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On ambiguity of definition of shear and spin-hall contributions to Λ polarization in heavy-ion collisions

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Non-central heavy-ion collisions at high energies are characterized by a huge global angular momentum of the order of 10^3–$10^5\hbar$, depending on the collision energy and centrality. Although a large part of the angular momentum is carried away by the spectator nucleons, its sizable fraction is accumulated in the created dense and highly excited matter, that implies a strong rotational motion of this matter. This matter is conventionally associated with a (participant) fluid because it is successfully described by the fluid dynamics. Such rotation leads to a strong vortical structure inside the produced fluid. Local fluid vorticity induces a preferential orientation of spins of emitted particles through spin-orbit coupling. The STAR Collaboration at the Relativistic Heavy-Ion Collider discovered the global polarization of emitted Λ hyperons, which indicated fluid vorticity of $\omega \approx (9 \pm 1) \times 10^{21}$ s^{-1} [1]. This result exceeds the vorticity of all ever known fluids in nature. This discovery have opened an entirely new direction of research in heavy-ion physics.

The major part of applications to heavy-ion collisions was performed within thermodynamic approach in terms of hadronic degrees of freedom [2–4]. In the present paper, we discuss this thermodynamic approach. The key quantity of the thermodynamic approach is thermal vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \qquad (1)$$

where $\beta_\mu = u_\mu/T$, u_μ is collective local four-velocity of the matter, and T is local temperature. The corresponding mean spin vector of Λ particles with four-momentum p, produced around point x on freeze-out hypersurface is

$$S^\mu_\varpi(x,p) = -\frac{1}{8m}[1 - f(x,p)]\, \epsilon^{\mu\nu\alpha\beta} p_\nu, \varpi_{\alpha\beta}(x), \qquad (2)$$

where $f(x,p) = 1/\{\exp[(u_\nu p^\nu - \mu)/T] + 1\}$ is the Fermi–Dirac distribution function, m is mass of the Λ hyperon and μ is the baryon chemical potential.

It was recently realized [5–7] that there are other additional contributions to the mean spin vector, if the thermal equilibrium is *local*. These are the so-called thermal-shear (S^μ_ξ) and spin-Hall (S^μ_ζ) contributions:

$$S^\mu_\xi(x,p) = \frac{1}{4m}[1 - f(x,p)]\epsilon^{\mu\nu\alpha\beta} \frac{p_\nu n_\beta p^\rho}{(n \cdot p)} \xi_{\rho\alpha}, \qquad (3)$$

$$S^\mu_\zeta(x,p) = \frac{1}{4m}[1 - f(x,p)]\epsilon^{\mu\nu\alpha\beta} \frac{p_\alpha n_\beta}{(n \cdot p)} \partial_\nu \zeta, \qquad (4)$$

where $\zeta = \mu/T$,

$$\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu\right), \qquad (5)$$

is the thermal-shear tensor, and n is a four-vector that is the main subject of the discussion below. In [5], the n four-vector is defined as the time direction in the center-of-mass frame of colliding nuclei: $n_\beta = \hat{t}_\beta = (1,0,0,0)$. Only the shear term was considered in [5]. In [6, 7], the n four-vector is identified with the four-velocity: $n_\beta = u_\beta$. In the mid-rapidity region these choices are very close because $u_\beta \approx \hat{t}_\beta$. However, at forward-backward rapidities, which are relevant to fixed-target polarization measurements [8–10], they may significantly differ.

In this paper, we consider consequences of these different choices at the example of the global polarization of Λ-hyperons. The global polarization is chosen because it allows a significant advance in the analytical treatment, if momentum acceptance is disregarded, and because it is relevant to fixed-target polarization measurements at moderately relativistic energies [8–10].

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The polarization of the Λ hyperon is measured in its rest frame, therefore the Λ polarization is

$$P^\mu(x,p) = S^{*\mu}(x,p)/S_\Lambda, \tag{6}$$

where $S_\Lambda = 1/2$ is the spin of the Λ hyperon, $S^\mu = S^\mu_\varpi + S^\mu_\xi + S^\mu_\zeta$, and $S^{*\mu}$ is the mean Λ-spin vector in the Λ rest frame

$$\mathbf{S}^*(x,p) = \mathbf{S} - \frac{\hat{t}\cdot S}{\hat{t}\cdot p + m}\mathbf{p}_\Lambda \stackrel{\text{def}}{=} \mathbf{S} - \Delta\mathbf{S}, \tag{7}$$

where $\Delta\mathbf{S}$ is the boost correction. The zeroth component of $S^{*\mu}$ identically vanishes.

It is shown that alternative definitions of the thermal-shear contribution to the polarization in heavy-ion collisions, [5] on the one hand and [6, 7] on the other, result in very different corrections to the global Λ polarization averaged over wide range of momenta. The spin-Hall contribution to the polarization, defined accordingly to [6, 7], results in identicaly zero correction to the global Λ polarization, if averaged over all momenta of Λ's. Only application of restrictive momentum acceptance and the boost (to Λ rest frame) correction result in nonzero global spin-Hall polarization. If the spin-Hall contribution were defined similarly to [5], the global spin-Hall polarization would be non-zero even without any acceptance and the boost correction.

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