(Anti)proton and Pion Source Sizes and Phase Space Densities in Heavy Ion Collisions

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Abstract

NA44 has measured mid-rapidity deuteron spectra from AA collisions at $\sqrt{s_{nn}} \approx 18$ GeV at the CERN SPS. Combining these spectra with published $p$, $\bar{p}$ and $\bar{d}$ data allows us to calculate, within a coalescence framework, $p$ and $\bar{p}$ source sizes and phase space densities. These results are compared to $\pi^\pm$ source sizes measured by Hanbury-Brown Twiss, HBT, interferometry and phase densities produced by combining pion spectra and HBT results. We also compare to $pA$ results and to lower energy (AGS) data. The $\bar{p}$ source is larger than the proton source at $\sqrt{s_{nn}} = 17.3$ GeV. The phase space densities of $\pi^+$ and proton are not constant but grow with system size. Both $\pi^+$ and proton radii decrease with $m_T$ and increase with $\sqrt{s_{nn}}$. Pions and protons do not freeze-out independently. The nature of their interaction changes as $\sqrt{s_{nn}}$ and the $\pi/p$ ratio increases.

Relativistic heavy ion collisions provide a mechanism to heat and compress nuclear matter to temperatures and energy densities comparable to those of the early universe when it was still a plasma of quarks and gluons. Such a state may be fleetingly restored in these collisions where temperatures of $T = 168 \pm 3$ MeV and energy densities $\epsilon = 3$ GeV/fm$^3$ are observed [1, 2]. These values are close to those of the phase transition found in lattice calculations [3]. If such a hot and dense state were formed one would expect a large increase in entropy and possibly a saturation of the density of particles in phase space. The coalescence of nucleons into deuterons is sensitive to both their spatial and momentum correlations. In this paper we report $p$, $\bar{p}$ and $\pi^+$ source sizes measured by coalescence and interferometry, and combine these with single particle spectra to derive phase space densities. The phase space densities depend on temperature, chemical potentials, and velocity fields in the system. This description of the final hadronic state serves as a boundary condition for models of possible quark gluon plasma production. We vary the total size of the system by studying $PbPb$, $SPb$, $SS$ and $pPb$ collisions. We also compare our results to lower energy AGS data where the $\pi/p$ ratio is much lower. This comparison shows that the freeze-out of pions and protons is coupled.

NA44 is a focusing spectrometer that uses conventional dipole magnets and superconducting quadrupoles to analyze the momentum of the produced particles and create a magnified image of the target in the spectrometer [4, 5, 6, 7, 8, 9, 10]. The systematic errors on the deuteron yields range from 14% for $SPb$ to 9% for $PbPb$. The $p$ and $\bar{p}$ spectra are corrected for feed-down from $\Lambda$ and $\Sigma$ decays using a GEANT simulation with the $(\Lambda/p)$ and $(\Sigma/p)$ ratios taken from the RQMD model [9, 10, 11]. The systematic error was estimated by varying these ratios by $\pm 25\%$. These errors are slightly correlated for $p$ and $\bar{p}$. Fig. [1] shows NA44 deuteron spectra and previously published proton spectra at $y = 1.9-2.3$ as a function of $m_T/A$ [12]. The centrality is $\approx 10\%$ for $SS$, $SPb$ and $PbPb$. The spectra get flatter for the larger systems consistent with a higher temperature and/or stronger sideward flow. As expected from coalescence, the slopes are similar for protons...
and deuterons. This was also found for lower energy data, \[13\]. The deuteron inverse slopes (in \(m_T\)) and yields are listed in Table 1. A comprehensive analysis of all NA44’s proton and light clusters spectra will be given in a later paper.

The model of deuteron production by final state coalescence of protons and neutrons with small relative momenta states that the production of deuterons with a certain velocity is proportional to the number of protons and neutrons that have similar velocities \[15, 16\]. This model successfully describes measured deuteron distributions in intermediate energy heavy ion collisions and high energy pA collisions, \[17\]. Near mid-rapidity, direct production of \(dd\) pairs is small due to the high \(dd\) mass threshold of 3.75 GeV/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 ratio

\[
B_2(p) = \frac{E_p d^3N_p}{dP^3} \frac{E_n d^3N_n}{dP^3} \frac{E_d d^3N_d}{dP^3}
\]

where the deuteron momentum \(P\) is twice the proton momentum \(p\) \[18\]. Since we do not measure neutrons we assume that the spectra have the same shape and take the \(n/p\) ratio to be 1.06 \pm 0.04 from RQMD \[11\]. At \(\sqrt{s_{nn}} = 4.9\) GeV the measured \(n/p\) ratio is 1.19 \pm 0.08 independent of \(m_T\) \[19\]. RQMD is in reasonable agreement with this result.

To facilitate comparison with NA44’s pion interferometry results, we assume a Gaussian distribution of the proton source. If one also assumes a Gaussian wave-function one can solve for the source size analytically \[20\]

\[
(R^2_G + \frac{\delta^2}{2})^{3/2} = \frac{3\pi^2 (\hbar c)^3}{2m_p B_2}
\]

where \(m_p\) is the proton mass and \(\delta = 2.8\) fm accounts for the size of the deuteron. In reality the deuteron wave function is not Gaussian but is more accurately represented by the Hulthen form

\[
\phi(r) = \sqrt{\frac{\alpha\beta(\alpha + \beta)}{2\pi(\alpha - \beta)}} \cdot \frac{e^{-\alpha r} - e^{-\beta r}}{r}
\]

with \(\alpha = 0.23\) fm\(^{-1}\) and \(\beta = 1.61\) fm\(^{-1}\) \[21\]. The convolution of such a wave function with a gaussian source cannot be done analytically but is straightforward numerically to solve for the source radius \(R_H\),

Table 1: Deuteron inverse slopes and yields. Systematic and statistical errors have been added in quadrature. The errors are dominated by statistics and the extrapolation out of the acceptance. The PbPb fit is from \[14\].
we will therefore compare the longitudinal radius \( R \) to the radius in the sidewards direction \( R_G \). The momentum of each pion pair is zero. In this scheme the longitudinal size of the source, when comparing to the coalescence parameter \( R_H \), shown by \( \bullet \), is derived numerically using the Hulthen wave function in Eqn. 3. The solid line is a fit to the numerical results. The dotted and dashed curves show \( R_G \) from Eqn. 2 with and without a correction for the deuteron size.

\[ \text{Figure 2: Comparison of proton source radii versus the coalescence parameter } B_2^{1/3}. R_H, \text{ shown by } \bullet, \text{ is derived numerically using the Hulthen wave function in Eqn. 3. The solid line is a fit to the numerical results. The dotted and dashed curves show } R_G \text{ from Eqn. 2 with and without a correction for the deuteron size.} \]

Note our \( R_H \) is the \( R_0 \) of [23]. Figure 2 shows a comparison of \( R_H \) and \( R_G \) versus the coalescence parameter \( B_2 \).

Since \( R_H \) is sensitive to both the transverse and longitudinal size of the source, when comparing to HBT results it is best to compare to \( (R_1^2 \cdot R_\parallel)^{1/2} \) (Eqn. 6.3 of [23]), where \( R_\perp \) and \( R_\parallel \) parametrize the extent of the source perpendicular and parallel to the beam [23]. NA44 has published HBT results in the Pratt-Bertsch frame in which the sum of the longitudinal momentum of each pion pair is zero. In this scheme the radius in the sidewards direction \( R_s = R_\perp \) and the longitudinal radius \( R_l \approx R_\parallel \) [23]. In this paper we will therefore compare \( R_H \) to \( (R_s^2 \cdot R_l)^{1/2} \). These parameters can be thought of as “lengths of homogeneity” of the source [24, 27]. One can think of the radii as lengths scales of the velocity and/or temperature gradients. They represent snapshots of the hadronic system at freeze-out which may occur at different times for \( \pi^- \) and protons. However since the cross sections for \( \pi\pi, p\pi \) and \( pp \) collisions are comparable the freeze-out times should be close.

A particle’s phase space density is defined as

\[ f(p, x) = (2\pi\hbar c)^3 \frac{d^6 N}{dp^3 dx^3}. \tag{4} \]

For a system in chemical equilibrium at a temperature \( T \) and chemical potential \( \mu \)

\[ f(E) = \frac{1}{e^{(E-\mu)/T} \pm 1} \tag{5} \]

where \( E \) is the energy and \( \pm 1 \) selects bosons or fermions. For a dilute system, \( f \ll 1 \), Eqn. 5 gives

\[ f_d \approx e^{-(E_d - \mu_n - \mu_p)/T}. \tag{6} \]

Since \( E_d = E_n + E_p \), Eqn. 3 implies that

\[ f_d(p, x) = f_p(p, x) f_n(p, x) = \frac{n}{p} f_p(p, x)^2. \tag{7} \]

A more general form of this relation was derived in Eqn. 3 of [28] assuming only that the system is hot and large compared to the deuteron. Averaging \( f_p \) over \( x \) gives

\[ \langle f_p \rangle = \frac{1}{3} \frac{E_d \frac{d^3 N_d}{dp^3}}{E_p \frac{d^3 N_p}{dp^3}} \cdot \frac{p}{n}. \tag{8} \]

where the factor of 3 accounts for the spin of the particles. For pions NA44 has measured the source size in 3 dimensions with HBT, as well as single particle spectra. Some of the pions come from the decay of long-lived resonances such as \( \eta, \eta' \) and \( \omega \). These pions reduce the strength of the correlation function \( \lambda \), which typically is \( < 1 \). The fraction of pions which do not come from resonances is \( \sqrt{\lambda} \). [24]. This has been shown experimentally for \( e^+ e^- \) collisions and for RQMD simulations of \( PbPb \) collisions [8, 31]. Dividing \( \sqrt{x} d^3 N_\pi / dp^3 \) by the Lorentz invariant volume, [17, 32, 33] gives

\[ \langle f_\pi \rangle = \frac{\sqrt{x}}{3} \frac{\sqrt{\lambda} \frac{d^3 N_\pi}{dp^3}}{\frac{1}{R_s \sqrt{R_\perp ^2 R_{long} - R_\parallel ^4}}}. \tag{9} \]
Again the factor of 3 accounts for the pion’s spin degeneracy. Here $R_l$ is the extent of the source along the beam direction; $R_o$ the extent in the outward direction, i.e., towards the observer and $R_s$ measures the source in the sideward direction, perpendicular to both the beam axis and the line of sight to the observer. The $R_{ol}$ term is the “out-longitudinal” cross term. For PbPb collisions setting $R_{ol} = 0$ in the HBT fit increases $\langle f_\pi \rangle$ by 9% ± 10%. For $pPb$, $SS$ and $SPb$ we assume $R_{ol} = 0$ but add a systematic error of 13% to $\langle f_\pi \rangle$. For $pPb$ deuteron spectra are not available and $\langle f_p \rangle$ was calculated using Eqn. 9, replacing the last term with $\frac{1}{R_{inv}}$. $R_{inv}$ was determined from $pp$ HBT data. For $pPb$ $R_H$ and $R_{inv}$ agree within their errors of ≈ 5%, [34].

We can test the usefulness of these coalescence methods using RQMD, coupled with a coalescence afterburner, [35]. Figure 3 shows a comparison of $\langle f_p \rangle$ and $R_H$ for both data and RQMD for $SS$ and $PbPb$. For the data both $\langle f_p \rangle$ and $R_H$ are larger in $PbPb$ but for RQMD only $R_H$ increases from $SS$ and $PbPb$ while $\langle f_p \rangle$ stays constant. This invariance of $\langle f_p \rangle$ may be an artifact of the coalescence mechanism used, which ignores the requirement of a third particle. Since $\langle f_p \rangle$ is constant in the model the increase in proton multiplicity from $SS$ to $PbPb$ is accommodated by a large increase in $R_H$. However, $R_H$ is less than the average transverse radius of freezeout, 5.4 fm for $SS$ and 10.3 fm for $PbPb$, indicating that coalescence is not sensitive to the full size of the source. A similar situation occurs in pion interferometry where correlations between position and momentum cause the observer to only “see” the side of the source closest to her, [36]. Since these correlations get stronger as the particles get faster the size of the source drops with $m_T$, [29, 36].

Figure 4 shows the system dependence of the phase space densities and source radii for $\pi^\pm$, $p$ and $\bar{p}$. The $p$ and $\bar{p}$ radii for PbPb are consistent with coalescence data at $p_T = 0$, and $pp$ interferometry results [37, 38]. The $\pi^+$ and $p$ phase space densities generally increase with system size. We find that

$$\langle f_p \rangle \ll \langle f_\pi \rangle \ll \langle f_{\pi^+} \rangle < \langle f_{\pi^-} \rangle \ll 1$$

For $SPb$ and $PbPb$ $\langle f_{\pi^+} \rangle$ was calculated in [39] using
a similar equation to Eqn. 4. However a parametrization of the pion spectrum was used rather than the spectrum itself. The authors of \cite{3} concluded that the pion phase density was universal at freeze-out but this is not the case, since $\langle f_{\pi^+}\rangle$ is considerably smaller for $pPb$ and $SS$ than for $SPb$ and $PbPb$. For pions $(R_s^2 \cdot R_t)^\frac{1}{4}$ increases steadily with the number of participants and for $PbPb$ there is a rapid increase in the radii parameters with multiplicity, \cite{3}. At low $p_T$ $R_H$ does not change much from $SS$ to $PbPb$ (nor with centrality for $PbPb$) despite the increase in the proton multiplicity by $\approx 3$, see Fig. 1(a). However the $m_T$ dependence of $R_H$ is weaker for $PbPb$ than for $SS$, see Fig. 3. The extra protons mainly increase the proton phase space density $\langle f_p\rangle$.

Because of their large annihilation cross-section, one might expect that antiprotons (particularly those at low $p_T$) would be emitted only from the surface of the system and would have a larger RMS freeze-out radius than protons. Our data are consistent with this idea. An alternative view assumes that proton and antiprotons are produced in the same volume but that antiprotons are suppressed in the interior of the source \cite{41}. Applying this idea to our data would imply that antiprotons are emitted only from within $1.0 \pm 0.2$ fm of the surface \cite{41}. Recent $AuPt$ and $AuPb$ results from E864 at $\sqrt{s_{nn}} = 4.9$ GeV and low $p_T$ imply that $R_H = (4.0 \pm 0.2)$ fm, $R_H^p = (2.2 \pm 0.9 \pm 0.6)$ fm and $\langle f_p\rangle = (4.0 \pm 1.9) \cdot 10^{-6}$ \cite{41}. At $\sqrt{s_{nn}} = 4.9$ GeV antiprotons are mainly produced in primary nucleon-nucleon collisions and so they may have a smaller source size than protons. Since $R_H$ is a gaussian radius it is necessary to multiply it by $\sqrt{5}$ in order to compare it to a hard sphere with the same RMS radius, \cite{42}. If this is done the antiproton source is roughly equal to the size of the colliding $Au$ nuclei at $\sqrt{s_{nn}} = 4.9$ GeV.

In order to study the energy dependence of freeze-out we compare our $PbPb$ data at $\sqrt{s_{nn}} = 17.3$ GeV to AGS $AuAu$ data at $\sqrt{s_{nn}} = 4.9$ GeV. Since our data are not at mid-rapidity but at $y=2$ we have compared results at the same scaled rapidity $y = \frac{1}{2}y_{beam}$. Figure 3 shows the phase space densities and source radii for $PbPb$ and $AuAu$ collisions as a function of $m_T$. At a given $m_T$, $\langle f_{\pi^+}\rangle$ increases with $\sqrt{s_{nn}}$ while $\langle f_p\rangle$ decreases. Fitting $\langle f_{\pi^+}\rangle$ to Eqn. 5 gives $\mu_{\pi^+}^+ = 0$, within errors, for both energies while $\mu_p^T$ decreases with $\sqrt{s_{nn}}$. Since $E = m_T \cdot \cosh(y)$, Eqn. 5 also implies that $f$ be exponential in $m_T$ for $f \ll 1$. However if the system is boosted due to transverse flow, $f(m_T)$ will become flatter \cite{43}. This effect is proportional to mass. The data support this scenario since the $\langle f_p\rangle$ distributions are much flatter than the $\langle f_{\pi^+}\rangle$ ones. The $m_T$ distribution of $\langle f_p\rangle$ becomes flatter as $\sqrt{s_{nn}}$ increases because of an increase in flow and/or freeze-out temperature. However in general the velocity profile cannot be determined without knowing the density profile and so a determination of a mean velocity from $\langle f_p\rangle$ is beyond the scope of this work.

![Figure 4: Phase space densities $\langle f \rangle$ and source radii for $\pi^+$ and $p$ at $\langle p_T \rangle \approx 240$ MeV/$c$, and for $\bar{p}$ at $\langle p_T \rangle \approx 490$ MeV/$c$. For $PbPb$, $\sqrt{s_{nn}} = 30$ GeV and the proton points are derived from $pp$ HBT data.](image-url)
Several hydrodynamical models have interpreted the HBT source radii as "lengths of homogeneity" which should decrease with increasing $m_T$ and this is consistent with our data \cite{24, 26}. Both pion and proton radii increase with $\sqrt{s_{nn}}$. However $\langle f_{p+}\rangle$ increases with $\sqrt{s_{nn}}$ while $\langle f_{p}\rangle$ drops. Since $\bar{p}/p \ll 1$ at both SPS and AGS energies \cite{2, 11, 12, 14, 15}, we know that most protons observed near mid-rapidity are remnants of the target or projectile that were slowed down by multiple collisions. At the higher energy the protons occupy a somewhat larger volume and they are spread over a larger momentum (i.e. $y, m_T$) range. Therefore $\langle f_{p}\rangle$ drops with $\sqrt{s_{nn}}$.

For pions the situation is different. At $\sqrt{s_{nn}} = 4.9$ GeV, they are outnumbered by protons and so their freeze-out is driven by that of the nucleons. At $\sqrt{s_{nn}} = 17.3$ GeV, they are the most numerous particle and control freeze-out. Since $\sigma_{\pi\pi} < \sigma_{pp} \langle f_{p+}\rangle$ increases with $\sqrt{s_{nn}}$. Note that the ratio $\langle f_{p+}\rangle/\langle f_{p}\rangle$ increases by a factor of about 16 from $\sqrt{s_{nn}} = 4.9$ GeV to 17.3 GeV while the $\pi/p$ ratio only increases by a factor of 7.

Using the (anti)deuteron as a measure of the nucleon-nucleon correlations we have used a coalescence formalism to make the first measurements of $p$ and $\bar{p}$ source radii and phase space densities as a function of $m_T$ at $\sqrt{s_{nn}} = 17.3$ GeV. At $\sqrt{s_{nn}} = 4.9$ GeV the antiproton source is smaller than the proton source while at $\sqrt{s_{nn}} = 17.3$ GeV it appears to be larger. We have compared the proton data to our $\pi^+$ radii and phase space densities derived from HBT and single particle results as a function of system size and $\sqrt{s_{nn}}$. This comparison reveals a linkage between proton and pion freeze-out that changes as the $\pi/p$ ratio increases. At $\sqrt{s_{nn}} = 4.9$ GeV the hadronic system is held together by protons while at $\sqrt{s_{nn}} = 17.3$ GeV it is held together by pions.

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Figure 5: Phase space densities (a) and radii (b) for $\pi^+$ and $p$ versus $m_T$ for $\sqrt{s_{nn}} = 17.3$ and 4.9 GeV. The shaded bands indicate the estimated systematic error on the correction for weak decays. The E866 points used data from [13, 44, 45].