## System-size dependence of the pion freeze-out volume as a potential signature for the phase transition to a Quark Gluon Plasma

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## Abstract

Hanburry-Brown-Twiss (HBT) correlation functions and radii of negatively charged pions from C+C, Si+Si, Cu+Cu, and In+In at lower RHIC/SPS energies are calculated with the UrQMD transport model and the CRAB analyzing program. We find a minimum in the excitation function of the pion freeze-out volume at low transverse momenta and around  $E_{lab} \sim 20 - 30 A$ GeV which can be related to the transition from hadronic to string matter (which might be interpreted as a pre-cursor of the QGP). The existence of the minimum is explained by the competition of two mechanisms of the particle production, resonance decays and string formation/fragmentation.

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Nowadays one expects that a (phase) transition from a hadron gas (HG) to the quarkgluon-plasma (QGP) is encountered in relativistic heavy-ion collisions (HICs). Since more than a decade it has been suggested that the onset of deconfinement happens in HICs at SPS/FAIR energies, an energy regime which is now also at the focus of the current RHIC low energy scan program. According to current lattice QCD calculations one expects - in order of increasing baryo-chemical potential - a cross over transition, a critical endpoint with a second order transition and for high baryon densities a first order phase transition. In fact, the combination of theoretically predicted signals and corresponding data, has led to the emergence of a complete phase diagram of strongly interacting matter [1–9]. Unfortunately, uncertainties still exist and the present data does not seem to allow for firm conclusion, especially when it comes to the location and observation of the critical point [6, 7, 10, 11]. To reduce these uncertainties and to draw final conclusions about the location of the critical endpoint and the boundary of the first order transition, a more careful beam-energy scan of these signals for the onset of deconfinement is currently undertaken and planned for the future. Current experimental efforts are centered at several international laboratories such as GSI at Darmstadt, CERN at Geneva, and RHIC at BNL and will go on with the SIS-100(300) [7], the NA61/SHINE [4, 6, 12], and the critRHIC [13, 14] program.

In the present paper we go back to a long standing idea to explore the regions of homogeneity by particle correlations, namely the Hanbury-Brown-Twiss (HBT) technique [15–17]. The HBT technique allows to extract information on the spatio-temporal evolution of the source of various two-particle species. A plethora of data on the whole beam-energy scan from AGS [18, 19], over CERN-SPS [20–22] up to RHIC energies [23–27] exists, however, mainly for the pion source from heavy systems. In Ref. [28] a systematic analysis of the pion freeze-out data at beam energies from AGS to RHIC is laid out for the first time and they found a steep decrease of the pion freeze-out volume at AGS energies and an increase throughout the SPS energy regime towards RHIC. It indicates the existence of a minimum between AGS and SPS energies and it is claimed that this is due to the transition from nucleon to pion dominated freeze-out between AGS and SPS energies. However, this behaviour can not be explained by transport model calculations [29, 30] within a cascade mode. Furthermore, the systematic and the statistic errors of the data are still large (for the apparently rather large systematic uncertainties, we refer the reader to the differences between the NA49 and the CERES data [10, 31]) and it is therefore difficult to draw firm

conclusion based on the currently existing data [7, 31].

When neglecting the strong space-time correlation, it is known that the ratio between the HBT radii in outward and sideward directions  $(R_O, R_S)$  is related to the emission duration of the source. Thus, a ratio larger than unity is expected when the system crosses the first-order phase transition [32] and remains for a long time in the mixed phase. However, an almost unity value has been shown by experiments throughout the beam energies from AGS to RHIC [30]. This seems to imply a strong space-momentum correlation [33] which has to be taken into account in the interpretation of the experimental data. In recent years both the non-monotonous energy dependence of the freeze-out volume and the small  $R_O/R_S$ -ratio present in the AGS, SPS, and RHIC energy regions have been explained fairly well by both analyzing non-Gaussian effects and by considering a stronger early pressure which comes from the contribution of mean-field potentials for both formed and preformed hadrons [33–36]. Recently, it was pointed out [37] that a sufficient spatial size of the fire ball is essential to locate the critical point, the crossover and the first-order phase transition in the phase diagram.

On the transport model side, benchmark test have been performed, which provide a solid basis for the present and future investigations. The results obtained previously are in line with the experimental facts that the extracted HBT radii are always rather small and change smoothly for the large span of explored beam energies. I.e. no unexpected observations about the freeze-out volume of two particle correlations is found at low SPS energies where the energy threshold for the onset of deconfinement might be reached. This implies that the expected sensitivity of the pion freeze-out volume to the possible phase transition is relatively weak and needs to be analyzed carefully. On the experimental side a detailed exploration of different collision systems is currently underway with the NA61 experiment taking data at beam energies from 10A GeV to 158A GeV for systems from p+p to Au+Au [4, 12]. Finally, we suggest to conduct a careful transverse-momentum analysis for the excitation function of the pion freeze-out volume in order to find out any although weak but unusual phenomenon for the phase transition.

In this work, we provide a baseline calculation for the system-size and the transversemomentum dependence of the excitation function of the HBT pion freeze-out volume within a relativistic transport model. In line with our previous findings, we explore two scenarios, the standard cascade calculations and a modified version of the model which includes mean field potentials of both formed and preformed hadrons to increase the pressure in the early stage of the reaction. As a tool we employ a modified version of the UrQMD model which apart from other changes - includes a repulsive interaction for the early stage of the reaction to mimic the explosive expansion of the source encountered at the highest energies (for details of the implementation, the reader is referred to [33–35]).

For the present analysis we simulate central collisions  $(\sigma/\sigma_{Total} < 5\%$ ,  $\sigma$  being the cross section) for four mass-symmetric reactions, C+C, Si+Si, Cu+Cu, and In+In, with beam energies from 2A GeV to 80A GeV (for detailed energy points, please see the figures below). Firstly we extract the inverse slope parameter T ("apparent temperature" or "temperature") from the transverse mass  $(m_t = (m^2 + p_t^2)^{1/2})$  spectra of negatively charged pions at midrapidity ( $|y_{cm}| < 0.5$ , where  $y_{cm} = \frac{1}{2} \log \frac{E+p_{\parallel}}{E-p_{\parallel}}$ , E and  $p_{\parallel}$  are the energy and longitudinal momentum of the pion meson in the center-of-mass system) according to the expression

$$\frac{1}{m_t} \frac{dN^2}{dm_t dy_{cm}} = f(y_{cm}) \exp(-\frac{m_t}{T}) \tag{1}$$

where  $f(y_{cm}) = const.$  Fig. 1 shows the excitation function of the extracted T values at AGS and SPS energies (up to 80A GeV). Calculations with ("SM-EoS") and without ("Cascade") mean-field potentials of both formed and preformed hadrons from C+C and In+In reactions are compared with each other. In order to extract the temperature parameter T a transverse mass upper limit is chosen to avoid potential problems with deviations from a single exponential spectrum. Here we use the range  $|m_t - m_{\pi}| < 0.65 \text{GeV}/c$  for the fitting process, in line with the transverse momentum range for the HBT analysis later on.

As shown in previous UrQMD calculations and the experimental results [38], the excitation function of the extracted temperature from pion spectra is weakly dependent on the size of the system, which is shown in Fig. 1. At AGS a rapid increase of the T from about 0.11 GeV to 0.14 GeV with increasing beam energies is seen. With the further increase of beam energies, the T becomes flat and shows no obvious beam-energy dependence especially for the light system and in cascade calculations. From the results shown in Fig. 1 one also finds that the mean-field potential contribution to the modification of T is also of minor importance and disappears completely for the light C+C system. Note that the mean-field potential for pre-formed hadrons (string fragments) is also considered in the present calculations. Therefore, the weak dependence of the apparent temperature on different equations of state in such a large beam-energy region implies that most of the previously predicted

signatures to the confinement-deconfinement phase transition would not be that bright in the real dynamic transport process [39, 40].

Let us now turn to the correlation's study. The program Correlation After Burner (CRAB) (version  $3.0\beta$ ) [41, 42] is used to analyze the two-particle interferometry. The correlator C of two particles is decomposed in Pratt's (so-called longitudinal co-moving system LCMS or "Out-Side-Long") three-dimensional convention (Pratt-radii). The three-dimensional correlation function is fit with the standard Gaussian form (using ROOT [43] and minimizing the  $\chi$ -squared)

$$C(q_L, q_O, q_S) = 1 + \lambda e^{-R_L^2 q_L^2 - R_O^2 q_O^2 - R_S^2 q_S^2 - 2R_{OL}^2 q_O q_L}.$$
 (2)

In Eq. (2),  $\lambda$  is usually referred to as an incoherence factor. However, it might also be affected by many other factors, such as the contaminations from long-lived resonances or the details of the Coulomb modification in final state interactions (FSI). Here we regard it as a free parameter and do not assign a specific physical meaning to it.  $R_L$ ,  $R_O$ , and  $R_S$  are the Pratt-radii in longitudinal, outward, and sideward directions, while the cross-term  $R_{OL}$  plays a role at large rapidities.  $q_i$  is the pair relative momentum  $\mathbf{q}$  ( $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ ) in the i direction. Furthermore, the correlator is also k-dependent (the transverse component is preferred under a rapidity cut), where  $k = (p_1 + p_2)/2$  is the average momentum of the two particles.

In following calculations,  $10^9$  negatively charged pion pairs are calculated at mid-rapidity with the two correlated particles at  $|Y_{\pi\pi}| < 0.5$  (where  $Y_{\pi\pi} = \frac{1}{2}\log(\frac{E_1+E_2+p_{\parallel}1+p_{\parallel}2}{E_1+E_2-p_{\parallel}1-p_{\parallel}2})$  is the pair rapidity with pion energies  $E_1$  and  $E_2$  and longitudinal momenta  $p_{\parallel}1$  and  $p_{\parallel}2$  in the center of mass system) in each CRAB analyzing run. Fig. 2 depicts excitation functions of the HBT parameters  $\lambda$  (upper-left),  $R_L$  (upper-right),  $R_O$  (bottom-left), and  $R_S$  (bottom-right) of  $\pi^- - \pi^-$  pairs from central C+C collisions at two  $k_T$  (=  $(p_{1T} + p_{2T})/2$ ) bins 0 - 100 MeV/c and 100 - 200 MeV/c. Calculations with cascade mode are shown with scattered symbols while calculations with SM-EoS are shown by different lines.

Similarly, Fig. 3 gives the results of In+In collisions. A beam-energy range 10A-80A GeV is selected and the number of calculated energy points is large enough in order to give clearer information about the energy dependence of these HBT parameters. The  $\lambda$  parameter is less than unity for both systems at AGS and SPS energies and decreases with increasing beam energy. This behaviour is related to the increasing importance of long

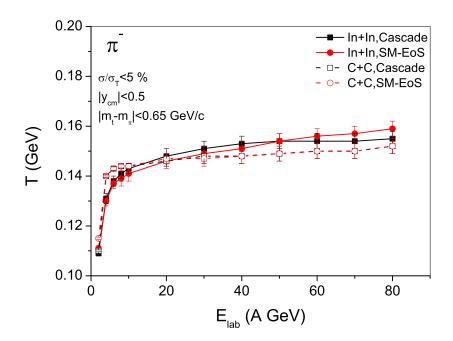


FIG. 1: Excitation function of the extracted temperature parameter T of negatively charged pions at mid-rapidity from central C+C and In+In reactions at AGS and SPS energies. The comparison of calculations between with and without mean-field potentials is shown for each colliding system.

lived resonances and substantial rescattering. It was shown that the excitation function of the experimental  $\lambda$  values from Au+Au collisions at AGS energies can be reproduced well by the RQMD model [18]. Although the effect of the mean-field potential on  $\lambda$  is weak in both reactions at all beam energies as shown in [18], it indeed becomes visible in the heavier In+In system especially at high SPS energies. We further find that at the low  $k_T$  bin the  $\lambda$  value is driven up slightly when potentials are considered and vice versa for the high  $k_T$  bin. This is easy to understand because the attractive potential leads to more rescattering process for pions with small momenta, which implies a larger incoherence. While the repulsive part of the potential leads to less rescattering of the resonances before freeze-out, which implies thus a larger coherence. If we turn to look into the beam-energy dependence of the HBT radii, surprisingly, we find some non-monotonous behaviour at low SPS energies, especially in the longitudinal direction. In C+C collisions and within the  $k_T$  bin  $0-100~{\rm MeV}/c$ , a minimum  $R_L$  is seen at  $\sim 25A~{\rm GeV}$  for calculations both with and without potentials. While the appearance of the minimum value of  $R_L$  from In+In collisions depends heavily on both the consideration of the potential and the  $k_T$  interval selected - the

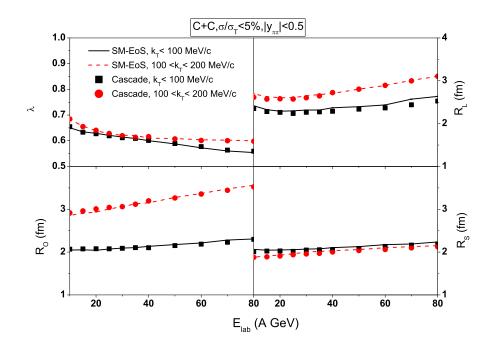


FIG. 2: Excitation functions of the HBT parameters  $\lambda$  (upper-left),  $R_L$  (upper-right),  $R_O$  (bottom-left), and  $R_S$  (bottom-right) of  $\pi^- - \pi^-$  pairs from central C+C collisions at two  $k_T$  bins 0-100 MeV/c and 100-200 MeV/c. A pion-pair rapidity cut  $|Y_{\pi\pi}| < 0.5$  is employed. Calculations in the cascade mode are depicted by symbols while calculations with SM-EoS are shown by the different lines.

minimum appears at  $\sim 35A$  GeV only from the calculation with potentials and at the larger  $k_T$  bin 100-200 MeV/c. Furthermore, a stronger beam-energy dependence of the HBT radii with mean-field potentials is also seen especially in the longitudinal direction of pion pairs from In+In collisions which is certainly due to the density dependence of the Skyrmelike terms in SM-EoS [33]. Therefore, it is seen clearly that for light system, the minimum point appears at both  $k_T$  bins, while for heavy system, the appearance of the minimum depends on the consideration of both the certain  $k_T$  bin and the mean-field potentials. This is interesting phenomenon which can be addressed by the system size and energy scan of the NA61 experiment.

Fig. 4 shows the excitation function of the pion source volume  $V_f$  (=  $(2\pi)^{3/2}R_LR_S^2$ ) at freeze-out (calculated as [28]) from central C+C (in plot (a) ), Si+Si ( (b) ), Cu+Cu ( (c) ), and In+In ( (d) ) collisions. First of all, for the calculations in the cascade mode, the excitation function of  $V_f$  shows a minimum only for light systems (especially for the

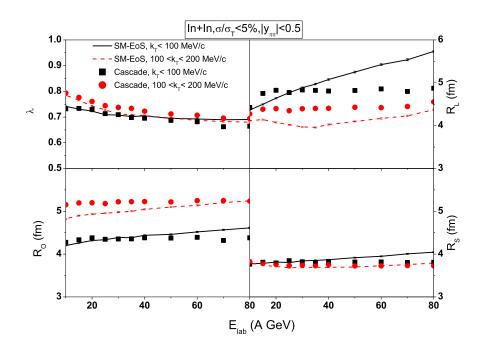


FIG. 3: Excitation functions of the HBT parameters  $\lambda$  (upper-left),  $R_L$  (upper-right),  $R_O$  (bottom-left), and  $R_S$  (bottom-right) of  $\pi^- - \pi^-$  pairs from central In+In collisions at two  $k_T$  bins 0-100 MeV/c and 100-200 MeV/c. A pion-pair rapidity cut  $|Y_{\pi\pi}| < 0.5$  is employed. Calculations in the cascade mode are depicted by symbols while calculations with SM-EoS are shown by the different lines.

middle-sized Si+Si system). In the In+In case, the minimum is not seen in any  $k_T$  bins. It implies that the occurrence of the minimum  $V_f$  is system-size dependent if the cascade mode is adopted in calculations. Secondly, let us explore the results with the inclusion of mean-field potentials (lines), in C+C case, the excitation function of  $V_f$  shows a minimum at low SPS energies for the calculation at lower  $k_T$  bin (the  $V_f$  value decreases about 7% from the beam energy 10A GeV to 20A GeV). This minimum keeps for heavier systems Si+Si, Cu+Cu, and In+In, but, the valley within the lower  $k_T$  becomes shallow and disappear while that in the higher  $k_T$  bin starts to become important (the amplitude of the decrease of  $V_f$  from 10A GeV to 35A GeV is about 9%). Therefore, the minimum seems always to be present (although in different  $k_T$  bins) in the excitation function of the pion source volume  $V_f$  of all systems for all calculations with the mean-field potentials. It implies that the occurrence of the minimum  $V_f$  is  $k_T$  dependent but not system-size dependent if the mean-field potentials are considered in calculations. Finally, the minimum, if it is present,

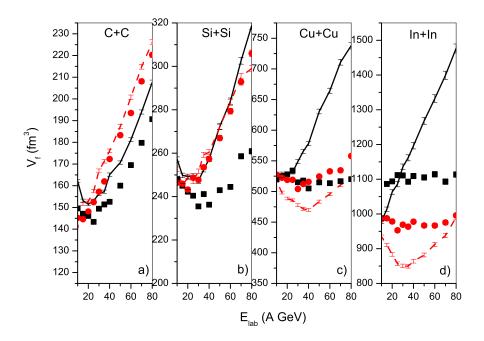


FIG. 4: Excitation functions of the pion source volume  $V_f$  from central C+C (in plot (a) ), Si+Si ( (b) ), Cu+Cu ( (c) ), and In+In ( (d) ) collisions at two  $k_T$  bins 0-100 MeV/c (solid lines and squares) and 100-200 MeV/c (dashed lines and circles). A pion-pair rapidity cut  $|Y_{\pi\pi}| < 0.5$  is employed. Calculations with cascade mode are shown with symbols while calculations with SM-EoS are shown by the different lines.

lies always around the beam energy 30A GeV. This is because the dominant mechanism of the particle production starts to change from the decay of resonances to the fragmentation of strings [44]. Although the transport of free quark degree of freedom is not considered in current version of the UrQMD, the mean-field potentials for the pre-formed hadrons may partly compensate the lack of pressure from the (missing) partonic stage. The decrease of the pion source volume before the minimum is due to the fact that more pions starts to be produced from the excitation and fragmentation of strings which happens at an earlier stage of the collision, i.e. at a smaller freeze-out size. With the further increase of the beam energy, the increase of the pion source volume is due to the increase of pion yields at high SPS energies. However this effect is washed out in heavier system since both the production of pions from the decay of resonance and the rescattering at the late stage of collisions play important roles.

In summary, we have calculated the HBT correlation functions of negatively charged pions for several systems from the light C+C, middle-sized Si+Si and Cu+Cu, to the heavy In+In system with the UrQMD transport model and the correlation after-burner CRAB 3.0. We found that the non-monotonous energy dependence of the pion freeze-out volume might signal a change in the degrees of freedom from hadronic to partonic matter around 30A GeV. The existence of the minimum was explained by the combination and competition of the resonance decay with the string excitation and fragmentation (which we interpreted as a pre-cursor to a QGP). The results presented here, especially for the middle-sized systems, are in reach of the NA61/SHINE experiment at the CERN-SPS.

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