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Similarity and specifics of polarization in hadronic and heavy-ion collisions

Oleg V Teryaev[1,2,3,†] **and Valentin I Zakharov**[2,4,5,‡]

[1] Joint Institute for Nuclear Research, 141980 Dubna, Russia
[2] Institute of Theoretical and Experimental Physics, NRC Kurchatov Institute, 117218 Moscow, Russia
[3] Dubna International University, 141980 Dubna, Russia
[4] School of Biomedicine, Far Eastern Federal University, 690950 Vladivostok, Russia
[5] Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia

E-mail: †`teryaev@jinr.ru`, ‡`vzakharov@itep.ru`

Abstract. The basic ingredients of baryon polarization emerging in the collisions of hadrons and heavy ions are compared. The apperance of the pseudovector as the normal to reaction plane, axial anomaly, as a spin-orbital interaction, and dissipation, as imaginary phase are discussed. The interplay beyween chenical potential and Regge behaviour and the hadronic analog of viscosity are outlined. The experimental studies of transition of hadrons to heavy ions, in particular at NICA (JINR) is discussed.

1. Introduction

The recent experimental discovery of STAR collaboration [1] indicate the presence of hyperon polarization in heavy-ion collisions. Such a polarization was well studied in *hadronic* collisions and it seems quite interesting to compare these effects.

Here we compare the three important ingredients of such polarization: necessity for some pseudovector (being the normal to the scattering plane in hadronic scattering), interference with the amplitude containing spin-orbital interaction and imaginary phase.

2. Polarization and pseudovectors

As the spin $-1/2$ polarization is a pseudovector, it should be directed along some pseudovector constructed from particles momenta.

In the case of heavy-ion collisions this is represented by the normal to the reaction plane. At the same time, the component normal to *scattering* plane was suggested [2] to disappear because of randomization in the course of formation of strongly interacting matter.

Note also, that other P-odd combinations of momenta may appear, being a sort of generalization[3] of handedness concept [4] in application to heavy-ion collisions.

Since nuclei have non-zero angular momentum in non-central collisions we can expect to find some P-odd effects in the final state.

To obtain information about polarization of particles in the initial state based on the properties of particles in the final the several methods were proposed based on computation

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of vector or triple product of 3-momenta of particles in the final state. These methods are suitable for processing experimental data.

In the first article [5] a pseudoscalar T was introduced:

$$T = \frac{1}{|\vec{p}|}([\vec{p_1}, \vec{p_2}], \vec{p_3}),$$

with $|\vec{p_1}| > |\vec{p_2}| > |\vec{p_3}|$, where $\vec{p_1}$, $\vec{p_2}$ and $\vec{p_3}$ - 3-momenta of particles in the final state, $\vec{p}$ - momentum of the particle in the initial state. Using T and quantities derived from it some reactions including electron-positron annihilation to hadrons and nucleon collisions were considered.

Later, independently, in [4] a new quantity called handedness was defined. It was proposed to investigate polarization of the initial quark or gluon. Longitudinal handedness is defined as follows:

$$H_{||} = \frac{N_l - N_r}{N_l + N_r},$$

where N_l and N_r - is the number of left- and right-handed combinations $\vec{k}$, $\vec{k_1}$, $\vec{k_2}$: Here, $\vec{k}$ - momentum of the initial particle, $\vec{k_1}, \vec{k_2}$ - momenta of particles (pions) in the final state. It was proposed to sort particles $\vec{k_1}$ and $\vec{k_2}$ according to their charge or magnitudes of momenta.

Based on these articles the following quantity was considered:

$$\eta = \frac{\sum(\vec{p_3}, \vec{p_2}, \vec{p_1})}{\sum|(\vec{p_3}, \vec{p_2}, \vec{p_1})|},$$

where $(\vec{p_3}, \vec{p_2}, \vec{p_1})$ - triple product $(\vec{p_3}, [\vec{p_2}, \vec{p_1}])$ with all vectors in a triplet in the same octant in the momentum space, $\vec{p_1}, \vec{p_2}, \vec{p_3}$ - momenta of pions in the final state. Momenta in each triple product were sorted:

$$|p_3|^2 < |p_2|^2 < |p_1|^2.$$

Hence eight values $\eta_i, i = 0..7$, one for each octant, were calculated.

Au+Au collisions were considered with projectile energy of 5GeV per nucleon in the laboratory frame with impact parameter $b = 7fm/c$. Heavy-ion collisions were modeled in Hadron-String Dynamics model [6]. The results indicated the small effects which can be revealed processing the high statistics data.

The similar method may be applied for *two* pions in final state and one fixed initial (longitudinal) momentum, so that only the transverse components of pion momenta will enter. The first attempts in this direction is briefly described in the presentation and of A. Martynova.

Note also, that inclusion of polarization pseudovector into the set of considered vectors will lead to the number of local polarizations. This will require the separate investigation.

3. Spin-Orbital Interaction

The appearance of spin-orbital interaction is a necessary ingredient of generation of polarization in hadronic collisions. For heavy ions, the very large orbital momentum is unlikely to be directly relevant, as it is a global distributed quantity, while spin-orbital coupling is a local one. This may lead to relative suppression of large polarization suggested in the pioneering work [7].

Instead, such local counterpart of orbital momentum as vorticity may be important which may be transformed to spin in various ways.

One of them is performed [8] in the framework of approach exploring local equilibrium thermodynamics [9] and hydrodynamical calculations of vorticity [10]. There is another (although related [11]) approach to polarization first proposed in [12] and independently in [13]. It is based on vortical effect (see e.g. [14]) that being the macroscopic manifestation of

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axial anomaly [15] leads to induced axial current of strange quarks which may be converted to polarization of Λ-hyperons [12, 13]. There is also the contribution of gravitational anomaly[16], suppressed due to the collective effects revealed in lattice simulations[17] .

It is interesting that rapid decrease of polarization with energy due to decrease of chemical potential happens also in Regge theory due to decrease of Regge cuts contributions. This may be compared with the explanation of anizotropic flows in Regge theory [19]. One may probably speak here about a sort of duality between dynamical and statistical description of heavy-ion collisions [20, 21, 22].

The anomalous mechanism and calculations of vorticity in PHSD model [18] are discussed in detail in the contributions of G. Prokhorov and Aleksei Zinchenko.

4. Imaginary phases and dissipation

The imaginary phases play crucial role in generation of single spin asymmetries, and their sources in QCD can be different.

QCD factorization allows one to express the cross-sections and polarization observables of hard processes in terms of convolutions of partonic subprocess and non-perturbative functions, describing the hadron-parton and hadron-parton transitions. The latter may be separated to two large classes, appearing in the exclusive and inclusive processes. The first one, containing the various types of wave functions (light-cone and generalized parton distributions and generalized distribution amplitudes) will be considered in the next section. The non-perturbative objects, appearing in the inclusive processes, in turn, belong to three classes.

The most widely known ones are parton distributions, describing the fragmentation of hadrons to partons and related to the forward matrix elements

$$\sum_X < P|A(0)|X >< X|A(x)|P >=< P|A(0)A(x)|P >$$

of renormalized non-local light-cone quark and gluon operators. As they do not contain any variable, providing the cut and corresponding imaginary phase (to put it in the dramatic manner, the proton is stable), the T-odd distributions functions can not appear in the framework of the standard factorization scheme. At the same time, they may appear effectively, when the imaginary phase is provided by the cut from the hard process, but may be formally attributed to the distribution.

Another well-known object is fragmentation function, describing the fragmentation of partons to hadrons and constructed from the time-like cutvertices of the similar operators

$$\sum_X < 0|A(0)|P, X >< P, X|A(x)|0 > .$$

Now, they may contain the cut with respect to the time-like parton momentum squared k^2(which was space-like in the case of distributions), corresponding, at the hadronic level, to the jet mass. This may give rise to the number of T-odd fragmentation functions, including jet handedness, Collins function and interference fragmentation function.

The FRACTURE function whose particular example is represented by the diffractive distribution (DD) is related to the object

$$< P_1|A(0)|P_2, X >< P_2, X|A(x)|P_1 >,$$

combining the properties of FRAgmantation and struCTURE functions. They describe the correlated fragmentation of hadrons to partons and vice versa.

They were successfully applied to describe the production of diffractive and leading hadrons in semi-inclusived Deep Inelastic Scattering and were also generalized to spin-dependent case.

Such functions can easily get the imaginary phase from the cut produced by the variable $(P_1 + k)^2$. Due to the extra momentum of produced hadron P_2, the number of the possible P-odd combinations increases. Therefore, they may naturally allow for the T-odd counterparts. The present report briefly describes the calculation of the short-distance subprocess accompanying the simplest T-odd Diffractive Distribution and the possibilities for their experimental observation.

The natural counterpart of imaginary phase in heavy-ion collisions is *dissipation* [23]. We were utilizing the model of pionic superfluidity induced by a chemical potential μ_3 breaking isotopic invariance, see [24] and references therein. It is not a realistic model for the quark-gluon plasma but this is a rare example when the effects of confinement and of spontaneous breaking of the chiral symmetry can be accounted for. We demonstrated that the average density of spins (polarizations) of baryons matches the density of the chiral vortical current in the medium:

$$< j^z_{5B} >_{baryons} \sim < \mu^2 \omega^z > , \tag{1}$$

where j_{5B} is the baryonic axial current and $< j^z_{5B} > \sim < \sigma^z >$, where σ^z is the component of the spin of baryons in the direction of the axis of the rotation. A crucial role in derivation of (1) is played by defects, or vortices. Formally, the vortices are infinitely thin. Baryons regularize the vortices at short distances and this is a source of irreversibility.

In our field theoretic example the rotation is transferred to spin of heavy degrees of freedom which are not dynamic but are introduced as ultraviolet cutoff in the effective theory of plasma. The loss of unitarity in field theory due to account of heavy degrees of freedom (represented by local operators) is a well known way to imitate dissipation in field theory, see, e.g., [25].

5. Viscosity for hadrons [26]

Another interplay of phases in matrix elements and dissipation is provided by the gravitational form factors [27], related to pressure, which may be also considered in the time-like region. This opportunity was recently explored in the exclusive production of pion pairs in the collisions if real and virtual photons to get the relevant information for pion [28].

It will be very interesting to extend this analysis for the production of $\pi\eta$ pairs with exotic quantum numbers $J^{PC} = 1^{-+}$, being the natural generalization of the production of exotic hybrid mesons [29].

The relevant matrix element of the quark symmetrized energy-momentum tensor

$$\langle \pi\eta(P, \Delta)| T_i^{\alpha\nu} |0\rangle_{\mu^2} = \eta_i(\mu^2) P^\alpha \Delta^\nu \tag{2}$$

may be considered as a sort of *shear viscosity*). Indeed, the relative momentum of the pair (being the counterpart of hybrid meson polarization vector) may be considered after crossing $P \leftrightarrow \Delta$ to GPD channel as corresponding to (average) velocity $v^\nu \sim P^\nu/M$ while the total momentum of the pair should correspond to (transverse) derivative in the viscosity tensor.

The viscosity interpretation in the GPD channel itself should naturally correspond to the appearance of transition GPDs, (naive) T-oddness and imaginary phases. The possible smallness of relevant matrix element might be related to famous holographic bound for viscosity. Needless to say, that the total average viscosity of quarks and gluons should be zero, which is a natural generalization of nullification of exotic hybrid meson coupling [29, 30]

6. Experimental tests of interplay between hadronic and nuclear polarization

The similarity and distinction between hadronic and nuclear polarization may be systematically explored at NICA Complex at JINR.

The MPD detector is well suited to study the hyperon polarization, including the kinematic and energy dependence and correlations to flows. The various versions of handedness may be studied as well. Its correlations with flows and polarization should reveal the structure of vortical effects in heavy-ion collisions.

The BM@N detector may allow one to explore the transition from local (normal to scattering plane) to global (normal to reaction plane) polarization. by studying the reactions with hadrons, light and heavy nuclei. It may also explore the spin dependence of short range correlations.

The SPD detector may study the reactions with polarized protons, and, especially deuterons. The latter option is the unique one. The deuteron tensor polarization may be studied in various hard reactions including the hadronic P-even single spin asymmetries and opens, among the other interesting possibilities, the way to study the shear forces [26] providing yet another link between hadronic and heavy ion physics. The studies of reactions with polarized deuterons may be also started at MPD.

7. Discussion and Conclusions

The polarization of baryons in hadronic and heavy-ion collisions have both common and distinct features.

Kinematically, in parity-conserving theory like QCD, some pseudovector is required. While in inclusive baryon production in hadronic collisions this is a scattering plane, the reaction plane takes this role for heavy-ion collisions. at the same time, various versions of handedness and related local polarizations may appear.

Dynamically, the transition of very large orbital momentum to spin should require some local coupling. This, in turn, requires some local quantity, like vorticity. In thermodynamical approach, under the assumption of local equilibrium with polarized baryon, this allows to determine the momentum dependent polarization. This effect is flavour blind, so that the sign of polarization is universal and dependent only on particle mass. Note also the general problem of transfer of (conserved) orbital angular momentum to the spin one in the case of symmetric energy-momentum tensor.

The use of anomalous mechanism, due to the appearance of chiral quarks as polarization carriers, will lead to the essential flavour dependence of polarization.

The extreme, although difficult for experimental studies, is the case of protons. While in the thermodynamoc approach their polarization is similar to that of baryons, in the anomalous one it should be very small due to division of axial charge between their large number.

The decrease of polarization with energy may be dual to the same phenomenon in Regge theory.

The imaginary phase in hadronic collisions corresponds to dissipation in heavy-ion ones. The model of pionic superfluidity leads to the natural realization of this property in the cores of quantized vortices.

Another link between dissipation at the levels of hadronic matrix elements and QCD medium is provided by the analog of viscosity for hadrons.

Finally, the detailed experimental studies of the polarization on hadronic and heavy-ion collisions may be achieved at MPD, BM@N and SPD detectors at NICA.

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References

[1] Adamczyk L *et al.* [STAR Collaboration] 2017 *Nature* **548** 62
[2] Jacob M and Rafelski j 1987 *Phys. Lett. B* **190** 173

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[3] Teryaev O and Usubov R 2015 *Phys. Rev. C* **92** 014906
[4] Efremov A V, Mankiewicz L and Tornqvist N A 1992 *Phys. Lett. B* **284** 394
[5] Nachtmann Otto 1977 *Nuclear Physics B* **127** 314
[6] Cassing W and Bratkovskaya E L 1999 *Phys. Reports* **308** 65
[7] Liang Z T and Wang X N *Phys. Rev. Lett.* **94** 102301 (2005)
[8] Becattini F, Csernai L and Wang D J 2013 *Phys. Rev. C* **88** 034905
[9] Becattini F, Bucciantini L, Grossi E and Tinti L 2015 *Eur. Phys. J. C* **75** 191
[10] Csernai L P, Magas V K and Wang D J 2013 *Phys. Rev. C* **87** 034906
[11] Prokhorov G, Teryaev O and Zakharov V 2018 *Phys. Rev. D* **98** 071901
[12] Rogachevsky O, Sorin A and Teryaev O 2010 *Phys. Rev. C* **82** 054910
[13] Gao J H, Liang Z T, Pu S, Wang Q and Wang X N 2012 *Phys. Rev. Lett.* **109** 232301
[14] Kalaydzhyan T 2014 *Phys. Rev. D* **89** 105012
[15] Son D T and Surowka P 2009 *Phys. Rev. Lett.* **103** 191601
[16] Baznat M, Gudima K, Sorin A and Teryaev O 2018 *Phys. Rev. C* **97** 041902
[17] Braguta V, Chernodub M N, Goy V A, Landsteiner K, Molochkov A V and Polikarpov M I 2014 *Phys. Rev. D* **89** 074510
[18] Cassing W and Bratkovskaya E L 2009 *Nucl. Phys. A* **831** 215
[19] Boreskov K G, Kaidalov A B and Kancheli O V 2009 *Phys. Atom. Nucl.* **72** 361
[20] Cleymans J, Lykasov G I, Sissakian A N, Sorin A S and Teryaev O V 2010 Duality of Thermal and Dynamical Descriptions in Particle Interactions *Preprint* arXiv:1004.2770 [hep-ph].
[21] Cleymans J, Lykasov g I, Sorin A S and Teryaev O V 2012 *Phys. Atom. Nucl.* **75** 725
[22] Cleymans J, Lykasov G I, Parvan A S, Sorin A S, Teryaev O V and Worku D 2013 *Phys. Lett. B* **723** 351
[23] Teryaev O V and Zakharov V I 2017 Phys. Rev. D **96** 096023
[24] Son D T and Stephanov M A 2001 *Phys.Rev.Lett.* **86** 592
[25] Endlich S, Nicolis A, Porto R A and Wang J 2013 *Phys.Rev. D***88** 105001
[26] Teryaev O 2019 *PoS DIS* **2019** 240
[27] Teryaev O V 2016 *Front. Phys. (Beijing)* **11** 111207
[28] Kumano S, Song Q T and Teryaev O V 2018 *Phys. Rev. D* **97** 014020
[29] Anikin I V, Pire B, Szymanowski L, Teryaev O V and Wallon S 2006 *Eur. Phys. J. C* **47** 71
[30] Anikin I V, Pire B, Szymanowski L, Teryaev O V and Wallon S 2004 *Phys. Rev. D* **70** 011501