Freezeout Density in Relativistic Nuclear Collisions Measured by Proton-Proton Correlations

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Proton-proton correlations were measured with the "Plastic Ball" detector for two systems, Ca + Ca and Nb + Nb, at 400 MeV/nucleon as a function of proton multiplicity. The source-size radii extracted from these measurements were found to have a cube-root dependence on the proton multiplicity of the event. The deduced freezeout density, the density at which collisions between fragments cease, was found to be about 25% of normal nuclear-matter density.

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Relativistic nuclear collisions produce a zone of hot matter that radiates protons, pions, and composite particles. The effective source size of this participant region has been investigated by a number of groups by use of either proton-pair correlations[1,2] or pion-pair correlations[2-4] at small relative momenta. Proton-proton correlations came into use for source-size measurements following the correlation predictions of Koonin[5] which, in addition to the second-order interference effect due to quantum statistics, also include nuclear and Coulomb-induced final-state interactions between the two outgoing protons. The use of this method in nucleus-nucleus collisions is still relatively novel and an effort is being made to explore its potential. One application is the extraction of freezeout densities, a quantity which is of interest both for an understanding of the reactions and for its bearing on models of fragment production near a critical phase change.[6] Previous measurements of freezeout densities in general used composite-particle yields which reflect chemical freezeout, not the thermal freezeout reported here.

We report source radii as a function of proton multiplicity for two different reactions: Ca on Ca and Nb on Nb, both at 400 MeV/nucleon. The proton-proton correlations were measured at the Bevalac with the "Plastic Ball," a 4π detector with several features that are of significant value in this application. One obvious advantage is the large solid angle and rapid data-collection ability. This is an important factor in these measurements where obtaining sufficient pair statistics is often a problem, particularly when selections are made on event type. Another important feature is the ability to detect most of the charged particles in each event, thus obtaining a direct measure of the participant multiplicity which is necessary for the freezeout-density determination. The main difficulty, that the resolution is limited by the finite angular size of the detector modules, has been overcome by smearing the theoretical calculation, thus permitting a direct comparison with the measurement.

A detailed description of the Plastic Ball detector system appears elsewhere,[7] but briefly it is a spherical array of 815 scintillator $\Delta E,E$ detector modules which cover the full solid-angle region surrounding the target from 9 to 160 deg. The density of modules is greater, with a center-to-center separation of 3.5 deg, in the forward region between 9 and 30 deg. For a typical proton energy of 50 MeV this corresponds to a Δp, $|p_1 - p_2|/2$, of 10 MeV/c. The rest of the ball is more coarsely segmented with a center-to-center separation of 7 deg. The protons used in the correlation analysis were limited to those stopped in the E detector, giving complete energy and particle-type information. The energy range of these protons is ~ 40 to 200 MeV. In addition to the Plastic Ball itself there is an array of plastic scintillators called the "Plastic Wall" located downstream from the target which covers the region from 0 to 9 deg. The wall is used to complete the measurement of proton multiplicity and to define a trigger for event recording.

In measuring the proton multiplicity, N_p, we attempt to account for all participant protons including those bound in light composites (d, t, ^{3}He, and ^{4}He). These bound protons add approximately 40% to the proton multiplicity. The proton energy threshold in the laboratory frame was adjusted to approximately 15 MeV, slightly above the detector threshold to avoid instrumental uncertainties and limit the contributions from target spectators. The energy threshold for charge-2 ions is roughly 2 or 3 times higher. The projectile spectators are largely eliminated by excluding a region in $p_\perp$-rapidity space that was identified by use of low-multiplicity, peripheral-reaction events. Thus, N_p is actually the baryon-charge multiplicity in the participant region, but we will abbreviate it simply to proton multiplicity.

Radii have been extracted by comparing measured correlation functions to theoretical predictions which depend on the source-size radius. In practice, the correlation function is obtained from the data as a function of Δp (either one of the proton momenta transformed into the center of mass of the pair) by summing all p-p pairs, event by event, in bins $[N_{\text{true}}(\Delta p)]$ according to Δp, and dividing by p-p pairs from different events $[N_{\text{mixed}}(\Delta p)]$ to give

$$F(\Delta p) = \text{norm} \times N_{\text{true}}(\Delta p)/N_{\text{mixed}}(\Delta p).$$

In forming the mixed-pair sums each proton was paired with each proton in the preceding five events so that the statistical error in the ratio due to the mixed-event pairs could be neglected compared to the true-pair statistics. Mixed-event pairs with both protons in the same detector module are rejected to be consistent with the ball's requirement of two different modules for true pairs. The measured correlation function defined above is normalized to unity in the region $\Delta p = 70$–100 MeV/c.

The theoretical correlation functions which we compare with our measurements were calculated by Koonin.[5] In the form used here the correlation function, $F(\Delta p)$, equals $1 + R(\Delta p)$ where $R(\Delta p)$ is the correlation function of Ref. 5. The degree of correlation between the two protons is strongest when they are close in space, time, and momentum. In the general form of Koonin's calculation the proton source density is treated as isotropic with a Gaussian distribution in space and time, and the proton momenta are assumed to be independent of position. The Gaussian spatial density, $\rho(r) = \exp[(-r/r_g)^2]$, may be thought of as representing the proton positions at the point of their last scattering. For our analysis we assume that the time parameter is zero, i.e., all the protons are emitted at the same time. Consequently, our extracted radii are expected to be somewhat larger than the true spatial extent of the source.[8] This simplified form of the correlation function (shown in Fig. 1) illustrates the effects of the final-state interactions between the two protons. At $\Delta p = 0$ the correlation function is zero as a result of the Coulomb repulsion. The peak in the correlation function at $\Delta p = 20$ MeV/c is generated by the attractive nuclear force. The amplitude of this enhanced correlation is strongly dependent on the source-size parameter r_g and increases as the source gets smaller. The peak, in this case for identical fermions, is suppressed by roughly a factor of 2 through Pauli exclusion. This suppression corresponds to the enhancement observed for identical bosons, the normal second-order interferometry effect in pion-pion correlation measurements. The problem for this work is to compare experimental and theoretical correlation functions for the purpose of extracting the source radius r_g.

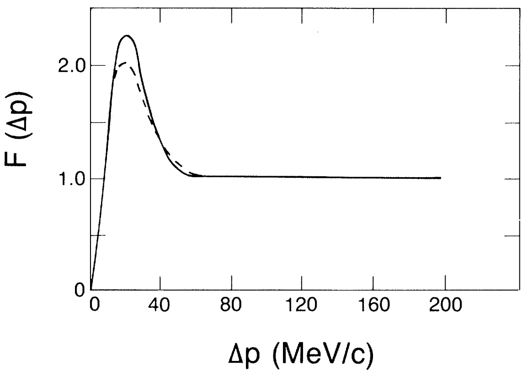

FIG. 1. The solid curve shows the p-p correlation function calculated by Koonin for a source of radius $r_g = 3$ fm and a source lifetime of $\tau = 0$. The dashed curve is the same correlation after applying the Plastic Ball distortion resulting from finite angular granularity.

The difficulty in this comparison is caused by the smearing of the measured correlation function by the finite angular resolution of the detector modules. This causes an error in Δp which differs for each pair, being dependent on the individual proton momenta. The nature of the distortion in the measured correlation function is therefore affected by the proton momentum distributions, functions that can change depending on cuts being made on the data. The problem has been solved by inclusion of the finite-angle distortion in the theoretical correlation by use of a Monte Carlo procedure. Our procedure uses the same mixed-event pairs that are used in the experimental determination of the correlation function and therefore automatically includes the correct proton momentum distributions. An example of a distorted correlation function is shown in Fig. 1 along with the original undistorted function. The effect of the distortion is to move strength from low Δp to higher Δp. The added contribution at Δp around 50 MeV/c is less apparent since the effect is diluted by the larger number of counts in both numerator and denominator as Δp increases. The distorted spectrum can now be directly compared with our measured correlation function. It should be pointed out that the

Plastic Ball has a reduced efficiency for detecting pairs in the low-Δp region since these pairs will tend to go both into the same detector. The efficiency has been determined from the relative number of mixed-event proton pairs occurring in the same module. The efficiency decreases from 70%, in the region of the correlation peak at $\Delta p = 20$ MeV/c, to 0 as Δp goes to 0. This loss in efficiency does not affect the ratio, but the resulting drop in statistics prevents careful comparison of data and theory at low Δp below the peak in the correlation function. However, the correlation function is well determined at $\Delta p = 20$ MeV and above and thus gives a good measure of the radius. In Fig. 2 we show an example of a measured correlation function along with the distorted theoretical correlation function. The distorted theoretical function in this case is a linear interpolation between the two bracketing predictions for $r_g = 4$ and 5 fm. This interpolated curve and corresponding radius of $r_g = 4.7$ fm was obtained by a least-squares fit to the measured correlation function. Measured correlations as well as the distorted theoretical functions are calculated separately for each proton multiplicity bin.

The extracted radii are shown as a function of proton multiplicity in Fig. 3. The error bars represent statistical errors only. For both the Ca + Ca and Nb + Nb systems the radius increases with multiplicity. These results agree with multiplicity-averaged π-π measurements of two other groups on a similar mass system (Ar + KCl) at higher bombarding energy. The result of one of these groups, Beavis *et al.*[3] at $E/A = 1.5$ GeV, is the same as ours at N_p equal to 30. The other π-π measurement, by Zajc *et al.*[4] at a beam energy of $E/A = 1.8$ GeV, is about 20% lower than our value. The proton-proton measurements with $E/A = 1.8$ GeV of Zarbakhsh *et al.*,[1] on the other hand, are roughly $\frac{1}{2}$ our values. They separate their results into two multiplicity bins and contrary to our measurements they see smaller radii at larger multiplicity.

Our radii in Fig. 3 are shown with a fit using the function $r_g = r_0(N_pA/Z)^{1/3}/(\frac{5}{2})^{1/2}$ where r_0 is a reduced radius (proportional to 1 over the density). N_p is the participant baryon charge multiplicity and A/Z has been included to reflect the presence of neutrons. The extracted radii are the radius parameters for a Gaussian source distribution, and so by inclusion of $(\frac{5}{2})^{1/2}$ in the above function r_0 becomes the radius parameter of an rms-equivalent sharp sphere.[9] The value of r_0 extracted from the fits is 1.9 fm for the two systems studied. Comparing this directly with $r_0 = 1.2$ fm, the sharp-sphere r_0 for normal nuclei, yields a participant-region freezeout density about 25% of normal nuclear density, considerably lower than the twice-normal den-

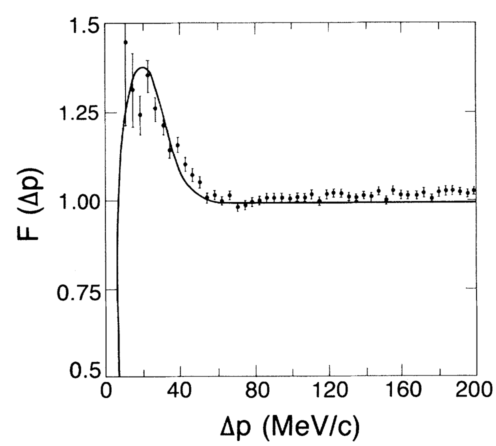

FIG. 2. The measured proton-proton correlation function for Ca + Ca with a proton multiplicity from 25 to 32. The solid curve is a least-squares fit interpolation between distorted theoretical correlation functions for radii of 4 and 5 fm which differ from each other by 25% at the peak.

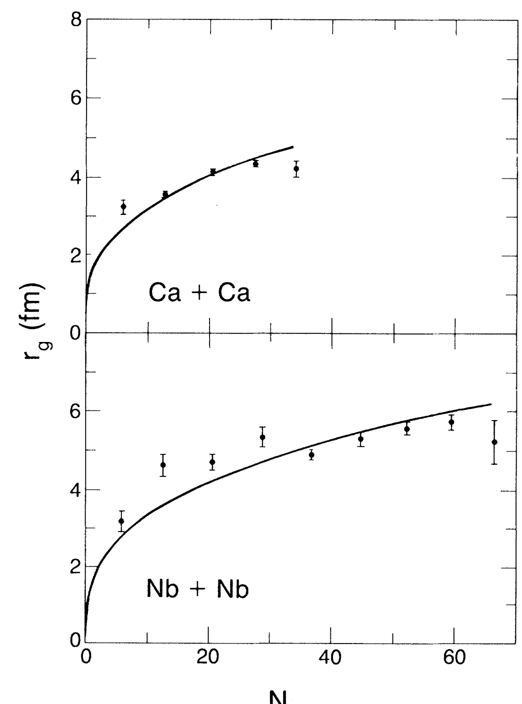

FIG. 3. Extracted Gaussian source radii as a function of proton multiplicity (N_p) for the two systems Ca + Ca and Nb + Nb at 400 MeV/nucleon. The curves are fits to the results with the function $r_g = r_0(N_pA/Z)^{1/3}/(\frac{5}{2})^{1/2}$.

sity derived[10] from the smaller radius values measured by Zarbakhsh *et al.*[1] Our density is also somewhat lower than the commonly accepted freezeout density values of 0.3 to 0.5 times normal nuclear density[11] and consequently will affect models of expanding nuclear systems.

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