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Interferometry for rotating sources

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ABSTRACT

The two particle interferometry method to determine the size of the emitting source after a heavy ion collision is extended. Following the extension of the method to spherical expansion dynamics, here we extend the method to rotating systems. It is shown that rotation of a cylindrically symmetric system leads to modifications, which can be perceived as spatial asymmetry by the "azimuthal HBT" method. We study an exact rotating and expanding solution of the fluid dynamical model of heavy ion reactions. We consider a source that is azimuthally symmetric in space around the axis of rotation, and discuss the features of the resulting two particle correlation function. This shows the azimuthal asymmetry arising from the rotation. We show that this asymmetry leads to results similar to those given by spatially asymmetric sources.

1. Introduction

Recently [1], by the experimental study of Λ and $\bar{\Lambda}$ polarization in Au + Au reactions in the energy range of $\sqrt{s_{NN}} = 7.7$–39 GeV/nucl., significant polarization of hyperons was detected. Furthermore the Λ and $\bar{\Lambda}$ polarizations pointed in the same direction that verified the mechanical, equipartition origin of the polarization in contrast to electromagnetic origin, which would have led to opposite polarizations for Λ and $\bar{\Lambda}$. The data were subsequently analyzed quantitatively [2] for energies $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4$ GeV, and emission energy and azimuth averaged polarizations of 1–5% were obtained, with $1.1 - 3.6\sigma$ significance. The polarization was pointing in the $-y$-direction, consistent with the angular momentum of peripheral collisions.

These measurements are in agreement with earlier hydro predictions of rotation [3] and turbulence [4], where vorticity and polarization were predicted [5,6] in the same direction, and the decrease of polarization with increasing energy was also observed and discussed in the calculations [5], as it was also observed in the recent, above mentioned experiments.

The experimental results indicate actually very strong rotation, because it is observed and significant in azimuthally averaged data, while the theoretical predictions showed similarly high level of polarization only for high p_x-particles in the reaction plane. The experimental data indicate also that the rotation is stronger at lower beam energies. This can be the consequence of competition among rotation, expansion and temperature decrease, indicating that rotation remains strongest at freeze out for lower energy collisions.

The other method to detect rotation is the study of two-particle correlations. Although there is nothing novel in the fact that collective flow, of any sort, influences the naively detected size of the source (as it was first pointed out by S. Pratt for radial expansion [7]), it was only pointed out recently how rotation effects the two-particle correlation results [8–10]. This was demonstrated in a full scale hydrodynamical model, PICR [8], as well as in a simplified exact hydrodynamical model [10]. As these works preceded the experimental detection of rotation, the theoretical models were applied for higher energies [8] and the exact model was presented using these parameters with smaller final angular velocities. The experiments now show that rotation at $\sqrt{s_{NN}} = 7.7$ GeV is more than 5 times stronger than at $\sqrt{s_{NN}} = 62.4$ GeV.

Here we point out an other important consequence of rotation, and for simplicity we use the exact hydrodynamic solutions for three dimensional, rotating and expanding cylindrically symmetric fireball [11–14].

The created system in relativistic heavy-ion collisions is microscopic and short-lived, so only the momentum spectrum of the emitted particles can be measured directly. However, the space–time structure of the collision region can be studied using Hanbury-Brown–Twiss interferometry [9]. This technique uses two particle correlations to probe the space–time shape of the parti-

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Table 1
Time dependence of characteristic parameters of the fluid dynamical calculation presented in Ref. [12]. R is the average transverse radius, Y is the longitudinal length of the participant system, φ is the angle of the rotation of the interior region of the system, around the y-axis, measured from the horizontal, beam, z-direction in the reaction, $[x, z]$, plane, $\dot{R}$ and $\dot{Y}$ are the speeds of expansion in transverse and longitudinal directions, and ω is the angular velocity of the internal region of the matter.

t (fm/c)	Y (fm)	$\dot{Y}$ (c)	ω (c/fm)	R (fm)	$\dot{R}$ (c)	φ (Rad)
0.	4.000	0.300	0.150	2.500	0.250	0.000
3.	5.258	0.503	0.059	3.970	0.646	0.307
8.	8.049	0.591	0.016	7.629	0.779	0.467

cle emission zone. The size and particularly the shape of reaction zone become thus accessible, with the “azimuthal HBT” method [15–21].

In this work we show that the naive use of “azimuthal HBT” leads to misleading results in case of rotation, just as expansion effects the apparent radial size of the system [7]. We here calculate two pion correlation function for a rotating and expanding QGP, formed in Pb + Pb collisions by using the exact hydro model [11,12], and we determine the effect of rotation on the correlation function (CF) for detectors at different positions. Finally we fit results by “azimuthal HBT” to extract the apparent size of the rotating system in different directions, although the exact model has no azimuthal asymmetry at all!

2. Correlation function

We use a simple Exact Model [11] for expanding and rotating systems to demonstrate the sensitivity of the two particle correlation method to diagnose rotation. Both polarization [22] and the two particle correlation [10] were already evaluated for this exact model, with parametrizations adapted for very high energy $\sqrt{s_{NN}} = 2.76$ TeV, peripheral heavy ion collisions [12]. Thus here we only present the model and the calculation of two particle correlations very briefly as this is done already in [10].

We consider an azimuthally symmetric system around the rotation axis, y, with Gaussian density profiles with characteristic radii, R and Y and constant temperature $T = 200$ MeV. The initial parameters are given in Table 1, for the very high energy collision, however, as recent experiments show at lower energies more than 5 times larger angular velocity is relevant.

The source function, $S(x, k)$, giving the emission rate in the phase space, x, k, should be integrated over all points, x, of the emitting source to obtain the correlation function:

$$\int d^4x S(x,k) \propto \int w_s \gamma_s \left(k_0 + \boldsymbol{k}\cdot\boldsymbol{v_s}\right) \times \exp\left[-\frac{\gamma_s}{T_s}\left(k_0 - \boldsymbol{k}\cdot\boldsymbol{v_s}\right)\right] e^{-s_\rho/2} e^{-s_y/2} \frac{ds_y\, ds_\rho\, d\varphi}{\sqrt{(s_y)}} . \tag{1}$$

Here the spatial integral is performed in cylindrical coordinates, s_y, s_ρ, φ, where s_y, and s_ρ are scaling variables, $s_y = y^2/Y^2$ and $s_\rho = (x^2 + z^2)/R^2$.

The correlation function was evaluated the same way as in Ref. [10]. We should see that the source function explicitly depends on the velocity field, $\boldsymbol{v_s}$, which includes both the expansion and the rotation of the system.

As the rotation axis is the y-axis, the $[x, z]$ plane is the reaction plane. Due to the azimuthal symmetry the radius of the system in the $[x, z]$ plane is R.

According to the conventions of two particle correlation functions in Heavy Ion Physics, the z-axis is the beam axis and determines the LONG direction. In the transverse plane, the x-axis (the direction of impact parameter) is transverse to the beam direction. In this way the OUT direction is the x-direction. The remaining y-axis determines the SIDE direction. Due to the azimuthal symmetry of our specific model the results for the LONG and OUT directions should be identical.

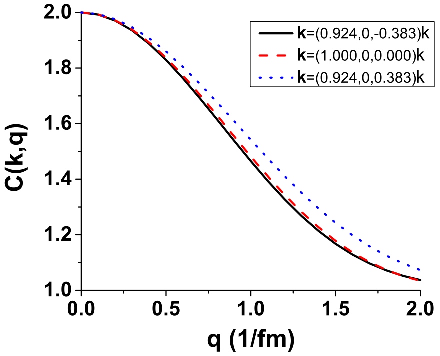

Fig. 1. (Color online.) Correlation Function, $C(k, q)$, for the exact hydro model for the $q = q_{OUT}$ direction. R = 2.50 fm, $\dot{R} = 0.25$ c, Y = 4.00 fm, $\dot{Y} = 0.30$ fm, $\omega = 0.30$ c/fm, at t = 0.0 fm/c with k = 5 fm^{-1}. The solid black line is for measuring the correlation function at $\boldsymbol{k}^- = (0.924, 0, -0.383)k$, the dashed red line is for $\boldsymbol{k} = (1, 0, 0)k$ and the dotted blue line is for $\boldsymbol{k}^+ = (0.924, 0, 0.383)k$.

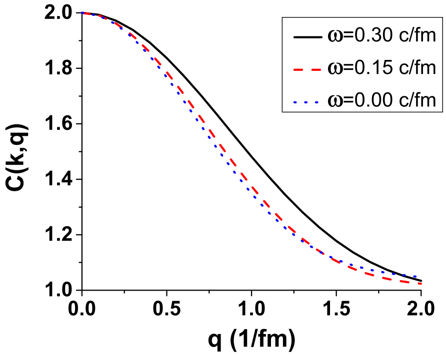

Fig. 2. (Color online.) Correlation Function, $C(k, q)$, for the exact hydro model, for the $q = q_{OUT}$ direction. $R = 2.50$ fm, $\dot{R} = 0.25$ c, $Y = 4.00$ fm, $\dot{Y} = 0.30$ fm at t = 0.0 fm/c with k = 5 fm^{-1}. The solid black line is for $\omega = 0.30$ c/fm, the dashed red line is for $\omega = 0.15$ c/fm and the dotted blue line is for $\omega = 0.00$ c/fm.

The velocity field in x, y, z coordinates is given by

$$\boldsymbol{v}_s = \Big(\dot{R}\sqrt{s_\rho}\,\sin(\varphi) + R\omega\sqrt{s_\rho}\,\cos(\varphi), \; \dot{Y}\sqrt{s_y}, \dot{R}\sqrt{s_\rho}\,\cos(\varphi) - R\omega\sqrt{s_\rho}\,\sin(\varphi)\Big) , \tag{2}$$

where ω is the angular velocity, and φ is the angle of rotation around the y-axis, and counted from the z-axis.

The mean transverse radius is $R = \sqrt{XZ}$, and we use this value when the exact model is studied.

In the practical calculations we use a detectors placed at $\boldsymbol{k}^+ = (k_x, k_y, k_z)k = (0.924, 0, 0.383)k$, $\alpha_{\boldsymbol{k}} = -22.5°$; $\boldsymbol{k} = (1, 0, 0)k$, $\alpha_{\boldsymbol{k}} = 0°$ and $\boldsymbol{k}^- = (0.924, 0, -0.383)k$, $\alpha_{\boldsymbol{k}} = 22.5°$ which are orthogonal to the rotation axis, $\boldsymbol{y}$.

3. Results

We calculate the CF for different values of the angular velocity, ω, to see how it is affected. The CFs are shown in Figs. 1 and 2.

Subsequently the correlation functions are fitted by the azimuthal HBT method and parametrization:

$$C(q,k) = 1 + exp\left(-\sum_{i,j=L,O,S} q_i q_j R_{ij}^2(k)\right) , \tag{3}$$