Two-Proton Correlations Relative To The Reaction Plane

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I. INTRODUCTION

Studies of the collective flow of hadrons in all of its forms - directed, elliptic, radial is an important direction in the understanding of the physics of heavy-ion collisions \cite{1}. The asymmetries observed in azimuthal distributions in momentum space imply underlying asymmetries in configuration space. But the experimental information about spatial properties of the flowing nuclear systems is at best sparse and is mostly obtained with pion measurements. The E877 collaboration reported \cite{2} that the parameters of the pion source created in Au+Au collisions at 10.8 AGeV/c appear to be different for particles emitted at different angles relative to the reaction plane. The information about space-time properties of the proton effective source involved in directed flow is totally absent. Since nucleons are the main carriers of the directed flow in nucleus nucleus collisions at the AGS energies, it is interesting to check whether the parameters of the nucleon source, probed with the help of two-proton correlations, exhibit any dependencies or asymmetries related to the reaction plane orientation. In this paper we present the preliminary results of the first study of the proton correlation function’s dependence on the orientation of the reaction plane.

II. EXPERIMENTAL SETUP

The measurements are made by the E877 collaboration at the BNL AGS during the 1994 run. The details of the E877 experimental setup can be found elsewhere \cite{3,4,5}. Here we will only briefly describe its features relevant to the present analysis. A set of two high granularity sampling calorimeters positioned around the target area provide an event by event measurement of the transverse energy ($E_T$) production in the interval of pseudo rapidity $-2.0<\eta<4.7$. A high-resolution forward magnetic spectrometer has been used for detection and identification of charged particles. Simultaneous measurements of the particle rigidity and time of flight in the spectrometer provide particle identification up to the momentum of the beam. The momentum resolution, found from Monte Carlo studies, is better than 3\% over the entire momentum range. The momentum resolution is in good agreement with the momentum dependence of the measured width of the charged particle mass peaks. Corresponding relative invariant momentum resolution is estimated to be of order of 7 MeV/c for $_{inv} \leq 40$MeV/c. In the same interval of $_{inv}$ the average rapidity of the protons is about 2.6 and the average transverse momentum about 0.3 GeV/c. Note that beam rapidity is about 3.1.

III. METHODS

A. Reaction Plane Determination

The reaction plane is a fundamental plane of symmetry of the reaction. Knowledge of it is clearly important for the two-particle correlation analysis which attempts to extract information about the spatial-temporal structure of the system created in the collision. Broad pseudo rapidity coverage and high segmentation of the E877 calorimeters provide the experiment with the information about the reaction plane. The method of an event by event reaction plane determination without particle identification is based on the idea of performing a Fourier analysis on the transverse energy deposited in a fixed pseudo-rapidity window \cite{3,4,5}. The Fourier coefficients of the expansion are given by:

\[ a_n = \frac{\sum_i \epsilon_i \cos(n\phi_i)}{\sum_i \epsilon_i}, \quad b_n = \frac{\sum_i \epsilon_i \sin(n\phi_i)}{\sum_i \epsilon_i}, \]  

(1)

where $\phi_i$ is the azimuthal angle of the $i$-th detector cell and $\epsilon_i$ is the energy deposited in that cell. The $n=1$ Fourier coefficients hold information regarding the azimuthal orientation of the energy flow in the collision. The vector $\text{Flow} = (a_1, b_1)$ points in the direction where most of the transverse energy is carried by the particles emitted from the collision zone. To put it another way, this vector is related to the azimuthal orientation of the impact parameter. Therefore, the azimuthal angle of the reaction plane may be determined as:

\[ \phi = \arctan\left(\frac{b_1}{a_1}\right). \]
\[ \psi_{\text{reac}} = \tan^{-1} \left( \frac{b_1}{a_1} \right) \] (2)

From the naive geometrical considerations one would expect that the proton source will be at its most symmetric configuration at impact parameter zero and maximum asymmetry will be at maximal impact parameter. So in order to study the reaction plane dependence one would need to use the most peripheral event sample. The interval of centralities chosen for our analysis represents a compromise between the necessity of a high statistics sample and the desire to utilize the least central collisions with the best achievable reaction plane resolution as well as a need for a fairly narrow interval of impact parameter. Events with centrality within the interval from 9% to 6% of total geometrical cross section are selected for this analysis. The reaction plane resolution at this centrality interval is about 40 degrees and is close to best achievable by the E877 setup.

**B. Proton Correlations**

Two-proton correlations are due to the attractive strong and repulsive Coulomb final state interactions and are also influenced by the effects of quantum statistics which requires an antisymmetrization of the two-proton wave function. Coulomb repulsion, together with antisymmetrization, decreases the probability of detection of pairs with relative momentum close to zero, while the strong interaction increases this probability. The interplay of these effects lead to a characteristic “dip+bump” shape of the correlation function. The height of the peak of the correlation function can be related to the space-time parameters of the emitting source. It has been shown \[7,8\] that, for simple static sources, the height, by which the peak deviates from unity, scales approximately inversely proportional to the source volume.

The experimental correlation function \( C_2 \) is defined as:

\[ C_2(P_{\text{cm}}) = \frac{N_{\text{tr}}(P_{\text{cm}})}{N_{\text{bk}}(P_{\text{cm}})} \] (3)

where \( P_{\text{cm}} \) is a momentum difference in the pair’s rest frame. For pairs of the same mass \( P_{\text{cm}} \) is equal to the four-momentum difference:

\[ P_{\text{cm}} = Q_{\text{inv}} = \sqrt{-(p_1^\mu - p_2^\mu)^2} \] (4)

The conventional variable for two-proton correlation studies is \( q_{\text{inv}} = \frac{1}{2} Q_{\text{inv}} \). \( N_{\text{tr}} \) and \( N_{\text{bk}} \) in (1) are the “true” and “background” two-particle distributions obtained by taking particles from the same and different events, respectively. A condition that the two particles do not share the same slat of the TOF hodoscope has been imposed on pairs from both distributions. In order to account for the distortions of the correlation function introduced by the two-track reconstruction inefficiency in high multiplicity events, cuts on separation of two tracks in the drift chambers are introduced. Monte Carlo studies show that the cuts effectively suppressed these distortions. In addition to standard cuts on pairs, more selection criteria are introduced. Proton pairs are subdivided into several groups depending on the azimuthal angle of emission relative to the reaction plane angle. For true pairs, both protons in a pair were required to have an angle of emission relative to the reaction plane to be within a certain interval.

Figure 1 presents a visualization of the cuts on the angles relative to the reaction plane. In the mixed events pool, every particle has its angle relative to the reaction plane stored as a part of its data structure. Subsequently, during the event mixing procedure, particles that make pairs are required to satisfy the same cuts on the angle relative to the reaction plane as were imposed on the true pairs.

**IV. RESULTS AND DISCUSSION**

1. **Opposite Side vs Same Side**

   This is the simplest possible cut. Pairs are divided into two subsets depending on the direction of the particle’s emission angle relative to the reaction plane. The “same side” subset is defined in the following way: each proton of a pair is required to have a positive cosine of the angle relative to the direction of the reaction plane. The “same side” subset yields 753k proton pairs. The “opposite side” subset is comprised of pairs with a negative cosine of the angle relative to the reaction plane. It has 568k pairs.

   Figure 2 shows the two-proton correlation functions for these two subsets. One can conclude from the figure that there is no significant differences between the “same side” and “opposite side” correlation functions.
Another set of cuts is intended to probe the differences between particles emitted close to the reaction plane and particles emitted out of the reaction plane. The “in-plane” subset is defined as having the absolute value of the cosine of an angle between the particle and the reaction plane direction smaller than \( \cos(\pi/4) \). Both particles of a pair are required to be in the same quadrant. In the case when the cosine is greater than \( \cos(\pi/4) \) pairs are labeled as emitted “out of plane”. The “in-plane” sample yields 596k events, the “out-of-plane”, 582k pairs.

Figure 3 shows the two-proton correlation functions for these “in-plane” and “out-of-plane” subsamples. It can be seen from the figure that there are no statistically significant differences between “in-plane” and “out-of-plane” correlation functions. However, both subsamples yielded correlation functions with peaks which are significantly higher than the correlation function for the case when no cut on the angle relative to reaction plane is imposed. Similar trend can be also observed on Figure 2 though it is not as pronounced. This behavior may be explained within the picture suggested by Voloshin [9] - a transverse radial expansion of the proton source which moves sideward in reaction plane. This model seems to be able to explain the behavior of some rather detailed features of the proton and pion directed flow [5,10]. In this framework the observed behavior of the proton correlation functions may be explained by a correlation between position and direction of emission induced by transverse expansion of the flowing system. Angular cuts select particles emitted in the same direction in the azimuthal plane (lower relative momentum) which are likely to be on the same “side” of the expanding system (smaller spatial separation). Both effects “amplify” the peak of the correlation function.

V. MODEL CALCULATIONS

In order to extract more physical information from the measured correlation function, we carried out a study using the phase space produced by the event generator RQMD(v2.3) [12,13]. This model describes classical propagation of the particles, together with quantum effects of stochastic scattering and Pauli blocking. It includes color strings and ropes, baryon and meson resonances, as well as finite formation time for created particles. It has been successful in the description of many features of relativistic heavy-ion collisions. In this model a particle’s freeze-out position is defined as a point of the last strong interaction. The structure of our approach is as follows: by taking the freeze-out phase-space distribution generated by RQMD and propagating the particles through the experimental acceptance, accounting for the resolution of the detectors, a subset of the phase-space points is obtained. Then the Koonin-Pratt method [14,15] is used to construct the proton-proton correlation function. This method provides a description of the final state interactions between two protons and antisymmetrization of their relative wave function.

Simulated pairs are subjected to the same cuts as real data. Angular cuts are performed relative to the impact parameter direction of the RQMD events. As an example Figure 6 shows the results of the calculations with “in-plane” cuts together with the calculated correlation function without the reaction plane cuts. It is clear that the model correlation functions exhibit behavior qualitatively similar to the one observed in data. Note that correlation functions on Figures 5 and 6 have different binning. Figure 6 shows calculated and measured correlation functions for the proton pairs emitted “in-plane”. One can see that the agreement between data and model calculations is rather good. Assuming that RQMD simulates the freeze-out phase-space and configuration space distributions correctly, one can try to gain some insight from studying the parameters of the proton source in RQMD. Statistical parameters of the distributions in relative coordinates and emission times are listed in the Table I. An interesting feature that can be seen from the Table I is that the difference between parameters of the two subsamples is less then half fermi. A case of a chaotic static source can not account for an observed difference in peak height of the correlation functions with and without angular cut. The difference is due to a momentum-position correlation of the model source.

| RMS     | \( \Delta X \) | \( \Delta Y \) | \( \Delta Z \) | \( \Delta cT \) |
|---------|----------------|----------------|----------------|----------------|
| In-Plane Cut | 5.44           | 5.36           | 16.9           | 18.36          |
| All pairs    | 5.80           | 5.83           | 16.4           | 18.66          |

1For details of model analysis of the influence of radial transverse expansion on two-proton correlation function see [11].
2For brevity sake we will limit our discussion to the “in-plane” cut. The “out of plane” one shows similar behaviour.
TABLE I. Width of the distribution of relative space and time coordinates for proton pair with and without in-plane cuts. All source parameters are in fermi. See description in the text.

VI. SUMMARY

In summary, we have investigated dependence of the two-proton correlation function on the orientation relative to the reaction plane in Au+Au collisions at 11.5 AGeV/c. We conclude that (at currently achieved sensitivity) the two-proton correlation function does not exhibit significant differences when a proton source is probed from different sides of the reaction plane, which suggest an azimuthal symmetry of the source. We also conclude that the observed difference in the correlation functions with and without cuts on the orientation of pairs relative to the reaction plane is likely to be linked to the momentum-space correlations induced during expansion of the proton source. Model calculations based on RQMD and Koonin-Pratt formalism agree with data fairly well.

VII. ACKNOWLEDGMENTS

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[1] W. Reisdorf, H.G. Ritter, Annu. Rev. Nucl. Part. Sci. 47 (1997) 663.
[2] D. Miskowiec et al., E877 Coll., Nucl. Phys. A 590 (1995) 473c.
[3] J. Barrette et al., Phys. Rev. Lett. 73 (1994) 2532.
[4] J. Barrette et al., Phys. Rev. C55 (1997) 1420.
[5] J. Barrette et al., Phys. Rev. C56 (1997) 3254.
[6] S. Voloshin, Y. Zhang, Z. Phys. C70 (1996) 665.
[7] S. Koonin, Phys. Lett. B 70 (1977) 43.
[8] R. Lednicky, V.L. Lyuboshits, Sov. J. Nucl. Phys. 35 (1982) 770.
[9] S.A. Voloshin, Phys. C55 (1997) 1630.
[10] S.A. Voloshin et al., E877 Coll., Quark Matter 97 proceedings (to be published), also preprint nucl-ex/9802001.
[11] The ALLADIN Collaboration, Darmstadt Nachrichten GSI 96-01 report.
[12] H. Sorge, A. von Keitz, R. Mattiello, H. Stöcker, and W. Greiner, Phys. Lett. B 243 (1990) 7.
[13] H. Sorge, R. Mattiello, H. Stöcker, and W. Greiner, Phys. Rev. Lett. 68 (1992) 286.
[14] S. Pratt et al., Phys. Rev. C 36 (1990) 2646.
[15] S. Pratt et al., Nucl. Phys. A 566 (1994) 103c.
FIG. 1. Schematic diagrams of the applied cuts on the orientation relative to the reaction plane. Upper panel: the “same” and “opposite” orientations relative to the reaction plane; Lower panel: “in-plane” and “out-of-plane” cuts.
FIG. 2. Two-proton correlation functions for the “same” and “opposite” orientations relative to the reaction plane.
FIG. 3. Two-proton correlation functions for the “in-plane” and “out-of-plane” orientations of proton pairs relative to the reaction plane. The correlation function obtained without reaction plane cuts is also shown with open circles.
FIG. 4. Model two-proton correlation functions for the “in-plane” (solid circles) orientation of proton pairs relative to the reaction plane. The correlation function obtained without reaction plane cuts is shown with stars.
FIG. 5. Model correlation function for the “in-plane” cut compared to with the measured one.