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Pion Source Parameters in Heavy Ion Collisions


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Measurements of two pion momentum correlations from relativistic collisions of $^{40}$Ar and $^{20}$Ne beams incident on symmetric mass target systems have been used to obtain sizes and lifetimes for the pion source. The combined data give for the radius $R$ and the lifetime $\tau$ (assuming Gaussian distributions):

$$R = (1.0 + 0.2) \times A^{1/3}_{fm}$$

$$c\tau = (0.8 + 0.3) \times A^{1/3}_{fm}$$
Following the early work of Goldhaber, Goldhaber, Lee, and Pais, many experiments have used the momentum correlations between identical bosons to determine the space-time extent of the pion source for various reactions between elementary hadrons. This technique, known as intensity interferometry, has recently been applied to nuclear collisions at both intermediate and very high energies. Here we report on measurements of the radius and lifetime of the pion source in the reactions $1.8 \cdot \text{GeV } ^{40}\text{Ar} + \text{KCl} \rightarrow 2\pi^{\pm} + X$ and $1.8 \cdot \text{GeV } ^{20}\text{Ne} + \text{NaF} \rightarrow 2\pi^{\pm} + X$.

In principle, intensity interferometry can provide a detailed picture of the size, shape, and lifetime of the pion source, as well as determining the extent to which the pion emission process is a coherent one. In practice, the complications due to finite statistics, final-state interactions and other ambiguities in the analysis procedure make precision measurements very difficult. A discussion of these effects in the context of the present analysis may be found elsewhere.

This letter concentrates on the results most relevant to space-time models of the pion source in relativistic nuclear collisions. In particular, we assume the pion source distribution is well-approximated by the form

$$\rho(r,t) = \frac{1}{\pi^{2}R^{3}_T} e^{-\frac{r^2}{R^2} - \frac{t^2}{T^2}}$$

(1)

In the above equation, the Gaussian distribution of the time variable reflects the expectation that the pion production process will consist of several independent emissions (thereby forming a statistical ensemble), rather than the decay of a single excited state (which would lead to an exponential dependence).

The fundamental result of intensity interferometry states that the correlation function $C_2(q,q_0)$, defined as the ratio of the two-particle
inclusive probability to the product of the single-particle probabilities, is given by

\[ C_2(q,q_o) = 1 + |\tilde{\rho}(q,q_o)|^2 \tag{2} \]

where \(\tilde{\rho}(q,q_o)\) is the Fourier transform of \(\rho(r,t)\) with respect to \(q\) and \(q_o\), and \(q,q_o\) are, respectively, the magnitudes of the momentum difference and the energy difference of the two pions. Therefore, calculation of \(C_2(q,q_o)\) from an appropriate set of two-pion events permits determination of both \(R\) and \(\tau\). Note that the normalization of \(\rho(r,t)\) implies that \(C_2(q=0,q_o=0) = 2\).

This result depends essentially on the assumption of statistically independent emission of the pions \(^6\) (more precisely, the pion field should be a maximally chaotic ensemble). While deviations of the intercept of \(C_2\) from the value of 2 are often cited as evidence for a coherent component in the pion source, the possibility of such trivial effects as final state interactions or pion production via the decay of long-lived resonances should be kept in mind.

This experiment used the Berkeley Bevalac to produce beams of 1.8 A·GeV \(^{40}\)Ar, incident on a KCl target; or 1.8 A·GeV \(^{20}\)Ne incident on a NaF target. Either case provides a near-symmetric projectile-target combination. Target thicknesses of 0.5 to 1.0 g/cm\(^2\) provided a good compromise between the demands of high counting rate and high momentum resolution. Pions produced at \((45 \pm 8)^0\) in the laboratory were accepted into a broadband magnetic spectrometer (Figure 1). The laboratory acceptance of this device corresponds to \((89 \pm 12)^0\) in the (nucleon-nucleon) center-of-mass system. Four MWPC's with 2mm wire spacing determine the momentum of accepted pions to better than 2% for \(|p_{lab}| > 200\) MeV/c.

A scintillator hodoscope is used to provide a two-pion trigger for each event. The geometric overlap of the 'A' counters with 'B' counters
defined a set of 17 possible AB combinations. A good two-pion trigger was
defined as the presence of any two (different) AB combinations in conjunc-
tion with signals from the S-counters and the MWPC's. The S-counters also
served to define t=0 for the time-of-flight measurements. The time-of-
flight and pulse-height in each of these counters are recorded to allow for
off-line proton rejection. In the case of the $^{40}$Ar+KCl system both $2\pi^-$ and
$2\pi^+$ data were taken, while for the $^{20}$Ne+NaF only $2\pi^-$ triggers were used.
On the order of $10^4$ two-pion pairs were analyzed for each of these pion
polarities and target-projectile combinations.

Off-line analysis begins by using geometric criteria to identify good
track candidates. These candidates are further selected by parametrizing
each particle's vector momentum and initial target location in terms of
MWPC hit coordinates. This parametrization is obtained by fitting Monte
Carlo generated data to a Chebyshev expansion. The intrinsic precision of
this procedure is very high, so that the final momentum resolution is com-
pletely determined (for low energy pions) by multiple scattering in the
target, air, and detectors; or (for high energy pions) by the finite
spatial resolution of the MWPC's.

Events containing a pair of accepted pions are used to generate the
correlation function. Each pion in a good pair event is required to have
$220 \text{ MeV/c} < |p_{\text{lab}}| < 800 \text{ MeV/c}$, which provides a sample of events with high
momentum resolution and very low proton contamination ($< 2\%$). The correla-
tion function is created from these events by dividing the number of actual
pairs in a $q$ and $q_o$ bin, $A(q,q_o)$, by the number of background pairs in the
same bin $B(q,q_o)$. The background events are generated by combining individu-
al pions taken from different good two-pion events.
Intuitively, it would appear that this procedure for creating the background removes all correlations between particles within an event, while accurately reflecting the effects of the spectrometer acceptance. However, it is straightforward to demonstrate that a residual influence of the correlations found in the real events persists in the $B(q,q_o)$ generated by mixing pions from different events. Extraction of the correlation function from the ratio of $A$ to $B$ therefore involves an iterative procedure. Also included in this iteration procedure is the effect of the Coulomb repulsion between the two like pions. Since this repulsion is maximal for those events where $q = q_o$, and since many of our events have $q \approx q_o$, it is essential that this effect, which tends to reduce the number of pairs with small relative momentum, be included in the analysis procedure. A detailed account of the Coulomb corrections and the iteration method may be found in Ref. 7.

Typical (Gamow-corrected) results are presented in Figure 2. Shown there are projected correlation functions $<C_2(q)>$ and $<C_2(q_o)>$ defined by

$$<C_2(q)> = \frac{\sum_q A(q,q_o)}{\sum_q B(q,q_o)}, \quad <C_2(q_o)> = \frac{\sum_q A(q,q_o)}{\sum_q B(q,q_o)}$$  \hspace{1cm} (3)

While these projections are no longer true correlation functions, they are indeed adequate to demonstrate the range of the data and the quality of the subsequent fits. Also shown in Figure 2 are the results of fitting the (unprojected) correlation functions to the form

$$\alpha \left(1 + \lambda e^{-\frac{1}{2}q^2R^2 - \frac{1}{2}q_o^2T^2}\right)$$  \hspace{1cm} (4)

which, aside from the parameter $\lambda$, is the $C_2$ corresponding to the source density given by Eq. 1. The parameter $\alpha$ is used to renormalize the $C_2$'s.
presented in Figure 2 so that their asymptotic value is one. The parameter \( \lambda \), which would be unity for a perfectly chaotic (i.e., incoherent) pion source, is left free to avoid introducing systematic errors in the determination of \( R \) and \( \tau \) due to possible effects of coherence, final state interactions, event contamination, etc.

The results of fitting to Eq. 4 via a Principle of Maximum Likelihood procedure are given in Table 1. The errors quoted in all cases are statistical only. The values obtained for \( \lambda \) are substantially less than unity, and are thus consistent with a sizeable (50\%) coherent component in the pion source. However, the iterative procedure used to calculate the correlation functions introduces systematic errors in the determination of \( \lambda \) that prohibit any strong statement concerning the significance of this result.

The measurement of \( R \) and \( \tau \) are much less subject to these difficulties, so that the statistical error is the dominant error in determining these quantities. The different data sets have been combined using an assumed \( A^{1/3} \) scaling to obtain

\[
R = (1.0 \pm 0.2) \times A^{1/3} \text{fm} \\
\tau = (0.8 \pm 0.3) \times A^{1/3} \text{fm}
\]

(The values for \(^{20}\text{Ne} \) versus those for \(^{40}\text{Ar} \) are in fact consistent with this assumption.) To present the allowed range in \( R \) and \( \tau \), confidence contours for the combined data are shown in Figure 3, along with the predictions of two models. The first is a simple calculation based completely on geometric overlap, which underestimates \( R \) by nearly a factor of two. The second prediction is the result of parametrizing the results of Monte Carlo cascade code calculations\(^8,9\), which gives a value for \( R \) consistent with geometric
overlap and thus inconsistent with the data. Although the predictions for the lifetime for the two models differ by a factor of two, both the geometric overlap value and the lower range of the cascade code prediction are consistent with our data.

The other measurements of the pion source parameters for Ar+KCl were 2π streamer chamber results which found at 1.2 A·GeV:

\[ \lambda = 0.74 \pm 0.17, \ R = 3.8 \pm 0.5 \text{ fm}, \ c\tau = 5.4 \pm 1.8 \text{ fm} \]

and, at 1.5 A·GeV:

\[ \lambda = 1.2 \pm 0.2, \ R = 4.7 \pm 0.5 \text{ fm}, \ c\tau = 4.2^{+1.8}_{-4.2} \text{ fm}. \]

It is difficult to compare the results of this experiment with ours due to the different energies, impact parameter biases, mean multiplicities, and production angles used.

It is clear that understanding the time evolution of the complicated many-body state formed in a heavy ion collision requires knowledge of both \( R \) and \( \tau \). Heavier target-projectile systems will provide a greater range of \( A \) for future intensity interferometry experiments. Further experimentation and theoretical work may also lead to an increased understanding of the origin and significance of the deviation of the \( \lambda \) parameter from unity.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics at the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76-SF00098. Further support was provided by the INS-LBL collaboration program, Institute for Nuclear Study, University of Tokyo, JAPAN. We would also like to acknowledge D. Greiner of the HISS collaboration at LBL for the provision of free computer time essential to the analysis of this experiment.
Table 1. Pion source parameters for Gamow corrected data.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>R(fm)</th>
<th>c1(fm)</th>
<th>$\lambda$</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar + KCl + $2\pi^-$ + X</td>
<td>2.88$^{+0.5}_{-0.9}$</td>
<td>3.29$^{+1.4}_{-1.6}$</td>
<td>0.63 ± 0.04</td>
<td>98.2/80</td>
</tr>
<tr>
<td>Ar + KCl + $2\pi^+$ + X</td>
<td>4.20$^{+0.4}_{-0.6}$</td>
<td>1.54$^{+2.4}_{-1.54}$</td>
<td>0.73 ± 0.07</td>
<td>67.1/81</td>
</tr>
<tr>
<td>Ne + NaF + $2\pi^-$ + X</td>
<td>1.83$^{+0.8}_{-1.6}$</td>
<td>2.96$^{+0.9}_{-1.0}$</td>
<td>0.59 ± 0.08</td>
<td>125.7/82</td>
</tr>
</tbody>
</table>
REFERENCES


Figure 2
$R = 1.03^{+0.20}_{-0.19} A^{1/3}$

$\tau = 0.76^{+0.31}_{-0.31} A^{1/3}$
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