Chapter 1

BEAM ENERGY DEPENDENCE OF TWO-PROTON CORRELATIONS AT THE AGS

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Abstract First measurements of the beam energy dependence of the two proton correlation function in central Au+Au collisions are performed by the E895 Collaboration at the BNL AGS. No significant changes with beam energy were observed. The imaging technique of Brown-Danielewicz is used in order to extract information about the space-time content of the
proton source at freeze-out. Extracted source functions show peculiar enhancement at low relative separation.

**Keywords:** heavy-ion collisions, two-particle correlations

1. **INTRODUCTION**

Two-particle correlations are widely considered to be a valuable tool in extracting information about the space-time extent of the system created in the collisions of heavy ions [1, 2, 4, 3]. The complex nature of the heavy-ion reaction requires utilization of different particle species in order to obtain reliable and complete picture of the system created in the collision. The majority of the existing experimental two-particle correlation data in ultra-relativistic heavy-ion collisions was obtained using mesons as a probe. The data on baryon correlations is sparse at best. Since the physics of heavy-ion collisions in the beam energy range between 1 and 11 AGeV is dominated by baryons and baryon resonances, the information related to the space-time extent of the baryon source, obtained via two-proton correlations is clearly very interesting. In this paper we present preliminary results of the first measurement of the beam energy dependence of the two-proton correlation function in the central Au+Au collisions at 2,4,6 and 8 AGeV performed by the E895 Collaboration at the Brookhaven National Lab (BNL) Alternating Gradient Synchrotron (AGS). Preliminary results of the pion correlation analysis were published elsewhere [5].

2. **EXPERIMENTAL DETAILS**

E895 is a fixed target experiment at the BNL AGS. The goal of E895 is to study multiparticle correlations and particle production with Au beams incident on a variety of targets, over a range of AGS energies. More information about the E895 experimental setup can be found elsewhere [6, 7]. We will describe in the following only details relevant to the presented analysis.

Beams of gold ions ($^{197}$Au) were available at different energies - 2,4,6 and 8 AGeV. They were used to bombard targets of different materials - Be, Cu, Ag and Au. Charged particles produced in the collision were detected with time projection chamber (TPC) [6], positioned in side the MPS magnet, and multi-sampling ionization chamber (MUSIC) [7] located downstream from the magnet. For the presented results only information from the TPC was used. The time projection chamber is filled with P10 gas and has rectangular fiducial volume which is about 150 cm long, 75 cm high, and 100 cm wide. The ionization produced by charged
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Particles in the chamber is detected by a segmented cathode plane at the bottom of the TPC. The cathode plane has 15360 (120 by 128) pads. The dimension of the pads are 0.8 cm by 1.2 cm. The signal from each pad is sampled 140 times at 10 MHz by a 12 bit flash ADC yielding more than 2 millions pixels per event used for track reconstruction. The TPC was capable of detecting and tracking software of reconstructing up to several hundreds tracks per event. The magnetic field of the MPS magnet was typically 0.75 or 1 Tesla. Particle identification was performed via simultaneous measurement of particle momentum and specific ionization in the TPC gas. It was possible to resolve positively charged particles up to charge 6 and obtain reliable identification of protons up to 0.9 GeV/c in momentum.

3. DATA ANALYSIS

Good momentum resolution and good particle identification capabilities together with high reconstructed charged particle multiplicity allowed the performance of two-particle correlation studies. In order to obtain the two-proton correlation function \( C_2 \) experimentally, the mixed event technique was used. We employ the following definition of the correlation function

\[
C_2(q_{\text{inv}}) = \frac{N_{\text{tr}}(q_{\text{inv}})}{N_{\text{bk}}(q_{\text{inv}})},
\]

where

\[
q_{\text{inv}} = q = \frac{1}{2} \sqrt{-(p_{1}^\mu - p_{2}^\mu)^2}
\]

is the half relative invariant momentum between the two identical particles with four-momenta \( p_{1}^\mu \) and \( p_{2}^\mu \). The quantities \( N_{\text{tr}} \) and \( N_{\text{bk}} \) are the “true” and “background” two-particle distributions obtained by selecting particles from the same and different events, respectively. Before calculating the correlation function, several cuts are applied. In order to insure a reliable particle identification and high purity of the proton sample, a cut on proton longitudinal momentum \( P_z < 800 \text{ MeV/c} \) is applied. Contamination of the identified proton sample by other particles, in this momentum interval, was estimated to be less than 2%. Event centrality selection is based on a reconstructed charged particles multiplicity. For the present analysis events are selected with a multiplicity cut corresponding to the upper 5% of the inelastic cross section for the Au+Au collisions. Single proton tracks are required to satisfy certain quality cuts. Number of hits belonging to the track should be greater than 20, thus suppressing short tracks from delta electrons and remnants.
of the split tracks. Track should point into vicinity of the event vertex with distance of closest approach (DCA) less than 2.5 cm. Tracks should be properly reconstructed by the tracking code with the corresponding $\chi^2$ per degree of freedom less than 1.5. Tracks are required to be reconstructed from fairly continuous sequence of hits with no significant hit losses, the fraction of hits assigned to the track should exceed 50% of the theoretically available number for the corresponding trajectory inside the fiducial volume of the TPC. This cut has been shown to be effective in suppression of the track splitting effects in the correlation analysis [5]. In order to suppress effects of track merging, a cut on angular separation of two tracks was imposed. For pairs from both “true” and “background” distributions the angle between two tracks was required to be greater than 3 degrees. Figure 1.1 shows measured two-proton correlation functions for Au+Au central collisions at 2, 4, 6 and 8 AGeV. Within currently available statistical accuracy no significant changes of the measured correlation functions with beam energy were observed.

4. SOURCE IMAGING

The so called source imaging technique of Brown-Danielewicz was used to extract information about the space-time extent of the proton source. Here we will give just a brief sketch of the method, see Refs [8, 9], for a more detailed description. The two-particle correlation function may be expressed in the following way:

$$C_P(q) = \frac{dN_2/dp_1 dp_2}{(dN_1/dp_1)(dN_1/dp_2)} \simeq \int dr |\Phi^{(-)}_q(r)|^2 S_P(r).$$  \hspace{1cm} (1.3)

$S_P(r)$ is the distribution of relative separation of emission points for the two particles, in their center of mass and $\Phi^{(-)}_q(r)$ is a relative wave function. Using single-particle sources,

$$S_P(r) = \int dR dt_1 dt_2 D(0, R + r/2, t_1)D(0, R - r/2, t_2).$$  \hspace{1cm} (1.4)

where $D$ is an averaged distribution of freeze-out points of the particles. In the proton-proton case, the angle and spin averaged relative wave function can be expressed as

$$|\Phi^{(-)}_q(r)|^2 = \frac{1}{2} \sum_{j \ell \ell'} (2j + 1) \left(g_{js}^{\ell \ell'}(r)\right)^2,$$  \hspace{1cm} (1.5)

where $g_{js}^{\ell \ell'}$ is the radial wave function with outgoing asymptotic angular momentum $\ell$, which can be calculated numerically given a particular
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Figure 1.1 Measured two-proton correlation functions for Au+Au central collisions at different beam energies.

description of the final state interaction. In the present analysis, the proton relative wave functions were calculated by solving the Schrödinger equation with the REID93[10] and Coulomb potentials. The imaging method is concerned with the determination of the relative source function ($S_p(r)$ in Eq. 1.3) knowing $C_p(q)$. Taking into account that the nontrivial part of the correlation function is deviation from unity, one may rewrite Eq. 1.3 in the following way

$$C_p(q) - 1 = \int dr \left( |\Phi_q^-|^2 - 1 \right) S_p(r) = \int dr K(q,r) S_p(r), \quad (1.6)$$

where $K = |\Phi_q^-|^2 - 1$. The problem of imaging then reduces to the more general problem of inversion [11] of $K$ in Eq. 1.6.

Figure 1.2 shows the relative distribution of emission points of protons for central Au+Au collisions at 2, 4, 6 and 8 AGeV obtained as a result of the application of the imaging technique described above. In
order to check the quality of the imaging and numerical stability of the inversion procedure the two-proton correlation functions are calculated using the relative source functions shown on Figure 1.2 as an input in Equation 1.3. The result of such “double inversion” procedure is shown on Figure 1.3 for the beam energy 4 AGeV. The agreement between the measured and reconstructed correlation function is quite good.

It can be seen from Figure 1.2 that the relative proton source functions have similar shapes at all measured energies. Extracted source functions show enhancement at low relative separation which may be induced by momentum position correlations in the source, possibly due to collective flow. Further investigation and understanding of the origin of this enhancement is clearly needed. Even though the source functions have a non-trivial overall shape, the tail of the relative source function may be fit by gaussian (1.7) or exponential (1.8) forms:

\[
S(r) = \frac{\lambda}{(2\pi R^2)^{3/2}} e^{r^2/2R^2} \quad (1.7)
\]

\[
S(r) = \frac{\lambda}{2R^3} e^{-r/R} \quad (1.8)
\]

Parameter \( \lambda \) is a so called generalized chaoticity parameter [8] defined as:

\[
\lambda(r_N) = \int_{r \leq r_N} dr \, S(r) \quad (1.9)
\]

and has the meaning of an integral of the source over a region \( (r < r_N) \) where the distribution is significant. Results of the fit of the tail of the correlation function using these two parameterizations are shown at Figure 1.4. Fit parameters are presented in Table 1.1. At the current level of precision of the data both parameterizations provide an adequate description of the relative source function, except for the separations smaller than 2 fm.

| \( E_b \) (AGeV) | \( \lambda \) Exp. | \( R \) Exp.(fm) | \( \lambda \) Gauss. | \( R \) Gauss.(fm) | \( R_N \) (fm) |
|-----------------|-------------------|-----------------|-------------------|-----------------|----------------|
| 2.0             | 1.37              | 6.85            | 0.98              | 9.00            | 18.7           |
| 4.0             | 1.27              | 6.95            | 0.87              | 9.45            | 21.2           |
| 6.0             | 0.97              | 5.61            | 0.69              | 7.88            | 18.7           |
| 8.0             | 1.10              | 5.66            | 0.79              | 7.89            | 19.2           |
5. SUMMARY

We reported preliminary results of the analysis of the beam energy dependence of the two-proton correlation function in the target fragmentation region ($P < 800$ MeV/c). The correlation functions were measured for the first time for protons in central Au+Au collisions at beam energies 2, 4, 6 and 8 AGeV. Within currently available statistical accuracy no significant changes with beam energy were observed. The source imaging technique of Brown-Danielewicz was used to extract information about the space-time extent of the proton source. It was found that the relative proton source functions have similar shapes at all measured energies. Extracted source functions show enhancement at low relative separation which may be induced by momentum-position correlations in the source, possibly due to collective flow. Further investigation of the origin of this enhancement is clearly needed.
Figure 1.3  Experimentally measured two-proton correlation function (open circles) and correlation function restored from the relative source (filled circles) for beam energy 4 AGeV. See description in the text.

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Figure 1.4  Gaussian and exponential fits to the relative source reconstructed for the beam energy 4 AGeV.

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