HBT INTERFEROMETRY AT SPS AND UNIVERSAL PION FREEZE-OUT*

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Recent pion HBT results from SPS are reviewed and compared to measurements at AGS and RHIC. The evaluation of the energy dependence leads to a universal freeze-out condition for pions. Implications of the HBT results on the dynamical evolution of heavy ion collisions are discussed.

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1. Introduction

Hanbury–Brown Twiss (HBT) interferometry of identical pions provides the most direct access to the space-time properties of the highly excited system created in ultra-relativistic heavy ion collisions (see [1] for a recent review). A complication arises in systems with collective expansion, where the extracted HBT radii do not simply reflect the geometrical size of the pion source at freeze-out. Depending on the expansion rate, the HBT radii result from a combination of geometrical and thermal length scales. The latter is characterized by the thermal velocity of the pions $\sqrt{T_{\rm f}/m_{\rm t}}$, with the thermal freeze-out temperature $T_{\rm f}$ and the transverse mass of the pion pair $m_{\rm t}$. Generally, the smaller of the two scales determines the size of the HBT radii. Therefore, a differential HBT analysis as function of $m_{\rm t}$ contains valuable information about the dynamical properties of the pion source at freeze-out. The extraction of the space-time quantities can be performed by comparison to model calculations, however, we refer to a set of useful 'pocket formulas' [1] which will be described below and have been proven to work very satisfactory.

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2. Results from SPS

The CERES experiment has performed a centrality dependent study of Bose–Einstein correlations of like-sign pions near mid-rapidity in Pb–Au collisions at 40, 80, and 158 AGeV/c. For the analysis of the correlation function, the common Bertsch–Pratt decomposition of the three-momentum difference vector into the components $\vec{p}_{\pi 1} - \vec{p}_{\pi 2} = \vec{q} = (q_{\rm long}, q_{\rm side}, q_{\rm out})$ was used, yielding the corresponding radius parameters $R_{\rm long}, R_{\rm side}$, and $R_{\rm out}$. For details of the analysis and the Coulomb correction procedure see [2].

Results for the HBT radius parameters in Pb-Au collisions at 158 AGeV/c are presented in Fig. 1 as function of $1/\sqrt{m_{\rm t}}$. At all centralities, $R_{\rm long}$ exhibits an approximately linear dependence on $1/\sqrt{m_{\rm t}}$. Having in mind that $1/\sqrt{m_{\rm t}}$ is proportional to the thermal velocity of pions, this behaviour resembles very much a Hubble-like expansion pattern, with strict proportionality between spatial extent and local velocity difference. As for the case of Hubble expansion, the lifetime $\tau_{\rm f}$ (or the 'age') of the system can be related to the slope of the data points in Fig. 1 as proposed by Makhlin and Sinyukov [3]:

$$R_{\rm long} = \tau_{\rm f} \sqrt{T_{\rm f}/m_{\rm t}}. \qquad (1)$$

The increase of the slope with centrality indicates a slight increase of the lifetime. For the most central collisions we derive $\tau_{\rm f} \approx$ 7–8 fm/c, assuming $T_{\rm f}$ = 160–120 MeV. Note that the dependence on $T_{\rm f}$ is weak since it enters only to the square root.

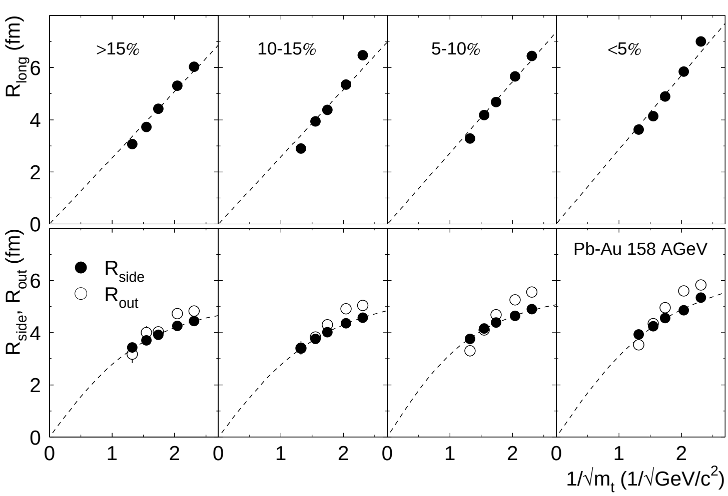

Fig. 1. HBT radius parameters at 158 AGeV/c as function of $1/\sqrt{m_{\rm t}}$. The curves show fits of Eqs. (1) and (2) to the data [2].

The radius parameter R_{side} in Fig. 1 shows also a significant dependence on $1/\sqrt{m_{\mathrm{t}}}$, however, it saturates at large $1/\sqrt{m_{\mathrm{t}}}$. This indicates that R_{side} (in contrast to R_{long}) is not entirely determined by the thermal length scale but limited by the finite transverse size of the system. For this case, another 'pocket formula' applies [4]:

$$R_{\mathrm{side}} = \frac{R_{\mathrm{geo}}}{(1+\eta_{\mathrm{f}}^2 \frac{m_{\mathrm{t}}}{T_{\mathrm{f}}})^{\frac{1}{2}}}\,, \tag{2}$$

where η_{f} is the transverse flow rapidity. A fit to the data allows the extraction of $\eta_{\mathrm{f}}^2/T_{\mathrm{f}}$. For the same range of T_{f} as above and a Gaussian source density profile we obtain the average transverse flow velocity $\langle v_{\mathrm{t}}\rangle = 0.5 - 0.6c$.

Particular interest is devoted to the parameter R_{out}. Since the component q_{out} contains the (transverse) energy difference of a pion pair, R_{out} is sensitive to the temporal extent of the source, or the duration of emission $\Delta\tau$ [5]. By comparison to R_{side}, the emission duration can be estimated via $R_{\mathrm{out}}^2 - R_{\mathrm{side}}^2 = \beta_{\mathrm{t}}^2 \Delta\tau^2$, with $\beta_{\mathrm{t}} = k_{\mathrm{t}}/m_{\mathrm{t}}$ and the mean transverse momentum k_{t} of the pion pair. At large $1/\sqrt{m_{\mathrm{t}}}$ (small k_{t}) a small but significant excess of R_{out} over R_{side} is observed, leading to a short emission duration of $\Delta\tau \approx 2$ fm$/c$. We note that very similar numbers are recently observed at RHIC after the treatment of the Coulomb repulsion was improved (see also the talks by R. Soltz and M. Lisa on this conference).

3. Beam energy dependence and universal freeze-out

It was noted as a major puzzle that the HBT parameters observed at RHIC are very similar to those observed at the much lower SPS energy. Indeed, the variation of HBT parameters over the presently explored energy range from AGS to RHIC is very subtle, as shown in Fig. 2. Only for R_{long} a systematic increase is observed over the SPS range and to RHIC, indicating a smooth increase of the lifetime. In the following, a possible explanation of the beam energy dependence in terms of a universal freeze-out condition for pions is given.

Assuming azimuthal symmetry in central collisions it is convenient to define a freeze-out volume[1] V_{f}:

$$V_{\mathrm{f}} = \sqrt{2\pi}^{3}\, R_{\mathrm{long}}\, R_{\mathrm{side}}^2. \tag{3}$$

In the left panel of Fig. 3 V_{f} is shown as function of the mean number of participants $\langle N_{\mathrm{part}}\rangle$ in Pb–Au collisions at 40, 80, and 158 AGeV$/c$. An

[1] It should be noted that V_{f} does not comprise the total reaction volume in the presence of collective expansion. The implications of this approach are discussed in [6].

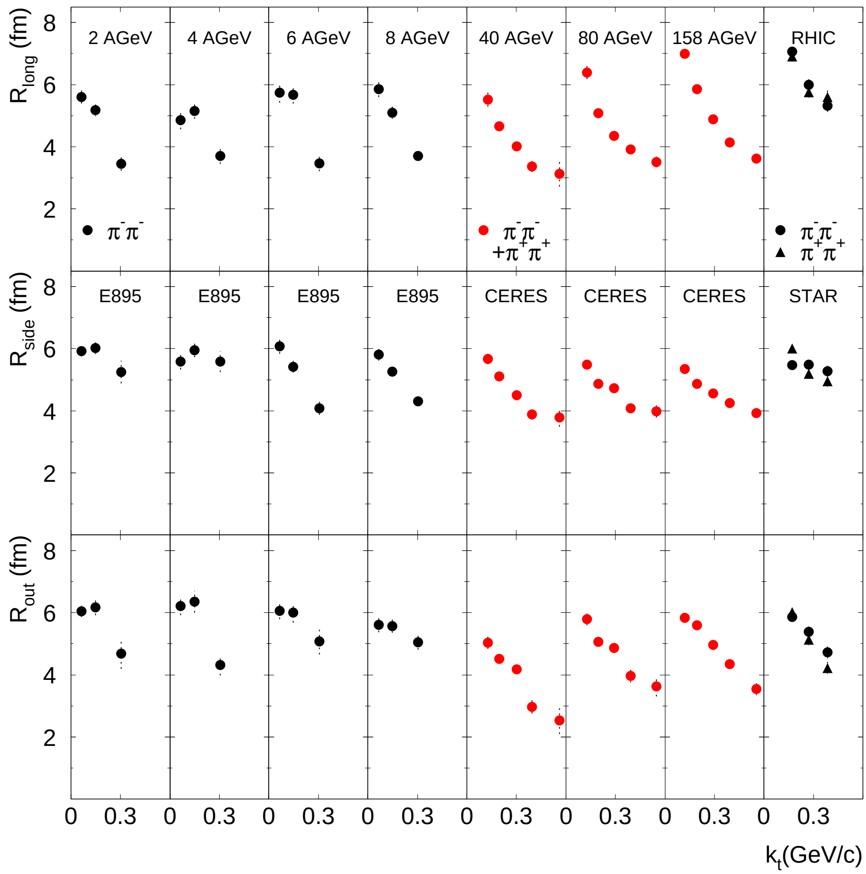

Fig. 2. Compilation of HBT radii in central collisions of lead and gold nuclei at mid-rapidity (from [2]). The RHIC data are at $\sqrt{s} = 130$ GeV.

approximately linear scaling with $\langle N_{\rm part}\rangle$ is observed at all beam energies. Implying that the total multiplicity at SPS energies scales approximately linear with $\langle N_{\rm part}\rangle$ as well, this might suggest that freeze-out happens at constant particle density. The beam energy dependence, however, rules out such a scenario: No significant increase of $V_{\rm f}$ is observed from 40 to 158 AGeV$/c$, although the multiplicity increases by more than 50%. This becomes even more clear, if $V_{\rm f}$ is plotted as function of beam energy (right panel of Fig. 3). While the particle multiplicity rises monotonically with beam energy, the freeze-out volume $V_{\rm f}$ exhibits a clear non-monotonic behaviour, with a pronounced minimum between AGS and SPS energies.

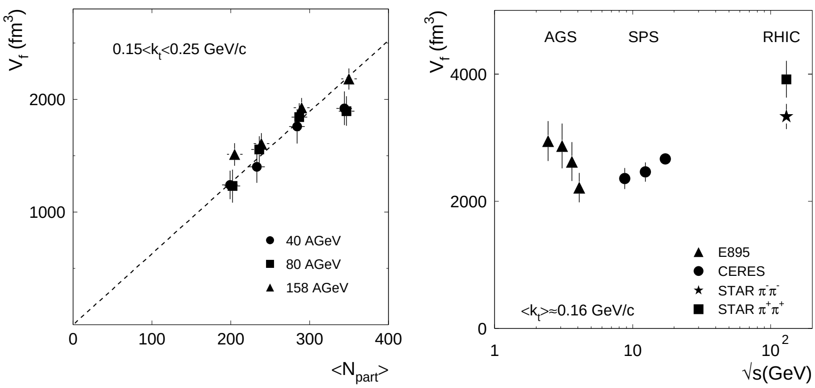

Fig. 3. Left: Freeze-out volume V_f as function $\langle N_\mathrm{part}\rangle$. Right: V_f as function of the beam energy (from [6]).

The key to understand this peculiar behaviour lies in the evaluation of the mean free path λ_f of pions at thermal freeze-out. We start from the definition:

$$\lambda_\mathrm{f} = \frac{1}{\rho_\mathrm{f}\,\sigma} = \frac{V_\mathrm{f}}{N\,\sigma}, \tag{4}$$

with the freeze-out density ρ_f, the particle number N and the cross section σ of pions with the surrounding medium. In case of a composed medium, the denominator $N\,\sigma$ has to be replaced by a sum over the particle species present in the fireball:

$$\begin{aligned} N\,\sigma &= N_N\,\sigma_{\pi N} + N_\pi\,\sigma_{\pi\pi} + \ldots && (5)\\ \text{with}\quad N_N &= 2\sqrt{2\pi}\,0.87\,\frac{dN_{p+\bar{p}}}{dy|_{y_\mathrm{mid}}}\,, && (6)\\ N_\pi &= 3\sqrt{2\pi}\,0.87\,\frac{dN_{\pi^-}}{dy|_{y_\mathrm{mid}}}\,, && (7)\end{aligned}$$

and $\sigma_{\pi N} = 72$ mb, $\sigma_{\pi\pi} = 13$ mb (for further explanation see also [6]).

The contributions to Eq. (5) from the most abundant particle species pions and (anti-)nucleons, and the total sum $N\,\sigma$, are shown in Fig. 4 (left panel). While the contribution from pions rises monotonically with beam energy, the nucleon contribution drops drastically over the AGS range and stays approximately constant from SPS to RHIC. Consequently, the sum $N\,\sigma$ is nucleon-dominated at low energies and pion-dominated at high energies. In the transition region, $N\,\sigma$ exhibits a minimum, in striking similarity to V_f (Fig. 4, right panel). According to Eq. (4), this suggests a universal mean free path of $\lambda_\mathrm{f} \approx 1$ fm of pions at freeze-out, independent of beam energy (and centrality). The observation of λ_f being much smaller than

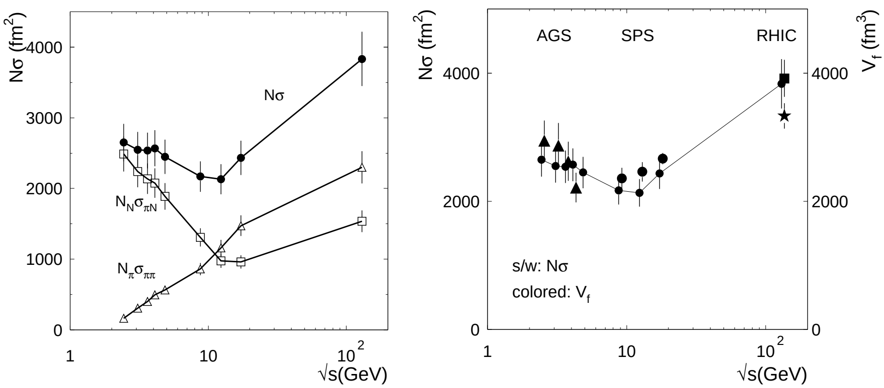

Fig. 4. Beam energy dependence of $N\sigma$ (from [6]). Left: Different contributions from nucleons and pions. Right: In comparison to V_{f}.

the system size may reflect the large expansion rate of the system. Such a small λ_{f} is surprising in view of a hadronic rescattering picture, which implies mean free paths of the order of the system size at freeze-out. In particular, the observation of a constant λ_{f} over a wide range of particle multiplicities conflicts with the notion of a rescattering-dominated late stage of the reaction.

The pion density $\rho_{f,\pi} = N_\pi/V_{\mathrm{f}}$ at thermal freeze-out can be extracted from Eqs. (3) and (7), yielding about 0.5 fm^{-3} at top SPS and RHIC energies [6]. A comparison to thermal model calculations of the pion density at *chemical* freeze-out indicates that the volume increase between chemical and thermal freeze-out is only 30% [7]. This results in an estimate of the time span between chemical and thermal freeze-out of approximately 1 fm/c, implying a typical (one-dimensional) transverse source size of $R_{\mathrm{side}} \approx 6$ fm and $v_{\mathrm{t}} \approx 0.5c$ (see above). This is consistent with the short emission duration observed by HBT, and puts a tight constraint on the lifetime of the hadronic phase, if chemical freeze-out happens at hadronization (see also the talk by M. Lisa). Finally, the temperature difference between chemical and thermal freeze-out can be estimated to be only about 15–20 MeV, assuming $V \propto T^{-3}$ for isentropic expansion. This is consistent with a short lifetime of the hadronic phase but in contradiction to the low thermal freeze-out temperatures reported *e.g.* from blast-wave analyses (see talk by M. Lisa).

To conclude, the space-time picture derived from HBT at SPS is very similar to recent observations at RHIC. The HBT data suggest consistently a large expansion rate and a short lifetime of the hadronic phase, indicated by $R_{\mathrm{out}} \approx R_{\mathrm{side}}$ and the universal freeze-out condition $\lambda_{\mathrm{f}} \approx 1$ fm. This implies a very early build-up of radial flow and a rapid freeze-out after hadronization. These observations are in contradiction to most hydrodynamical and transport calculation which predict significantly longer reaction and emission time scales. The understanding of the dynamics of heavy ion collisions including their space-time properties is therefore still incomplete.

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