Two-proton small-angle correlations in central heavy-ion collisions: a beam-energy and system-size dependent study

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Abstract. Small-angle correlations of pairs of protons emitted in central collisions of Ca + Ca, Ru + Ru and Au + Au at beam energies from 400 to 1500 MeV per nucleon are investigated with the FOPI detector system at SIS/GSI Darmstadt. Dependences on system size and beam energy are presented which extend the experimental data basis of pp correlations in the SIS energy range substantially. The size of the proton-emitting source is estimated by comparing the experimental data with the output of a final-state interaction model which utilizes either static Gaussian sources or the one-body phase-space distribution of protons provided by the BUU transport approach. The trends in the experimental data, i.e. system-size and beam energy dependences, are well reproduced by this hybrid model. However, the pp correlation function is found rather insensitive to the stiffness of the equation of state entering the transport model calculations.

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1 Introduction

Two-proton correlation functions at small relative momenta can probe the space-time extent of the reaction zone created in energetic heavy-ion reactions. This is due to the fact that the magnitude of nuclear and Coulomb final-state interactions (FSI) as well as anti-symmetrization effects depend on the spatial separation of the two protons during the emission process \[\mathbf{q} = (\mathbf{p}_1 - \mathbf{p}_2)/2.\] The interplay of the attractive S-wave nuclear interaction and the Coulomb repulsion and anti-symmetrization produce a minimum at \(q=0\) and a maximum in the correlation function at \(q \sim 20\) MeV/c [1]. Most analyses give only upper limits for the spatial extent of the source due to the ambiguity of radius and lifetime of the source, i.e. model calculations simulating large sources with short lifetimes will give very similar correlation functions as model calculations simulating small sources with long lifetimes [15].
At beam energies below about 100 A-MeV, heavy-ion experiments performed mainly at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) \[3,5,11,12,13,14,15,16,17\] have been proposed. Thus, recently, the technique of source imaging [23-28], i.e. the numerical inversion of the correlation function, has been applied successfully to pp correlations studied in heavy-ion experiments not only in the MSU-NSCL energy range \[23,27,28\] but also at significantly higher beam energies provided by the Brookhaven-AGS \[29\] or even by the CERN-SPS \[30\].

However, in the energy domain of the heavy-ion synchrotron SIS at GSI Darmstadt, ranging from about 100 to 2000 A-MeV, only few data on pp correlations are available: proton-proton correlations at small relative momenta \[i.e. 29\] and angular correlations \[31\]. Freeze-out densities of about 25% of normal nuclear-matter density were extracted. Two-proton small-angle correlations were studied of about 25% of normal nuclear-matter density as a function of proton multiplicity \[9\]. Freeze-out densities source function from two-particle correlations have been proposed. Thus, recently, the technique of source imaging [23-28], i.e. the numerical inversion of the correlation function, has been applied successfully to pp correlations studied in heavy-ion experiments not only in the MSU-NSCL energy range \[23,27,28\] but also at significantly higher beam energies provided by the Brookhaven-AGS \[29\] or even by the CERN-SPS \[30\].

2 The experiment

The experiments have been performed at the heavy-ion synchrotron SIS at GSI Darmstadt. Symmetric collisions are carried out by irradiating targets of 1 % interaction thickness of \(^{40}\text{Ca}\) and \(^{197}\text{Au}\) with the corresponding ions of beam energies between 400 and 1500 A-MeV. At a projectile energy of 400 A-MeV the system of intermediate mass, \(^{96}\text{Ru} + ^{98}\text{Ru}\), is included which was explored extensively with respect to the space-time difference of light charged particles emission in central collisions \[22\].

The present analysis uses a subsample of the data, taken with the outer Plastic Wall/Helitron combination of the FOPI detector system \[35,39\]. The Plastic Wall delivers - via energy loss vs. time-of-flight (TOF) measurement - the nuclear charge \(Z\) and the velocity \(\beta\) of the produced particles and the corresponding hit positions. The Helitron gives the curvature (which is a measure of momentum over charge \((p/Z)\)) of the particle track in the field of a large super-conducting solenoid. Since the momentum resolution of the Helitron is rather moderate, this detector component serves for particle identification only. The mass \(m\) is determined via \(mc = (p/Z)_{\text{Hel}}/(3\gamma/Z)_{\text{Pla}}\), where \(\gamma = (1 - \beta^2)^{-1/2}\). The Plastic Wall and the Helitron have full overlap only for polar angles between 8.5 degrees and 26.5 degrees. The corresponding flight paths amount to 450 cm and 380 cm, respectively. Monte-Carlo simulations have been performed in order to study the influence of the finite detector granularity and of the TOF and position resolutions on the velocity and finally on the proton momentum. The resolution of both quantities is governed by the TOF resolution, which is \(\sigma_{\text{TOF}} = 80\) (120) ps for
Typically, a few hundred thousand to a million central events are collected for each individual collision system by demanding large charged-particle multiplicities to be measured in the outer Plastic Wall. The corresponding integrated cross sections for the collision systems Ca + Ca, Ru + Ru, and Au + Au comprise about 15%, 10% and 10% of the total cross section, respectively. For the present central-event class one would expect - within a geometrical impact parameter distribution of about 1 fm as found from GEANT simulations \[40\], the number of participants in short (long) scintillator strips located at small (large) polar angles \[38\]. The velocity can be determined with a precision of \(\delta \beta / \beta < 1\%\).

### 2.1 Event classification

Let \(Y_{12}(p_1, p_2)\) be the coincidence yield of pairs of particles having momenta \(p_1\) and \(p_2\). Then the two-particle correlation function is defined as

\[
1 + R(p_1, p_2) = N \sum_{\text{events, pairs}} Y_{12}(p_1, p_2). \tag{1}
\]

The sum runs over all events fulfilling the above mentioned global selection criterion and over all pairs satisfying certain conditions given below. Event mixing, denoted by the subscript "mix", means to take particle 1 and particle 2 from different events. The normalization factor \(N\) is fixed by the requirement to have the same number of true and mixed pairs. The statistical errors of all the correlation functions presented below are governed by those of the coincident yield, since the mixed yield is generated with two orders of magnitude higher statistics. The correlation function \(1\) is then projected onto the relative momentum

\[
q = \frac{1}{2} |p_1^{\text{cm}} - p_2^{\text{cm}}|. \tag{2}
\]

Here, \(p_i^{\text{cm}}\) are the particle momenta calculated in the c.m. system of the colliding nuclei. From the velocity resolution as estimated in sect. \[2\] the corresponding \(q\) resolution is deduced to be \(\delta q = (4 \pm 1)\) MeV/c. A similar value can be derived directly from the experimental dispersion of the resonance due to the narrow 2.186 MeV state of \(^6\)Li (\(J^\pi = 3^+, \Gamma = 24\) keV) in the \(\alpha-d\) correlation function \[22\]. All theoretical correlation functions presented in sect. \(3\) are folded with this \(q\) resolution.

As in previous proton-proton correlation analyses \[20\] an enhanced coincidence yield at very small relative angles is observed, which is due to double counting caused mainly by scattering in the scintillator strips. This disturbing yield is reduced strongly by the requirement to match the particle hits on the Plastic Wall with the corresponding tracks in the forward drift chamber Helitron. The remaining left-over of doubly counted scattered particles is eliminated by excluding, around a given hit, positions within a rectangular segment of azimuthal and polar angle differences \(|\phi_1 - \phi_2| < 4^\circ\) and \(|\theta_1 - \theta_2| < 2^\circ\). The same procedure is applied to the uncorrelated background, hence keeping the influence of the exclusion onto the correlation function as small as possible. GEANT simulations \[19\] have shown that at very small relative momenta, \(q < (12 - 15)\) MeV/c, still a small bias of the correlation function can not be excluded \[20, 22\]. Thus, the corresponding regions in the correlation functions are not taken into consideration when comparing the experimental data with model predictions.

### 2.2 Correlation function

For description of the FSI model we refer to ref. \[22\] and references cited therein. As source distributions we use either Gaussian density profiles in coordinate and momentum space or the output of the BUU transport model. The theoretical correlation function is given as

\[
1 + R(\mathbf{r, p}) = \int d^3r S(\mathbf{r, p}) |\Psi_q(\mathbf{r})|^2. \tag{3}
\]

Here, the wave function \(\Psi\) describes the relative motion of the two emitted particles and \(S\) is the source function. Gaussian sources are defined in \[22\]. In case of calculating the single-particle phase-space distribution within the BUU model the source function is given as

\[
S(\mathbf{r, p}) = N_p \sum_{i,j} \delta(P \cdot R_{i,j}) \delta(P \cdot R_{i,j}) \times \\
\delta(r - (r_i - r_j) + \frac{P}{2m} (t_i - t_j)). \tag{4}
\]
\[ \mathbf{r}_i, t_i, \text{and } \mathbf{p}_i \text{ are the space, time and momentum coordinates of particle } i \text{ at freeze out. The parameter } \mathbf{P} \text{ represents the sum momentum of the observed particle pair. The normalization } \mathcal{N}_p \text{ is chosen such that} \]
\[ \int d^3 \mathbf{r} \, S(\mathbf{r}, \mathbf{P}) = 1. \quad (5) \]

To allow the summation over a sufficient number of particles, the \( \delta \) function treating the momentum is replaced by a Gaussian with dispersion \( \Delta_p \),
\[ \delta(\mathbf{p}) \rightarrow \left( \frac{1}{2\pi \Delta_p^2} \right)^{3/2} \exp\left( - \frac{\mathbf{p}^2}{2\Delta_p^2} \right). \quad (6) \]

Note that all coordinates are calculated in the c.m. system of the colliding nuclei. The relevant BUU input parameters are i) the number of test particles per nucleon (i.e. parallel runs or pseudo events, here chosen to 200), ii) nuclear charge and mass numbers of target and projectile, \( A_t, Z_t, A_p, Z_p \), iii) the projectile energy \( E_{\text{proj}} \), iv) the impact parameter \( b \), and v) the stiffness of the Equation of State (EoS), either hard (\( \kappa = 380 \text{ MeV} \)) or soft (\( \kappa = 215 \text{ MeV} \)) [14]. A proton is considered “emitted” when the surrounding density falls below a value of \( \rho_{\text{cut off}} = 0.02/\text{fm}^3 \) and when subsequent interaction with the mean field does not cause recapture into regions of higher density until the calculation is terminated at 150 fm/c. The cutoff value of about one eighth of normal nuclear matter density implies ceasing NN interactions in a sufficiently diluted nuclear matter. This choice was approved in systematic investigations of proton-proton correlations in \( ^{14}\text{N}+^{27}\text{Al} \) and \( ^{14}\text{N}+^{197}\text{Au} \) reactions at 75 AMeV [5], in \( ^{36}\text{Ar}+^{45}\text{Sc} \) collisions at 80 AMeV [11,14] and in \( ^{40}\text{Ar}+^{197}\text{Au} \) reactions at 200 AMeV [10].

Finally, for each run and each proton, the septuplet of space-time-momentum coordinates \( N_i = (x, y, z, t, p_x, p_y, p_z) \), is taken from the BUU approach at the corresponding freeze-out time and then processed within the FSI model. The relevant parameters of the FSI model are the so-called “observation quantities”, i.e. the sum momentum \( P \), the momentum dispersion \( \Delta_p \) and the polar angle \( \theta^m \). These quantities are taken directly from the experimental distributions in the c.m. system, e.g. \( P = 2 \langle p^m \rangle \). Typical values are \( \theta^m = 45^\circ \), \( \Delta_p = 150 \text{ MeV/c} \), and \( \langle p^m \rangle = 300 \text{ (400) MeV/c for 400 (1500) AMeV beam energy.} \)

### 3.1 System-size dependence

Figure 1 shows, for 400 AMeV beam energy, the system-size dependence of the pp correlation function. Clearly, the pp-correlation peak decreases with increasing system size and almost vanishes for the largest collision system Au + Au. The peaks (i.e. data within a relative-momentum range of \( 15 < q/\text{MeV/c} < 50 \)) of the experimental correlation functions (symbols) are best described by the theoretical ones (lines) for apparent Gaussian radii of

\[ R_0^* = \sqrt{\frac{R_0^2}{1 + \epsilon}} + (\nu \tau)^2, \quad (7) \]

where \( \tau \) is the duration of emission, \( \nu = P/2m \) is the pair velocity, and \( \epsilon = \epsilon_{\text{flow}}/\epsilon_{\text{therm}} \) represents the ratio of radial flow energy \( \epsilon_{\text{flow}} \) and the energy of the random thermal motion \( \epsilon_{\text{therm}} = \frac{3}{2}T \).

For both the small and the medium-size systems, our results can be compared directly with existing data: Gaussian radii \( r_g \) were derived from pp correlations measured with the “Plastic Ball” at BEVALAC for the reactions \( \text{Ca}+\text{Ca} \) and \( \text{Nb}+\text{Nb} \), both at 400 MeV per nucleon, as function of proton multiplicity [9]. Taking into account the different radius definitions, i.e. \( r_g = \sqrt{2}R_0^* \), the apparent source radii for central collisions agree perfectly. Consequently, the freeze-out density of about 25% of normal nuclear matter density deduced in ref. [9] is in accordance

[Fig. 1. Correlation functions of proton pairs from central collisions of Ca + Ca, Ru + Ru, and Au + Au at 400 AMeV. Experimental data (symbols) are compared to predictions of the FSI model with Gaussian sources and zero lifetime (lines). The corresponding apparent source radii are indicated. \( R_0^* = (3.0 \pm 0.1) \text{ fm for Ca + Ca, (4.0 \pm 0.15) fm for Ru + Ru and (5.1 \pm 0.2) fm for Au + Au collisions. Note that the term “apparent” means that neither the contribution of the finite emission duration (inappropriately called “lifetime”, leading to an increase of the effective source radius) nor the effect of collective radial expansion of the participant zone (leading - via strong correlations of coordinate and momentum space - to a reduction of the effective source size) are taken into account [20]. In the following, the asterisk indicates apparent quantities, e.g. the sharp-sphere and r.m.s. radii \( R_{ss}^* = \sqrt{3}R_0^* \) and \( R_{rms}^* = \sqrt{3}R_0^* \), respectively. For Gaussian source distributions the effective radius can be written as [23] \]

\[ R_0^* = \sqrt{\frac{R_0^2}{1 + \epsilon}} + (\nu \tau)^2, \quad (7) \]
with our results presented in sect. 3.2 below. Instead of disentangling the space-time-flow ambiguity of eq. (7), in the following we try to reproduce the experimental correlation functions by BUU+FSI model calculations.

Before we confront the data with theoretical correlation functions we briefly focus onto the coordinate-space distributions of freeze-out points from BUU calculations displayed in fig. 2 for the three systems at 400 A·MeV beam energy. Note that the coordinates are not taken at fixed time but when the local density drops below the cutoff value. As expected, the proton source increases with increasing system size. Additionally to the coordinate-space distribution shown in fig. 2 as an example for the Au + Au system fig. 3 displays the momentum distribution projected onto the reaction plane \((p_x, p_z)\), the \((y, x)\) distribution for a central \(z\) slice and the radial density profile. Here, the effective density is given in units of normal nuclear matter density, \(\rho_0 = 0.168/fm^3\). The corresponding r.m.s. radius \(R_{rms} = \sqrt{\langle r^2 \rangle}\) of the proton emitting source is indicated by an arrow. No essential changes are observed from these phase-space plots when increasing the beam energy, except a trivial extension in momentum space. Since even the r.m.s. radius of the breakup configuration (cf. arrow in lower right panel) is almost the same for 400 and 1500 A·MeV beam energy, one would expect a very similar height of the pp correlation peak. However, also the correlation of coordinate and momentum space, constituting a fast collective motion known as radial expansion, is expected to increase with beam energy. It should lead to a reduction of the apparent source radius and hence to an increase of the pp peak height (cf. eq. (7)). This presumption will be verified in sect. 3.2.

For 400 A·MeV beam energy, fig. 4 compares the experimental system-size dependence of the pp correlation function with the corresponding output of the BUU+FSI model. Hardly any differences have been found between the pp correlation functions derived from BUU simulations using the three different parameterizations of the EoS as can be inferred from the narrow hatched bands in Fig. 4 (Similar findings have been reported for \(^{14}\)N+\(^{27}\)Al collisions at 75 A·MeV \([5,8]\) and for \(^{40}\)Ar+\(^{197}\)Au reactions at 200 A·MeV \([10]\).) Therefore, in the following we will restrict ourselves to the medium stiff EoS.

### 3.2 Beam-energy dependence

Figure 5 shows the excitation function of experimental pp correlations from central collisions of Ca + Ca at beam energies from 400 to 1500 A·MeV (symbols). A strong increase of the correlation peak is obvious corresponding to a decrease of the apparent source size. Indeed, when comparing with the theoretical correlation functions derived from the FSI model with static Gaussian sources and zero lifetime (lines), the experimental pp peak is best reproduced with apparent radii systematically decreasing from 3.0 fm at 400 A·MeV to 2.5 fm at 1500 A·MeV.
shrinking of the apparent source has to be traced back to two facts. First of all, at higher beam energies when the heavy-ion collisions is processing faster, the contribution of the emission duration onto the effective source radius is smaller. Usually, finite emission times imply a reduced Pauli suppression in emission direction and hence lead to an increase of the effective source radius. Typically, for the energy range we are dealing with in the present investigation, these times are in the order of 10 fm/c. Secondly, also the collective (radial) expansion increases with increasing projectile energies. It is well known that strong correlations of coordinate and momentum space lead to a drastic reduction of the apparent source radius as derived from a comparison of the data with results of a FSI model incorporating the Koonin-Pratt formalism with static Gaussian sources and finite lifetime times. 30% smaller radii are observed for Ca + Ca (Au + Au) collisions at beam energies of 1500 A·MeV. These numbers increase to values of 0.47 ± 0.11 (0.60 ± 0.10) for Ca + Ca (Au + Au) at beam energies of 1500 A·MeV. Here, we remind once more to the fact that these apparent breakup densities are not corrected for both the effects of collective radial expansion and finite duration of emission (cf. eq. (7)).

Finally, we confront the experimental beam-energy dependence of two-proton correlations with the predictions of the BUU+FSI hybrid model. Figure 7 shows the excitation function of pp correlations for central Ca + Ca collisions in comparison to the model results. With the standard parameters in the transport approach the excitation functions are surprisingly well reproduced. Also for the larger system, Au + Au, the energy dependence is nicely described (cf. fig. 8). Here, the experimental pp correlation peaks are systematically slightly underestimated.

We want to point out that the agreement between our experimental correlation functions and those predicted by BUU calculations overestimated the measured central collision data of the reactions Ar + Au.
Au+Au, central collisions

\[
\begin{array}{cc}
R_0 / \text{fm} & E_{\text{proj}} / \text{A}\text{MeV} \\
4.0 & 1500 \\
4.2 & 1200 \\
4.3 & 1000 \\
4.4 & 800 \\
4.7 & 600 \\
5.1 & 400 \\
\end{array}
\]

q/(GeV/c) 0.02 0.04 0.06 0.08 0.1 0.12

Fig. 6. The same as figure 5, but for Au + Au collisions.

at 200 A·MeV [10] and of Ar + Sc at 120 and 160 A·MeV [10]. This deficiency of the BUU model was attributed to its inability to treat the population of particle unbound resonances and their decay via delayed particle emission [10, 25]. Obviously, at our higher beam energies this slow-emission component of the source function becomes unimportant, presumably since the number of heavy fragments drops strongly with energy [45]. Thus, the fast expansion-explosion scenario seems to be well modelled within the transport approach.

4 Summary

In the present paper, small angle correlations of pairs of protons emitted in central heavy-ion collisions at beam energies from 400 to 1500 A·MeV are investigated. New data are presented which substantially enlarge the experimental data basis on pp correlations in the SIS energy range.

The system-size and beam-energy dependences of the pp correlation peak are studied. The peak decreases, i.e. the apparent source radius increases, with increasing system size. This system-size dependence is expected from the larger volume due to a larger number of participants in the central source. With increasing beam energy the peak of the pp correlation function increases, and hence the apparent source radius decreases. This behaviour is interpreted as the common action of shorter time scales and stronger collective radial expansion. Correlations of coordinate and momentum space constituting the latter radial flow are known to be responsible for the apparent shrinking of the source size found in small-angle correlation studies.

Both findings, shorter emission durations due to shorter time scales of the central heavy-ion collision and stronger radial expansion due to increasing with pressure - space-momentum correlations, are well incorporated within microscopic transport models. Accordingly, using the Boltzmann-Uehling-Uhlenbeck transport approach, the phase-space points at freeze out are calculated and afterwards processed within a final-state-interaction model providing the two-proton correlation function. This BUU+FSI model well reproduces the system-size and beam-energy dependences of the experimental correlation function. However, the pp correlation function is found rather insensitive to the stiffness of the equation of state used in the transport model.

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Fig. 8. The same as figure 7, but for Au + Au collisions.

1. Au+Au, central collisions

2. $E_{\text{proj}}$ exp. BUU

3. 1500 □

4. 1200 ○

5. 1000 ▼

6. 800 ▲

7. 600 ■

8. 400 ●

9. $q/(\text{GeV}/c)$

10. 0.02 0.04 0.06 0.08 0.1 0.12

11. $1+R(q)$

12. 0.95 1 1.05 1.1 1.15 1.2

13. 0.02 0.04 0.06 0.08 0.1 0.12

14. 400 600 800 1000 1200 1500

15. $E_{\text{proj}}$ proj. exp. BUU

16. $q/(\text{GeV}/c)$

17. 400 600 800 1000 1200 1500

18. 1+R(q)

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