Azimuthal anisotropy and fundamental symmetries in QCD matter at RHIC

V.A. Okorokov

a Moscow Engineering Physics Institute (State University), Kashirskoe Shosse 31, 115409 Moscow, Russian Federation
e-mail: VAOkorokov@mephi.ru; Okorokov@bnl.gov

Abstract

A study of collective behavior in heavy ion collisions provides one of the most sensitive and promising probes for investigation of possible formation of new extreme state of strong interacting matter and elucidating its properties. Systematic of experimental results for final state azimuthal anisotropy is presented for heavy ion interactions at RHIC. Experimental data for azimuthal anisotropy indicate that the final state strongly interacting matter under extreme conditions behaves as near-ideal liquid rather, than ideal gas of quarks and gluons. The strong quenching of jets and the dramatic modification of jet-like azimuthal correlations, observed in Au+Au collisions, are evidences of the extreme energy loss of partons traversing matter which contains a large density of color charges. For the first time, dependence of the jet suppression on orientation of a jet with respect to the reaction plane is found at RHIC experimentally. The model of compound collective flow and corresponding analytic approach are discussed. The possible violations of $P$ and $CP$ symmetries of strong interactions in heavy ion collisions at different initial energies are considered. Thus, now the fact is established firmly, that extremely hot and dense matter created in relativistic heavy ion collisions at RHIC differs dramatically from everything that was observed and investigated before.

Research a heavy ion interactions at high energies and search of a new state of strongly interacting matter at extremely high density and temperatures has essential interdisciplinary significance. Study of collective and correlation characteristics of interactions allows to obtain new and unique information concerning various stages of space-time evolution of collision process, to establish fundamental relation between geometry of collision and dynamics of final state formation. In heavy ion collisions, metastable vacuum domains may be formed in the QCD vacuum in the vicinity of the deconfinement phase transition in which fundamental symmetries ($P$ and/or $CP$) are spontaneously broken. Thus the study of nuclear collisions allows to investigate one of the most important problem of strong interaction theory. Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory has started to run for physics 2000. RHIC is the world accelerating complex specially designed and intended entirely for researches in the field of the physics of strong interactions. The experimental base of RHIC facility consists of four detectors: small - BRAHMS, PHOBOS and large - PHENIX, STAR for physics programm with heavy ion beams. Now there are huge bases of experimental data with high statistics for Au+Au(Cu+Cu) at $\sqrt{s_{NN}} = 19.6(22.4) - 200$ GeV, for d+Au and p+p at $\sqrt{s_{NN}} = 200$ GeV. Also runs have been executed with small integrated luminosity for Au+Au at $\sqrt{s_{NN}} = 55.8$ GeV, for p+p...
at $\sqrt{s_{NN}} = 409.8$ GeV, and at low energies: $\sqrt{s_{NN}} = 22/9.2$ GeV - for p+p/Au+Au-interactions. Now experimental data are collected on the large RHIC detectors only.

# Azimuthal anisotropy

One of the most essential features of non-central AA collisions is the violation of azimuthal symmetry of secondary particle distributions, caused by spatial asymmetry of area of overlapping of colliding heavy ions. The collective behaviour of secondary particles manifests itself both in one-particle $p_{T}$-spectra and in asymmetry of azimuthal particle distribution with respect to the reaction plane. The first effect is due to radial azimuthally symmetric expansion, the second effect is characterized by flow parameters $v_{n} = \langle \cos [n (\phi - \Psi_{RP})] \rangle$.

The directed flow carries the information about very early stages of evolution of collision process. The systematic study of the directed flow $v_{1}$ has been executed in experiments at RHIC at various $\sqrt{s_{NN}}$ values [1 - 4]. Dependence $v_{1}(\eta(y) - y_{0})$ is presented at Fig.1a at initial energy range $\sqrt{s_{NN}} = 8.8 - 200$ GeV for semi-central heavy ion collisions, where $y_{0}$ - rapidity of beam particles. The results obtained at various RHIC energies agree with SPS data [5] in the region of fragmentation of a beam particle. The most of transport models underestimates of flow $v_{1}$ for central rapidity region and agrees with experimental results at the large values of $|\eta|$ more reasonably. The correlation between the first and second harmonics indicates on the development of elliptic flow in plane of event [1]. The recent results show that the directed flow depends on initial energy but not on the type of colliding nuclei [4].

It was observed, that the dependences $v_{2}(p_{T})$, integrated $v_{2}$ and differential $v_{2}(p_{T})$ parameters on particle mass (type) are described by phenomenological calculations on the basis of hydrodynamics up to $p_{T} \sim 2$ GeV/c well enough for different particles [6, 7]. The indicated above range of $p_{T}$ contains $\sim 99\%$ of secondary particles. Thus, the global dynamic feature of the created matter is the collective behaviour described in the framework of relativistic hydrodynamical model at qualitative level. The increasing of $v_{2}$ and systematic decreasing of $v_{2}(p_{T})$ with growth of particle masses is the additional and essential indication on presence of the common velocity fields. Dependence $v_{2}(\sqrt{s_{NN}})$ is presented on the Fig.1b based on [8, 9]. One can see the $v_{2}(\sqrt{s_{NN}})$ increases smoothly at $\sqrt{s_{NN}} > 5$ GeV. The flow energy dependence was fitted by function $a_{0} + a_{1} \left[\frac{\sqrt{s_{0}}}{\left(\sqrt{s_{NN}} - 2m_{p}\right)}\right]^{a_{2}} + a_{3}\lambda^{a_{4}} + a_{5}\lambda^{a_{6}} + a_{7}[\ln \lambda]^{a_{8}} (\lambda \equiv s_{NN}/s_{0}, \ s_{0} = 1 \text{GeV}^{2}, \ m_{p} - \text{proton mass})$ which is similar to that for $\sigma_{tot}^{pp}$ approximation [10]. This function agrees with all available data reasonably, but the approximation with best statistical quality ($\chi^{2}/ndf = 3.83$) shows the decreasing in TeV energy range (Fig.1b, curve 1). There is some poor quality ($\chi^{2}/ndf = 4.83$) for curve 2 (Fig.1b) which shows a reasonable behaviour for all energy domain understudy. One can see the experimental data for both ultra-high energy range (LHC) and for intermediate energies $\sqrt{s_{NN}} = 5 - 50$ GeV (FAIR, NICA) are essential for more unambiguous approximation of $v_{2}(\sqrt{s_{NN}})$. As seen, the PHOBOS point at $\sqrt{s_{NN}} = 19.6$ GeV agrees well with the results observed at close SPS energies. It is important to note, that at high RHIC energies the hydrodynamical limit for elliptic collective flow parameter is reached for the first time. The dependence of $v_{2}$ on centrality emphasizes additionally of importance of more exact knowledge for initial state in a nuclei-nuclear collisions for the correct description of final state matter evolution. Essential nonzero value
and the basic dependences for $v_2$ are observed for various types of colliding (symmetric) heavy ion beams [11, 12]. Dependence $v_2(\eta)$ has been obtained at RHIC for various initial energies both for Au+Au, and for Cu+Cu collisions. The different phenomenological

Figure 1: (a) Parameter $v_1$ for the charged particles at SPS (Pb+Pb) and RHIC (Au+Au) energies. Collision centralities are specified. (b) Energy dependence of $v_2$ parameter for midrapidity domain in heavy ion collisions. A thick solid curve corresponds to the hydrodynamical calculations for strongly interacting matter EOS with phase transition, a dashed curve – for the EOS of hadron gas without phase transition. Inner picture shows predictions up to the ultra-high energies (see text for more detail). Statistical errors are indicated only.

models describe the $v_2(\eta)$ at qualitative level. Essential excess for partonic cross-sections used in such models above pQCD predictions can indicates on significant non-perturbative effects in the partonic matter formed on the RHIC.

Experimental $v_2$ results, obtained both for charged hadrons and for the identified particles of various types, allow to make a choice in favour of the equation-of-state (EOS) of strongly interacting matter with presence a quark-gluon phase at early stages of space-time evolution of the formed medium with the subsequent transition in hadronic phase (Fig.1b). Moreover the hybrid model with jet quenching, unlike hydrodynamics, predicts saturation of $v_2$ in the intermediate $p_T$ domain with the subsequent decreasing at higher transverse momentum and describes dependence $v_2(p_T)$ for $p_T > 2$ GeV/c at large density of gluons $dN_g/dy \sim 10^3$ qualitatively [6]. This experimental result (together with other ones) is the direct evidence of hot and dense matter formation in which there are partonic hard scattering and finite energy loses of partons and products of their fragmentation at traversing of this medium. The comparative analysis of p+p, d+Au and Au+Au collisions at energy $\sqrt{s_{NN}} = 200$ GeV has demonstrated that there is a significant contribution from anisotropic (elliptic) flow namely in non-central nuclei-nuclear collisions up to, at least, $p_T \approx 10$ GeV/c [13]. The large elliptic flow signal indicates on the one hand on the fast achieving of thermodynamic equilibrium at RHIC energies, and on the other hand - the medium constituents should interact with each other intensively enough at the early stages of space-time evolution of matter already, that more corresponds to conditions of a liquid.
than gas.

At RHIC experimental results have been obtained for parameter of a collective elliptic flow for identified $\pi^0$-mesons and inclusive $\gamma$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The obtained experimental indication on small $v_2$ values for direct photons makes preferable the naive scenario of direct photon production in processes of the hard scattering, which occurs at the earliest stages of space-time evolution of the created matter [14]. The universal dependence of parameter $v_2/n_q$ on normalized kinematic variables ($p_T/n_q, E_{kT}/n_q, n_q$ – constituent quark number) is observed for a wide set of secondary mesons and baryons [12, 15]. This scale behaviour is the experimental evidence of presence of an essential collective partonic flow and similar character of $s$-quark flow with elliptic flow of light $u$, $d$-quarks.

The experimental RHIC data for elliptic flow $v_2$ for light flavour particles assume that final state matter is characterized by small free path length of constituents in comparison with the sizes of system and value of $\eta_s/s \sim 0.1$ ($\eta_s$ - shear viscosity, $s$ - entropy density) is close to the bottom quantum limit for strong coupling systems in the energy domain $\sqrt{s_{NN}} \sim 100$ GeV. The elliptic anisotropy of the particles with heavy flavour quarks has been investigated in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This result together with results for nuclear modification parameter $R_{AA}(p_T)$ is strong evidence in favour of the conclusion about strong coupling of heavy quarks with the final state matter [16]. Experimental values of $v_2^{HF}$ are larger essentially of model predictions based on pQCD. The Langevin transport model with small relaxation times and / or small diffusion coefficients of heavy quarks $K_{HQ}^d$ allows to obtain a reasonable agreement at a qualitative level between experimental and calculated flow values. Estimations for $\eta_s/s$, obtained in such way, are close to the bottom quantum limit also and these estimations agree with results for sector of light quarks. Thus, interpretation of experimental RHIC results for azimuthal anisotropy on the basis of hypothesis about creation at early stage (quasi)ideal partonic liquid is the most proved at present. The alternative approach to explanation of small $\eta_s/s$ value is based on the presence of anomaly shear viscosity $\eta^A_s$, arising due to turbulence of the color magnetic and electric fields generated by expanding quark-gluon system [17].

The higher order even harmonics have been obtained in STAR experiment for charged particles in Au+Au collisions at initial energy $\sqrt{s_{NN}} = 200$ GeV. Values of even harmonics for charged particles, averaged over $p_T$ and $\eta$ ($|\eta| < 1.2$) for minimum bias events, are equal (%): $v_2 = 5.180 \pm 0.005$; $v_4 = 0.440 \pm 0.099$; $v_6 = 0.043 \pm 0.037$; $v_8 = -0.06 \pm 0.14$ [18].

Identification of jets in relativistic heavy ion interactions was carried out on a statistical basis so far. Two peaks are observed in experimental correlation functions $C_2(\Delta \phi) \propto \int d\Delta \eta N(\Delta \phi, \Delta \eta)$ for AA collisions, which correspond two-jet event structure. The significant suppression of peak at large relative azimuthal angles ($\Delta \phi \simeq \pi$) was observed in azimuthal correlations of two particles with high $p_T$ for central Au+Au in comparison with p+p. Moreover, this effect increases with centrality increasing in nuclei-nuclear interactions. The experimental observations have been interpreted as the critical evidences of large losses of parton energy in dense deconfinement matter, predicted by pQCD as a state of quark-gluon plasma. Control experiments with d+Au collisions have shown that the back-to-back peak is present in this case and its characteristics are close to ones which are observed in p+p interactions. Therefore, experimental RHIC results on two-hadron azimuthal correlations are one of the most obvious and important evidences in favour of creation of new state of strongly interacting matter at final stage of central nuclei-nuclear collisions. This final state matter is characterized by large energy losses and by opacity for
partons with high $p_T$ and for products of their fragmentation. The subsequent study at higher $p_T$ both for trigger particles and for associated ones have allowed to find clear two peaks in $C_2(\Delta \phi)$, corresponding two-jet event structure both in semicentral and even central Au+Au collisions as well as in d+Au. As expected, the back-to-back peak is suppressed essentially in central Au+Au events (as well as at smaller $p_T$) [19]. This is the first direct experimental observation of two-jet event structure in central AA collisions, corresponding to pQCD predictions at qualitative level. Researches of back-to-back peak characteristics have been executed for collisions with various ion types and initial energies [20]. These experimental results indicate on the essential response of medium on energy deposition of hard parton traversed it. At present there are a several scenarios for medium response on hard jet traversing. It seems the experimental results agree with shock wave model at qualitative level only [20, 21]. Thus, additional experimental data and theoretical study are necessary for more unambiguous observation and explanation of cone topology in two dimensions.

Fig. 2 shows experimental results for investigations of hadron jet correlations with respect to the reaction plane at SPS energy [22] and RHIC one [13] in Pb+Au and Au+Au collisions, accordingly. The jet was considered as directed in reaction plane, if $|\xi| < \pi/4 \cup |\xi| > 3\pi/4$, and directed out of reaction plane, if $\pi/4 < |\xi| < 3\pi/4$, where $\xi \equiv \phi^{tr} - \Psi_2$ – relative azimuthal angle between a reaction plane estimated by angle of second order event plane ($\Psi_2$), and a trigger particle. Experimental data obtained at various initial energies, for small and large relative azimuthal angles domain are compared on Fig.2a, 2b, accordingly. As seen, excess over a level of elliptic flow is much weaker at SPS energy $\sqrt{s_{NN}} = 17.3$ GeV, than for RHIC energy in the $\Delta \phi \sim 0$ domain (Fig.2a). At $\Delta \phi \sim \pi$ the values of SPS correlation functions are close to zero level (Fig.2b). One can see correlation functions for various directions of a trigger particle agree with each other well at SPS energy for both cases $\Delta \phi \sim 0$ (Fig.2a) and for $\Delta \phi \sim \pi$ (Fig.2b), that essentially differs from behaviour of jet-like correlations on RHIC in case of hadron jets passed inside medium with various

![Figure 2: Azimuthal two-particle correlation functions at SPS and RHIC energies in the ranges of small (a) and large (b) relative azimuthal angles. The open symbols correspond to emission of trigger particles in-plane, solid symbols – out of plane direction for AA interactions. Statistical errors are presented only.](image.png)
directions with respect to the reaction plane. Therefore, suppression effect at RHIC is stronger significantly for hadron jet traversing of hot and dense matter on direction out of reaction plane, and suppression is weaker in the case of jet passing inside a matter on direction in-plane. This RHIC result is the first experimental evidence of strong correlation of suppression strength of hard hadron jets traversing the volume of hot and dense strongly interacting matter, with path lengths which are passed by jets inside of this matter.

The model of (multi)component collective elliptic flow has been suggested in [23 - 25] based on the experimental RHIC data for azimuthal anisotropy. In the framework of this model the correlations with respect to the reaction plane are supposed both for soft particles, and for hard particles (hadronic jets). The model of compound flow takes into account the number of jets per event, average multiplicity per jet, dependence of jet yield on the orientation with respect to the reaction plane, and independent ”soft” particle production. The generalized formulas were derived for two-particle distribution on a relative azimuthal angle and for two-particle distributions in / out with respect to the reaction plane [23 - 25]. These analytic calculations provide the framework for a consistent description of the elliptic flow measured via the single-particle distribution with respect to the reaction plane, jet yield per event, and the amplitude of flow-like modulation in the two-particle distribution in the relative azimuthal angle. It seems, the difference between soft particle flow and parameter of jet correlations with respect to the reaction plane is (very) close to zero at RHIC energies. But jet production will give a more significant contribution at higher (LHC) energies and this difference may be more visible. The model of compound flow agree with expectations, that energy losses of partons are sensitive to energy-momentum tensor \( T^\mu_\nu = (\epsilon + p)u^\mu u^\nu - pg^\mu_\nu \), described the global properties of created matter. Hence, partons and products of their fragmentation can be sensitive not only to the equation-of-state, but to the common velocity fields of collective flow also, i.e. hard jets appear ”enclosed” in collective expansion of surrounding medium at all.

2 Fundamental symmetries in QCD-matter

The possible \( \mathcal{P} \) and/or \( \mathcal{CP} \) violation in strong interactions requires the deconfinement state of matter with restored chiral symmetry [26, 27]. Thus the positive and reliable experimental results for \( \mathcal{P} \) and/or \( \mathcal{CP} \) violation in the strong interactions would be prove the clear evidence of deconfinement and chirally symmetric phase creation and establish experimentally the presence of topological configurations of gluon fields and their role in chiral symmetry breaking [27]. The lattice calculations show the non-trivial topological structure of gluon fields which can be characterized by topological charge (winding number) \( Q_W = \eta \int d^4x G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \), \( \eta \equiv g_5^2/32\pi^2 \). The gauge (color) fields with non-zero \( Q_W \) induce difference between number of left- and right-handed fermions. The topological charge changing transitions are exponentially suppressed at zero temperature (instanton modes). But the such transitions unsuppressed at finite temperature (sphaleron modes). In chiral limit the charge difference will be created between two sides of a plane perpendicular to the chromo-magnetic field. Thus one can define chiral magnetic effect as a charge separation by gauge field configurations with non-zero \( Q_W \) in the presence of background (electric) magnetic field. The clear equation for effect strength was derived in [28]. One needs to emphasize two features which are essential for experimental investigations namely. First of all chi-
ral magnetic effect corresponds to the early collision stages because of magnetic field falls off rapidly. Secondly, electrical charge is conserved in hadronization. Thus charge separation for quarks implies charge separation with respect to the reaction plane for hadron states observed experimentally.

The presence of non-zero angular momentum in non-central AA collisions is equal of the external magnetic field. Thus the experimental investigation of electrical charge separation of produced particles in non-central heavy ion collisions makes it possible to study \( P \) and/or \( CP \)-odd domains. A correlator, directly sensitive to \( P \)-event quantitative parameter is \( \langle \cos (\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \) \[29\]. The three-particle correlations allow to use a following characteristic: \( \langle \cos (\phi_\alpha + \phi_\beta - 2\phi_\gamma) \rangle = \langle \cos (\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle v^2_\gamma \), which is more useful for experimental applications \[18\]. The preliminary experimental results were obtained by STAR experiment at RHIC for Cu+Cu and for Au+Au collisions at initial energies 62.4 and 200 GeV \[30\]. The signal of charge separation in Cu+Cu collisions is some larger than that for Au+Au for the same centralities and the experimental signal has a typical hadronic ”width” \[30\]. This feature agrees qualitatively with scenario of stronger suppression of the back-to-back correlations in heavier (Au+Au) collisions. Thus the preliminary STAR experimental results agree at qualitative level with the magnitude and main features of the theoretical predictions for \( P \) violation in nuclear collisions at RHIC \[30\]. At present there is no indication on the some other effects which could be imitate the experimental signal and the fundamental symmetry violation in heavy ion collisions. But one need more rigorous study of such possible imitation effects for more unambiguous conclusion. The energy dependence of strength of parity violation effect is not trivial. It seems the necessary conditions can be reached in nuclei-nuclear collisions in sufficiently wide energy range. The some important medium properties are very sensitive to the vicinity of phase transition boundary. Therefore, perhaps, the effect of hypothetic fundamental symmetry violation in strong interaction might be more clear at lower energies \[27\].

3 Summary

The main RHIC results and corresponding phenomenological models are presented for two-particle azimuthal correlations. Investigation of azimuthal anisotropy has allowed to obtain a set of the important experimental results for the first time. Fast space-time evolution is observed for volume of the final state matter. This evolution is described by significant gradients of pressure at early stages. Azimuthal anisotropy agrees well enough with calculations in the framework of hydrodynamical models with phase transition and very small viscosity for the small transverse momentum domain. The manifestation of scale properties predicted by model of quark coalescence, significant values of elliptic flow for multistrange baryons and heavy flavour quarks allow to assume, that the collective behaviour on partonic stages is observed. The final state matter is opaque for partons and products of their fragmentation passed inside of it, and the degree of suppression depends on thickness of a layer of a traversed matter significantly. The generalized formulas have been derived for azimuthal correlation functions with taking into account various components (soft and hard) of elliptic collective flow and for different (in/out) orientations with respect to the reaction plane. These equations are based on experimental RHIC results for azimuthal asymmetry for both soft and hard particles. Thus, the matter created in a final state of nuclei-nuclear
collisions at high RHIC energies, differs qualitatively from all matter state created and investigated in laboratory conditions early, and color degrees of freedom namely are adequate ones for the description of the early stages of space-time evolution of the RHIC matter. The created matter is rather similar on (quasi)ideal liquid of color constituents (partons), than on (quasi)ideal quark-gluon gas, as expected earlier. The preliminary experimental results indicate the possible $\mathcal{P}$-violations in nuclear collisions at RHIC. This observation qualitatively agree with theoretical expectations for fundamental symmetry violations in QCD-matter under extreme conditions. At present the new direction of investigations is formed intensively which can be designated as ”relativistic nuclear physics of condensed / continuous matter”.

References

[1] STAR Collab. (J. Adams et al.), Phys. Rev. C 72, 014904 (2005).
[2] STAR Collab. (J. Adams et al.), Phys. Rev. C 73, 034903 (2006).
[3] PHOBOS Collab. (B. B. Back et al.), Phys. Rev. Lett. 97, 012301 (2006).
[4] STAR Collab. (B. I. Abelev et al.), 0807.1518[nucl-ex] (2008).
[5] NA49 Collab. (C. Alt et al.), Phys. Rev. C 68, 034903 (2003).
[6] STAR Collab. (J. Adams et al.), Nucl. Phys. A 757, 102 (2005).
[7] PHENIX Collab. (K. Adcox et al.), Nucl. Phys. A 757, 184 (2005).
[8] R. Stock, J. Phys. G: Nucl. Part. Phys. 30, S633 (2004).
[9] P. F. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. C 62, 054909 (2000).
[10] S. B. Nurushev and V. A. Okorokov, 0711.2231[hep-ph] (2007).
[11] PHOBOS Collab. (B. Alver et al.), Phys. Rev. Lett. 98, 242302 (2007).
[12] PHENIX Collab. (A. Adare et al.), Phys. Rev. Lett. 98, 162301 (2007).
[13] STAR Collab. (J. Adams et al.), Phys. Rev. Lett. 93, 252301 (2004).
[14] PHENIX Collab. (S. S. Adler et al.), Phys. Rev. Lett. 96, 032302 (2006).
[15] STAR Collab. (J. Adams et al.), Phys. Rev. Lett. 95, 112301 (2005).
[16] PHENIX Collab. (A. Adare et al.), Phys. Rev. Lett. 98, 172301 (2007).
[17] M. Asakawa et al., Phys. Rev. Lett. 96, 252301 (2006).
[18] STAR Collab. (J. Adams et al.), Phys. Rev. Lett. 92, 062301 (2004).
[19] STAR Collab. (J. Adams et al.), Phys. Rev. Lett. 97, 162301 (2006).
[20] PHENIX Collab. (A. Adare et al.), Phys. Rev. Lett. 98, 232302 (2007).
[21] STAR Collab. (B. I. Adare et al.), 0805.0622[nucl-ex] (2008).
[22] CERES Collab. (G. Agakichiev et al.), Phys. Rev. Lett. 92, 032301 (2004).
[23] V. A. Okorokov and K. V. Filimonov, in Proceedings of the VIII International workshop "Relativistic nuclear physics: from hundreds MeV to TeV". Dubna, JINR, 2006, p. 165.
[24] V. A. Okorokov, in Proceedings of the XXXIII International Conference of High Energy Physics (ICHEP 2006). World Scientific 1, 389 (2007); nucl-th/0611005 (2006).
[25] V. A. Okorokov, Yad. Fiz. 72, 2009 (in press).
[26] D. Kharzeev, R. D. Pisarski, M. H. G. Tytgat, Phys. Rev. Lett. 81, 512 (1998).
[27] D. Kharzeev, private communications.
[28] D. Kharzeev, L. D. McLerran, H. J. Warringa, Nucl. Phys. A 803, 227 (2008).
[29] S. Voloshin, Phys. Rev. C 70, 057901 (2004); hep-ph/0406125 (2004).
[30] S. Voloshin, 0806.0029 [nucl-ex] (2008).