Vortex rings in heavy-ion collisions at energies $\sqrt{s_{NN}} = 3–30$ GeV and possibility of their observation

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The ring structures that appear in Au+Au collisions at collision energies $\sqrt{s_{NN}} = 3–30$ GeV are studied. The calculations are performed within the model of three-fluid dynamics. It is demonstrated that a pair of vortex rings are formed, one at forward and another at backward rapidities, in ultra-central Au+Au collisions at $\sqrt{s_{NN}} > 4$ GeV. The vortex rings carry information about early stage of the collision, in particular about the stopping of baryons. It is shown that these rings can be detected by measuring the ring observable $R_\Lambda$ even in rapidity range $0 < y < 0.5$ (or $-0.5 < y < 0$) on the level of 0.5–1.5% at $\sqrt{s_{NN}} = 5–20$ GeV. At forward/backward rapidities, the $R_\Lambda$ signal is expected to be stronger. Possibility of observation of the vortex-ring signal against background of non-collective transverse polarization is discussed.

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I. INTRODUCTION

Vortex rings are inherent in fluid dynamics. They are developed in a cylindrically symmetric flow of fluid with the longitudinal velocity depending on the radius. Such flow results in formation of toroidal vorticity structures, i.e. the vortex rings. An example of such vortex rings is the smoke rings.

Formation of vortex rings in heavy ion collisions at high collision energies, $\sqrt{s_{NN}} = 40–200$ GeV, was predicted in hydrodynamic \cite{1} and transport \cite{2,3} simulations. Later, the vortex rings were reported at lower energy of 7.7 GeV in simulations in Refs. \cite{4,5}. Earlier, ring-like structures, i.e. half rings, were noticed in semi-central Au+Au collisions at even lower energy of 5 GeV \cite{6,7}. The authors of Refs. \cite{6,7} called this specific toroidal structure as a femto-vortex sheet. In recent paper \cite{8}, formation of the vortex rings was predicted in Au+Au collisions at $\sqrt{s_{NN}} = 7.7–11.5$ GeV and even at 4.5 GeV, where the ring structure turns out to be more diffuse.

Formation of vortex rings is a consequence of partial transparency of colliding nuclei at high energies. The matter in the central region is more strongly decelerated because of thicker matter in the center than that at the periphery. Therefore, two vortex rings are formed at the periphery of the stronger stopped matter in the central region, one at forward rapidities and another at backward rapidities. The peripheral matter acquires a rotational motion. Matter rotation is opposite in these two rings. A schematic picture of the vortex rings is presented in Fig. 1.

The partial transparency takes place at the early stage of the collision, even before equilibration of the produced matter. It determines the strength of vorticity in the vortex rings. Therefore, the vortex rings carry information about this early stage of the collision.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{vortex_rings.png}
\caption{(Color online) Schematic picture of the vortex rings at forward/backward rapidities. Curled arrows indicate direction of circulation of the matter.}
\end{figure}

In Ref. \cite{9}, the analysis of the toroidal vortex structures was extended to proton-nucleus collisions. It was predicted that vortex rings are created in such collisions at the energy of $\sqrt{s_{NN}} = 200$ GeV. Vortex rings produced by jets propagating through the quark-gluon medium were considered in Ref. \cite{10}. The above predictions \cite{11–10} were obtained within different models. Thus, it looks like the vortex rings are quite common for the high-energy nucleus(nucleus)-nucleus collisions. The question is how to observe them.

Authors of Refs. \cite{9,10} suggested a ring observable

$$R_\Lambda(y) = \left\langle \frac{P_\Lambda \cdot (e_z \times p)}{|e_z \times p|} \right\rangle_y ,$$

(1)

where $P_\Lambda(p)$ is the polarization of the $\Lambda$ hyperon, $p$ is its spacial momentum, and $e_z$ is the unit vector along the beam, i.e. along $z$ axis. Averaging $\langle \ldots \rangle_y$ runs over all momenta with fixed rapidity $y$. As argued in Ref. \cite{9,10}, the ring structure may be quantified by means of $R_\Lambda$.

However, the same ring observable turns out to be nonzero in proton-proton and proton-nucleus collisions, see, e.g., Refs. \cite{11,12} where a brief survey of earlier experiments is also presented. It is referred as a transverse...
polarization in those experiments. At least in proton-proton reactions, the nonzero $R_\Lambda$ is related to the correlation of the produced $\Lambda$ with beam direction rather than to the collective ring structure. To be precise, only the collective contribution to $R_\Lambda$ due to the vortex rings are estimated below while the discussion of the background of direct $\Lambda$ production is postponed to the end of the paper.

This ring observable was applied to analysis of ultra-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [9]. It was found that nonzero values of $R_\Lambda$ appear only at rapidities $|y| > 4$, i.e. far beyond the midrapidity window accessible in collider experiments. Therefore, questions arise: (i) whether the vortex rings can be observed at lower-energy collider experiments at BES RHIC (Beam Energy Scan program at the Relativistic Heavy Ion Collider) and NICA (Nuclotron-based Ion Collider fAcility) within the experimental midrapidity window and (ii) whether the vortex rings are formed in lower-energy collisions of the STAR fixed-target program (FXT-STAR) at RHIC the forthcoming experiments at the Facility for Antiproton and Ion Research (FAIR), where measurements at backward rapidities are possible?

In the present paper, the ring structures in Au+Au collisions at collision energies $\sqrt{s_{NN}} = 3–30$ GeV are studied and the resulting ring observable is estimated. The calculations are performed within the model of the three-fluid dynamics (3FD) [13]. The 3D approximation is a minimal way to simulate the early, nonequilibrium stage of the produced strongly interacting matter. It takes into account counterstreaming of the leading baryon-rich matter at the early stage of nuclear collisions. This counterstreaming results in formation of the vortex rings.

The simulations are done with two different equations of state (EoS’s): two versions of the EoS with the deconfinement transition [14], i.e. a first-order phase transition (1PT) and a crossover one. The physical input of the present 3FD calculations is described in Ref. [15].

where $n_F(x, p)$ is the Fermi-Dirac distribution function and $m$ is mass of the considered particle. The polarization vector of $S$-spin particle is defined as $P_S^\mu = S^\mu/S$.

Let us first consider the structure of the thermal-vorticity field in heavy-ion collisions in the $x\eta_s$ plane, where $\eta_s = (1/2) \ln \left((t + z)/(t - z)\right)$ is the longitudinal space-time rapidity and $z$ is the coordinate along the beam direction. The advantage of this $\eta_s$ is that it is equal to the kinematic longitudinal rapidity defined in terms of the particle momenta in the self-similar one-dimensional expansion of the system.

The plot of $\varpi_{zx}$ in ultra-central ($b = 0$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 4.9–11.5$ GeV in the $x\eta_s$ plane is presented in Fig. 2. In order to suppress contributions of almost empty regions, the displayed thermal-vorticity $\varpi_{zx}$ is averaged with the weight of proper energy density (also presented in Fig. 2) similarly to that in Refs. [1, 4]. The $x\eta_s$ plane would be a reaction plane in case of non-central collisions. In our case ($b = 0$ fm), all the planes passing through the $z$ axis are equivalent because of the axial symmetry. These are the plots at time instants close to the freeze-out. In order to see correlations of the thermal-vorticity with other quantities, plots of the proper energy density, kinematic $zx$ vorticity

\[ \varpi_{\mu\nu} = (1/2)(\partial_\mu u_\nu - \partial_\nu u_\mu), \]

divided by temperature, $x$-component of the baryon current ($J_x$) and the proper baryon density are also displayed.

As seen, the thermal-vorticity reveals a ring structure similar to that schematically displayed in Fig. 1. The $x\eta_s$ plane is a cut of these rings by the plane passing through the axis of these rings. This ring structure is seen even at $\sqrt{s_{NN}} = 4.9$ GeV. The kinematic $zx$ vorticity (the third column of panels in Fig. 2) reveals the same ring structure. This indicates that these rings are due to the incomplete stopping of the peripheral parts of the colliding nuclei. If the rings were formed as a result of the hydrodynamic quasi-one-dimensional expansion of initially stopped matter, then the sign of $\varpi_{zx}/T$ would be opposite because the longitudinal flow velocity would decrease from the center of the flow to its periphery, as in the case of high-energy proton-nucleus collisions [9].

Comparing the scales of $\varpi_{zx}$ and $\varpi_{zx}/T$ in Fig. 2 we see that approximately half of the magnitude of the thermal vorticity results from derivatives of the inverse temperature.

As seen from Fig. 2 these thermal-vorticity rings correlate with transverse component of the baryon current ($J_x$). It means that the vortical rings expand, which is important for their observation. At the same time, the proper energy and density distributions reveal a disk rather than ring structure although at the same space-time rapidities. At 4.9 GeV, this is already a central fireball rather than two disks.

II. VORTICAL RINGS IN CENTRAL COLLISIONS

The particle polarization is treated within the thermodynamic approach [10], in which it is related to the thermal vorticity

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

where $\beta_\mu = u_\mu/T$ with $u_\mu$ and $T$ being the local collective velocity of the matter and its temperature, respectively. The thermal vorticity is directly related to the mean spin vector of spin 1/2 particles with four-momentum $p$, produced around point $x$ on freeze-out hypersurface

\[ S^\mu(x, p) = \frac{1}{8m}[1 - n_F(x, p)] \rho_\sigma \epsilon^{\mu\nu\rho\sigma} \varpi_{\rho\sigma}(x), \]
FIG. 2: (Color online) Columns from left to right: the proper energy density (GeV/fm$^3$), the proper-energy-density weighted thermal $zx$ vorticity, similarly weighted kinematic $zx$ vorticity divided by temperature ($T$), $x$-component of the baryon current ($J_x$) in units of normal nuclear density ($n_0 = 0.15 ~1/fm^3$), and the proper baryon density ($n_B$) in units of $n_0$ in the $x\eta_s$ plane at time instant $t = 12 ~fm/c$ in the ultra-central ($b = 0 ~fm$) Au+Au collisions at $\sqrt{s_{NN}} = 4.9$–11.5 GeV. $\eta_s$ is the space-time rapidity along the beam ($z$ axis) direction. Calculations are done with the crossover EoS. The bold solid contour displays the border of nuclear matter with $n_B > 0.1n_0$.

At considered moderately relativistic energies, the expansion dynamics of the system is not of the self-similar one-dimensional character. Therefore, the space-time rapidity $\eta_s$ is not equal to the kinematic longitudinal rapidity in terms of the particle momenta. Nevertheless, it can be used to approximately estimate the rapidity location of these vortex rings. As seen from Fig. 2, at 4.9 GeV these rings are located slightly below $|\eta_s| \approx 0.5$ and at $|\eta_s| \approx 0.5$, if $\sqrt{s_{NN}} = 7.7$ GeV. This location does not restrict their observation because the FXT-STAR experiments allow measurements at very backward rapidities. At $\sqrt{s_{NN}} = 11.5$ GeV, where the estimation in terms of $\eta_s$ is more reliable, these vortex rings are already located at $|\eta_s| \approx 0.5$–1.0, which is slightly beyond the rapidity window of the collider experiment. Nevertheless, the inner parts of these rings are still at $|\eta_s| < 0.5$. Therefore, their effect can be observed.

III. RING OBSERVABLE

To quantify the above qualitative considerations, let us turn to the ring observable of Eq. 1. Our goal is to estimate the expected ring observable in the ultra-central ($b = 0 ~fm$) Au+Au collisions rather than to calculate it.

In terms of hydrodynamic quantities, the contribution of an element of the freeze-out surface $d\Sigma_\nu$ to the ring observable reads

$$R_\Lambda(x,p) = \frac{\epsilon^{\mu\nu\rho\sigma}P_\Lambda^{\mu}n_\nu e_\rho p_\sigma}{|\epsilon^{\mu\nu\rho\sigma}n_\nu e_\rho p_\sigma|}.$$  \hspace{1cm} (4)

where $e^\sigma = (0,0,0,1)$ is the unit vector along the beam ($z$) axis, $n_\nu$ is the normal vector to the element of the freeze-out surface. This expression coincides with Eq. (10) in Ref. [9].

To calculate the ring observable $R_\Lambda(y_h)$, $R_\Lambda(x,p)$ should be averaged over the whole freeze-out surface $\Sigma$ and particle momenta

$$R_\Lambda(y_h) = \frac{\int (d^3p/p^0) \int_{\Sigma(y_h)} d\Sigma_\Lambda p^\Lambda n_\Lambda(x,p) R_\Lambda(x,p)}{\int (d^3p/p^0) \int_{\Sigma(y_h)} d\Sigma_\Lambda p^\Lambda n_\Lambda(x,p)},$$ \hspace{1cm} (5)

where $n_\Lambda$ is the distribution function of $\Lambda$’s. Here the approximation has already been made: the constraint of fixed rapidity ($y$) imposed on the momentum integration is replaced by that of fixed hydrodynamical rapidity

$$y_h = \frac{1}{2} \ln \frac{u^0 + u^3}{u^0 - u^3},$$ \hspace{1cm} (6)

based on hydrodynamical 4-velocity $u^\mu$, similarly to that in Ref. [17]. The $y_h$ constraint is imposed on the freeze-out surface integration and is denoted as $\Sigma(y_h)$ in Eq.
At moderately relativistic energies, the hydrodynamic rapidity is a more reliable approximation to the true rapidity than the space-time rapidity \( \eta_s \).

Let us further proceed with approximations. Similarly to that in Ref. \[17\], let us use a simplified version of the freeze-out, i.e., an isochronous one that implies \( n_s = (1, 0, 0, 0) \) and \( \frac{d(p^4 p^0) \Sigma \rho}{d^3 p} = d^3 p \). The freeze-out instant is associated with time, when the energy density averaged over the central region reaches the value deduced from the conventional 3FD freeze-out. In conventional 3FD simulations, a differential, i.e. cell-by-cell, freeze-out is implemented \[18\].

Expression (3) for \( S^R_\Lambda(x,p) \) is also simplified. The factor \( (1 - n_\Lambda) \approx 1 \) is taken because the \( \Lambda \) production takes place only in high-temperature regions, where Boltzmann statistics dominates. As spatial components of \( \varpi_{\mu \nu}(x) \) are of the prime interest, the approximation \( \varpi_{\mu \nu} \approx \varpi_{00} \approx m_\Lambda \varpi_{\mu \nu} \) is made. The latter approximation, \( \varpi_{00} \approx m_\Lambda \), reduces \( S^R_\Lambda(x,p) \), which is quite suitable for the purpose of upper estimate of the ring observable. The boost of \( S^R_\Lambda(x,p) \) is neglected, which also reduces \( S^R_\Lambda(x,p) \). After application of all these approximations, \( S^R_\Lambda \) and hence \( P^R_\Lambda \), becomes momentum independent. Therefore, the momentum averaging in Eq. \[5\] can be performed first, leaving \( P^R_\Lambda \) beyond the scope of this averaging:

\[
R_\Lambda(y_h) \approx \frac{\int_{\Sigma(y_h)} d^3 x \rho_\Lambda(x) \frac{P^\Lambda \cdot (u \times e_z)}{(u_T^2 + 2T/m_\Lambda)^{1/2}}}{\int_{\Sigma(y_h)} d^3 x \rho_\Lambda(x)},
\] (7)

where \( \rho_\Lambda(x) \) is the density of \( \Lambda \)’s, \( u_T \) is transverse component of the fluid velocity, and \( T \) is the temperature. This expression is obtained in the non-relativistic approximation for the transverse collective motion. Indeed, at the freeze-out \( T \approx 100 \text{ MeV} \ll m_\Lambda \) and \( v_T \lesssim 0.4 \) at midrapidity \[19\]. At the forward/backward rapidities considered here, these values are even smaller. Here \( (u_T^2 + 2T/m_\Lambda)^{1/2} \) stands for \( \langle |p_T| \rangle / m_\Lambda \).

It is important that the system together with the vortex rings radially expands at the freeze-out stage. This expansion even determines the sign of \( R_\Lambda \), as seen from Eq. \[7\]. The contributions to \( R_\Lambda \) from particles emitted along the \( u \) (more precisely, with momenta \( p_T \cdot u_T > 0 \)) and in opposite to \( u \) directions (i.e. \( p_T \cdot u_T < 0 \)) partially cancel each other. The effect of this partial cancellation is described by the \( (u_T^2 + 2T/m_\Lambda)^{1/2} \) denominator in Eq. \[7\]. This cancellation is negligible if the speed of the radial expansion is much larger than the thermal velocity of the fluid constituents.

Based on the axial symmetry of the ultra-central \( (b = 0) \) collisions, averaging in Eq. \[7\] can be restricted by the quadrant \( (x > 0, z > 0) \) of the “reaction” plane \( xz \), the \( (x > 0, \eta_s > 0) \) quadrant in Fig. \[2\], if \( y_h > 0 \). For negative \( y_h \), it is \( (x > 0, z < 0) \) quadrant. Thus, this averaging becomes identical to that done in Ref. \[17\] for calculation of the global polarization but in a restricted region, i.e. the \( (x > 0, z > 0) \) quadrant. The only difference is that the averaging over cells runs with additional weight \( x \ u_x/(u_x^2 + 2T/m_\Lambda)^{1/2} \), where \( x \) takes into account that the integration runs over \( rdr \ dz \) in cylindrical coordinates at fixed azimuthal angle.
Fig. 4: (Color online) Time dependence of the $R_\Lambda$ quantity, averaged over rapidity range of $0 < y < 0.6$ (solid line) and at $y = 0.5$ (dashed line), in the ultra-central ($b = 0$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV. Calculations are done with the crossover EoS.

Fig. 5: (Color online) Rapidity dependence of the $R_\Lambda$ quantity in the ultra-central ($b = 0$) Au+Au collisions at $\sqrt{s_{NN}} = 3.3–19.6$ GeV. Calculations are done with the crossover (left panel) and 1PT (right panel) EoS’s.

IV. SUMMARY AND DISCUSSION

The ring structures that appear in Au+Au collisions at energies $\sqrt{s_{NN}} = 3 – 30$ GeV were studied, and the resulting ring observable was estimated. The calculations were performed within the 3FD model [13]. It was demonstrated that a pair of vortex rings are formed, one at forward and another at backward rapidities, in ultra-central Au+Au collisions at $\sqrt{s_{NN}} \gtrsim 4$ GeV. The matter rotation is opposite in these two rings. They are formed because at the early stage of the collision the matter in the vicinity of the beam axis is stronger decelerated than that at the periphery. Thus, the vortex rings carry information about this early stage, in particular about the stopping of baryons.

Such 3FD dynamics with the incomplete stopping turned out to be successful in describing the global $\Lambda$ polarization [17, 21], bulk [15, 22] and flow [23, 24] observables at moderately relativistic energies. Therefore, the present predictions of the vortex rings have a solid background.

These rings can be detected by measuring the ring observable $R_\Lambda$ even in rapidity range $0 < y < 0.5$ (or $-0.5 < y < 0$). The $R_\Lambda$ signal is stronger in wider rapidity ranges. For instance, magnitude of the ring observable may reach values of 2–3% at $\sqrt{s_{NN}} = 5–20$ GeV, if rapidity window is extended to $0 < y < 0.8$. Measurements in fixed-target experiments, such as FXT-STAR and the forthcoming experiments at FAIR, give additional advantage. They allow measurements at backward rapidities, where the $R_\Lambda$ signal is expected to be more pronounced.

Only ultra-central Au+Au collisions were considered in this paper because the axial symmetry of the system makes the $R_\Lambda$ estimation easier in this case. Asymmetric vortex rings are also formed in semi-central collisions at $\sqrt{s_{NN}} > 5$ GeV. The corresponding $R_\Lambda$ polarization should be asymmetric in the reaction plain.

The $R_\Lambda$ quantity also contains contribution of direct $\Lambda$ production with the $\Lambda$ polarization correlated with beam direction. In heavy-ion collisions this type of polarization is expected to be diluted due to rescatterings in the medium [25, 26]. A vanishing $\Lambda$ polarization has been proposed as a possible signature for the formation of a Quark Gluon Plasma (QGP) in relativistic heavy-ion collisions [25]. This prediction was one of motivations of the experimental study of the transverse polarization of $\Lambda$ hyperons produced in Au+Au collisions (10.7A GeV) [27]. The result revealed no significant differences of the polarization from those observed in $pp$ and $pA$ collisions. However, the question of the nature of the obtained polarization remains open, i.e., which part of it results from the direct $\Lambda$ production and which part, from to vortex rings.

Different transverse-momentum dependence may be used to distinguish these two mechanisms of the transverse polarization. While the magnitude of the transverse polarization due to the direct $\Lambda$ production linearly rises with $\Lambda$ transverse momentum, low-$p_T$ $\Lambda$’s should dominate in the $R_\Lambda$ due to vortex rings because these rings are collective phenomena. The $p_T$ dependence of the vortex-ring $R_\Lambda$ is expected to be decreasing, similarly to that for the global polarization [28, 30]. Therefore, limiting the transverse momentum from above would enhance the contribution of the vortex rings.

Any case, the calculations of the $R_\Lambda$ due to vortex rings
should be complemented by simulations of the $Λ$ transverse polarization due to the direct $Λ$ production, similarly to that done for the ultra-central Au+Au collisions at $\sqrt{s_{NN}} = 9$ GeV in Ref. [31]. That simulation disregarded the polarization dilution due to rescatterings in the medium. Therefore it gave the upper limit ($\approx -5\%$) on magnitude of the mean transverse $Λ$ polarization. For the practical use, such simulations should take into account this dilution [26].

The transverse $Λ$ polarization measured in $pp$ collisions so far is consistent with zero [32]. On the other hand, this dilution [26] should be complemented by simulations of the $Λ$ transverse polarization due to the direct $Λ$ production, similarly to that done for the ultra-central Au+Au collisions at $\sqrt{s_{NN}} = 9$ GeV in Ref. [31]. That simulation disregarded the polarization dilution due to rescatterings in the medium. Therefore it gave the upper limit ($\approx -5\%$) on magnitude of the mean transverse $Λ$ polarization. For the practical use, such simulations should take into account this dilution [26].

Therefore, $R_Λ$ looks to be a good observable to detect the vortex rings.

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