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) collected in 2010, 2011, 2014, and 2016 by the STAR detector. Charged-particle tracks were measured in the time projection chamber (TPC) [19], which covers the full azimuth and a pseudorapidity range of \( |\eta| < 1 \). The collision vertices were reconstructed using the measured charged-particle tracks and were required to be within 30 cm relative to the TPC center in the beam direction for the 2010 and 2011 datasets to ensure a good acceptance of reconstructed tracks. The narrower vertex selection to be within 6 cm was applied in the 2014 and 2016 data due to online trigger requirement for the Heavy Flavor Tracker installed prior to 2014 data taking. The vertex in the radial direction relative to the beam center was also required to be within 2 cm to reject background from collisions with beam pipe. Additionally, the difference in the vertex positions along the beam direction from the vertex position detectors (VPD) [20] located at forward and backward pseudorapidities (4.24 < \( |\eta| < 5.1 \)) was required to be less than 3 cm to suppress pileup events in which more than one heavy-ion collision occurred. These selection criteria yielded about 180 (350) million minimum bias (MB) events for the 2010 (2011) dataset, 1 billion MB events for the 2014 dataset, and 1.5 billion MB events for the 2016 dataset. The MB trigger requires hits of both VPDs and the zero-degree calorimeters (ZDCs) [21], which detect spectator neutrons in \( |\eta| > 6.3 \). The collision centrality was determined from the measured multiplicity of charged particles within \( |\eta| < 0.5 \) and a Monte-Carlo Glauber simulation [22, 23].

The first-harmonic event plane angle \( \Psi_1 \) as an experimental estimate of the impact parameter direction was determined by measuring the neutron spectator deflection [24] in the ZDCs equipped with Shower Maximum Detectors (SMD) [25–27]. The event plane resolution [28] is largest (~41%), the resolution is better if it is closer to 100%) at 30%-40% collision centrality for the 2014 and 2016 datasets, and is decreased by 4% for the 2010 and 2011 datasets [6].

![FIG. 1. (Color online) Invariant mass distributions of \( \Xi^- (\Xi^+) \) and \( \Omega^- (\Omega^+) \) for 20%-80% centrality in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) taken in 2014. Vertical dashed lines indicate three standard deviations (3\( \sigma \)) from the peak positions, assuming a normal distribution.](image-url)
used in this analysis; $\alpha_\Lambda = 0.732 \pm 0.014$, $\alpha_\Xi = -0.401 \pm 0.010$, and $\alpha_\Omega = 0.0157 \pm 0.0021$. When comparing to earlier measurements, the previous results are rescaled by using the new values, i.e. $\alpha_{\text{old}}/\alpha_{\text{new}}$. In case of the $\Xi$ and $\Omega$ hyperon polarization measurements via measurements of the daughter $\Lambda$ polarization, the polarization transfer factors $C_{\Xi(\Omega)\Lambda}$ from Eqs. 4 and 6 are used to obtain the parent polarization.

The largest systematic uncertainty (37%) was attributed to the variation of the results obtained with datasets taken in different years. Weighted average over different datasets was used as the final result, and all other systematic uncertainties were assessed based on the weighted average: by comparing different polarization signal extractions [6] (11%), by varying the mass window for particles of interest from $3\sigma$ to $2\sigma$ (15%), by varying the decay lengths of both parent and daughter hyperons (4%), and by considering uncertainties on the decay parameter $\alpha_H$ (2%), where the numbers in parentheses represent the uncertainty for the $\Xi$ polarization via the daughter $\Lambda$ polarization measurement. A correction for non-uniform acceptance effects [34] was applied for the appropriate detector configuration for the given dataset. This correction, depending on particle species, was less than 2%. Due to a weak $p_T$ dependence on the global polarization [6], effects from the $p_T$ dependent efficiency of the hyperon reconstruction were found to be negligible.

Figure 2 shows the collision energy dependence of the $\Lambda$ hyperon global polarization measured earlier [5, 6, 10, 34] together with the new results on $\Xi$ and $\Omega$ global polarizations at $\sqrt{s_{NN}} = 200 \text{ GeV}$. (Note that the statistical and systematic uncertainties for the $\Lambda$ are smaller than the symbol size.) For both $\Xi$ and $\Omega$ polarizations, the particle and antiparticle results are averaged to reduce the statistical uncertainty. Also to maximize the significance of the polarization signal, the results were integrated over the centrality range 20%-80%, transverse momentum $p_T > 0.5$ GeV/$c$, and rapidity $|y| < 1$. Global polarization of $\Xi^-$ and $\Xi^+$ measurements via daughter $\Lambda$ polarization show positive values, with no significant difference between $\Xi^-$ and $\Xi^+$ ($P_\Xi$ ($\%$) = $0.77 \pm 0.16$ (stat.) $\pm 0.49$ (syst.) and $P_\Xi$ ($\%$) = $0.49 \pm 0.16$ (stat.) $\pm 0.20$ (syst.)). The average polarization obtained by this method is $\langle P_\Xi \rangle$ ($\%$) = $0.63 \pm 0.11$ (stat.) $\pm 0.26$ (syst.). The $\Xi^-$ polarization was also measured via analysis of the angular distribution of daughter $\Lambda$ in $\Xi$ rest frame. This result, $\langle P_\Xi \rangle$ ($\%$) = $-0.07 \pm 0.19$ (stat.)$\pm 0.50$ (syst.), has larger uncertainty in part due to a smaller value of $\alpha_\Xi$ compared to $\alpha_\Lambda$, which leads to smaller sensitivity of the measurement. The weighted average of the two measurements is $\langle P_\Xi \rangle$ ($\%$) = $0.47 \pm 0.10$ (stat.) $\pm 0.23$ (syst.), which is larger than the polarization of inclusive $\Lambda + \bar{\Lambda}$ measured at the same energy for 20%-80% centrality, $\langle P_\Lambda \rangle$ ($\%$) = $0.24 \pm 0.03 \pm 0.03$ [6], although the difference is still not significant considering the statistical and systematic uncertainties of both measurements. Note that the above quoted values for the inclusive $\Lambda$ have been rescaled by the new decay parameter as mentioned earlier.

Calculations [35] carried out with a multi-phase transport model (AMPT) can describe the particle species dependence in data at 200 GeV as well as the energy dependence for $\Lambda$. These calculations indicate that the lighter particles with higher spin could be more polarized by the vorticity [35]. The multi-strange particles might freeze out at earlier times, which may lead to larger polarization for $\Xi$ and $\Omega$ compared to $\Lambda$ [8]. The feed-down effect can also lead to a 15 ~ 20% reduction of the primary $\Lambda$ polarization [7, 36–38], while the $\Xi$ has less contribution from the feed-down. All these effects can contribute to small differences in the measured polarizations between inclusive $\Lambda$ and $\Xi$ hyperons.

Global polarization of $\Omega^-$ was also measured and is presented in Fig. 2 under the assumption of $\gamma_\Omega = +1$ and therefore $C_{\Omega\Lambda} = 1$, as discussed with respect to Eq. 6. The result has large uncertainty, $\langle P_\Omega \rangle$ ($\%$) = $1.11 \pm 0.87$ (stat.) $\pm 1.97$ (syst.) for 20%-80% centrality. Assumption of $\gamma_\Omega = -1$ (therefore $C_{\Omega\Lambda} = -0.6$) results in $\langle P_\Omega \rangle$ ($\%$) = $-0.67 \pm 0.52$ (stat.) $\pm 1.18$ (syst.). Assuming the validity of the global polarization picture, the
In summary, we have presented the first measurements of the global polarization for $\Xi$ hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the reaction $p_T < 1$, $p_T > 0.5$. The polarization looks larger than that of the inclusive $\Lambda$ in more peripheral collisions as expected from the centrality dependence of the fluid vorticity [39, 40]. The $\Xi$ polarization looks larger than that of the inclusive $\Lambda$ in peripheral collisions as already discussed in relation to Fig. 2, although the uncertainties preclude a more definite conclusion.

The centrality dependence of $\Xi^+ + \bar{\Xi}^-$ polarization via the measurement of daughter $\Lambda$ polarization is shown in Fig. 3, where the inclusive $\Lambda$ polarization [6] is plotted for comparison. The hyperon polarization increases in more peripheral collisions as expected from the centrality dependence of the fluid vorticity [39, 40]. The $\Xi$ polarization looks larger than that of the inclusive $\Lambda$ in peripheral collisions as already discussed in relation to Fig. 2, although the uncertainties preclude a more definite conclusion.

In summary, we have presented the first measurements of the global polarization for $\Xi^-$ ($\Xi^+$) hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Our results of $\Xi$ hyperon polarization, along with the previous measurements of $\Lambda$ polarization, confirm the global polarization picture based on the system fluid vorticity. The average polarization of $\Xi^+ + \Xi^-$ seems to be larger than that of the inclusive $\Lambda$, which is qualitatively captured by the AMPT model. The measured polarization seems to exhibit a centrality dependence as expected from the impact parameter dependence of the vorticity. Global polarization of $\Omega^-$ hyperons was, also for the first time, extracted via measurements of the polarization of the daughter $\Lambda$ and presented with the assumption that $\gamma_\Omega = +1$. Future measurements with higher precision will shed light on the uncertainty of the decay parameter $\gamma_\Omega$, as well as experimental results on the global polarization of spin-3/2 particles, providing critical information about spin dynamics in heavy-ion collisions.

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result favors $\gamma_\Omega \approx +1$ instead of $\gamma_\Omega \approx -1$, but the uncertainties are large and more precise measurements are needed to make a definitive statement.

The centrality dependence of $\Xi^+ + \bar{\Xi}^-$ polarization via the measurement of daughter $\Lambda$ polarization is shown in Fig. 3, where the inclusive $\Lambda$ polarization [6] is plotted for comparison. The hyperon polarization increases in more peripheral collisions as expected from the centrality dependence of the fluid vorticity [39, 40]. The $\Xi$ polarization looks larger than that of the inclusive $\Lambda$ in peripheral collisions as already discussed in relation to Fig. 2, although the uncertainties preclude a more definite conclusion.

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