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Global and local spin polarization in heavy ion collisions: a brief overview

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Abstract

We give a brief overview about recent developments in theories and experiments on the global and local spin polarization in heavy ion collisions.

Keywords: global polarization, spin-orbital coupling, vorticity, angular momentum, heavy-ion collision

1. Introduction

There is inherent correlation between rotation and polarization in materials as shown in the Barnett effect [1] and the Einstein-de Haas effect [2]. We expect that the same phenomena also exist in heavy ion collisions. Huge global angular momenta are generated in non-central heavy ion collisions at high energies [3–8]. How such huge global angular momenta are transferred to the hot and dense matter created in heavy ion collisions and how to measure them are two core questions in this field. There are some models to address the first question: the microscopic spin-orbital coupling model [3, 4, 8, 9], the statistical-hydro model [10–16] and the kinetic model with Wigner functions [17–20]. For the second question, it was proposed that the global angular momentum can lead to the local polarization of hadrons, which can be measured by the polarization of Λ hyperons and vector mesons [3, 4].

The global polarization is the net polarization of local ones in an event which is aligned in the direction of the event plane. Recently the STAR collaboration has measured the global polarization of Λ hyperons in the beam energy scan program [21, 22]. At all energies below 62.4 GeV, positive polarizations have been found for Λ and $\bar{\Lambda}$. On average over all data, the gobal polarization for Λ and $\bar{\Lambda}$ are $\Pi_\Lambda = (1.08 \pm 0.15)\%$ and $\Pi_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$. As will be discussed at the end of Sec. 3, this implies that the matter created in ultra-relativistic heavy ion collisions is the most vortical fluid ever produced in the laboratory.

In this note, we give a brief overview about recent developments in theories and experiments on the global and local spin polarization in heavy ion collisions.

2. Theoretical models in particle polarization

In this section we first give a brief introduction to the global orbital angular momentum and local vorticity, which are basic concepts in this topic. Then we introduce three theoretical models which have been

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widely used in this field. All these models address the same global polarization problem in different angles and are consistent to each other. The spin-orbital coupling model is a microscopic model and the Wigner function and statistical-hydro model are macroscopic models and of statistical type. The thermal average of the local orbital angular momentum in the microscopic model gives the vorticity of the fluid in macroscopic models. The same freeze-out formula for the polarization of fermions are abtained from the Wigner function and statistical-hydro model, which has been used to calulate observables in experiments. The Wigner function model is a quantum kinetic approach where quantum effects like the chiral magnetic and vortical effect and chiral anomaly can be naturally incorporated. The statistical-hydro model is a generalization of the statistical model for a thermal system without rotation to a hydrodynamical one with rotation. With the statistical-hydro model one can easily derive the spin-vorticity coupling term for a system of massive fermions and then the spin polarization density which is proportional to vorticity.

2.1. Global orbital angluar momentum and local vorticity

Let us consider two colliding nuclei with the beam momentum per nucleon $\mathbf{p}_{\rm beam} \equiv p_{\rm beam}\mathbf{e}_z$ (projectile) and $-\mathbf{p}_{\rm beam}$ (target). The impact parameter $\mathbf{b} \equiv b\mathbf{e}_x$ whose modulus is the transverse distance between the centers of the projectile and target nucleus points from the target to the projectile. The normal direction of the reaction plane or the direction of the global angular momentum is along $\hat{\mathbf{b}}\times\hat{\mathbf{p}}_{\rm beam} = -\mathbf{e}_y$. We should keep in mind that due to event-by-event fluctuations of the nucleon positions, the global orbital angular momentum does not in general point to $-\mathbf{e}_y$. The discussion in this subsection is the ideal case only for theoretical simplicity. The magnitude of the total orbital angular momentum L_y and the resulting longitudinal fluid shear can be estimated within the wounded nucleon model of particle production [3, 8]. The transverse distributions (integrated over y) of participant nucleons in each nucleus can be written as

$$\frac{dN_{\rm part}^{\rm P,T}}{dx} = \int dydz\rho_A^{\rm P,T}(x,y,z,b), \tag{1}$$

where $\rho_A^{\rm P,T}$ denotes the number of participant nucleons in the projectile and target, respectively. One can use models to estimate $\rho_A^{\rm P,T}$ such as the hard-sphere or Woods-Saxon model. Then we obtain

$$L_y = -p_{\rm in}\int dxx\left(\frac{dN_{\rm part}^{\rm P}}{dx} - \frac{dN_{\rm part}^{\rm P}}{dx}\right). \tag{2}$$

The average collective longitudinal momentum per parton can be estimated as

$$p_z(x,b;\sqrt{s}) = p_0\frac{dN_{\rm part}^{\rm P}/dx - dN_{\rm part}^{\rm T}/dx}{dN_{\rm part}^{\rm P}/dx + dN_{\rm part}^{\rm T}/dx}, \tag{3}$$

where $p_0 = \sqrt{s}/[2c(s)]$ denotes the maximum average longtitudinal momentum per parton. The average relative orbital angular momentum for two colliding partons separated by Δx in the transverse direction is then $l_y \equiv -(\Delta x)^2 dp_z/dx$. Note that l_y is expected to be proportional to the local vorticity.

As we all know the strongly coupled quark gluon plasma (sQGP) can be well described by relativistic hydrodynamic models. So the sQGP can be treated as a fluid which is characterized by local quantities such as the momentum, energy and particle-number densities $\mathbf{p}(\mathbf{r})$, $\epsilon(\mathbf{r})$ and $n(\mathbf{r})$, respectively. The total angluar momentum of a fluid can be written as $\mathbf{L} = \int d^3r\,\mathbf{r}\times\mathbf{p}(\mathbf{r})$. The fluid velocity is defined by $\mathbf{v}(\mathbf{r}) = \mathbf{p}(\mathbf{r})/\epsilon(\mathbf{r})$. In non-relativistic theory, the fluid vorticity is defined by $\boldsymbol{\omega} = \frac{1}{2}\nabla\times\mathbf{v}(\mathbf{r})$. Note that a 1/2 prefactor is introduced in the definition of the vorticity, which is different from normal convention, this is to be consistent to the convention of the vorticity four-vector in relativistic theory. For a rigid-body rotation with a constant angular velocity $\bar{\omega}$, the velocity of a point on the rigid body is given by $v = \bar{\omega}\times\mathbf{r}$. We can verify that $\omega = \frac{1}{2}\nabla\times(\bar{\omega}\times\mathbf{r}) = \bar{\omega}$, i.e. for a rigid body in rotation the vorticity is identical to the angular velocity. With the local vorticity, the total angluar momentum can be re-written as $\mathbf{L} = \int d^3r\,\epsilon(\mathbf{r})[r^2\boldsymbol{\omega} - (\boldsymbol{\omega}\cdot\mathbf{r})\mathbf{r}]$. We see that $\mathbf{L}$ is an integral of the moment of inertia density and the local vorticity. The time evolution of the local velocity and vorticity field can be simulated through the hydrodynamic model [23–25], the AMPT model [26, 27] or the HIJING model with a smearing technique [28].