Deuteron Production, Source Sizes and Phase Space Densities

Michael Murray for the NA44 Collaboration

Relativistic nucleus-nucleus collisions create matter at high energy density. The transverse mass spectra of produced hadrons appear to be thermal in nature, and allow study of rescattering and collective expansion. Protons and deuterons are sensitive probes of collective expansion due to their large masses. Pions are by far the most copiously produced particles and they reflect the total entropy of the collisions. We measure source sizes via coalescence and interferometry, and combine these with single particle spectra to derive phase space densities. This allows us to quantify the freeze-out conditions for different particles as a function of m_T, the number of participant nuclei and $\sqrt{s}$, and so constrain models of possible quark gluon plasma production.

The model of deuteron production by final state coalescence of protons and neutrons with small relative momenta has been very successful [1, 2]. Near mid-rapidity, direct production of $d\bar{d}$ pairs is small due to the high $d\bar{d}$ mass threshold of 3.75GeV/c^2, and pre-existing deuterons are unlikely to survive the many collisions required to shift them to mid-rapidity. Since coalescence depends on the distribution of nucleons, one can determine a nucleon source size from the d/p^2 ratio [3]. To facilitate comparison with our HBT interferometry results, in this analysis we assume a Gaussian distribution of the proton source [4]. Ignoring the 2.2MeV binding energy of the deuteron, the source radius R_G is

$$R_G^3 = \frac{3\pi^{\frac{3}{2}}(\hbar c)^3}{2m_p} \frac{\frac{E_p d^3 N_p}{dp^3} \frac{E_n d^3 N_n}{dp^3}}{\frac{E_d d^3 N_d}{dP^3}} \qquad (1)$$

where m_p is the proton mass, p is the proton momentum and $P = 2p$ is the deuteron momentum, Since R_G is sensitive to both the transverse and longitudinal size of the source, when comparing to HBT results it is best to compare to $(R_\perp^2 \cdot R_{||})^{\frac{1}{3}}$ (Eqn. 6.3 of [5]), where $R_\perp$ and $R_{||}$ parametrize the extent of the source perpendicular and parallel to the beam [6]. NA44 has published HBT results in the Pratt-Bertsch frame where $R_s = R_\perp$ and $R_l \approx R_{||}$. We will therefore compare R_G to $(R_s^2 \cdot R_l)^{\frac{1}{3}}$.

One can also characterize the system by the density of particles in phase space

$$f(\mathbf{p},\mathbf{x}) \equiv \frac{(2\pi\hbar c)^3}{(2s+1)} \frac{d^6 N}{dp^3 dx^3} \qquad (2)$$

where s is the spin of the particle. For a system with temperature T and chemical potential μ

$$f(E) = \frac{1}{e^{(E-\mu)/T} \pm 1} \qquad (3)$$

where E is the energy and ± 1 selects bosons or fermions. For a dilute system, *i.e.* $f \ll 1$, Eqn. 3 gives

$$f_p \approx e^{-(E_p-\mu)/T} \qquad (4)$$

$$f_n \approx e^{-(E_n-\mu)/T} \qquad (5)$$

$$f_d \approx e^{-(E_d-2\mu)/T}. \qquad (6)$$

Since $E_d = E_n + E_p$, Eqns. 4-6 imply

$$f_d(\mathbf{P},\mathbf{x}) = f_p(\mathbf{p},\mathbf{x}) f_n(\mathbf{p},\mathbf{x}). \qquad (7)$$

We assume that the proton and neutron spectra are identical, since any nucleons measured at $y \approx 2$ must have suffered many collisions and are almost as likely to be protons as neutrons. Averaging f_p over x gives

$$\langle f_p \rangle \equiv \frac{\int d^3x f_p^2}{\int d^3x f_p} = \frac{2}{3} \frac{d^3N_d/dP^3}{d^3N_p/dp^3}. \qquad (8)$$

For pions we have measured the source size in three dimensions as well as single particle. Dividing d^3N_π/dp^3 by the invariant volume, gives

$$\langle f_\pi \rangle = \pi^{\frac{3}{2}} (\hbar c)^3 \frac{d^3N_\pi}{dp^3} \frac{\sqrt{\lambda}}{R_s R_o R_l} \qquad (9)$$

where λ is the strength of the correlation function and $\sqrt{\lambda}$ accounts for the effect of resonances on $\langle f \rangle$ [7].

The m_T distributions are approximately exponential over the NA44 acceptance, and become harder (*i.e.* have larger inverse slopes) for larger systems, consistent with an increase of transverse flow. The ratio $\langle m_t \rangle / A$ is a measure of the average transverse velocity. It is almost equal for protons and deuterons, as well as for $\bar{p}$ and $\bar{d}$ from $PbPb$ collisions, as would be expected from coalescence. Similar behavior is seen for $AuAu$ collisions at the AGS ($\sqrt{s} = 4.9$GeV/A) but the spectra are softer, implying less flow and/or a lower freeze-out temperature [8].

Figure 1 shows the system dependence of the phase space densities and source radii for pions and protons. Antiproton data are also shown for $PbPb$ collisions. The π^+ and p phase space densities increase with system size, with $\langle f_{\bar{p}} \rangle \ll \langle f_p \rangle \ll \langle f_{\pi^+} \rangle \ll 1$. For central $PbPb$ collisions, the pion phase space density $\langle f_\pi \rangle$ at $\langle p_T \rangle \approx 240\text{MeV}/c$ is still much

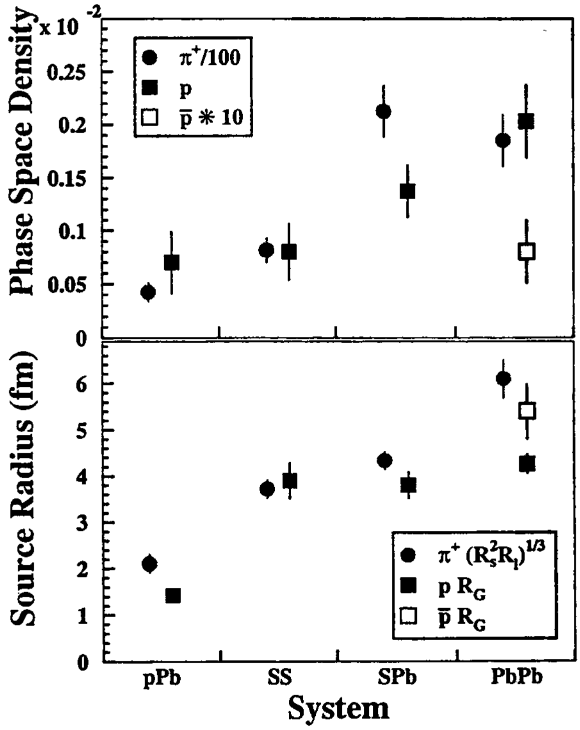

Figure 1: Phase space densities $\langle f \rangle$ and source radii for π^+ and p at $\langle p_T \rangle \approx 240\text{MeV}/c$, and for $\bar{p}$ at $\langle p_T \rangle \approx 490\text{MeV}/c$.

less than one, however f_π is presumably larger towards the centre of the source and at lower p_T. The pion and proton source radii increase with system size, however for nucleus-nucleus collisions the pion source size grows more quickly with the number of participants than the proton source. The increased π^+ multiplicity (or entropy) is associated with a corresponding large increase in the pion source size, whereas for protons the increased multiplicity occurs with a roughly constant source size. Since the π^+ are at lower m_T than the protons, this implies an increasing m_T dependence of the source radii with system size, which can be understood in terms of stronger flow for $PbPb$ than for SS collisions.

Because of their large annihilation cross-section, one might expect that $\bar{p}$s would only be emitted from the surface of the system and would have a larger RMS freeze-out radius than protons. However, the p and $\bar{p}$ source radii are comparable presumably because π-nucleon scattering is more important than nucleon-nucleon scattering.

In order to study the energy dependence of freeze-out we compare our $PbPb$ data at $\sqrt{s}$ = 17.3GeV/A to AGS $AuAu$ data at $\sqrt{s}$ = 4.9GeV/A, at the same scaled rapidity $y = \frac{1}{3} y_{beam}$. Fig. 2 shows the phase space densities and source radii for $PbPb$ and $AuAu$ collisions as a function of m_T. At a given m_T, f_{π^+} drops with $\sqrt{s}$ while f_p increases. Thus the ratio μ/T decreases with $\sqrt{s}$ for protons but rises for pions. Since $E = m_T cosh(y)$, Eqn. 3 also implies that f be exponential in m_T for $f \ll 1$ as is the case for our data. However if the system is boosted due to transverse flow, $f(m_T)$ will be "blue-shifted" to higher m_T values [9]. The slope of f_{π^+} versus m_T is the same within errors at both energies, but f_p is much flatter at the higher energy. This is because the large proton mass makes it more sensitive to the transverse flow.

The m_T dependence of the source sizes is stronger at higher energy. Several hydrodynamical models have interpreted the HBT source radii as "lengths of homogeneity" which should decrease with increasing m_T [12, 13]. The larger size and stronger m_T dependence of the radii at the higher energy may reflect a larger initial pressure and energy density.

Both pion and proton radii increase with $\sqrt{s}$. However f_{π^+} increases with $\sqrt{s}$ while f_p drops. Since $\bar{p}/p \ll 1$ at both SPS and AGS energies [14, 15, 16], we know that most protons observed near mid-rapidity are remnants of the target or projectile that have been slowed down by multiple collisions. At the higher energy they are distributed over a larger momentum (*i.e.* y, m_T) space and, if they did not interact with other particles, one might expect them to freeze out at the same phase space density, and therefore a smaller radius. However the large number of additional pions produced at $\sqrt{s}$ = 17.3GeV/A prolong π-nucleon scattering until the proton source has reached a larger size than it does at $\sqrt{s}$ = 4.9GeV/A. Since both the momentum space and physical space increase while the number of protons is roughly constant, the proton phase space density decreases with $\sqrt{s}$.

For pions the situation is different. At $\sqrt{s}$ = 4.9GeV/A, they are outnumbered by protons and so their freeze-out is driven by that of the nucleons. At $\sqrt{s}$ = 17.3GeV/A, they are the most numerous particle and they control freeze-out. However since the pion-pion cross-section is smaller than the pion-nucleon cross-section, f_{π^+} increases with $\sqrt{s}$. Thus at $\sqrt{s}$ = 4.9GeV/A the hadronic system is held together by protons while at $\sqrt{s}$ = 17.3GeV/A it is held together by pions.

References

[1] S. Butler and C. Pearson, Phys. Rev. **129**, 836 (1963).

[2] J. Kapusta, Phys. Rev. C **21**, 1301 (1980).

[3] A.Z. Mekjian, Phys. Rev. C **17**, 1051 (1978).

[4] W.J. Llope *et al.*, Phys. Rev. C **52**, 2004 (1995).

[5] R. Scheibl and U. Heinz, Phys. Rev. C **59**, 1585 (1999).

[6] U. Heinz, B. Tomášik, U.A. Wiedemann, and Y.-F Wu, Phys. Lett. B **382**, 181 (1996).

[7] D. Ferenc, U. Heinz, B. Tomášik, and U.A. Wiedemann, Phys. Lett. B **457**, 347 (1999). hep-ph/9902342.

[8] L. Ahle *et al.*, Phys. Rev. C60 064901 (1999).

[9] B. Tomášik, U.A. Wiedemann and U. Heinz, nucl-th/9907096.

[10] R. A. Solz *et al.*, Nucl. Phys. A **661** 439c (1999).

[11] L. Ahle *et al.*, Phys. Rev. C **57**, R466 (1998).

[12] T. Csörgő and B. Lörstad, Phys. Rev. C **54** 1390 (1996).

[13] U.A. Weidemann and U. Heinz, nucl-th/9901094.

[14] I.G. Bearden *et al.*, Phys. Rev. C **57**, 837 (1998).

[15] M.J. Bennett *et al.*, Phys. Rev. C **56**, 1521, (1997).

[16] T.A. Armstrong *et al.*, Phys. Rev. C **59**, 2699, (1999).

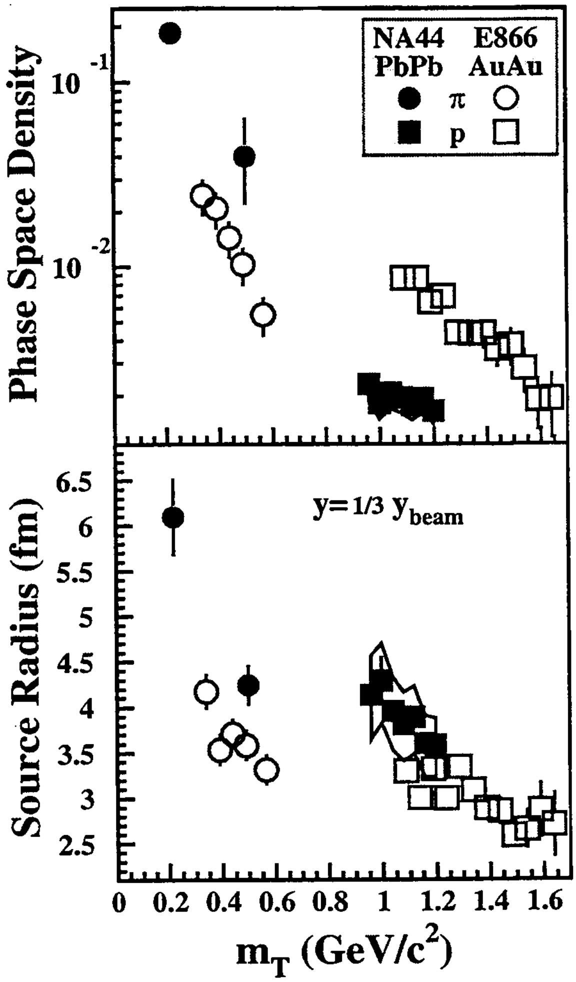

Figure 2: Phase space density and radii for π^+ and p versus m_T for $\sqrt{s}$ = 17.3 and 4.9GeV/A [8, 10, 11].