A summary of current interferometry data in relativistic heavy ions is presented. At $\sqrt{s_{NN}} = 17\text{GeV}$ a sudden increase in the pion source volume is observed for central PbPb collisions. This seems to imply that the pion phase density has reached a limit. The source size of different particles decreases with mass when the transverse velocity is held constant but increases with mass when $m_T$ is held constant. The antiproton source radius is larger than the proton source radius. So far no long lived source has been seen. The pion source size varies slowly with rapidity but more rapidly with $m_T$ implying strong transverse flow. There is very slow increase of pion radii with $\sqrt{s}$.

1 Introduction

The goal of studying relativistic heavy ion collisions is to heat and compress nuclear matter to such an extent that it undergoes a phase transition to a quark gluon plasma. Such a phase transition should also make a significant difference in the Equation of State of nuclear matter and may therefore reveal itself in the space-time evolution of the source. Hanbury Brown and Twiss interferometry is sensitive to this evolution and can thus play a crucial role in searching for a phase transition. Multi-dimensional correlation function analysis allows extraction of the duration of particle emission.

With HBT we hope to answer the following questions:

- Duration of Freezeout: Can we see a long lived source? For a mixed phase of QGP and Hadron gas we might hope to see a long lived duration of emission via a difference in the outward and sideward radii.
- Azimuthal Flow: What is the source shape in the reaction plane?
- Multiplicity Dependence: Is there a critical multiplicity above which source size increases rapidly?
- Rapidity, $\sqrt{s}$, $m_T$ & $\gamma_T$ dependence: Have we produced a boost invariant source? Is there a critical $\sqrt{s}$? Can we see transverse flow?
- 3-Particle Correlations: Is the source chaotic?
- Phase Densities: Have we saturated phase space?

This paper is an attempt to answer such questions.
2 Two-Particle Correlations

For a set of events that are azimuthally symmetric, the correlation function $C_2$ is often fitted with the following three-dimensional Gaussian parameterization:

$$C_2 = 1 + \lambda \exp(-R_l^2 Q_l^2 - R_o^2 Q_o^2 - R_s^2 Q_s^2).$$

(1)

The momentum difference $\vec{Q} (= \vec{p}_1 - \vec{p}_2)$ of the particle pair is resolved into three dimensions; $Q_l$ parallel to the beam axis; $Q_o$ is parallel to the sum of transverse momentum of particle pairs and and $Q_s$ which is perpendicular to $Q_l$ and $Q_o$. Typically the Longitudinal Center of Mass System (LCMS) is chosen as reference frame ($p_{z1} + p_{z2} = 0$).

2.1 Rapidity and $m_T$ Dependence

The NA49 collaboration has measured pion radii over a wide range of rapidity and transverse mass $m_T$. Their results are shown in Fig. 1 and are in good agreement with those of NA44. At $\sqrt{s_{nn}} = 17\text{GeV}$, the transverse radii $R_o$ and $R_s$ are boost invariant while in the longitudinal direction $R_l$ falls as one moves away from central rapidity. The radii decrease as $k_T = m_T - m_\pi$ increases, which is suggestive of a hydrodynamic expansion. In such a system, the HBT source radii are “lengths of homogeneity” that are set by velocity and/or temperature gradients in the fluid.

Figure 2 shows source radii for different particles versus $m_T$, $\gamma_T$ the Lorentz factor in the transverse direction, and for LEP data the mass of the particle. At fixed $\gamma_T$ the source radius decreases with increasing mass of the particle, while at fixed $m_T$ the radii increase with mass. This could imply that the lighter pions leave the source before the protons have frozen out.

2.2 Energy and Multiplicity Dependence

At the AGS $\sqrt{s_{nn}} = 4.9 \text{ GeV}$, the pion radii increase as the impact parameter decreases, and the multiplicity increases. This is also true at CERN energies. Figure 2.2 shows a measure of the “homogeneous volume” for pions versus the multiplicity of the events at $\sqrt{s_{nn}} \approx 17\text{GeV}$. As expected, the source volume increases with increasing multiplicity. For SA and peripheral PbPb collisions, the volume rises more slowly than the multiplicity, implying an increase in the phase space density. However, for central PbPb collisions there is a sharp increase in the slope of the curve. This can be interpreted as the phase space density reaching some limit. It will be interesting to see if this limit holds at the much higher multiplicities achieved at RHIC. At the same time,
the duration of pion emission $\delta \tau \approx \sqrt{R_o^2 - R_s^2/\beta_T}$, seems to saturate with increasing multiplicity at about 4fm.

One of the most interesting results of this conference is that STAR has found that the pion radii increase by less than 20% while $\sqrt{s}$ increases by a factor of 7.5. This may be due to very rapid expansion of the source.

2.3 Sizes in and out of the Reaction Plane

E895 has measured the source size with respect to the reaction plane and has found that for semi-central collisions $R_s$ is larger along the reaction plane than perpendicular to it.

3 Three-Particle Correlations

Two-particle interferometry is unable to provide a measurement of the phase of the source functions. However, this information can be deduced from three
particle correlations, if the emission is fully chaotic. This phase reflects asymmetries in the source which may be induced by geometry, flow, or resonance decays. If the source is not completely chaotic, the interpretation is more difficult. One can measure the strength of the 3-particle correlation by defining

\[
W \equiv \frac{\{C_3(Q_3) - 1\} - \{C_2(Q_{12}) - 1\} - \{C_2(Q_{23}) - 1\} - \{C_2(Q_{31}) - 1\}}{2 \sqrt{\{C_2(Q_{12}) - 1\}\{C_2(Q_{23}) - 1\}\{C_2(Q_{31}) - 1\}}}. \tag{2}
\]

For a fully chaotic system we expect \(W = 1\). Figure 2.2 shows \(W\) versus \(Q_3\) for SPb and PbPb for \(\sqrt{s_{nn}} \approx 17\text{GeV}\). For PbPb the system is more chaotic than for SPb.

### 4 Phase Space Density

A particle’s phase space density is defined as

\[
f(p, x) = \frac{(2\pi\hbar c)^3}{(2s + 1)} \frac{d^6N}{dp^3dx^3}, \tag{3}
\]

where \(s\) is the particle’s spin. Averaged over the “homogeneous” volume, \(f_\pi\) can be derived from the ratio of the single-particle spectrum to the volume as measured by HBT,

\[
\langle f_\pi \rangle = \frac{\pi^2(\hbar c)^3}{(2s + 1)} \frac{\sqrt{\lambda}d^3N_\pi}{dp^3} \frac{1}{R_{ol}^3}. \tag{4}
\]

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Figure 5 shows the system dependence of the phase space densities and source radii for $\pi^+$, p and $\bar{p}$. The $\pi^+$ and p phase space densities generally increase with system size. At $\sqrt{s_{nn}} = 17.3$GeV

$$\langle f_{\bar{p}} \rangle < \langle f_p \rangle < \langle f_{\pi^+} \rangle < \langle f_{\pi^\mp} \rangle < 1.$$  

The large antiproton radius may be, because only $\bar{p}$s emitted from the surface of the source can avoid annihilation. This would imply that the observed $\bar{p}$'s would have a larger RMS freeze-out radius than the protons.

5 Conclusions

Interferometry is now a mature field able to make detailed observations of the hadronic source. It is now possible to measure the extra width of the source in the reaction plane and the duration of the pion emission. At $\sqrt{s_{nn}} = 17$GeV, we see a sudden increase in the pion source volume above a certain multiplicity. This seems to imply that the pion phase space has reached some kind of limit. It will be interesting to see if this limit is broken at RHIC. At $\sqrt{s_{nn}} = 17$GeV collisions, the duration of pion emission rises with multiplicity and then saturates at $\delta \tau \approx 4$fm. So far, no long lived source has been seen. The pion source size varies slowly with rapidity but more rapidly with $m_T$, implying strong transverse flow. It is not clear how to compare radii from different particles. Should we study them at the same transverse velocity or the same transverse mass? The antiproton radius looks larger than the proton radius. However, this may be due to annihilation in the interior of the source. The first data from STAR show radii very similar to those seen at lower energies. In looking to the future we should draw inspiration from the past. Hanbury Brown and Twiss invented the interferometry technique to measure the size of stars using the interference of photons. Perhaps the next great advance in our field will come from photon interferometry of heavy ion collisions. This would allow us to “see” the beginning of these collisions and
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References

1. S. Pratt, Phys. Rev. D 33, 1314 (1986).
2. P. Seyboth (NA49 Coll.) in Proc. 8th Int. Workshop on Multiparticle Production, Correlations and Fluctuations, eds. T. Csörgő et al (WSPC, Singapore, 1999) p.168.
3. I.G. Bearden et al, Phys. Rev. C 58, 1656 (1998).
4. T. Csörgő and B. Lörstad, Phys. Rev. C 54, 1390 (1996).
5. U.A. Weidemann and U. Heinz, Phys. Rep. 319, 145 (1999).
6. M.A. Lisa (E895 Coll.), Nucl. Phys. A 661 444c.
7. I. Bearden et al, Eur. Phys. J. C 18, 317 (2000).
8. W. Christie (STAR Coll.), these proceedings.
9. I.V. Andreev, M. Plümer and R.M. Weiner, Int. J. Mod. Phys. A 8, 4577 (1993); B. Lörstad, Int. J. Mod. Phys. A 4, 2861 (1989); U. Heinz and Q.H. Zhang, Phys. Rev. C 56, 426 (1997) and H. Heiselberg and A.P. Vischer, Phys. Rev. C 55, 874 (1997).
10. H. Bøggild et al, Phys. Lett. B 455, 77 (1999).
11. M.M. Aggarwal et al, Phys. Rev. Lett. 85, 2895 (2000).
12. G.F. Bertsch, Phys. Rev. Lett. 72, 2349 (1994); ibid. 77, 789(E) (1996).
13. J. Barrette et al, Phys. Rev. Lett. B 78, 2916 (1997), Nucl. Phys. A 312, 491 (1978).
14. S. Mrózewiński, Phys. Lett. B 308, 216 (1993).
15. M. Murray, “Source Sizes and Phase Space Densities in Heavy Ion Collisions” [nucl-ex/0008006] accepted by Phys. Rev. C

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