Polarization in Heavy Ion Physics

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Abstract. Role of polarization studies in heavy ion physics is discussed with emphasis on the search for quark-gluon plasma formation and studies of its dynamical properties.

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INTRODUCTION

The main goal of the experiments performed with heavy ion collisions is generation of the deconfined state of the QCD matter and studies of its properties. Existence of deconfined state was predicted prior to the QCD era (cf. e.g. [1] and references therein). Asymptotic freedom of QCD has led straightforwardly to the prediction that the deconfined state should be a weakly bounded state of quarks and gluons. Important tools in the studies of the nature of the new form of matter are the anisotropic flows which are the quantitative characteristics of the collective motion of the produced hadrons in the nuclear interactions. With their measurements one can obtain a valuable information on the early stages of reactions and observe signals of QGP formation. Despite that the polarization measurements in this field are complementary, they nevertheless are very useful tool for the searches for the deconfined state and study of its nature. Of course, in heavy-ion collisions spin states of final particles can only be measured.

POLARIZATION AND SEARCH FOR QUARK-GLUON PLASMA

Assuming different dynamics of hadron and nuclear collisions, i.e. that high densities of matter reached in nuclear collisions would lead to QGP formation, the idea to use vanishing polarization of $\Lambda$ hyperons produced in nuclear collisions as a signal of QGP has been exploited in the early studies [2, 3, 4].

Indeed, in hadron interaction the experimental situation with hyperon polarization is widely known and stable for a long time. Polarization of $\Lambda$ produced in the unpolarized inclusive $pp$–interactions is negative and energy independent. It increases linearly with $x_F$ at large transverse momenta ($p_\perp \geq 1 \text{ GeV}/c$), and for such values of transverse momenta is almost $p_\perp$-independent, this dependence is represented in Fig. 1. It should be noted that polarization was measured with respect to the production plane, i.e. the plane spanned over the vector of the initial momentum and the vector of the produced particle momentum. It was supposed that in the nuclear collisions the produced transient state has an isotropic distribution of parton momenta and therefore QGP lose any memory of the initial state momenta. The only existing vector is the vector of the final state...
momentum. But due to parity conservation polarization along this direction should be zero. Thus, the absence of hyperon polarization w.r.t. production plane was predicted to be a signal of QGP formation. Vanishing hyperon polarization w.r.t. production plane in central nuclear collisions follows from various models also.

However, there are no experimental measurements at high energies of hyperon polarization w.r.t. production plane in nuclear collisions and this prediction is still a hypothesis.

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**FIGURE 1.** Transverse momentum dependence of polarization of Λ.

**FIGURE 2.** Reaction plane in hadron and nuclei collisions.

Here we turn to another aspect of the same problem. For this purpose it is important to make a remark that in the recent paper [5], which provides an emphasis on the historic aspects of the QGP searches, the conclusion made that the deconfined state of matter has being observed in hadronic reactions during a long time and it would be interesting to study collective properties of transient state in reactions with hadrons and nuclei simultaneously since the dynamics is qualitatively the same and differences are merely quantitative. Another array of theoretical predictions is related to prediction of significant polarization w.r.t. reaction plane in the non-central hadron and nuclear
collisions due to the presence of the large orbital angular momentum in such collisions. Reaction plane is the plane spanned over the vectors of the initial momentum $\vec{p}$ and the impact parameter of colliding particles or nuclei $\vec{b}$. This definition is illustrated in Fig. 2, where the normal to the reaction plane is directed along the $y$ axis.

The determination of the reaction plane in the non-central hadronic collisions could be experimentally feasible with use of the standard procedure. The relationship of the impact parameter with the final state multiplicity is a useful tool in these studies similar to the studies of the nuclei interactions. The value of impact parameter can be determined through the centrality and then, e.g. global polarization, directed or elliptic flow can be analyzed by selecting events in a specific centrality ranges.

It is evident that orbital angular momentum can have very large values. It can be estimated as follows

$$L(s,b) \simeq \alpha b \frac{\sqrt{s}}{2} D_C(b), \quad (1)$$

where $D_C(b)$ describes distribution of matter in the overlap region (cf. Fig. 2). It should be noted that $L \rightarrow 0$ at $b \rightarrow \infty$ and $L = 0$ at $b = 0$ (Fig. 3). In nuclear collisions at RHIC and LHC average values of orbital angular momentum are of order $(\hbar = 1) \, 10^5$ (RHIC) and $10^7$ (LHC)\[1\].

It is natural that the question arises: what are the observable effects of the large angular orbital momentum presented in the peripheral heavy-ion and hadron collisions? Carruthers supposed that orbital angular momentum would be released in the coherent burst of polarized vector mesons [6]. Yang and Chou pointed out to the strong necessity for the spins of the outgoing particles to line up parallel to each other in the transverse direction to the reaction plane [7], i.e. $\langle \sigma_1^T \cdot \sigma_2^T \rangle_{\text{average}} > 0$ due to a net deficiency in the left and right-moving outgoing systems. The reaction plane is perpendicular to the orbital angular momentum direction. Thus, in a process of high energy hadron and nuclear collisions large initial orbital angular momentum can, in principle, be converted into the spin angular momentum of final particles resulting in their polarization relative to the reaction plane. We will try to connect this possibility with the nature of transient strong interaction matter.

1 In nuclear collisions orbital angular momentum has a maximum at $b \simeq R_A$. 

\[\text{FIGURE 3. Qualitative dependence of the orbital angular momentum } L \text{ on the impact parameter } b.\]
Polarization and Dynamics of Quark-Gluon Plasma

Weakly-coupled matter of QGP (parton model with final state interactions) does not allow coherent collective rotation of the system and therefore finite transverse gradient of the average longitudinal momentum per produced parton should exist in the overlap region. It is claimed that relative OAM in collision of partons will lead to global quark polarization due to spin-orbital coupling [8].

Significant (order of 0.3) polarization of hyperons relative to reaction plane was anticipated due to global polarization of quarks. Similar ideas were used for the hyperon polarization in hadron non-central collisions [9]. The idea to observe circularly polarized direct photons as a signal of quark polarization in the QGP was proposed in [10, 11].

The measurements of global polarization $\Lambda$ and $\bar{\Lambda}$ were performed at RHIC (STAR Collaboration) in $Au + Au$ collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV and upper limit $|P_{\Lambda,\bar{\Lambda}}| \leq 0.02$ has been obtained [12]. It should be noted that global spin alignment for $\phi$ and $K^{*0}$ were also not observed for the different centralities [13]. Thus, if we will not consider scenario of complete dilution of polarization by hadronization mechanism, we should conclude that at the moment no experimental evidence exists for conversion of the orbital angular momentum into the spin angular momentum in nuclear collisions and this conclusion is correlated but not necessarily follow from the result on the strongly interacting nature of transient matter observed at RHIC.

It is well known that discovery of the deconfined state of matter has been announced by the four major experiments at RHIC Despite the highest values of energy and density have been reached, a genuine quark-gluon plasma QGP was not found. The deconfined state reveals the properties of the perfect liquid, being strongly interacting collective state and therefore it was labelled as sQGP. The question arise again: what are the experimental manifestations of the large orbital angular momentum could be in the case of strongly interacting transient matter?

First, observation of an ideal liquid as a transient state means that this state of matter has low viscosity, i.e. large interaction cross-section (estimates provide the value about 22 mb). Then we should conclude that in these circumstances the preexisting large orbital angular momentum will lead to rotation of the transient deconfined matter in the overlap region as a whole, i.e. all parts have the same angular velocity and the orbital angular momentum does not convert to the spin angular momentum. This rotation will

![Figure 4](image-url)
lead to the directed flow $v_1$ as it was shown in [14]. Assumed there particle production mechanism at moderate transverse momenta is an excitation of a part of the rotating transient state of massive constituent quarks (interacting by pion exchanges) by the one of the valence constituent quarks with subsequent hadronization of the quark-pion liquid droplets (cf. Fig. 4). The directed flow $v_1$ in nuclei collisions as well as in hadron reactions depends on the rapidity difference $y - y_{beam}$ and not on the incident energy. The mechanism therefore can provide a qualitative explanation of the incident-energy scaling $[15, 16, 17, 18]$ of $v_1$ observed at RHIC (Fig. 5).

FIGURE 5. Dependence of directed flow on $\eta - y_{beam}$ in $Au + Au$ and $Cu + Cu$ collisions at 62.4 GeV and 200 GeV at RHIC.

Thus, the strongly interacting nature of transient state would lead to the non-zero directed flow $v_1$ and vanishing global polarization.

**EXPECTATIONS FOR THE LHC ENERGIES**

The evident question nowadays is about the nature of the matter which will be produced at the LHC.

If the vanishing directed flow $v_1$ would be observed then one could conclude on the weakly-coupled system, or genuine QGP. But then what about global polarization? Is this a signal of QGP formation? Not necessarily, and the reason is the existence of the reflective (antishadow) scattering at the LHC energies. This particular mechanism is not related to the question on what kind of deconfined matter was produced $[19, 20]$. The geometric picture at the energy which is beyond the black disc limit can be described as a scattering off the partially reflective and the partially absorptive disk surrounded by the black ring which turns out into a grey area at larger values of the impact parameter. The evolution with energy is characterized by increasing albedo due to the interrelated increase of reflection and decrease of absorption at small impact parameters. This mechanism results from unitarity saturation and leads to the peripheral production of secondary particles in the impact parameter space. The emerging global polarization of produced particles will appear then due to the imbalance of the orbital angular momentum in the initial and final states. Indeed, the enhancement of the peripheral particle
production would destroy the balance between orbital angular momentum in the initial and final states; most of the particles in the final state would carry out significant orbital angular momentum. To compensate this orbital momentum the spins of the secondary particles should become lined up.

CONCLUSION

Concluding on the polarization studies in heavy ion physics, it is evident that there are more questions than answers in this field at the moment. Nevertheless, there are no doubts that polarization measurements combined with anisotropic flow measurements will be able to help in detecting QGP and revealing its dynamical properties more unambiguously. At RHIC there is another possibility of the directed flow measurements in the polarized proton collisions. As it was discussed above, the magnitudes of global polarization and directed flow are in a prompt relation with the nature of the transient matter, namely, depending on whether it is weakly or strongly coupled matter, these observables have different values. The role of polarization measurements in heavy ion physics certainly deserves further studies — both experimental and theoretical.

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