Core meets corona: a two-component source to explain $\Lambda$ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions

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We compute the $\Lambda$ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions modelling the source as consisting of a high-density core and a less dense corona. We show that when more $\Lambda$s than $\bar{\Lambda}$s are produced in the corona, and this is combined with a smaller number of $\Lambda$s coming from the core, as compared to those coming from the corona, an amplification effect for the $\bar{\Lambda}$ with respect to that of $\Lambda$ polarization can occur. This amplification becomes more important for lower collision energies and quantitatively accounts for the $\Lambda$ and $\bar{\Lambda}$ polarizations measured by the STAR beam energy scan.

The polarization asymmetry of a given baryon species produced in high-energy reactions is defined as the ratio of the difference between the number of baryons with their spin pointing along and opposite to a given direction, to their sum. This direction is usually chosen as either the baryon momentum or the normal to the production plane. In the former case one speaks of the longitudinal, whereas the latter is referred to as the transverse polarization.

Among the baryons whose polarization properties can be studied, $\Lambda$ plays an important role. In addition of being the lightest hyperon with strange quark content, it has a self-analyzing polarization power due to its parity-violating weak decay, since the decay protons follow preferentially the spin direction of the original $\Lambda$.

$\Lambda$ and $\bar{\Lambda}$ polarization have been extensively studied, both from the experimental and the theoretical points of view. On the experimental side, these studies date back to the pioneering Fermilab measurements [1]. $\Lambda$ and $\bar{\Lambda}$ appear polarized over a wide range of collision energies and systems from $p + p$ [20], $p + \Lambda$ [11, 12], deep inelastic scattering [13-15] and even in $e^+ + e^-$ [16, 17] collisions. The polarization mechanism is not well understood. A wealth of theoretical explanations have been put forward with varying degrees of success depending on the kind of colliding systems and energy ranges [18-38]. In recent years, the interest on $\Lambda$ and $\bar{\Lambda}$ polarization has been further increased due to the possibility to link this observable to the properties of the medium produced in relativistic heavy-ion collisions [39-44]. For non-central reactions, the inhomogeneity of the matter density profile in the transverse plane produces the colliding region to develop an orbital angular momentum [50], quantified in terms of the thermal vorticity [51], defined as $\omega_{\mu\nu} = (\partial_{\nu}\beta_\mu - \partial_{\mu}\beta_\nu)/2$, where $\beta_\mu = u_\mu(x)/T(x)$,
$u_\mu(x)$ is the local fluid four-velocity and $T(x)$ is the local temperature. In the non-relativistic limit and assuming global equilibrium, the thermal vorticity can be written as the ratio of a constant angular velocity and a constant temperature. By choosing the direction of reference as the angular momentum, which coincides with the normal to the reaction plane, it is possible to measure the so called global polarization.

The ALICE and STAR collaborations have reported results for global Λ and $\bar{\Lambda}$ polarization. In particular, the STAR Beam Energy Scan (BES) has shown that as the collision energy decreases, the $\bar{\Lambda}$ polarization increases more steeply than the Λ polarization. To explain this behavior, different space-time distributions and freeze-out conditions for Λ and $\bar{\Lambda}$ have been invoked. Also, since the $s$ ($\bar{s}$)-quark, thought to be the main responsible for the Λ ($\bar{\Lambda}$) polarization, has negative (positive) electric charge, it has been suggested that differences between the Λ and $\bar{\Lambda}$ global polarization may be due to the strong, albeit short-lived, magnetic field that is produced in non-central collisions. The possibility that Λ and $\bar{\Lambda}$ align their spins with the direction of the angular momentum, during the life-time of the system created in the reaction, has been recently put on firmer grounds in Refs. [57, 58].

In non-central collisions Λ and $\bar{\Lambda}$ hyperons can be produced from different density zones within the interaction region. This scenario was put forward in Ref. [59]. The Λ and $\bar{\Lambda}$ polarization properties can therefore differ depending on whether these particles come from the denser (core) or less dense (corona) regions. In this work, we explore such two-component scenario. We show that since the ratio of the number of $\bar{\Lambda}$s to Λs coming from the corona is less than 1, the global $\bar{\Lambda}$ polarization can be larger than the global Λ polarization, in spite of the intrinsic, thermal vorticity-produced, Λ polarization in the core being larger than the $\bar{\Lambda}$ polarization. This amplifying effect is favored when the number of Λs coming from the core is smaller than the number of $\bar{\Lambda}$s coming from the corona. The latter can happen for collisions with intermediate to large impact parameters, which at the same time, correspond to the kind of collisions that favor the development of a larger thermal vorticity.

Consider the scenario where in a peripheral heavy-ion reaction, the number of $\bar{\Lambda}$s, come from two regions: a high-density core and a less dense corona, such that $N_\Lambda = N_{\Lambda\text{QGP}} + N_{\Lambda\text{REC}}$, where $N_{\Lambda\text{QGP}}$ is the number of produced Λs coming from the core and $N_{\Lambda\text{REC}}$ is the number of produced $\bar{\Lambda}$s coming from the corona. These zones are illustrated in Fig. 1. The subscripts “QGP” and “REC” refer to the kind of processes responsible for the production of these hyperons, that is, QGP in the core and recombination induced process in the corona, respectively. The latter are similar to the polarization producing processes in $p + p$ reactions. The expression for the Λ and $\bar{\Lambda}$ polarization is given by

$$P_\Lambda = \frac{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) - (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)}{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) + (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)},$$

$$P_{\bar{\Lambda}} = \frac{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) - (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)}{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) + (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)},$$

After a bit of straightforward algebra, we can express the Λ and $\bar{\Lambda}$ polarization, Eq. (1) as

$$P_\Lambda = \frac{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) - (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)}{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) + (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)},$$

$$P_{\bar{\Lambda}} = \frac{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) - (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)}{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{REC}}^\uparrow) + (N_{\Lambda\text{QGP}}^\downarrow + N_{\Lambda\text{REC}}^\downarrow)},$$

where

$$P_{\text{REC}}^\Lambda = \frac{N_{\Lambda\text{REC}}^\uparrow - N_{\Lambda\text{REC}}^\downarrow}{N_{\Lambda\text{REC}}^\uparrow + N_{\Lambda\text{REC}}^\downarrow},$$

$$P_{\bar{\Lambda}}^\text{REC} = \frac{N_{\bar{\Lambda}\text{REC}}^\uparrow - N_{\bar{\Lambda}\text{REC}}^\downarrow}{N_{\bar{\Lambda}\text{REC}}^\uparrow + N_{\bar{\Lambda}\text{REC}}^\downarrow}. \tag{3}$$

Notice that $P_{\text{REC}}^\Lambda$ and $P_{\bar{\Lambda}}^\text{REC}$ refer to the polarization along the global angular momentum produced in the corona. Although nucleons colliding in this region partake of the vortical motion, reactions in cold nuclear matter are less efficient to align the spin in the direction of the angular momentum than in the QGP. Thus, as a working approximation we set $P_{\text{REC}}^\Lambda = P_{\text{REC}}^\Lambda = 0$ to write

$$P_\Lambda = \frac{(N_{\Lambda\text{QGP}}^\uparrow - N_{\Lambda\text{QGP}}^\downarrow)}{(N_{\Lambda\text{QGP}}^\uparrow + N_{\Lambda\text{QGP}}^\downarrow)} \left(1 + \frac{N_{\Lambda\text{QGP}}^\downarrow}{N_{\Lambda\text{QGP}}^\uparrow}\right),$$

$$P_{\bar{\Lambda}} = \frac{(N_{\bar{\Lambda}\text{QGP}}^\uparrow - N_{\bar{\Lambda}\text{QGP}}^\downarrow)}{(N_{\bar{\Lambda}\text{QGP}}^\uparrow + N_{\bar{\Lambda}\text{QGP}}^\downarrow)} \left(1 + \frac{N_{\bar{\Lambda}\text{QGP}}^\downarrow}{N_{\bar{\Lambda}\text{QGP}}^\uparrow}\right). \tag{4}$$

However, since reactions in the core are more efficient to align particle spin to global angular momentum, one expects that the intrinsic global Λ and $\bar{\Lambda}$ polarizations namely,

$$z = \frac{N_{\Lambda\text{QGP}}^\uparrow - N_{\Lambda\text{QGP}}^\downarrow}{N_{\Lambda\text{QGP}}},$$

$$\bar{z} = \frac{N_{\bar{\Lambda}\text{QGP}}^\uparrow - N_{\bar{\Lambda}\text{QGP}}^\downarrow}{N_{\bar{\Lambda}\text{QGP}}}, \tag{5}$$

are finite, albeit small. In Eq. (5), we have used that in the QGP one expects $N_{\bar{\Lambda}\text{QGP}} \simeq N_{\Lambda\text{QGP}}$. Therefore, Eq. (4) can be written as

$$P_\Lambda = \frac{z N_{\Lambda\text{QGP}}}{(1 + z N_{\Lambda\text{QGP}})},$$

$$P_{\bar{\Lambda}} = \frac{\bar{z} N_{\bar{\Lambda}\text{QGP}}}{(1 + \bar{z} N_{\bar{\Lambda}\text{QGP}})}. \tag{6}$$

Cold nuclear matter collisions in the corona are expected to produce more $\Lambda$s than $\bar{\Lambda}$s, since these processes are related to $p + p$ reactions, where three anti-quarks coming from the sea are more difficult to produce than
only one $s$. Then, we can write $N_{\Lambda_{\text{REC}}} \equiv w N_{\Lambda_{\text{REC}}}$, and thus

$$P_{\Lambda} = \frac{\Lambda \frac{N_{\Lambda_{\text{QGP}}}}{N_{\Lambda_{\text{REC}}}}}{1 + \frac{N_{\Lambda_{\text{QGP}}}}{N_{\Lambda_{\text{REC}}}}}, \quad P_{\bar{\Lambda}} = \frac{\bar{\Lambda} \frac{N_{\Lambda_{\text{QGP}}}}{N_{\Lambda_{\text{REC}}}}}{1 + \frac{1}{w} \frac{N_{\Lambda_{\text{QGP}}}}{N_{\Lambda_{\text{REC}}}}}.$$  \tag{7}$$

where the energy dependent coefficient $w$ is expected to be also smaller than 1. This expectation is in fact met, as shown in Fig. 2, where $w$ is plotted as a function of $\sqrt{s_{NN}}$, using data compiled from different experimental results for p + p collisions [60–71]. The function describing the experimental points corresponds to a fit given by $w(\sqrt{s_{NN}}) = A \ln \sqrt{s_{NN}} + B$, with $A = 0.237 \pm 0.007$ and $B = -0.40 \pm 0.03$. Notice that the $\Lambda$ and $\bar{\Lambda}$ polarization depend, in addition of $z$, $\bar{z}$ and $w$, also of the ratio $N_{\Lambda_{\text{QGP}}}/N_{\Lambda_{\text{REC}}}$. Although $\bar{z}$ is expected to be smaller than $z$, the amplifying effect from the factor $1/w > 1$ produces that $P_{\bar{\Lambda}} > P_{\Lambda}$ for a range of $w$ values. This is illustrated in Fig. 3 where we plot $P_{\bar{\Lambda}}/P_{\Lambda}$ as a function of $w$. In the extreme situation where $\bar{z} = z$ and $N_{\Lambda_{\text{QGP}}}/N_{\Lambda_{\text{REC}}} = 1$, $P_{\bar{\Lambda}}/P_{\Lambda}$ is always larger than 1 for $0 < w < 1$. For a more realistic scenario with $\bar{z} < z$ and with $N_{\Lambda_{\text{QGP}}}/N_{\Lambda_{\text{REC}}}$ smaller than 1, there is still a range of $w$ values for which $P_{\bar{\Lambda}}/P_{\Lambda}$ is larger than 1. This region shrinks when $N_{\Lambda_{\text{QGP}}}/N_{\Lambda_{\text{REC}}} > 1$.

In order to check whether non-central collisions at different energies and impact parameters favor an scenario where $N_{\Lambda_{\text{QGP}}}/N_{\Lambda_{\text{REC}}} \lesssim 1$ and thus $P_{\bar{\Lambda}} > P_{\Lambda}$, we proceed to study $\Lambda$ production in the QGP and REC regions. Recall that the average number of strange quarks produced in the QGP scales with the number of participants $N_{\text{p}_{\text{QGP}}}$ in the collision roughly as $\langle s \rangle = N_{\Lambda_{\text{QGP}}} = c N_{\text{p}_{\text{QGP}}}$, where in Ref. [72], $c$ is found to be in the range $0.001 \leq c \leq 0.005$, assuming, for the sake of simplicity, that as a result of hadronization, only $\Lambda$s and $\bar{\Lambda}$s are obtained from these produced $s$-quarks. Hereafter we work explicitly with a proportionality factor $c = 0.0025$ corresponding to an intermediate value of the above range to account for the fact that $\Lambda$s are not the only strange hadrons produced in the reaction. The number of $\Lambda$s originating in
Λ polarization compared to data

Λ polarization can occur, Λ polarization in a semi-central heavy-ion collision is mod-
ified as functions of the collision energy. The formation within the QGP is taken to lie between
54 x 59 section for Λ production in p + p reactions. We obtain

where the density of participants

the QGP can be computed from the relation

where the density of participants

with \( \vec{b} \) the vector directed along the impact parameter on the nuclei overlap area and \( \sigma_{NN} \) the collision energy-dependent nucleon-nucleon cross-section [73, 74].

\( n_c = 3.3 \text{ fm}^{-2} \) is the critical density of participants above which the QGP can be produced [75]. The thickness function \( T_A \) is given by

where we take as the nuclear density \( \rho_A \) a Woods-Saxon profile with a skin depth \( a = 0.41 \text{ fm} \) [76] and a radius for a nucleus with mass number \( A \) of \( R_A = 1.1A^{1/3} \text{ fm} \). On the other hand, the number of Λs produced in the corona can be written as

\( N_{A,REC} = \sigma_{NN}^{\Lambda} (\sqrt{s_{NN}}) \int d^2s \ T_B (\vec{b} - \vec{s}) \)

\times \ T_A (\vec{s}) \ [ n_c - n_p (\vec{s}, \vec{b}) ] ,

where \( \sigma_{NN}^{\Lambda} \) is the collision-energy dependent cross-section for Λ production in p + p reactions. We obtain this function fitting experimental data from Refs. [67–69, 77, 78]. The fit is given by

\( \sigma_{NN}^{\Lambda} (\sqrt{s_{NN}}) = C \ln \sqrt{s_{NN}} + D, \) with \( C = 1.67 \pm 0.05 \text{ mb} \) and \( D = -1.60 \pm 0.08 \text{ mb} \).

Figure 4 shows an example of \( N_{A,REC} \). The bands correspond to the polarization
obtained for 1.5 fm < \( t < 4.5 \) fm.

We now put together all these ingredients to study Λ and \( \bar{\Lambda} \) polarization as functions of the collision energy. We resort to the results of Ref. [58] where the relaxation times \( \tau \) and \( \bar{\tau} \) for the alignment between the spin of a s or a \( \bar{s} \) with the thermal vorticity, respectively, are computed as functions of the collision energy. When the s and \( \bar{s} \) polarization translate into the Λ and \( \bar{\Lambda} \) polarization, respectively, during the hadronization process, the intrinsic polarization \( \bar{z} \) and \( \bar{\xi} \) can be computed from these relaxation times as \( \bar{z} = 1 - \exp (-t/\tau) \) and \( \bar{\xi} = 1 - \exp (-t/\bar{\tau}) \), as functions of the Λ and \( \bar{\Lambda} \) formation time \( t \) within the QGP.

Figure 5 shows the Λ and \( \bar{\Lambda} \) polarization thus computed compared to results from the BES [53]. The band shows the result of the calculation when the time for Λ and \( \bar{\Lambda} \) formation within the QGP is taken to lie between 1.5 fm \( < t < 4.5 \) fm for \( b = 8 \text{ fm} \), corresponding to the average impact parameter in the 20-50% centrality range where data are taken. Notice that the polarization data is well described by the calculation over the entire collision energy range.

In conclusion, we have shown that when the source of \( \Lambda \) and \( \bar{\Lambda} \) in a semi-central heavy-ion collision is mod-
elled as composed of a high-density core and a less dense corona, their global polarization properties as a function of the collision energy can be understood. Indeed, when a larger abundance of \( \Lambda \) as compared to \( \bar{\Lambda} \) in the corona is combined with a smaller number of \( \Lambda \) coming from the core as compared to those coming from the corona—which happens for semi-central to peripheral collisions—an amplification effect for the \( \bar{\Lambda} \) polarization can occur, in spite of the intrinsic Λ polarization \( \bar{z} \) being larger than the intrinsic \( \bar{\Lambda} \) polarization \( \bar{\xi} \). This amplification is more prominent for lower collision energies. A more detailed analysis to relax the approximation of equal number of \( \Lambda \) and \( \bar{\Lambda} \) produced in the QGP, and a vanishing polarization in the corona, as well as including a weighted average over contributing impact parameters and formation times, is currently being performed and will be reported elsewhere.

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[70] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 75, 064901 (2007).
[71] E. Abbas et al. (ALICE Collaboration), Eur. Phys. J. C 73, 2496 (2013).
[72] J. Letessier, J. Rafelski, and A. Tounsi Phys. Lett. B 389, 586 (1996).
[73] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010).
[74] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88, 044909 (2013).
[75] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. 77, 1703 (1996).
[76] Q. Y. Shou et al., Phys. Lett. B 749, 215 (2015).
[77] K. Jaeger, D. Colley, L. Hyman, and J. Rest, Phys. Rev. D 11, 2405 (1975).
[78] V. Blobel et al. (Bonn-Hamburg-Munich Collaboration), Nucl. Phys. B 69, 454 (1974).
[79] D. Drijard et al. (CERN-Dortmund-Heidelberg-Warsaw Collaboration), Z. Phys. C 12, 217 (1982).